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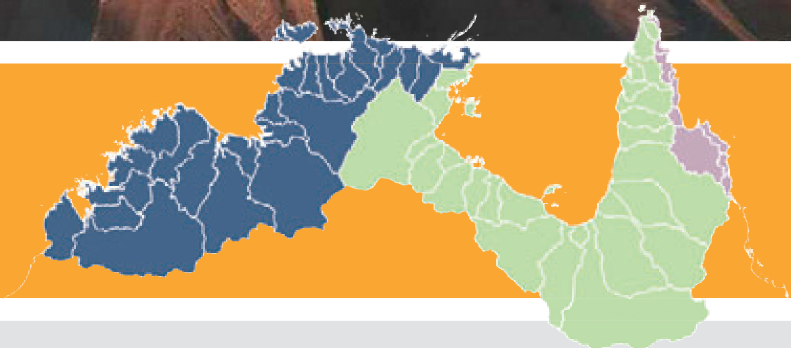

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Water in the Timor Sea Drainage Division

A report to the Australian Government from the CSIRO Northern Australia Sustainable Yields Project

August 2009

Australian Government
National Water Commission
Raising National Water Standards Program

Northern Australia Sustainable Yields Project acknowledgments

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The Project was guided and reviewed by a Steering Committee (Kerry Olsson, NWC – co-chair; Chris Schweizer, Department of the Environment, Water, Heritage and the Arts (DEWHA) – co-chair; Tom Hatton, CSIRO; Louise Minty, Bureau of Meteorology (BoM); Lucy, Vincent, Bureau of Rural Sciences (BRS); Tom Crothers, QDERM; Lyall Hinrichsen, QDERM; Ian Lancaster, NRETAS; Mark Pearcey, DoW; Michael Douglas, Tropical Rivers and Coastal Knowledge (TRaCK); Dene Moliere, Environmental Research Institute of the Supervising Scientist (*eriss*); secretariat support by Angus MacGregor, DEWHA) and benefited from additional reviews by a Technical Reference Panel and other experts, both inside and outside CSIRO.

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Courtesy of the Western Australia Department of Water

Photographer: Suzi Wild

Director’s Foreword

Following the November 2006 Summit on the southern Murray-Darling Basin (MDB), the then Prime Minister and MDB state Premiers commissioned CSIRO to undertake an assessment of sustainable yields of surface and groundwater systems within the MDB. The project set an international benchmark for rigorous and detailed basin-scale assessment of the anticipated impacts of climate change, catchment development and increasing groundwater extraction on the availability and use of water resources.

On 26 March 2008, the Council of Australian Governments (COAG) agreed to expand the CSIRO assessments of sustainable yield so that, for the first time, Australia would have a comprehensive scientific assessment of water yield in all major water systems across the country. This would allow a consistent analytical framework for water policy decisions across the nation. The Northern Australia Sustainable Yields Project, together with allied projects for Tasmania and south-west Western Australia, will provide a nation-wide expansion of the assessments.

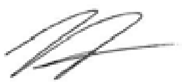
The CSIRO Northern Australia Sustainable Yields Project is providing critical information on current and likely future water availability. This information will help governments, industry and communities consider the environmental, social and economic aspects of the sustainable use and management of the precious water assets of northern Australia.

The projects are the first rigorous attempt for the regions to estimate the impacts of catchment development, changing groundwater extraction, climate variability and anticipated climate change on water resources at a whole-of-region scale, explicitly considering the connectivity of surface and groundwater systems. To do this, we are undertaking the most comprehensive hydrological modelling ever attempted for the region, using rainfall-runoff models, groundwater recharge models, river system models and groundwater models, and considering all upstream-downstream and surface-subsurface connections.

To deliver on the projects CSIRO is drawing on the scientific leadership and technical expertise of national and state government agencies in Queensland, Tasmania, the Northern Territory and Western Australia, as well as Australia’s leading industry consultants. The projects are dependent on the cooperative participation of over 50 government and private sector organisations. The projects have established a comprehensive but efficient process of internal and external quality assurance on all the work performed and all the results delivered, including advice from senior academic, industry and government experts.

The projects are led by the Water for a Healthy Country Flagship, a CSIRO-led research initiative established to deliver the science required for sustainable management of water resources in Australia. By building the capacity and capability required to deliver on this ambitious goal, the Flagship is ideally positioned to accept the challenge presented by this complex integrative project.

CSIRO has given the Sustainable Yields Projects its highest priority. It is in that context that I am very pleased and proud to commend this report to the Australian Government.



Dr Tom Hatton

Director, Water for a Healthy Country

National Research Flagships

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Executive Summary

A lot of rain falls on northern Australia, but its arrival is restricted in time and uneven in its distribution. Where and when it occurs is generally impractical for water resource development and there are large variations in how much comes year to year. There is little or no rain for three to six months every year and potential evapotranspiration rates are very high. Runoff follows a similar pattern to rainfall. The landscape is generally not amenable to storing water and the climate is not conducive to keeping it. Consequently, few rivers flow during the dry season and those that do are fed by groundwater, mostly at discrete points. Groundwater offers potential for increased extractions, but aquifers are seasonally dynamic and there is little opportunity to increase groundwater storage as the aquifers fill during the wet season and drain through the dry. Any change to surface or groundwater regimes will likely have consequences to the environment. Future rainfall is expected to be similar to that experienced historically, with future potential evapotranspiration being slightly higher throughout the year.

The Northern Australia Sustainable Yields Project

The National Water Commission – on behalf of the Council of Australian Governments and in consultation with the Australian Government Department of the Environment, Water, Heritage and the Arts – commissioned CSIRO to assess the water resources of northern Australia, covering the Timor Sea and Gulf of Carpentaria drainage divisions and that part of the North-East Coast Drainage Division that lies north of Cairns. This area comprises 64 Australian Water Resources Council (AWRC) river basins, including the Torres Strait Islands, Gulf of Carpentaria islands and Tiwi Islands. Building on the success of the Murray-Darling Basin Sustainable Yields Project (completed in 2008), the Northern Australia Sustainable Yields Project has developed a methodology for a spatially contiguous and repeatable assessment of water resources and has applied those methods to assess water resources under four scenarios:

- historical climate (1930 to 2007) and current development
- recent climate (1996 to 2007) and current development
- future climate (~2030) and current development
- future climate (~2030) and likely future development.

Development refers to the use of surface and groundwater supplies, and this project assumes full allocation of existing (current) and planned (future) water entitlements, as determined by the jurisdictions. Wherever possible, actual use, which is generally less than entitlements for northern Australia, is also assessed for modelling and discussion. The project presents the potential changes in the hydrological regime at sites of important environmental assets (which are often important social and cultural sites); considers the unique seasonal climate characteristics of northern Australia; and investigates surface–groundwater interactions. The project also assesses current water storages and storage options, including groundwater storage, under the different scenarios, but has not carried out a site specific assessment, nor carried out a storage-yield-reliability assessment.

This project is a desktop study. No new data have been collected. New data were generated through numerical modelling using existing data as a base, while new interpretations of existing data were undertaken. The project highlights areas (regions and information) that require further investigation, and includes a gap analysis.

Assessments, and subsequent reporting, have been made at the region scale, with regions ranging from 45,000 km^2 to 165,000 km^2, and comprising one or more river basins. Thirteen regions are defined for this purpose. Modelling, however, is performed at a resolution of about 29 km^2 (0.05 by 0.05 degree cells) for rainfall, evapotranspiration, recharge and runoff analysis, and at variable resolution for the groundwater analyses. These results are aggregated to the region scale; commentary at the local scale would require further, more detailed investigations. Generally, however, there are inadequate data to test models at the finer scale.

This project marks the first time a consistent, robust and transparent assessment has been carried out across the three jurisdictions of northern Australia, and the first time models have included an assessment of possible future climate implications. The findings from this project derive from the outcomes of modelling and the synthesis of existing data and information used to calibrate and substantiate that modelling. Some of these findings echo previous commentary, such as can be found in the National Land and Water Resources Audit.

This project constitutes the first activity under the Northern Australia Water Futures Assessment (NAWFA) and provides critical information for the Northern Australia Land and Water Taskforce (NALWT).

This project provides three division reports (one for each of three drainage divisions, and including the 13 region reports), as well as Science Reports. This report records the results of investigations across the Timor Sea Drainage Division. The Timor Sea Drainage Division comprises 26 Australian Water Resources Council river basins, which, for ease of reporting, have been amalgamated into six regions. This executive summary provides 18 key findings derived from the assessment of the Timor Sea Drainage Division.

Assessing water resources across the Timor Sea Drainage Division

For each region this project assesses past, present and possible future water resources. Future climate estimates use internationally recognised global climate models. Where feasible, water availability is assessed through modelling surface water, groundwater and surface–groundwater interaction. This project does not assess sustainable yield. A complete **water sustainable yield assessment**, which incorporates consideration of the purposes of water use and its environmental, social, cultural, economic and political values, is outside the scope of biophysical modelling that CSIRO was commissioned to complete within this project.

A **water resource assessment** (Figure I) has been achieved for all regions of the Timor Sea Drainage Division. This identifies how much water there is, in all its guises, at any given location, at any given time within the constraints of the current data. Climate data (rainfall, solar radiation, maximum and minimum temperature, relative humidity) are measured at an adequate spatial and temporal resolution for a regional assessment; landscape information is available at a reliable resolution; and sufficient surface and groundwater monitoring data have been gathered to make an informed assessment of components of the hydrological cycle. The climate data provide input for the rainfall-runoff modelling, generation of streamflow data and diffuse groundwater recharge modelling.

Key finding 1

Water availability assessments can be made for parts of key catchments

Where detailed numerical river systems and groundwater modelling is possible, an increased level of assessment can occur. If sufficient information on storage and release potential is available, or where no surface water regulation exists, a **water availability assessment** may be possible. The aim of a water availability assessment is to determine the amount of water that could be diverted or extracted from each source, at any given location, at any given time. Numerical modelling requires adequate data to calibrate the models and to provide sufficient spatial and temporal information to represent past conditions. A sufficient period of monitoring is required to provide both baseline conditions and confidence in forward projections. In the Timor Sea Drainage Division, there are two groundwater models and three surface water models that are suitable for regional-scale water availability assessment. Thus, the Darwin River Dam of the Van Diemen region, the Daly River basin and the Lower Ord catchment, downstream of Lake Argyle, have calibrated surface water models, while the Darwin Rural Area-McMinn's-Howard East part of the Van Diemen region and the Katherine-Douglas-Daly areas of the Daly region both have numerical groundwater models (Figure I).

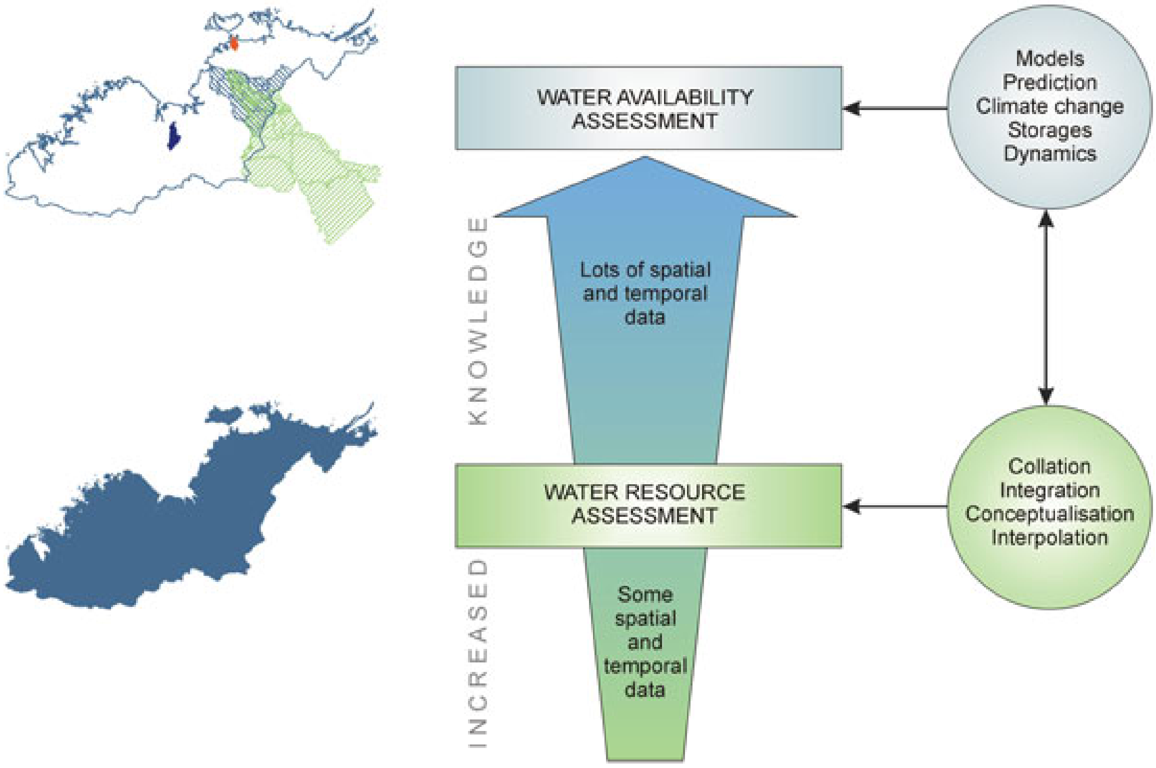

Figure I. Schematic illustrating the levels of water assessment capability for the Timor Sea Drainage Division as defined under this project. Shaded areas have sufficient information and numerical models to carry out the labelled level of assessment

Integral to this project is the identification of gaps in three areas: data, information and knowledge. A key limitation of the project lies in the lack of water-related data for northern Australia. We restrict climate analyses to the 77 years from 1930 to 2007. Prior to this there are too many gaps across northern Australia to allow a contiguous analysis. Even today, there are still significant spatial gaps in rainfall data that restrict detailed analysis, particularly in the important headwater regions (Figure II). Stream gauging stations and reliable groundwater monitoring bores are sparsely located. The level of confidence in low flow records at many gauging stations is poor. The paucity of flow datasets greatly inhibits the potential to assess the linkages between ecological systems and hydrological regime. Data are especially sparse in floodplain regions where maintenance of recording equipment is difficult. For streamflow data, establishing rating curve relationships can be difficult and confidence in data can be compromised. Reliable groundwater monitoring bores are also sparse, but locally have adequate concentration for modelling.

Key finding 2

There is a paucity of quality data for water resource accounting

Surface water model calibration relies heavily on streamflow data from the 1970s and 1980s, with only a few locations having streamflow data extending back to the 1950s and a reduced data set through to the present due to closures of gauging stations in recent years. Groundwater information is locally available, but large areas remain devoid of any quantitative groundwater data.

Across the Timor Sea Drainage Division, climate data was modelled at a daily time step since 1930 (more than 28,000 days) at a spatial resolution of roughly 29km^2 across 573,400 km^2 (generating nearly 50,000 grid cells). Twenty-six variables were processed for each cell for each day. Future scenario modelling required this to be repeated for 15 global climate models (GCMs) to produce climate data for our best estimate of future (around 2030) conditions. These data were fed into rainfall-runoff models, which were run at the same spatial and temporal resolution. This generated streamflow data for more than 330 stream reporting nodes (SRNs), which included all gauging station locations, sites of environmental importance and key tributary junctions and surface water storage locations. Additional SRNs can be extracted for any river reach within the Daly region. Streamflow conditions were assessed for low and high flow regimes and annual flow metrics were produced at 22 environmental sites. The streamflow data was assessed against gauging station data, of which there are only 77 still in operation across the entire drainage division.

The climate data also feed into a diffuse recharge model to provide potential shallow groundwater recharge estimates across the 12 major soil types of northern Australia; for 3 different vegetation habitats.

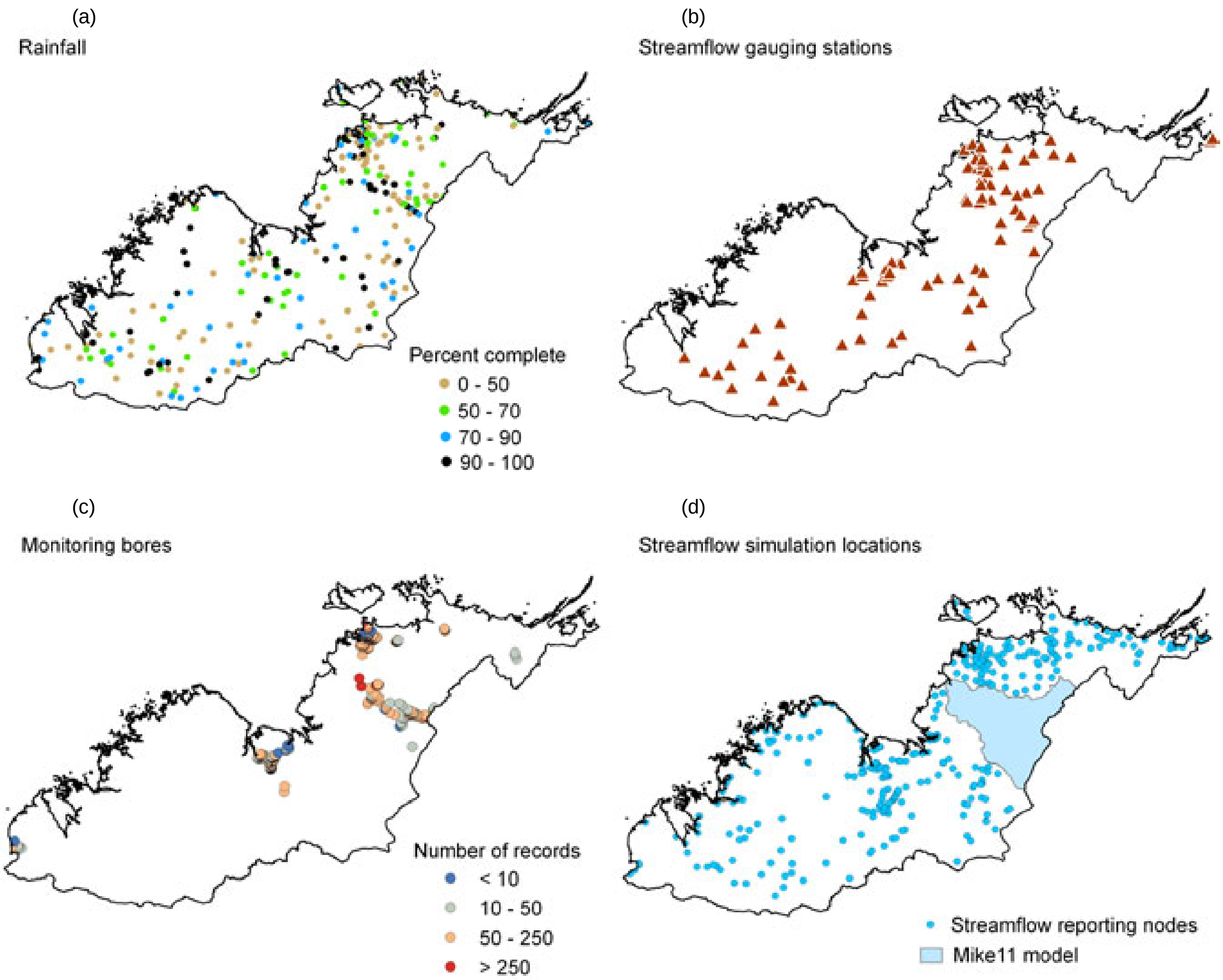

Figure II. Locations across the Timor Sea Drainage Division of (a) Australian Bureau of Meteorology stations measuring daily rainfall used in the SILO database for the current decade; (b) currently active streamflow gauging stations, (c) current groundwater monitoring bores and (d) streamflow reporting nodes for this project

An extreme climate

The Timor Sea Drainage Division receives a substantial amount of rainfall each year. An average 500,000 GL (equivalent to 45 times the capacity of Lake Argyle, or 1000 Sydney Harbours) of rain fell across the drainage division each year between 1930 and 2007. From year to year, however, there is great variability in this amount, (Figure III). The driest year, 1952, received half (244,000 GL) the mean amount; the wettest year, 2000, received nearly twice (820,000 GL) as much. Averages belie this variability and a single extremely wet year can dramatically increase the long-term average. This variability increases away from the coast and towards the south: The Fitzroy (WA) region in the south-west has twice the coefficient of variability for rainfall compared to the Van Diemen region in the north (Table I).

Key finding 3

There is high inter-annual climate variability

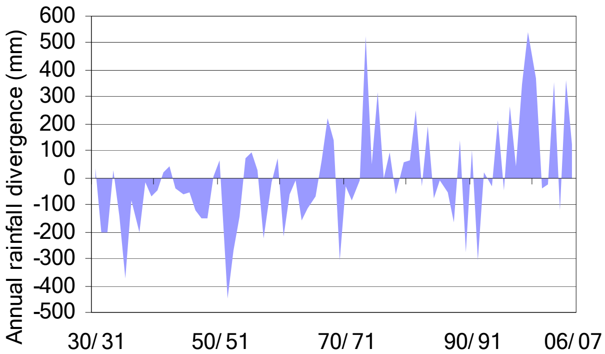

Figure III. Annual historical rainfall divergence (mm) from the historical mean, averaged over the Timor Sea Drainage Division

Over 95 percent of annual rainfall falls between November and April, and between three and six months of the year receive little or no rain at all. The potential for evaporation, and for plant transpiration, is high throughout the year. On average, potential evapotranspiration is greater than the amount of rainfall received for ten months of the year. During a few months in the wet season rainfall exceeds potential evapotranspiration and this drives seasonal stream flow. Climatically, on an annual basis, rainfall is insufficient to meet evaporative demand and the landscape may be described as water-limited (Figure IV).

Key finding 4

The climate is extremely seasonal and the landscape may be described as annually water-limited

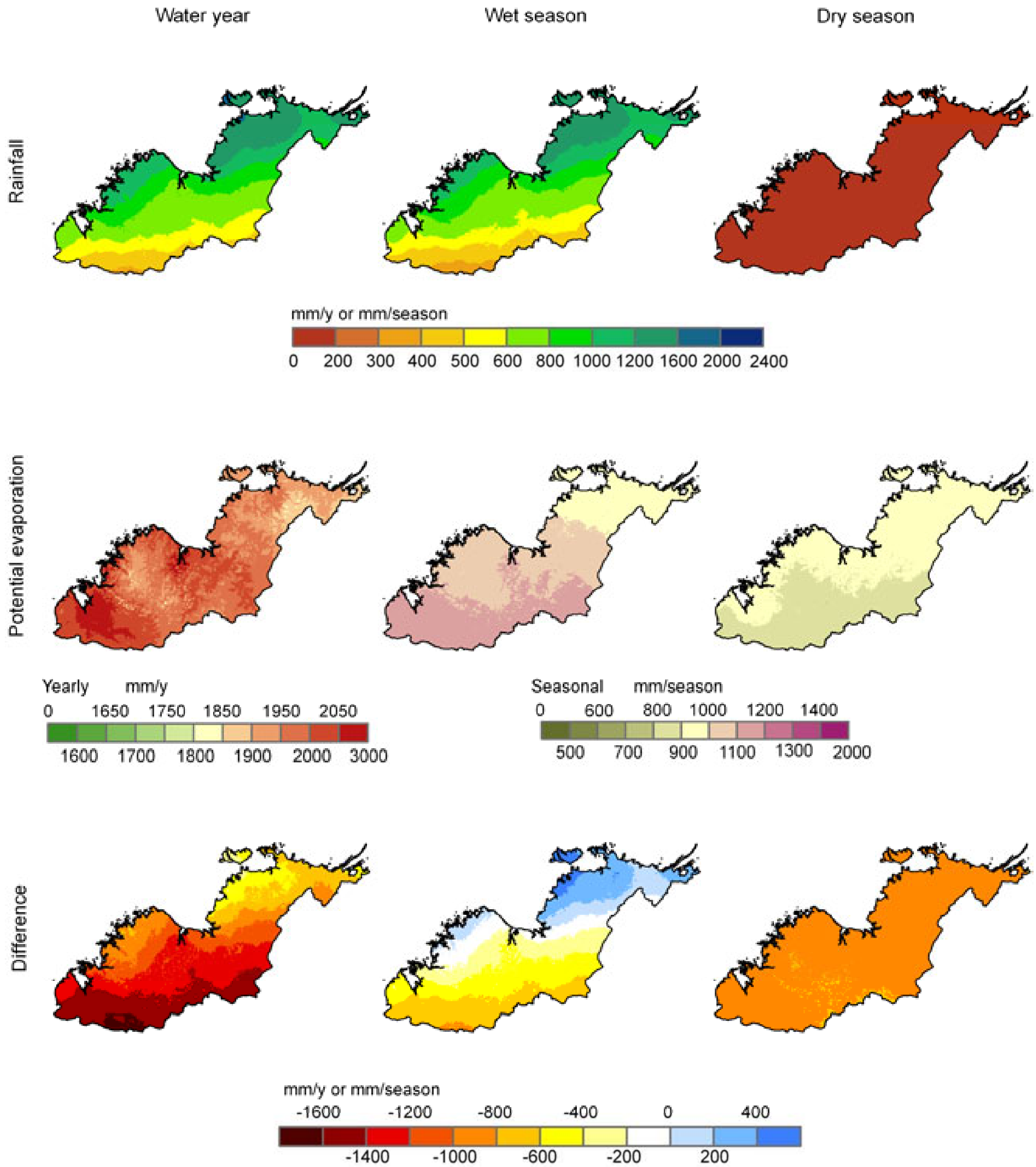

Figure IV. Spatial distribution of historical mean annual (water year = 1 September to 31 August), wet season (1 November to 30 April) and dry season (1 May to 31 October) rainfall and areal potential evapotranspiration (potential evaporation) and their difference (rainfall less areal potential evapotranspiration) across the Timor Sea Drainage Division

Historical and current water resources

Key finding 5

Most rain, and runoff, occurs near the coast, not the headwaters

Most rain falls near the coast, on the estuaries, not in the rivers' headwaters (unlike the Murray-Darling Basin for example) (Figure V). Rainfall decreases away from the northern coast and runoff patterns mimic this rainfall distribution. Runoff varies from 40 to less than 3 percent of rainfall from north to south, generating about 90,000 GL of streamflow across the drainage division. (This compares to 83,000 GL reported by the jurisdictions for the National Land and Water Resources Audit). This pattern of runoff combines with the generally low relief for much of the coastal region to provide little opportunity to increase surface storages. Surface storage opportunities occur mainly in the upper reaches of catchments. In these areas, however, rainfall is lower and more sporadic, and potential evapotranspiration is highest. The high evaporation rates require large storages to compensate for evaporative losses and the high inter-annual variability means that storage areas volumes need to be substantially larger than an equivalent requirement in the southern parts of Australia for an equivalent yield and reliability of supply the country. There are few opportunities to increase surface water storage that satisfy all these requirements, and possible locations have been identified by jurisdictions.

Key finding 6

There are few opportunities for surface water storage

The Van Diemen region – the catchments surrounding Darwin – has a combination of high rainfall and adequate relief and additional potential storages have been identified. Their likely development, however, is beyond the time frame of this study (i.e. beyond 2030).

The surface waters of the lower Ord system provide water for three uses: irrigation, hydropower and environmental water provision. Level of use of diverted water for irrigation is low, but variable hydropower demand can require over 50 percent of releases from Lake Argyle.

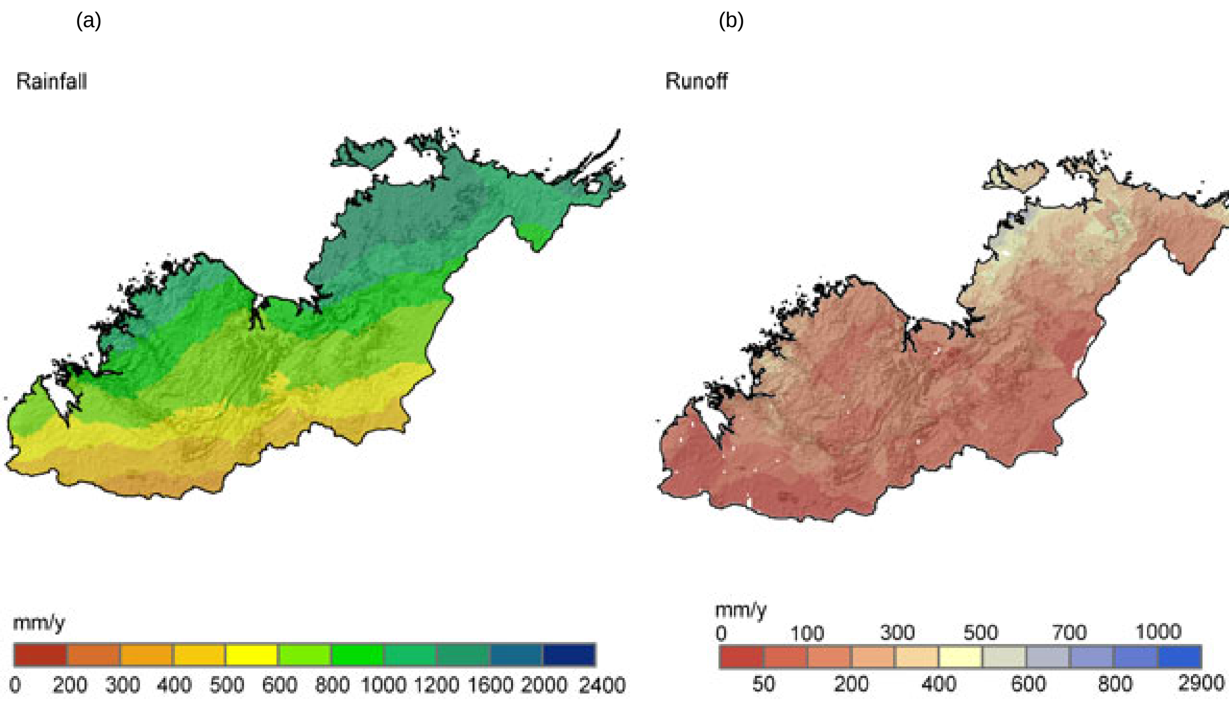

Figure V. Spatial distribution of historical mean annual (a) rainfall and (b) modelled runoff across the Timor Sea Drainage Division overlaid on a relative relief surface. White pixels on the runoff map are areas that were not modelled

Key finding 7

Most catchments have largely unimpeded flow

The majority of rivers in the drainage division, however, and the catchments they support, have little or no regulation. The few regulated rivers have a high level of regulation and this has had local consequences to flow regimes downstream of regulation structures. Of note are the Ramsar-listed sites of Lake Argyle and Lake Kununurra, created through regulation of the Ord River.

Key finding 8

There are very few perennial river reaches and these have a high cultural, social and ecological value

The high evaporation rates and the long dry season mean that there are very few rivers that flow year-round. Indeed, very few river reaches across the 573,400 km^2 of the Timor Sea Drainage Division are identified that continue to flow through the dry season and consequently these are highly valued. Values for these reaches are inter-twined and these perennial streams are often of environmental, cultural, social and developmental value. They support endemic ecosystems, provide tourism and fishing opportunities and have high spiritual significance for Indigenous and non-Indigenous people alike.

Key finding 9

Inland perennial rivers are sustained by point discharge of groundwater

Critically, the inland rivers that flow through the dry season are sustained through localised groundwater discharge: Discharge occurs where streams cross outcrops of shallow aquifers, or in high rainfall areas where rejected recharge (from aquifers that fill to capacity) maintains river flow (Figure VI). These localised points of discharge are few and the risk of impact from development is high. In these environments, ecosystems have adapted to stream flow conditions that are rainfall-dependent in the wet season and groundwater-dependent in the dry season.

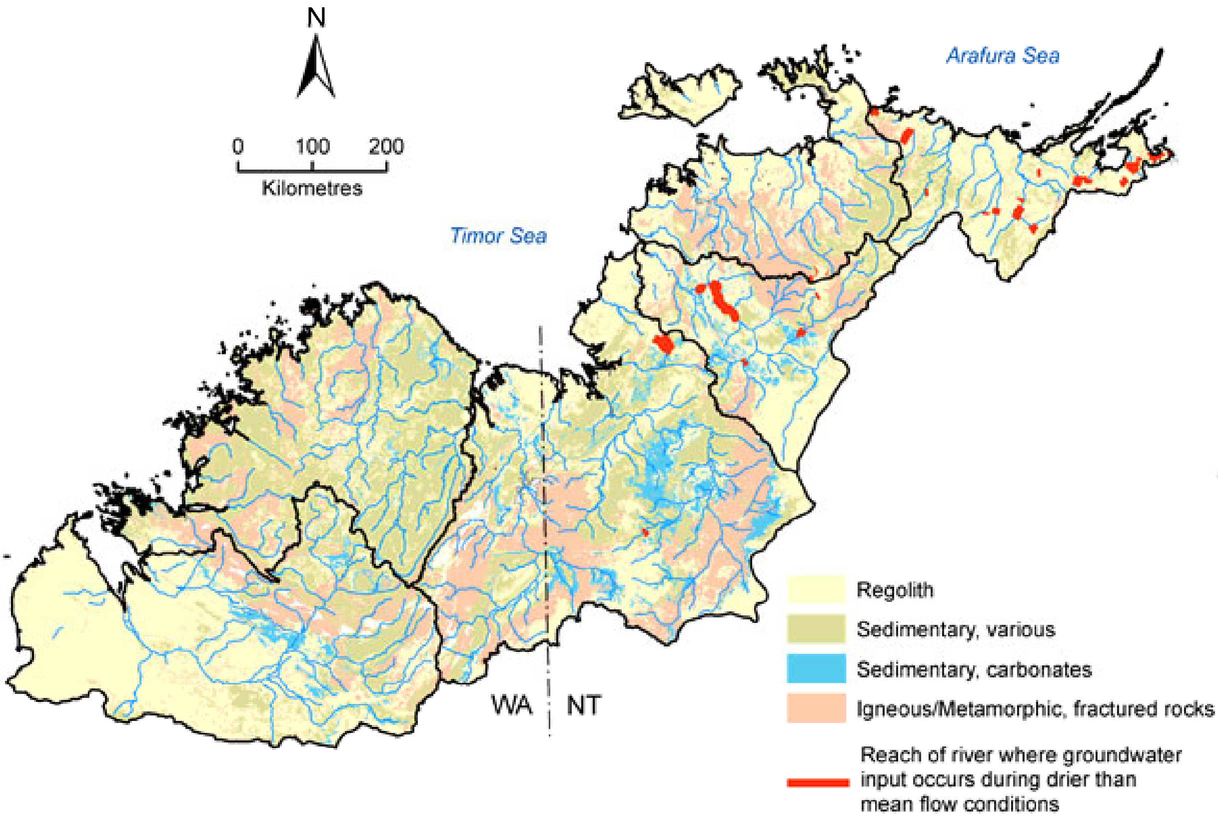

Figure VI. Surface–groundwater connectivity map for the TImor Sea Drainage Division. The few rivers that flow during the dry season are related to discharge from carbonate aquifers or from regulated flow releases (e.g. Lower Ord). An assessment has not been made for Western Australia due to insufficient data

Key finding 10

Shallow groundwater provides opportunities for development, but its dynamic behaviour poses risks of impacting local streamflow

Water tables in shallow aquifers respond dramatically to the seasonal rains, often rising by more than 15 m each year. Many aquifers fill to capacity, and drain slowly during the dry season.

The shallow groundwaters generally have good quality water, reflecting the annual fill and spill cycle, and can provide good supplies of potable water. Extractable yields are determined by the extent to which these dynamic systems can recover each year. The annual natural rise and fall of water levels, however, means these shallow systems have lower extractable yields than deeper, more regional groundwater systems, and there is a risk of extraction reducing stream flow of local rivers reliant on groundwater input.

The extensive carbonate aquifers of the Tindall Limestone and Oolloo Dolostone (and their geological equivalents), for example, may support use of over 100 GL/year. These aquifers, however, are also commonly the primary sources of water maintaining local perennial streams, so groundwater extractions adjacent to streams may need to be regulated to ensure groundwater discharge does not fall below critical limits. Monitoring and models are vital to help constrain levels of extraction. Notably, where water allocation plans are being undertaken, or are currently being developed, in the Northern Territory – such as for the Tindall Limestone around Katherine, the Oolloo Dolostone around Daly and the Darwin-Howard East area – all are resulting in caps to groundwater extraction.

Modelling in the Katherine and Douglas-Daly areas of the Daly region, for example, indicate that current allocations are at the limit of recoverable groundwater extraction. Extractions from the fractured rock aquifer systems near Darwin are also at or near capacity. Under current development in the Darwin Rural Area-McMinn's-Howard East part of the Van Diemen region, the aquifer system is functioning in overdraft mode. That is, the majority of years see a decline in groundwater levels through the dry season, with recovery during the subsequent wet season. Some years of below average rainfall, however, do not result in full recovery of groundwater levels. Any further development of this system is deemed unsustainable in the short term, though long-term recovery is possible based on the variability seen in historical records.

Groundwater recharge rates are variable across the landscape, and depend on soil type, vegetation and topography as well as rainfall amount and other climate variables. The complex interplay between these parameters means there is not a direct correlation between groundwater recharge rates and rainfall amount. Modelling indicates that rainfall regime (rain per rain day, number of rain days) is critical, and lower total rainfall might still result in higher recharge. There are also complex pathways for water infiltration to water tables, via sinkholes or dissolution hollows, for example, and these may change in importance through the year. Hence, rivers may recharge groundwaters during the wet months, whilst discharging groundwater may maintain river flow during the dry months. The large areas of carbonate aquifers across the east of the Timor Sea Drainage Division develop karst features and sinkholes and dissolution features are important channels for water to penetrate the ground.

Key finding 11

Groundwater recharge is complex and not directly proportional to rainfall amount

Groundwater data is very sparse for most aquifers across the drainage division and there are large uncertainties regarding the volumes of groundwater that might be safely extracted. This uncertainty is greater than the variability inherent in any possible changes expected due to climate change. Increased extraction will have consequences downstream that currently cannot be fully evaluated.

There is little potential to increase the storage of shallow aquifers through artificial, or managed aquifer, recharge (MAR). These systems fill and spill with the seasons, and the time when the aquifers have drained sufficiently to accept more water coincides with the time when there is little surface water with which to recharge them. Further, much of the terrain is heavily weathered, with laterites restricting the ability to use infiltration pits. Hence, more expensive injection wells would be required, reducing the economic viability.

Key finding 12

There is little potential for increased groundwater storage

Floods are vital ecosystem events, flushing nutrients into the near-shore marine environment and providing vast on-shore breeding grounds. Flooding across floodplains also fills hollows and pools that persist through the dry season, sustaining vital ecosystems until the next wet season.

Key finding 13

Floods are essential to sustain ecosystems, but there are few ecosystem response indicators for changes in flow regimes

Across the 26 river basins in the Timor Sea Drainage Division, 22 sites on the Directory of Important Wetlands were examined. Only three of these have ecosystem response indicators against which to judge whether a change in flow would be detrimental to the ecosystem. Approaches to address this lack of information are being investigated as part of the Northern Australia Water Futures Assessment Ecological Program.

Key finding 14

Consequences of flow changes on ecological systems are largely unknown

The Ord-Bonaparte, Daly and Fitzroy (WA) regions have had sufficient research for the development of site-specific ecological flow metrics against which changes to flow regime can be assessed; this is a rarity for northern Australia. Despite the existence of these metrics for some environmental assets there is still a general lack of quantitative relationships between flow and specific ecological entities (e.g. macrophyte populations, fish passage, faunal and floral habitats), meaning that the consequences of flow changes on ecological systems are largely unknown.

Historical and recent climate trends

Examination of historical (1930 to 2007) climate suggests a slightly increasing in rain per rain day and that the recent past (back to 1996) for the Timor Sea Drainage Division has been 30 percent wetter than the previous 66 years (Figure VII). The recent past does not exhibit the full range of climatic variability seen in the historical record, nor the extremes of possible future conditions. There is considerable risk in using recent past conditions to guide future water planning. A single very wet year can significantly bias the historical mean.

Key finding 15

The wetter recent past is not indicative of historical conditions, nor the possible range of future conditions

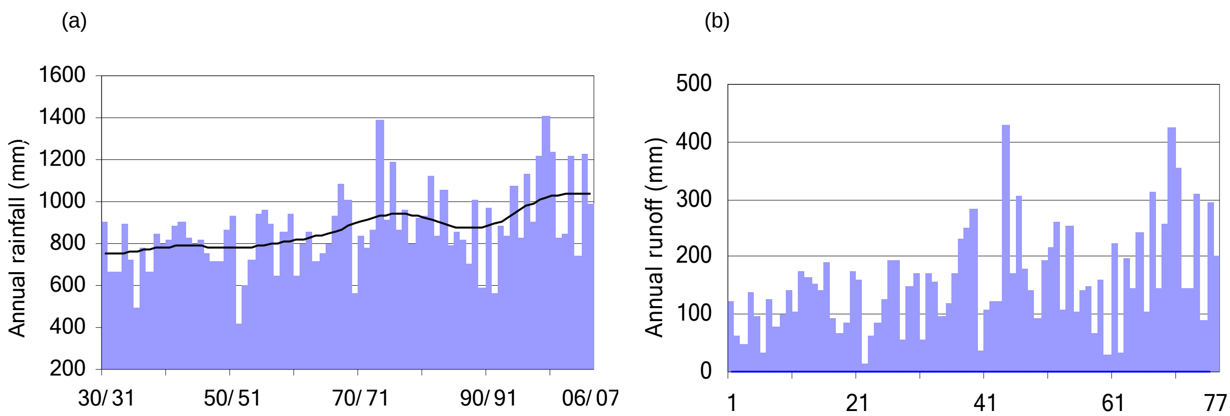

Figure VII. Historical annual (a) rainfall and (b) modelled runoff averaged over the Timor Sea Drainage Division. The low-frequency smoothed line in (a) indicates longer term variability

What the future holds

The consensus in modelling future (around 2030) conditions, using the global climate models (GCMs) suggested by the Intergovernmental Panel of Climate Change in their latest (4th) Assessment Report of 2007, is that rainfall across the Timor Sea Drainage Division will be similar to conditions of the 1990s, with slightly higher evaporation rates.

The GCMs used to model future conditions generate a range of possible future conditions based on the range of input assumptions. A consensus of models provides confidence in the predictions. Modelling provides confidence at large (regional) scales, becoming less predictive at small (local) scales. Results provide a good indication of possible trends, but should not be used to identify local changes. For the Timor Sea Drainage Division, the consensus of models predict little change in rainfall relative to ~1990 conditions, within a range of plus or minus five percent, whilst most models predict an increase in potential evapotranspiration of between one and four percent (Figure VIII).

Key finding 16

Global climate models suggest future rainfall will be similar to historical averages; potential evapotranspiration may be slightly higher

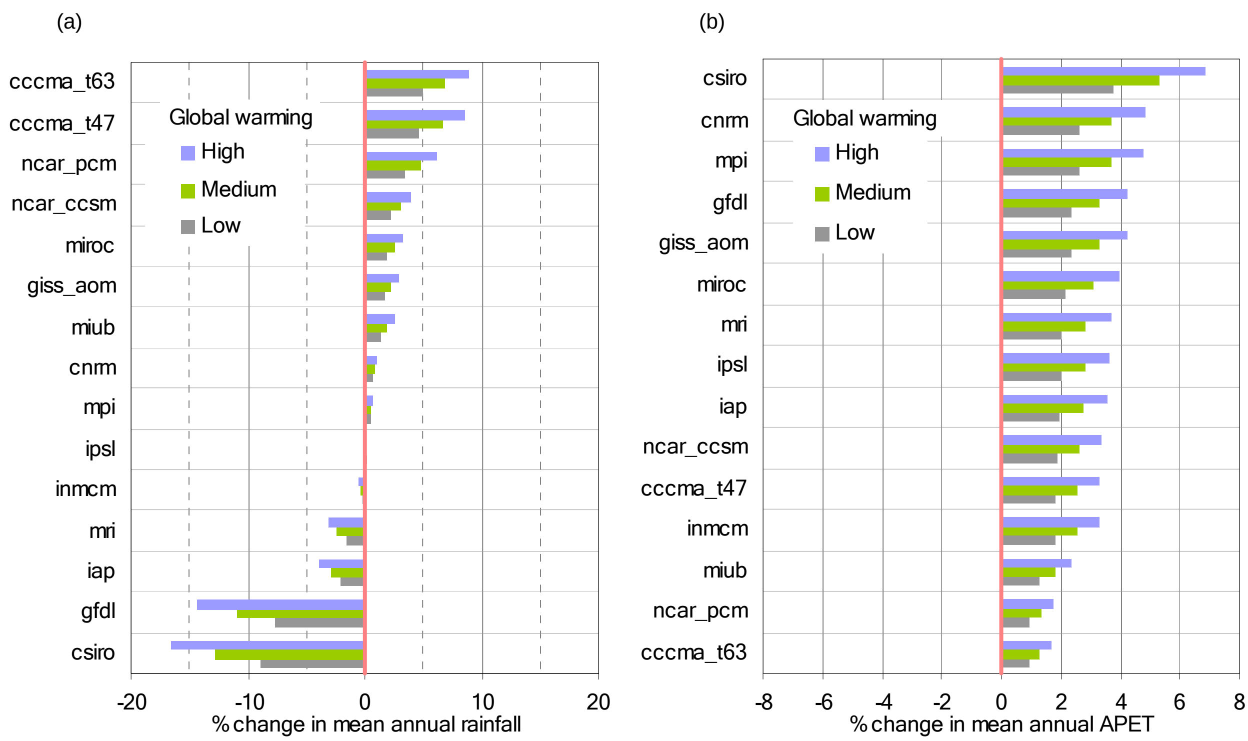

Figure VIII. Percentage change in mean annual (a) rainfall and (b) areal potential evapotranspiration under the 45 future climate simulations (15 global climate models and three global warming scenarios), relative to historical rainfall and areal potential evapotranspiration (~1990)

Key finding 17

Planned development will have minimal regional water resource consequences, but will have local impact

Consideration of planned development (where jurisdiction plans include increased water use) will not have significant impact on water resources at the regional scale in the short term (to around 2030). Longer-term impacts may have negative consequences, however, particularly where groundwater is being extracted. Local consequences may be significant, particularly where groundwater extraction and surface-groundwater interaction is prevalent.

Within the Lower Ord system, reliability of surface water supply is expected to be good into the future, unless a dry extreme climate develops. Seasonality of flow has been significantly affected since the Ord River Dam was built and these changes have resulted in a far greater change to downstream flow than is projected from climate change.

Within the Daly region, two aquifer systems are under development: the Tindall Limestone and the overlying Oolloo Dolostone. The former is mostly developed in the Katherine area; the latter around the Douglas-Daly confluence area to the north-west of the region. Current groundwater extraction is very low in both regions, but planned development in both areas is expected to increase.

Under groundwater extraction at full current entitlements the aquifers reach a new dynamic equilibrium within ten to 15 years and groundwater levels will be generally comparable to historical levels. Increasing the levels of extraction to reflect potential use in 2030, however, results in generally lower groundwater levels, most notably in the Oolloo Dolostone, with significant negative implications on the flow of the lower Daly River and hence on associated environmental regimes.

Key finding 18

Groundwater travels much slower than surface water, hence responses to any change will be measured in years, not months

Importantly, groundwaters take considerably longer than surface waters to move through the landscape. The slower flow times of groundwater compared to surface water means both that groundwater-fed rivers can continue to flow during the dry, but also that any downstream consequences of groundwater extraction may not be realised for many years. The impact of changing an extraction regime for the Tindall Limestone at Katherine, for example, will take 50 or more years for the consequences to be felt at the Daly River Middle Reaches Wetland, nearly 200 km downstream. Models thus require adequate time-series data (generally >10 years) for calibration if they are to be predictive.

Smaller groundwater developments (10 to 100 GL/year) have been developed in the Proterozoic carbonate aquifers in the Darwin Rural Area, and these have reached their extraction limit. Additional smaller developments might be feasible within the aquifers of the Canning Basin in the south-west of the Timor Sea Drainage Division but more data are required to confirm this.

Even smaller extractions (i.e. less than 10 GL/year) are feasible across most of the division, and include areas of the Cretaceous sandstone aquifers. Many of the shallow groundwater resources, including alluvial aquifers bordering major rivers, are highly dynamic, responding rapidly to seasonal rainfall and river flows.

Low flow conditions may be the most sensitive to modelled climate change. However, the paucity of calibration data provides low confidence in the quantitative assessments of flow regime change.

Region results

This report is organised by regions (Figure IX). For each region, three chapters are provided: first, a synopsis of the water resources addresses the Terms of Reference; second, contextual information compiles relevant data collected by others prior to this project; and third, the results of the modelling for each region is presented in some detail. Further details of the modelling are reported in separate Water for a Healthy Country Flagship Science Reports. Facts and figures for each region are summarised in Table I, and are compared across all regions of the project, as well as summarised by drainage division and (where applicable) for the entire project area.

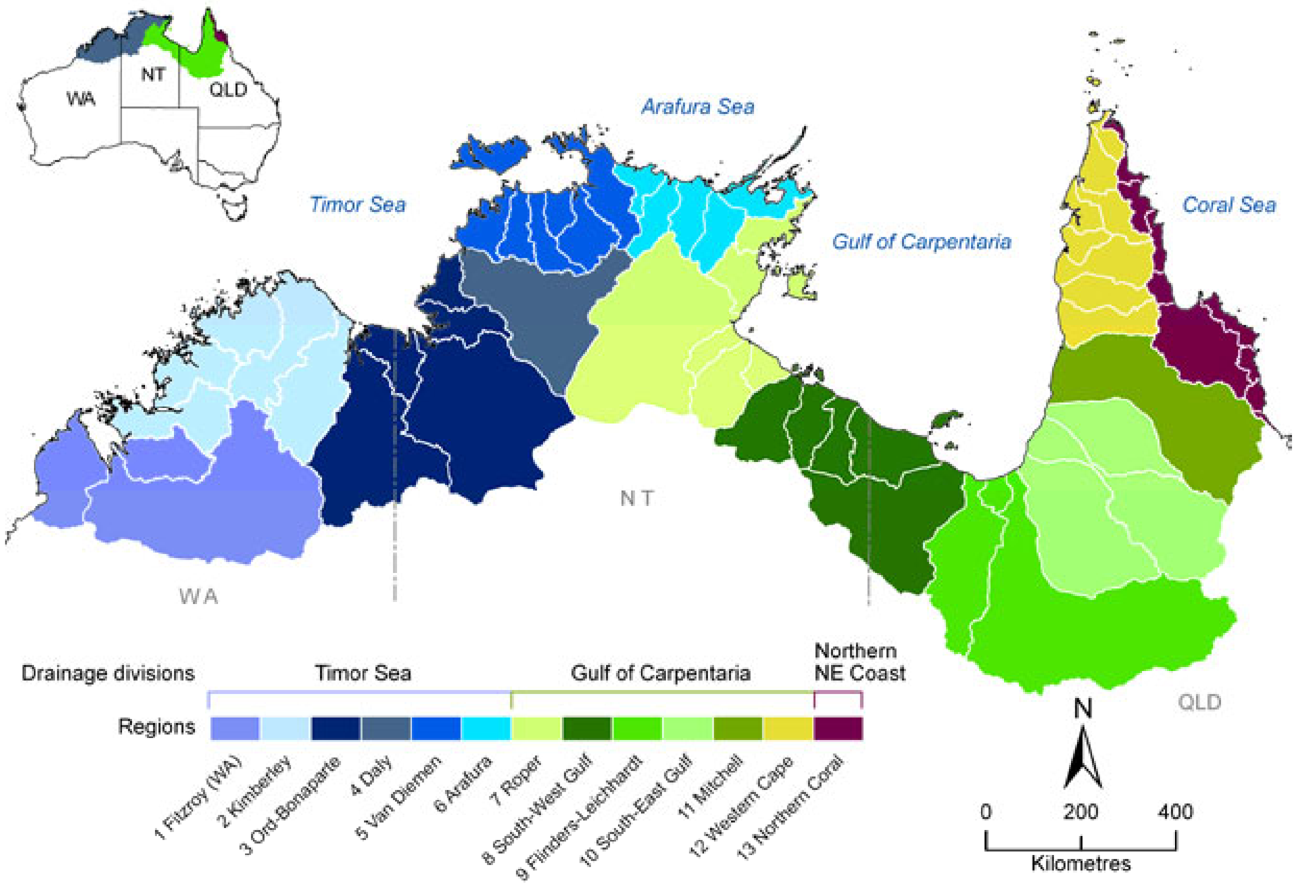

Figure IX. Reporting regions for the Northern Australia Sustainable Yields Project

Table I. Summary facts and figures for each region, drainage division and all-of-project area

	Regions of the Timor Sea Drainage Division					
	Fitzroy (WA)	Kimberley	Ord-Bonaparte	Daly	Van Diemen	Arafura
Area (km^2)	131,606	109,761	164,529	54,423	67,586	45,499
Relief (m)	980	906	919	478	568	464
Data availability	sparse	very sparse	sparse (locally reasonable)	sparse (locally reasonable)	locally dense	sparse
Climate						
Rainfall inter-annual variability	high	high	high	moderate	moderate	moderate
Rainfall coefficient of variation	0.39	0.30	0.32	0.25	0.21	0.23
Mean annual rainfall (mm)	577	950	730	1019	1390	1186
Mean annual volume of rain (TL)	76	104	120	55	94	54
10^{th} percentile rainfall (mm/y)	963	1223	1486	1493	1695	1383
90^{th} percentile rainfall (mm/y)	383	628	441	667	1155	920
Annual APET	high	high	high	high	high	high
Mean annual APET (mm)	2023	1994	1988	1942	1936	1898
Mean annual rainfall deficit (mm)	-1446	-1044	-1258	-923	-546	-712
Seasonality of rainfall	strong	strong	strong	strong	strong	strong
Mean wet season rainfall (mm)	534	898	689	975	1327	1140
Median wet season rainfall (mm)	515	876	682	954	1308	1136
Percent wet season rainfall	93%	95%	94%	96%	95%	96%
Daily rainfall intensity	high	high	high	high	high	high
Daily rainfall intensity trend	increasing	increasing	increasing	increasing	increasing	increasing
Wettest year	2000	2000	1974	1974	2000	2001
Driest year	1953	1936	1952	1952	1952	1952
Rainfall gradient	moderate	moderate	moderate	moderate	moderate	moderate
Rainfall gradient (mm/km)	1.8	1.4	1.8	1.9	3.0	1.6
Recent rainfall relative to historical	wetter	wetter	wetter	wetter	wetter	wetter
Recent rainfall percent difference	37%	27%	35%	25%	19%	22%
Future rainfall relative to historical	same	same	same	same	same	same
Future rainfall percent difference	0%	1%	2%	1%	0%	1%
Future rainfall relative to recent	drier	drier	drier	drier	drier	drier
Surface water						
Runoff inter-annual variability	high	high	moderate	moderate	low	low
Mean annual runoff (mm)	76	153	112	159	375	240
Mean percent of rainfall	13%	16%	15%	16%	27%	20%
Runoff coefficient range	3-25%	10-30%	5-30%	3-35%	15-40%	10-40%
Annual coefficient of variation	0.93	0.78	0.67	0.69	0.49	0.48
Wet season mean runoff (mm)	73	148	110	149	361	217
Wet season median runoff (mm)	45	129	93	127	336	195
Volume of streamflow (TL/y)	10	17	18	9	25	11
Percent runoff during wet season	96%	97%	98%	94%	96%	90%
Groundwater dependence for dry season flow?	yes	yes	yes	yes	yes	yes
Modelled availability (GL/y)	nm	nm	4257	8184	nm	nm
Estimated surface water use (GL/y)	NM	NM	348*	minimal	NM	NM
Current level of use	NR	NR	8%	<1%	NR	NR
Major perennial rivers	sub-flow	yes	artificial	yes	yes	yes
Monitoring of surface water use?	limited	no	yes	some	yes	no
Recent runoff percent difference	51%	71%	56%	66%	44%	38%
Future (Cmid) runoff difference	-3%	-1%	0%	1%	1%	1%

* Does not include water release for hydropower generation (up to 2500 GL/year)
na is not applicable; NR is not reported; nm is not modelled; NM not measured.

Regions of the Gulf of Carpentaria Drainage Division						Drainage divisions			All-of-project area
Roper	South-West Gulf	Flinders-Leichhardt	South-East Gulf	Mitchell	Western Cape	Timor Sea	Gulf of Carpentaria	Northern North-East Coast*	
128,518	111,890	145,223	122,094	72,229	66,766	573,400	627,000	46,551	**1,246,951**
441	431	1078	1068	1355	814	980	1355	1377	**1377**
sparse	very sparse	locally reasonable	locally reasonable	locally reasonable	locally reasonable	sparse	sparse	sparse	**sparse**
Climate									
high	high	very high	high	moderate	moderate	high	high	moderate	**high**
0.30	0.39	0.42	0.38	0.29	0.22	0.30	0.35	0.27	**0.33**
843	670	493	750	965	1417	868	779	1338	**850**
108	75	72	92	70	95	504	511	62	**1077**
1357	1168	812	1078	1615	1803	1688	1806	3640	**3640**
592	405	331	490	714	1054	383	334	917	**331**
high	high	high	high	high	high	high	high	high	**high**
1928	1961	1939	1980	1905	1874	1979	1939	1853	**1954**
-1085	-1291	-1446	-1230	-940	-457	-1111	-1160	-515	**-1104**
strong	strong	strong	strong	strong	strong	strong	strong	strong	**strong**
805	631	437	710	917	1370	822	735	1233	**802**
812	549	396	675	913	1403	822	716	1252	**785**
95%	94%	89%	95%	95%	97%	95%	94%	92%	**94%**
high	high	high	high	high	high	high	high	high	**high**
increasing	increasing	increasing	increasing	increasing	increasing	increasing	increasing	increasing	**increasing**
2001	2001	1974	1974	1974	1999	2000	1974	1974	**1974**
1952	1952	1952	1952	1952	1961	1952	1952	1961	**1952**
moderate	moderate	weak	weak	weak	moderate	weak	weak	very steep	**weak**
1.4	1.4	1.0	1.1	0.7	2.1	1.3	1.3	6.2	**0.2**
wetter	wetter	similar	similar	similar	similar	wetter	similar	similar	**wetter**
30%	37%	12%	10%	10%	11%	30%	19%	9%	**24%**
same	same	same	same	same	same	same	same	same	**same**
0%	0%	0%	0%	1%	1%	1%	0%	1%	**0%**
drier	drier	same	same	same	drier	drier	same	drier	**drier**
Surface water									
moderate	high	very high	very high	moderate	low	moderate	high	low	**moderate**
112	89	44	110	198	479	157	144	373	**159**
13%	13%	9%	15%	21%	34%	18%	19%	28%	**19%**
4-35%	4-20%	3-25%	4-16%	15-60%	15-50%	3-40%	3-60%	10-50%	**3-60%**
0.65	1.00	1.51	1.49	0.75	0.43	nm	nm	0.49	**nm**
103	87	43	109	194	458	149	140	333	**nm**
94	57	22	67	172	454	nm	nm	317	**nm**
14	10	6	13	14	32	90	90	17	**197**
92%	98%	98%	99%	98%	96%	nm	nm	89%	**nm**
yes	yes	yes	yes	yes	yes	yes	yes	yes	**yes**
nm	nm	3391	3724	6786	nm	na	na	nm	**na**
NM	NM	218	29	81	NM	>348	>328	NM	**>676**
NR	NR	6%	8%	1%	NR	na	na	na	**na**
yes	yes	no	no	no	yes	yes	yes	yes	**yes**
no	no	yes	no	no	no	some	limited	no	**locally**
54%	78%	9%	-13%	16%	27%	56%	30%	19%	**41%**
-2%	-3%	2%	-1%	-1%	1%	-1%	-1%	1%	**-1%**

* Metrics for the Northern Coral region are the same as for the Northern North-East Coast Drainage Division.

Table I (cont'd). Summary facts and figures for each region, drainage division and all-of-project area

	Regions of the Timor Sea Drainage Division					
	Fitzroy	Kimberley	Ord-Bonaparte	Daly	Van Diemen	Arafura
Groundwater						
Surface–groundwater interaction	significant	none	strong	strong	strong	strong
Significant aquifers	alluvial/ Canning	fractured rock	carbonates	carbonates	carbonates/ sandstones	carbonates/ sandstones
Inter-regional groundwater system	yes	no	yes	yes	no	yes
Groundwater development	minor	none	minor	significant	part	none
Deep aquifers	Canning Basin	fractured rock	carbonates/ sandstones	carbonates	carbonates/ sandstones	carbonates
Quality	variable	good	variable	good	good	good
Shallow groundwater	alluvials	fractured rock	alluvials	carbonate	laterites	laterites
Monitoring of groundwater use?	some	no	some	some	some	most
Dominant groundwater use	irrigation/ public supply	none	minimal	irrigation/ public supply	public supply	mining
Impact of groundwater use on surface water	significant	significant	minimal	highly significant	significant	significant
Recharge mechanisms	diffuse	local	diffuse	local	local	complex
Modelled diffuse recharge (mm/y)	50	120	70	150	295	190
Groundwater extraction (GL/y)	17	NM	40	>30	37	>15
Future development	gas hub	not expected	not expected	irrigation	urban growth	not expected
The environment						
Importance of groundwater to ecosystems	local	minimal	minimal	significant	minimal	minimal
Endemic wildlife	yes	yes	yes	yes	yes	yes
Tidal influence	significant	local	local	significant	local	local
Directory of Important Wetland sites	10	3	7	3	9	2
Sites selected for analysis	4	3	4	3	6	2
Number of stream reporting nodes	8	4	8	5	14	4
Nodes with reliable high flows	4	3	5	5	13	4
Nodes with reliable low flows	2	2	3	5	10	2
Sites with ecosystem response metrics	1	0	1	1	0	0
Flow conditions under future climate	similar	similar	similar	possible decrease	possible decrease	possible decrease

na is not applicable; NR is not reported; nm is not modelled; NM not measured

Regions of the Gulf of Carpentaria Drainage Division						Drainage divisions			All-of-project area
Roper	South-West Gulf	Flinders-Leichhardt	South-East Gulf	Mitchell	Western Cape	Timor Sea	Gulf of Carpentaria	Northern North-East Coast*	
Groundwater									
strong	limited	limited	limited	limited	strong	strong	limited	strong	**strong**
carbonates	carbonates	GAB	GAB	GAB	GAB	carbonates	carbonates/ GAB	GAB	**carbonates/ GAB**
yes	yes	yes	yes	yes	yes	yes	yes	yes	**yes**
none	none	undeveloped	undeveloped	undeveloped	capped	important	limited	none	**-**
carbonates	carbonates	GAB	GAB	sandstones	GAB	various	GAB	GAB	**various**
good	variable	variable	variable	variable	good	good	variable	variable	**variable**
laterites	sandstones	alluvials	alluvials	alluvials	sandstones	various	alluvials	alluvials	**various**
no	no	some	some	some	no	some	some	no	**some**
GDEs	mining	industry/ public supply	GDEs	stock and domestic	mining	various	various	various	**various**
significant	minimal	minimal	minimal	minimal	significant	significant	minimal	minimal	**significant**
complex	diffuse	diffuse	local	local	local	local	diffuse	local	**local**
95	55	20	70	120	335	120	115	265	**110**
NM	NM	73	12	5	31	>140	>120	14	**>275**
mining	mining	not expected	wild rivers	irrigation	wild rivers	various	various	negligible	**various**
The environment									
significant	significant	minimal	springs	local	significant	local	significant	minimal	**significant**
yes	yes	yes	yes	yes	yes	yes	yes	yes	**yes**
local	significant	significant	significant	significant	local	significant	significant	local	**significant**
2	12	6	6	4	10	34	35	18	**87**
2	5	3	3	1	4	22	16	5	**43**
6	12	3	3	1	16	42	42	12	**96**
0	5	3	1	1	14	34	24	9	**67**
0	0	3	1	1	4	24	9	3	**36**
0	0	0	0	0	0	3	0	0	**3**
possible decrease	possible decrease	possible increase	possible increase	possible decrease	possible decrease	possible decrease	possible decrease	possible decrease	**similar**

GAB – Great Artesian Basin aquifers; GDEs – groundwater-dependent ecosystems

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Water in the Van Diemen region

Water in the Arafura region

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Abbreviations and acronyms

Abbreviation or acronym	Description
AHD	Australian Height Datum
AMTD	Adopted Middle Thread Distance (the distance along a river upstream from its outlet)
APET	Areal potential evapotranspiration
AR4	The fourth assessment report of the Intergovernmental Panel on Climate Change
ARI	Average recurrence interval – the statistical length of time that might be expected to pass before a similar condition is repeated
AWRC	Australian Water Resources Council
BFI	Baseflow index – the ratio of baseflow volume to total flow volume over a specified period, commonly assumed to be the amount of groundwater input to stream flow
BRS	Bureau of Rural Sciences, Department of Agriculture, Fisheries and Forestry
CLW	CSIRO Division of Land and Water
CMAR	CSIRO Division of Marine and Atmospheric Research
CMB	Chloride mass balance
CO_2	Carbon dioxide
COAG	Council of Australian Governments
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DEM	Digital elevation model
DERM	(Queensland) Department of Environment and Resource Management
DEWHA	Department of the Environment, Water, Heritage and the Arts, Australian Government
DNRM	Previous incantation of DERM
DNRW	Previous incantation of DERM
DTW	Depth to watertable
E	Extraction
E/B	Extraction to baseflow ratio
E/R	Extraction to recharge ratio
E_f	Future groundwater extraction
EC	Electrical conductivity, a measure of salinity. 1 EC (µS/cm) ≈ 0.6 mg/L TDS
ET	Evapotranspiration
FDC	Flow duration curve
GAB	Great Artesian Basin
GCM	Global climate model, also known as general circulation model
GDA	Geographic datum of Australia
GDE	Groundwater-dependent ecosystem
GRCI	Groundwater resource condition indicator
IQQM	Integrated Quantity and Quality Model – a river systems model
MAR	Managed aquifer recharge
MDB	Murray-Darling Basin
MGSH	Maximum gauged stage height
MSLP	Mean sea level pressure
NAILSMA	Northern Australia Indigenous Land and Sea Management Alliance
NAS	Network attached storage
NALWT	Northern Australia Land and Water Taskforce (http://www.nalwt.gov.au/)
NAWFA	Northern Australia Water Futures Assessment (http://www.environment.gov.au/nawfa/)
NRETA	Previous incantation of NRETAS
NRETAS	Northern Territory Department of Natural Resources, Environment, the Arts and Sport
NSE	Nash-Sutcliffe Efficiency coefficient used to assess the predictive power of hydrological models. Values range from -∞ to +1, where +1 is a perfect match to observations. Analogous to the R^2 coefficient of determination
PET	Potential evapotranspiration
R	Recharge
RAM	Random access memory
RSF	Recharge scaling factor
SAN	Storage area network

Abbreviation or acronym	Description
SILO	Enhanced meteorological datasets (http://www.bom.gov.au/silo/index.shtml)
SRN	Streamflow reporting node
TDS	Total Dissolved Solids (mg/L ≈ 1.7 EC)
TRaCK	Tropical Rivers and Coastal Knowledge Research Hub
WRON	Water Resources Observation Network

Units of measurement

Measurement units	Description
ML	Megalitres, 1,000,000 litres
GL	Gigalitres, 1,000,000,000 litres
TL	Teralitres, 1,000,000,000,000 litres
Cumecs	Cubic metres per second; m^3/sec; equivalent to 1,000 litres per second
1 Sydney Harbour	~500 GL
1 Lake Argyle	10,380 GL

Glossary of terms

Term	Description
Scenarios	Defined periods or conditions for comparative evaluation of water resource assessments. Each scenario has three variants: wet, mid and dry, representing the 90th, 50th and 10th percentile of ranked results for each modelled condition. These are referred to as the wet extreme, median and dry extreme variants for each scenario, A, B, C and D. Additional variants include: C range which represents the inter-quartile range of values (25-75% of values) and AN which represents the pre-development (i.e. near pristine) scenario based on Historical data. AN can be defined where river systems models are available
Historical	Scenario A: 1st September, 1930 to 31st August, 2007 – except for recurrence interval calculation, when Historical refers to the period 1st September, 1930 to 31st August, 1996 (i.e. prior to Recent)
Recent	Scenario B: 1st September, 1996 to 31st August, 2007
Future	Scenario C: Climate conditions estimated for ~2030 compared to ~1990 conditions
Development	The use of surface and groundwater supplies. This assessment assumes that all current entitlements are being fully used and, where possible, actual use is also considered. Future development assumes all entitlements projected to be made available in 2030 are fully utilised. This is referred to as Scenario D
Without development	Scenarios AN, BN and CN. Represent conditions that would be expected under the climate scenarios without development, i.e. near-pristine conditions. These can be defined for systems with river systems models
Water Resource Assessment	An assessment that identifies the partitioning of rainfall through the water cycle, i.e. how much water there is in all its guises, at any given location, at any given time
Water Availability Assessment	An assessment that determines the amount of water that could be diverted or extracted from each water source, at any given location, at any given time
Water Sustainable Yield Assessment	An assessment that determines the amount of existing water resources that are available for consumptive use after the informed and equitable allocation of the resource between human uses and the environment
FCFC	Forest Cover Flow Change (*see* <http://www.toolkit.net.au/Tools/FCFC>)
AWBM, Sacramento, SIMHYD, SMARG	Rainfall-runoff models (*see* http://www.toolkit.net.au/Tools/RRL)
IHACRES Classic	IHACRES (Identification of unit Hydrographs And Component flows from Rainfall, Evaporation and Streamflow data) is a catchment-scale, rainfall-streamflow, modelling methodology that characterises the dynamic relationship between rainfall and streamflow, using rainfall and temperature (or potential evaporation) data, and predicts streamflow, developed by the Integrated Catchment Assessment and Management (iCAM) Centre, Faculty of Science, The Australian National University
MODFLOW	A groundwater flow model (http://water.usgs.gov/nrp/gwsoftware/modflow.html)
WAVES	An analytical recharge model developed by Zhang and Dawes (1998) used to estimate groundwater recharge under different soils, vegetation and climate scenarios
SRES 1B	A future (2100) greenhouse gas emissions scenario used to compare climate model forecasts
Unallocated water	Water that is identified as water potentially available for future allocation
General Reserve	Unallocated water which may be granted for any purpose
Strategic Reserve	Unallocated water which may only be granted for a state purpose

Preamble

Northern Australia Sustainable Yields Project

This project assesses, and quantifies within the limits of available data, the change to water resources under a number of theoretical climate scenarios, and hence helps define the potential change to water availability under those climate regimes. This can aid in identifying regions that may come under increased, or decreased, stress following climate change, based on what has been observed in the historical past. The paucity of long-term information for the quantification of water resources of northern Australia limits this assessment to a comparison to 77 years of climate records across the entire region (from 1930 to 2007), though locally records may extend back beyond 100 years. In many regions, however, reasonable quality data extends back only to the 1960s, while a number of catchments still remain almost devoid of good water resource information.

This project is a desktop study. No new data have been collected. New data were generated through numerical modelling using existing data as a base, while new interpretations of existing data were undertaken. The project highlights areas that require further investigation, and includes a gap analysis.

The assessments made under this project provide key information for further investigations into environmental impacts and socio-economic impacts as well as generating information to facilitate stakeholder and community consultation. Ultimately, this will inform water resource planning, management and investment (Figure 1).

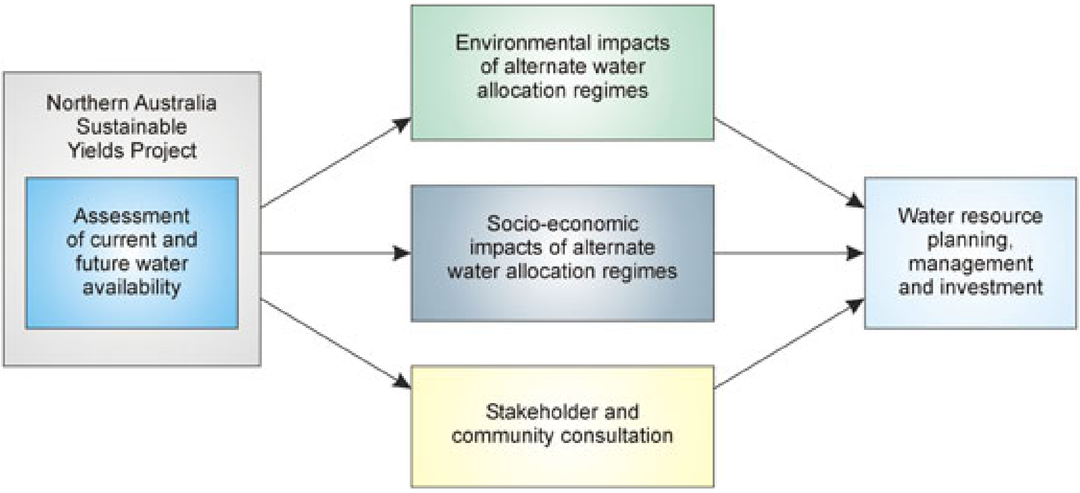

Figure 1. Project context

Determination of sustainable yield and/or over-allocation requires choices by communities and governments about the balances of outcomes (environmental, economic and social) sought from water resource management and use. These choices are best made in the light of sound technical information, and the fundamental underpinning information is a robust description of the extent and nature of the water resource.

While existing records of rainfall, streamflow and groundwater levels (and simulation models based on these data) provide a description of the resource from the past to the present, it is increasingly widely recognised that these data do not provide the best description of the likely extent and nature of the resource into the future, and thus no longer provide the best basis for planning. A careful examination of the likely implications of climate change on water resources is required as the basis for planning into the future. This includes a consideration of the direct effects (such as changes in rainfall and changes in evaporation) and indirect effects (such as changes in bushfire frequency and water demand).

The baseline information that is required for determining sustainable yields is thus an assessment of the current and likely future extent and variability of surface and groundwater resources. This project – commissioned by the National Water Commission (NWC) on behalf of the Council of Australian Governments (COAG) and in consultation with the Department of the Environment, Water, Heritage and the Arts (DEWHA) – has undertaken such an assessment of northern Australia. This one-year project (July 2008 to June 2009) covers key surface and groundwater systems and basins within the surface water drainage divisions (as defined by the Australian Water Resources Council (AWRC, 1987)) of the Timor Sea and Gulf of Carpentaria, and that part of the North-East Coast Drainage Division north of Cairns (herein referred to as the Northern North-East Coast Drainage Division) (Figure 2).

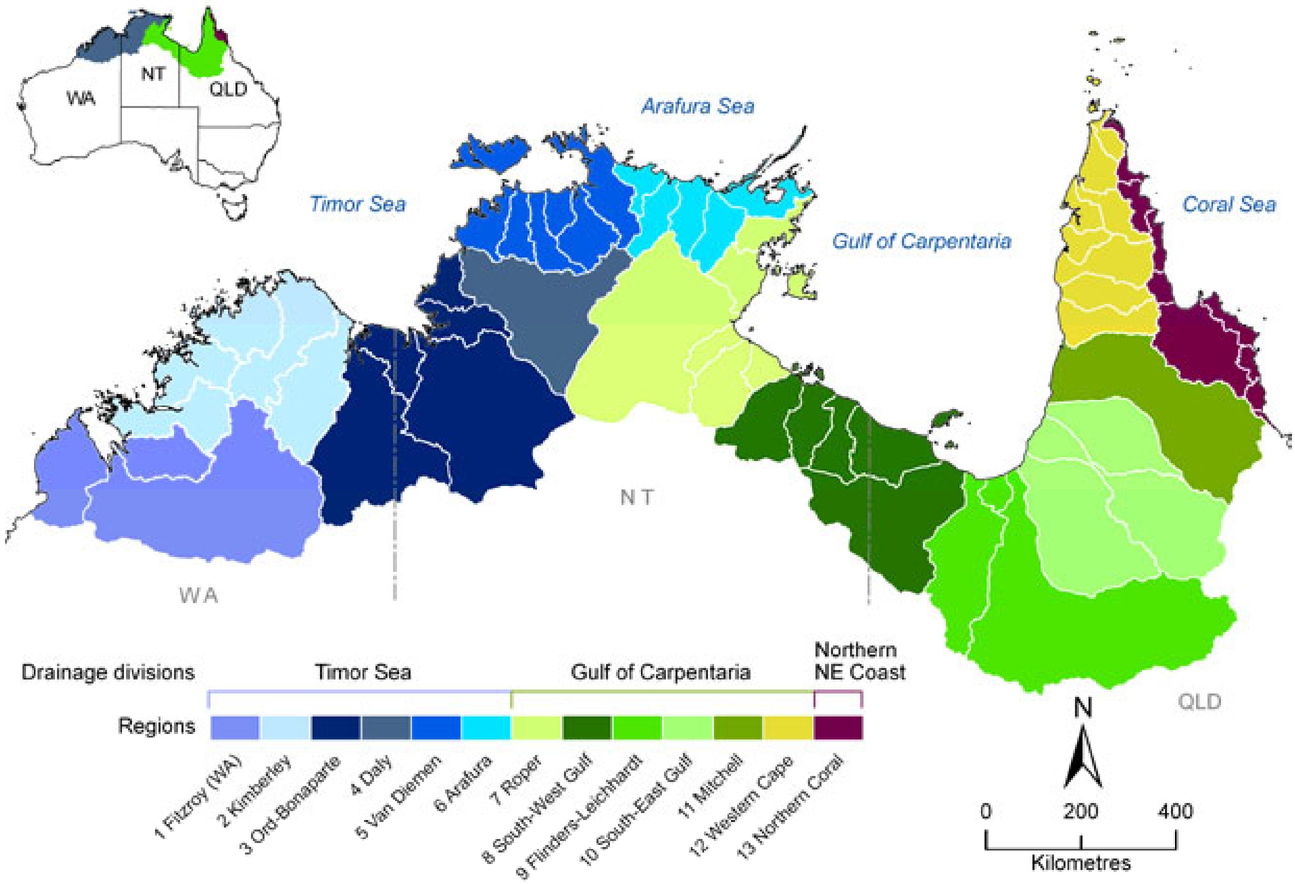

Figure 2. Extents of surface water river basins, regions and drainage divisions (inset) for the Northern Australia Sustainable Yields Project

Under the Terms of Reference, 'the CSIRO will:

1. Develop transparent, consistent and robust methodologies for determining the extent of available water resources in the catchments/aquifers of the study area, including guidance on:
    a. how to utilise the historical flow records used in surface water models and the recharge assumptions used in groundwater models, to factor in climate change and other risks;
    b. how to address the interaction between surface and groundwater systems;
    c. appropriate models/methodologies to use in regions which do not have existing surface water or groundwater models and/or which do not have comprehensive water resource data;
    d. ensuring that models/methodologies are capable of incorporating a range of 'development' scenarios or land use change activities;
    e. identifying significant knowledge and information gaps.

2. In the application of the methodologies, use existing legislation, water plans or other arrangements to guide the assessment. For catchments or aquifers either without current water resource arrangements or with plans for which environmental outcomes and/or levels of extractive use are not clear, these parameters may be inferred and any assumptions clearly stated.
3. Apply the above methodology to estimate water availability and demand in 2030 in the light of climate change and other risks to provide:
    a. Estimates of water resources on an individual catchment and aquifer basis using four different scenarios:
        i. historical climate and current development (Scenario A);
        ii. climate for the last 10 years and current development (Scenario B);
        iii. 2030 climate change and current development (Scenario C);
        iv. 2030 climate change and 2030 development of farm dams, plantations, groundwater systems and proposed irrigation development (Scenario D).
    b. For each of the scenarios (i) to (iv) above, provide an assessment of the impact of current and future predicted water resource development on key environmental assets.
4. Take into account the unique seasonal characteristics and the interconnectivity of surface and groundwater systems in northern Australia and advise on how these impact on water availability.
5. Assess water storage options in agreed catchments, including the storage of water in aquifers.
6. Work will be guided by a steering committee, chaired by the Commonwealth, with membership from the governments of Queensland, Western Australia, the Northern Territory, and the CSIRO.
7. The project will take account of current water resource assessment projects and activities underway in northern Australia where applicable, in particular those associated with the TRaCK (Tropical Rivers and Coastal Knowledge research hub) program, the Indigenous Water Policy group within NAILSMA (North Australian Indigenous Land and Sea Management Alliance) and any consultancy projects as identified by project contact group members.'

Limitations and confidence levels

This project does not define the sustainable yields of water resources of northern Australia. The term 'sustainable yield' refers to the amount of a water resource that is available for use for human development after the informed and equitable allocation of the resource between human uses and the environment. A precise definition is elusive as sustainable yield is essentially a subjective measure that varies according to the nature of the resource and stakeholder priorities (Kalf and Woolley, 2005). Whilst sustainable yield is a term that applies to all water resources, greatest discussion occurs over its use relative to groundwater resources, where slow, and often indeterminate, response times of systems mean that real-time evaluations are problematic. For surface water systems, and particularly in the north, each year represents a re-setting of that water resource availability. The vagaries of the inter-annual variability of the Australian climate may thus produce several consecutive years of below-average rainfall. In this case, drought recurrence interval becomes important. Indeed, the north may be considered as experiencing drought conditions for several months every year. This, combined with the extremely high evaporation rates experienced in the north, means that most development will require water storages that are sufficient to supply water for many years (Petheram et al., 2008). The high evaporation rates and flat landscape across much of the north limits the use of surface water storages; hence groundwater may provide an important water storage resource potential.

Report structure

This report is one of three prepared for the COAG Water Sub Group by the Northern Australia Sustainable Yields Project. A separate report is provided for each of the three drainage divisions of the north: Timor Sea, Gulf of Carpentaria and

Northern North-East Coast (north of Cairns). All follow a similar structure that reflects the requirements of the Terms of Reference listed above.

The **Executive Summary** summarises the key messages from the project.

This **Preamble** covers the background and context of the project.

Chapter 1 provides an overview of the drainage division, covering general physiography, climate, land use, vegetation, environmental assets, a summary of the drainage division's water resources, and an indication of water resource knowledge gaps.

Chapter 2 outlines the assessment approaches for different components of the water cycle. Climate, surface water and groundwater methodologies are summarised and the techniques used to assess surface–groundwater interaction are outlined. Metrics are also developed which are derived from these assessments and which illustrate changes to the hydrological regime at sites of environmental, social and cultural importance. These assessment methods are illustrated using results at a division scale; they also apply to assessments made at the regional scale. Detailed aspects are provided in an accompanying technical report on methods (CSIRO, 2009).

Subsequent regional chapters report on the water resources of individual regions as defined in Figure 2. These chapters are distinguished with a two-letter prefix designating the region under evaluation: FI (Fitzroy (WA), KI (Kimberley), OB (Ord-Bonaparte), DA (Daly), VD (Van Diemen), AR (Arafura), RO (Roper), SW (South-West Gulf), FL (Flinders-Leichhardt), SE (South-East Gulf), MI (Mitchell), WC (Western Cape), and NC (Northern Coral). For each region, there are three chapters (replace 'ID' with the two-letter prefix for the region to obtain the actual chapter number):

Chapter ID-1 summarises the water resources of the region, using information from Chapter ID-2 and Chapter ID-3, and directly addresses the Terms of Reference, specifically terms 3, 4 and 5. Essentially, this chapter provides a synoptic view of the region and covers water resource assessment; changes to flow regime at environmental assets; seasonality of the resources; surface–groundwater interaction; and water storage options. This chapter also summarises data and knowledge gaps relevant to water resource management in the region.

Chapter ID-2 summarises the background information for the region, outlining existing knowledge of water resources and prior and current investigations relevant to the water resources of the region. This chapter also outlines the current and potential future legislation, water plans and other water resource management arrangements.

Chapter ID-3 describes the modelling results and the assessment of water resources undertaken by this project. Detailed, quantified assessments are made where possible and relevant, and confidence is estimated. This chapter focuses on climate, recharge, conceptual groundwater models, groundwater and rainfall-runoff modelling, and river system water balance. Changes to flow regimes at environmental assets are also assessed.

A series of CSIRO Water for a Healthy Country Flagship Science Reports accompanies these reports. These provide further detailed analysis of the modelling methods and results, as well as additional analyses relevant to water resources of northern Australia. Some are relevant for water resources across Australia, in particular those that relate to all Sustainable Yields Projects currently being carried out.

A significant component of this project is the exposure of information and knowledge gaps that require further investigation if the water resources of northern Australia are to be adequately managed. Whilst many of these gaps are presented within these reports, an accompanying Gaps Analysis report focuses on areas of research that would further our understanding of water resources of northern Australia and outlines regions that require additional data for adequate modelling and forecasting to take place.

Northern Australia Water Futures Assessment and Northern Australia Land and Water Taskforce

The Northern Australia Sustainable Yields Project comprises the first phase of the Northern Australia Water Futures Assessment (NAWFA, <http://www.environment.gov.au/nawfa>), an Australian Government initiative. The objective of the NAWFA is to develop an enduring knowledge base of northern Australia's water resources, so that development proceeds in an ecologically, culturally and economically sustainable manner.

Subsequent phases of the NAWFA will comprise an ecological program, a social and cultural program, and the development of an enduring knowledge platform. These form the intermediate components of Figure 1, required before water planning should be undertaken. The role of this project, therefore, is not to report on consequences of changes to the water regime of the north as this will be undertaken under the subsequent programs of the NAWFA. The combined information from the completed NAWFA will take us closer to an assessment of sustainable yield for northern Australia.

The Northern Australia Sustainable Yields Project is also of interest to the Northern Australia Land and Water Taskforce <http://www.nalwt.gov.au>. The Northern Australia Land and Water Taskforce is a high-level independent group of Australian experts drawn from broad areas, including Indigenous groups, business, academia, conservation, tourism, agriculture, and the minerals and energy resource industries. The Taskforce is examining the potential for new developments in northern Australia that rely on significant local or regional water resources and are consulting with stakeholders in the north to identify opportunities for further development. The Taskforce will be informed of the outcomes of the Northern Australia Sustainable Yields Project through the Northern Australia Water Futures Assessment.

Companion science reports

A series of CSIRO Water for a Healthy Country Flagship Science Reports accompanies this division report and contains the technical support material from which the observations and results presented in this report are drawn. These companion reports will be released in October 2009. Table 1 lists the indicative titles that will be available via the project website <www.csiro.au/partnerships/NASY>.

Table 1. List of indicative titles and authors for companion science reports

Indicative title	Authors (provisional)
Data and knowledge gaps related to water resource assessment of northern Australia	Cresswell RG, Petheram C, Harrington GA, McVicar TR, McJannet DL, Hartcher M et al.
Diffuse groundwater recharge modelling across Northern Australia	Crosbie RS, McCallum JL and Harrington GA
Developing and implementing a report delivery framework for the Northern Australia Sustainable Yields Project	Cuddy SM, Schmidt B and McGillion T
Groundwater modelling of Fitzroy River Alluvium, Western Australia. Internal working document.	Dawes WR
Groundwater modelling in the Darwin Rural area, Northern Territory	Evans P, Arunakumaren J, Burrows W. and Raue J
Preliminary groundwater balances for northern Australia	Harrington GA, Dawes WR, Wiltshire E, Cranswick R, Evans R, Jolly P, Knapton A and Foster L
Groundwater model for the Tindall Limestone	Knapton A et al.
Climate data and their characterisation for hydrological scenario modelling across northern Australia	Li LT, Donohue RJ, McVicar TR, Van Niel TG, Teng J, Potter NJ, Smith IN, Kirono DGC, Bathols JM, Cai W, Marvanek SP, Chiew FHS and Frost AJ
High and low flow regime changes at environmental assets across northern Australia under future climate and development scenarios	McJannet DL, Wallace JW, Henderson A, McMahon J
Information supporting river modelling undertaken for the Northern Australia Sustainable Yields project	Petheram C, Hughes D, Rustomji P, Smith K, Van Neil TG and Yang A
Rainfall-runoff modelling across northern Australia	Petheram C, Rustomji P and Vleeshouwer J
Regionalisation of hydrologic indices. Northern Australia sustainable yields.	Sinclair Knight Merz

References

AWRC (1987) 1985 Review of Australia's Water Resources and Water Use, Volume 1: Water Resources Data Set, Department of Primary Industries and Energy, AGPS, Canberra.

CSIRO (2009) Description of project methods. Report to the Australian Government from the CSIRO Northern Australia Sustainable Yields Project. CSIRO Water for a Healthy Country Flagship, Australia. *In prep.*

Kalf F and Woolley D (2005) Applicability and methodology of determining sustainable yield in groundwater systems. Journal of Hydrogeology**,** 295-312.

Petheram C, McMahon T and Peel M (2008) Flow characteristics of rivers in northern Australia: Implications for development. Journal of Hydrology 357**,** 93-111.

1 Overview of the drainage division

This chapter summarises attributes relevant to understanding the water resources of the Timor Sea Drainage Division. This chapter covers general physiography, climate, land use, vegetation and environmental assets. This chapter also summarises the drainage division's water resources and indicates water resource knowledge and information gaps. Detailed analyses of water resources are covered in the regional chapters. This chapter is divided into the following sections:

- physiography
- climate, land use and vegetation
- environmental assets
- current water resources of the division
- knowledge and information gaps.

1.1 Physiography

The Timor Sea Drainage Division (Figure 3) includes most of the Top End and the Kimberley, and covers an area of 564,647 km^2.

Much of the landscape forms a patchwork of harsh, dry escarpments and tablelands and low-lying river flats. It is hot and dry during the dry season from May to October and often flooded during the wet season. Streams run generally west or north to the Indian Ocean and the Timor Sea, respectively, and can be very large by Australian standards. On a streamflow per area basis, it is the second wettest drainage division in Australia (after the North-East Coast Drainage Division).

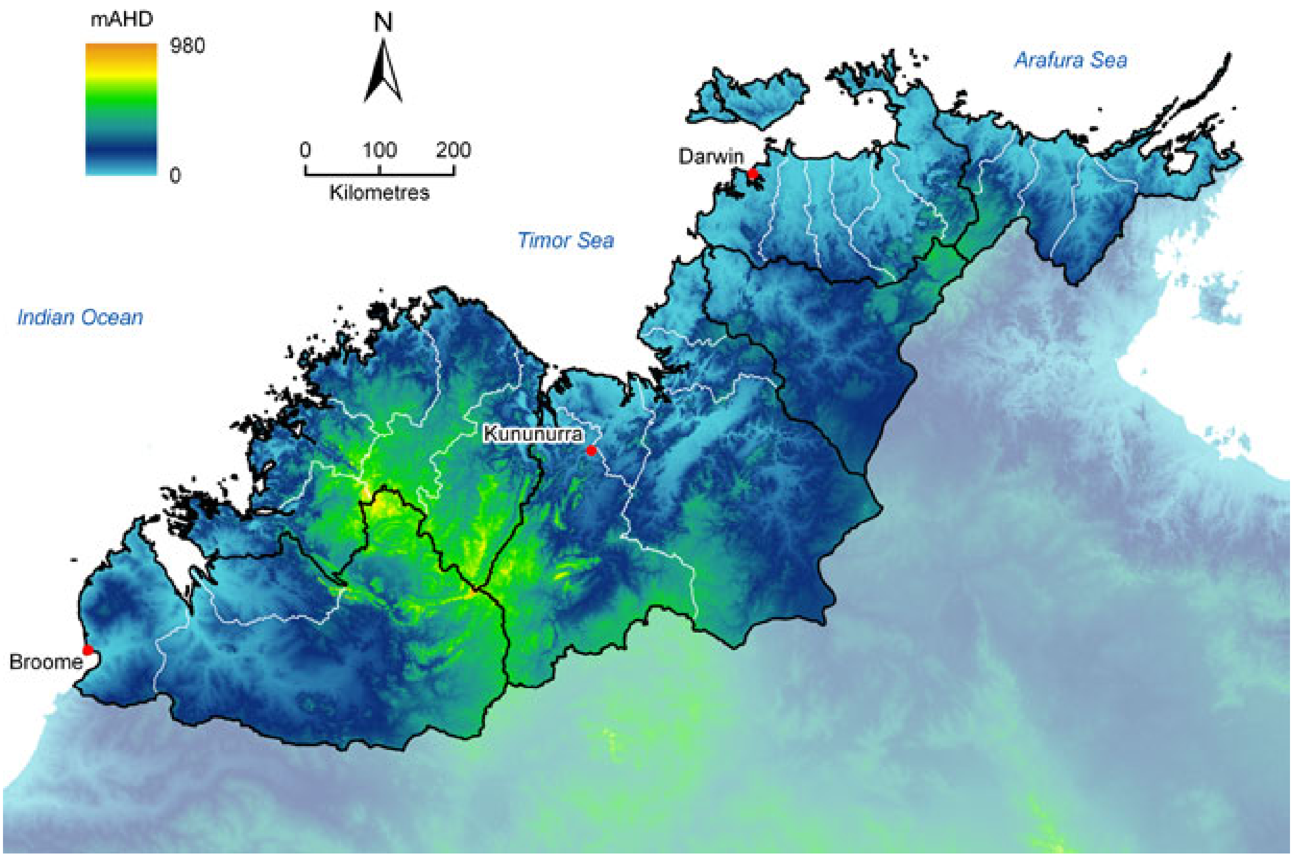

Figure 3. Topography of the Timor Sea Drainage Division showing project regions (black lines) and river basins (white lines)

The Timor Sea Drainage Division has a generally low and flat relief (Figure 4). Large river systems (Ord, Victoria, Daly and Fitzroy) have relatively low gradients; predominantly drain expansive savannah woodland plains and form extensive floodplain and coastal wetland complexes. Areas of more dissected topography (Kimberley in the south-west and Arnhem Land in the north-east) have short river basins with high gradients. Most rivers drain to coastal floodplain and wetland complexes, although the rivers of the Kimberley drain to a dissected coastal landscape with an extensive archipelago of coastal islands. Relatively shallow seas surround the drainage division, resulting in low wave energy and large tidal ranges.

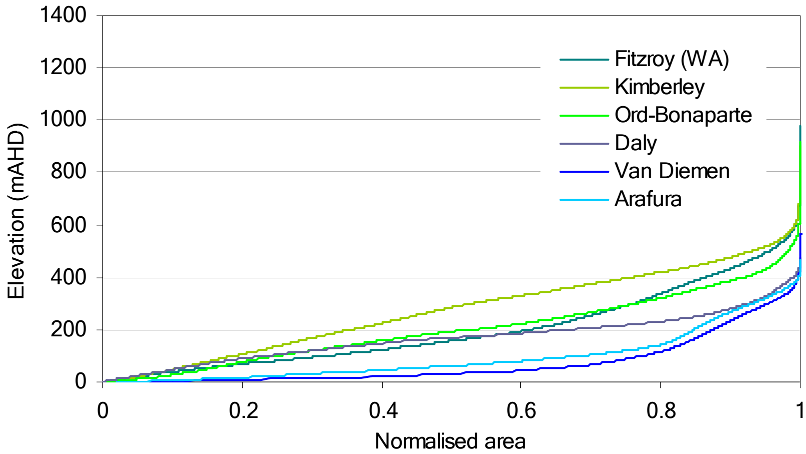

Figure 4. Hypsometric (relative relief) curves for the Timor Sea Drainage Division regions

1.2 Climate, vegetation and land use

The Timor Sea Drainage Division has climate gradients that are aligned with the coast, with a strong north–south component (Figure 5) ranging from 1687 mm in the north to 383 mm in the south. Historical (1930 to 2007) mean annual rainfall is 868 mm (Figure 6) with a high inter-annual variability. The highest annual rainfall was 1412 mm in 2000 and lowest annual rainfall was 421 mm in 1952. To the south of the drainage division, the climate becomes hotter and more arid and rainfall becomes less seasonal.

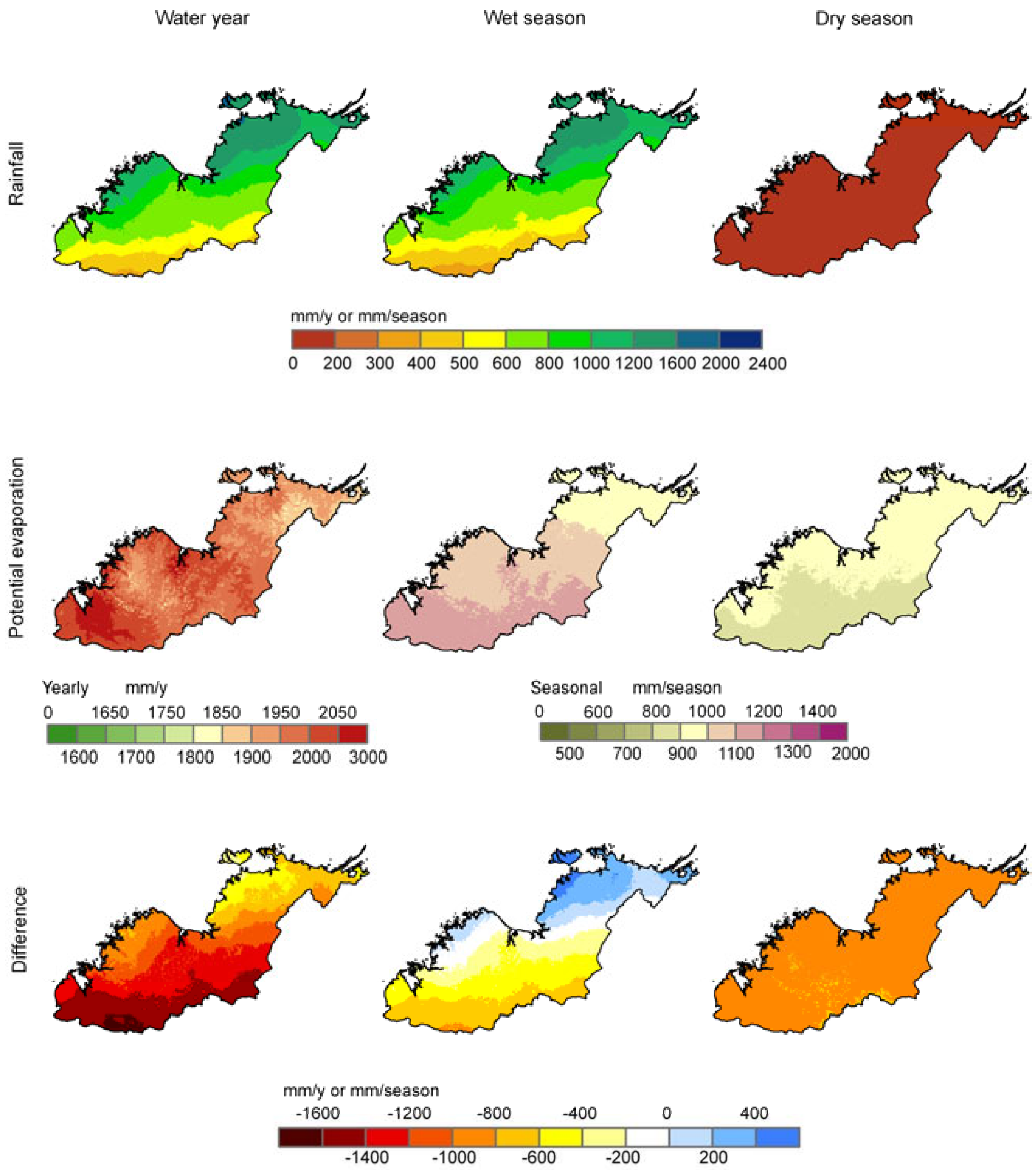

Figure 5. Spatial distribution of historical mean annual (water year = 1 September to 31 August), wet season (1 November to 30 April) and dry season (1 May to 31 October) rainfall and areal potential evapotranspiration (potential evaporation) and their difference (rainfall less areal potential evapotranspiration) across the Timor Sea Drainage Division

A distinct wet season extends from November to April when rainfall averages approximately 137 mm/month. In the dry season (May to October) an average of only 8 mm/month is received. This means that 95 percent of the annual rainfall is received during the wet season.

On an annual scale, the drainage division can be climatologically defined as a ‘water-limited’ environment where the atmospheric, or evaporative, demand for water (the so-called potential evapotranspiration) exceeds the input of water provided by rainfall. Another way of stating this is that mean annual potential evapotranspiration (1979 mm) is greater than the mean annual rainfall (868 mm). However, due to the strong seasonality of highly intense rainfall, during which there will be times when rainfall is greater than potential evapotranspiration, there is a corresponding strong seasonality of streamflow, and the landscape moisture follows this strong cyclical pattern, resulting in vegetation adapted to dealing with such conditions.

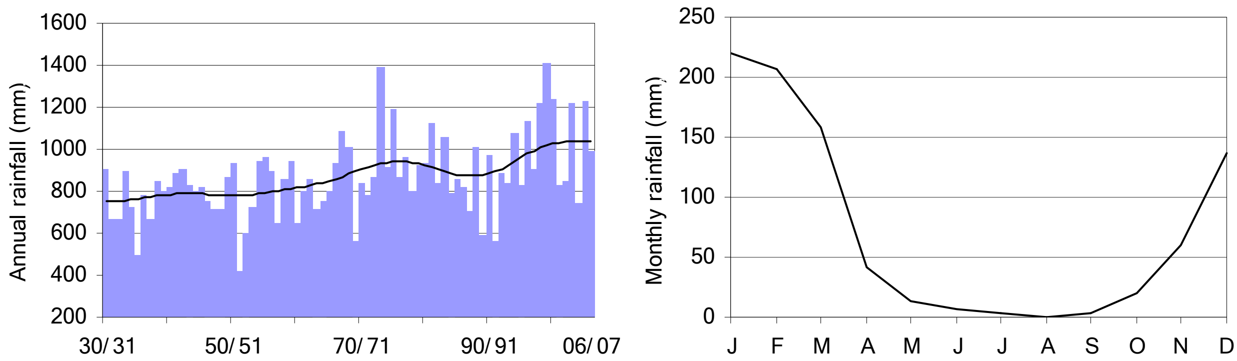

Figure 6. Historical (a) annual and (b) mean monthly rainfall, averaged over the Timor Sea Drainage Division. The low-frequency smoothed line in (a) indicates longer term variability

The drainage division has a predominantly tropical climate characterised by high temperatures year-round (averaging 28 °C) and high, yet very seasonal, rainfall. Climate grades from tropical savannah along and inland from the coast, into open savannah (hot grassland) towards the divide with the Western Plateau Drainage Division (Figure 7).

Only small areas of the division have been cleared (<1 percent) or are under intensive land use. Tree clearing has occurred mainly in eucalypt woodlands and open forests.

Native vegetation cover and condition has been extensively affected by grazing pressure, altered fire regimes and weeds, with complex interactions between the three processes. Sustained grazing pressure is associated directly and indirectly with reduced ground vegetation cover. Reduced vegetation cover can result in lower fire fuel loads, reduced fire frequency and increase in woody vegetation. Where grazing pressure is less intense, annual, late, dry season burning can reduce woody vegetation and density of savannah woodland tree cover.

An increased incidence of introduced grass species and an increasing intensity and frequency of fires is observed in some areas. Mission grass, gamba grass and buffel grass are introduced pasture species that are capable of dominating the ground layer and altering the fire ecology and ultimately the vegetation structure. In areas of change in fire regime, the extent and condition of fire-sensitive vegetation communities (i.e. deciduous vine thickets) and associated biota can be extensively impacted. Impacts from changes to vegetation cover are realised through changes to habitat availability, primary productivity and increased soil erosion.

Dominant land use is grazing, with large areas of nature conservancy and areas under Indigenous use.

Extensive areas of highly productive seasonal coastal wetlands support important prawn and finfish fisheries. It also has the second greatest diversity of freshwater fish species, with almost 100 different species recorded (27 of them endemic to the division) and is host to an extraordinary variety of bird life, both resident and migratory.

Population figures for major centres in Table 2 are from the Australian Bureau of Statistics census of 2006 which is conducted in early August. Figures relate to urban centres and localities.

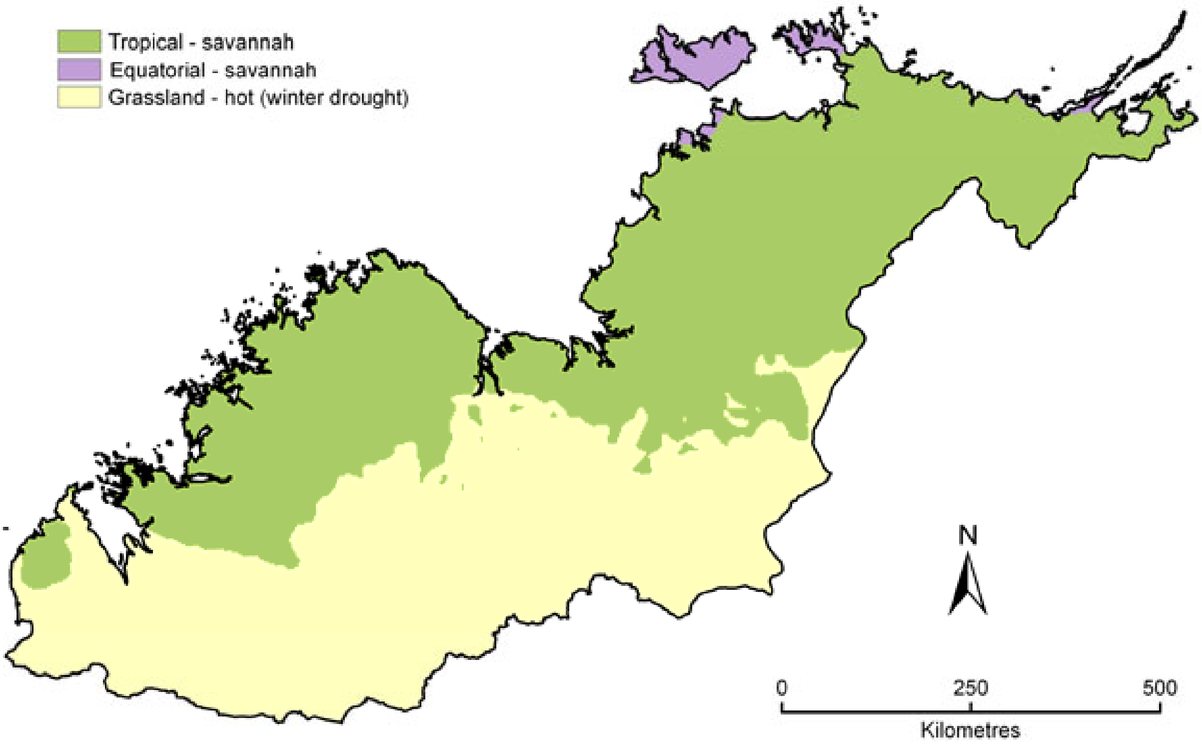

Figure 7. Climate zones of the Timor Sea Drainage Division (Stern et al., 2000)

The population of the division is sparse, with the majority of people living in Darwin and its suburbs and in Broome. The division is home to about 186,000 people; approximately 30 percent are of Indigenous descent.

Because of the low population density, much of the native vegetation in the drainage division remains relatively intact. Key environmental issues include land clearing for a variety of purposes; rapid population growth; and the lack of a sustainable fire-management policy.

Table 2. Major towns of the Timor Sea Drainage Division and their populations*

Town	Region	Total population	Indigenous population
Darwin	Van Diemen	103,506	5,175
Palmerston	Van Diemen	23,614	2,769
Broome	Fitzroy (WA)	16,271	4,881
Katherine	Daly	5,849	1,692
Nhulunbuy	Arafura	4,112	235
Kununurra	Ord-Bonaparte	3,748	993
Halls Creek	Ord-Bonaparte	1,211	853
Jabiru	Van Diemen	1,135	156
Fitzroy Crossing	Fitzroy (WA)	928	625
Wyndham	Ord-Bonaparte	669	256

* Populations are for urban centres from 2006 Australian Bureau of Statistics data <http://www.censusdata.abs.gov.au>.

1.3 Environmental and cultural assets

Environmental assets were chosen from wetlands which are listed in the Directory of Important Wetlands in Australia (Environment Australia, 2001). From this directory, environmental assets were shortlisted for assessing changes to the hydrological regime under the climate and development scenarios. The selection of this shortlist was undertaken in consultation with state governments and the Australian Government through direct discussions and through internal reviews. The shortlist was selected by identifying only those assets where stream gauging data was available at, or in close proximity to, the asset, thereby increasing confidence in the results reported at that asset. This shortlist was then reduced, where possible, to cover only the range of wetland and geographic types identified for the project area.

The shortlist is far from comprehensive and there are many more highly significant water-dependent assets, both environmental and cultural, which are not included in this report. The assessment approach utilised is based around changes to flow regime at distinct locations within the catchments considered. For a more comprehensive analysis of ecological impacts of changes in flow regime, the river system should be considered as a whole.

All nationally, or internationally, important wetlands listed for the Timor Sea Drainage Division in the Directory of Important Wetlands in Australia (Environment Australia, 2001) are detailed in Table 3, with asterisks identifying the assets shortlisted for assessment for this division, and shown in Figure 8. In deciding whether it is feasible to report hydrological metrics for these shortlisted assets, it is important to consider the confidence levels in modelled streamflow (as described in Section 2.2.6 of the division-level Chapter 2). Regional chapters (Section ID-1.3 in Chapter ID-1 and the final section in Chapter ID-3) present the assessment of these shortlisted assets and reports metrics for those assets which have sufficient confidence in the modelled streamflow to enable analysis.

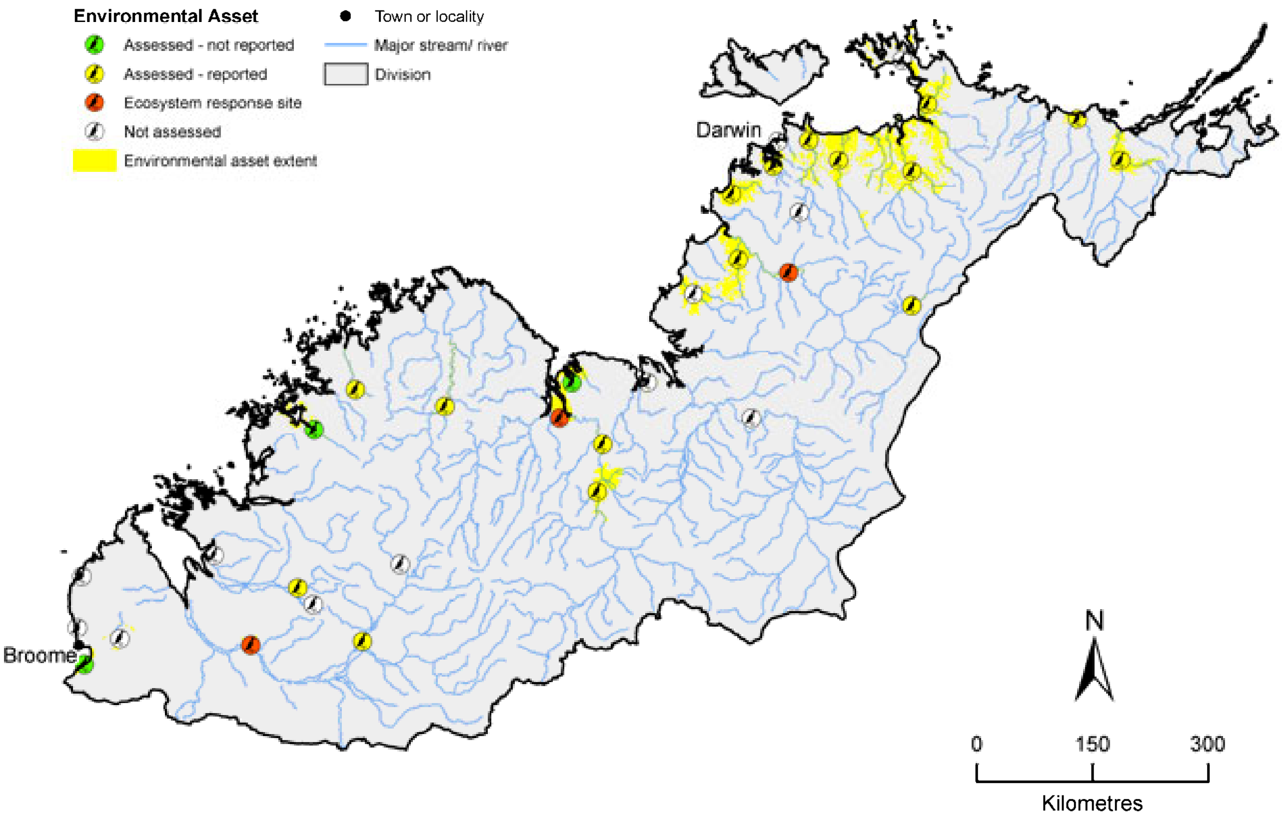

Figure 8. Location of environmental assets selected for assessment for the Timor Sea Drainage Division

Table 3. List of Wetlands of National Significance located within the Timor Sea Drainage Division

Site code	Name	Area	Region
		ha	
WA020 *	Roebuck Bay	50,000	Fitzroy
WA114	Big Springs	<10	Fitzroy
WA016	Bunda-Bunda Mound Springs	23	Fitzroy
WA017 *	Camballin Floodplain (Le Livre Swamp System)	30,000	Fitzroy
WA019 *	Geikie Gorge	272	Fitzroy
WA111	Gladstone Lake	<10	Fitzroy
WA021	Roebuck Plains System	1,180	Fitzroy
WA012	Tunnel Creek	20	Fitzroy
WA022	Willie Creek Wetlands	2,950	Fitzroy
WA013 *	Windjana Gorge	20	Fitzroy
WA098 *	Lake Kununurra	2,500	Ord-Bonaparte
WA062 *	Drysdale River	5,670	Kimberley
WA063 *	Mitchell River System	1,120	Kimberley
WA064 *	Prince Regent River System	19,100	Kimberley
WA097 *	Lake Argyle	98,000	Ord-Bonaparte
WA100 *	Parry Floodplain	9,000	Ord-Bonaparte
WA099 *	Ord Estuary System	94,700	Ord-Bonaparte
NT033	Bradshaw Field Training Area	<10	Ord-Bonaparte
NT024 *	Daly-Reynolds Floodplain-Estuary System	159,000	Daly
NT030	Legune Wetlands	10,300	Ord-Bonaparte
NT027	Moyle Floodplain and Hyland Bay System	74,700	Ord-Bonaparte
NT001 *	Daly River Middle Reaches	1,470	Daly
NT018 *	Katherine River Gorge	354	Daly
NT023	Cobourg Peninsula System	254,000	Van Diemen
NT028 *	Murgenella-Cooper Floodplain System	81,500	Van Diemen
NT017 *	Kakadu National Park	233,000	Van Diemen
NT020 *	Adelaide River Floodplain System	134,000	Van Diemen
NT025 *	Finniss Floodplain and Fog Bay Systems	81,300	Van Diemen
NT026 *	Mary Floodplain System	128,000	Van Diemen
NT031	Mount Bundey Training Area - Mary River Floodplain	<10	Van Diemen
NT029 *	Port Darwin	48,800	Van Diemen
NT032	Shoal Bay - Micket Creek	<10	Van Diemen
NT021 *	Arafura Swamp	71,400	Arafura
NT022 *	Blyth-Cadell Floodplain & Boucaut Bay System	35,500	Arafura

* Asterisk against the site code identifies those assets shortlisted for assessment of changes to hydrological regime.

Given that rivers have little rain water to ensure a continuous flow during the dry season, all perennial rivers and ephemeral springs are important sources of water, and most are also sacred sites (Altman and Branchut, 2008). Water values pervade all aspects of Indigenous life, as is evidenced from the recurring themes of water myths, spirits and species that pervade Indigenous art.

1.4 Water resources

An extreme climate

The rainfall of the Timor Sea Drainage Division is very strongly seasonal, with high inter-annual variability and a strong north–south gradient.

Historical (1930 to 2007) mean annual rainfall is 868 (± 303) mm and ranges between 383 and 1688 mm. Annually, rainfall provides about 503 TL (503,000 GL) of water to the drainage division. Approximately 95 percent of this rain falls during the wet season, mostly between December and March. Rainfall amount varies across the region from a mean annual value of about 350 mm in the south, up to about 1700 mm in the far north. The distribution is not uniform with steeper gradients near the coast. Roughly 50 percent of all rain falls over only 40 percent of the total land area (Figure 9).

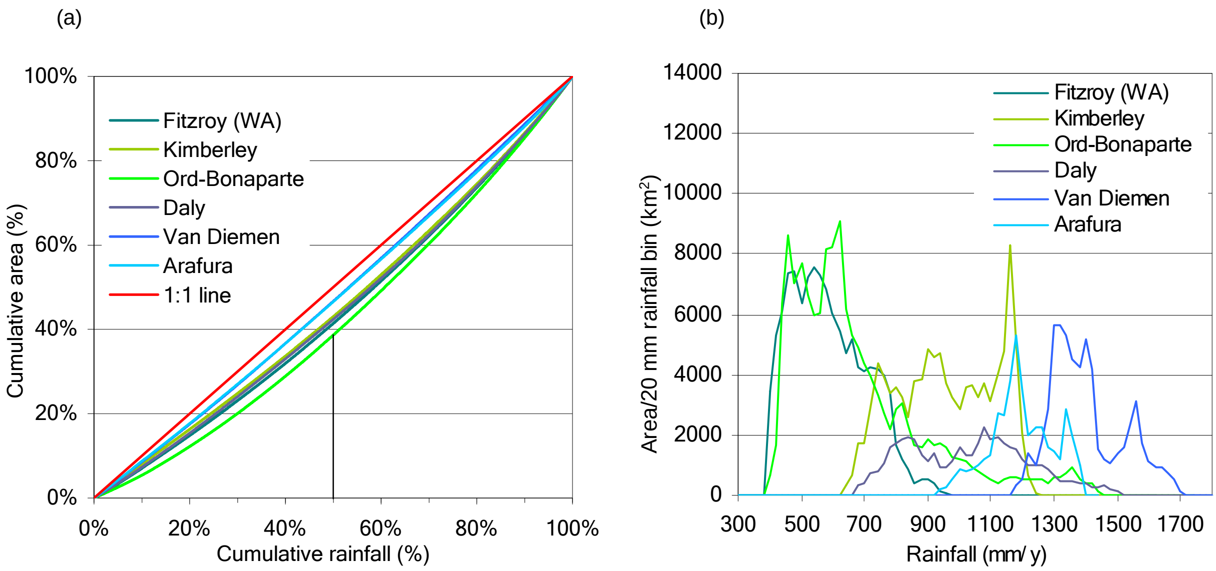

Figure 9. Rainfall plotted as a function of area for each of the six regions of the Timor Sea Drainage Division. Ranked percentage values (a) indicate that more rain falls near the coast than inland. The areal distribution of rainfall amounts (b) shows that the Fitzroy and Ord-Bonaparte regions receive mostly low rainfall amounts, whilst the Van Diemen region receives mostly high rainfall amounts

Runoff follows this pattern with largest flows between January and April. A historical annual mean of 90 TL flows across the landscape, though more than a quarter of this occurs in the Van Diemen catchments, which have a historical mean annual runoff of 375 mm.

High levels of net radiation (more in the dry season than the wet season) and vapour pressure deficit (more in the wet season than the dry season) combine to result in high areal potential evapotranspiration (APET) rates year-round. Historical mean annual APET is 1979 (± 51) mm and ranges between 1801 and 2116 mm. Wet season APET is about 15 percent higher than the dry season APET. Annually rainfall is usually less than APET and the landscape may be described as water-limited.

There is a strong rainfall gradient away from the northern coasts, and this combines with the generally low relief of most of the coastal region to provide little opportunity to increase surface storages. The higher relief in the Kimberley is offset by the fractured nature of the geology which drains too rapidly for sustainable storages. Surface storage opportunities occur mainly in the upper reaches of catchments, where rainfall is lower and more sporadic, yet where APET is highest. The major surface storages in the Ord River catchment provide some of the only locations where storages can be maintained throughout the year. Lake Argyle, near Kununurra, covers on average 1000 km^2, but can extend to 2000 km^2 at maximum flood stage which would hold 35 TL of water. Average storage is about 6 TL, with a nominal storage capacity of 10.7 TL. The lake filled in the first wet season after the dam wall was completed (1973) and currently provides irrigation water to 150 km^2 of farmland.

The coastal regions of the far north and far west are flood-dominated, which can locally result in poorer quality surface water, both through increased sediment load and increased tidal influence. Rainfall intensity also decreases rapidly away from the northern coast. Extreme rainfall events (>100 mm/day) occur along the northern coast during the wet season.

Groundwater recharge is also strongly seasonal and dependent on the recharge capability of the surface soils and outcrops.

Historical and recent climate

The recent (1996 to 2007) climate has been statistically significantly different to the historical climate for most of the region, with the wettest year experienced in 2000. The years 1996 to 2007 have been 18 percent wetter than the years 1930 to 1996. The driest year was 1952. Highest APET, however, occurred in 1992 and the lowest in 1945.The relative difference shows that all of the drainage division received increased rainfall in 1996 to 2007 compared to the 66 years from 1930 to 1996 (Figure 10). The majority of the drainage division is significantly wetter at the P = 0.05 level, with most of the area being significantly wetter at the P = 0.01 level (Figure 10).

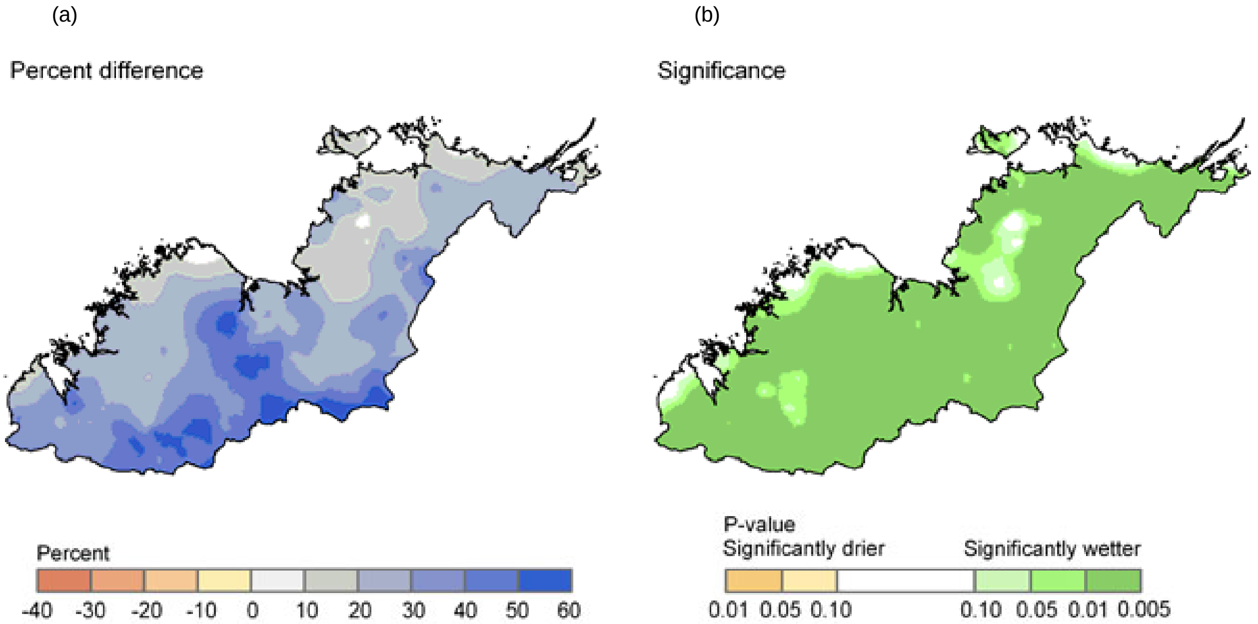

Figure 10. Spatial distribution of (a) the relative percent difference between the mean historical and recent rainfall; and (b) the statistical significance of that difference across the across the Timor Sea Drainage Division. (Note that historical in this case is the 66-year period 1930 to 1996)

An average recurrence interval was calculated for the drainage division (Figure 11). This is the average waiting time until an independent 11-year wet (or dry) sequence would occur that is equal to or wetter (or drier) than the 11 years from 1996 to 2007 (i.e. the recent past). This is calculated assuming that the climate is stationary.

Average recurrence of the climate of the 11 years from 1996 to 2007 is more than 100 years for most of the region, reflecting the dissimilarity between recent and historical climate conditions.

There has been a slight increase in rainfall intensity over the 1930 to 2007 period, with a slight increase both in rain days and rainfall per day, though again, this is not statistically significant except for the northern catchments.

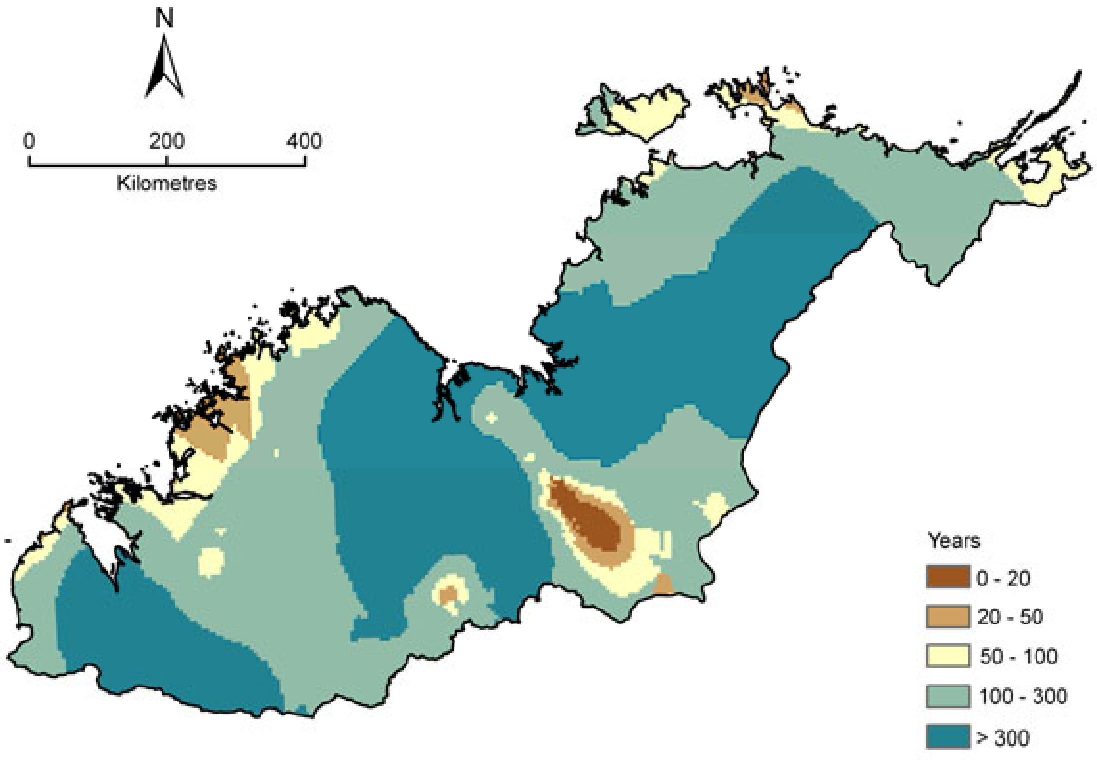

Figure 11. Spatial distribution of average recurrence intervals of recent rainfall relative to historical rainfall across the Timor Sea Drainage Division

Future climate

Future climate (~2030) is expected to be similar to the historical climate, with a mean annual rainfall of 875 mm (median modelled result). Under future climate, 94 percent of this rain falls in the wet season. Modelling gives a future range of between 14 percent lower and 5 percent higher rainfall. APET increases under all future scenarios, possibly up to 4 percent relative to the historical climate.

Extreme rainfall events are expected to increase along the northern coast, particularly in the Arafura region. We have not, however, considered the implications with respect to the El Niño-Southern Oscillation (ENSO) index.

Change in runoff is more strongly controlled by rainfall than APET (Chiew, 2006). Hence, despite higher future APET, it is unlikely to result in a significantly different runoff regime, and future runoff is expected to be similar to historical runoff. Future recharge is also expected to be similar to historical levels based on potential recharge modelling. Recharge is generally low across the drainage division, hence even large percentage changes do not result in large actual change.

There are three parts to estimating future streamflow. The first is estimating what the future climate will look like, in particular rainfall which is the main driver of streamflow. This generally comes from global warming projections from the International Panel on Climate Change (IPCC) and simulations of local/regional climate from global climate models (GCMs) (IPCC, 2007). The second is obtaining catchment-scale climate time series, informed by GCM simulations for the future and current climates, to drive the hydrological models. The methods range from (i) empirically scaling the historical climate series, (ii) statistically downscaling synoptic large-scale atmospheric predictors to catchment-scale climate and (iii) dynamic downscaling to provide climate at a higher spatial resolution. The third is driving the hydrological models with the future climate series to estimate future streamflow.

The tools for the second and third parts are generally available. There are methods available to convert large-scale GCM projections to catchment-scale climate (see above), and continuing research on development and testing will further improve these methods. There are hydrological modelling initiatives in Australia to improve runoff prediction in ungauged catchments, river system modelling in managed systems and adapting/extrapolating models for climate change impact assessment (e.g. relative runoff sensitivity to rainfall and temperature, model calibration over wet/dry periods, altered hydrological processes, etc.). For climate change impact assessment, the hydrological models need to be driven with multiple replicates of synthetic future climate series that take into account climate variability and climate change.

The largest uncertainty in estimating future streamflow characteristics and water availability is the future rainfall projections. For the short to medium term projection, the largest uncertainty comes from the large range of GCM projections of future local and regional rainfall. The GCM projections should become more accurate and consistent with progress in climate change and climate modelling science, which is a key area of research in Australia and elsewhere.

Cyclones and El Niño events

Cyclones are important events in producing heavy rainfall events in the Timor Sea Drainage Division. Note that the term cyclone here includes the low prior to it reaching cyclone strength and the low after it has declined below cyclone strength. An example of some cyclones that have brought heavy to very heavy rain to northern Australia: Charlotte in January 2009, Craig in March 2003, Steve in February 2000, Les in January 1998, May in February 1998, Sadie in January 1994, and Sandy in March 1985.

One of the key findings of the IPCC and its advisory committees is that it is *likely* that future tropical cyclones will become more intense, with larger peak wind speeds and heavier precipitation. This conclusion, however, relates to continental, regional and ocean basin scales, where numerous long-term changes in climate have been observed. These include changes in the intensity of tropical cyclones.

A link between the intensity of hurricanes (tropical cyclones) in the Atlantic Ocean with sea surface temperature (Emanuel, 2005) triggered a flurry of research into the relationship between tropical cyclones and climate change. While the relationship between intensity of tropical cyclones and sea surface temperature is now more widely accepted, at least for the Atlantic, the continuation of the causal link into the future has been questioned. The critical issue is whether the observed increase in hurricane intensity in the Atlantic is due to the relatively higher increase in sea surface temperature in the Atlantic relative to other ocean basins or whether it is related directly to the absolute increase in sea surface temperature, regardless of what is happening in other ocean basins (Vecchi et al., 2008). If tropical cyclone intensity is linked to relative sea surface temperatures, then the intensity might relax to earlier levels as inter-ocean basin sea surface temperatures equilibrate. On the other hand, if intensity is related to absolute sea surface temperatures, then the link between climate change and cyclone intensity is strong, with even more intense cyclones expected later this century. The observational record is not yet long enough, and the basic process-level understanding is not yet good enough, to distinguish between the two possible futures (Will Steffen, pers. comm.).

El Niño events appear to become more prevalent after 1977 (Power and Smith, 2007) and this has coincided with a decrease in the total number of tropical cyclones in the Queensland region. At the same time, there is some evidence that the number of severe tropical cyclones has increased (CSIRO and BoM, 2007).

The current, state-of-the-art coupled climate models used in the IPCC Fourth Assessment (AR4) (IPCC, 2007) have a typical resolution of 1.5 to 3 degrees in the atmosphere and 1 degree in the ocean. In neither component are some key aspects of the climate system (such as the influence of ocean eddies, orographic forcing of the atmosphere, tropical cyclones) adequately represented. Predicting cyclone activity is a current topic of much scientific research, and therefore not available in current GCM output used in the three Sustainable Yields Projects, and hence was not available for future climate scenarios in this project.

The AR4 (IPCC, 2007) documented that a robust result in high resolution model simulations of tropical cyclones in a warmer climate has been that there will be an increase in precipitation associated with cyclones. They have stated that the mechanism is simply that as the water vapour content of the tropical atmosphere increases, the moisture convergence for a given amount of dynamical convergence is enhanced.

The IPCC has also noted that the resolution of current global climate models limits the proper representation of tropical cyclones and heavy rainfall. For the modelling carried out for this project, we assessed rainfall amounts, intensity and rain days, with no reference to rainfall source, be it a cyclonic event, low pressure system or small convective cell. Hence, only rainfall processes were explicitly incorporated.

Surface water potential

Whilst a specific assessment for new surface water storages has not been carried out as part of this project, it is considered that any potential intermediate and large carry-over surface water storages have already been identified for the Timor Sea Drainage Division.

The strong rainfall gradient away from the northern coast combines with the generally low relief for most of the coastal region to provide little opportunity to increase surface storages. Surface storage opportunities occur mainly in the upper reaches of catchments; however, in these areas rainfall is lower and more sporadic, and potential evapotranspiration is highest. The main exception to this occurs in the Van Diemen region in the catchments surrounding Darwin.

To increase current supply to Darwin, the Darwin River Dam is having its dam wall raised by 1.3 m. This will increase available yield by 20 percent to 49,100 ML/year. Darwin's current demand for water is about 40,000 ML/year, and current total licensed extraction totals 46,420 ML/year. Whilst the nearby Manton Dam has an additional 7000 ML/year potential supply, recreational activities preclude its use except in emergencies.

New dam options were identified 20 years ago for consideration for long term water supplies. Three sites have potential:

1. Land for a potential future Marrakai Dam (next to Marrakai Crossing on the Adelaide River) has been bought and sub-leased for low level grazing. The extensive and generally low-lying catchment area upstream, however, would necessitate extensive engineering works and water treatment before use. The tidal limit for the Adelaide River can also extend this far upstream.
2. The catchment of the potential future Warrai Dam (about 18 km upstream of the Adelaide River township on the Adelaide River) is more compact than the other sites and good quality water might be collected without the need for chemical pre-treatment. About one third of the catchment is already protected within the Litchfield National Park. This site would also provide flood protection for the Adelaide River townsite and possibly could be configured to provide hydro-electric supply.
3. The potential future site of the Mt Bennet Dam on the Finniss River to the west of the Darwin River Dam is the site of high Indigenous values and there are environmental concerns related to the Rum Jungle mining operations.

New storages would have large evaporation losses. High variability in streamflow also necessitates larger carry-over storages compared to rivers in southern parts of the country (or elsewhere in the world), for a given rainfall regime. Drought severity is also greater than elsewhere, hence future storages would require two to ten times the volume of a similar supply for elsewhere, to ensure sufficient carry-over storage as provision for runs of multiple dry years.

Elsewhere in the drainage division, streamflow is largely event-driven, with a rapid rise and fall of flow. Off-stream development, supported by water harvesting, is compromised by the requirement to harvest water from the falling phase of flow. The rapid decrease in flow typical of northern Australian rivers provides for little opportunity for water take-off, following an event.

Groundwater potential

There are several karstic carbonate aquifers (Tindall Limestone and equivalents, and Oolloo Dolostone and equivalents) that potentially provide opportunities for large-scale (greater than 100 GL/year) groundwater development in the drainage division. These aquifers mainly occur in the Daly region in the Northern Territory. The level of groundwater extraction from these aquifers is currently low, although existing and potential future volumetric entitlements may be approaching extraction limits in some local areas, e.g. the Katherine-Douglas-Daly irrigation area. Water allocation plans undertaken, or currently being developed, in the Northern Territory – such as for the Tindall Limestone around Katherine, the Oolloo Dolostone around Daly and the Darwin-Howard East area – are all resulting in caps to groundwater extraction.

Smaller groundwater developments (i.e. 10 to 100 GL/year) are feasible within the aquifers of the Canning Basin and have been developed in the Proterozoic carbonate aquifers in the Darwin Rural Area. The latter, however, have also reached their extraction limit and there is currently a moratorium on any further groundwater development.

Even smaller extractions (i.e. less than 10 GL/year) are feasible across most of the division, and include areas of the Cretaceous sandstone aquifers. Many of the shallow groundwater resources, including alluvial aquifers bordering major rivers, are highly dynamic, responding rapidly to seasonal rainfall and river flows. The alluvial aquifers of the Fitzroy (WA) region are examples, though yields and quality is variable. The aquifer properties are poorly quantified, however.

Groundwater recharge rates are not well constrained. There is little information to validate the diffuse recharge modelling carried out in this project. This is thought to be the dominant recharge mechanism in the regions of clay and sandy soils. Over the carbonate soils of the Daly and Ord-Bonaparte regions, however, in regions where opportunities are highest, localised, indirect recharge via karstic openings and through stream beds is more important, and annually, shallow aquifers may recharge to capacity, though often drain rapidly during the dry season. Each year, the aquifers fill from wet season rains, but then drain through the dry season to progressively lower levels. This fill and spill regime is being maintained due to wetter-than-average rainfall regimes experienced over the last 10 to 20 years. If climate conditions return to those experienced prior to the 1990s, it is likely that there will be years when the aquifers do not return to full capacity.

Across the drainage division, there is limited opportunity to augment groundwater supplies with managed aquifer recharge (MAR). Most aquifers currently in use rapidly recharge to full capacity during the wet season, but also rapidly discharge during the dry season, with large fluctuations (>10 m) in water tables. Under current development MAR in the alluvial aquifers would have limited applicability as storages will be at full capacity towards the end of the wet season when surface water is available for injection. Furthermore, the low-conductivity soils that cover much of the floodplains in the drainage division preclude the use of infiltration pits for MAR. Any potential future scheme would therefore need to use injection wells to recharge the aquifer, the costs of which would be prohibitive for irrigation.

The Canning Basin sandstone aquifers probably have the greatest potential for MAR, but further investigations are required to better understand the groundwater flow and storage characteristics of these aquifers before such a scheme could be considered. Total storage in the Canning Basin aquifers has been estimated at 46×10^{12} m^3 (46,000,000 GL) (Laws, 1990), though much of this is of poor quality.

The carbonate aquifers of the Daly Basin have potential for the implementation of a MAR scheme. For carbonate aquifers the main storage and flow is in solution-enhanced fractures. Carbonate aquifers are the most suitable for consideration of MAR using borehole recharge in order to recharge water directly into the aquifer. Water can be injected into a borehole and recovered from another, some distance away, to increase travel time and benefit from the water treatment capacity of the aquifer. The technology needed to construct these structures can be quite complex in order to restrict the ingress of suspended solids that would rapidly clog the system and to restrict the inflow of contaminants that might pollute the groundwater body.

Surface–groundwater interaction

There is an intricate balance between surface and groundwater flows (and the environmental regimes they support, resulting in a high level of endemic species across northern Australia. The nature of this interaction is poorly quantified, and is the focus of current investigations in the Daly and Fitzroy river catchments.

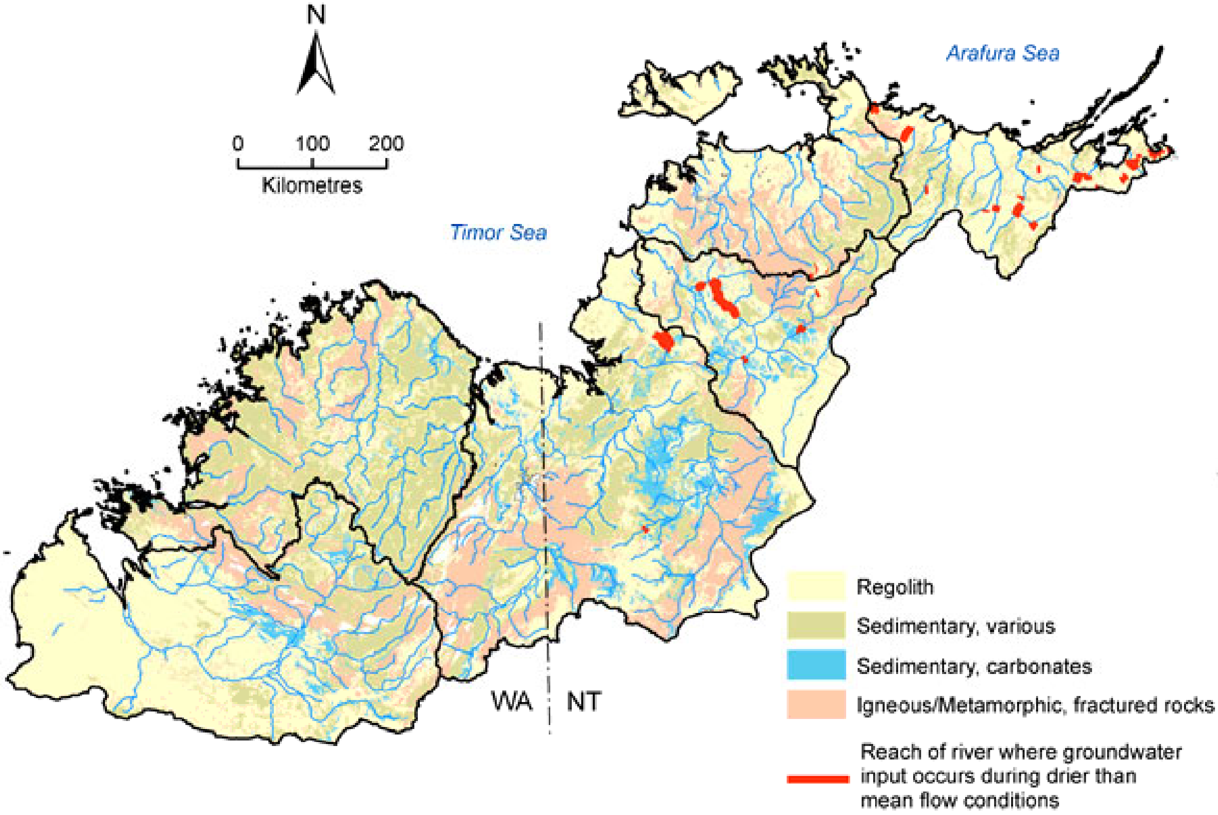

Figure 12. Surface–groundwater connectivity map for the Timor Sea Drainage Division

1.5 Knowledge and information gaps

Paucity of data is a major limitation both for water resources assessment and development evaluation. Even for relatively good datasets, such as the rainfall records, there are both spatial and temporal gaps in the data, particularly in the important headwater regions. Data are especially sparse in floodplain regions where maintenance of recording equipment is difficult. To allow better estimates of confidence in both surface water and groundwater modelling, daily estimates of error in the input climate datasets are needed, as these can then be propagated through these models, allowing levels of confidence to be better conveyed to managers and policy-makers.

Many of the streamflow gauging stations in the Timor Sea Drainage Division are remote and are inaccessible by land during the wet season. These factors make it challenging to establish mid to high flow rating curves, and means that many of the gauging stations have a low maximum gauged stage height with respect to their maximum stage height. Although many of the streamflow gauging stations in the Timor Sea have a significant proportion of their total flow volume above their maximum gauged stage height (Figure 13), the proportion of stations with more than 80 percent of their flow occurring above their maximum gauged stage height is lower than the Gulf of Carpentaria Drainage Division. This is in part due to the proximity of a large number of stations to Darwin and the difficulty establishing rating curves in the Gulf Country.

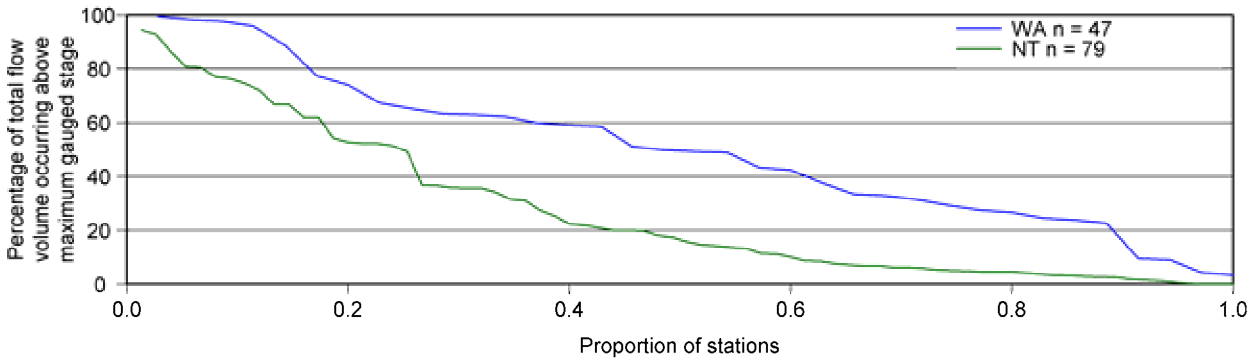

Figure 13. Proportion of streamflow gauging stations in the Timor Sea Drainage Division which have the percentage of their total flow volume occurring above their maximum gauged stage height. This analysis only includes stations with a minimum of ten years of record

For many environmental assets it is not possible to calculate the potential impacts of the various scenarios because the high and low ends of the flow regime are not well defined. The collection of further reliable flow data, especially high and low flows, is required to remedy this situation.

In some streams dry season low flows are largely sustained by groundwater flows. To predict the potential impacts of the various scenarios these streams require hydrological models that combine surface and groundwater regimes, which are rarely available in the northern Australian rivers. Further combined surface and groundwater modelling is therefore required to produce more accurate dry season low flows.

Flooding is an important factor that sustains many environmental assets and this occurs when the stream breaks out of its banks (a level known as bankfull stage or discharge). However, bankfull discharge is not known for many streams, nor is the relationship between area flooded and stage height, so it is difficult to predict when assets are inundated. Further information about bankfull stage and discharge are needed for most environmental assets.

The conversion of river high and low flows into environmental impacts requires quantitative relationships between flow and specific ecological entities (for example, macrophyte populations, fish passage, faunal and floral habitats, etc.). These are available for a couple of locations in the Timor Sea Division, but further survey of key ecological assets is required under a range of flow conditions. Many environmental assets depend not simply on duration above or below certain flow levels, but on triggers (e.g. for reproduction or migration) set by the rate of change of flow. Further analysis is therefore required to look at how the timing and rate of rise and fall in flow rates at critical times of the season will vary under the range of climate and development scenarios.

Some environmental assets depend on the frequency and duration of events that occur less than annually (i.e. once every 5, 10 or 20 years or more). Further analysis is therefore required to quantify how the frequency and duration of these events varies under the various scenarios.

To assess the quantity of water that could be available for consumptive use requires an assessment of the storage potential of each catchment. Once this has been established, it can be coupled with the hydrological characteristics of the rivers in the region to make a preliminary assessment of the yield that could feasibly be achieved for various degrees of reliability. The current development of the national 30 m digital elevation model (DEM) presents a new opportunity to make an objective and consistent assessment of the storage potential for every catchment across Australia. This information is essential to informing the debate about Australia's potentially exploitable water resources.

Whilst the entire drainage division can be assessed for its water resources (Figure 14), only the Daly and parts of the Ord and Finniss catchments can be assessed for water availability. This is restricted to a surface water availability assessment in the lower Ord and a combination of surface water and groundwater availability assessments in parts of the Daly and Finniss. Restricted parts of these latter two catchments may be assessed for the sustainable yield of water under current conditions, but require considerable further information on environmental, social, economic and cultural needs and expectations. These are the only two areas across northern Australia that might be assessed at this level, but this is still not at a sustainable yield level. This is purely from a consumptive water use perspective and does not consider environmental, social or political constraints.

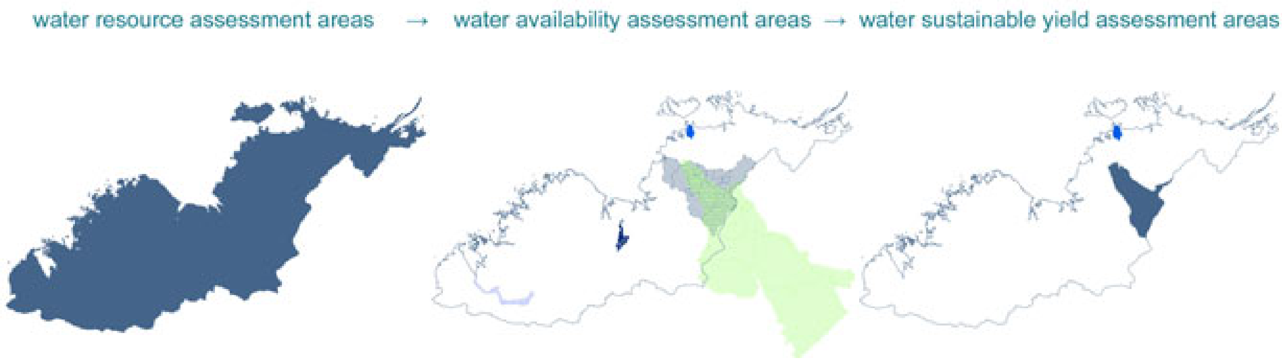

Figure 14. Water assessment capability within the Timor Sea Drainage Division. Shaded areas have sufficient information and models to carry out the labelled level of assessment

1.6 References

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2 Assessment approaches

Term of Reference 1

This chapter outlines the assessment approaches for different components of the water cycle. Climate, surface water and groundwater methodologies are summarised and the techniques used to assess surface–groundwater interaction are outlined. Metrics are also developed which are derived from these assessments and which illustrate changes to the hydrological regime at sites of environmental, social and cultural importance. These assessment methods are illustrated using results at a division scale; they also apply to assessments made at the regional scale. Detailed aspects are provided in an accompanying technical report on methods (CSIRO, 2009).

As in real hydrological systems, the assessment approach relies on integration of different components of the water cycle and requires a process requiring interaction between the different teams assessing different components of the water cycle to provide an internally consistent, defensible, measured assessment of water resources. Where applicable, this also includes the provision of water availability assessment through the use of groundwater and river systems models. Assessments of flow regimes also incorporate information from ecological environmental assessments, while water models require knowledge and information on water use and governing principles.

The process adopted by this project is illustrated in Figure 15. Interactions and flow of activities are illustrated with arrows. Additional information required to make the assessments are presented in red boxes and some contextual information on these elements is presented in the region contextual chapter. Additional work on these elements is being carried out through the other programs of the Northern Australia Water Futures Assessment (NAWFA). The information provided through the modelling described in this chapter will also be integrated into the other NAWFA programs.

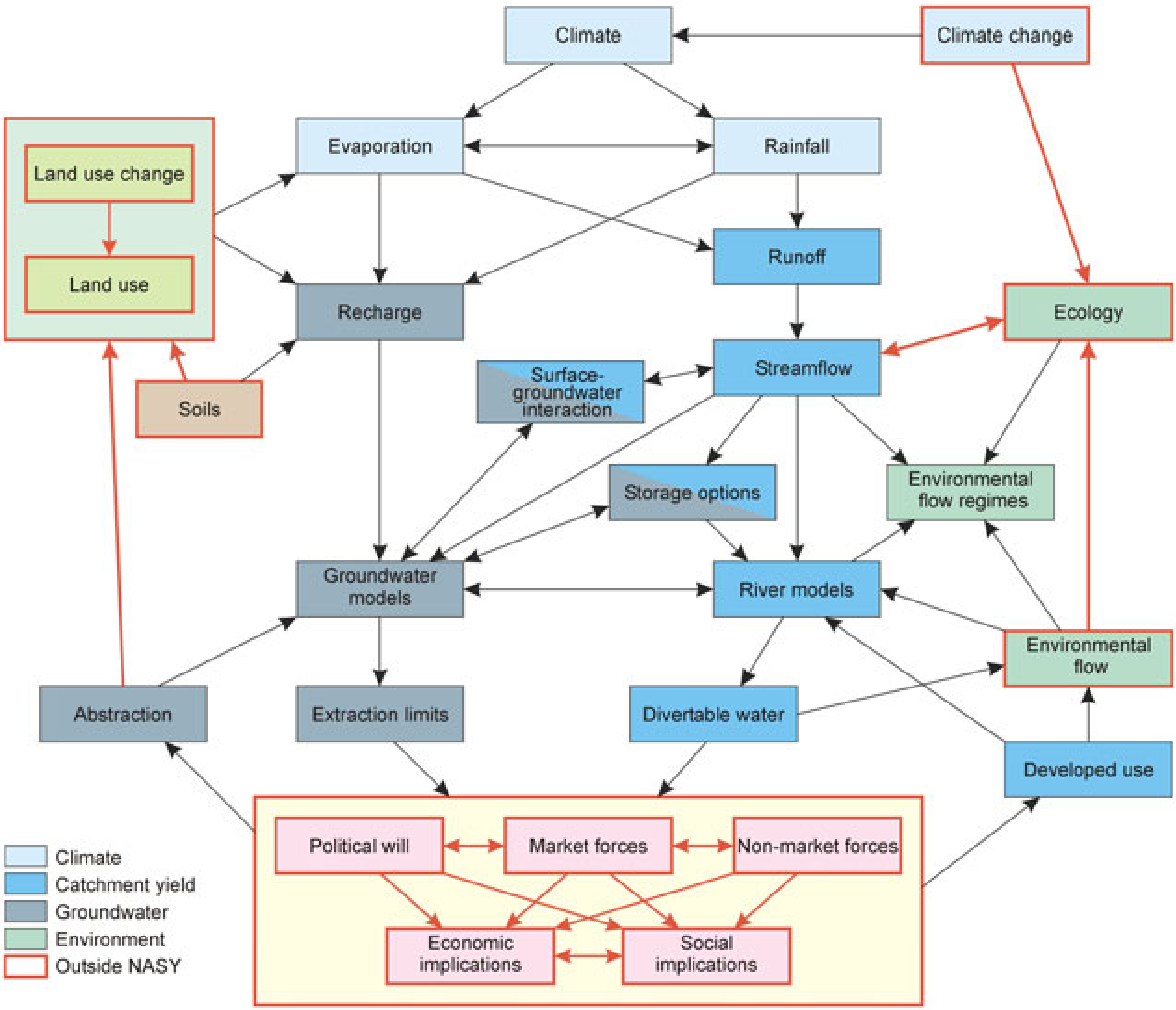

Figure 15. Concept diagram for assessment activities carried out under the Northern Australia Sustainable Yields Project. Red boxes and arrows indicate activities outside the scope of this project

The drainage division is the most appropriate scale to describe the climate data, so additional information is provided in this chapter for rainfall and evapotranspiration results. Surface water is best considered at the catchment scale, thus most data relating to surface water assessments may be found in the regional chapters. Similarly, whilst groundwater systems may underlay significant portions of the drainage division, impacts and studies are generally carried out at the regional scale, hence groundwater results may also be found in the regional chapters.

Further, whilst climate provides the primary drivers for water resources, water planning is carried out for surface and groundwaters only, hence a regional assessment of these components of the hydrological cycle is warranted.

Assessing the hydrological regime at environmental assets is carried out at the local (stream reporting node) scale. Again this is reported within the region chapters.

This chapter describes the water resource assessment approaches applied across and within the Timor Sea Drainage Division. This chapter covers:

- climate scenario estimations
- surface water assessment
- groundwater assessment and modelling
- surface–groundwater interaction assessment
- changes to hydrological regimes.

For each component, a section outlining the confidence in the data is presented.

2.1 Climate scenario estimation

Water resources are assessed under four scenarios:

- historical (1930 to 2007) climate and current development (Scenario A)
- recent (1996 to 2007) climate and current development (Scenario B)
- future (~2030) climate and current development (Scenario C)
- future (~2030) climate and future (~2030) development of farm dams, plantations, groundwater systems and proposed irrigation development (Scenario D).

The following three sub-sections describe the methods used to generate the required climate data for scenarios A, B and C (note that Scenario D uses the same climate data as Scenario C). Following this, confidence levels are discussed.

2.1.1 Historical climate (Scenario A)

Historical daily climate data from 1 September 1930 to 31 August 2007 at 0.05 x 0.05 degree (~ 5 x 5 km) grid cells across the project area are used. The source of the data is the SILO database developed and maintained in real-time by the Queensland Climate Change Centre of Excellence <http://www.longpaddock.qld.gov.au/silo/> and (Jeffrey, 2006; Jeffrey et al., 2001). SILO provides surfaces of daily climate data interpolated from point measurements made by the observation network developed and maintained by the Australian Bureau of Meteorology (BoM).

As rainfall data are highly discontinuous in space and time, due to the processes governing tropical cyclone activity and local thunderstorms, their interpolation is particularly challenging. To overcome as many difficulties as possible, thereby maximising the quality of the resultant data, Jeffrey (2006) implemented an interpolation strategy where a rainfall normalisation parameter was interpolated with ordinary kriging and after removal of stations with large residuals the revised dataset is interpolated and the normalisation reversed. To capture air temperature lapse rates, and other near-surface elevation-dependent processes (McVicar et al., 2007), surfaces for the other climate variables were interpolated using a trivariate thin plate spline as a function of longitude, latitude and elevation (Jeffrey et al., 2001).

In addition to daily rainfall data, the rainfall-runoff models also require areal potential evapotranspiration (APET) to limit the actual evapotranspiration. Morton's wet environment APET (Chiew and Leahy, 2003; Morton, 1983) was calculated for a daily time step at 0.05 x 0.05 degree resolution using the following SILO data: temperature; relative humidity (calculated as actual vapour pressure divided by saturation vapour pressure); and incoming solar radiation. APET is defined as the evapotranspiration that would take place, assuming unlimited water supply, from an area large enough that the effects of any upwind boundary transitions are negligible, and local variations are integrated to an areal average.

The rainfall-runoff modelling results are much less sensitive to errors in the APET data than they are to errors in the rainfall data. It is also easier to provide reliable APET data for the rainfall-runoff modelling as APET is relatively conservative in space with smaller day-to-day variation than rainfall.

2.1.2 Recent climate (Scenario B)

The recent climate scenario (Scenario B) covers the period from 1 September 1996 to 31 August 2007 and was used to assess future water availability should the climate in the future prove to be similar to that of the recent past (i.e. 1 September 1996 to 31 August 2007).

To compare the two non-overlapping periods from the total rainfall in the two periods, the relative differences were calculated as (P_{recent} – $P_{historical}$) / $P_{historical}$ (then expressed as a percentage). To assist with interpretation of this difference and percentage difference, a statistical test was performed using a two-sided, non-overlapping two-sample t-test with equal (pooled) variances across the two time periods (Li et al., 2009). The recurrence interval for the conditions of the recent past was also calculated within the data of the historical period.

The average recurrence intervals (ARIs) were calculated through a simulation approach. For each rainfall station, Scenario A rainfall was modelled with the lag-one autoregressive model of Frost et al. (2007). This model allows for non-Gaussian distributions using Box-Cox transformation and considers parameter uncertainty using Bayesian methods with Markov Chain Monte Carlo parameter estimation. The prior distribution of the Box-Cox lambda parameter was bounded between –2 and 2. Frost et al.'s (2007) model was used to generate 100 replicates of 100,000 years of 'water year' (1 September to 31 August) rainfall. The ARI for Scenario B rainfall was then calculated directly from the 100,000-year water year replicates as the mean time between successive upcrossings (i.e. crossings from below) of a threshold equal to the mean of the recent rainfall. As the distribution of the ARI estimates can be highly skewed, particularly for the higher ARIs, the median ARI from the 100 estimates was reported as the ARI for Scenario B rainfall; full details of method used to calculate and interpret the ARIs are found in Potter et al. (2008).

The ARI is the average waiting time until an independent 11-year wet (or dry) sequence would occur that is equal to or wetter (or drier) than the recent past (i.e. Scenario B). Note that estimates of the ARIs are calculated under an assumption of climate stationarity. As rainfall in some of the project area can not be considered stationary over the Scenario A time period (i.e. increasing trends in rainfall since 1930 are present for most the Timor Sea Division and the western and northern portions of the Gulf of Carpentaria Division) it is expected that the method will result in extremely large ARIs. In this case, the large ARIs are indicative of non-stationary (trending) rainfall, and subsequent bias in the model parameters. In other words, it is likely that the wet conditions observed in recent years will occur sooner than is estimated by the ARI for those rainfall stations showing significant upward trends in rainfall.

To determine the number of rainfall stations on which to run the ARI algorithm, the number of BoM stations recording rainfall in each of the 13 regions comprising the project area, and the combined area, were identified. Then to ensure that interpolation was performed (as opposed to extrapolation) when a surface was generated for the project area from the ARI results calculated at the isolated BoM stations, the number of stations in a 2 degree (~200 km) buffer around the project area was calculated (denoted Buffered area in Table 4). Results presented in Table 4 show that at strict levels of completeness (e.g. > 90 percent) there are several regions that did not have a single rainfall station that passed the threshold. Consequently the threshold was relaxed to be 70 percent complete, as at this level at least one rainfall station was present in each region; there are 146 stations in the project area increasing to 279 when including all those within the buffer. At each station missing rainfall data were infilled from the SILO surfaces so that continuous daily rainfall records were presented to the algorithm used to calculate the ARI.

Table 4. Number of rainfall stations passing completeness thresholds in each region, the project area and an associated buffered area

Region	60%	65%	70%	75%	80%	85%	90%	95%
Fitzroy	25	23	21	20	15	13	6	2
Kimberley	1	1	1	0	0	0	0	0
Ord-Bonaparte	22	20	20	17	12	9	7	2
Daly	4	4	3	2	2	2	0	0
Van Diemen	5	4	4	4	2	2	1	1
Arafura	3	3	3	3	1	1	1	1
Roper	7	7	3	2	1	1	0	0
South-West Gulf	5	5	5	5	5	4	3	2
Flinders-Leichhardt	49	44	38	34	29	26	20	12
South-East Gulf	24	21	21	21	19	14	11	7
Mitchell	12	12	12	10	10	7	6	5
Western Cape	6	5	5	3	3	3	3	1
Northern Coral	15	12	10	7	6	6	5	2
Total project area	**178**	**161**	**146**	**128**	**105**	**88**	**63**	**35**
Buffered area	342	309	279	247	211	177	129	77

The ARI shown in Figure 16 quantify the probability of occurrence of Scenario B rainfall in the context of the variability of Scenario A rainfall. Results show that ARIs are less than 50 years along the eastern coast of the Northern North-East Coast Drainage Division and the south-eastern portion of the Gulf of Carpentaria Drainage Division; and in the western part of the Gulf of Carpentaria Drainage Division and for most of the Timor Sea Drainage Division rainfall ARIs are generally large (i.e. > 100 years and in some cases exceeding 300 years). A spatial surface of the ARIs was generated using Kriging interpolation and the input data available from the isolated BoM stations (Figure 16), noting that the ARI analysis was conducted at stations outside the area so the resultant surface was generated using interpolation not extrapolation. Results of this interpolation are shown in Figure 16 where the output surface clearly shows the east-west divide in rainfall ARIs experienced across the project area. This spatial pattern has general accordance with the long-term trends in rainfall.

Rainfall intensity was calculated by dividing the total rainfall, calculated annually and for the wet (1 November to 30 April) and dry (1 May to 31 October) seasons, by the number of rainy days, or days with recorded rainfall. Low and high rainfall events were not distinguished, though this analysis needs to be carried out if patterns of rainfall intensity are to be described.

Long-term rainfall trends suggest an increase in rainfall over the past 77 years, particularly along the northern coast. However whether this is due to: (1) an increase in the number of rain days; (2) an increase in the rainfall intensity; or (3) a combination of these is not known. Trend analysis was performed by fitting a linear regression (ordinary least squares) to each grid cell and determining the slope of the relationship for both the number of rain days and rainfall intensity analysis in the 77-year period. This was performed for the water year, wet season and dry season.

Results suggest that the increasing trend in rainfall intensity is the primary factor driving increasing rainfall trends over much of northern Australia (Li et al., 2009).

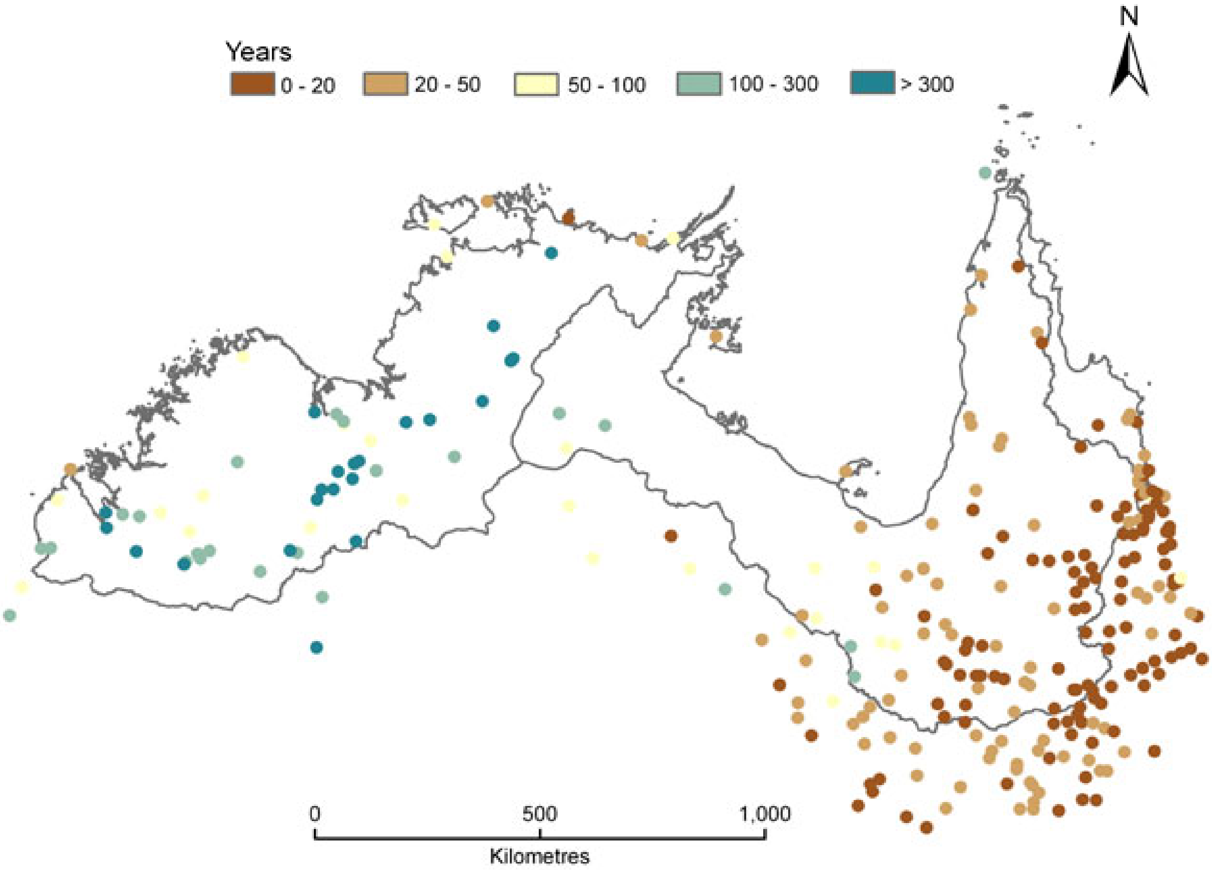

Figure 16. Average recurrence intervals for rainfall at Bureau of Meteorology stations in northern Australia under recent climate (Scenario B) relative to historical climate

2.1.3 Future climate (Scenario C)

The future climate scenario (Scenario C) was used to describe a range of possible climate conditions ~ 2030. This was achieved by scaling the climate data from 1 September 1930 to 31 August 2007 to represent the climate ~2030, based on analyses of 15 global climate models (GCMs) under three global warming scenarios. Thus, 45 future climate variants, each with 77 years of daily climate sequences for 0.05 x 0.05 degree grid cells across the project area, could be used for the rainfall-runoff modelling. The 15 GCMs are listed in Table 5. These represent the subset of GCMs that can generate daily sequences of data.

Table 5. List of 15 global climate models used

Model	Modelling group, country	Horizontal resolution
		km
CCCMA T47	Canadian Climate Centre, Canada	~250
CCCMA T63	Canadian Climate Centre, Canada	~175
CNRM	Meteo-France, France	~175
CSIRO-MK3.0	CSIRO, Australia	~175
GFDL 2.0	Geophysical Fluid, Dynamics Lab, USA	~200
GISS-AOM	NASA/Goddard Institute for Space Studies, USA	~300
IAP	LASG/Institute of Atmospheric Physics, China	~300
INMCM	Institute of Numerical Mathematics, Russia	~400
IPSL	Institut Pierre Simon Laplace, France	~275
MIROC-M	Centre for Climate Research, Japan	~250
MIUB	Meteorological Institute of the University of Bonn, Germany Meteorological Research Institute of KMA, Korea	~400
MPI-ECHAM5	Max Planck Institute for Meteorology DKRZ, Germany	~175
MRI	Meteorological Research Institute, Japan	~250
NCAR-CCSM	National Center for Atmospheric Research, USA	~125
NCAR-PCM1	National Center for Atmospheric Research, USA	~250

The method implemented to generate the Scenario C climate data was based upon that used in the Murray-Darling Basin Sustainable Yields Project, and the material herein draws heavily from Chiew et al. (2008). There are a variety of possible methods to obtain future catchment-scale climate data to drive hydrological models (see Chiew (2006) for an overview of methods). Statistical and dynamic downscaling methods that relate large synoptic-scale atmospheric variables to catchment-scale rainfall can potentially provide more reliable future rainfall inputs to drive hydrological models. However, the use of downscaling methods was not possible given the time constraints of this project. Additionally, downscaling methods may not necessarily provide more reliable future rainfall than the method used in this project because: (i) downscaling research is still developing and has not been used for hydrological investigations of this scale; (ii) it is difficult to calibrate the downscaling method for a large region like northern Australia; and (iii) there are limited archived daily GCM simulations from which to downscale to provide the range of uncertainties in the future climate.

The future climate scenario (Scenario C) provides estimates of possible conditions around the year 2030 under three potential global warming scenarios. This was achieved by using 'scaling factors', derived from GCM outputs, that rescaled the 1930 to 2007 historical climate data for each warming scenario.

Three global warming scenarios for ~2030 relative to ~1990 were used based on projected high, median and low greenhouse gas emissions. These three scenarios were inferred from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment (AR4) (IPCC, 2007) and the latest climate change projections for Australia (CSIRO and BoM, 2007). For this project, the increases in global mean near-surface air temperatures resulting from these low, median and high emissions scenarios are 0.7, 1.0 and 1.3 °C, respectively. (The corresponding values for the Murray-Darling Basin Sustainable Yields Project were 0.45, 1.03 and 1.60 °C, respectively. The slight difference in values used here is due to increased understanding of global temperature rises associated with projected low, medium and high emissions.)

The method used to derive Scenario C climate estimates is broadly outlined below. For more methodological detail, see Chiew et al. (2008).

1. Scaling factors for rainfall, net radiation, air temperatures and relative humidity were derived. Archived monthly simulations from 15 AR4 GCMs were analysed to produce scaling factors that denote the percent change in rainfall, solar radiation, maximum and minimum air temperature, and relative humidity per °C warming (i.e. globally averaged air temperature). For each of these climate variables, seasonal scaling factors were produced for each grid cell in the project area. Daily scaling factors for rainfall were also obtained. In total 15 sets of seasonal scaling factors were produced: one set from each GCM.

2. An interim ~2030 APET was calculated and scaling factors for APET were derived. The GCMs do not produce estimates of future APET, hence APET scaling factors could not be derived directly from the GCM

outputs. Instead, interim estimates of future solar radiation, maximum and minimum air temperature, and vapour pressure were calculated using respective rescaling factors and assuming a 1 °C rise in global air temperature. The four scaling factors (i.e. solar radiation, maximum and minimum air temperature, and vapour pressure) were then used to create an interim ~2030 APET. Scaling factors for APET were derived from the simulated future APET.

3. Estimates of ~2030 climate were produced by rescaling the historical climate data. Each set of scaling factors was multiplied by the amount of projected temperature increase (0.7, 1.0 and 1.3 °C) and then used to rescale historical climate variables to simulate possible 2030 climates. Rescaling of rainfall used both the seasonal and daily scaling factors. In total, 45 estimates of future climate were produced.

Monthly scaling factors were calculated for rainfall (and other climate variables) for the period 1870 to 2100 by plotting the simulated rainfall (or other climate variable) against the simulated global average air temperature. An ordinary linear regression is fitted through the data points and the slope of the linear regression is the scaling factor which gives the change in rainfall (or other climate variable) per degree of global warming. The scaling factors were then multiplied by the change in temperature for each of the global warming scenarios for ~2030 relative to ~1990 to obtain changes for rainfall (and other climate variables) for the different global warming scenarios. This was performed for each of the 15 GCMs, for each quarter (season) for each GCM grid cell. The 77-year historical daily climate data with 0.05 x 0.05 degree (~ 5 x 5 km) resolution grids were then scaled by the monthly scaling factors for each climate variable.

To account for changes in the future daily rainfall distribution, an additional percentile scaling factor was applied to daily rainfall. The scaling factors for the different rainfall percentiles/amounts were determined by comparing daily rainfall simulations from the 15 GCMs for a single SRES A1B run (IPCC, 2000) for two 20-year time slices, 2046 to 2065 and 1981 to 2000. The method used compared the 2046 to 2065 and 1981 to 2000 daily rainfall distributions, and developed a smooth transition in the 'daily scaling' factors. The percent changes were estimated by averaging the rainfall amounts over percentile ranges: 1st percentile (all points less than 2nd percentile), 5th percentile (all points between 2.5th and 7.5th percentiles), 10th percentile (all points between 7.5th to 12.5th percentiles), and every five percentile range downwards to the 'lowest category', where all the small rainfall amounts were considered together. This lowest category bound was defined by the percentile at which the observed rainfall was less than 1 mm, or the 30th percentile if the percentile at which the observed rainfall was less than 1 mm was less than the 30th percentile. This was performed as rainfall events less than 1 mm, or those below the 30th percentile, are not important for runoff generation. All rainfall events below the lowest category bound were lumped together and used to determine the single value of percent change. The percent changes at the discrete percentile values were then interpolated to obtain the percent changes for all the rainfall percentiles.

For each of the 15 GCMs and each of the three global warming scenarios, the above daily scaling factors were used to scale the different daily rainfall amounts in the 77-year daily rainfall series to obtain a daily rainfall series for a ~2030 climate relative to a ~1990 climate. The entire series was then scaled, using a different constant factor for each of the quarters (seasons), to ensure that the mean rainfalls in the quarters were the same as those determined using the seasonal scaling factors. This is because the seasonal scaling factors were determined using a large number of data points from several ensemble runs from the archived GCM continuous monthly simulations over more than 200 years, while the archived GCM daily simulations used to estimate the daily scaling factors were available only for two time slices from limited modelling runs. In addition, because of the large spatial resolution of GCMs, the monthly simulations were more realistic than the daily simulations. This daily scaling was only implemented for rainfall, as this is the most important variable for runoff generation; and, while some locations may experience lower annual total rainfall, the frequency of high intensity rainfall may increase resulting in increases in runoff for these conditions.

The project method took into account two types of uncertainties. The first uncertainty is in the global warming projection, due to the uncertainties associated with projecting greenhouse gas emissions and predicting how sensitive the global climate is to greenhouse gas concentrations. The second uncertainty is in GCM modelling of local climate in the project area. The method also took into account different changes in each of the quarters (seasons) as well as changes in the daily rainfall distribution. The consideration of changes in the daily rainfall distribution was important because many GCMs indicate that future extreme rainfall in an enhanced greenhouse climate is likely to be more intense, even in some regions where a decrease in mean seasonal or annual rainfall is projected. As high rainfall events generate large runoff, the use of simpler methods that assume the entire rainfall distribution to change in the same way would lead to an underestimation of total runoff.

The project method is similar to, but not the same as, the approach used by CSIRO and the BoM (2007) to provide the climate change projections for Australia. The key differences are: (i) this project used 15 of the 23 AR4 GCMs, while the CSIRO/BoM projections use all 23 GCMs; (ii) this project assessed the extreme range of global warming by ~2030; and (iii) this project also considered changes in the daily rainfall distribution.

As the future climate series (Scenario C) was obtained by scaling the historical daily climate series for the 1931 to 2007 northern Australia water years (Scenario A), the daily climate series for scenarios A and C have the same length of data (77 years) and the same sequence of daily climate (potential changes in the frequency and timing of daily rainfall were not considered). Scenario C is therefore not a forecast climate at 2030, but a 77-year daily climate series based on 1931 to 2007 water year data for projected global temperatures at ~2030 relative to ~1990.

The range of rainfall and APET for the ~2030 climates relative to ~1990 levels for the three warming scenarios for the 15 GCMs (i.e. 45 climate estimates in total) are shown for rainfall (Figure 17 and Table 6) and APET (Figure 17 and Table 7) across the project area. Some notable features emerge:

2. for rainfall all global warming scenarios have GCMs that predict both increases and decreases in rainfall
3. in contrast, for APET all GCMs in all three global warming scenarios predict increased APET
4. the absolute relative changes of rainfall are predicted to be greater than APET for all warming scenarios
5. for rainfall the high global warming scenario predicts greater absolute extreme values than the medium global warming scenario, which in turn predicts greater extreme values than the low global warming scenario
6. for APET the high global warming scenario consistently predicts larger change than the medium global warming scenario, which in turn predicts consistently larger change than the low global warming scenario.

As the three global warming scenarios each produced 15 estimates of ~2030 rainfall and APET, three climate estimates were identified from the 45 which were considered to represent the breadth of range in the simulated ~2030 climates. The three representations are: a relatively wet ~2030 climate ('Cwet'), a mid-range ~2030 climate ('Cmid'), and a relatively dry ~2030 climate ('Cdry'). As the high global warming scenario generally produced the wettest and driest climate simulations, the Cwet and Cdry climates were selected from the 15 climate simulations produced using the high global warming (+1.3 °C) scenario.

Cwet was identified at the second wettest climate (i.e. second highest mean annual rainfall) from within the 15 high global warming scenario climate estimates (see Table 6).

Cmid was identified as the median climate (i.e. eighth highest mean annual rainfall) from within the 15 medium global warming scenario climate estimates (see Table 6).

Cdry was the second driest climate (i.e. second lowest mean annual rainfall) from within the 15 high global warming scenario climate estimates (the high global warming scenario is used, not the low global warming scenario, as the high global warming scenario produced the largest changes in rainfall – refer to Table 6 and Figure 17).

This selection procedure was applied separately to each region, to each division and to the whole Northern Australia Sustainable Yields Project area. This means that adjacent regions can have ~2030 climates generated from different GCMs, and that the representative ~2030 climate for a division may not be the same as the aggregate of the representative climates of all its constituent regions.

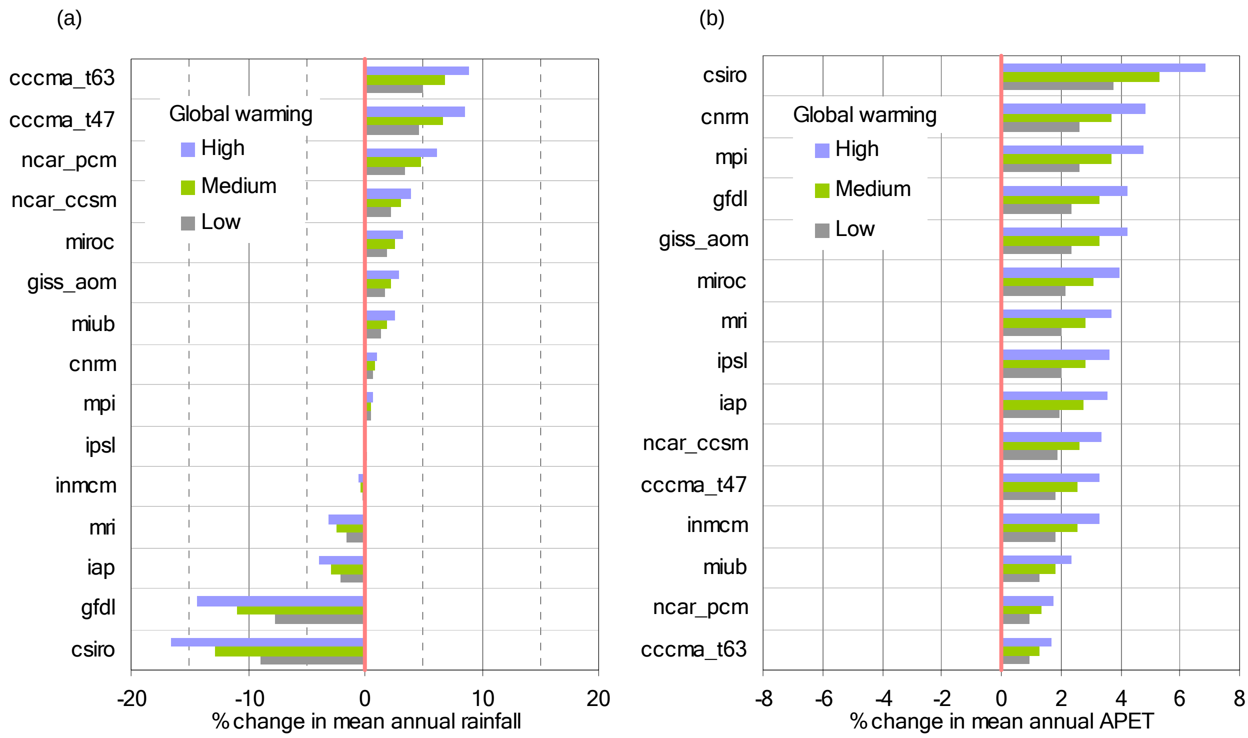

Figure 17. Percentage change in mean annual (a) rainfall and (b) areal potential evapotranspiration under the 45 future climate simulations (15 global climate models and three global warming scenarios), relative to historical rainfall and areal potential evapotranspiration (~1990) for the Timor Sea Drainage Division

Table 6. Mean annual rainfall and its percentage change relative to historical climate under the 45 future climate (Scenario C) simulations for the Timor Sea Drainage Division

High global warming			Medium global warming			Low global warming		
Model	Rainfall		Model	Rainfall		Model	Rainfall	
	mm/y	percent change		mm/y	percent change		mm/y	percent change
csiro	734	-16.63%	csiro	767	-12.89%	csiro	801	-8.95%
gfdl	**754**	**-14.33%**	gfdl	784	-10.97%	gfdl	813	-7.61%
iap	846	-3.92%	iap	854	-2.96%	iap	863	-2.01%
mri	853	-3.13%	mri	859	-2.36%	mri	866	-1.58%
inmcm	876	-0.45%	inmcm	878	-0.29%	inmcm	879	-0.14%
ipsl	880	-0.03%	ipsl	881	0.03%	ipsl	881	0.09%
mpi	886	0.61%	mpi	885	0.52%	mpi	884	0.43%
cnrm	889	1.04%	**cnrm**	**888**	**0.85%**	cnrm	886	0.66%
miub	902	2.48%	miub	898	1.96%	miub	893	1.44%
giss_aom	906	2.88%	giss_aom	900	2.26%	giss_aom	895	1.65%
miroc	909	3.26%	miroc	903	2.56%	miroc	897	1.86%
ncar_ccsm	914	3.89%	ncar_ccsm	907	3.04%	ncar_ccsm	900	2.20%
ncar_pcm	934	6.09%	ncar_pcm	922	4.74%	ncar_pcm	910	3.38%
cccma_t47	**955**	**8.54%**	cccma_t47	939	6.62%	cccma_t47	922	4.70%
cccma_t63	958	8.87%	cccma_t63	941	6.88%	cccma_t63	923	4.88%

Table 7. Mean annual areal potential evapotranspiration and its percentage change relative to historical areal potential evapotranspiration under the 45 future climate (Scenario C) simulations for the Timor Sea Drainage Division

High global warming			Medium global warming			Low global warming		
Model	APET		Model	APET		Model	APET	
	mm/y	percent change		mm/y	percent change		mm/y	percent change
cccma_t63	2011	1.65%	cccma_t63	2004	1.29%	cccma_t63	1997	0.93%
ncar_pcm	**2013**	**1.73%**	ncar_pcm	2005	1.35%	ncar_pcm	1998	0.97%
miub	2025	2.34%	Miub	2014	1.82%	miub	2004	1.30%
inmcm	2044	3.30%	inmcm	2029	2.56%	inmcm	2014	1.82%
cccma_t47	2044	3.31%	cccma_t47	2029	2.57%	cccma_t47	2014	1.82%
ncar_ccsm	2045	3.36%	ncar_ccsm	2030	2.60%	ncar_ccsm	2015	1.85%
iap	2049	3.56%	Iap	2033	2.76%	iap	2017	1.96%
ipsl	2050	3.63%	**ipsl**	**2034**	**2.81%**	ipsl	2018	1.99%
mri	2051	3.67%	mri	2035	2.84%	mri	2018	2.02%
miroc	2057	3.96%	miroc	2039	3.07%	miroc	2021	2.17%
giss_aom	2062	4.22%	giss_aom	2043	3.27%	giss_aom	2024	2.32%
gfdl	2062	4.23%	gfdl	2043	3.27%	gfdl	2024	2.32%
mpi	2073	4.77%	mpi	2051	3.69%	mpi	2030	2.61%
cnrm	**2074**	**4.81%**	cnrm	2052	3.72%	cnrm	2030	2.63%
csiro	2114	6.86%	csiro	2083	5.30%	csiro	2052	3.74%

2.1.4 Confidence levels for climate assessment

The gridded climate data were derived from observations that have been quality checked by the BoM and subjected to additional error checking by the Queensland Climate Change Centre of Excellence (Jeffrey et al., 2001). Nevertheless, it is inevitable that there will still be errors in the data; interpolation routines also introduce errors. In general, the data accuracy is expected to be lower in areas where the observation density is low relative to the climate gradients. In this context, it should be noted that rainfall has lower spatial and temporal auto-correlation than other climate variables. This has been compensated for by the BoM purposefully establishing the rainfall observation network with a higher density than for other climate variables, noting that the observing densities of both rainfall and maximum air temperature have increased over time.

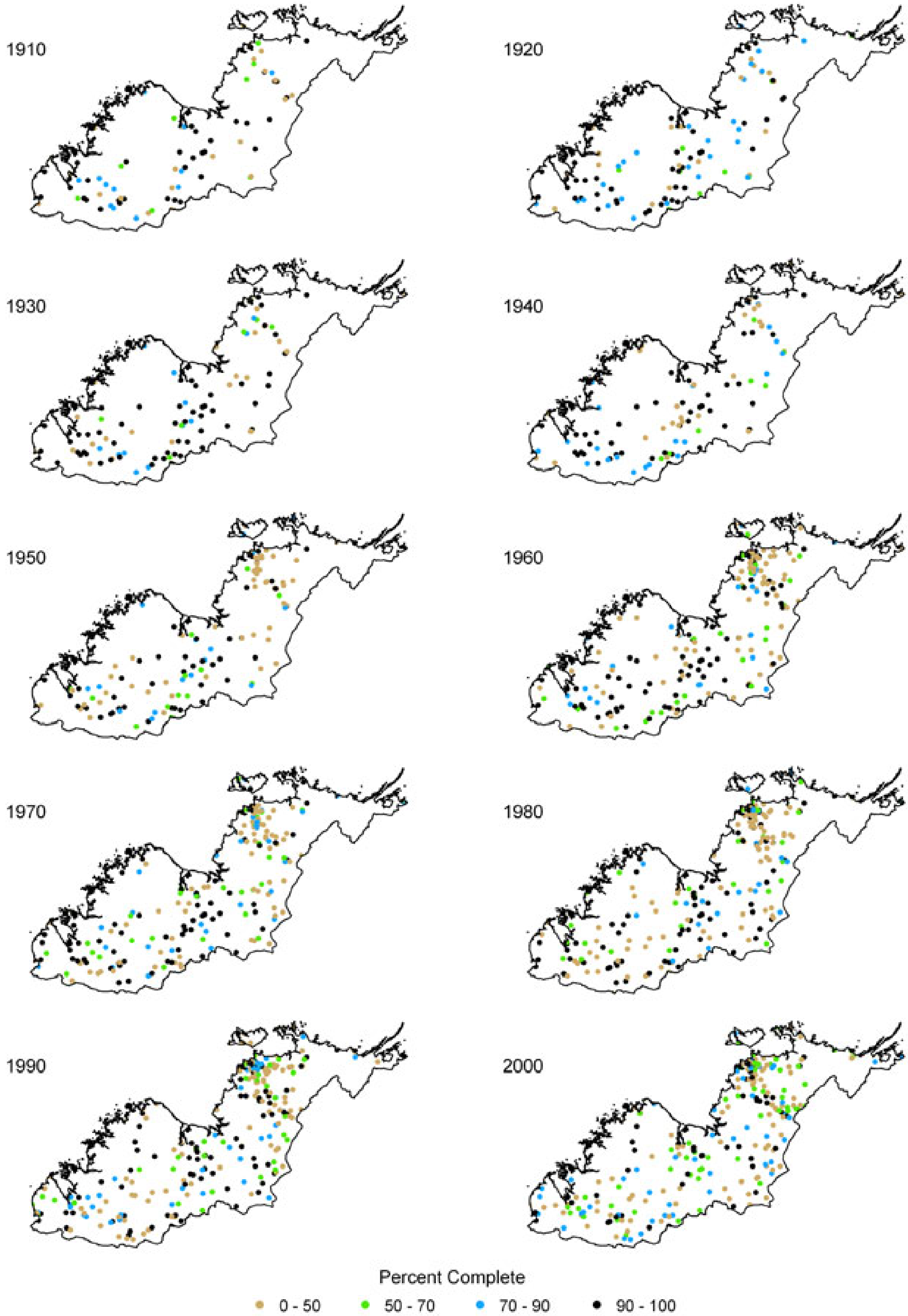

Figure 18. Location of Australian Bureau of Meteorology stations in the Timor Sea Drainage Division measuring daily rainfall used in the SILO database for each decade from 1 January 1910 to 31 December 2009

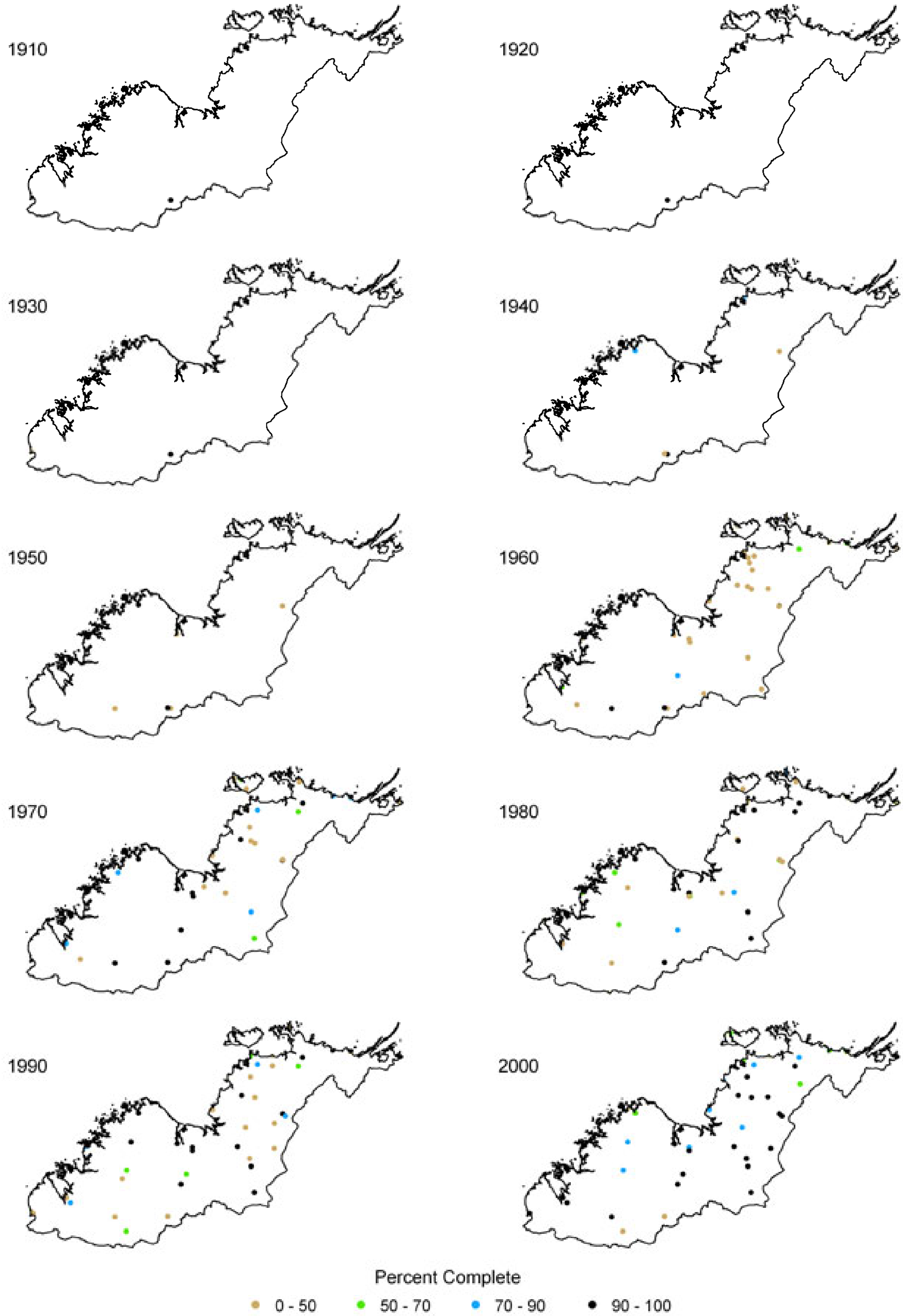

Figure 19. Location of Australian Bureau of Meteorology stations in the Timor Sea Drainage Division measuring daily maximum air temperature used in the SILO database for each decade from 1 January 1910 to 31 December 2009

A variety of metrics were calculated to characterise the level of confidence associated with the forcing data for the scenarios. Note that the term 'confidence level' analysis is used to mean a characterisation of the confidence, or uncertainty, involved in each scenario.

As rainfall is the variable with the greatest uncertainty when interpolating, and is the primary variable controlling runoff (Chiew, 2006), it is important to understand the confidence associated with this when interpreting rainfall-runoff modelling results. Both temporally-varying all-Australian averaged error statistics and temporally-static long-term mean maps of error have been reported (Jeffrey et al., 2001) which indicate levels of confidence of the data used in the construction of scenarios A, B and C. In this project an analysis to reflect the combined spatio-temporal dynamics was undertaken by analysing, on a decadal time step, both the distance of each grid cell to the nearest input station and the completeness of the record of that station per decade. This is termed the 'distance-completeness index', and the spatial distribution of this metric for rainfall and maximum air temperature for the decade 2000 to 2009 is shown in Figure 20. In this figure, a value of 1.0 indicates that the location is a station with a complete rainfall record, and the index decreases with distance away from stations and/or with decreasing completeness of rainfall record.

Given the greater spatial auto-correlation in air temperature when compared to rainfall, the spatial density of stations measuring temperature is, as expected, lower. The decadal evolution of the distance-completeness index from the 1930s to 2000s is shown in Li et al. (2009).

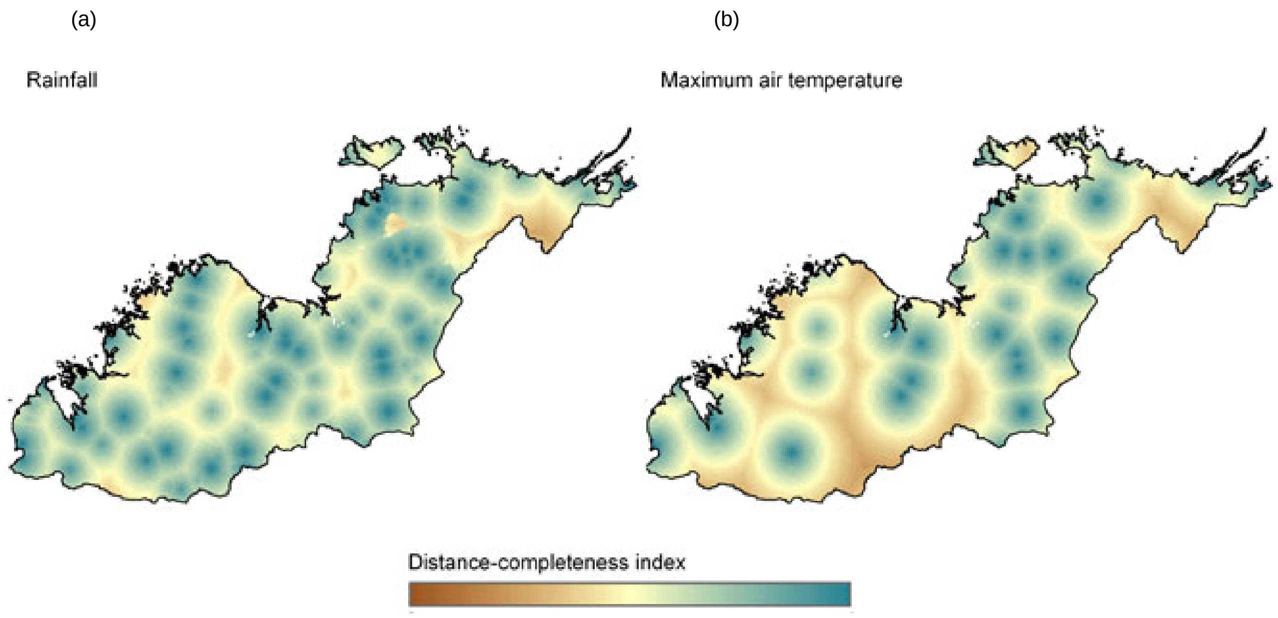

Figure 20. Spatial distribution of the distance-completeness index for the current decade for (a) rainfall and (b) maximum air temperature across the Timor Sea Drainage Division

The distance-completeness index is a unitless metric, scaled consistently over the time series, which provides a quantitative illustration of the dynamics of the underpinning observation network. However, it should be noted that this metric cannot be used to propagate error in the rainfall-runoff modelling. To do this requires that daily surfaces of error, with the same units as the meteorological variable, are made available by providers of daily meteorological variables. Currently the Queensland Climate Change Centre of Excellence do not provide such daily error surfaces, and while the BoM do provide them at a similar resolution to this project (i.e. 0.05 x 0.05 degree or ~ 5 x 5 km) and for daily data, the BoM record only starts at 1 January 2005. This is not long enough for the modelling performed in this project (starting 1 September 1930).

2.2 Surface water assessment

2.2.1 General approach

The surface water assessment involved six separate tasks:

- gauging station selection and data preparation
- rainfall-runoff modelling at the regional scale for scenarios A, B and C
- river system modelling
- assessment of regions without river models
- evaluation of levels of confidence
- an alternative approach using multiple linear regression to compute key hydrological metrics.

Data assessment and rainfall-runoff modelling were undertaken on a region-by-region basis and are reported in the region chapters. Multiple linear regression was undertaken at the whole of northern Australia scale and a summary of the results from that analysis are presented in this chapter. A more detailed description of the rainfall-runoff modelling methods and the multiple regression analysis is provided by Petheram et al. (2009) and SKM (2009) respectively.

2.2.2 Gauging station selection and data preparation

The difficulty of operating and maintaining streamflow gauging stations in the harsh northern Australian environment meant that relative to the total project timelines, considerable time and resources were invested in assessing streamflow data quality. Establishing the streamflow station database for use in this project involved a trade off between maintaining high quality data and having a good spatial distribution of gauging stations.

Daily discharge and stage height data were obtained from government agencies for the 24 hour period from 9am(which coincides with the standard reporting period for rainfall). Each of the three jurisdictions use different codes to assign measures of data quality to stage height and discharge data. For this project these quality codes were standardised so that data coded the equivalent of satisfactory or good were accepted, and data coded the equivalent of poor or missing were rejected.

The initial criterion for the selection of gauging stations for this analysis was that they had a minimum of eight years of ‘acceptable’ monthly discharge data, although this criterion was relaxed where data were sparse. Because of the paucity of streamflow data in northern Australia, no minimum or maximum criteria for catchment area were specified nor was a calibration period between specified dates imposed. Nevertheless because most stations commenced operation after 1960, the majority of stations were calibrated over a period during the last 45 years. However, gauging stations were rejected if: their contributing area was deemed to be an ‘open’ system (as not being able to explicitly determine the catchment area draining to the gauging station violates the assumptions for the rainfall-runoff models used in this analysis); there was distributary flow into or out of the catchment upstream of the gauge, or if high or low flows were impeded at the 10 percent level (i.e. due to diversions or storages).

For the Queensland gauging stations, the non-descriptive nature of the data quality codes meant it was necessary to impose an additional requirement on those stations, such that a station could not have more than 60 percent of its total volume of flow occur at a height greater than its maximum gauged stage height. The selection of 60 percent was intuitive and based on a compromise between ensuring a reasonable spatial representation of gauging station and data quality. Recent maximum gauged stage height information was provided by Queensland state hydrographers. For stations in the Northern Territory, rating curves for most stations were inspected and those stations with a poor spread of gauged stage heights were rejected. Department policy in Western Australia meant supply rating curve information could not be provided, but qualitative assessments of the quality of low and mid- to high flow ratings were provided. Petheram et al. (2009) provide further details on station selection.

Every gauging station and streamflow reporting node was manually snapped to a streamline coverage, generated from the third version of the 9-second digital elevation model (DEM). The area upstream of each gauging station was computed and compared to areas stated in the Australian Water Resources Council (AWRC) gauging station catalogue. Where the computed area differed by more than 15 percent from the AWRC value, the relevant stage agency was approached. In the majority of instances it was agreed the gauging station had been appropriately sited on the DEM streamline network and the DEM-derived area was correct. Establishing the correct catchment area was important because catchment area is strongly correlated to streamflow. Streamflow reporting nodes (SRNs) were also sited on the DEM streamline network. These nodes were located at catchment outlets, gauging stations, environmental assets and other 'dummy' locations to provide an even spread of SRNs across the project area. In those AWRC river basins where river system models were available (i.e. Ord-Bonaparte, Daly and Van Diemen), SRNs were located so that they corresponded to the nodes within the river system model.

To produce spatially coherent maps of runoff, a subcatchment boundary (and subcatchment ID) were assigned to the relatively extensive coastal regions downstream of the SRNs. This resulted in each region being assigned between one and three 'coastal subcatchments', depending upon the length of its coastline, the diversity of climate along its length and the locations of suitable gauging stations.

2.2.3 Rainfall-runoff modelling

The rainfall-runoff modelling was used to estimate 77 years of daily catchment flows for three scenarios:

1. Scenario A (historical climate sequence (1 September 1930 to 31 August 2007) and current development) – one single simulation based on the historical climate series
2. Scenario B (recent climate sequence (1 September 1996 to 31 August 2007) and current development) – one simulation of the climate from the past 11 years run seven consecutive times
3. Scenario C (future (~2030) climate and current development).

For future development, projections of the growth in commercial forestry were obtained from jurisdictions. In the Northern Territory the majority of expansion in commercial forestry – 30,000 to 70,000 ha – was expected to occur within the Daly River catchment. While this is the largest projected expansion of commercial forestry in northern Australia, it represents less than one percent of the area of the Daly River catchment. Based on work elsewhere, changes in catchment yield due to commercial forestry operations that occupy less than 10 percent of the land area will be smaller than the 'noise' in the streamflow data and rainfall-runoff modelling. Although it should be noted that commercial forestry could result in large changes to catchment water yield at local scales (e.g. the scale of Stray Creek), this aspect is beyond the scope of this broad analysis. Projections for the growth in farm dams in northern Australia to 2030 indicate these will be negligible.

Therefore no Scenario D analyses were undertaken for the rainfall-runoff modelling because nowhere in the drainage division would future development differ significantly (i.e. within the error bounds of analyses) from current development (Scenario C).

Five lumped conceptual daily rainfall-runoff models (SIMHYD, Sacramento, IHACRES Classic, SMARG and AWBM) were trialled. Preliminary testing indicated that the ensemble of Sacramento and IHACRES Classic was the optimal combination of models for this project. This combination balanced model performance with the practicalities of running multiple rainfall-runoff models at a 5 x 5 km grid cell scale, across an area of 1.25 million km^2 in a short space of time.

The Sacramento and IHACRES Classic models were used to extend streamflow records at existing gauging station locations and to simulate runoff at each 0.05 degree grid cell over the entire project region for each scenario. See Petheram et al. (2009) for further details on model selection.

The rainfall-runoff modelling steps were:

1. The rainfall-runoff modelling ensemble was set up to run at 0.05 x 0.05 degree (~ 5 x 5 km) grids across northern Australia. The use of a 0.05 degree grid allowed the best representation of the spatial patterns and gradients in rainfall, allowing improved accounting for the non-linear relationship between rainfall and runoff.

2. The 0.05 degree gridded daily rainfall and APET data across northern Australia for 1930 to 2007 was compiled (obtained, analysed and prepared). The SILO gridded data (Jeffrey et al., 2001; and <www.nrm.qld.gov.au/silo>) were used. APET was used, calculated from the SILO daily climate surfaces using Morton's wet environment evapotranspiration algorithms (see <www.bom.gov.au/climate/averages> and Chiew and Leahy, 2003). The 0.05 degree grid cells were then mapped into each gauged catchment and SRN.

3. The rainfall-runoff models were calibrated against observed streamflow data from unregulated catchments (the same parameter values were used for all grids within a catchment). Calibration was carried out using an

objective function that incorporated the Nash-Sutcliffe efficiency (Nash and Sutcliffe, 1970) of daily and monthly streamflow, dry season monthly streamflow, and the goodness-of-fit of daily flow duration curves, together with constraints to ensure that the total flow volumes were well modelled. Because objective functions that incorporate the Nash-Sutcliffe efficiency are biased towards the high flows, lower flow are typically less well modelled, and this was reflected in the Nash-Sutcliffe efficiency for dry season monthly metrics and consequent representation in the lower half of the flow duration curve (FDC).

As the seasonality of flows in northern Australia needed to be addressed, it was necessary to improve the low flow calibrations. To do this several alternate objective functions which favoured good simulations at the low flows were trialled. This was primarily done by raising the observed and simulated terms in the objective function to the power of λ (see Chiew et al., 1993). Calibrations were undertaken for values of λ of 1, 0.5, 0.35, 0.2, 0.1 and 0.05, resulting in six optimised parameter sets for each model and for each calibration catchment. Using values of λ less than 1 during the calibration reduced the bias towards high flows. However, improving low flow calibrations usually comes at a cost to high flow calibrations. As flow volumes are strongly biased by high flow events, care needed to be taken to ensure that high flow calibrations did not markedly decrease. In most cases when selecting a parameter set from the six optimised sets, it was possible to considerably improve the Nash-Sutcliffe efficiency of low flow metrics through small sacrifices in the Nash-Sutcliffe efficiency of high flow metrics (typically resulting in a sacrifice of less than 0.05 Nash-Sutcliffe efficiency for daily flows). Streamflow routing was not explicitly incorporated by these implementations of IHACRES Classic and Sacramento; however, in small to medium sized catchments the use of 0.05 degree grids meant that routing was implicit in the calibration.

In the Daly and Fitzroy catchments (in the Daly and Fitzroy (WA) regions respectively), a ‘residual flow’ approach was undertaken at a middle and a lower reach for each of these river systems. Here, simulated runoff values from headwater/upstream gauging stations were subtracted from the observed time series at the downstream gauge to produce a residual flow time series. The rainfall-runoff models were then calibrated to the residual flow time series using an objective function based on monthly flow data (rather than daily flow data as per Step 3). The use of an objective function that utilised monthly flow data overcame the need to account for lag and attenuation when subtracting the upstream flow time series from the downstream flow time series. This approach was deemed most suitable for the Daly and Fitzroy catchments, because they are large catchments (greater than 50,000 km^2) with suitable gauging stations in series along their main river system. See Petheram et al. (2009) for more details.

4. “Average” the calibration results to produce Nash-Sutcliffe efficiency for the two model ensemble (where each model had an equal weighting).
5. The ability of the model ensemble to estimate streamflow in ungauged catchments was assessed using the nearest neighbour approach, but also taking into account climatic gradients. Where multiple catchments were equally close, preference was given to the catchment with similar climatic characteristics (i.e. largely based upon distance from coast). The ability of the model ensemble to estimate streamflow in ungauged catchments is briefly discussed in each region chapter and a more detailed discussion is provided by Petheram et al. (2009).
6. Parameter values for all 0.05 degree grids across northern Australia were then estimated. Parameter values for the ungauged grids were based on a combination of values from the closest, or most hydrologically similar, grid and/or catchment where calibration was possible (e.g., Merz and Bloschl, 2004; Chiew and Siriwardena, 2005; Reichl et al., 2006). All grids within the contributing area of a SRN were allocated the same parameter set values.
7. The rainfall-runoff modelling ensemble was run in simulation mode using historical climate data (1930 to 2007) to estimate daily runoff for 0.05 degree grids across northern Australia. An ensemble runoff time series was generated taking the mean of the run time series generated by the Sacramento and IHACRES Classic models and spatially reporting the mean runoff for each grid cell.
8. The mean and 10th, 50th and 90th percentiles of annual and monthly runoff and daily FDC were then reported at the regional scale.

Once simulations for Scenario A were completed, simulations for Scenario B were run. For this scenario the rainfall-runoff modelling ensemble was run over the recent 11-year sequence, seven consecutive times, to give a time series of equal length (77 years) to Scenario A.

For each region, the Sacramento and IHACRES Classic models were run using the daily climate series for Scenario C and the two model runs were averaged. This provided 45 series of 77 years of modelled daily runoff (i.e. one climate series from each of the 15 GCMs for each of the low, medium and high global warming scenarios). For each region a Cdry, Cmid and Cwet scenario was reported. Scenarios Cdry and Cwet corresponded to the 10th and 90th percentiles of mean annual runoff in the high emissions scenario (i.e. obtained from the 14th and 2nd wettest GCM from the high global warming scenario). Scenario Cmid corresponded to the 50th percentile of mean annual runoff and was obtained from the 8th ranked GCM from the medium warming series. This represents the median result from the future climate models, and, for northern Australia, is indicative of the majority of GCM results.

The net effect of global warming and increased CO_2 concentrations on forest water use is difficult to estimate due to a lack of research data on the complex interactions between climate and the biosphere in northern Australia. Higher CO_2 concentrations, for example, may increase forest growth and leaf area index, resulting in higher interception loss, but this may be compensated by lower stomatal conductance and transpiration rates. No attempt was made, therefore, to quantify the effects of CO_2 fertilisation on plant water use and catchment yield.

2.2.4 River system modelling

Where possible river system models were used. These models encapsulate descriptions of current infrastructure, water demands and water management and sharing rules and can be used to assess the implications of the changes in inflows described in the rainfall-runoff section on the reliability of water supply to users. They may also be used to support water management planning by assessing the trade-offs between supplies to various competing categories of users. Given the time constraints of the project and the need to link the assessments to jurisdiction water planning processes, it was necessary to use the river system models currently used by these agencies. Where data information on infrastructure, water demand, water management and sharing rules or future development were not provided, a river modelling section was not warranted. Regions without river models are referred to as Tier B regions and are discussed further in Section 2.2.5.

Regions where river system models exist are referred to as Tier A regions. In these regions a variety of metrics are reported, including water availability, level of consumptive use and storage behaviour of spills.

In the Timor Sea Drainage Division river system models only exist for the Daly (coupled MIKE11–FEFLOW) and Ord (Mike Basin) and there is a simple reservoir model for the Darwin River Dam. For the river system modelling section, Scenario A refers to the 77-year historical climate sequence. Scenario B and C refer to the recent and future climate respectively. For all scenarios the models were started on the 1 September 2007. Results are then reported over the period 1 September, Year 1 to 31 August, Year 77.

The modelled ensemble runoff series from Sacramento and IHACRES Classic were used directly as subcatchment inflows to the Mike Basin model (Ord-Bonaparte region), but not the Darwin River Dam (Van Diemen Gulf region) or the coupled Mike 11–FEFLOW model (Daly region). Instead, the relative difference between the mean monthly runoff values of the historical climate Scenario A and the remaining scenarios (Scenarios B and C) normalised by the mean annual runoff values of the historical climate Scenario A and the remaining scenarios (Scenarios B and C) were used to modify the existing inflows series in the river system models. The Scenarios B and C inflow series for the river system modelling therefore have the same daily sequences, but different volumes to the Scenario A river system modelling series. The same method was applied to rainfall and evaporation data.

2.2.5 Regions without river system models

In the Tier B regions of the Timor Sea Drainage division there were generally few suitable gauging stations in series. In these regions modelled ensemble runoff series were used directly to provide predictions of streamflow at each SRN within the region. Where suitable gauging stations existed, streamflow was modelled at that station using the ensemble results from the Sacramento and IHACRES Classic models. Where a SRN node did not coincide with a suitable gauging station, a streamflow time series was generated by aggregating the grid based runoff values (from Section 2.2.3) between the SRN and any upstream gauging stations. The aggregated runoff time series was then multiplied by its sub-catchment area and added to the streamflow time series modelled at the upstream gauges to give a streamflow time series at the downstream node. Daily flow volumes less than 0.1 ML/day were set to zero. This approach, while being simple, was commensurate with available data and the time constraints imposed on the project, and minimised the extent to which errors were propagated downstream. Outside of the Daly there was little information to support the use of routing parameters. With the exception of the Ord, Victoria and Fitzroy, the remaining catchments had relatively short flow paths. The streamflow time series at SRNs were used for the metric analysis in the environment Section **Error! Reference source not found.** and are presented in Petheram et al. (2009). In the Timor Sea Drainge Division, these Tier B regions are Arafura, Van Diemen, Kimberley and Fitzroy, although, with more time, river system models could have been built for the Adelaide River in the Van Diemen Gulf region and the Fitzroy River in the Fitzroy (WA) region.

2.2.6 Confidence levels for surface water assessment

The Timor Sea Drainage Division had few streamflow gauging stations prior to 1955. The number of stations rapidly increased in the 1960s when the Commonwealth government provided an injection of funding to the state-based surface water data collection programs. This is particularly evident in the Northern Territory, which was heavily reliant on Commonwealth funding. During the late 1980s the Commonwealth government redirected funding for the collection of hydrological data elsewhere. In the Timor Sea Drainage Division this resulted in a sudden reduction in the number of operating streamflow gauging stations (Figure 21). Currently in the drainage division there are about 90 operational streamflow gauging stations. The majority of operational stations are in the Ord and Daly catchments and in catchments near Darwin. The Kimberley and Arafura Sea regions each have less than three operating streamflow gauging stations. The spatial distribution of the operational and closed stations is shown in Figure 22. Closure of stations resulted in stations having relatively short record lengths and in some cases insufficient length of record for inclusion in this study. It also made it difficult to choose a common time period over which to calibrate the rainfall-runoff models.

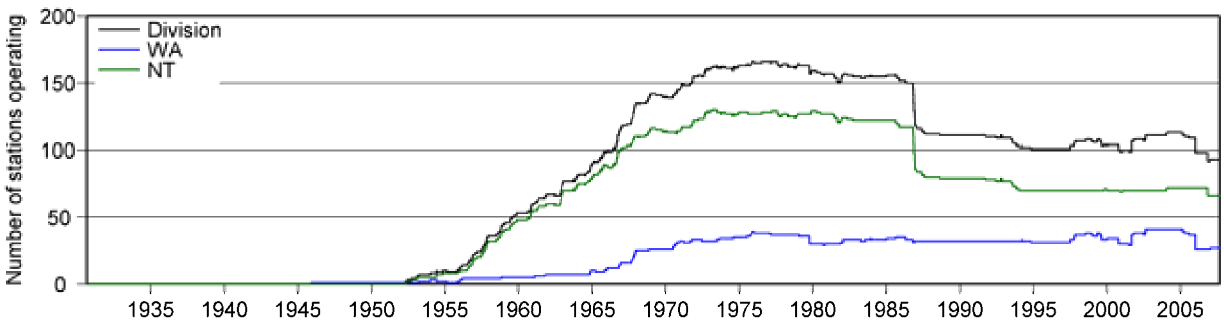

Figure 21. Number of operating streamflow gauging stations in the Timor Sea Drainage Division by state (Northern Territory and Western Australia) and the entire drainage division between 1930 and 2007

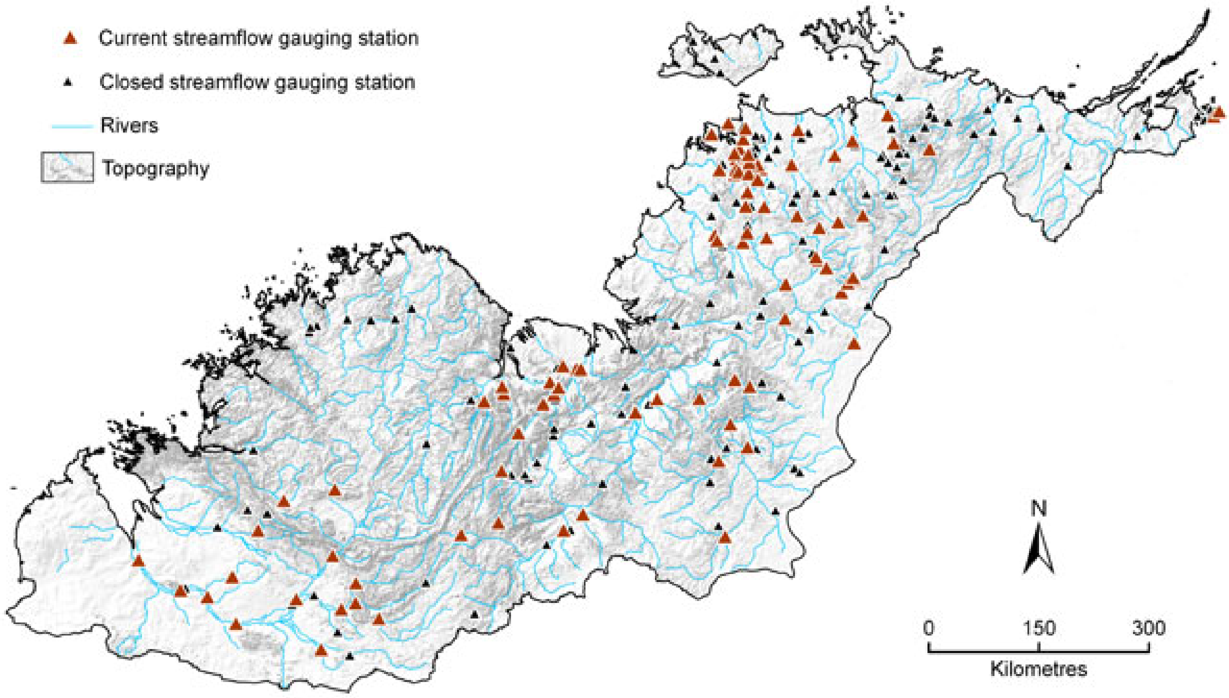

Figure 22. Location of operating (current) and closed streamflow gauging stations in the Timor Sea Drainage Division overlaid on a relative relief surface

There is, thus, a spatial and temporal restriction on the confidence in the data. This makes regionalisation difficult. An assessment can be made, however, on the confidence in individual gauge information, as well as some informed judgement on the process of extrapolation across each region.

For rainfall-runoff modelling, the Nash-Sutcliffe efficiency (NSE) metrics provide a direct measure of level of confidence. These metrics were computed for every calibration catchment. However, in northern Australia there are vast ungauged areas. To assess the skill to which model parameters can be transposed from a gauged catchment to an ungauged subcatchment, cross-verification simulations were undertaken. In this analysis every calibration catchment was simulated using the parameters from every other calibration catchment, generating a cross-verification matrix of NSE values. For every calibration catchment a distribution of NSE values was then generated by randomly selecting with replacement 1000 donor catchments from the cross-verification matrix. Each NSE value was weighted by the inverse of the distance between the donor and target catchment and this weighting was applied to the frequency axis (i.e. distance-weighted frequency). A smoothed curve was then fitted through the frequency distribution of NSE values and the NSE value at the modal point was selected (i.e. 0.62 for the example in Figure 23).

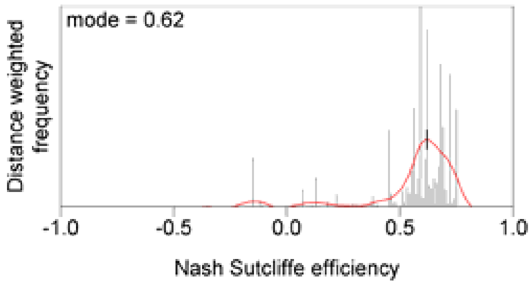

Figure 23. Example of a distance-weighted frequency and Nash-Sutcliffe efficiency values for a streamflow gauging station. The red line is a smoothed curve fitted to the distribution. In this example the modal point on the curve corresponds to a Nash-Sutcliffe efficiency of 0.62

A continuous surface of transposed NSE values was then generated by interpolating (using nearest neighbour spatial interpolation method) between the selected transposed NSE values as described above. The surface of transposed NSE metrics was combined with a map of calibration NSE metrics at gauged catchments to produce maps indicating the level of confidence in the rainfall-runoff and streamflow predictions.

Because rainfall-runoff models are biased in their calibration to a particular range of flows, usually the mid-to high flows (i.e. peak flow events), the level of confidence for the high and low flow predictions may be different within the same subcatchment. Hence separate levels of confidence were provided for the mid- to high flows and for the dry season flows. The NSE values for daily flow were used to provide a measure of the level of confidence associated with the mid- to high flows and the NSE value of the monthly dry season flow was used to provide a relative measure of the level of confidence associated with dry season flows.

However, the use of the NSE metrics alone cannot properly convey the level of confidence in the rainfall-runoff and streamflow predictions for a region because in some cases qualitative information was also incorporated into the assessment. Consequently for each subcatchment the areal-mean NSE metrics were transformed into a generalised ranking, 1 through 5 as shown in Table 8. Subcatchments assigned a 1 were deemed to have the highest level of confidence and 5 was assigned to subcatchments with the lowest level of confidence. To account for the additional uncertainty associated with transposing parameters, ungauged subcatchments attracted a penalty of 0.1 to the mean NSE value as shown in Table 8.

Table 8. Levels of confidence ranking using Nash-Sutcliffe efficiency values from calibration and cross-verification results

Level of confidence ranking	Calibration catchment	Ungauged catchment
1	mean NSE* > 0.8	mean NSE > 0.9
2	0.8 > mean NSE > 0.6	0.9 > mean NSE > 0.7
3	0.6 > mean NSE > 0.4	0.7 > mean NSE > 0.5
4	0.4 > mean NSE > 0	0.5 > mean NSE > 0
5	mean NSE < 0	mean NSE < 0

* NSE – Nash-Sutcliffe efficiency value

Once a confidence level ranking had been assigned to each subcatchment on the basis of their NSE, the qualitative information was then incorporated into the assessment. Subcatchments attracted a penalty of 1 or more confidence rankings if they exhibited any of the following traits (details provided in Petheram et al., 2009):

- large catchment area
- potentially violated rainfall-runoff model assumptions (i.e. not a closed system)
- gauging station quality questionable
- markedly different hydrogeology between donor and target catchments (low flow penalty only)
- mean annual runoff values anomalous to the broader region (but no justification to remove the gauging station from the analysis)

- long distance between donor calibration catchment and ungauged target subcatchment
- uncertainty associated with input climate data (e.g. under-prediction in regions with strong orographic rainfall gradients like the North-East Coast)
- distributary flow channel above the gauging station.

It should be noted that the maps of level of confidence are not statistical confidence levels and are intended to only convey a broad reliability of prediction. The level of confidence map for dry season flow in particular requires careful interpretation. For example across most of northern Australia there is a high degree of confidence that dry season runoff is low because it is known that rainfall and baseflow are low during the dry season. Instead the level of confidence for the dry season flow map should be interpreted as providing a relative indication of how well dry season metrics, such as mean annual dry season flow and cease-to-flow criteria, are simulated. Metrics controlled by dry season flows may be important when assessing environmental flow requirements or potential dry season diversions.

It should also be noted that the level of confidence in streamflow predictions may vary slightly from the predictions for runoff. For example, for the simulation of runoff in a large calibration catchment (e.g. greater than 40,000km^2) there may be a high level of confidence in the simulated streamflow volume at the gauging station. However, there may be a much lower level of confidence in the spatial distribution of runoff within the large catchment. Furthermore, there may be a low level of confidence associated with ungauged runoff grid cell values immediately downstream of the large calibration catchment. However, the level of confidence in the streamflow volume immediately downstream of the large calibration catchment may still be high because that additional area of the ungauged runoff grid cells would be small in comparison to the area of the calibration catchment, and hence it would be expected that the streamflow volume would be similar.

2.2.7 Multiple linear regression approach

A multiple linear regression approach to predicting streamflow metrics in northern Australia was undertaken in parallel to the rainfall-runoff modelling described in Section 2.2.3. This alternative approach was undertaken because of the large area of ungauged land in northern Australia and the uncertainty associated with predicting streamflow in ungauged catchments. Comparing the results from the rainfall-runoff modelling with an alternative and independent method provided an additional assessment of the level of confidence of the predictions. At those SRN where there was good agreement between approaches, there is a higher level of confidence than at those SRN where there was poor agreement. Having two complementary approaches also enabled the better of the two approaches to be selected for a particular task, where one approach was superior to the other.

The multiple linear regression approach used a subset of the initial calibration catchment gauges. Two primary factors were taken into account when initially selecting a set of candidate gauged catchments. These were the period of record and data quality. The selection of gauges involved a trade-off between these two factors and the number of candidate catchments that are made available for use in the subsequent regression analyses. For example, longer periods of record provide more reliable temporal estimate of the hydrological indices being calculated, but this lowers the sample size of candidate catchments and hence results in less reliable regression equations used to estimate the ungauged hydrological indices. When considering data quality, it is important to ensure that the data being used represents actual catchment behaviour as far as possible, and therefore has minimal infilling. Infilling the data can introduce hydrological characteristics which are an artefact of the infilling technique rather than the stream itself. SKM (2007) adopted a selection threshold allowing no more than 10 percent of the streamflow record to be infilled. CSIRO considered thresholds of both 5 and 10 percent.

A further criterion for a multiple regression approach was that gauging stations had a minimum of 90 percent of their record complete between 1972 and 1987. Stations were also excluded from the analysis if the station was known to have an unstable low flow rating curve, or considerable uncertainty associated with the high flow estimates, or if streamflow was considered to be impeded at the 10 percent level.

For the multiple linear regression the hydrological metric of interest was related to independent catchment (e.g. slope, mean elevation, percentage tree cover, drainage density etc) and climatic attributes (e.g. mean annual rainfall, mean length of dry season) using multiple regression analysis, where the model was derived one step, one independent variable at a time. Independent variables were selected based upon a physical understanding of the key factors controlling each flow parameter. The streamflow metrics investigated were:

- mean annual, wet season and dry season flow
- coefficient of variation of annual flow (i.e. standard deviation of annual flow divided by the mean annual flow)
- 10th percentile annual flow
- 50th percentile daily runoff
- 80th percentile annual flow
- percentage cease-to-flow
- base flow index (BFI).

Once the multiple linear regression equations were established they were then used to predict the hydrological metrics at each SRN. A full description of the multiple linear regression method is provided in SKM (2009).

Comparison of results from multiple regression approach and rainfall-runoff modelling

A comparison of the two approaches was undertaken using a set of gauging stations that were common to both approaches. For each gauging station a time series was generated using the calibration parameters for the gauge and calibrated parameters from the nearest neighbouring gauging station. The hydrological metrics listed above were then computed for each time series and compared to the observed streamflow data (between 1972 and 1987) and the values computed using multiple linear regression.

The results of the comparison of the two approaches indicate that over the 1972 to 1987 time period, the multiple regression approach (Figure 24b) is slightly better (NSE value of 0.71 versus 0.58) at predicting mean annual flow in ungauged catchments in the Timor Sea Drainage Division than transposing rainfall-runoff model parameters on the basis of nearest neighbour (Figure 24a), although the skill of the two methods is indistinguishable at the all-of-project-area scale (Figure 24b). Figure 24a plots cross-verified (XV) rainfall-runoff (RR) modelling results against observed flow (mm/day) and Figure 24b plots regression modelled results against observed flow (mm/day). In Figure 24, Figure 25 and Figure 26, Division is the Timor Sea Drainage Division, NASY is the all-of-project area, NSE Division is the NSE value for the division, and NSE NASY is the NSE value for the all-of-project area.

The multiple regression and transposition of rainfall-runoff parameter methods had a similar predictive capability in the Timor Sea division and at the all-of-project-area scale for the high flow dominated metrics, namely mean wet season flow (NSE value for the Timor Sea Drainage Division of 0.64 and 0.62 respectively), 10th percentile of daily flow (NSE value for the Timor Sea Drainage Division of 0.68 versus 0.74) and 20th percentile of daily flow (NSE value for the Timor Sea Drainage Division of 0.62 versus 0.56).

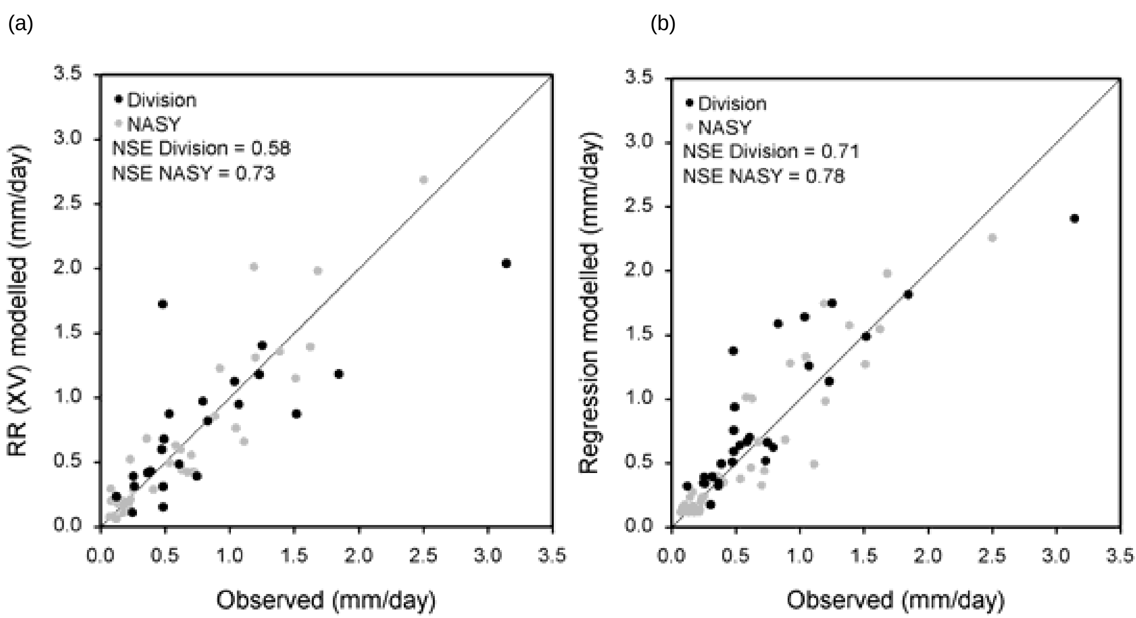

Figure 24. Comparison of (a) cross-verified rainfall-runoff modelling and (b) multiple linear regression methods for predicting mean annual flow in ungauged catchments for the Timor Sea Drainage Division (black dots) and the all-of-project area (grey dots). See text for discussion

Both methods demonstrated lower skill at predicting low flow metrics in ungauged catchments over the 1972 to 1987 period, although the multiple regression approach appeared superior at both Timor Sea Drainage Division and all-of-project-area scale. Figure 25 illustrates the predictive skill of the two methods at predicting total dry season flow in ungauged catchments over the 1972 to 1987 period. The multiple regression approach appeared to be superior for computing total dry season flow between 1972 and 1987 in the Timor Sea Drainage Division, although the two methods are comparable at all-of-project area.

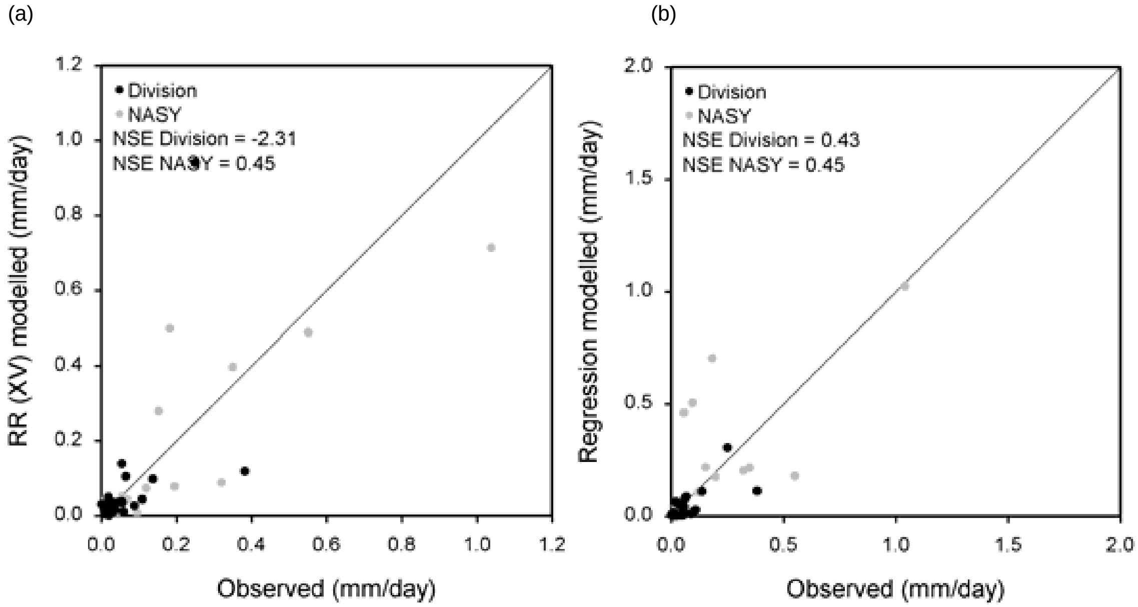

Figure 25. Comparison of (a) rainfall-runoff modelling and (b) multiple linear regression methods for predicting total dry season flow in ungauged catchments for the Timor Sea Drainage Division (black dots) and the all-of-project area (grey dots)

The multiple regression approach was also superior at predicting low flow metrics (i.e. cease-to-flow and 50th percentile and 80th percentile daily flow values). Figure 26 compares the two approaches at predicting the cease-to-flow condition (where zero flow was assumed to be less than 0.1 ML/day) for the Timor Sea Drainage Division and all-of-project area. Transposing rainfall-runoff parameters was similar to the multiple regression approach at predicting the coefficient of variation of annual flow and the baseflow index in ungauged basins in the Timor Sea Drainage Division and all-of-project-area scale.

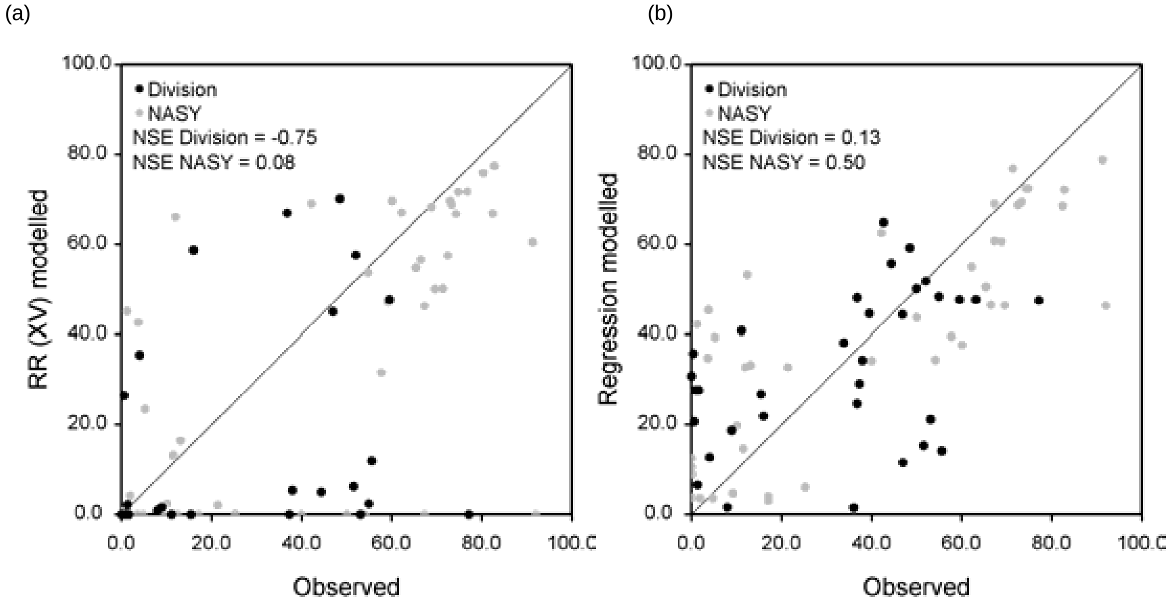

Figure 26. Comparison of (a) cross-verified rainfall-runoff modelling and (b) multiple linear regression methods for predicting cease-to-flow in ungauged catchments for the Timor Sea Drainage Division (black dots) and the all-of-project area (grey dots)

While the approaches used different gauging information and time periods (i.e. there was no specified start or end date for calibrating the rainfall-runoff models), it could be inferred that the skill of the two approaches at predicting mean annual flow, mid- to high flow metrics, and coefficient of variation of annual flows was broadly comparable.

Applying these two approaches concurrently provides an additional measure of the level of confidence in each prediction. For example, where the predictions of the two approaches are similar the level of confidence in the predicted value is greater than where the predictions made by the two approaches disagree.

The multiple regression approach appears to be the more suitable for predicting the low flow metrics, cease-to-flow and the 50th percentile and 80th percentile of daily flow, although when many of the observed values are small the NSE values can be biased by outlying values. Nevertheless this result is not surprising given the rainfall-runoff models were calibrated primarily to the mid- to high flows and parameters sets were transposed to ungauged catchments using the nearest neighbour approach. This approach of transposing parameter sets does not appear to be a suitable method for regionalising rainfall-runoff storage parameters. In the future there may be opportunity to integrate the two approaches to improve the low flow metric predictions from the rainfall-runoff models. This was beyond the scope of this project.

2.3 Groundwater assessment and modelling

2.3.1 General approach

The groundwater assessment and modelling component of the project collated existing data and knowledge to report on the occurrence, status and possible future condition of groundwater resources across the six regions within the Timor Sea Drainage Division. Reporting is at the region scale. However contextual information and detailed assessments are focussed on the important aquifers and how they interact with one another and surface water systems, and these may extend beyond the surface water catchments that define each region (Figure 27).

As a minimum, all regions have an assessment of current and future levels of groundwater allocations and use, a conceptual groundwater recharge-flow-discharge model and a detailed analysis of diffuse groundwater recharge rates under historical, recent and future climates.

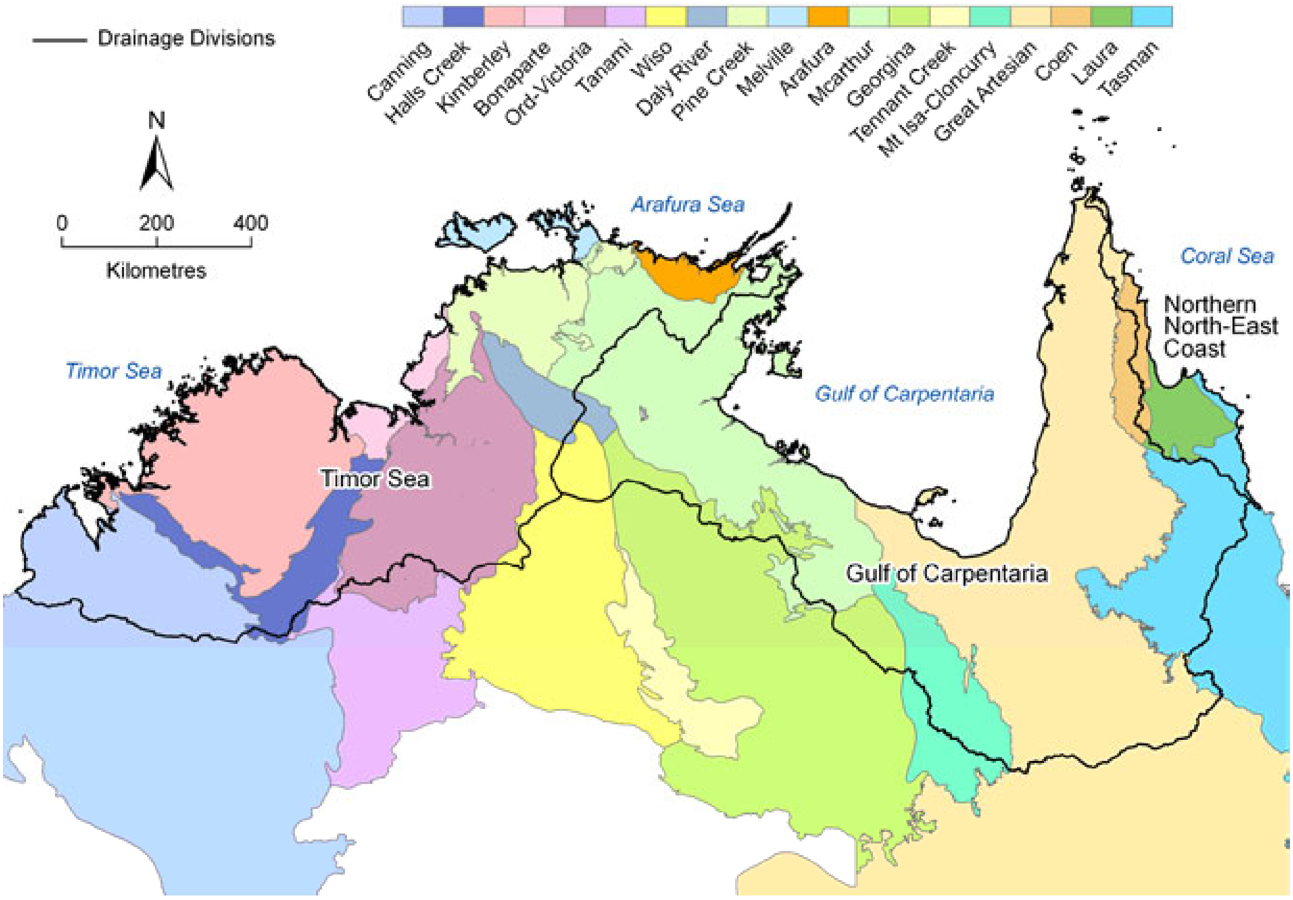

Figure 27. Extents of groundwater basins that (at least in part) underlie the drainage divisions of northern Australia. Note that only the north-flowing region of the Great Artesian Basin is considered in this project

2.3.2 Prioritisation of aquifers

Regions were ranked by prioritising the main aquifers within each of them using two simple criteria (i) a preliminary estimate of the ratio of groundwater extraction relative to recharge (the latter has been used elsewhere as a proxy for sustainable yield, which is not determined in this project), and (ii) a preliminary estimate of the mean annual recharge volume. The assumption in this approach is that highly-developed aquifers with large seasonal recharge warrant a higher priority for assessment at the national level than do undeveloped aquifers that receive minimal recharge. The prioritisation score for each region was determined through a development against recharge matrix, with potential scores ranging from 1 (low priority) to 5 (high priority). Under this scheme, a national ranking may be achieved. Within the Timor

Sea Drainage Division, the Daly region received a score of 3; the Fitzroy (WA), Arafura and Van Diemen regions a score of 2; and the Kimberley and Ord-Bonaparte regions a score of 1.

Six criteria were then used to determine the minimum level of assessment for each priority level in order to provide adequate technical support for future groundwater management in the region. The assessment levels were termed: minimal (priority 1), simple (priority 2), moderate (priority 3), thorough (priority 4) and very thorough (priority 5), following the methodology used in the Murray Darling Basin Sustainable Yields project (Richardson, 2008). Some of the important aquifers within the Arafura and Van Diemen regions failed to meet the criteria specified for even the minimum (albeit simple) level of assessment, either due to insufficient monitoring data, limited or no metered extraction data and a very rudimentary conceptual model. The Fitzroy (WA) region was deemed to meet the criteria necessary for a simple (priority 2) level of assessment; the Kimberley and Ord-Bonaparte regions met the criteria necessary for the minimal (priority 1) level of assessment. The existing level of data, conceptual understanding and numerical groundwater (and coupled surface water) model for the Daly region enabled a thorough (priority 4) level of assessment, exceeding the minimum (moderate for priority 3) level of assessment required.

Because some regions have a level of data and/or models different to that required for the minimum level of assessment, a simple five tier approach was adopted for this project, ranking regions from 1 (highest) to 5 (lowest) (CSIRO, 2008b). Across the entire project area, the highest tiered region was the Daly region (Timor Sea Drainage Division), classified as Tier 3; the Fitzroy (WA), Flinders-Leichhardt, Mitchell and Roper regions as Tier 4; and the remaining eight regions (including Arafura, Van Diemen, Kimberley and Ord-Bonaparte in the Timor Sea Drainage Division) as Tier 5.

2.3.3 Potential diffuse recharge estimation

The method used for the estimation of the changes in dryland diffuse recharge for this project is based upon the method used for the Murray-Darling Basin Sustainable Yields Project (Crosbie et al., 2008). This involves modelling potential diffuse recharge at a series of control points throughout the area and upscaling to a 0.05 x 0.05 degree grid using mean annual rainfall, soils and vegetation as co-variates.

WAVES (Zhang and Dawes, 1998) is a one-dimensional, soil-vegetation-atmosphere-transfer model that was used to model recharge for this project. This model was chosen because of its balance in complexity between modelling plant physiology, soil physics and the water balance. One of its advantages is the ability to simulate plant growth. WAVES can model the impact that changes in climate might have upon recharge via changes in different elements of the water balance. These include transpiration and the interception of rainfall on the plant canopy. WAVES requires three data sets to run: climate, soils and vegetation. The 77-year historical climate sequence was extracted from SILO for 23 control points selected to cover the rainfall gradient. The soils data was extracted from the ASRIS database for major soil types found in northern Australia and these were grouped according to the Australian Soils Classification (Isbell, 2002). This generated 12 soil classes for modelling. The vegetation was simplified from the Integrated Vegetation Coverage dataset (BRS, 2003) into three classes: savannah (including woodland and forests), perennial grasslands, and cleared areas which were modelled as annual vegetation. The WAVES model was used to model every combination of soil and vegetation type at every (rainfall) control point. The output from WAVES represents the drainage from a 4 m soil column assuming a free-draining lower boundary condition. This drainage is assumed to reach a shallow watertable and has therefore been termed recharge for this project.

The results of the WAVES modelling are used to create regression equations between mean annual rainfall and mean annual recharge for each combination of soil and vegetation type. This allows the recharge to be upscaled to a raster coverage of soils, vegetation and mean annual rainfall using a grid spacing of 0.05 x 0.05 degrees. Consecutive 23-year sequences from the 77-year historical sequence used for WAVES modelling were analysed and ranked to generate three 23-year variants of the historical climate (Awet, Amid and Adry variants) for forward groundwater modelling to 2030. In contrast to surface water assessments, groundwater systems do not re-set each year, but respond to longer period changes in rainfall. For this reason, representative sequences from the historical record were chosen to estimate groundwater responses in 23 years (2030) for a wetter than average, average and drier than average rainfall regime.

For the recent climate (Scenario B), relationships were established between mean annual rainfall and mean annual recharge from the recent (1996 to 2007) years of modelling, enabling a raster to be constructed. Dividing this new raster by the Scenario A raster produces a raster of recharge scaling factors (RSFs) used in further analysis.

For the future climate (Scenario C), the climate sequences extracted from SILO were scaled to account for a changed climate as projected by 15 different GCMs for three global warming scenarios. The 45 climate variants were modelled using WAVES at the 23 control points for every combination of soil and vegetation types. Regression equations were developed between mean annual rainfall and mean annual recharge for the 45 future climate variants and the 77-year historical base case. These regression equations allow upscaling of the results to produce 45 rasters of RSFs in the same manner as Scenario B. The mean RSF was aggregated to a region level and the different GCMs were ranked. Scenario Cwet is taken from the 14th ranked raster from the high global warming scenario, Scenario Cmid from the 8th ranked raster from the medium global warming scenario, and Scenario Cdry from the 2nd ranked raster from the high global warming scenario. For the groundwater models, the 23-year time period used for scenarios Cwet, Cmid and Cdry is the same as that used for the Amid variant.

In some locations, increasing recharge is modelled during periods of decreased mean annual rainfall. This counter-intuitive result can be explained if we consider the effects of the non-rainfall amount drivers of the model (Crosbie et al., 2009). Figure 28 presents a sensitivity analysis showing the effect of changes to three different climate variables on the estimation of recharge using WAVES (independent of changes in total rainfall).

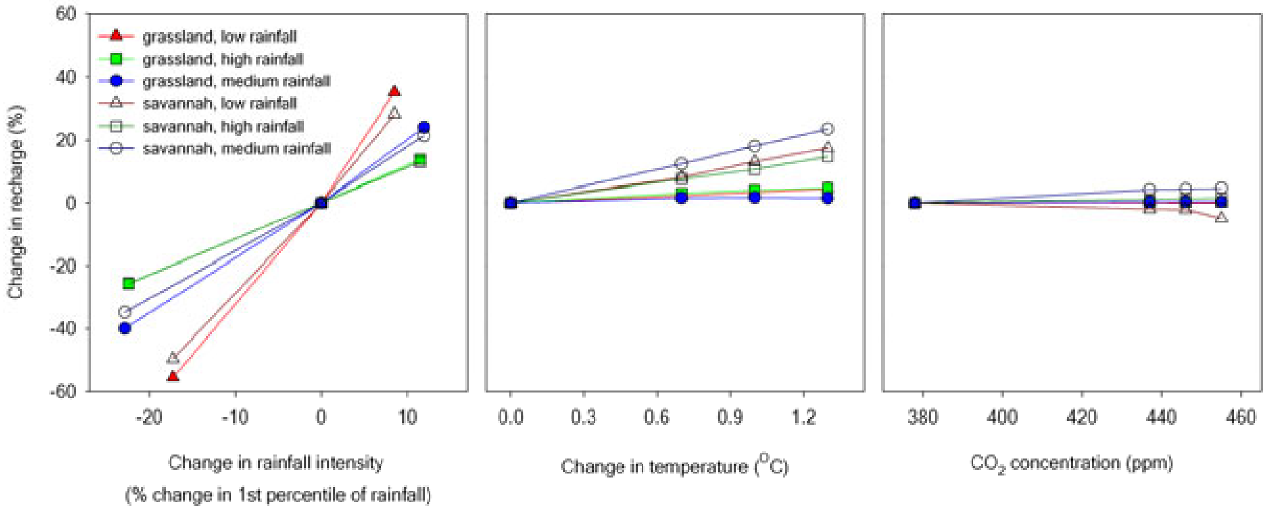

Figure 28. Results of a sensitivity analysis of WAVES estimates of recharge to changes in climate variables independent of changes in total rainfall. Three climate variables were investigated for two vegetation types and three rainfall zones

Changes in daily rainfall intensity have a large impact on the estimation of recharge, with increases in intensity resulting in increased recharge (Figure 28). This means that in some instances, total rainfall decreases, but WAVES may simulate an increase in recharge as a result of increased rainfall intensity. In this case, less rainfall is intercepted by the vegetation canopy, resulting in more rainfall infiltrating the soil and subsequently becoming recharge. Further, increased intensity of rainfall is accompanied by reduced evaporation, thereby making more rainfall available for recharge (and runoff). The amount of water reaching the ground surface exceeds the amount being removed by evaporation, hence infiltration will take place. During periods of lower intensity rainfall, however, recharge may significantly decrease, due to drying of the profile inhibiting infiltration. As runoff occurs as a result of an excess of water at the surface, this will only occur once the infiltration rate is exceeded, and is favoured at moderate to high rainfall intensities. Increased rainfall intensity with lower mean annual rainfall, therefore, implies a greater proportion of lower rainfall days, where runoff will be negligible, but recharge may still operate. Hence, on a longer time frame such as annually, it is possible for recharge to increase even if rainfall decreases.

Increases in temperature also lead to increased recharge even though potential evapotranspiration will rise (Figure 28). This is a function of plant physiology. Above an optimum temperature, plants assimilate carbon less efficiently resulting in less leaf area. A decrease in leaf area results in less interception, more infiltration and subsequently increases in recharge (and runoff).

Increases in CO_2 concentration can lead to an increase or decrease in recharge, although the magnitude of changes is comparatively small (Figure 28). Increased CO_2 concentration in the atmosphere allows plants to assimilate carbon more efficiently and thus use less water. The direction of the change in recharge depends upon whether the reduction in transpiration is offset by an increase in interception due to increased leaf area.

This sensitivity analysis shows the directions of changes in recharge under a future climate scenario are not necessarily in the same direction as changes in rainfall. It must be noted, however, that these are all relative changes. In general, recharge is still roughly an order of magnitude lower in absolute volumes, than runoff, which in turn is up to an order of magnitude less than rainfall.

2.3.4 Groundwater assessments

Quantitative modelled assessments of groundwater in the Timor Sea Drainage Division were only possible in the Tier 3 Daly region, the Tier 4 Fitzroy (WA) region and a very small part of the Tier 5 Van Diemen region, due to limited data and no existing groundwater models for the remaining three regions (Kimberley, Ord-Bonaparte and Arafura).

Daly region

The Daly region is represented with an existing, calibrated, regional-scale, FEFLOW numerical groundwater flow model coupled to a calibrated MIKE11 surface water model (Knapton, 2006). The input to the MIKE11 model is via the NAM rainfall-runoff module which generates runoff discharges based on climatic data. The recharge input to the FEFLOW was generated using the WAVES model. Surface–groundwater interaction along the rivers occurs where the MIKE11 model is joined to the FEFLOW model. Input climatic data were consistent for both the NAM and WAVES models. The coupled model enabled quantitative assessment of the impacts of climate change and current and future development through implementation of the four scenarios (scenarios A, B, C and D). This assessment included analysis of interactions between surface water and groundwater resources (Section 2.4.3).

Fitzroy (WA) region

For the Fitzroy (WA) region a new MODFLOW groundwater model was built, focussing on the Fitzroy River alluvial aquifer (Dawes, 2009). Due to limited data, particularly historical water-level monitoring results and aquifer hydraulic parameters, this model only provided a first-order water balance for the alluvial aquifer. Assessment of potential future groundwater development impacts on other users and river flows was undertaken on a theoretical basis using well-known analytical solutions.

Van Diemen region

The Darwin Rural Area FEFLOW model (EHA, 2007) was used to simulate groundwater levels and key hydrogeological processes under the various climate and development scenarios. Unlike the model for the Daly region (above) this groundwater model is not linked to a surface water routing model and therefore simultaneous assessment of surface water flows and groundwater processes under each scenario was not possible. Nevertheless, the FEFLOW model was used to estimate groundwater balances at key environmental sites where baseflow is thought to be important.

2.3.5 Groundwater assessment in sparsely monitored aquifers

Groundwater monitoring is in general very limited across the Timor Sea Drainage Division; the main aquifers in the Daly region are by far the most comprehensively monitored in the division. Across the remaining aquifers, including those in the Tier 4 Fitzroy (WA) region, monitoring records are very sparse. For these aquifers groundwater assessment was limited to simple water balance considerations that were reliant upon limited literature and single point-in-time measurements from bores, mostly corresponding to the time of drilling.

2.3.6 Managed aquifer recharge feasibility assessment

Managed aquifer recharge (MAR) involves the artificial storage of excess surface water in aquifers for subsequent beneficial use. Recharge is generally achieved through either infiltration pits or injection bores. In the case of northern Australia, artificial recharge would occur in the wet season for groundwater extraction in the following dry season.

There are a number of criteria available for assessing the feasibility of a MAR scheme; these ultimately relate to end-user demand, aquifer properties, the availability and characteristics of source water, requirements for detention and level of expertise (Dillon et al., 2009). In general terms, the aquifers best suited to MAR in northern Australia will likely have the following physical and chemical attributes (after Dillon and Jimenez, 2008):

- storage capacity at the end of the wet season. In the case of unconfined aquifers this requires peak groundwater levels below the top of the aquifer. In the case of confined aquifers this requires a high storage coefficient
- carbonate matrix, which is generally least susceptible to physical clogging through injection of dissolved organic carbon
- ambient groundwater salinity <10,000 mg/L as total dissolved solids.

The lateritic soils that cover much of northern Australia will preclude the use of infiltration pits for MAR. In areas where infiltration can occur, recharge rates are comparatively high and the aquifer will be full at the end of each wet season. Therefore MAR will only have potential where groundwater development is already depleting the resource to the extent that recovered water levels at the end of the wet season do not fill the aquifer.

In this project, the opportunities for future MAR schemes are explored for each region but only in terms of the aquifer properties. Feasibility assessments beyond this level would require detailed field site investigations.

2.3.7 Quality considerations

Understanding the geochemistry of groundwater systems is of fundamental importance for predicting salt, metal and nutrient mobility in the subsurface environment. The inherent connectivity between groundwater and surface water systems and lag-time of solute transport in aquifers relative to rivers make it difficult to predict future water quality issues that may arise if hydrological systems are altered. In the Daly region, connectivity between the different aquifer units was assessed from existing water quality data maintained by the Northern Territory government. Water quality sampling sites provided good coverage of the broader catchment. However, sampling intervals are often greater than five years for individual sites and distances between sites are commonly greater than 10 km. This prevents the assessment of temporal and spatial variations in water chemistry. Water chemistry results can provide a qualitative assessment of inter-aquifer connectivity and interpretation of subsurface geochemical processes. These factors are critical indicators of the aquifers' ability to transmit soluble contaminants (i.e. fertilizers and agrochemicals) to the surface water systems, and potential issues that may arise if an aquifer is over-developed (pumped).

2.4 Surface–groundwater interaction

2.4.1 Baseflow analysis for groundwater assessments

Dry season, groundwater-fed river flows have been estimated using a digital recursive filter (Lyne and Hollick, 1979) with a filter parameter value of 0.925. This analysis provides an estimate of baseflow index (BFI), the ratio of the baseflow volume to total flow volume over the time period of analysis. The filtered baseflow value represents the components of river flow that are predominantly groundwater discharge, but also includes: delayed surface water flow; delayed groundwater flow (perched aquifers); bank storage; and unsaturated-zone flow. It is important to note that the technique used in this project to estimate dry season flow is derived from standard signal processing methods and does not explicitly represent the physical processes of surface–groundwater interaction.

The analysis was only performed on historical gauged data (i.e., no simulated or extrapolated flows) for the project area. A total of 159 gauges were selected based on the following criteria:

- more than 20 years of record in which less than 20 percent of daily flows are missing; or
- more than 40 years of record, regardless of the amount of daily data missing.

2.4.2 Surface–groundwater connectivity mapping

The Northern Territory Government has recently completed a map for the whole of the Northern Territory showing locations of recorded springs and streams that flow throughout the dry season (Tickell, 2008). This map is the culmination of over a decade of work by many people, combining results from regular and occasional streamflow gauging and groundwater monitoring with anecdotal evidence from field staff and Indigenous communities. Reporting regions within the Northern Territory use this map as the basis for describing surface-groundwater connectivity.

For regions that either fully or partially fall within Western Australia this project has attempted to expand the Northern Territory map across the entire project area. Given the time constraints of this project, incorporation of all available historical data and anecdotal evidence was not possible. Instead the approach adopted was to utilise groundwater level data from shallow (less than 40 m total depth), surveyed wells and river bed levels to infer where streams are likely to be either gaining or losing. This assessment provided a basis for discussions with key field officers from both state governments, which highlighted where streams were known to be perennial.

2.4.3 Modelling surface–groundwater interaction

For the Daly region, the regional groundwater FEFLOW model of Knapton (2006) is linked directly to a MIKE-11 river routing model, enabling simultaneous simulations of groundwater head, surface water stage and thus surface–groundwater exchange fluxes. In particular, baseflow in the main river channel was assessed under all four scenarios (scenarios A, B, C and D) using groundwater recharge scaling factors from WAVES (Section 2.3.3) and runoff scaling factors from rainfall-runoff modelling (Section 2.2.2).

The new MODFLOW groundwater flow model developed for the alluvial aquifer in the Fitzroy (WA) region (Dawes, 2009) provides indicative surface–groundwater exchange fluxes under a recent climate. Whilst these processes are found to be of paramount importance to the groundwater balance of the alluvial aquifer, very little data are available and current understandings are very rudimentary.

2.4.4 River flow impact assessment

Groundwater pumping initially depletes water storage within the aquifer but can eventually deplete flow in nearby rivers. The extent of river depletion depends on the magnitude of pumping and the connectivity between the river and the aquifer, and the variable time lag associated varies with aquifer properties (namely transmissivity and specific yield) and the perpendicular distance between the river and the pumping activity (referred to as groundwater development).

River flow impact can be assessed where coupled surface–groundwater models are used. This is only the case for the Daly region, where a coupled MIKE11–FEFLOW model is used. Where sufficient data are available, or a general model has been developed, an analytical solution can be investigated. For the Timor Sea Drainage Division, this is the case only within the Fitzroy (WA) region.

Given the low level of groundwater development in the Fitzroy (WA) region, analysis in this area was based on the assumption that extraction is equal to the full allocation. The existing groundwater licences were grouped into two categories depending on whether they source water from an unconfined alluvial aquifer or a deeper confined aquifer.

For the unconfined alluvial aquifer in the Fitzroy (WA) region, the most commonly used river depletion model of Glover and Balmer (1954) was utilised. This model assumes a semi-infinite homogenous unconfined aquifer is in full hydraulic connection with a fully penetrating river. The outcome of this analysis is the magnitude of river depletion and its timing.

For licensed extraction from the deeper confined aquifers in the Fitzroy (WA) region, the solution of Hunt (2003) was used. However, since little is known about the deeper aquifers and their hydraulic connection to rivers, only a comparative analysis was conducted. In this type of analysis, all the model parameters were assumed to be equal with the only remaining variable being the distance between the river and the groundwater development. The outcome of this analysis is a hierarchy of impacts, which highlights priority areas where further investigations need to be focussed in the future.

Similar stream depletion analysis was not possible for the four Tier 5 regions within the Timor Sea Division (Kimberley, Ord-Bonaparte, Arafura and Van Diemen) due to insufficient data and limited conceptual understanding of the groundwater systems. Such analysis was also not performed for the Tier 3 Daly region as the numerical model was used to investigate impacts of pumping on the groundwater-surface water balances.

2.5 Changes to hydrological regime

Flow requirements for environmental assets and the ecosystems that they support are largely unknown across northern Australia. In the Timor Sea Drainage Division the Daly River (see Erskine et al., 2003) the Fitzroy River (see Morgan et al., 2005) and the Ord River (Trayler et al., 2006; Braimbridge and Malseed, 2007) have environmental flow information. The remaining assets have no quantitative information. To include these assets in our analysis and provide a consistent means for cross-region comparison a common set of standard metrics of hydrological regime change to report against were derived. These standard metrics are described in Section 2.5.1, followed by a description of site-specific metrics for the Daly, Fitzroy (WA) and Ord-Bonaparte regions.

The main uncertainties involving analysis and reporting of changes to hydrological regime at selected assets include:

- Aquatic and wetland ecosystems are highly complex and many factors in addition to water regime can affect ecological features and processes. Water quality and land use practices are key factors.
- The indicators are based on limited hydrological parameters with no direct quantitative relationships for environmental responses. This project only makes general observations on the potential implications of changed water regimes and some related ecological responses.
- Considering only a few of the important environmental assets and using a limited number of indicators to represent overall aquatic ecosystem outcomes is a major simplification. Actual effects on these and other assets or localities are likely to vary.
- Uncertainties affecting the hydrological information used for the environmental assessments.

2.5.1 Standard regime metrics

One of the key characteristics of the rivers of northern Australia is their highly seasonal flow regimes which can be partitioned into flood events and low flow (or no flow) periods (Hamilton and Gehrke, 2005). Each of these regimes, which are at opposite ends of the flow spectrum, will have different implications for aquatic biota and ecosystem processes. For example, flood events can be important for such things as wetland connectivity and floodplain rejuvenation (Douglas et al., 2005) while low flows can be crucial for survival of riparian vegetation (Lamontagne et al., 2005), maintenance of ecosystem production and food webs (Townsend and Padovan, 2005; Webster et al., 2005), and provision of refuge for sustaining populations of aquatic species (Hamilton et al., 2005).

Many metrics have been used in the literature to report changes to the low flow regime of a river (Olden and Poff, 2003; Nathan and McMahon, 1992; Kennard et al., In press). One of the most commonly used metrics is the flow that is exceeded for 90 percent of the time (Gordon et al., 1992). To determine changes to the low flow regime of northern Australian rivers, this metric was calculated for each of the 77 years in Scenario A, then the number of days that flow fell below this threshold in any hydrological year (September to August) was calculated for all other scenarios. The mean number of days below this threshold across all years was calculated and reported for all scenarios. It has been noted by Petheram (2008) that for many of the streams of northern Australia the value of this metric is zero, therefore it is best suited to rivers where flow is perennial. In streams that cease to flow a more suitable metric is the mean number of days per year with zero flow. Finally, changes to the low flow regime were also assessed through changes to the mean dry season (May to October) flow.

Many of the wetlands of northern Australia require flood or high level flows to facilitate connectivity with other water bodies, therefore it was essential that metrics for assessing the change to the high flow regime at selected assets were defined. The flow above which floodplains commence inundation was not known for most of the asset locations. Therefore, a surrogate metric of high flow was required. Other studies have used high flow metrics based on flows exceeded between 10 and 1 percent of the time (Olden and Poff, 2003; Kennard et al., In press). In this project the flow exceeded 5 percent of the time for all 77 years was calculated for Scenario A. The number of days above this threshold was then calculated for each hydrological year and for all scenarios. This project reports, under all scenarios, the mean number of days per year that flow is above this threshold. Changes to high flows were also assessed through changes to the mean wet season (November to April) flow.

The final and most general metric reported is changes to the mean annual flow. Such a metric when combined with wet season and dry season metrics described above gives a good indication of the direction of changes to the hydrological regime under the climate and development scenarios.

The above low and high flow metrics are summarised as:

- annual flow (mean)
- wet season flow (mean)
- dry season flow (mean)
- low flow threshold (discharge exceeded 90 percent of the time under Scenario A)
- number of days below low flow threshold (mean)
- number of days of zero flow (mean)
- high flow threshold (discharge exceeded 5 percent of the time under Scenario A)
- number of days above high flow threshold (mean).

In reporting changes to the hydrological regime at an environmental asset it is important to consider the confidence levels in modelled streamflow. Confidence in results for low and high flows is reported separately on a scale of 1 to 5, with 1 indicating results with the highest confidence (see Section 2.2.6 in this chapter). Hydrological regime metrics for both high and low flows are only reported where confidence levels are 1, 2 or 3. If either the high or low flow metrics were ranked 4 or 5, results are not reported.

The Daly region of the Timor Sea Drainage Division offered a unique opportunity within this project as it has a groundwater model which enabled assessment of the changes to groundwater depths and flows under the different scenarios. Similar metrics to those employed for surface water flows were used to assess changes to groundwater flows. Groundwater assessments are important to assess changes to stream baseflow and depth to groundwater under different scenarios. Groundwater flows are important for discharge of streams while groundwater depth is important for groundwater dependent ecosystems.

The most general metric reported is changes to the mean annual contribution of groundwater flow to streamflow at a location. Such a metric when combined with similar wet and dry season metrics gives a good indication of the direction of changes to the hydrological regime under the given scenarios. To determine changes to the low flow groundwater regime the flow exceeded 90 percent of the time was calculated for Scenario A then the number of days flow fell below this threshold is reported for all scenarios. Similarly, changes to the high flow groundwater regime were assessed using a similar method though using the flow exceeded 5 percent of the time. The metric used to assess change to groundwater depth under different scenarios was mean dry season groundwater depth. Only the dry season depth was used as a metric because this reflects the period when groundwater dependent ecosystems are likely to be most stressed. Groundwater level is reported as depth below the soil surface. A reduction of groundwater level under a given scenario (i.e. negative value) means the groundwater level is shallower and vice versa.

The groundwater flow metrics are summarised as:

- annual groundwater contribution to streamflow (mean)
- wet season (November to April) groundwater flow (mean)
- dry season (May to October) groundwater flow (mean)
- low flow threshold (discharge exceeded 90 percent of the time under Scenario A)
- number of days below low flow threshold (mean)
- high flow threshold (discharge exceeded 5 percent of the time under Scenario A)
- number of days above high flow threshold (mean)
- dry season depth to groundwater (mean).

2.5.2 Site-specific regime metrics

In the Timor Sea Drainage Division site-specific environmental flow metrics exist for assets in both the Daly, Fitzroy (WA) and Ord-Bonaparte regions. Details are given as follows:

Daly River – Daly River Middle Reaches

The reports by Erskine et al. (2003; 2004) summarise the results from five projects within the National River Health Environmental Flow Initiative. The aim of these projects was to provide recommendations on environmental flows consistent with maintaining the biota and wider ecosystem values of the Daly River. These projects made a range of environmental streamflow recommendations and some of these were suitable for assessment under this project's scenario analysis.

The work by Georges et al. (2002) reported in Erskine et al. (2003; 2004) gives data for the success of Pig-Nosed Turtle (*Carettochelys insculpta*) nesting and their main food source, the aquatic macrophyte *Vallisneria nana*. In these reports turtle nesting success and *V. nana* bed occurrence are related to Daly River flow at the Oolloo Gauge. The Erskine et al. (2004) report recommends that at least 80 percent of flow should exceeding 1.037 GL/day to provide habitat for Pig-Nosed Turtles and *V. nana*.

Erskine et al. (2003) also reviewed the existing data on riparian vegetation water use along the Daly River and concluded that all of the riparian vegetation water use could be met by maintaining a streamflow of less than 0.17 GL/day during the dry season, assuming no loss of streamflow to regional aquifers.

The specific metrics assessed under each scenario are:

- for Pig-Nosed Turtle nesting success and *V. nana* bed occurrence - the mean number of days per year at Oolloo Gauge with flows below identified threshold of 1.037 GL/day
- for riparian vegetation water requirements - the mean number of days per year at Oolloo Gauge with flows below the identified threshold of 0.17 GL/day.

Fitzroy River – Camballin Floodplain

Morgan et al. (2005) reported that the level of water of the Fitzroy River at the Camballin Barrage (gauge G802003) required for fish passage is ~11 m, or 1 m above the Barrage itself. Using this metric they calculated the number of consecutive days per year that the river stage was above this height. This ranged from ~20 to 250 days per year, with most years (80 percent) having a fish passage duration of less than 3 months. Morgan et al. (2005) also calculated the number of days when the Barrage was completely inundated, as this was associated with a stage height of 12.3 m. They found that this occurred in all years between 1986 and 2004 except one (1994). Following these analyses, the same metrics were used for all scenarios being assessed for the Camballin Floodplain asset. The above height metrics were converted to flow thresholds using the rating curve for the gauge. The metrics assessed under each scenario were:

- for flows at which fish could negotiate the Camballin Barrage - the mean number of days per year where stage height exceeded 11.0 m (equivalent to 8.09 GL/day)
- for complete barrage inundation of Camballin Barrage and unobstructed fish passage - the mean number of days per year where stage height exceeded 12.3 m (equivalent to a discharge of 28.81 GL/day).

Ord River – Lake Kununurra

Extensive analyses of the environmental flow requirements of the lower Ord River downstream of the Lake Kununurra Diversion Dam have been carried out by Trayler et al. (2006). They derived a range of relationships between key river hydraulics parameters and ecological health indices associated with macroinvertebrates, fish, riparian vegetation and ecosystem processes and connectivity. Further analyses of these relationships was carried out by Braimbridge and Malseed (2007) which allowed for the definition of a number of low and high flow conditions that provide thresholds above and below which undesirable ecological impacts may occur. The environmental water release rules for the lower Ord River are based on the recommendations of the Braimbridge and Malseed (2007) report. One of the recommendations for the 58 km section of the Ord River downstream of the Kununurra Dam was that a low flow threshold of 3.63 GL/day should be sustained throughout the dry season in order to meet the environmental flow requirements for fish and macrophyte habitats and pools for algal production. In the same river reach, high flow thresholds are also recommended, for example, the maintenance of wet season flows in excess of 10.8 GL/day for at least 10 days per year in order to sustain regular inundation of riparian zones and deep backwater pools. An even higher wet season flow threshold was recommended to maintain fish passage, i.e. 36.7 GL/day for at least 2 days per year.

The specific metrics assessed under each scenario for the lower Ord River downstream of the Lake Kununurra were:

- for fish and macrophyte habitats and pools for algal production - the mean number of days per year with flows below the identified threshold of 3.63 GL/day
- to sustain regular inundation of riparian zones and deep backwater pools - the mean number of days per year with flows above the identified threshold of 10.8 GL/day
- to maintain fish passage - the mean number of days per year with flows above identified threshold of 36.7 GL/day.

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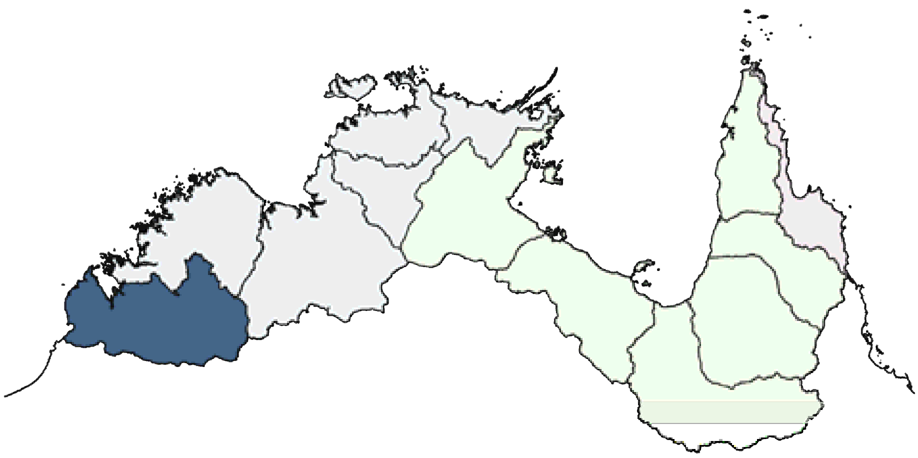
Water in the Fitzroy (WA) region



FI-1 Water availability and demand in the Fitzroy (WA) region

The first part of this report (the Preamble, Chapter 1 and Chapter 2) reports at the division level, including division-wide descriptions of climate and geology and methods which apply to all regions. Subsequent chapters report at the region level. In particular, Chapters FI-1, FI-2 and FI-3 focus on the Fitzroy (WA) region (Figure FI-1).

This chapter summarises the water resources of the Fitzroy (WA) region, using information from Chapter FI-2 and Chapter FI-3, and directly addresses the Terms of Reference, specifically terms 3, 4 and 5 as listed in the Preamble. Essentially, this chapter provides a synoptic view of the region and covers:

- regional observations
- water resource assessment
- seasonality of water resources
- surface–groundwater interaction
- changes to flow regime at environmental assets
- water storage options
- data and knowledge gaps.

For further details on the context of the region (physical and climate descriptions, hydrogeology and legislation) see Chapter FI-2. Region-specific methods and results are provided in Chapter FI-3. Modelling results are reported under climate and development scenarios as defined at the division level in Section 2.1 of Chapter 2.

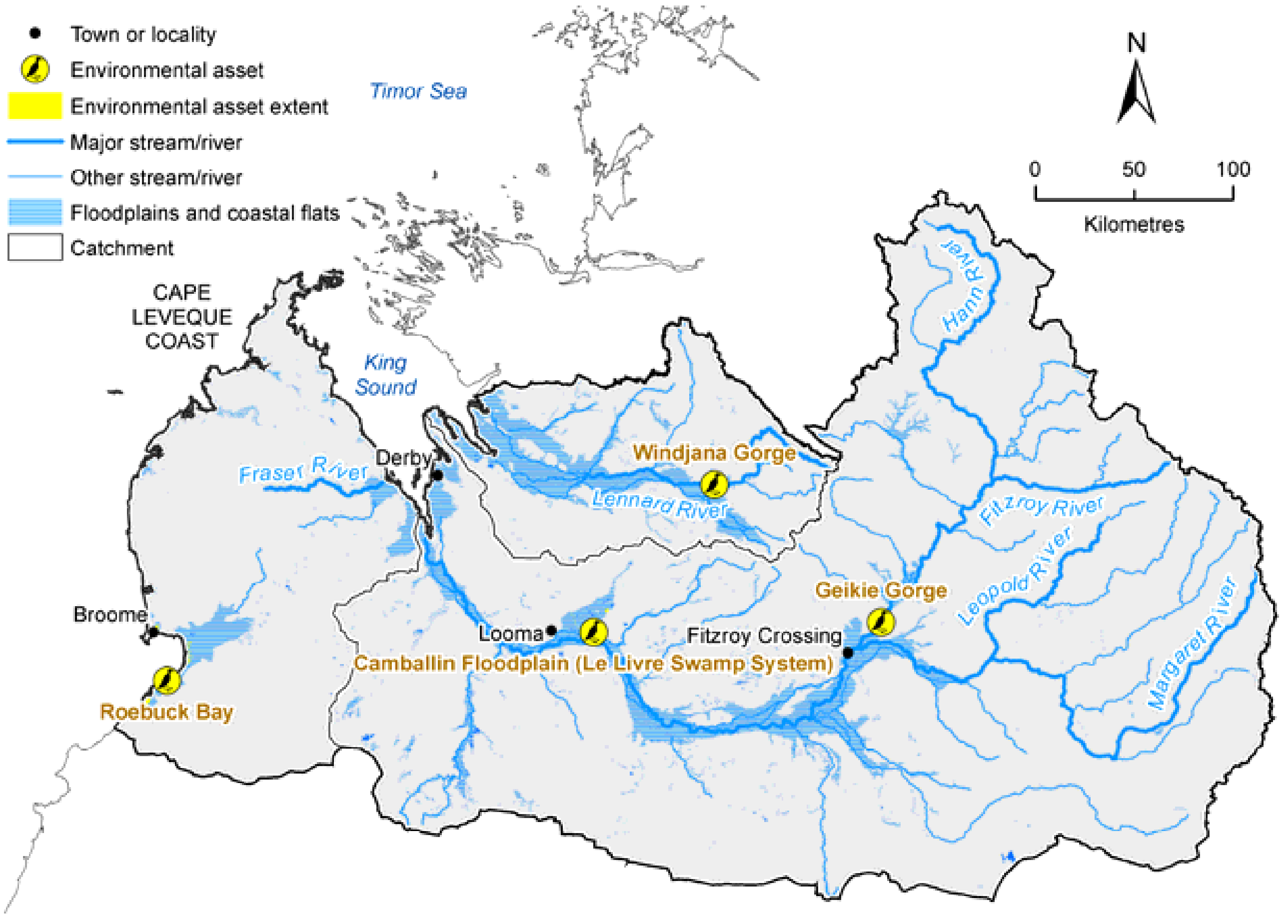


Figure FI-1. Major rivers, towns and location of environmental assets selected for assessment of changes to hydrological regime in the Fitzroy (WA) region

FI-1.1 Regional summary

This section summarises key modelling results from this project and provides other relevant water resource information as context about water availability and demand in the Fitzroy (WA) region.

The historical (1930 to 2007) mean annual rainfall for the region is 577 mm. Mean annual areal potential evapotranspiration (APET) is 2023 mm. The mean annual runoff averaged over the modelled area of the Fitzroy (WA) region is 76 mm, 14 percent of rainfall. These values are low in comparison to other regions across northern Australia. Under the historical climate the mean annual streamflow over the Fitzroy (WA) region is estimated to be 10,002 GL.

The Fitzroy (WA) region has a high inter-annual variability in rainfall and hence runoff and recharge. Relative to the rest of northern Australia, coefficients of variation are among the highest of the regions and reflect multiple consecutive years of significantly below, or above, average rainfall.

There is a strong seasonality in rainfall patterns, with 93 percent of rainfall falling in the wet season, between November and April, and a very high dry season (May to October) APET. The region has relatively high rainfall intensities, and this is reflected in rapid runoff and a short lag between rainfall and runoff. Ninety-seven percent of runoff occurs within the months of December and April. There has been a slightly increasing amount and intensity of rainfall over the period from 1930 to 2007.

There is a strong north–south rainfall gradient and hence also runoff, with the runoff coefficient decreasing from 25 to 3 percent of precipitation in the same direction.

APET is annually greater than rainfall; hence the region may be considered water-limited. This is the case throughout the year, with only short periods during the wet months when rainfall exceeds APET.

The recent (1996 to 2007) climate record is statistically significantly wetter than the historical (1930 to 2007) record. Rainfall was 31 percent higher; runoff was 53 percent higher. It is likely that future (~2030) conditions will be similar to historical conditions, and future runoff and recharge will also be similar to historical levels, but lower than the recent past.

There are few opportunities for surface water storage, except in the eastern, wetter headwater areas. Storage sites in the lower reaches are flood dominated and estuaries experience high tidal ranges.

Deep Canning Basin aquifers contain the largest storage of water, but limited data mean quantification of this resource is not possible. The shallow alluvial aquifers are characterised by variable thickness and groundwater quality and are limited as a resource by the amount of river recharge. It is a relatively undeveloped groundwater resource.

There is an intricate interaction between surface and groundwaters; river valleys are frequently flooded during the wet season and the region is groundwater-dependent in the dry. Pools are maintained into the dry season via shallow sub-surface flow, with sand bars supporting the river.

At environmental assets, flows are highly dominated by wet season flows, with dry season flows only a small fraction of total annual flow. However, environmental assets are adapted to this strong seasonality and any significant changes in the frequency and duration of wet season high flows and dry season low flows are likely to have an environmental impact.

In the recent past there has been significantly more flow, with fewer low flow days and more high flow days than historically. Annual and seasonal flows are not expected to change much under the median future climate; hence there is little change in the high and low flow threshold exceedance. In contrast, modelling predicts large changes to the high flow threshold exceedance under the wet extreme and dry extreme future climate and this could have negative environmental impacts. An analysis of site-specific high flow metrics for the Camballin Barrage has shown that opportunities for fish passage were more frequent in the recent past and would be restricted under the dry extreme future climate.

The region is generally datapoor.

FI-1.2 Water resource assessment

Term of Reference 3a

FI-1.2.1 Under historical climate and current development

Term of Reference 3a (i)

The mean annual rainfall and modelled runoff averaged over the Fitzroy (WA) region are 577 mm and 76 mm respectively. The mean wet season and dry season runoff averaged over the Fitzroy (WA) region are 74 mm and 2 mm respectively. These values are low in comparison to other regions.

Licensed groundwater extraction is currently low in the Fitzroy (WA) region (Table FI-1), particularly from the shallow alluvial aquifer but also from deeper Canning Basin aquifers. Recharge to the alluvial system is likely to be dominated by leakage from the Fitzroy River during high-stage wet season flows and, to a lesser extent, by infiltration of overbank flows across the floodplain. Accordingly, under a continued historical climate with current levels of development, groundwater resource condition is likely to remain stable. Furthermore, dry season groundwater discharge to the major rivers in the region (Table FI-1 and Figure FI-2) is likely to be maintained.

Table FI-1. Estimated groundwater contribution (baseflow) to streamflow, modelled diffuse recharge and groundwater extraction for the Fitzroy (WA) region under historical climate

Station	River	Station name	Annual BFI *	Dry season BFI *	Dry season baseflow *
					GL
802002	Mount Pierre Ck	Mt Pierre Gorge	0.05	0.33	0.3
802055	Fitzroy	Fitzroy Crossing	0.15	0.51	30.8
802137	Fitzroy	Dimond Gorge	0.20	0.50	17.6
802198	Margaret	Me No Savvy	0.05	0.08	0.8
802202	Leopold	Mt Winifred	0.13	0.18	1.2
802203	Margaret	Mt Krauss	0.22	0.60	58.1
802213	Hann	Phillips Range	0.22	0.59	8.0
803001	Lennard	Mt Joseph	0.15	0.43	1.2
803002	Lennard	Mt Herbert	0.14	0.64	0.8
803003	Fletcher	Dromedary	0.10	0.04	0.0
		Historical recharge **	Estimated groundwater extraction		
		GL/y			
Entire Fitzroy (WA) region		6580			17.2

* BFI (baseflow index) and baseflow volume derived from gauged data.
** Aggregated recharge from Zhang and Dawes (1998).

The Canning Basin aquifers are mostly recharged further inland in more arid areas located outside of the project area. Given the scale and inertia of such a large groundwater system, it is unlikely that a continued historical climate with current levels of development would change the water balance of this system.

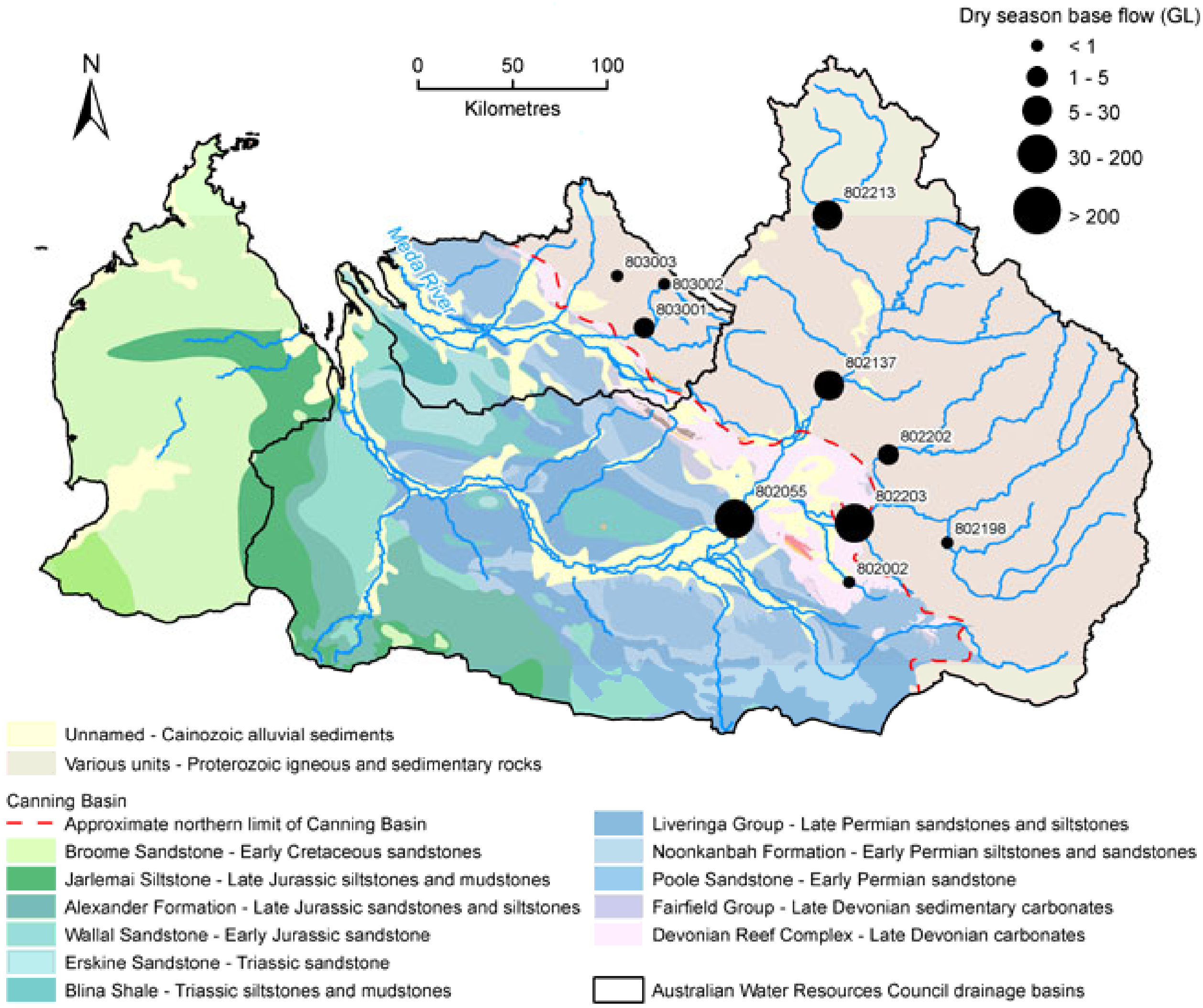


Figure FI-2. Surface geology of the Fitzroy (WA) region with mean dry season baseflow

FI-1.2.2 Under recent climate and current development

Term of Reference 3a (ii)

The mean annual rainfall and runoff under the recent (1996 to 2007) climate are 32 percent and 51 percent higher respectively than the historical (1930 to 2007) mean values.

Under the recent climate, diffuse groundwater recharge is significantly higher than the historical average rates. Because the alluvial aquifers are completely filled each wet season by recharge from the rivers and, to a lesser degree, by diffuse recharge across the floodplains, it is likely that under a recent climate with current development average groundwater levels and fluxes would be similar to historical values.

FI-1.2.3 Under future climate and current development

Term of Reference 3a (iii)

Rainfall-runoff modelling with climate change projections from eight of the GCMs shows a reduction in mean annual runoff, while rainfall-runoff modelling with climate change projections from seven of the GCMs shows an increase in mean annual runoff. Rainfall-runoff modelling with climate change projections from five of the GCMs indicates a decrease in mean annual runoff greater than 10 percent while rainfall-runoff modelling with climate change projections from three of the GCMs indicates an increase in mean annual runoff greater than 10 percent. Under the wet extreme, median and dry extreme climates, mean annual runoff increases by 25 percent and decreases by 3 and 41 percent relative to values calculated under the historical climate. By comparison, the range based on the low global warming scenario is a 13 to -24 percent change in mean annual runoff.

Under the future climate diffuse groundwater recharge is likely to be slightly higher than the historical average. Without a detailed numerical groundwater flow model for the Fitzroy alluvial aquifer, the impacts of this climate and either current or future groundwater development cannot be predicted with any certainty.

FI-1.2.4 Under future climate and future development

Term of Reference 3a (iv)

No major dam developments are planned or expected. Use of surface water resources to meet small demands at a local scale is difficult, as assets on any watercourse must be protected against flooding and the reliability of runoff from small catchments is low, given the high variability between years. Development is likely to be small scale and distributed in nature, generally as forms of pastoral diversification. Developments would be dependent primarily on alluvial groundwater, with potential (albeit limited – see Section FI-1.6.2) to be supplemented by some form of managed infiltration or aquifer recharge. Given current knowledge, further investigation and research will be essential before distributed small-scale developments could proceed.

FI-1.3 Changes to flow regime at environmental assets

Term of Reference 3b

Section 1.3 of the division-level Chapter 1 describes how environmental assets were shortlisted for assessment by this project. Four environmental assets were shortlisted for the Fitzroy (WA) region: Roebuck Bay, Camballin Floodplain (Le Livre Swamp System), Geikie Gorge and Windjana Gorge. These assets are characterised in Chapter FI-2 and detailed results presented in Chapter FI-3.

In deciding whether it is feasible to report hydrological regime metrics for these shortlisted assets, it is important to consider the confidence levels in modelled streamflow (as described in Section 2.2.6 of the division-level Chapter 2). Confidence in results for low flows and high flows was calculated separately. Hydrological regime metrics (as defined in Section 2.5 of the division-level Chapter 2) for either low flows or high flows are reported only where confidence levels are sufficiently high. If confidence in the low flow or high flow is too low, metrics are not reported, and hence an important gap in our knowledge is identified.

Some of the assets in this region have multiple nodes at which streamflow modelling results are available. When reporting hydrological regime metrics for such assets a single node was selected. The selected node was that with the highest streamflow confidence level and the largest proportion of streamflow to the asset. The locations of nodes for each asset are shown on satellite images in Section FI-2.1.3. Results for all nodes are presented in McJannet et al. (2009).

Confidence in streamflow results was too poor to enable reporting of dry flow regimes at the Camballin Floodplain and Windjana Gorge. Confidence was moderately reliable for reporting high flows and low flows at Geikie Gorge and high flows at Camballin Floodplain and Windjana Gorge. At these assets, annual flow is dominated by wet season flow, which has been up to 60 percent higher than historical levels in the recent past. Dry season flows have also been much higher than the historical flows in the recent past. Future flows are likely to be similar to historical flows. Under a dry extreme future climate, flows are more than 30 percent lower than historical levels.

Zero flow days have increased greatly under the dry extreme future climate at Geike Gorge. The number of days modelled when flow is less than the low flow threshold does not change under the median future climate, but increases greatly under the dry extreme future climate.

Under the recent climate, high flows are almost twice as frequent as under the historical climate at all sites. There is little change in high flow threshold exceedance under the median and wet extreme future climate, though under the dry extreme future climate a moderate decrease is seen at all sites.

There is no development scenario for assets in this region.

FI-1.4 Seasonality of water resources

Term of Reference 4

Under the historical climate 93 percent of rainfall and 97 percent of runoff occurs during the wet season. Under the recent climate 94 percent of rainfall and 90 percent of runoff occurs during the wet season. Under the median future climate 93 percent of rainfall and 97 percent of runoff occurs during the wet season. Runoff is highest in January and February.

FI-1.5 Surface–groundwater interaction

Term of Reference 4

During the wet season, large rainfall events related to monsoonal and cyclonic weather patterns generate increasing river flows in the Fitzroy River. Initially, significant volumes of water are thought to flow away from the river, recharging the alluvial aquifer through the incised sediments. If river levels overflow into the wider floodplain, vertical recharge is also thought to occur, albeit more slowly. As rainfall decreases in April and May, river levels begin to fall and the alluvial aquifer discharges back towards the river. Into the dry season the aquifer continues to discharge to the river, maintaining decreasing flows and semi-permanent pools until groundwater levels fall below the river beds (at which point the river becomes dry and evapotranspiration becomes a major discharge mechanism).

It is thought that similar dynamics would be seen in the Meda/Lennard River Alluvium, while in the smaller rivers the regional aquifers are likely to receive some recharge locally, from higher wet season flows.

The dynamics of groundwater discharge to the Fitzroy River can be inferred from salinity data taken at points along the river. Lindsay and Commander (2005) suggest that more saline groundwater near Noonkanbah discharges through the alluvial aquifer and is in evidence as higher river salinity during dry season flows near Noonkanbah. More detailed river water chemistry results have been recently collected as part of the Tropical Rivers and Coastal Knowledge (TRaCK) project. Preliminary results have shown both rapid and gradual changes to river salinity and chemistry from Fitzroy Crossing to Willare Bridge, which are inferred to be the result of groundwater discharge of varying flowpaths and quality in the vicinity of Noonkanbah. Further sampling will attempt to identify end member groundwater characteristics to allow a better understanding of the dynamics of the groundwater–river interaction.

FI-1.6 Current water storage options

Term of Reference 5

FI-1.6.1 Surface water storages

There is currently no intact surface water storage in the region. The water storage on the Fitzroy River at 17 Mile Dam is no longer intact, and is not planned to be restored. This had a capacity of 5489 ML, but this volume has been significantly reduced. The Fitzroy Barrage at Camballin currently provides 6 GL allocation for local irrigation of fodder crops. Local capacity is afforded by weirs (e.g. at Mary River Crossing near Fitzroy Crossing), but these suffer from wash-out of structures during major floods.

FI-1.6.2 Groundwater storages

Groundwater development in the Fitzroy (WA) region is low and the alluvial aquifers are highly variable both in terms of hydraulic properties and water quality. Under current development managed aquifer recharge (MAR) in the alluvial aquifers would have limited applicability as storages will be at full capacity towards the end of the wet season when surface water is available for injection. Furthermore, the low-conductivity soils that cover much of the floodplains in the region preclude the use of infiltration pits for MAR. Any potential future scheme would therefore need to use injection wells to recharge the aquifer, the costs of which would be prohibitive for irrigation.

The Canning Basin sandstone aquifers probably have the greatest potential for MAR, but further investigations are required to better understand the groundwater flow and storage characteristics of these aquifers before such a scheme could be considered.

FI-1.7 Data gaps

Term of Reference 1e

FI-1.7.1 Climate data

There are currently inadequate error surfaces for meteorological data. The Australian Bureau of Meteorology provides daily error surfaces at an appropriate (0.05 x 0.05 degree (~ 5 x 5 km) grid cells) scale, but only for the last 4 years, which is insufficient to provide a statistical analysis.

There are few meteorological stations across the region, with none for the interior of the Cape Leveque sub-region nor for the southern zone of the Fitzroy catchment.

FI-1.7.2 Surface water data

The majority of streamflow gauging stations are located in the headwater catchments of the Fitzroy (WA) region. While there are a number of stations in series along the mid to lower reaches of the Fitzroy River, rating curve data at these stations are relatively poor. Rating curves are currently being re-developed at these and other stations by the Western Australia Department of Water using hydraulic modelling methods and high resolution digital elevation model data. Some of these data were available for this project. No stations are or have been sited on the Dampier Peninsula.

There are 14 gauging stations currently operating in the Fitzroy (WA) region at a density of one gauge for every 9,400 km^2. For the 13 regions the median number of currently operating gauging stations per region is 12 and the median density of gauging stations per region is one gauge for every 9,700 km^2.

FI-1.7.3 Groundwater data

There is inadequate long-term groundwater level and water quality information for the alluvial aquifer, particularly in close proximity to the Fitzroy River. Ideally there needs to be several nests of monitoring wells completed at different depths within the aquifer, and located at various distances away from the river. Routine or continuous monitoring of these wells for both water level and quality (at least salinity) would provide greater insight to the key recharge and discharge mechanisms for the aquifer, including surface–groundwater interaction. The application of hydrochemical and isotopic techniques would enable differentiation between groundwater that has been recharged locally (i.e. near the river) and that introduced via inflow from the Canning Basin aquifers.

FI-1.8 Knowledge gaps

Term of Reference 1e

The current understanding of key hydrogeological processes in the Fitzroy (WA) region is very limited. As discussed in the previous section, dedicated monitoring wells completed in (at least) the alluvial aquifer will enable collection of time series groundwater level and water quality data to inform processes such as recharge through the alluvial flats, surface–groundwater interactions and contributions of water from the Canning Basin sediments to the Fitzroy River.

Only one of the environmental assets in this region has any site-specific metrics by which to gauge the potential impacts of future climate change and development. In the absence of site-specific metrics a set of standard metrics related to high flows and low flows have been utilised; however, the conversion of these metrics into environmental impacts still requires development of quantitative relationships between flow and specific ecological entities (for example, macrophyte populations, fish passage, faunal and floral habitats, etc.).

Flooding is an important factor that sustains many environmental assets and this occurs when the stream breaks out of its banks (a level known as bankfull stage or discharge). However, bankfull discharge is not known for many streams, nor is the dependence of area flooded on increasing stream depth, so it is difficult to predict when assets are inundated. Further information about bankfull stage and discharge are needed for most environmental assets.

Dry season flows are poorly understood in this region therefore the ability to predict the potential impacts of the various scenarios on low or zero flows at environmental assets is very limited. Improved monitoring of low streamflow conditions is needed along with the development of hydrological models that combine surface and groundwater regimes. Further monitoring of groundwater levels is also required so that the potential impacts of climate change and development on groundwater-dependent ecosystems can be better understood.

Many environmental assets depend not simply on duration above or below certain flow levels, but on triggers (e.g. for reproduction or migration) set by the rate of change of flow. In addition, some environmental assets depend on the frequency and duration of events that occur less than annually (i.e. once every 5, 10 or 20 years or more). Further analysis is therefore required to look at how the timing, duration and rate of rise and fall in flow rates at critical times of the season will vary under the various scenarios.

FI-1.9 References

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McJannet DL, Wallace JW, Henderson A and McMahon J (2009) High and low flow regime changes at environmental assets across northern Australia under future climate and development scenarios. A report to the Australian Government from the CSIRO Northern Australian Sustainable Yields Project. CSIRO Water for a Healthy Country National Research Flagship, Division of Land and Water, Canberra. *In prep.*

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FI-2 Contextual information for the Fitzroy (WA) region

This chapter summarises the background information for the region, outlining existing knowledge of water resources and prior and current investigations relevant to the water resources of the region. This chapter also outlines the current and potential future legislation, water plans and other water resource management arrangements. This chapter is arranged into four sections:

- physical and climate descriptions
- data availability
- hydrogeology
- legislation, water plans and other arrangements.

FI-2.1 Overview of the region

FI-2.1.1 Geography and geology

The Fitzroy (WA) region comprises the Australian Water Resources Council basins of the Fitzroy River, the Lennard River and the Cape Leveque Coast. The region is bounded to the north by the King Leopold Ranges, an escarpment that separates the Fitzroy (WA) region from the Kimberley region. The Fitzroy and Lennard rivers both originate in the King Leopold ranges and drain west into King Sound. The Fitzroy catchment covers almost 94,000 km^2; the Lennard an additional 15,000 km^2 and the Cape Leveque Coast a further 23,000 km^2. The Fitzroy is the longest river, traversing 730 km from source to coast. During the wet season (November to April), the Fitzroy can swell to extend 15 km across the floodplain, with the alluvial sediments covering over 32,000 km^2 of the catchment.

The region overlies late Palaeozoic to mid-Mesozoic sediments of the Canning Basin (Figure FI-3), which extends off-shore into the North-west shelf. The surface geology is dominated by exposed igneous and metamorphic rocks of Proterozoic age in the north eastern one-third of the region, and alluvium elsewhere.

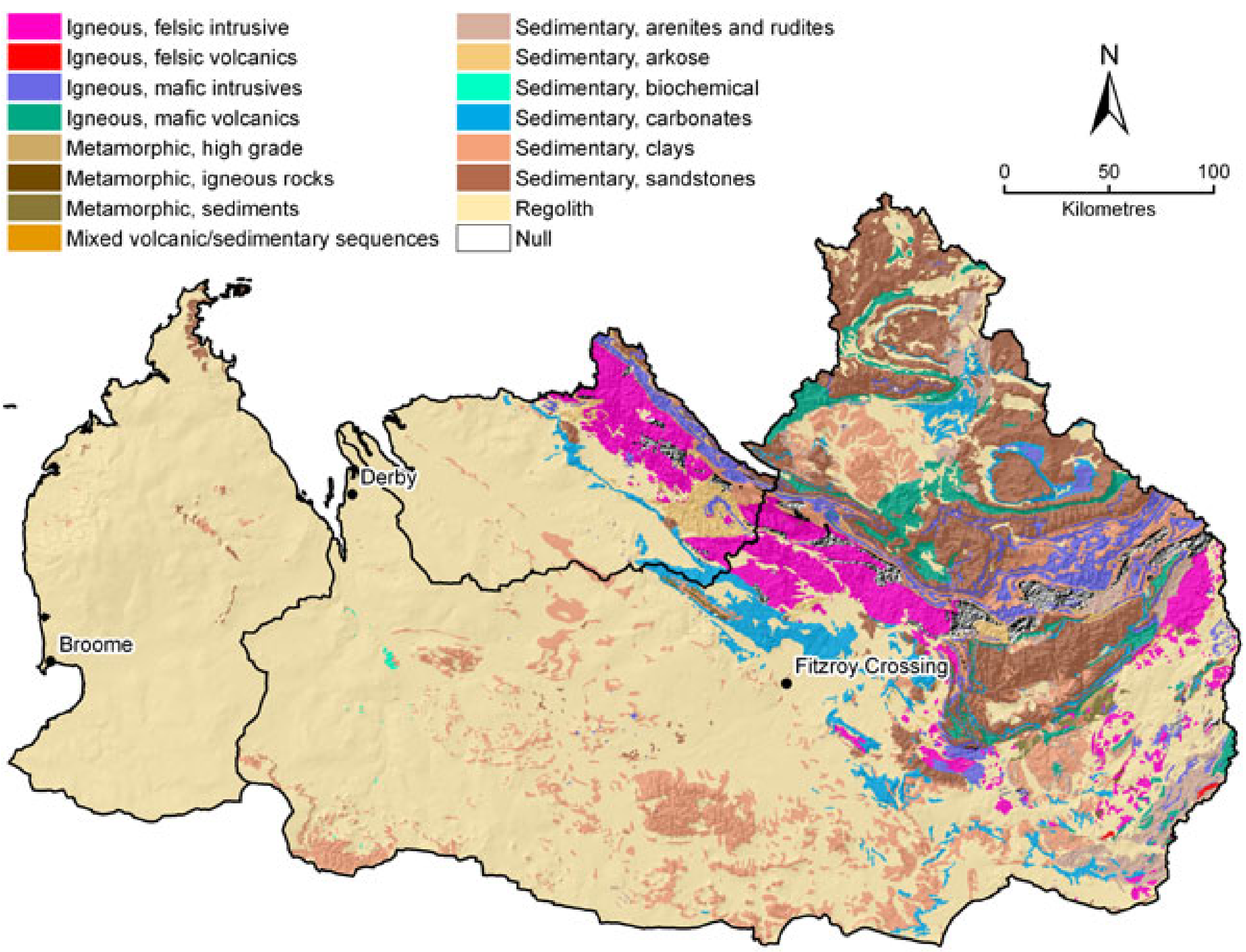

Figure FI-3. Surface geology of the Fitzroy (WA) region overlaid on a relief surface

FI-2.1.2 Climate, vegetation and land use

The Fitzroy (WA) region receives an average of 560 mm of rainfall over the September to August water year, most of which (500 mm) falls in the November to April wet season (Figure FI-4). Across the region there is a strong north–south gradient in annual rainfall, ranging from 960 mm in the north to 380 mm in the south. Over the first half of the historical (1930 to 2007) period, annual rainfall was relatively constant at around 450 mm. Conversely, the second half of the historical period saw an increase in mean annual rainfall to approximately 600 mm. The highest yearly rainfall received was 1130 mm which fell in 2000, and the lowest was 250 mm in 1952.

Areal potential evapotranspiration (APET) is very high across the region, averaging 1980 mm over a water year, and varies moderately across the seasons. APET generally remains higher than rainfall throughout the year resulting in year-round water-limited conditions, to which the vegetation has adapted.

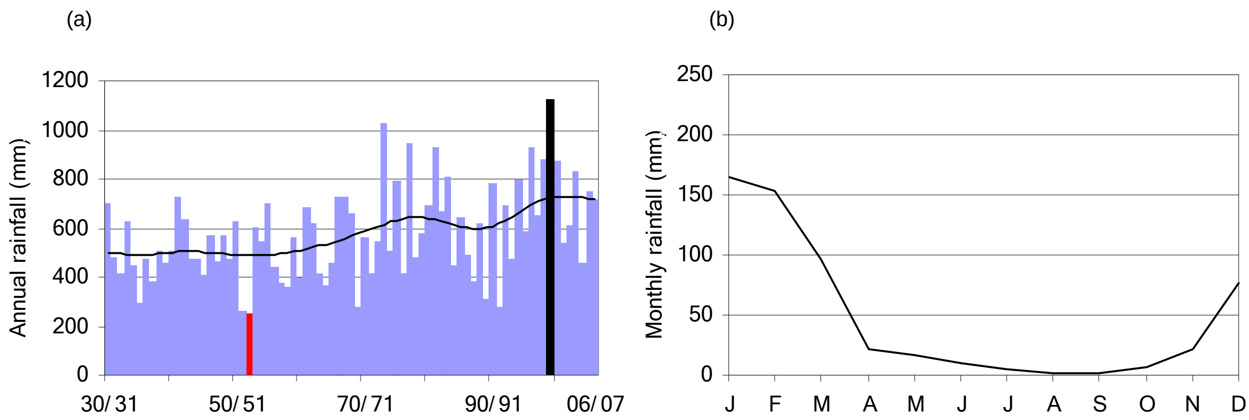

Figure FI-4. Historical (a) annual and (b) mean monthly rainfall averaged over the Fitzroy (WA) region

The region is part of the Dampierland bioregion, consisting of two distinctly different landscapes: ranges and extensive plains. In the north-east the Oscar and Napier Ranges are formed from Devonian limestones. The limestone formed a barrier reef about 350 million years ago. The limestones have eroded to form spectacular gorges and limestone features. The ranges include Brooking, Geikie, Windjana Gorges and Tunnel Creek. The plains are characterised by Quaternary red sands and alluvial plains of grey-brown clays. Low uplands of sandstone and limestone have shallow stony soils (Beard, 1990).

The region is characterised by acacia thickets with scattered trees, areas of grasslands and savannahs. Fire periodically destroys the acacia thickets and ground layer of grasses (Figure FI-5). The grasses quickly regenerate and form grasslands with scattered trees. Gradually the acacia shrubs grow up and suppress the grasses. After several years the vegetation has three layers comprising a sparse grass layer, shrub thickets and scattered trees. Areas of semi-desert spinifex steppe occur in the centre and east of the bioregion. The north and east is characterised by sparse tree steppe over spinifex (*Triodia intermedia*) and *T. wiseana* hummock grasses (Thackway and Cresswell, 1995).

The land tenure includes mainly Indigenous land and pastoral leases. Less than 5 percent of the bioregion is in nature conservation reserves including Windjana Gorge, Tunnel Creek, Geikie Gorge and Point Coulumb National Parks. There are two new nature reserves proposed for the bioregion and these are Mandora Nature Reserve and Edgar Range Nature Reserve (Figure FI-6).

The main enterprises in the bioregion are tourism, pearling and extensive cattle grazing. Broome was established in the 1880s with the discovery of pearl oysters in Roebuck Bay. In the 1900s it was the major producer of the world's pearls. Pearling remains one of the town's major industries with production estimated at $150 million in 1997/98. Broome is the major tourism destination for the region.

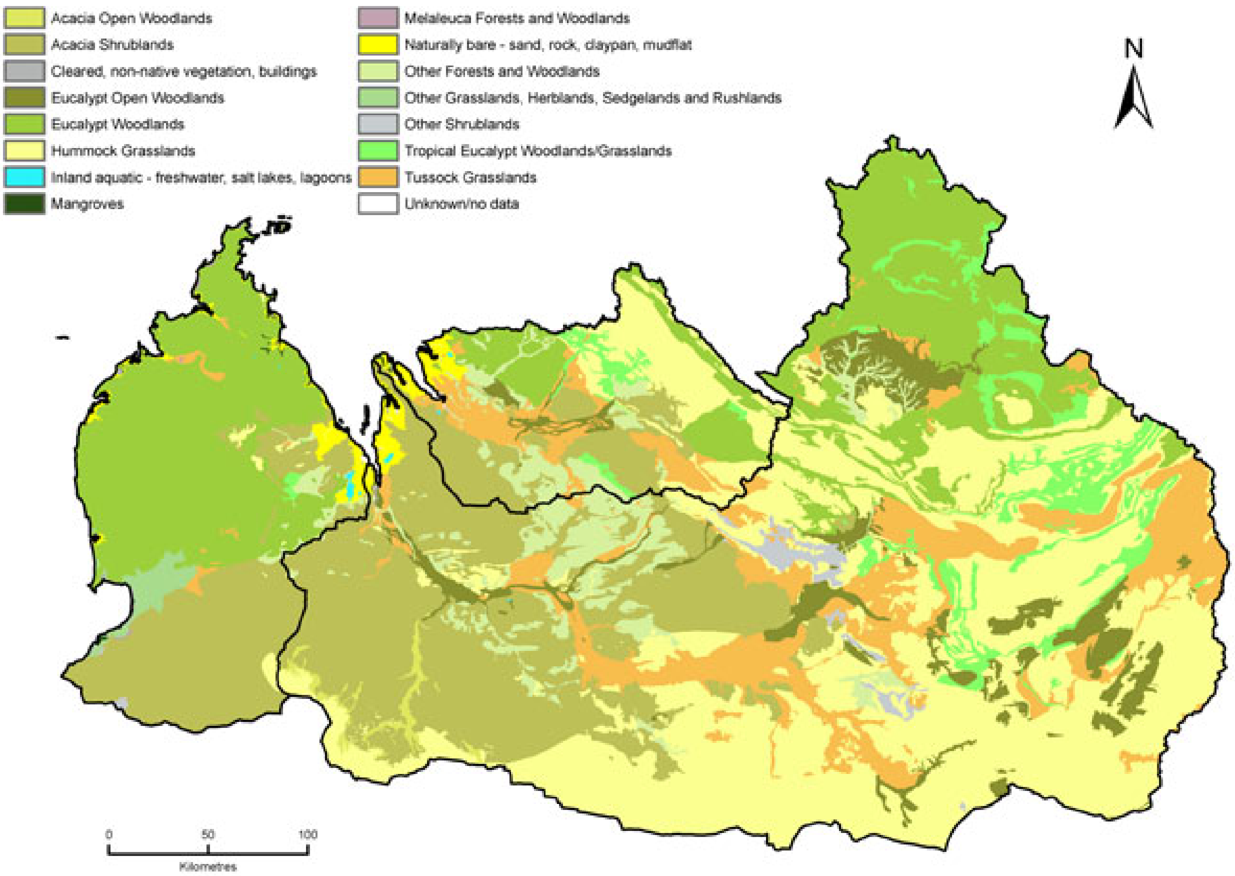

Figure FI-5. Map of current vegetation types across the Fitzroy (WA) region (source DEWR, 2005)

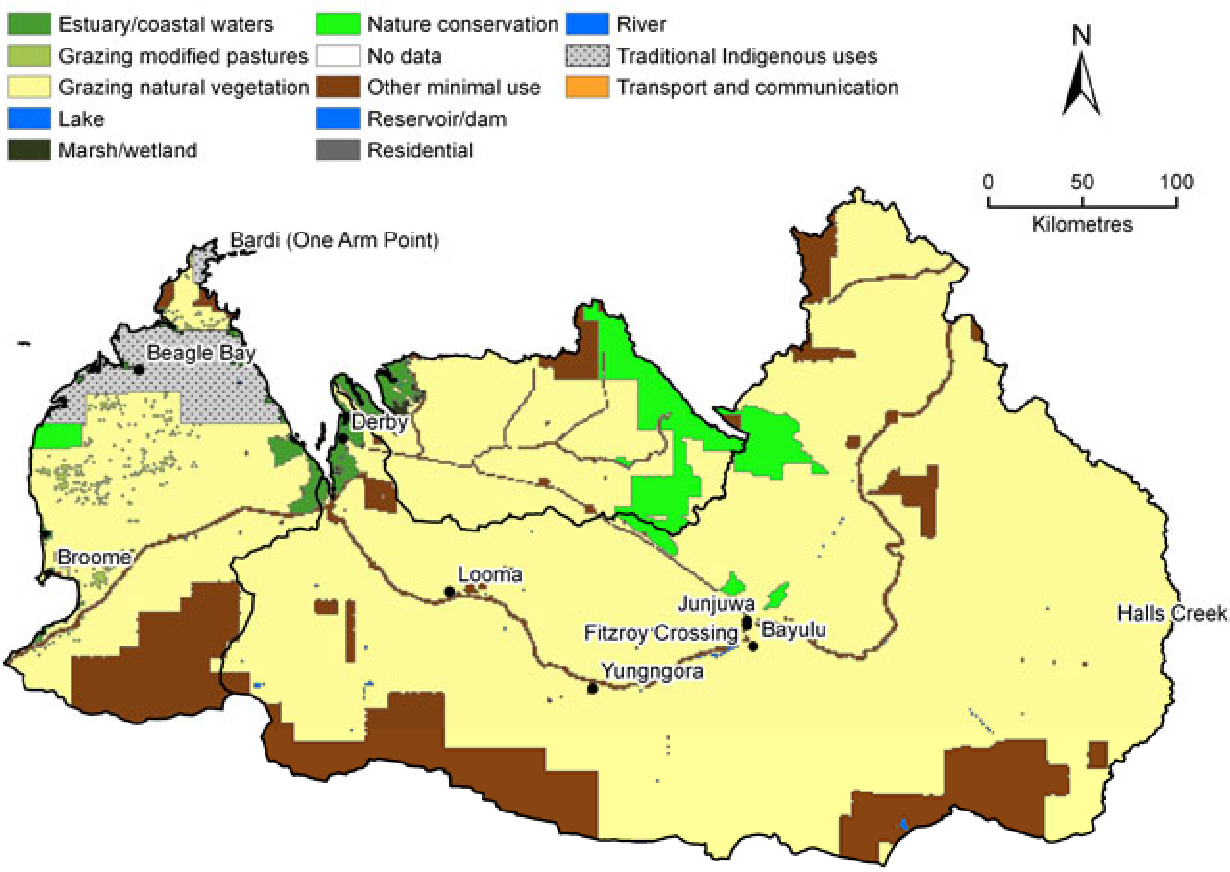

Figure FI-6. Map of dominant land uses of the Fitzroy (WA) region (after BRS, 2002)

FI-2.1.3 Regional environmental asset description

Environmental assets were chosen from wetlands which are listed in the Directory of Important Wetlands in Australia (Environment Australia, 2001). From this directory, environmental assets were shortlisted for assessing changes to the hydrological regime under the climate and development scenarios. The selection of this shortlist was undertaken in consultation with state governments and the Australian Government through direct discussions and through internal reviews (see Section 1.3 in the division-level Chapter 1 for further detail).

All nationally, or internationally, important wetlands listed for the Fitzroy (WA) region in the Directory of Important Wetlands in Australia (Environment Australia, 2001) are detailed in Table FI-2, with asterisks identifying the four shortlisted assets: Roebuck Bay, Camballin Floodplain, Geikie Gorge and Windiana. The location of these shortlisted wetlands is shown in Figure FI-1. There are no wetlands classified as Ramsar sites in this region. Wetlands may be nationally or regionally significant depending on more locally specific criteria. All wetlands are important for a variety of ecological reasons or because they bear historical significance or have high cultural value, particularly to Indigenous people.

The following section characterises these shortlisted wetlands and is based largely on the description of these assets as outlined by Environment Australia (2001). Chapter FI-3 presents the assessment of those shortlisted assets, and reports hydrological regime metrics for those assets which have sufficient confidence in the modelled streamflow to enable analysis.

Table FI-2. List of Wetlands of National Significance located within the Fitzroy (WA) region

Site code	Name	Area	Ramsar site
		ha	
WA020 *	Roebuck Bay	50,000	Yes
WA114	Big Springs	<10	No
WA016	Bunda-Bunda Mound Springs	23	No
WA017 *	Camballin Floodplain (Le Livre Swamp System)	30,000	No
WA019 *	Geikie Gorge	272	No
WA111	Gladstone Lake	<10	No
WA021	Roebuck Plains System	1,180	No
WA012	Tunnel Creek	20	No
WA022	Willie Creek Wetlands	2,950	No
WA013 *	Windjana Gorge	20	No

* Asterisk against the Site code identifies those selected for assessment of changes to hydrological regime
Source: Environment Australia, 2001

In the Fitzroy (WA) region, Roebuck Bay, the Camballin Floodplain, Giekie Gorge and Windjana Gorge were chosen for assessment of changes to hydrological regime under the different scenarios. The following section provides a brief characterisation of these environmental assets and is based largely on the description of the assets given by Environment Australia (2001) and comprehensive environmental water assessments by Bartolo et al. (2008).

Roebuck Bay

Roebuck Bay is on the Cape Leveque Coast and is an International Ramsar site. It is a tropical marine bay with extensive, highly biologically diverse, intertidal mudflats (covering an area of about 160 km^2) (Figure FI-7). The site is internationally important for at least 20 species of migratory shorebirds with total numbers of waders using the site each year estimated at over 300,000. The site is one of the most important migration stopover areas for shorebirds in Australia and globally. It is the arrival and departure point for large proportions of the Australian populations of several shorebird species, some of which fly non-stop between continental East Asia and Australia. A total of 64 waterbird species have been recorded, including four darters and cormorants, 11 herons and allies, 34 shorebirds and 11 gulls and terns. In addition to being a rich waterbird feeding ground, Roebuck Bay supports an exceptionally high amount of benthic invertebrates, including many species believed new to science.

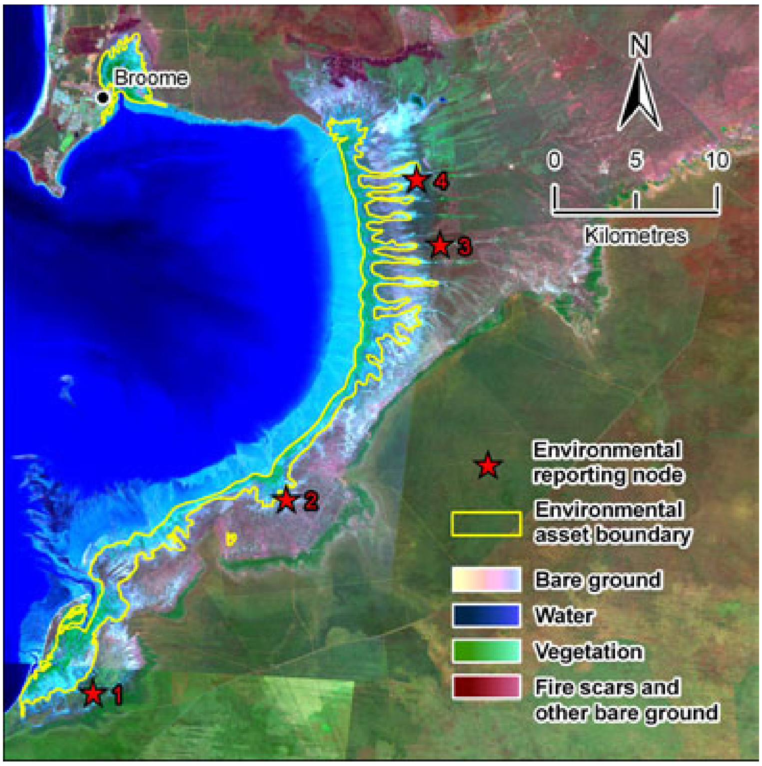

Figure FI-7. False colour satellite image of Roebuck Bay (derived from ACRES, 2000). Clouds may be visible in the image

Camballin Floodplain

The Camballin Floodplain is in the central reaches of the Fitzroy River and includes the Le Livre Swamp System and numerous other seasonal wetlands (Figure FI-8) (Environment Australia, 2001). Halse and Jaensch (1998) have reported that the Camballin Floodplain is an important bird habitat and that there are at least 67 recorded species and bird numbers often exceed 20,000. The Fitzroy river channel is an important habitat for fish, especially as its large deep pools provide dry season refuges. The river contains a high diversity of fish, including some that are listed as threatened species, for example, the Northern River Shark and the Freshwater Sawfish – see Storey et al. (2001) and Morgan et al. (2002). The middle reaches of the Fitzroy River contain the Camballin Barrage and Morgan et al. (2005) have shown that it presents a considerable barrier to fish migrations. They found that in most years (~80 percent) since 1987 the Barrage was only negotiable by fishes for up to three months a year. There is therefore a considerable bottleneck at the Barrage affecting fish passage which may disrupt the natural ecological balance of the river. A more comprehensive description of the Camballin floodplain wetlands is given by Sutton (1998) and van Dam et al. (2008).

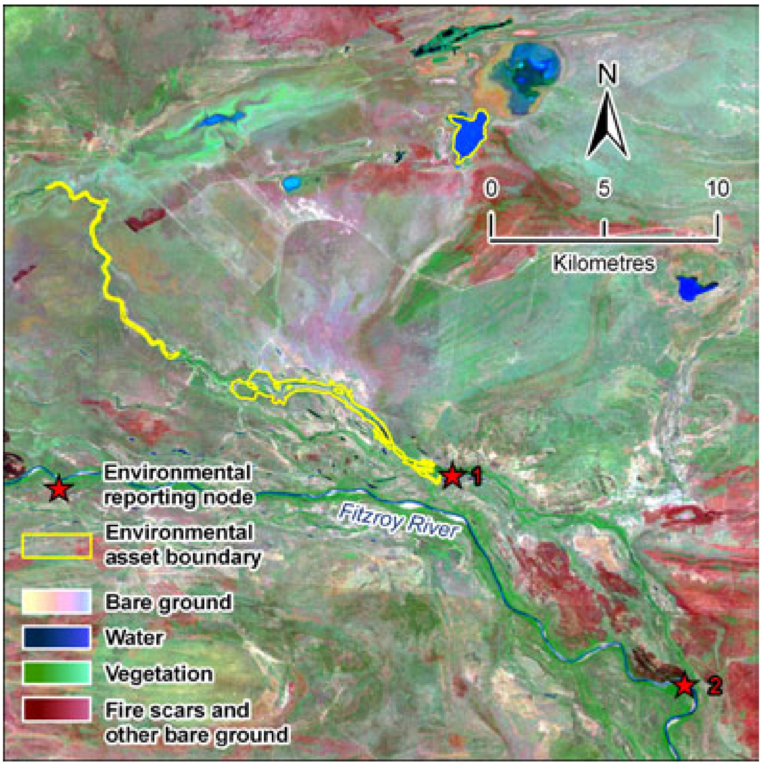

Figure FI-8. False colour satellite image of Camballin Floodplain (Le Livre Swamp System) (derived from ACRES, 2000). Clouds may be visible in the image

Geikie Gorge

Geikie Gorge is in the upper Fitzroy catchment approximately 30 km upstream of Fitzroy Crossing. It is a permanent pool on the Fitzroy River about 13 km long and 100 m wide (Figure FI-9). The gorge is an important refuge area for freshwater and marine fish, especially during periods of drought (van Dam et al., 2008). The gorge's permanent water and food resources are valuable to Indigenous people, who are now involved in promoting the park's cultural values to tourists.

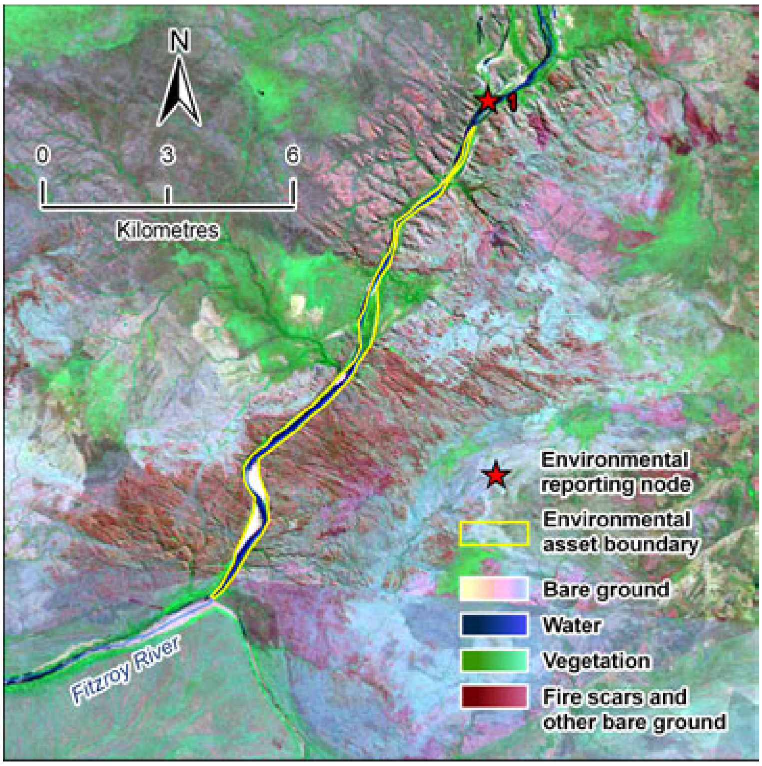

Figure FI-9. False colour satellite image of Geikie Gorge (derived from ACRES, 2000). Clouds may be visible in the image

Windjana Gorge

Windjana Gorge is in the Lennard River catchment adjacent to the Fitzroy catchment (Figure FI-10). It is a 3.5 km long gorge that cuts through a 300 million year old Devonian Reef system. River flows are ephemeral and the gorge contains pools of freshwater outside the wet season that provide a vital habitat for a wide range of animals, birds and fish, including freshwater crocodiles. The site is of considerable cultural significance to Indigenous people and is the site of a number of cave paintings including the 'wandjina' figure.

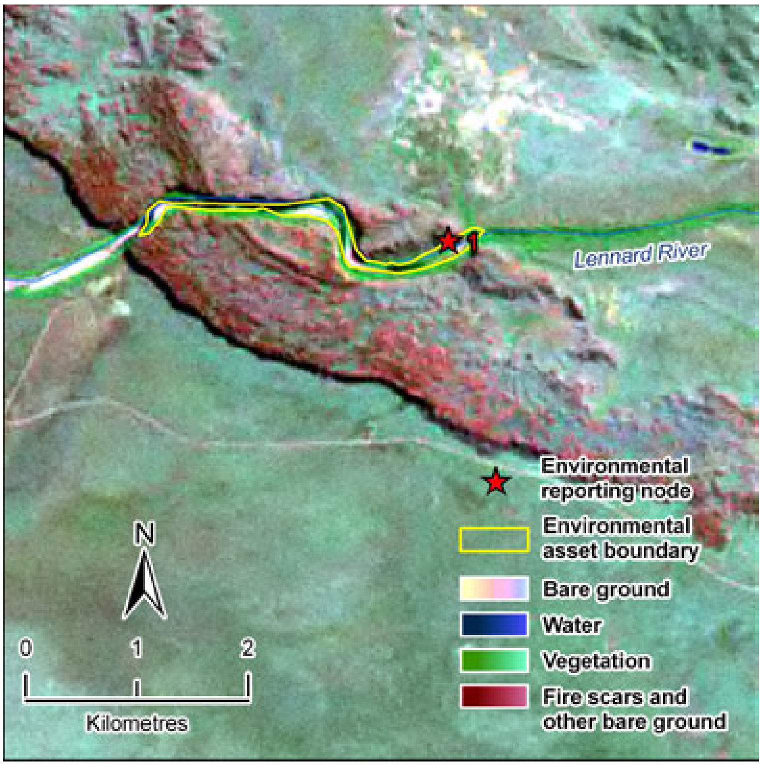

Figure FI-10. False colour satellite image of Windjana Gorge (derived from ACRES, 2000). Clouds may be visible in the image

FI-2.2 Data availability

FI-2.2.1 Climate

The rainfall-runoff modelling uses historical daily climate data (Scenario A) from the SILO database for the period 1 September 1930 to 31 August 2007 at 0.05 x 0.05 degree (~ 5 x 5 km) grid cells. Full details and characterisation of the SILO database are provided at the division level in Section 2.1 of Chapter 2. Scenario B and Scenario C climate data are rescaled versions of the Scenario A data; this is also discussed in Section 2.1 of Chapter 2.

FI-2.2.2 Surface water

Streamflow gauging stations are or have been located at 22 locations within the Fitzroy (WA) region, 18 of these in the Fitzroy catchment and four in the Lennard catchment (Figure FI-11). Eleven of these gauging stations are either: flood warning stations and measure stage height only, or have less than ten years of measured data. Of the remaining 11 stations six recorded more than half of their total volume of flow during events that exceed the maximum gauged stage height (MGSH). In the hard rock upland area of the Fitzroy region the majority of gauging stations are situated at rock bar controls and consequently have relatively stable low flow rating tables.

Rating curves are currently being re-developed by the Western Australia Department of Water for selected stations along the Fitzroy catchment floodplain and headwater areas using hydraulic modelling methods and high resolution digital elevation model data. Some of these data were available for this study. No gauging station in the Fitzroy (WA) region with more than 10 years of good quality data have its flow impeded.

There are 14 gauging stations currently operating in the Fitzroy region at a density of one gauge for every 9400 km^2. For the 13 regions the median number of currently operating gauging stations per region is 12 and the median density of gauging stations per region is one gauge for every 9700 km^2. The Fitzroy (WA) region has an average density of current gauging stations relative to other regions across northern Australia. However the density of stations is low relative to the Murray-Darling Basin average. The mean density of current stream gauging stations across the entire Murray-Darling Basin is one gauging station for every 1300 km^2.

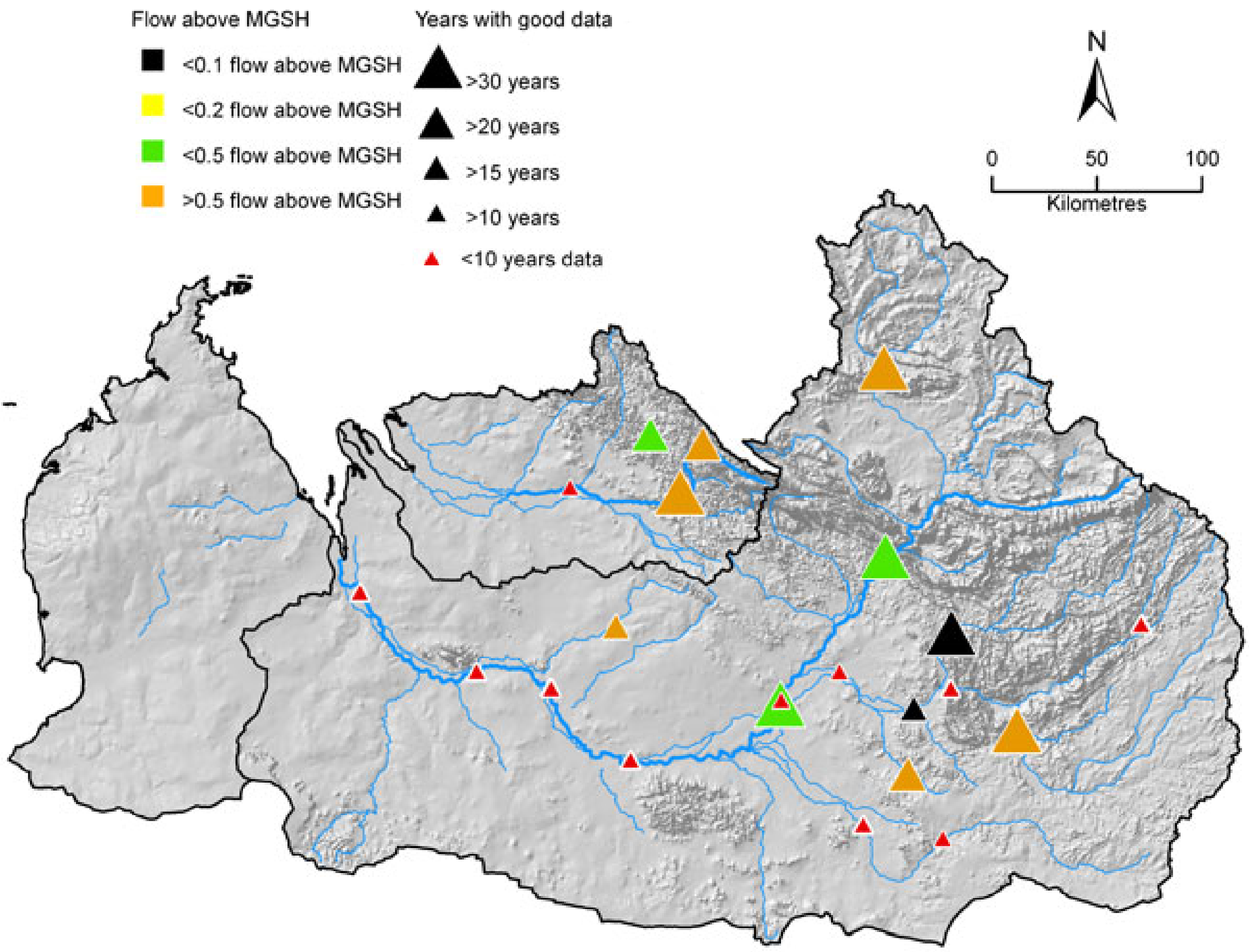

Figure FI-11. Location of streamflow gauging stations overlaid on a relative relief surface showing the proportion of stations with flow above their maximum gauged stage height across the Fitzroy (WA) region

FI-2.2.3 Groundwater

The Fitzroy (WA) region contains 2392 registered groundwater bores. Of these, 172 have surveyed elevations that could enable watertable surfaces to be constructed for the main aquifers. However these bores are not necessarily monitored on a regular basis. There are 646 water level monitoring bores in the region; 463 are historical and 183 are current (Figure FI-12).

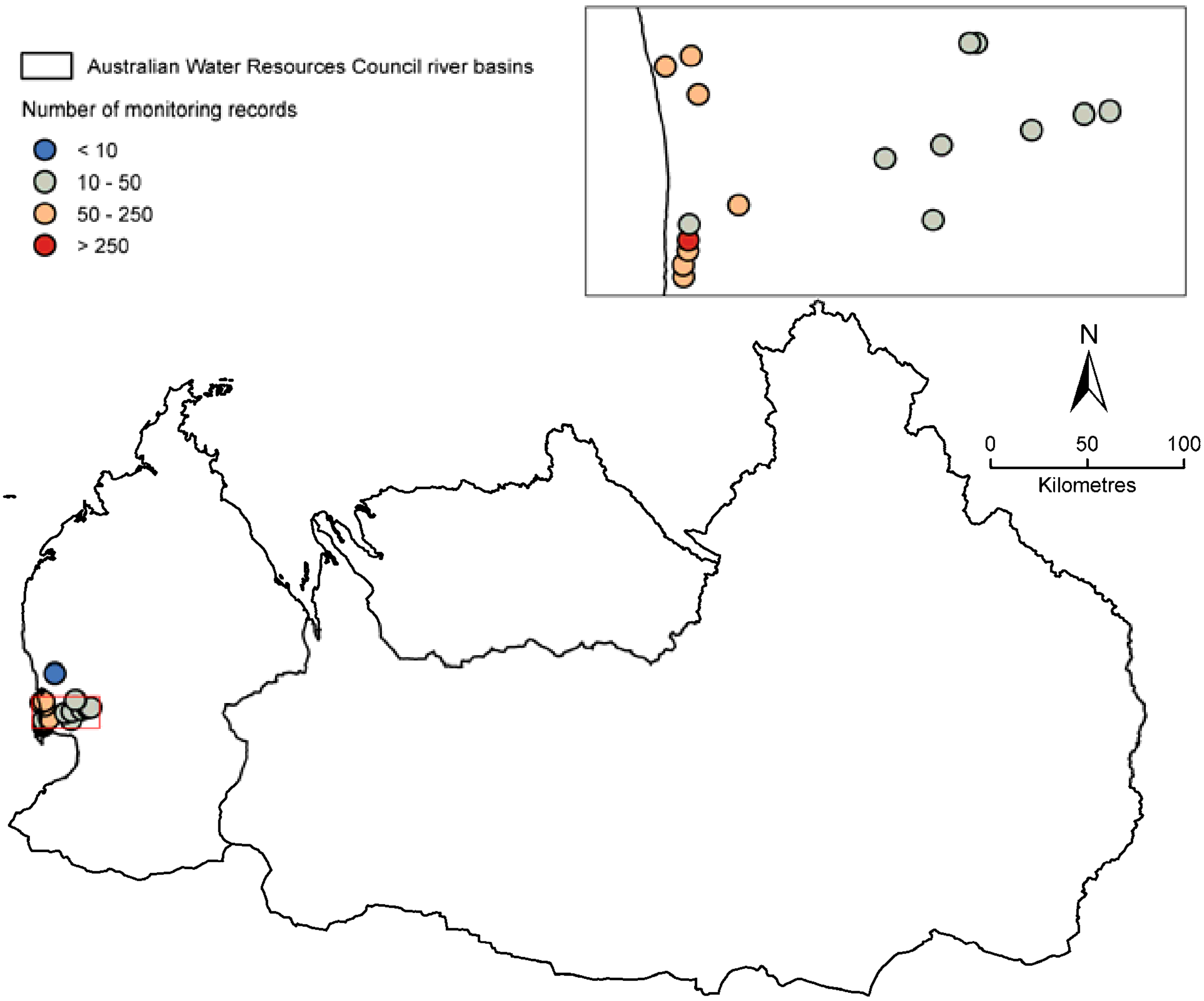

Figure FI-12. Current groundwater monitoring bores in the Fitzroy (WA) region

FI-2.2.4 Data gaps

Historical groundwater level and salinity monitoring data are very sparse for the Fitzroy (WA) region. The absence of such data has meant that the conceptual models presented in this report are largely theoretical. Furthermore, until a comprehensive groundwater monitoring network is established and data are available, there can be no quantitative analysis of current or future impacts of groundwater development or climate change.

FI-2.3 Hydrogeology

FI-2.3.1 Aquifer types

There are essentially four main aquifer types in the Fitzroy (WA) region; namely (i) alluvial aquifers that border major rivers such as the Fitzroy and Lennard, (ii) Canning Basin sedimentary rocks, (iii) Devonian reef limestone, and (iv) fractured igneous and metamorphic rocks (Figure FI-2).

Fractured rock aquifers

Precambrian fractured rock aquifers lie in the upper sections of both the Fitzroy and Lennard River catchments to the north-east of the Canning Basin (Figure FI-2). Bores drilled in this aquifer have highly variable yields dependent on fracture variability, and have a range of groundwater salinities. Small water supply bores have been successfully drilled in this aquifer; however, detailed information is limited.

Devonian limestone aquifers

There are several potentially significant limestone aquifers located along the north-eastern boundary of the Canning Basin on the Lennard Shelf (Figure FI-2). These units have karstic features and outcrop most notably at the Windjana and Geike Gorges where prolonged dry season flows are maintained in the Lennard River and Fitzroy River, respectively (Hardman, 1884). Several studies have been undertaken on these complex units from a geological perspective by Playford and others (e.g., Playford and Lowry, 1966), but the aquifer characteristics have not been investigated in detail and are likely to be highly variable.

Canning Basin aquifers

The aquifers of the northern Canning Basin intersect approximately two-thirds of the Fitzroy (WA) region. Individual geological units extend in thickness from several tens to hundreds of metres and have a wide range of hydraulic properties and salinities. The main regional aquifers of the Canning Basin are the Broome Sandstone, Wallal Sandstone, Erskine Sandstone, Poole Sandstone (Laws, 1990) and to a lesser extent the Liveringa Group and Alexander Formations (Lindsay and Commander, 2005). They are used for Derby's water supply (WRC, 2001a), the supply at Fitzroy Crossing where salinities are generally less than 300 mg/L Total Dissolved Solids (DERMD, 2004), and Broome's water supply, which is the largest urban groundwater use in the region (WRC, 2001b). Yields from the Canning Basin aquifers are largely unknown, but individual bore yields range from 150 to 2000 m^3/day (Laws, 1990). Most of the above units are both confined and unconfined depending on location; the majority of bores drilled are relatively shallow and access the unconfined parts of each respective aquifer.

Alluvial aquifers

The largest alluvial aquifer in the region is the Fitzroy alluvium associated with the Fitzroy River, which commonly consists of 20 to 30 m of Quaternary sands and gravels, overlain by 10 m of black silt and cracking clays. The alluvium extends along approximately 275 km of the Fitzroy River (Figure FI-2), with a surface area of 3200 km^2 and a thickness of 20 m (Lindsay and Commander, 2005). Yields from the Fitzroy Alluvium have been estimated from 300 to 400 m^3/day (Laws, 1990).

Similar alluvial aquifers exist in the north-east of the region along the Meda and Lennard Rivers (Playford, 1992), but little documented information exists for these aquifers. The nature of the surface–groundwater interaction and aquifer properties in these alluvial aquifers are likely to resemble those of the Fitzroy alluvial aquifer.

Smaller and very localised alluvial aquifers may exist along other rivers (Playford, 1992), but these are not expected to be significant with respect to surface–groundwater interaction or as a groundwater resource.

FI-2.3.2 Inter-aquifer connection and leakage

Groundwater in the regional Canning Basin aquifers that lie within the Fitzroy (WA) region generally flows towards the Fitzroy River and north-west, towards the coast. The Fitzroy alluvium is therefore a likely discharge zone and may have good connection with Canning Basin aquifers. The volume of discharge is likely to vary greatly amongst aquifers. Both upward and downward leakage are said to occur between many of the units, and it is suggested that artesian conditions are present along much of the coast (Laws, 1990). There are also areas where groundwater extraction has induced seawater intrusion in the vicinity of the Broome and Derby water supplies (Laws, 1990).

FI-2.3.3 Recharge, discharge and groundwater storage

Annual rainfall is highly variable and also significantly decreases with distance from the coast. As a result, rainfall recharge is thought to occur less frequently in the inland areas of the Fitzroy (WA) region. It is likely that only very large rainfall events which result in pooling of water would overcome the soil moisture deficit to recharge the groundwater. This would occur locally in depressions or drainage lines in the landscape and most effectively where units subcrop or outcrop. Recharge has been estimated by Laws (1990) for the Broome Sandstone as 5 to 6 percent of annual rainfall.

The Fitzroy alluvial aquifer (and presumably the Meda/Lennard alluvial aquifers) are recharged predominantly via river recharge in the wet season, and to a lesser degree by vertical infiltration from both direct rainfall and floodwater when overbank flow causes inundation of the floodplain. The alluvial aquifers are also thought to receive lateral inflow from the regional Canning Basin aquifers, with the majority of this flow occurring in the dry season when river and groundwater levels in the alluvial aquifers are lower. Groundwater discharge to the Fitzroy River and Meda/Lennard River from the alluvial aquifers is likely towards the end of the wet season and maintains flows and semi-permanent pools in the dry.

The Derby Hydrogeological Mapsheet of Playford (1992) suggests that groundwater discharge occurs in the upper reaches of the Alexander and Meda Rivers.

In addition to local discharge to the Fitzroy alluvial aquifer, larger scale throughflow and discharge into the Indian Ocean is likely to occur from the Canning Basin aquifers. Regional throughflow for the whole Canning Basin has been estimated by Laws (1990) for the Broome Sandstone (90 GL/year) and Wallal Sandstone (250 GL/year). It is likely that less than one-third of this throughflow would occur within the Fitzroy (WA) region based on distance parallel to the coast and additionally a large proportion of this groundwater would be both very deep and potentially saline.

Groundwater storage in the Canning Basin has been estimated by Laws (1990) to total 46,446 TL (Table FI-3). Much of the deeper groundwater is saline and/or not economically viable to exploit. These estimations are based on limited information. Further investigations would be required before any resource management decisions are considered.

Table FI-3. Estimated volume of groundwater storage in the Canning Basin (after Laws, 1990)

Formation	Area	Saturated thickness	Saturated volume	Specific yield	Stored water
	km^2	m	TL*		TL*
Broome Sandstone	40,000	100	4,000	0.2	800
Alexander Fmn	100,000	20	2,000	0.05	100
Wallal Sandstone	105,000	250	26,000	0.2	5,200
Erskine Sandstone	2,800	100	280	0.2	56
Liveringa Group	65,000	150	9,800	0.05	490
Triwhite Sandstone	40,000	20	800	0.05	40
Poole Sandstone	260,000	100	26,000	0.2	5,200
Grant Group	350,000	1000	350,000	0.1	35,000
Total					**46,446**

* 1 TL = 1000 GL

Historical groundwater level data is limited in this region with all long-term monitoring bores being associated with the Broome Water Supply. As shown in Figure FI-13, groundwater levels for Bore 80119403 and Bore 80119404 (open at different depths to the Broome Sandstone of the Canning Basin, and located approximately 20 km north-east of Broome) have a falling trend into the mid-1990s and then begin to rise during the late 1990s. The rising trend flattens in the early 2000s and becomes a slowly falling trend in recent years. These groundwater level trends closely match the trends in cumulative deviation from mean monthly rainfall, with an apparent lag of approximately three years. This suggests that despite the large regional scale of the Canning Basin aquifers, they are responsive to medium term variations in climatic conditions – whether the aquifers receive direct local recharge or are simply exhibiting a pressure response caused by fluctuations in groundwater levels in overlying aquifers requires further assessment.

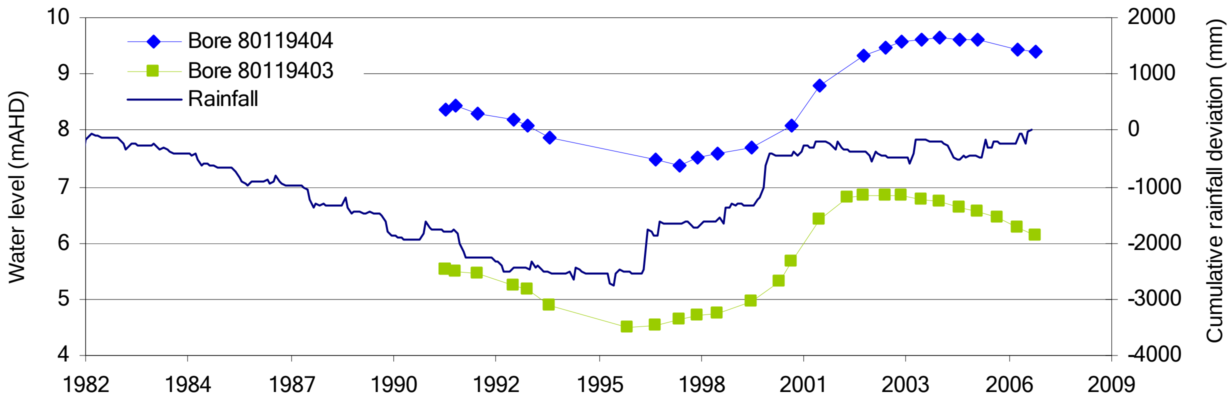

Figure FI-13. Groundwater levels for bores 80119404 and 80119403 and cumulative deviation from mean monthly rainfall at Broome

FI-2.3.4 Groundwater quality

Groundwater quality in the Fitzroy alluvial aquifer has been best estimated from dry season river salinities which range between 250 and 950 mg/L Total Dissolved Solids and are commonly less than 250 mg/L in the wet (Lindsay and Commander, 2005). Higher river salinities near Noonkanbah suggest that the alluvial aquifer here is influenced by inflow from the more saline Noonkanbah Formation (Lindsay and Commander, 2005).

Salinities in the Canning Basin aquifers are more variable and presumably dependent on recharge conditions, geology, distance along groundwater flowpaths (affected by evapotranspiration and water–rock interaction) and mixing with water from other aquifers. Groundwater salinity is generally lower where units subcrop or outcrop and where the aquifers are recharged by high river levels. It is apparent that groundwater salinities generally increase with depth (Laws, 1990). Table FI-4 summarises the salinity ranges described in Lindsay and Commander (2005).

Table FI-4. Range of typical groundwater salinity in the Canning Basin aquifers

Aquifer	Salinity range
	mg/L
Wallal Sandstone (unconfined)	< 1000
Wallal Sandstone (confined)	2000
Wallal Sandstone (west of Willare)	2800 – 3800
Blina Shale (Willare Bridge Roadhouse)	1100
Blina Shale (regional)	7000 – 10000
Liveringa Group	500 – 3000
Liveringa Group (west towards Willare)	7000
Noonkanbah Formation	> 1000
Grant Group and Poole Sandstone (Ellendale)	300
Grant Group and Poole Sandstone (regional)	500 - 2000

Source: Lindsay and Commander (2005)

Figure FI-14 shows a map of the region with all available groundwater salinity data (DoW, 2008a). The data are limited predominantly to initial salinities when the bores were first drilled but does include some time series data. Groundwater salinities are highly variable with areas of lower salinity found along the eastern margin of the Canning Basin and the fractured rock aquifer in the north-east, with higher salinity found in the centre and southern parts of the region. These trends appear approximately consistent with the Department of Water state-wide salinity estimates. The salinity data shown in Figure FI-14 have not been assessed with respect to screened intervals or time of sampling due to limitations in the dataset, and display general salinity trends only.

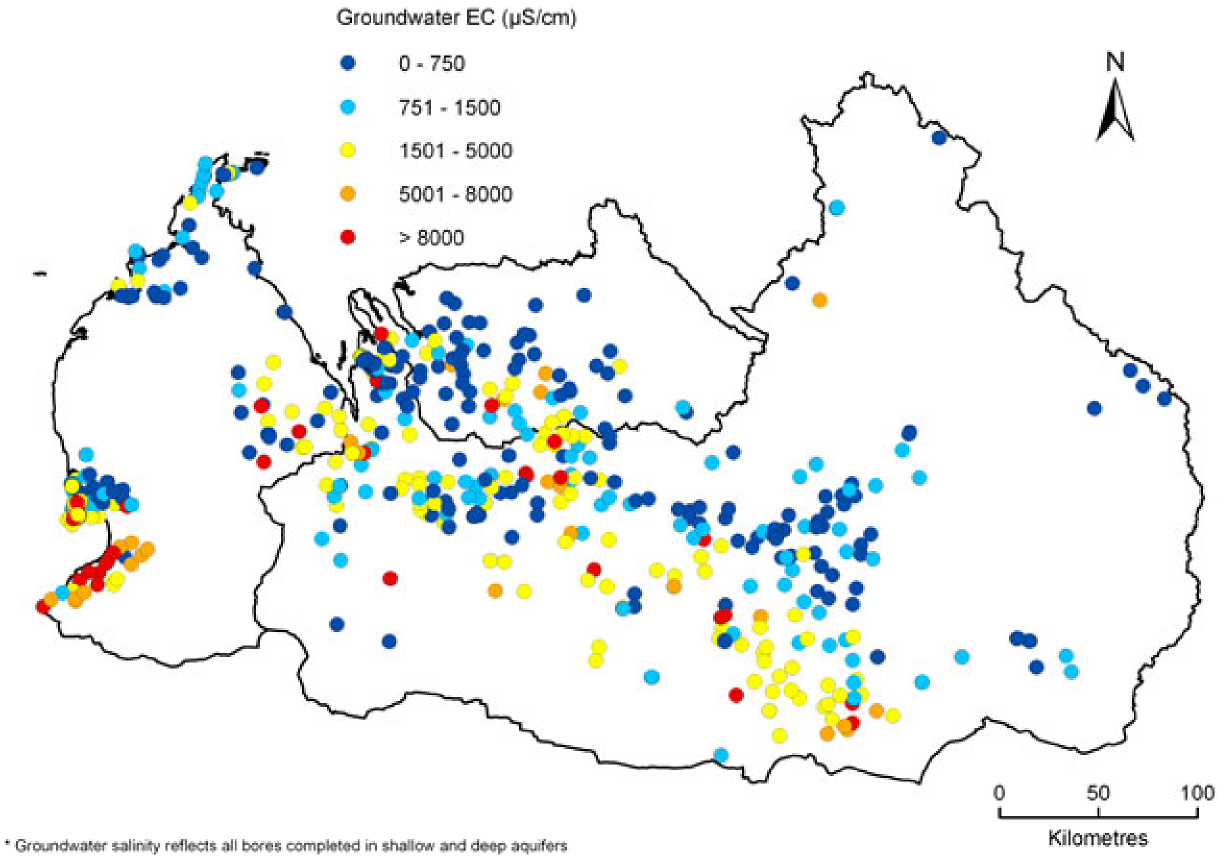

Figure FI-14. Groundwater salinity distribution for all bores drilled in the Fitzroy (WA) region

FI-2.4 Legislation, water plans and other arrangements

FI-2.4.1 Legislated water use, entitlements and purpose

In 1998, the Western Australia Department of Water commenced work on a *Kimberley Regional Water Allocation Plan*. This plan is still being developed and will provide a broad strategic plan establishing a Kimberley-wide (i.e. regional) framework to guide water allocation decisions and licensing policy for individual water resources or sub-regions (e.g. La Grange groundwater basin, the Ord River) within the Kimberley. The department uses regional allocation plans to determine the priority environmental values and beneficial uses of surface and groundwater resources within a particular region. The *Kimberley Regional Water Allocation Plan* will provide a preliminary assessment of the amount of groundwater and surface water development that is considered to be ecologically sustainable after taking into account of ecological and social water values and will be subject to review by the Environmental Protection Agency. The *State Water Plan (2007)* provides a strategic framework to sustainably meet growing water demands.

The *La Grange Groundwater Subareas Water Management Plan – Allocations* (DoW, 2008b) describes the principles and policies that will guide water licensing for existing and future water users, in the region south of Broome, to ensure the sustainability of groundwater resources, while maximising benefits to the community and state. The plan outlines the department's expectations on water use and management. The La Grange subareas cover just under 100,000 km^2 straddling the southern boundary of the Fitzroy (WA) region adjacent to the coast.

The La Grange groundwater subareas contain two aquifers, the unconfined, shallow Broome Sandstone Aquifer and the underlying Wallal Sandstone Aquifer. Allocation limits of 50 GL/year have been determined for the Broome Sandstone Aquifer which is the aquifer considered in this plan. Deeper aquifers are currently not considered in this plan, as they are impractical to tap but may be included in future plans. The La Grange groundwater subareas are situated within the Canning Kimberley groundwater area. This area was proclaimed in 1997 under the provisions of the *Rights in Water and Irrigation Act 1914*. Expansion of horticulture (pastoral diversification) along the coast and possible expansion of mining activities in the south (outside the area covered by this project) is likely to increase demand on water supplies.

The Cape Leveque Coast, north of Broome, has high tourism and indigenous values and the coast is being evaluated as a site for a development hub for the off-shore gas field. There are currently small plantation trials, with proposals for larger developments.

There has been some interest in water from the Fitzroy River for inter-basin transfer (i.e. water for Perth), and this remains an on-going point of discussion. Currently, water is taken mainly for small to large rural and remote communities and some small-scale irrigation, mainly for fodder crops. A Water Quality Protection Plan exists for the area around Fitzroy Crossing to protect the drinking water supply for the area.

Groundwater quality is good, but the available hydrogeological data are limited and the analysis of likely yields is very preliminary. A substantial investigation program consisting of aerial geophysical survey, investigation drilling and pumping tests will need to be carried out to define the extent and properties of the aquifers prior to confirming a sustainable extraction yield.

Current

Figure FI-15 shows the distribution of current groundwater extraction licences, totalling 20.63 GL/year. These licences range from small community water supplies (<10 ML/year) to larger mining supplies (~4000 ML/year). They include the public water supply for Fitzroy Crossing (250 ML/year; DERMD, 2004), Camballin (50 ML/year; WRD, 2006), Derby (1500 ML/year; WRC, 2001a), Broome (4200 ML/year; WRC, 2001b) and 2359 ML/year for the La Grange area. (Note that a further 3000 ML/year is licensed for extraction within the La Grange area outside of the Fitzroy (WA) region, DoW, 2008b). The majority of allocations are for taking water from the Canning Basin aquifers with few in the fractured rock aquifers in the north-east of the region and apparently none in the Fitzroy alluvial aquifer. Nevertheless, pumping from bores screened in aquifers below the Fitzroy alluvium (e.g. at Fitzroy Crossing) would likely have a direct influence on the water levels in the overlying alluvial aquifer.

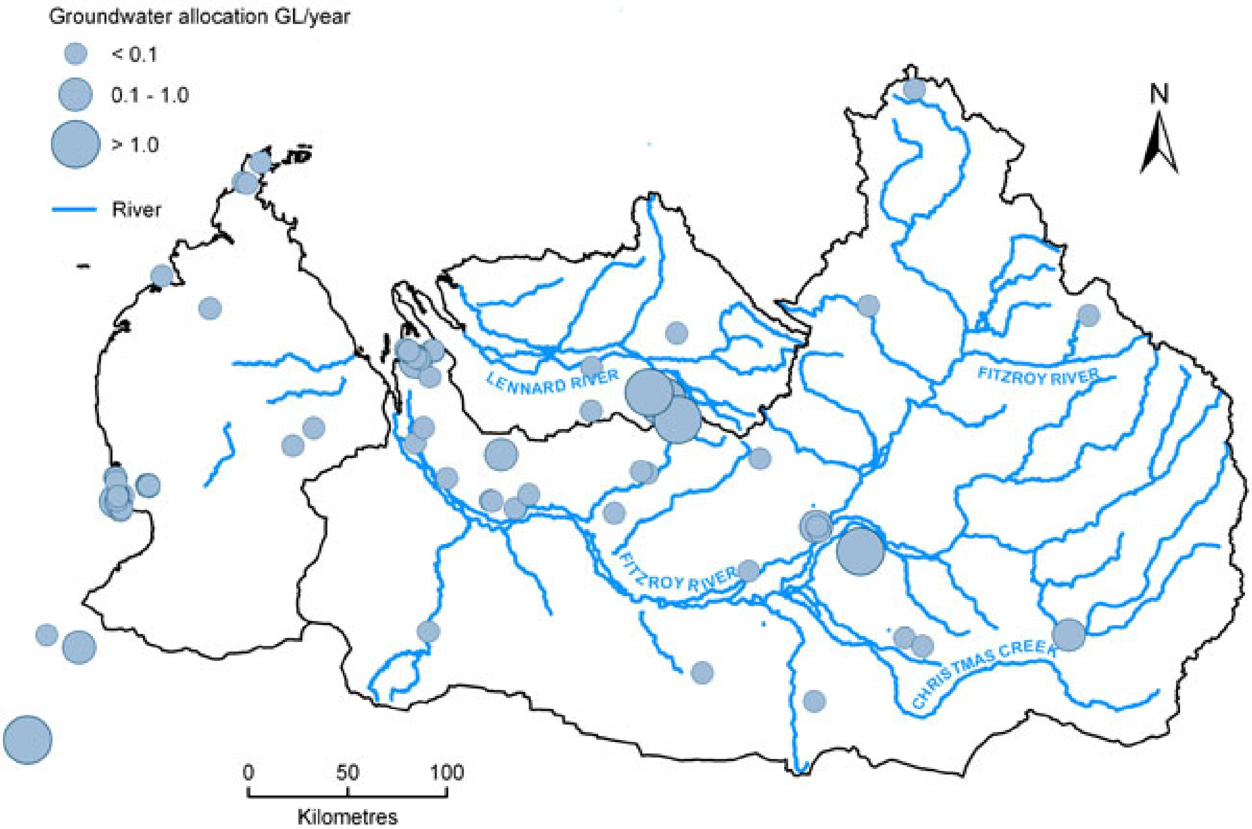

Figure FI-15. Existing groundwater allocations in the Fitzroy (WA) region, plus three allocations in the La Grange area outside of the region (data from DoW, 2008a, 2008b)

Future

It is likely there will be increased demand for groundwater with population growth in the region. Broome, Derby and Fitzroy Crossing water supplies in particular have identified increasing demands in addition to any future development or mining in the region. It is difficult to estimate this increase in groundwater demand with any certainty.

FI-2.4.2 Rivers and storages

The previous Western Australian (Labor) Government advanced a policy that there will not be any dams on the Fitzroy River. This is a policy position and has not been made law. However small-scale distributed irrigation developments, based on alluvial groundwaters and nearby soils is potentially an appropriate style and scale for developments in the region. The Department of Water is likely to acknowledge the potential for this approach in its regional water strategy for the Kimberley. However, considerable additional assessment and stakeholder consultation is required on the approach and its practicability, especially given that the development areas are likely to be flood prone. Over the next several years, the department intends to complete current studies, carry out further investigations where possible and develop suitable conservative allocation limits (or where appropriate, consumptive pools) for this style of development in the region.

These opportunities have not been considered in our modelling process.

FI-2.4.3 Unallocated water

The granting of licences under the *Rights in Water and Irrigation Act 1914* is the main management tool for accounting for the water taken. To account for the water taken from unlicensed groundwater users, the department will set aside sufficient water before allocations are made to licensed water users, ensuring sustainable outcomes. Licensing may not be appropriate for very small groundwater users, such as domestic bore owners, or for occasional water uses such as fire fighting. There is also a community expectation that land owners will be able to access the groundwater resources for domestic purposes with few restrictions.

Allocation of unallocated water will be managed adopting a precautionary approach. Environmental, water security and Indigenous needs will be recognised, as will the importance of agriculture and other developments in meeting the future economic needs of the community and the region.

FI-2.4.4 Social and cultural considerations

Some attention has been given to social and cultural values associated with water in the Fitzroy River catchment in response to proposals to dam the Fitzroy River and utilise both surface and groundwater for irrigated agriculture. A review of stakeholder views on water allocation planning (Beckwith and Associates, 1999) noted that stakeholders wished to see regional water allocation plans that would identify valuable attributes of the region (e.g. Ramsar listings) that might be affected negatively, or positively, by water allocation decisions. A description of the impacts of past land and water management activities in the Kimberley on waterways such as the Ord River and Fitzroy River was also viewed as needed. A specific example cited was the impact of the cattle industry on riparian areas and rivers.

The agricultural proposals attracted opposition as did the proposal to dam the Dimond Gorge or any tributary of the Fitzroy River (Beckwith and Associates, 1999). Concerns about regulation of the Fitzroy River or its tributaries included:

- potential impacts on local fish stocks, fish passage and migration
- damage to the riverine environment
- loss of places of cultural significance due to inundation
- the loss of areas with high eco-tourism potential (e.g.Dimond Gorge).

Both Indigenous and non-Indigenous stakeholders raised the issue of alteration of the natural flow regime of the Fitzroy River system should it be regulated. The limited scientific understanding of the Fitzroy River Valley was highlighted by a number of stakeholders.

Specific mention was made of an Australian Society of Limnology workshop on the limnology of the Fitzroy River (ASL, 1998) and the issues it raised. In response to the initial irrigated cotton proposal, this scientific workshop focused on the possible impacts on the aquatic ecology of the Fitzroy River system as a result of river regulation (e.g.. dams/weirs). The workshop noted:

- on the basis of waterbird populations, parts of the Fitzroy Valley floodplain meet criteria for listing as Ramsar wetlands while other parts have been poorly surveyed
- the Freshwater Saw Fish and the Freshwater Whipray, which occur in the Fitzroy River, are listed as ‘endangered’ by the IUCN
- alteration of the regular flooding events on the Fitzroy floodplain could decrease the high productivity of the river system that is in part due to its ‘flood-pulse advantage’
- alteration of the flow regime could threaten flora through changes to community structure and composition; invasion and expansions by weeds; decreased vigour; and reduced opportunities for recruitment
- the relationship between flooding in the Fitzroy River and the recharge of groundwater systems in the region (e.g. Fitzroy Valley aquifers, Derby town water supply) was raised as an issue requiring investigation.

There was a strong perception among many stakeholders that damming of the Fitzroy River would negatively impact on recreational fishing. While the economic value of the inshore recreation fishery is unknown, the demand for recreational fishing continues to grow.

The need to assess and protect the Indigenous cultural values of the area was highlighted in consultations reported in Beckwith and Associates (1999). Of particular concern were those values associated with water resources such as seasonal water holes and soaks. This was cited as an example of the close linkages between the ecology of the area and Indigenous cultural values. The important role of groundwater as a life force in the spiritual beliefs of the local community was also raised.

More recently, Toussaint et al. (2005) described the many different sources of and meanings associated with water amongst the Indigenous societies of the Fitzroy Valley. The authors note that the different language groups of the region all conceptualise water sources and rivers, along with the land, as derived from the Dreaming.

Yu prepared a case study on the significance of water to Fitzroy River Indigenous communities for a Land and Water Australia Scoping Study (Jackson and O'Leary, 2006). She stated:

> "The Fitzroy River, in the Kimberley region of north-western Australia, travels through the traditional countries of many language groups, and the complexity of cultural relationships to the river country has been further compounded by the historical relocation of desert groups on the station properties along the river. Whilst each group has distinct cultural responsibilities and articulates their relationship in varying ways, the groups are united through a system of Law that weaves together complex narratives and rituals required for the sustenance of the river country and its complex ecosystems. There is no single name for the river except marduwarra, which is a generic word for river. Rather, the Fitzroy River is conceptualised as series of linked narratives which arise from the many permanent pools along the riverbed and, which are subjected to the seasonal processes of flooding (warramba) and receding waters.
>
> Physically, the Fitzroy River is a major unregulated system characterised by a braided main channel, anabranching and billabongs on the floodplain, and significant lowland floodplain storage. The river flows are highly unpredictable and ecological processes are typically described as "boom and bust" corresponding broadly to "wet and dry" periods (Storey et al., 2001). The country of the river and its tributaries is also dotted with natural spring systems which as permanent water sources are also culturally significant. Recently there have been a number of development proposals for irrigated agriculture in the Fitzroy catchment, which would require mechanisms to impound (i.e. dam) and regulate the river flows, and therefore threaten to create enormous impact on the cultural and ecological values of the river system."

Yu's (2000) report provides a brief review of some anthropological literature relevant to the cultural significance of water to Indigenous people. Based on literary sources, she concludes that Indigenous concepts of serpents living in water-holes, rainmaking and "living water" were found throughout much of Indigenous Australia (Yu, 2000). She noted that literature focusing on the water systems of the wet-dry tropical Kimberley region was scarce.

Identification and discussion of cultural values of the Fitzroy river country such as the narratives, rituals, ancestral beings, totemic tracks, paintings and other elements intrinsic to Indigenous notions of landscape, have no meaning without establishing their relationship to the fundamental concept of Pukarrikarra/ Bukarrarra/ Ngarranggani. This concept defines the landscape and people's relationship with country, and in this sense the river valley basin can be defined as a cultural landscape to the Indigenous people, as much as it is a physical one.

Despite universality in conceptual understandings of the river country, there nevertheless is great regional variation in cultural detail. There are differing narratives and traditions, with many subtleties and variations, through which each of the groups along the river system explain the origins, and the continued cultural significance of the river and its ecosystem.

Indigenous values are known to exist in the area of Geike Gorge. As yet these have not been identified, documented or assessed for National Estate significance by the Commission. The Geikie Gorge is on the Register of the National Estate.

The Kimberley region has recently been declared for its heritage significance. The West Kimberley, about 22,500,000 ha, generally extending from Roebuck Bay in the west to the Hann River (including Drysdale River National Park) in the east, and from the Fitzroy River in the south to, and including, the Bonaparte and Buccaneer Archipelagos in the north, is now listed on the National Heritage List.

Jackson et al. (2008) found evidence of conflict over perceptions of abundance and inter-basin transfer to meet southern Australia's growing water demand in their focus group interviews in Derby in 2006. Drought-proofing schemes for Perth and Adelaide have investigated the transfer of large volumes of water from the Kimberley region to meet urban water demands. Respondents at the Derby focus group challenged the perception that tropical water is being wasted when it flows to the sea, arguing that it is being used by the river systems and serves the needs of the local population. Concerns over the commodification of water through market exchange were aligned with this issue, particularly in the Derby forum where water trading was seen to represent a threat to 'the social control of water'; "It's really important that control of water stays in the hands of the community, not special interest groups. We should all get together and get a better understanding of it all" (Jackson, 2008).

Yu's published study of cultural values in the La Grange Basin, in the west of the region, which is predominantly the traditional country of the Karajarri, is a valuable source of knowledge of this area (Yu, 2003). She also documents the cultural significance of groundwater and groundwater dependent ecosystems to the Karajarri noting that the "Karajarri have a well-defined understanding of the source of freshwater" (Yu, 2000). The local Indigenous people identify three layers of water – surface waters, such as temporary lakes and lirri, underground water that sources springs and jila, and a deeper source of pressurised underground water referred to as 'bottom water' or jarrurru.

FI-2.4.5 Changed diversion and extraction regimes

The Camballin barrage was built in the 1950s to support large scale irrigation of rice and other crops. It is located 150 km from the tidal zone up the Fitzroy River. Impounded water was diverted up the Uralla Creek to fill the Seventeen Mile Dam, which was capable of storing about 5 GL of water. The barrage was designed to collapse when the river level was approximately twelve inches over the shutters, but was repeatedly damaged by floods and is now in a derelict state after the scheme was abandoned in 1983. The barrage facilities were sold to Liveringa Station in 1995 and some ongoing diversion of water down Snake Creek supports irrigated fodder crops.

There are other smaller weirs on tributaries to the Fitzroy River, but no major structures.

FI-2.4.6 Changed land use

Alluvial aquifer extraction will be a likely future water source in the dry season but ongoing work on the interconnectedness of the groundwater and surface water will determine to what extent this may occur.

FI-2.4.7 Environmental constraints and implications of future development

Although ecological water requirements have yet to be determined, it is expected that constraints on the consumptive use of the alluvial aquifer will be the need to maintain dry season river flows and permanent pools, which will limit allowable drawdown at the river bed (Lindsay and Commander, 2005).

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FI-3 Water balance results for the Fitzroy (WA) region

This chapter describes modelling results and the assessment of the water resources undertaken by this project for the Fitzroy (WA) region. Detailed, quantified assessments are made where possible, and relevant, and confidence is estimated. Modelling results are reported under climate and development scenarios as defined at the division level in Section 2.1 of Chapter 2. This chapter is sub-divided into:

- climate
- recharge estimation
- conceptual groundwater models
- groundwater modelling results
- rainfall-runoff modelling results
- river system water balance
- changes to flow regimes at environmental assets.

FI-3.1 Climate

FI-3.1.1 Historical climate

The Fitzroy (WA) region receives an average of 577 mm of rainfall over a September to August water year (Figure FI-16), most of which (534 mm) falls in the November to April wet season (Figure FI-17). Across the region there is a strong north–south gradient in annual rainfall (Figure FI-18), ranging from 963 mm in the north to 383 mm in the south. Over the first half of the historical (1930 to 2007) period, annual rainfall has been relatively constant at around 450 mm. The second half of the period has seen an increase in mean rainfall to approximately 650 mm. The highest yearly rainfall received was 1127 mm which fell in 2000, and the lowest was 249 mm in 1953.

Historical areal potential evapotranspiration (APET) is very high across the region, averaging 2023 mm over a water year (Figure FI-16), and varies moderately across the seasons (Figure FI-17). APET generally remains higher than rainfall throughout the year resulting in year-round water-limited conditions.

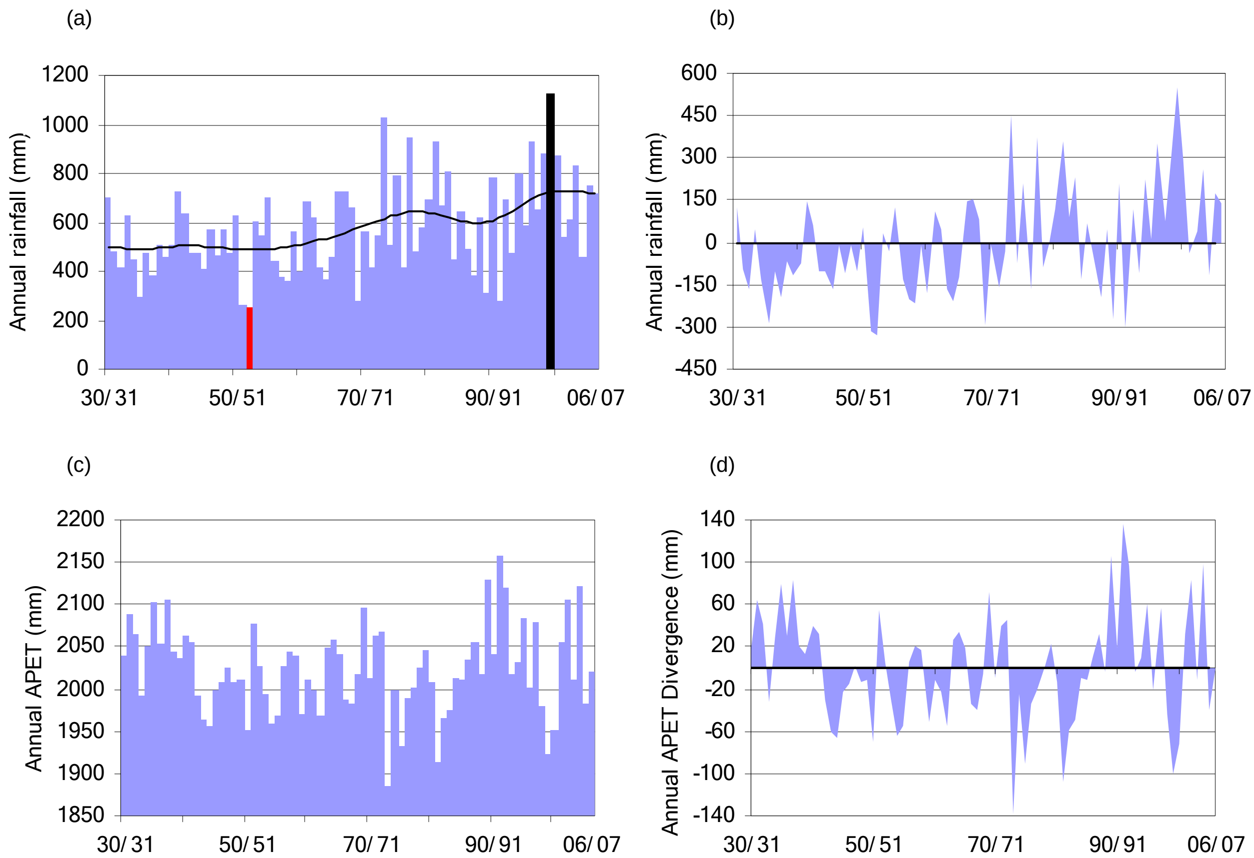


Figure FI-16. (a) Historical annual rainfall and (b) its divergence from the long-term mean; and (c) historical annual areal potential evapotranspiration and (d) its divergence from the long-term mean averaged over the Fitzroy (WA) region. The low-frequency smoothed line in (a) indicates longer term variability

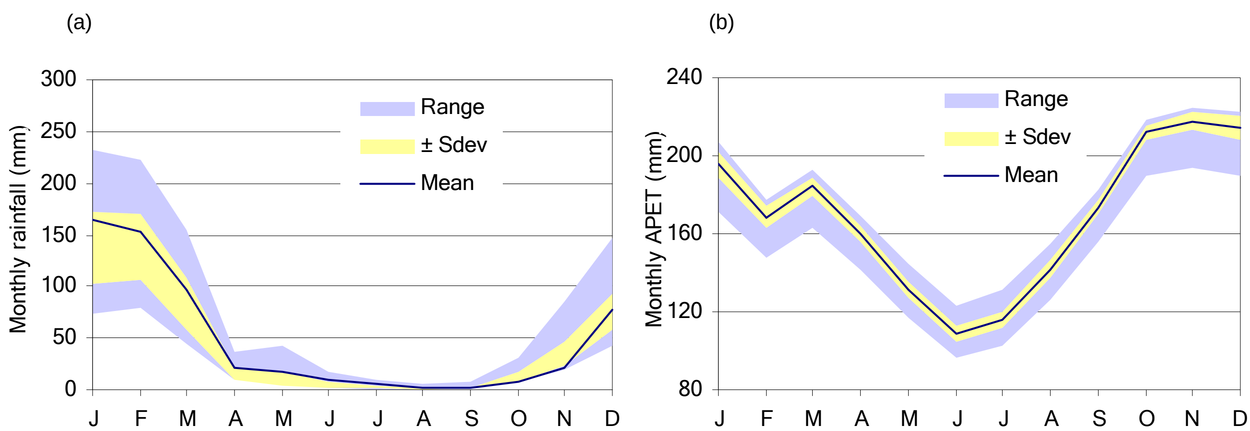


Figure FI-17. Historical mean monthly (a) rainfall and (b) areal potential evapotranspiration and their temporal variation (range and ± one standard deviation) averaged over the Fitzroy (WA) region

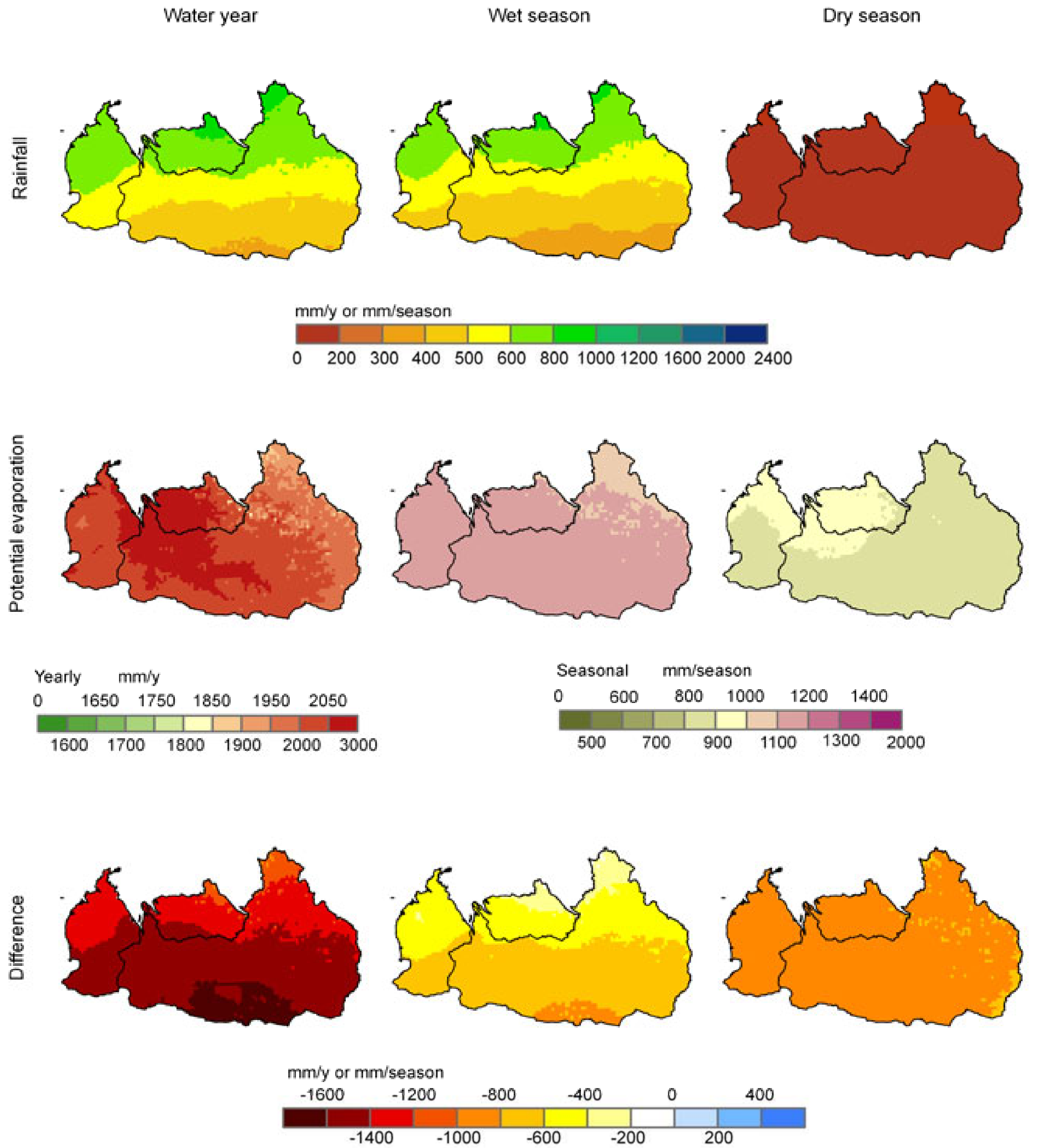


Figure FI-18. Spatial distribution of historical mean annual (water year), wet season and dry season rainfall and areal potential evapotranspiration (potential evaporation) and their difference (rainfall less areal potential evapotranspiration) across the Fitzroy (WA) region

FI-3.1.2 Recent climate

Figure FI-19 compares recent (1996 to 2007) to historical (in this case the 66-year period 1930 to 1996) mean annual rainfall for the Fitzroy (WA) region. Across the whole region, recent rainfall is between 10 and 60 percent higher than historical rainfall – a statistically significant difference for most of the region.

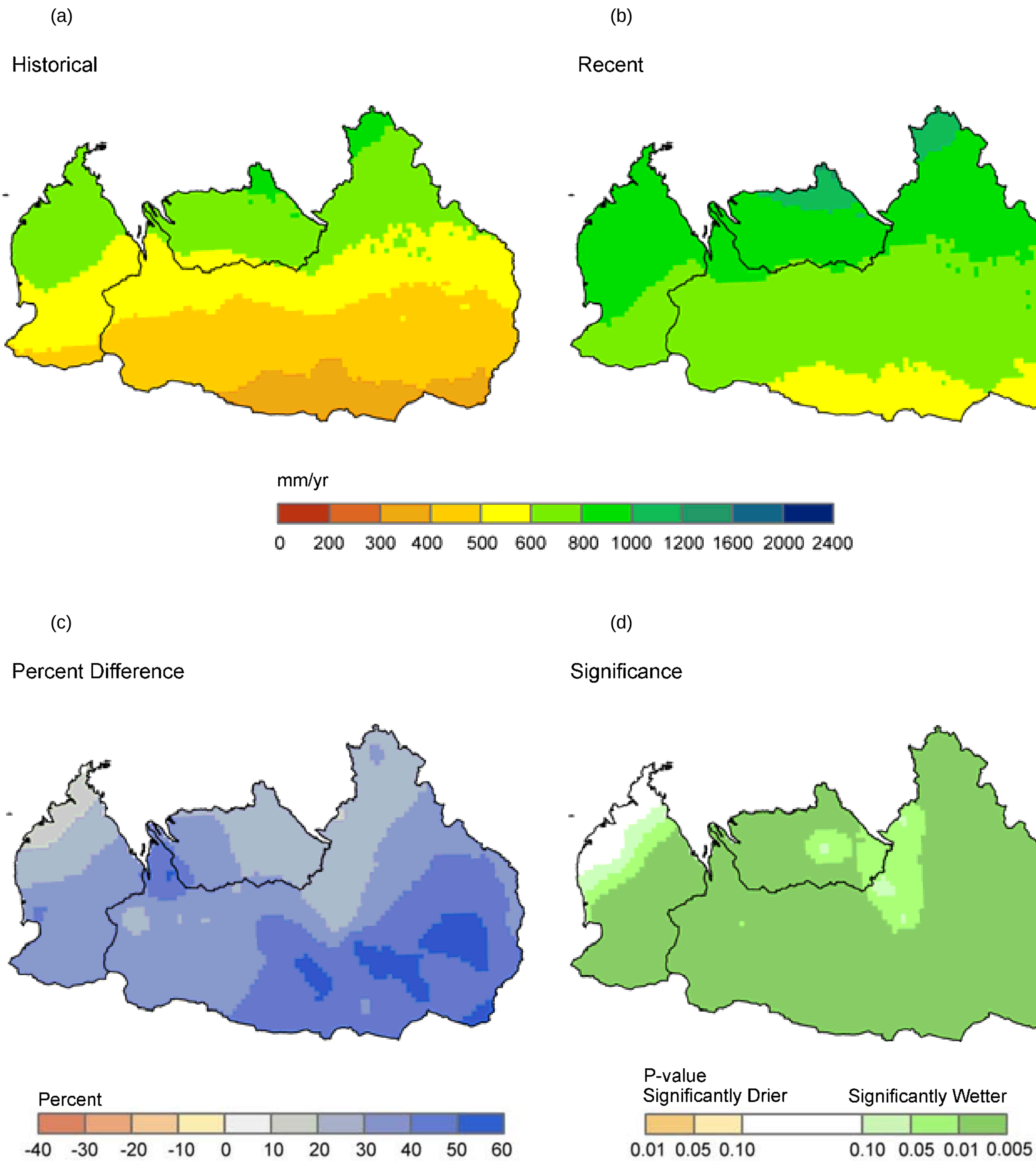


Figure FI-19. Spatial distribution of (a) historical and (b) recent mean annual rainfall; and (c) their relative percent difference and (d) the statistical significance of these differences across the Fitzroy (WA) region. (Note that historical in this case is the 66-year period 1930 to 1996)

FI-3.1.3 Future climate

Under Scenario C annual rainfall varies between 469 mm and 612 mm (Table FI-5) compared to the historical mean of 577 mm. Similarly, APET ranges between 2077 and 2109 mm compared to the historical mean of 2023 mm.

A total of 45 variants of Scenario C were modelled (15 global climate models (GCMs) for each of the high, medium and low global warming scenarios). Subsequently, results from an extreme 'wet', median and extreme 'dry' variant are shown (referred to as scenarios Cwet, Cmid and Cdry). Under Scenario Cwet annual rainfall and APET increase by 6 percent and 4 percent, respectively. Under Scenario Cmid annual rainfall increases by less than 1 percent and APET increases by 3 percent. Under Scenario Cdry annual rainfall decreases by 19 percent and APET increases by 4 percent.

Under Scenario Cmid long-term monthly averages of rainfall and APET do not differ much from historical values (Figure FI-20). The historical mean rainfall lies well within the range in values from all 45 future climate variants. The seasonality of rainfall and APET is not expected to change substantially. In the wet season rainfall is reasonably high under the historical climate and Scenario Cmid compared to the full range in values expected under Scenario C. The historical mean APET lies at the lower end of the range, as does the APET under Scenario Cmid.

The spatial distributions of rainfall and APET under Scenario C are compared to the historical distribution in Figure FI-21 and Figure FI-22. Under Scenario C the strong north–south gradient in rainfall is retained, but with a southwards shift under Scenario Cwet and a northwards shift under Scenario Cdry. Under scenarios Cmid and Cdry the rainfall gradient changes due to relatively greater decreases in rainfall occurring along the northern coastlines compared to the south of the region. The spatial distribution of APET under Scenario C is similar to the highly regionalised historical distribution. The greatest changes to APET occur in the south and east of the region.

Table FI-5. Mean annual (water year), wet season and dry season rainfall and areal potential evapotranspiration averaged over the Fitzroy (WA) region under historical climate and Scenario C

Scenario	Water year	Wet season	Dry season
	mm/y	mm/season	
Rainfall			
Historical	577	534	43
Cwet	612	562	42
Cmid	579	530	42
Cdry	469	423	39
Areal potential evapotranspiration			
Historical	2023	1140	883
Cwet	2095	1175	915
Cmid	2077	1167	906
Cdry	2109	1189	915

* Note that the sum of the wet season and dry season values does not always equal the water year values because the combined wet season and dry season period (November to October) is different to the water year period (September to August).

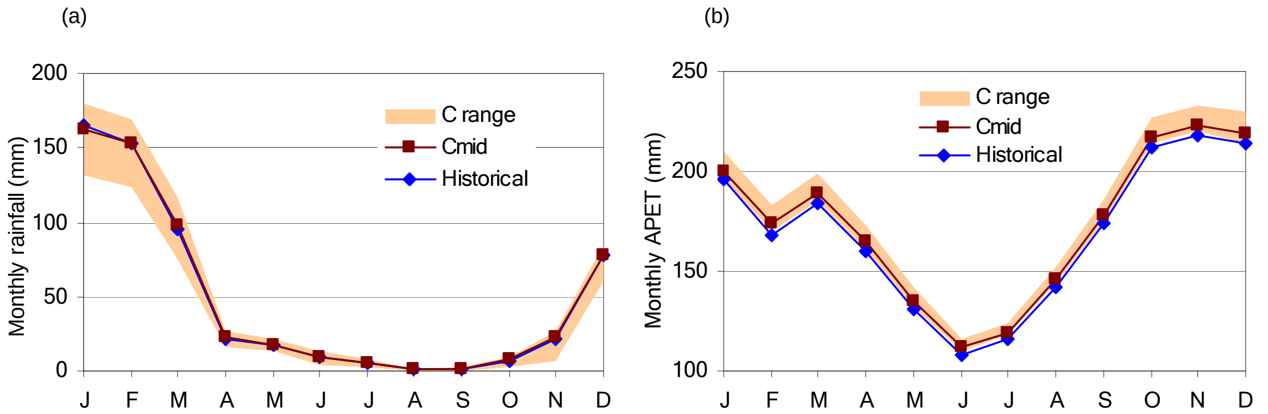


Figure FI-20. Mean monthly (a) rainfall and (b) areal potential evapotranspiration averaged over the Fitzroy (WA) region under historical climate and Scenario C. (C range is the range under the 45 Scenario C simulations – the lower and upper limits in C range are therefore not the same as scenarios Cdry and Cwet)

FI-3.1.4 Confidence levels

Analysis of confidence of the climate data are reported in Section 2.1.4 of the division-level Chapter 2.

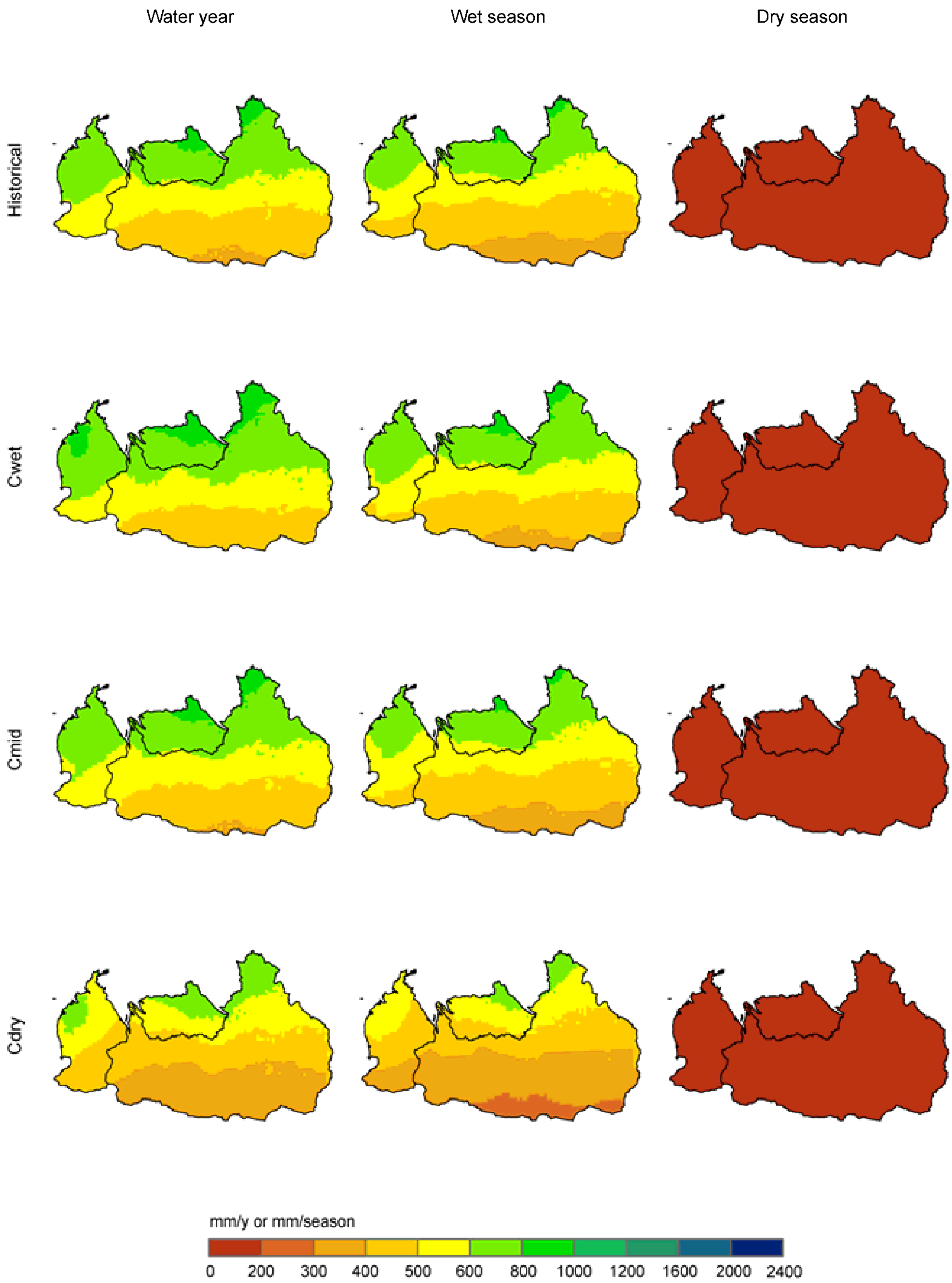


Figure FI-21. Spatial distribution of mean annual (water year), wet season and dry season rainfall across the Fitzroy (WA) region under historical climate and Scenario C

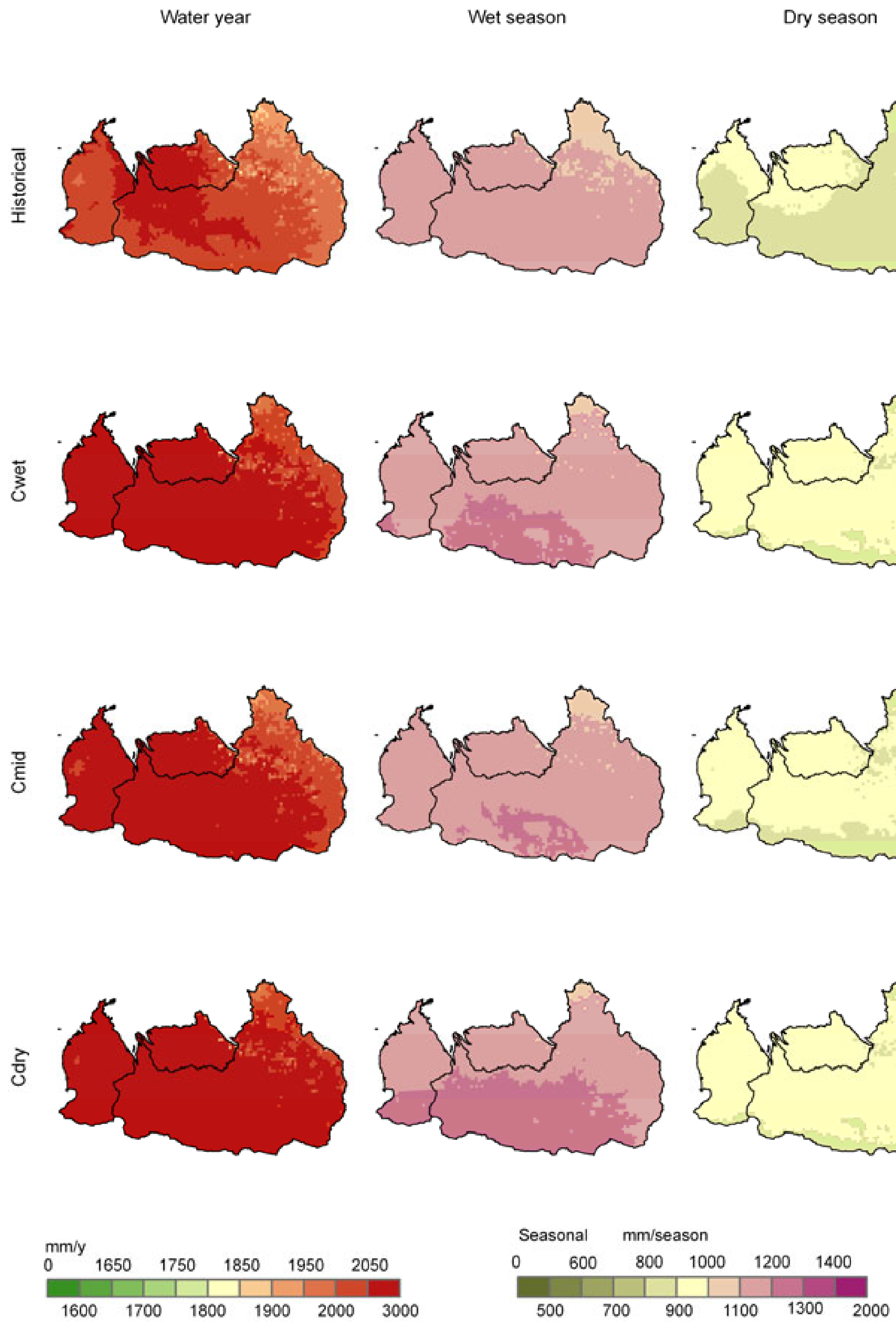


Figure FI-22. Spatial distribution of mean annual (water year), wet season and dry season areal potential evapotranspiration across the Fitzroy (WA) region under historical climate and Scenario C

FI-3.2 WAVES recharge estimations

The WAVES model (Zhang and Dawes, 1998) was used to estimate the change in groundwater recharge across the Fitzroy (WA) region under a range of different climate scenarios. WAVES is a vertical recharge flux model that can model plant physiological feedbacks in response to increased CO_2, as well as modelling the water balance of different soil, vegetation and climate regimes. This model was chosen for its balance in complexity between plant physiology and soil physics. This model was also chosen to assess recharge for the Murray-Darling Basin Sustainable Yields Project (Crosbie et al., 2008).

FI-3.2.1 Under historical climate

The historical recharge in the Fitzroy (WA) region is comparatively low when compared to the other regions of the project. Recharge is lowest on the vertosol soils that cover the floodplains of the major rivers, and highest in the north of the region where the rainfall is greater (Figure FI-23). The historical record was assessed to establish any difference between wet and dry periods of recharge. A 23-year period was used, which allows projections of recharge estimates to 2030 – in other words, to estimate recharge in 2030 assuming future climate is similar to historical climate (Scenario A).

For the three variants of Scenario A the recharge does change for the 23-year period when compared to the 77-year historical value (Table FI-6). For the recharge that is exceeded in 10 percent of 23-year periods (Awet), recharge is on average 11 percent greater than the 77-year historical average (i.e. a recharge scaling factor (RSF) averaged across the region of 1.11). For the recharge that is exceeded in 50 percent of 23-year periods (Amid), recharge is 2 percent lower (average RSF of 0.98) than the 77-year historical average. For the recharge that is exceeded in 90 percent of 23-year periods (Adry), recharge is on average 13 percent lower (average RSF of 0.87) than the 77-year historical average. Where unweathered bedrock outcrops occur, confidence in the modelled results is reduced. The locations of these outcrops in the Fitzroy (WA) region are shown on the historical recharge map in Figure FI-23.

Table FI-6. Recharge scaling factors in the Fitzroy (WA) region for scenarios A, B and C

Region	Awet	Amid	Adry	B	Cwet	Cmid	Cdry
Fitzroy (WA)	1.11	0.98	0.87	1.50	1.26	1.06	0.87

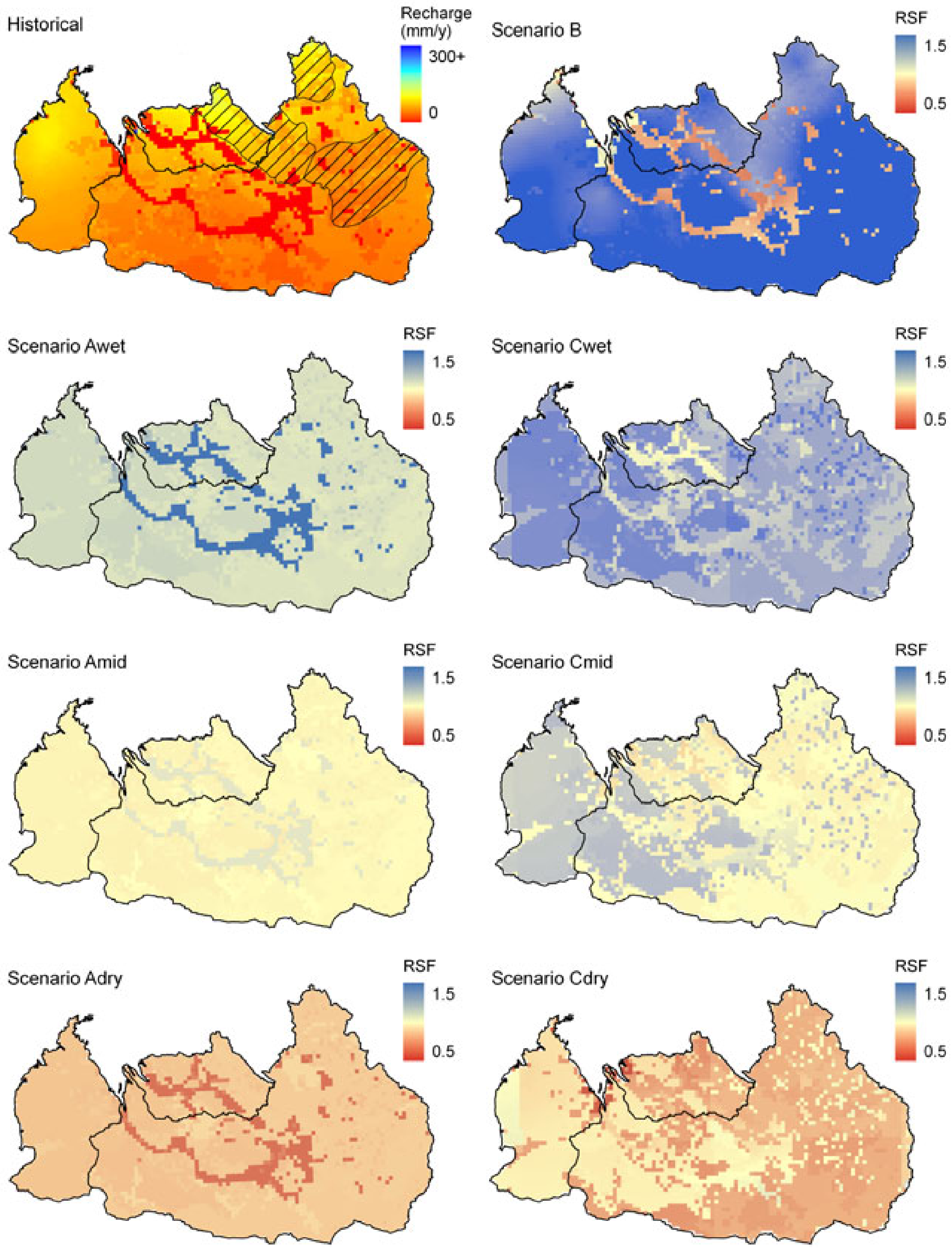


Figure FI-23. Spatial distribution of historical mean recharge rate; and recharge scaling factors in the Fitzroy (WA) region for scenarios A, B and C. The hatched region on the historical recharge map identifies where unweathered bedrock outcrops occur

FI-3.2.2 Under recent climate

The recent (1996 to 2007) climate in the Fitzroy (WA) region has been wetter than average and consequently the calculated recharge has seen an increase of 50 percent compared to the average of the historical (1930 to 2007) period (Figure FI-16). This increase has not been spatially uniform with the vertosol soils along the Fitzroy River floodplain showing a substantial decrease in recharge when expressed as a recharge scaling factor; however the magnitude of the recharge here is very small (Figure FI-23).

FI-3.2.3 Under future climate

Figure FI-24 shows the percentage change in modelled mean annual recharge averaged over the Fitzroy (WA) region under Scenario C relative to Scenario A for the 45 scenarios (15 GCMs for each of the high, medium and low global warming scenarios). The percentage change in the mean annual rainfall and recharge from the corresponding GCMs is also tabulated in Table FI-7. In some scenarios the recharge is projected to increase despite a decrease in rainfall. This is because total rainfall is not the only climate variable that has an influence over recharge. Daily rainfall intensity, temperature and CO_2 concentration are also important drivers (see Section 2.3.3 in the division-level Chapter 2), and specific situations can result in this counter-intuitive result. In particular, rainfall intensity is seen as a significant factor in this relationship.

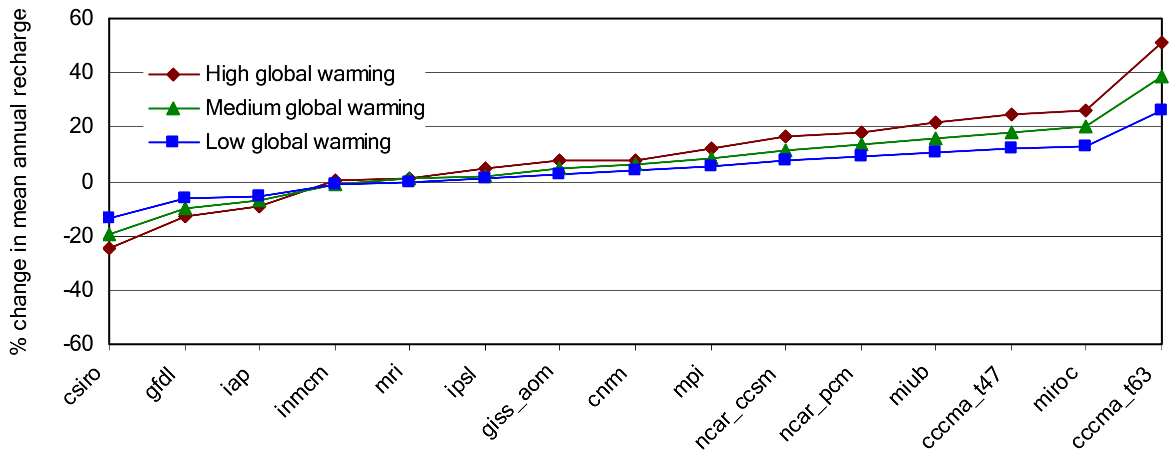


Figure FI-24. Percentage change in mean annual recharge under the 45 Scenario C simulations (15 global climate models and three global warming scenarios) relative to Scenario A recharge

Table FI-7. Summary results under the 45 Scenario C simulations (numbers show percentage change in mean annual rainfall and recharge under Scenario C relative to Scenario A)

High global warming			Medium global warming			Low global warming		
GCM	Rainfall	Recharge	GCM	Rainfall	Recharge	GCM	Rainfall	Recharge
csiro	-19%	-24%	csiro	-15%	-19%	csiro	-10%	-14%
gfdl	**-19%**	**-13%**	gfdl	-14%	-10%	gfdl	-10%	-6%
iap	-10%	-9%	iap	-8%	-7%	iap	-5%	-5%
inmcm	0%	0%	inmcm	0%	-1%	inmcm	0%	-1%
mri	-1%	1%	mri	-1%	1%	mri	0%	0%
ipsl	-2%	5%	ipsl	-2%	2%	ipsl	-1%	1%
giss_aom	2%	8%	giss_aom	1%	5%	giss_aom	1%	2%
cnrm	-2%	8%	**cnrm**	**-2%**	**6%**	cnrm	-1%	4%
mpi	0%	12%	mpi	0%	9%	mpi	0%	5%
ncar_ccsm	5%	16%	ncar_ccsm	4%	11%	ncar_ccsm	3%	7%
ncar_pcm	2%	18%	ncar_pcm	2%	13%	ncar_pcm	1%	9%
miub	1%	22%	miub	1%	16%	miub	1%	11%
cccma_t47	5%	25%	cccma_t47	4%	18%	cccma_t47	3%	12%
miroc	**6%**	**26%**	miroc	5%	20%	miroc	3%	13%
cccma_t63	10%	51%	cccma_t63	8%	39%	cccma_t63	5%	26%

Under Scenario Cwet the Fitzroy (WA) region is calculated to have a mean increase in recharge of 26 percent; the greatest increase is expected in the west of the region. Under Scenario Cmid the region is calculated to have, on average, an increase in recharge of 6 percent, with the greatest increase in the west of the region. Under Scenario Cdry the region is calculated to have, on average, a decrease in recharge of 13 percent with the greatest decrease in the east of the region (Figure FI-23).

FI-3.2.4 Confidence levels

The estimation of diffuse dryland recharge using WAVES, as done here, is only indicative of the actual recharge and has not been validated with field measurements. The WAVES modelling results will be most uncertain for areas where shallow or no soil cover exists, such as the fractured rocks outcropping in the north-east of the region. A steady state groundwater chloride mass balance approach was adopted as an independent measure of recharge (Crosbie et al., 2009). The results for the Fitzroy (WA) region show that the historical (1930 to 2007) estimate of recharge using WAVES (50 mm/year) is within the range of estimates made using the chloride mass balance (7 to 120 mm/year). However the WAVES estimate is higher than the best estimate obtained using the chloride mass balance (34 mm/year).

FI-3.3 Conceptual groundwater models

FI-3.3.1 Precambrian fractured rock aquifers

Fractured sandstone aquifers in the north-east of the region are thought to recharge locally by large rainfall events and discharge regionally via evapotranspiration and throughflow. Throughflow occurs both south-west towards the shallow Fitzroy and Meda River alluvial aquifers and towards deeper Canning Basin aquifers. Local shallow groundwater flow is likely to discharge to rivers towards the end of the wet season and early dry season while being recharged by elevated river elevations at the beginning of the wet. Rivers are not likely to receive prolonged groundwater discharge through the dry season in their upper reaches due to the nature of the aquifer, which has active fractures that are highly variable in distribution and hydraulic characteristics.

FI-3.3.2 Devonian limestone aquifer

Recharge to the Devonian limestone aquifer is thought to be dominated by rainfall entering solution features at the surface and potentially from throughflow from adjacent fractured rock aquifers. Regional discharge occurs towards the south-west, while local discharge is to the Fitzroy River. Parts of the aquifer are thought to be karstic in nature and provide groundwater discharge to the Fitzroy River throughout the dry season in most years.

FI-3.3.3 Canning Basin aquifers

The Canning Basin aquifers are recharged following extended periods of intense rainfall in the Great Sandy Desert, and most effectively where units sub-crop or outcrop. Both shallow and deep throughflow occur and any vertical leakage between units is dependent on the hydraulics of the particular part of the Basin. The aquifers generally discharge towards the centre of the Basin and to the north-west into the Indian Ocean. Local discharge occurs into the Fitzroy alluvial aquifer and possibly alluvium of other smaller rivers. Both horizontal and vertical gradients between the Canning Basin aquifers and rivers are likely to be reversed between seasons. Fresher groundwater salinities occur in this aquifer at shallow depths in the vicinity of the Fitzroy Alluvium and it is thought that the floodwaters that recharge the Fitzroy alluvial aquifers may continue to locally recharge the shallow areas of some Canning Basin aquifers. These processes are also shown in Figure FI-25.

FI-3.3.4 Fitzroy alluvial aquifer

In the wet season, the Fitzroy River levels rise and induce water flow to the Fitzroy alluvial aquifer through both the river bed and the alluvial sediments where they are incised by the river. The aquifer is recharged predominantly through this mechanism in addition to vertical recharge from both rainfall and floodwaters following overbank flows. Recharge from direct rainfall and flooding is thought to be negligible where low permeability black clay soils (vertosols) exist, however recharge is more significant where other Quaternary sediments exist at ground surface (approximately 50 percent of the Fitzroy alluvial plain is covered by the black clay soils). Enhanced recharge may also occur at the edge of the floodplain.

At the end of the wet season, most of the groundwater stored in the alluvial aquifer starts flowing back towards and into the river. As the groundwater levels in the alluvial aquifer fall, flow in the river slows until semi-permanent pools are established. Slower moving or stagnant pools eventually dry up when groundwater levels drop below the river bed due to discharge via evapotranspiration, throughflow and predominantly direct evaporation. A schematic representation of river–groundwater interactions during the dry and wet seasons are displayed in Figure FI-25.

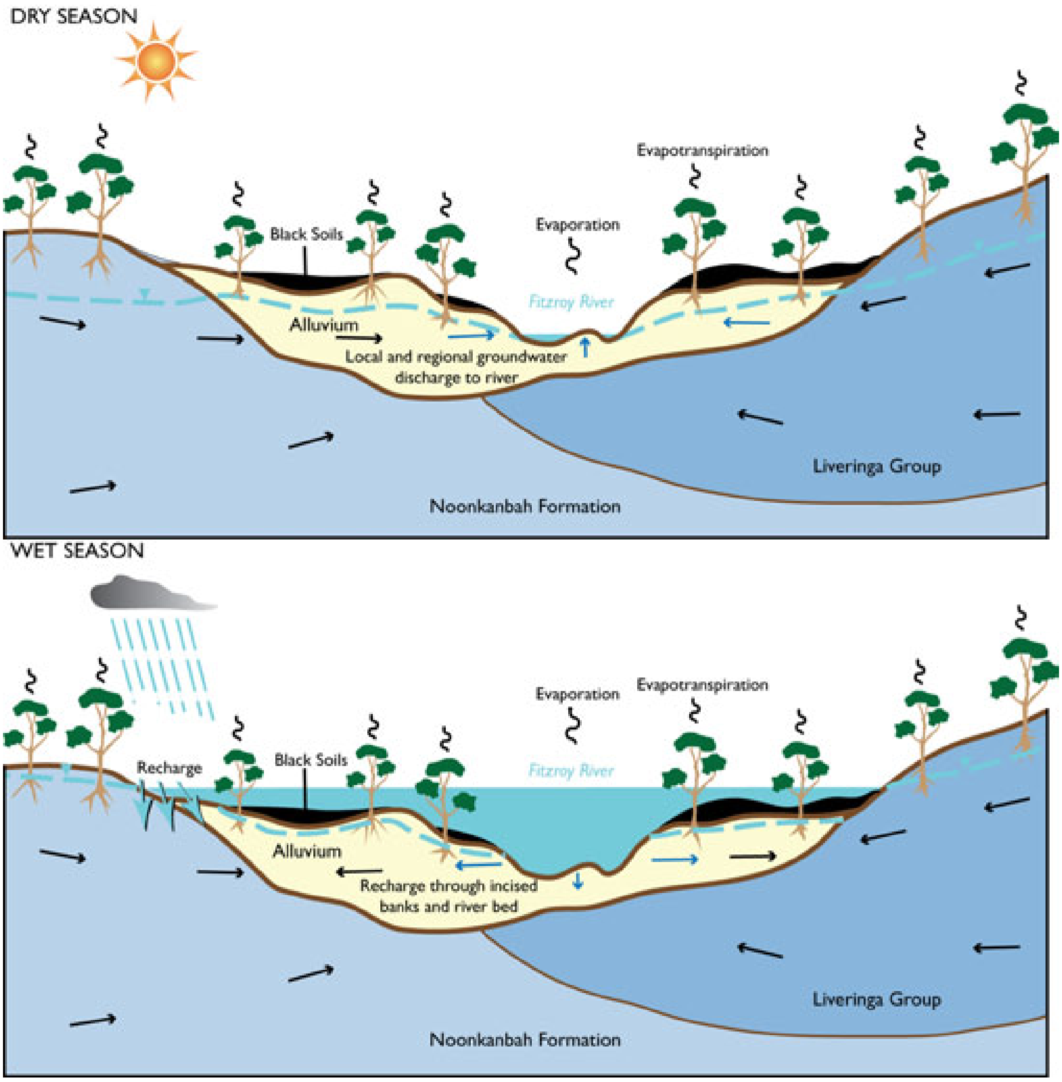


Figure FI-25. Schematic of the river–groundwater interactions of the Fitzroy River during the dry and wet seasons

FI-3.3.5 Baseflow index analysis

The results of the baseflow analysis for suitable gauges in the Fitzroy (WA) region are provided in Table FI-1. The annual BFI values range from 0.05 to 0.22 with a median of 0.14 (n=10). Average dry season baseflow volumes are shown schematically in Figure FI-2 with the highest flows recorded at the Fitzroy Crossing and Margaret River gauges. Because these gauges are situated downstream and adjacent to carbonate rock areas, respectively, the results indicate that higher volumes of dry season groundwater discharge are derived from carbonate rock aquifers than from fractured rock aquifers.

FI-3.4 Groundwater modelling results

FI-3.4.1 Historical groundwater balance

In order to determine the relative importance of the various hydrogeological processes in the Fitzroy (WA) region, a series of four preliminary groundwater balances were created. These estimate the key water balance components of the Fitzroy alluvial aquifer (both in the wet and dry seasons), the portion of the Canning Basin aquifers intersecting the region, and the fractured rock aquifers in the north-east of the region. A detailed breakdown of each input and output of the water balance for each aquifer is provided in Table FI-8 and Table FI-9, respectively. The total sum of all inputs and outputs is then summarised in Table FI-10. Technical details surrounding how these estimates were made are provided in Harrington et al. (2009).

Table FI-8. Groundwater inputs for the aquifers in the Fitzroy (WA) region

Inputs	Diffuse recharge		Valley edge recharge		River recharge		Regional aquifer discharge	
	mm*	GL*	mm*	GL*	mm*	GL*	mm*	GL*
Fitzroy alluvial aquifer								
Wet season	30	96	0.05	0.2	69	220	0.56	2
Dry season	0	0	0	0.0	0	0	0.63	2
	mm/y	GL/y	mm/y	GL/y	mm/y	GL/y	mm/y	GL/y
Fractured rock aquifers	30	1080	0.01	0.2	0.83	30	-	-
Canning Basin aquifers	20	1846	0.00	0.1	0.16	15	-	-

* Values are for the entire wet or dry season, i.e. mm/6 months, GL/6 months

Table FI-9. Groundwater outputs for the aquifers in the Fitzroy (WA) region

Outputs	Discharge to rivers		Evaporation		Evapotranspiration		Throughflow		Groundwater extraction	
	mm*	GL*	mm*	GL*	mm*	GL*	mm*	GL*	mm*	GL*
Fitzroy alluvial aquifer										
Wet season	-	-	-	-	20	64	0.05	0	-	-
Dry season	69	220	9	28	15	48	0.03	0	0.12	0.4
	mm/y	GL/y	mm/y	GL/y	mm/y	GL/y	mm/y	GL/y	mm/y	GL/y
Fractured rock aquifers	0.08	3	1	23	30	1080	0.51	18	0.02	0.6
Canning Basin aquifers	0.01	1	0	38	20	1846	0.08	7	0.21	19.7

* Values are for the entire wet or dry season, i.e. mm/6 months, GL/6 months

Table FI-10. Summary of groundwater inputs and outputs for the aquifers in the Fitzroy (WA) region

	Inputs	Outputs	Difference
	mm/6 months		percent
Fitzroy alluvial aquifer (wet season)	99	20	-
Fitzroy alluvial aquifer (dry season)	1	93	-
	mm/y		
Fitzroy alluvial aquifer	100	113	6.0%
Fractured rock aquifers	31	31	0.6%
Canning Basin aquifers	20	21	1.3%

These tables show that the dominant inputs and outputs in the Fitzroy (WA) region are:

- for the Fitzroy alluvium – river recharge (in) and discharge to rivers (out)
- for the fractured rock aquifers – direct recharge (in) and evapotranspiration (out)
- for the Canning Basin aquifers – direct recharge (in) and evapotranspiration (out).

Note this assessment is a Tier 4 water balance, based on very limited datasets and no field testing. Accordingly, the results should only be used for conceptualisation of the groundwater systems, and not for water allocation planning.

FI-3.4.2 Groundwater model development

The conceptual model of Lindsay and Commander (2005) which Varma used in the same report for limited MODFLOW modelling was adopted for the project. The alluvial aquifer consists of a surface layer of silt and clay approximately 10 m thick overlying and confining a sand and gravel layer 20 to 40 m thick. The river has cut entirely through the upper layer and has good hydraulic connection with the lower layer. There are essentially five natural fluxes that impact the water balance of the Fitzroy alluvium:

- direct rainfall infiltration to the upper layer
- direct evaporation from the upper layer
- transfer between the upper and lower layers
- transfer between the river bed and the lower layer
- transfer between the lower layer and bedrock.

The upper layer covering the Fitzroy River floodplain consists of black cracking clay soils. A similar type of soil occurs in Queensland and the important features are described for agricultural purposes by (DPI, 2006). 'These soils occur in river and creek flats with coolibah or blue gum woodland, usually they have high clay content and high water holding capacity. The black clays swell as they wet, and shrink and crack as they dry. Initial infiltration rates with open cracks and dry soil is greater than 0.5 m/day but this rate decreases by 1 to 2 orders of magnitude as the soil wets up and the cracks close. Evaporation losses from an open cracked soil are negligible.' WAVES modelling by (Crosbie et al., 2009) for this type of soil (vertosol profile) yielded estimates of recharge to groundwater of less than 0.2 mm/year. Assuming this is the case across the entire alluvial aquifer, the first two components of rainfall and evaporative losses from the upper layer were removed from the conceptual model for the purposes of groundwater modelling. Some transfers may still occur between the upper and lower layers as storage changes.

A new model of the Fitzroy River alluvium was created using the MODFLOW-2000 groundwater model (Harbaugh et al., 2000). The physical size of the alluvium that winds over an area 220 by 120 km was simplified by straightening the perennial stream length of 275 km from Fitzroy Crossing to the mouth, with a maximum width of 25 km at Fitzroy Crossing and varying along the length according to the mapped extent of the 3200 km^2 floodplain. The simplification of a straight aquifer will not greatly influence the results of the model as longitudinal head gradients are a factor of 10 to 100 less than the vertical and horizontal gradients surrounding the stream channel. It did however greatly simplify inputs to the model, reduce the size of spatial arrays, and reflect accurately our level of understanding of the system.

FI-3.4.3 Under historical climate

The new groundwater model of the Fitzroy River alluvium is driven primarily by flows in the river, and not widespread diffuse recharge. Without long-term historical gauged or modelled river flows the model could not be run for selected periods of the 77-year historical climate.

FI-3.4.4 Under recent climate

The model was run for ten years at a monthly step with actual stage and rainfall data from January 1999 to December 2006, with mean monthly values used for one year before as a warm up and one year after to complete the water year.

There was comparatively little modelled river leakage to the lower layer using mean monthly stage, so river stage was modified to be flow–weighted by first determining the average monthly flow at Willare and then using the corresponding stage height. This change increased the river leakage. The river stage was further modified to account for height differences at the three gauging stations with overlapping flow records by interpolation between stations, and while this reduced total river leakage it is more representative of flows and travel times along the whole river.

The average MODFLOW simulated water balance terms for the entire aquifer system over 9 water years are summarised in Table FI-11.

Table FI-11. Mean annual water balance components for the Fitzroy (WA) region derived from the MODFLOW model for water years 1998/99 to 2006/07

Component	Volume	Alluvial area equivalent	Catchment area equivalent
	ML/y	mm/y	
Transfer from river to gravel aquifer	292,858	91	3.11
Canning Basin flow to gravel aquifer	10,950	3.4	0.1
Transfer from gravel aquifer to river	308,011	95.7	3.28
Average streamflow at Willare 1999/00–2005/06*	9,522,500		101.3
Alluvial aquifer storage (est. 20 m thickness)*	13,000,000		138.3

FI-3.4.5 Under future climate and development

The future climate and land use scenarios in the Fitzroy (WA) region will to a large extent not affect the alluvial aquifer as the recharge components are determined from river flow rather than diffuse recharge. If river flows decreased to the point where the gravel aquifer no longer returns enough flow during the dry season to maintain flow and large pools this would be significant. The major relevant future change is increased pumping from the alluvial aquifer. For all the complexity of the real system, gross simplifications made in MODFLOW and general lack of knowledge of the system, means the use of analytical models to examine the response of the system to pumping is warranted.

A simple method for estimating the degree of watertable drawdown that might occur in the Fitzroy alluvium as a result of future pumping is the analytic solution of (Theis, 1935). The Theis equation provides estimated drawdown curves over time at nominated pumping rates as well as estimates of the radius of influence.

Future groundwater pumping at a rate of, for example, 6000 ML/year is directly relevant to the alluvial aquifer and can be modelled with these analytical solutions. Assuming extraction is spread evenly across the year (i.e., a best case scenario) this 6000 ML/year equates to 16.5 ML/day and, with maximum estimated pumping rates from the alluvium of 0.4 ML/day (Laws, 1990), this would require a minimum of 41 individual bores pumping continuously. For the following examples the alluvial aquifer is the same as that modelled by Varma (in (Lindsay and Commander, 2005) with transmissivity of 300 m^2/day and storativity 0.20.

Modelling results indicate that groundwater pumping from this aquifer at 0.4 ML/day continuously for 6 months would start producing interference between wells that are spaced 2 km apart, i.e. each well will independently create drawdown 1 km away (Dawes, 2009). The results also showed that the distance from a well to where drawdown is less than 10 cm reaches 500 m in just over 5 months, and over 750 m after one year.

FI-3.4.6 Surface–groundwater interaction

The existing groundwater allocations in the Fitzroy (WA) region amount to about 20.63 GL/year, which is small compared to the annual volume of surface water flow. Almost 56.7 percent of the existing groundwater allocations are sourced from the Canning-Grant aquifer, 19.7 percent is sourced from the Canning limestone aquifer, and 14.7 percent is sourced from the Canning Broome aquifer with the remaining 8.9 percent distributed across the other aquifers in the region.

In this section, the impact of groundwater extractions on surface water yields is considered; the 'impact' is to stream depletion whereby pumped groundwater eventually is sourced from a nearby river. The locations of existing groundwater licences and their proximity to the river network are shown in Figure FI-15 in Section 2.4.1. The distance between a groundwater pump and a nearby river greatly affects the time before river water is drawn into the aquifer towards the pump.

Fitzroy alluvium

About 0.39 GL/year of the total existing allocations are for bores tapping the Fitzroy alluvium. The current impact of extracting this volume of groundwater from the Fitzroy alluvium on streamflow is about 0.17 GL/year, with a predicted impact of 0.3 GL/year occurring by 2030. The influence of current groundwater development in the Fitzroy alluvium on the Fitzroy River flows is therefore marginal.

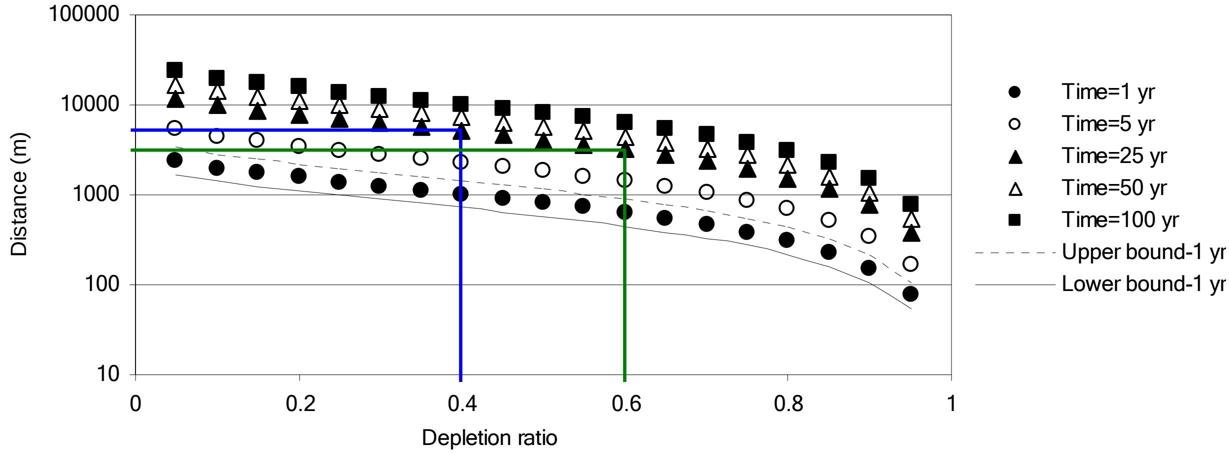


Figure FI-26. Impact of hypothetical scenarios in the Fitzroy alluvium on stream depletion

However, there is potential for growth in groundwater development within the Fitzroy alluvium. Figure FI-26 shows results of stream depletion calculations for hypothetical scenarios in the Fitzroy alluvium to provide some insight into the potential future impacts of further groundwater development. Figure FI-26 can be used as a management tool in two different ways:

- locating bores to minimise stream depletion. For example, if a proponent wanted to pump groundwater at 0.010 GL/day and was not allowed to deplete the river by more than 0.004 GL/day (i.e. depletion ratio = 0.4) on any occasion during the next 25 years, the pumping bores would need to be located no closer than 5 km from the river (see blue lines in Figure FI-26).
- determining maximum groundwater pumping rates at specified distances from the stream. For example, if a proponent wanted to pump groundwater from a bore located 3 km from a river and was not permitted to deplete the river by more than 0.004 GL/day on any occasion during the next 25 years, the corresponding depletion ratio would be 0.6 (see green lines in Figure FI-26) and the maximum pumping rate is 0.004/0.6 = 0.007 GL/day.

There is a great uncertainty in estimating representative aquifer parameters for this analysis (T=400 m^2/day and S=0.2). One can define upper and lower limits for this uncertainty and hence estimate corresponding upper and lower bounds for impacts. The example shown in Figure FI-26 represents the likely impacts (after 1 year) for a 100 percent uncertainty in aquifer transmissivity.

Given the ephemeral nature of the Fitzroy River, one future management option could be to limit groundwater pumping activities during the dry season. However, the impacts of groundwater extraction on nearby rivers have time lags and hence turning off a pump at the beginning of the dry season does not instantaneously stop stream depletion (or even alleviate its effects during the same season). A modelling exercise was conducted to demonstrate this phenomenon for a hypothetical bore located about 2 km from the Fitzroy River with an allocation of 0.25 GL/year. For the cyclic pumping scenario, pumping was assumed to operate only for six months every year (i.e., only during the wet season). Figure FI-27 shows a comparison between the impacts of continuous and cyclic (half-yearly) pumping. These results suggest that the impacts of cyclic pumping reach a state of dynamic equilibrium after about 10-15 years. The impacts are of course lower than those during continuous pumping, in fact they are only half because pumping is only active half of the time. Thus the time lags that delay the adverse impacts of pumping also delay the favourable impacts of cessation of pumping.

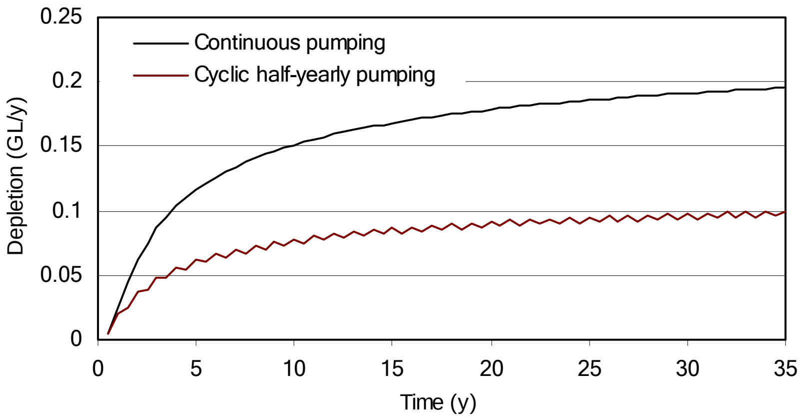


Figure FI-27. Impacts of continuous and cyclic (half-yearly) pumping on stream depletion

The development of management rules to control groundwater development in order to minimise the adverse effects on nearby ephemeral rivers should be informed by detailed groundwater modelling coupled with surface water modelling such that the mass balances of both systems are accounted for simultaneously. In groundwater models (such as MODFLOW), the boundary that represents a river (which is an infinite source of water to the model domain) should be removed when the river ceases to flow. It is important to recognise that such a modelling exercise is not straightforward as hypothetical pumping scenarios would in turn change the dynamics of river perenniality (which in turn affects the presence of a river boundary).

Canning Basin and fractured rock aquifers

The combined volume of existing groundwater allocations from the fractured rock aquifers and the Canning Basin amount to about 20.24 GL/year. Using the distances of the nearest rivers from these existing groundwater developments, the impact of groundwater pumping (at rates equivalent to the full allocation) on surface flow in each river were estimated. The results of this exercise are shown in Table FI-12 and are based on several assumptions about the type of interaction between these (often confined) aquifers and the nearby rivers.

A comparative analysis of short-term (up to 10 years) and long-term (up to 100 years) impacts on stream depletion show that the long-term impact usually corresponds to the allocation size because the full impacts are likely to be realised at large times, however for short-term impacts the distance to the stream is more important and so the impact does not correspond as well to the allocation. For example, note the first four rows in Table FI-11 where the allocation rank and the level of long-term impact are identical. However, the Deep Creek, Fitzroy River, and Fraser Creek violate this rule (rows 5-7 in Table FI-11). This is merely because those allocations are located at very large distances from the river (range from 30 to 70 km), which makes their impacts insignificant over the time frame under investigation. The short-term impact, on the other hand, follows a different trend. Note that the highest short-term impact is realised at Mount Wynne Creek where a sizable allocation of 4.38 GL/year is located at an average distance of about 5 km.

Any new groundwater developments in the alluvial aquifers should be located as far as possible from rivers to minimise the short term (seasonal) impact, which can potentially reduce flow during the dry season. By locating developments away from the river, the impacts on streamflow are delayed but the aquifer is depleted (rather than the river). This situation may be acceptable because the aquifer can be recharged during the wet seasons.

Table FI-12. Modelled impact of groundwater development of fractured rock and Canning Basin aquifers on stream depletion in the Fitzroy (WA) region

River	Allocation	Level of short term impact#	Level of long term impact#
	GL/y		
McSherry Creek*	7.28	6	1
Mount Wynne Creek*	4.38	1	2
Mount Pierre Creek	4.00	7	3
Yeeda River*	0.64	3	4
Deep Creek*	0.59	18	16
Fitzroy River*	0.29	19	15
Fraser River*	0.24	20	19
Margaret River	0.13	2	5
Mount Hardman Creek*	0.08	8	6
Six mile Creek*	0.06	10	7
Fraser River South*	0.06	17	12
Cherrabun Creek	0.03	14	10
May River*	0.02	5	8
Little Fitzroy River	0.02	4	9
Adcock River	0.01	9	11
Hann River	0.01	13	14
Cunningham River	0.01	11	13
Lennard River	0.005	16	18
Geegully Creek	0.003	12	17
Hann/Barnett Rivers	0.001	15	20

* Have multiple licences

\# 1 = highest impact, 20 = lowest impact

FI-3.4.7 Confidence levels

Confidence in the output of the groundwater models used in this project is linked to the amount of data available for parameterisation and calibration. Reducing the numerical modelling to essentially three water balance terms is a reflection of the fact that groundwater fluxes are inferred from a limited number of above ground observations. Using an analytical Theis solution to simulate potential future development is an indication of the small size of the future pumping changes compared with current water balance terms, and the desire not to overstate the usefulness or accuracy of the numerical model. Any future field work that includes pump tests and monitoring of groundwater levels in the alluvium would inform the analytical results, which would inturn refine the numerical groundwater model. Future work that determined mixing of stream and alluvial derived water would place limits on the surface–groundwater interaction and allow calibration of the numerical model.

FI-3.5 Rainfall-runoff modelling results

In this section the term runoff is the sum of overland flow, interflow and baseflow. It is equivalent to streamflow expressed as a mm depth equivalent. All plots show data averaged over the modelled subcatchments of the Fitzroy (WA) region. For this reason rainfall reported in this section may vary slightly from that reported elsewhere due to differences between the catchment boundaries (shown in Figure FI-1) and the DEM-derived catchment boundaries used here. In this section, where annual data are reported years are represented by numbers 1 through 77. Consistently throughout this report, annual data are based on the water year (1 September to 31 August) and the dry season is defined as 1 May to 31 October. Unless stated otherwise scenarios Cwet, Cmid and Cdry are selected on the basis of the ranked mean annual runoff. For more details on methods refer to Section 2.2 of the division-level Chapter 2.

FI-3.5.1 Regional synopsis

The rainfall-runoff modelling estimates runoff in 0.05 degree grid cells in 25 subcatchments (Figure FI-28). Optimised parameter values from eight calibration catchments are used. Seven of these calibration catchments are in the Fitzroy (WA) region, and one is in the Ord-Bonaparte region. The latter calibration catchment is used to model runoff from the coastal areas of the Fitzroy (WA) region and the Dampier Peninsula. The majority of the calibration catchments are located in headwater areas of the Fitzroy (WA) region (Figure FI-28). Gauging stations are, however, located in the lower reaches of the Fitzroy (WA) catchment at Fitzroy Crossing (802055) and Looma (802007). The station at Looma has recently had a rating curve generated based on LIDAR data and hydraulic modelling methods. Stations 802055 and 802007 were calibrated to the residual flow as described in Section 2.2.2 in the division-level Chapter 2. A small discrepancy between the AWRC river basin boundary layer and the DEM-derived catchment boundaries is evident along the southern boundary of the Fitzroy (WA) region (Figure FI-28).

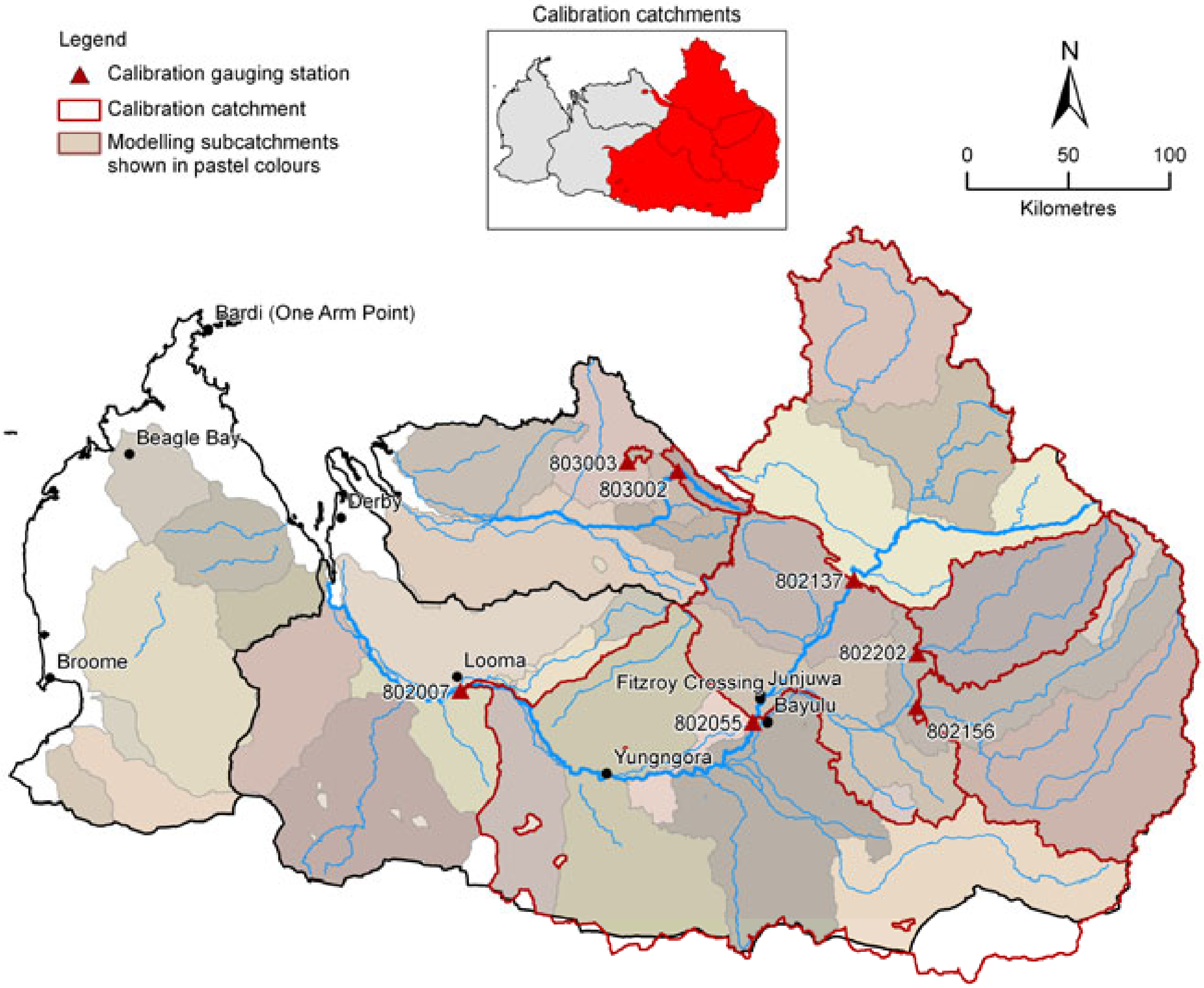


Figure FI-28 Map of the modelling subcatchments, calibration catchments and calibration gauging stations used for the Fitzroy (WA) region with inset highlighting (in red) the extent of the calibration catchments

FI-3.5.2 Model calibration

Figure FI-29 compares the modelled and observed monthly runoff and the modelled and observed daily flow exceedance curves for the eight calibration catchments. Nash-Sutcliffe efficiency (NSE) values provide a quantitative measure of how well simulated values match observed values. NSE values are described in more detail in Section 2.2.3 of the division-level Chapter 2. On the monthly plots, NSE is the monthly Nash-Sutcliffe efficiency value and NSE (dry season) is the dry season monthly Nash-Sutcliffe efficiency value. On the daily flow exceedance plots, NSE is the daily flow exceedance curve Nash-Sutcliffe efficiency value and NSE (50 to 100 percent) is the lower half of the daily flow exeedance curve Nash-Sutcliffe efficiency value.

The results indicate that the ensemble calibration of the rainfall-runoff models Sacramento and IhacresClassic can reasonably reproduce the observed monthly runoff series (NSE values generally greater than 0.8) and the daily flow exceedance characteristic (NSE values generally greater than 0.9). The volumetric constraint used in the model calibration also ensures that the total modelled runoff is within 5 percent of the total observed runoff.

The calibration method places more importance on the simulation of high runoff, and therefore rainfall-runoff modelling of the medium and high runoff is considerably better than the modelling of low runoff. It should be noted, however, that while the relative difference between the observed and simulated low flow values may be large (which is what gives rise to the low monthly dry season NSE values for example), the absolute difference between the observed and simulated low flow values is generally small because both values are small. Nevertheless, an optimisation to reduce overall error variance can result in some underestimation of high runoff and overestimation of low runoff. This is evident in some of the scatter plots comparing the modelled and observed monthly runoff and many of the daily flow exceedance curves. In the majority of the calibration catchments the disagreement between the modelled and observed daily runoff characteristics is discernable for runoff that is exceeded less than 1 percent of the time, This is accentuated in the plots because of the linear scale on the y-axis and normal probability scale on the x-axis. In any case, the volumetric constraint used in the model calibration ensures that the total modelled runoff is always within 5 percent of the total observed runoff. As indicated by the relatively low NSE values for the lower half of the daily flow exceedance curve and monthly dry season there may be considerable disagreement between observed and modelled low flow values (i.e. cease-to-flow). Overall the monthly NSE values are considered sufficient for the general purposes of estimating long-term mean annual runoff.

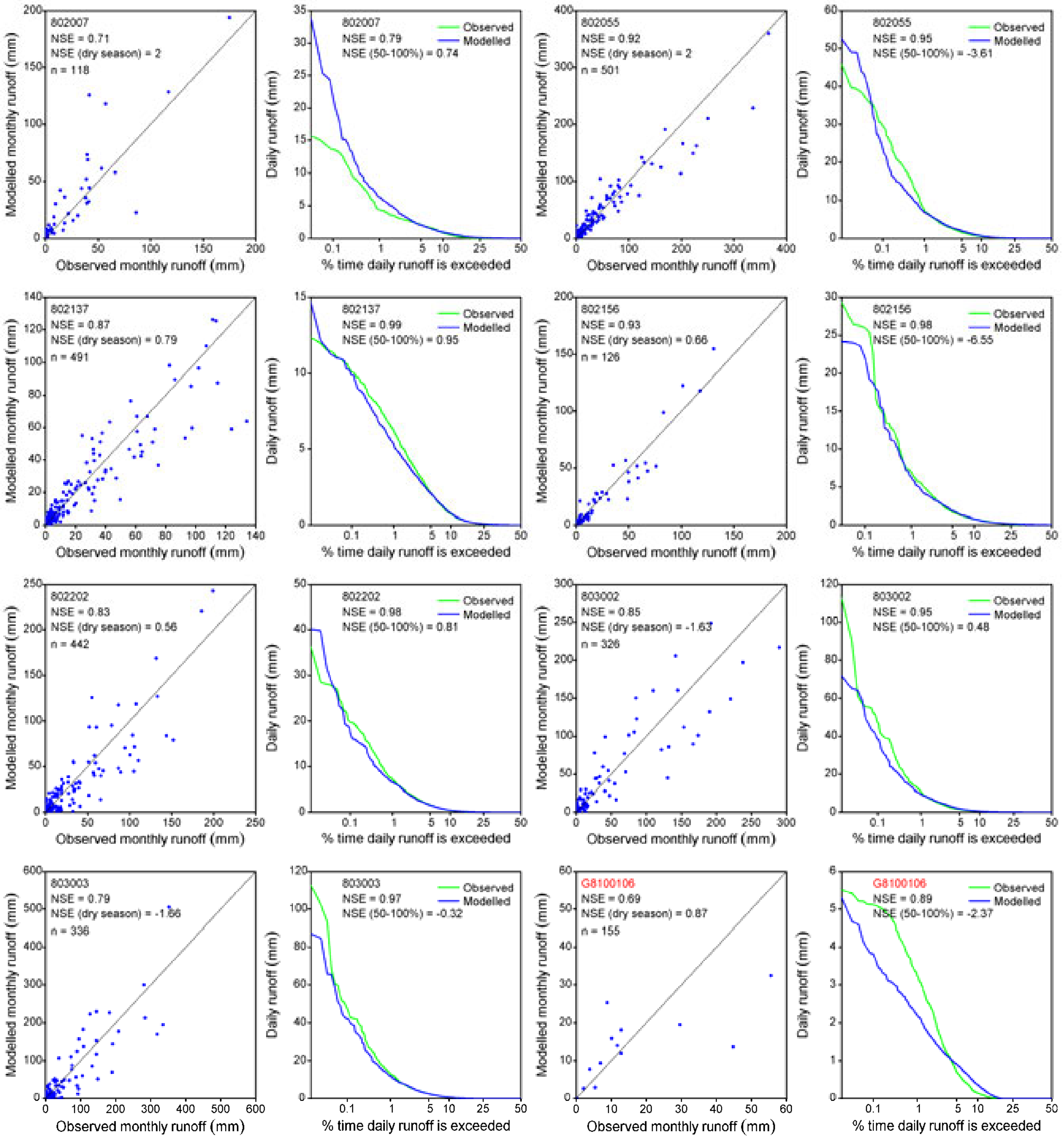


Figure FI-29. Modelled and observed monthly runoff and daily flow exceedance curve for each calibration catchment in the Fitzroy (WA) region (Red text denotes catchments outside the region; blue text denotes catchments used for streamflow modelling only)

FI-3.5.3 Under historical climate

Figure FI-30 shows the spatial distribution of mean annual rainfall and runoff under Scenario A (averaged over 1930 to 2007) across the Fitzroy (WA) region. Figure FI-31 shows the mean annual rainfall and runoff averaged over the region.

The mean annual rainfall and runoff averaged over the Fitzroy (WA) region are 578 mm and 76 mm respectively. The mean wet season and dry season runoff averaged over the Fitzroy (WA) region are 74 mm and 2 mm respectively.

In this project, all runoff grids are presented as long-term mean annual values. However, the distribution of monthly and annual runoff data in northern Australia can be highly skewed; consequently the median and additional percentile values spatially averaged over the region are also reported. The 10th, median and 90th percentile annual runoff values across the Fitzroy (WA) region are 190, 49 and 11 mm respectively. The median wet season and dry season runoff averaged over the Fitzroy (WA) region are 45 mm and 1 mm respectively.

The mean annual rainfall varies from about 800 mm in the north to less than 400 mm in the south. The mean annual runoff varies from over 300 mm in the northern parts of the Lennard catchment to less than 40 mm in the south of the Fitzroy catchment (Figure FI-30). The blank spaces in the runoff grid are sinks that were deliberately left in the DEM (Section 2.2). Although no gauging stations exist on the Dampier Peninsula, anecdotally runoff is very low. In this study the Dampier Peninsula was modelled using parameter set from calibration catchment G8100106, which gave a range of runoff values for the Dampier Peninsula between 15 and 80 mm (i.e. about 5 percent of rainfall). Discounting the Dampier Peninsula, runoff coefficients vary across Fitzroy (WA) region from 8 percent to 28 percent of rainfall. The majority of rainfall and runoff occurs during the wet season months December to April (Figure FI-31). Rainfall and runoff can vary considerably from year to year with long periods over several years or decades that are considerably wetter or drier than others (Figure FI-31). The coefficients of variation of annual rainfall and runoff averaged over the Fitzroy (WA) region are 0.33 and 0.93 respectively.

The Fitzroy (WA) is one of 13 regions which cover the three divisions studied in this project. Mean annual rainfall and runoff, as well as coefficients of variation, have been calculated for all of these 13 regions, and it is useful to compare the Fitzroy (WA) results to results across all 13 regions. Across all 13 regions in this project 10th percentile, median and 90th percentile values are 1371, 936 and 595 mm respectively for mean annual rainfall and 374, 153 and 78 mm respectively for mean annual runoff. The mean annual rainfall (578 mm) and runoff (76 mm) averaged over the Fitzroy (WA) region fall in the lower end of this range. Across all 13 regions in this project the 10th percentile, median and 90th percentile values are 0.34, 0.26 and 0.19 respectively for the coefficient of variation of annual rainfall and 1.39, 0.69 and 0.48 for the coefficient of variation of runoff. The coefficients of variation of annual rainfall (0.33) and runoff (0.93) averaged over the Fitzroy (WA) region are among the highest of the 13 reporting regions.

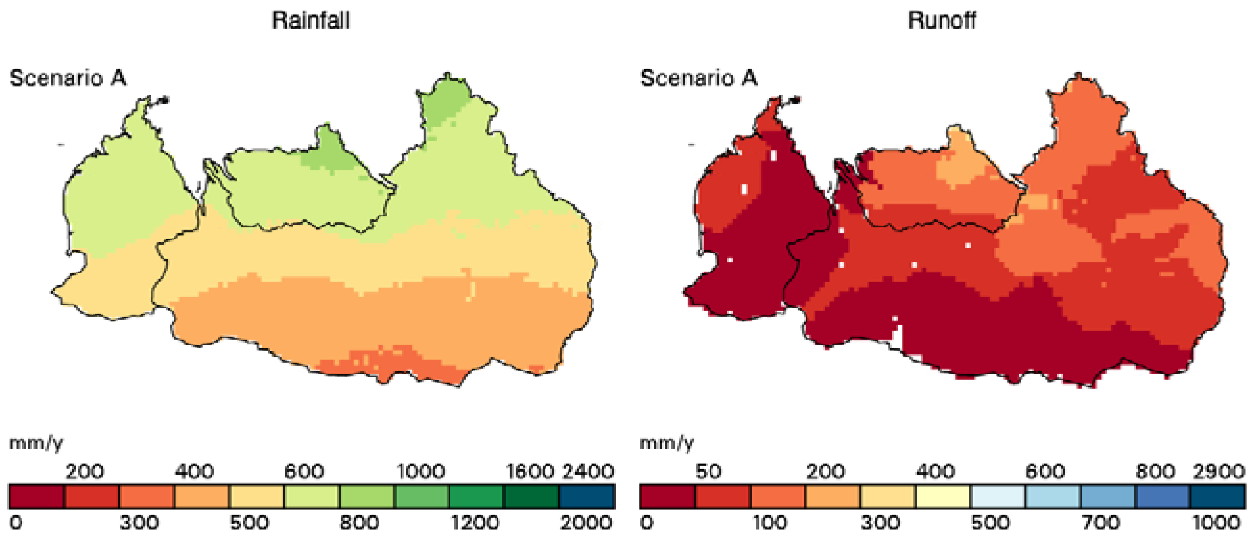


Figure FI-30. Spatial distribution of mean annual rainfall and modelled runoff across the Fitzroy (WA) region under Scenario A

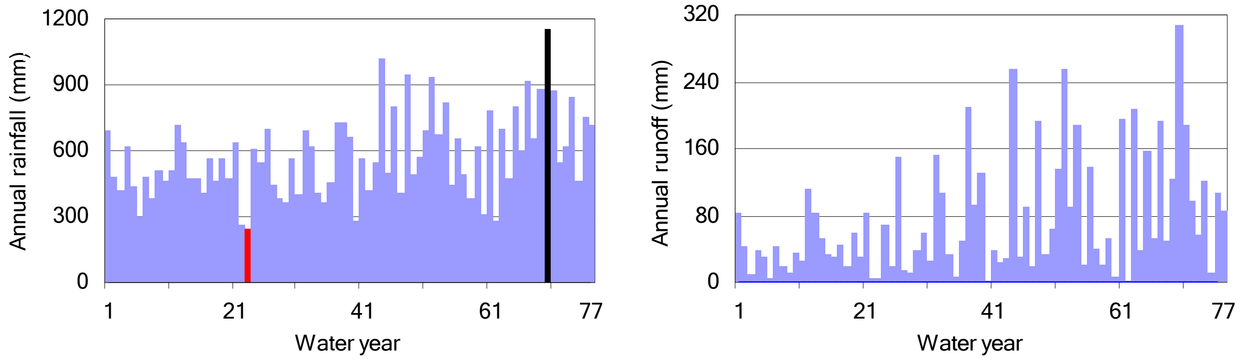


Figure FI-31. Annual (a) rainfall and (b) modelled runoff in the Fitzroy (WA) region under Scenario A

Figure FI-32a,b shows the minimum and maximum monthly rainfall and runoff and the range of values between the 25th and 75th percentile monthly rainfall and runoff. Figure FI-32c,d shows the mean and median monthly flows and the range of values between the 25th and 75th percentile monthly rainfall and runoff. The large difference in the mean and median wet season monthly runoff values indicates that the distribution of monthly runoff in the Fitzroy (WA) region is highly skewed.

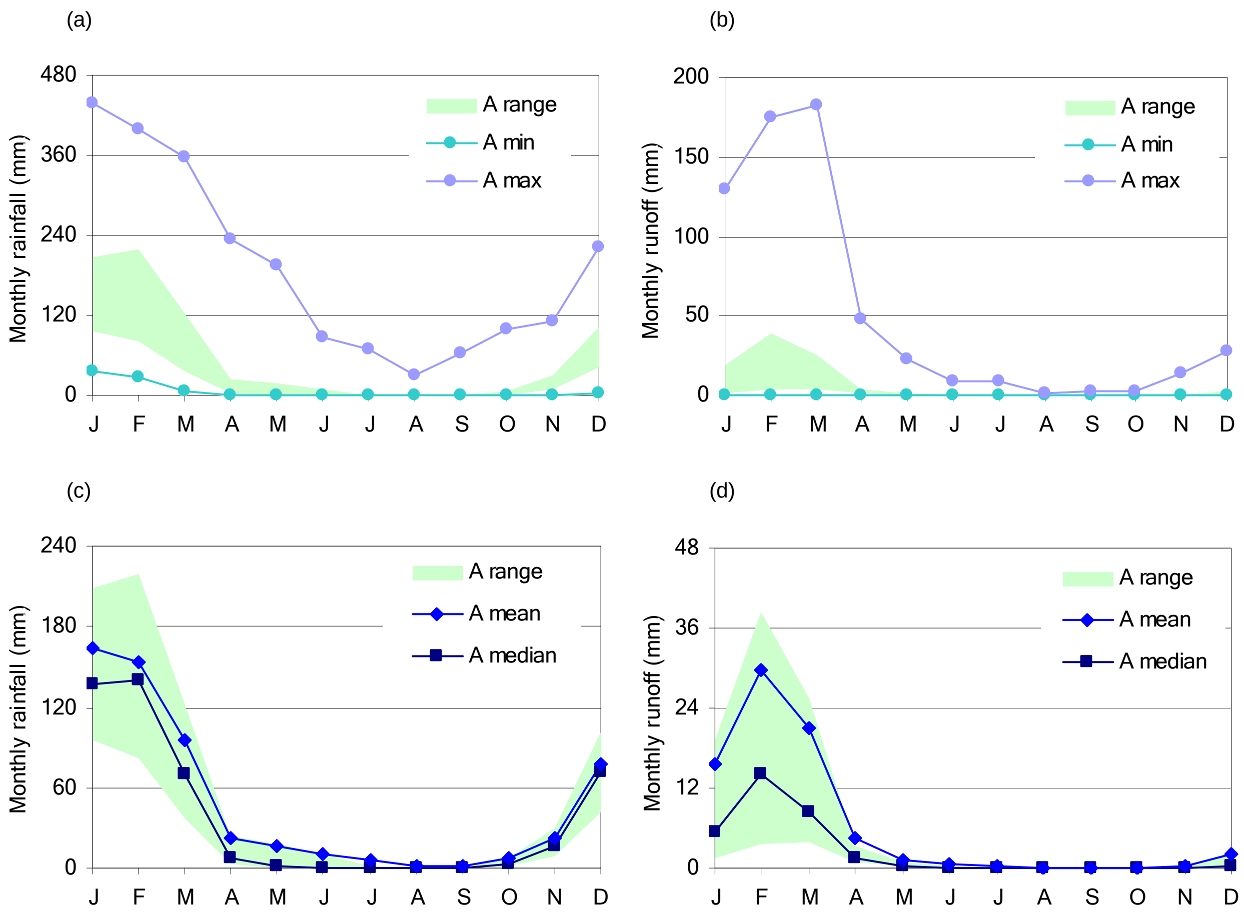


Figure FI-32. Minimum, maximum and A range monthly (a) rainfall and (b) modelled runoff; and mean, median and A range monthly (c) rainfall and (d) modelled runoff in the Fitzroy (WA) region under Scenario A (A range is the 25th to 75th percentile monthly rainfall or runoff)

FI-3.5.4 Under recent climate

The mean annual rainfall and runoff under Scenario B (1996 to 2007) are 32 percent and 51 percent higher respectively than the historical (1930 to 2007) mean values. The spatial distribution of rainfall and runoff across the Fitzroy (WA) region under Scenario B is shown in Figure FI-33.

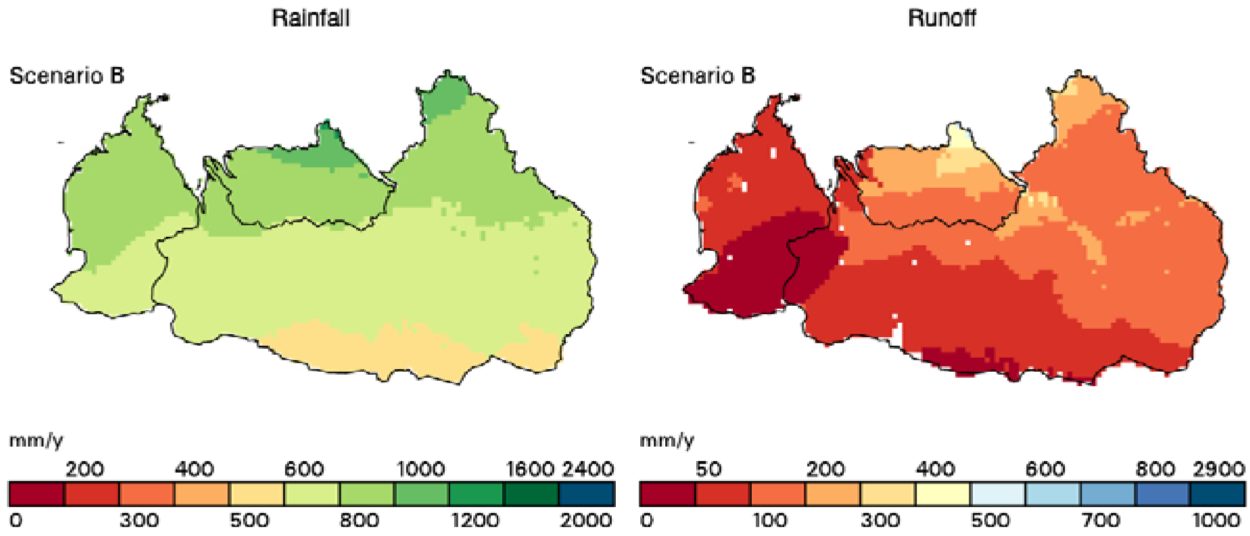


Figure FI-33. Spatial distribution of mean annual rainfall and modelled runoff across the Fitzroy (WA) region under Scenario B

FI-3.5.5 Under future climate

Figure FI-34 shows the percentage change in the mean annual runoff averaged over the Fitzroy (WA) region under Scenario C relative to Scenario A for the 45 scenarios (15 global climate models (GCMs) for each of the high, medium and low global warming scenarios). The percentage change in the mean annual runoff and rainfall from the corresponding GCMs are also tabulated in Table FI-13.

The figure and table indicate that the potential impact of climate change on runoff can be very significant. Although there is considerable uncertainty in the estimates, the results indicate that runoff in ~2030 in the Fitzroy (WA) region is as likely to decrease than increase. Rainfall-runoff modelling with climate change projections from eight of the GCMs shows a reduction in mean annual runoff, while rainfall-runoff modelling with climate change projections from seven of the GCMs shows an increase in mean annual runoff. The wide range of mean annual runoff values shown in Figure FI-34 and Table FI-13 is primarily due to the wide range of future projections of rainfall by the 15 GCMs.

Because of the large variation between GCM simulations and the method used to obtain the climate change scenarios, the biggest increase and biggest decrease in runoff come from the high global warming scenario. For the high global warming scenario, rainfall-runoff modelling with climate change projections from five of the GCMs indicates a decrease in mean annual runoff greater than 10 percent while rainfall-runoff modelling with climate change projections from three of the GCMs indicates an increase in mean annual runoff greater than 10 percent.

In subsequent reporting here and in other sections, only results from an extreme 'wet', 'mid' and extreme 'dry' variant are shown (referred to as scenarios Cwet, Cmid and Cdry). Under Scenario Cwet, results from the second highest increase in mean annual runoff from the high global warming scenario are used. Under Scenario Cdry, results from the second highest reduction in mean annual runoff from the high global warming scenario are used. Under Scenario Cmid, the median mean annual runoff results from the medium global warming scenario are used. These are shown in bold in Table FI-13.

Under scenarios Cwet, Cmid and Cdry, mean annual runoff increases by 25 percent and decreases by 3 and 41 percent relative to Scenario A. By comparison, the range based on the low global warming scenario is a 13 to -24 percent change in mean annual runoff. Figure FI-35 shows the mean annual runoff across the Fitzroy (WA) region under scenarios A and C. The linear discontinuities that are evident in Figure FI-35 are due to GCM grid cell boundaries.

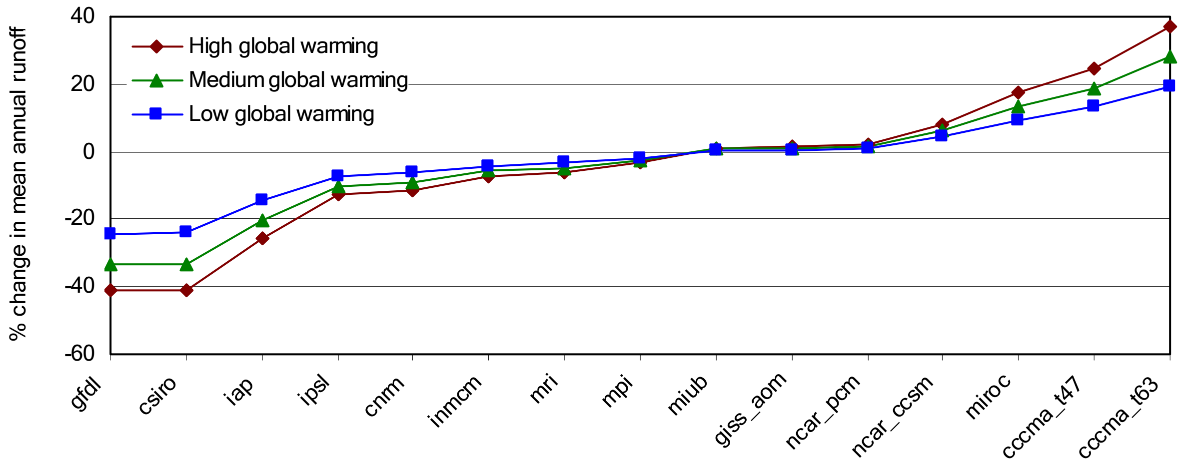


Figure FI-34. Percentage change in mean annual modelled runoff under the 45 Scenario C simulations (15 global climate models and three global warming scenarios) relative to Scenario A

Table FI-13. Summary results under the 45 Scenario C simulations for the modelled subcatchment in the Fitzroy (WA) region (numbers show percentage change in mean annual rainfall and modelled runoff under Scenario C relative to Scenario A)

High global warming			Medium global warming			Low global warming		
GCM	Rainfall	Runoff	GCM	Rainfall	Runoff	GCM	Rainfall	Runoff
gfdl	-19%	-41%	csiro	-15%	-33%	csiro	-10%	-25%
csiro	**-19%**	**-41%**	gfdl	-15%	-33%	gfdl	-10%	-24%
iap	-10%	-25%	iap	-8%	-20%	iap	-6%	-14%
ipsl	-2%	-13%	ipsl	-2%	-10%	ipsl	-1%	-7%
cnrm	-3%	-11%	cnrm	-2%	-9%	cnrm	-1%	-6%
inmcm	0%	-7%	inmcm	0%	-6%	inmcm	0%	-4%
mri	-1%	-6%	mri	-1%	-5%	mri	-1%	-3%
mpi	0%	-3%	**mpi**	**0%**	**-3%**	mpi	0%	-2%
miub	1%	1%	miub	1%	1%	miub	1%	1%
giss_aom	2%	1%	giss_aom	1%	1%	giss_aom	1%	1%
ncar_pcm	2%	2%	ncar_pcm	2%	1%	ncar_pcm	1%	1%
ncar_ccsm	5%	8%	ncar_ccsm	4%	6%	ncar_ccsm	2%	4%
miroc	6%	18%	miroc	5%	13%	miroc	3%	9%
cccma_t47	**5%**	**25%**	cccma_t47	4%	19%	cccma_t47	3%	13%
cccma_t63	10%	37%	cccma_t63	8%	28%	cccma_t63	5%	19%

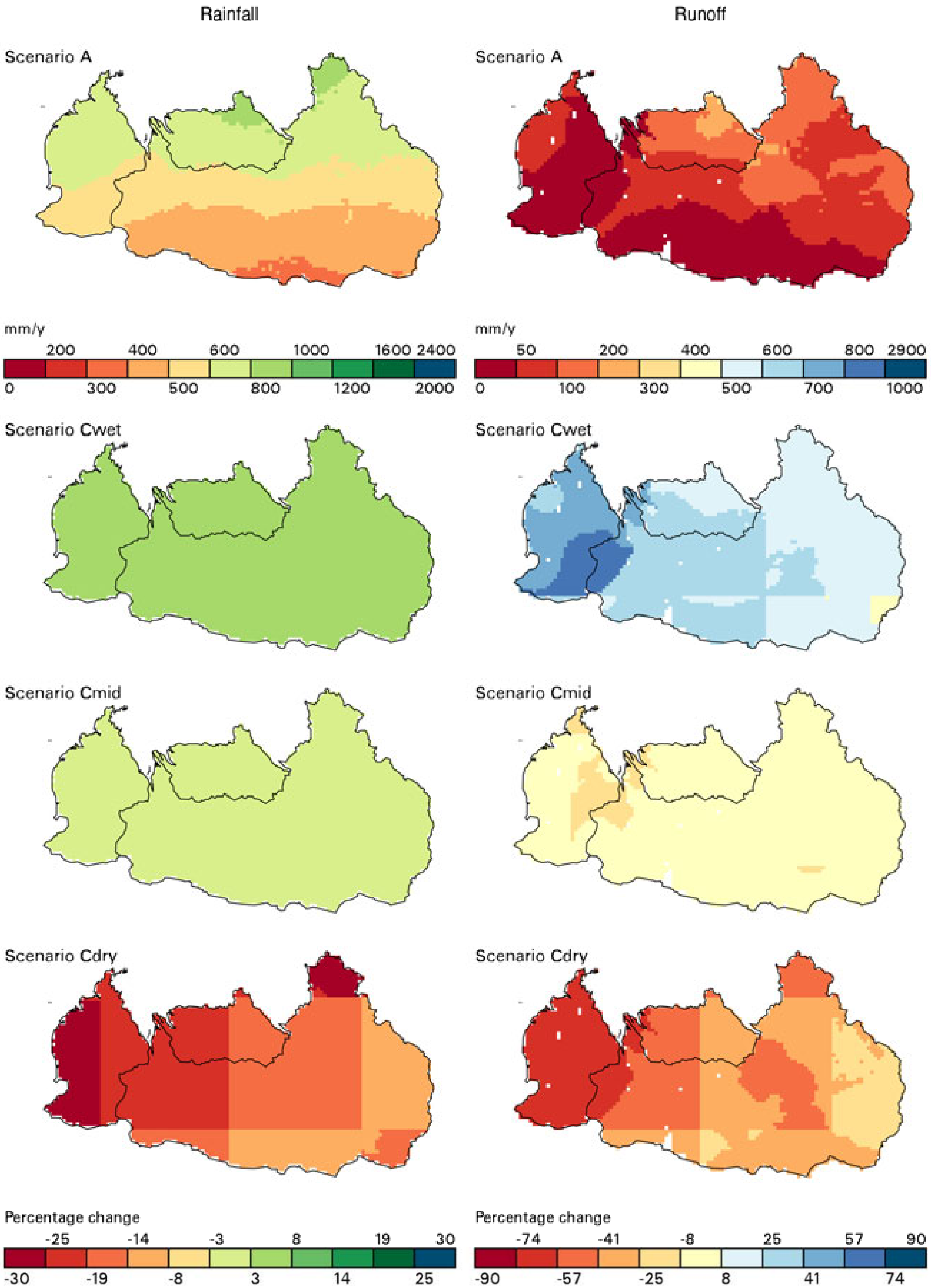


Figure FI-35. Spatial distribution of mean annual rainfall and modelled runoff across the Fitzroy (WA) region under Scenario A and under Scenario C relative to Scenario A

FI-3.5.6 Summary results for all scenarios

Table FI-14 shows the mean annual rainfall, runoff and actual evapotranspiration under Scenario A averaged over the Fitzroy (WA) region, and the percentage changes in the rainfall, runoff and actual evapotranspiration under scenarios B and C relative to Scenario A. The Cwet, Cmid and Cdry results are based on the mean annual runoff, and the rainfall changes shown in Table FI-14 are the changes in the mean annual value of the rainfall series used to obtain the runoff under scenarios Cwet, Cmid and Cdry. The changes in mean annual rainfall do not necessarily translate directly to the changes in mean annual runoff because of changes in seasonal and daily rainfall distributions and the relationship between rainfall and runoff is non-linear. The latter factor usually results in small changes in rainfall to be amplified in runoff (Table FI-13).

Figure FI-36 shows the mean monthly rainfall and runoff under scenarios A and C averaged over 1930 to 2007 years for the region. Figure FI-37 shows the daily rainfall and flow exceedance curves under scenarios A and C averaged over the region. In Figure FI-36 Cmid is selected on a month-by-month basis, while in Figure FI-37 Cmid is selected for every day of the daily flow exceedance curve.

Table FI-14. Water balance over the entire Fitzroy (WA) region under Scenario A and under scenarios B and C relative to Scenario A

Scenario	Rainfall	Runoff	Evapotranspiration
		mm	
A	578	76	502
		percent change from Scenario A	
B	32	61	28
Cwet	5	25	2
Cmid	0	-3	1
Cdry	-19	-41	-16

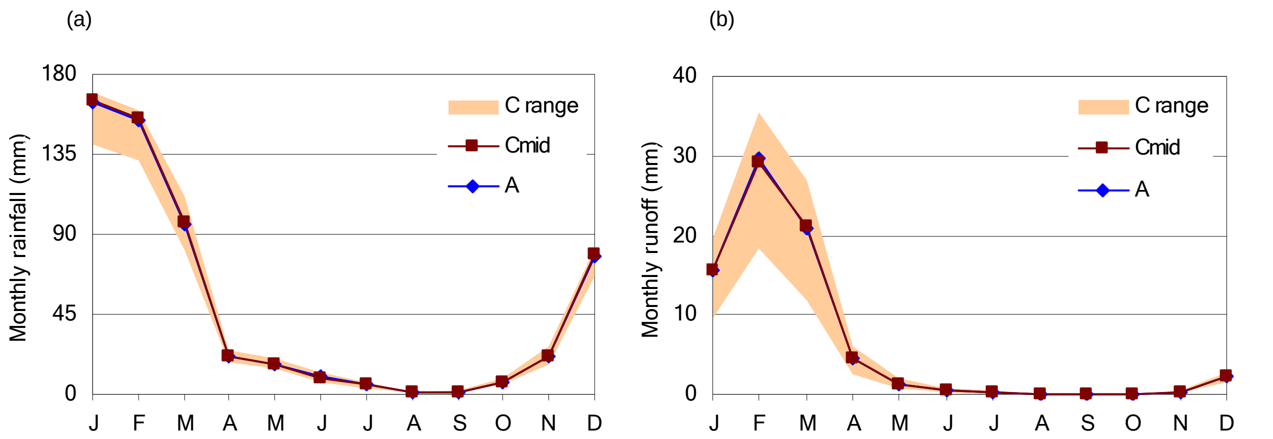
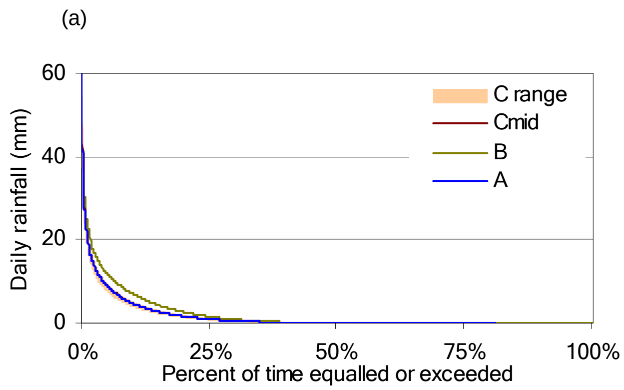


Figure FI-36. Mean monthly (a) rainfall and (b) modelled runoff in the Fitzroy (WA) region under scenarios A and C. (C range is based on the consideration of each month separately – the lower and upper limits in C range are therefore not the same as scenarios Cdry and Cwet)



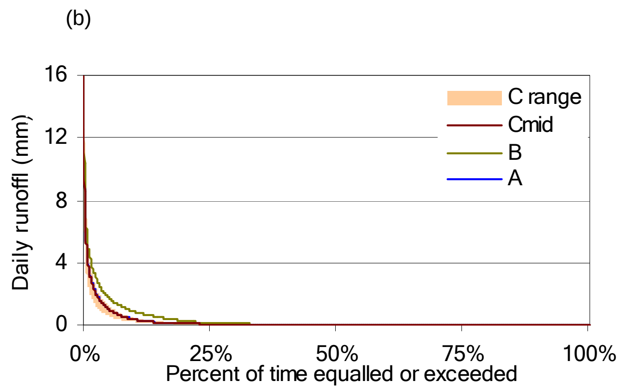


Figure FI-37. Daily flow exceedance curves for (a) rainfall and (b) modelled runoff in the Fitzroy (WA) region under scenarios A, B and C. (C range is based on the consideration of each rainfall and runoff percentile separately – the lower and upper limits in C range are therefore not the same as scenarios Cdry and Cwet)

FI-3.5.7 Confidence levels

The rainfall-runoff model verification analysis with data from 123 catchments from across all of northern Australia indicates that the mean annual runoff for ungauged catchments are under estimated or over estimated, when using optimised parameter values from a nearby catchment, by less than 20 percent in 40 percent of catchments and by less than 50 percent in 80 percent of the catchments. In the Fitzroy (WA) region, however, it is unlikely that model parameters from the headwater catchments could accurately simulate runoff on the extensive floodplain areas. For this reason it was important to be able to utilise streamflow data from stations 802007 and 802055.

Fortunately the Government of Western Australian recently obtained LIDAR DEM data (through funding from the Bureau of Meteorology) at key locations across the Fitzroy (WA) region. The Western Australia Department of Water used these data in conjunction with hydraulic modelling methods to improve the rating curve information at key streamflow gauging stations in the region, including 802007 and 802055. To utilise data from stations 802007 and 802005 it was necessary to calibrate the models to the residual flow (i.e. the difference in flow between upstream and downstream gauging stations). However, to overcome issues associated with lag and attenuation of flow, these stations were calibrated using monthly data (as described in Section 2.2.2 of the division-level Chapter 2). While monthly calibration NSE values for these stations are high (Figure FI-29) daily flows were less well represented by the models (daily NSE of less than zero for 802007 and less than 0.5 for 802055) due to the effect of lag and attenuation. Hence the residual upstream areas for stations 802007 and 802005 are assigned a low level of confidence even though the level of confidence in the total volume of flow at each station may be relatively high (Figure FI-38). Headwater gauging stations have relatively high daily NSE values. However, headwater station 802137 has a large catchment area (approximately 17,000 km^2), so while there is a relatively high level of confidence in the total volume of runoff, there is less confidence in the spatial distribution of runoff (i.e. in large catchments the rainfall-runoff models will tend to over estimate runoff in high rainfall zones and under estimate runoff in low rainfall zones).

There are no streamflow gauging stations on the Dampier Peninsula. Based on anecdotal information runoff on the Dampier Peninsula is very low. Consequently this area was modelled using optimised parameters from a low yielding catchment on the coastal plains of the Keep River, which is in the Ord-Bonaparte region (G8100106). Both regions appear to be characterised by deep sandy soil. When the Dampier Peninsula is modelled using parameter sets from G8100106, runoff is low. While runoff on the Dampier Peninsula is most likely to be low, the level of confidence in the runoff simulations on the Dampier Peninsula has been categorised as low because it is unknown how well the parameters from calibration catchment G8100106 can reproduce timing and intensity of runoff at a location more than 1000 km away.

Figure FI-38 shows the level of confidence in the modelling of the mid- to high runoff events (i.e. peak flows) and dry season runoff for the modelling subcatchments of the Fitzroy (WA) region. It should be noted that these maps of level of confidence are not statistical confidence levels and are intended to only convey a broad reliability of prediction. The level of confidence in streamflow predictions will vary slightly from the level of confidence in runoff predictions shown below and as discussed in Section 2.2.6 of the division-level Chapter 2.

There is a high degree of confidence that dry season runoff in the Fitzroy (WA) region is low because it is known that rainfall and baseflow are low during the dry season. The level of confidence for dry season flow map shown in Figure FI-38 provides a relative indication of how well dry season metrics, such as mean annual dry season flow and cease-to-flow criteria, are simulated.

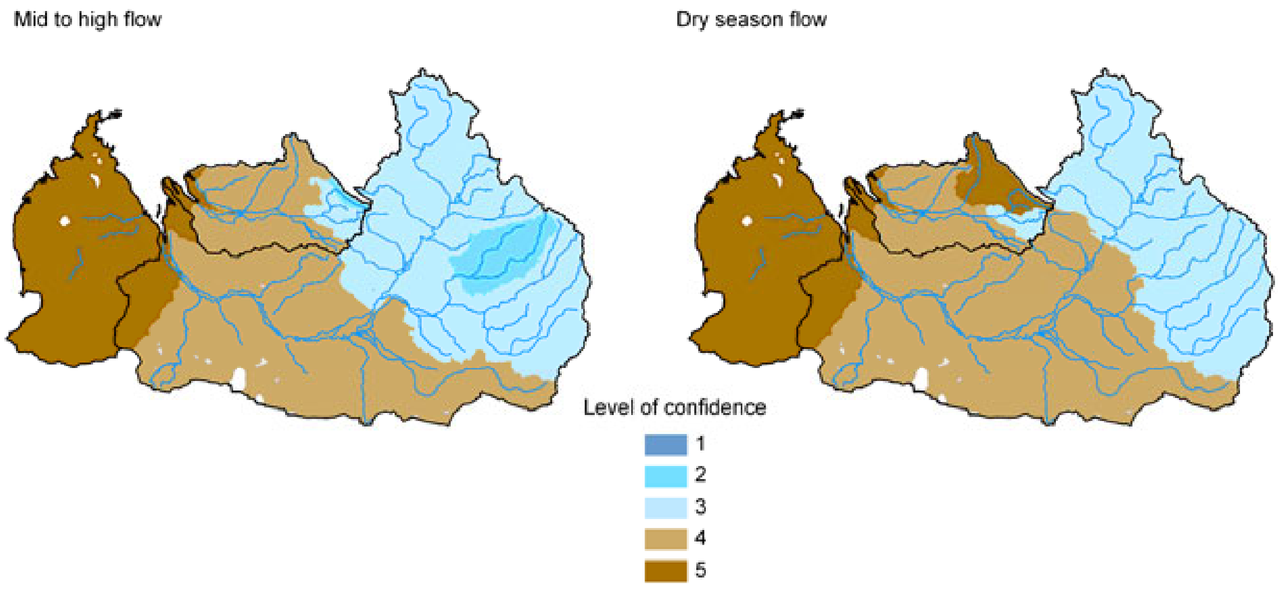


Figure FI-38. Level of confidence in the modelling of runoff for (a) mid- to high flow events and (b) monthly dry season flow events for the modelling subcatchments of the Fitzroy (WA) region. 1 is the highest level of confidence, 5 is the lowest

FI-3.6 River system water balance

FI-3.6.1 River model configuration

The Fitzroy (WA) region is comprised of three AWRC river basins and has an area of 131,606 km^2. Under the historical climate the mean annual runoff across the region is 76 mm (Section FI-3.5.3), which equates to a mean annual streamflow across the region of 10,002 GL.

No information on infrastructure, water demand and water management and sharing rules or future development were available, and consequently there is no river modelling section to the Fitzroy (WA) region report. Streamflow time series have been generated for each streamflow reporting node (SRN) based on the upstream grid cell rainfall-runoff simulations, as described in Section 2.2.5 of the division-level Chapter 2. The locations of these nodes are shown in Figure FI-39. Summary streamflow statistics for each SRN are reported in (Petheram et al., 2009).

In addition to the streamflow time series generated by the rainfall-runoff model ensemble, a range of hydrological metrics computed using regression analysis are also available for each SRN (as described in Section 2.2.7 of the division-level Chapter 2). The complete set of results for the multiple regression analysis is reported in (SKM, 2009). The merit of each approach is discussed in Section 2.2.7 of the division-level Chapter 2.

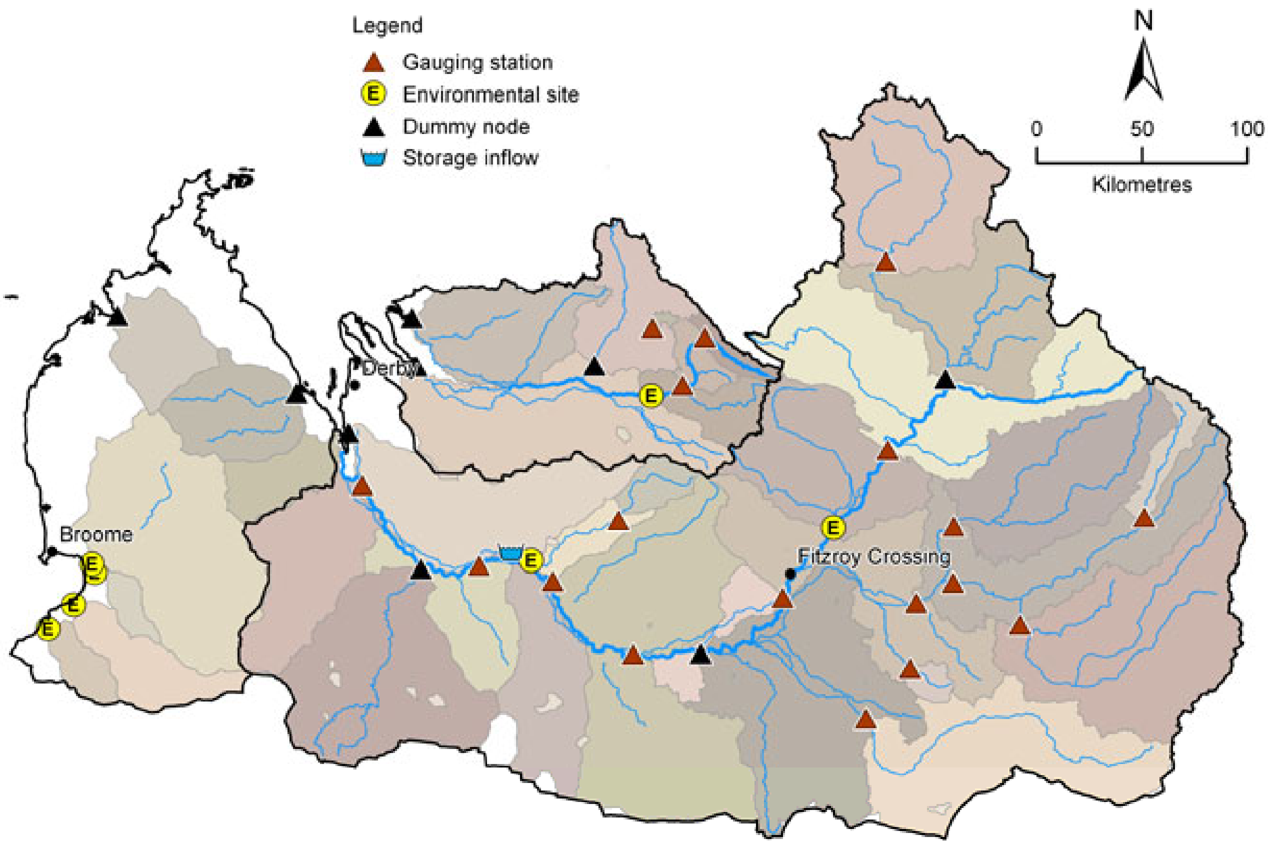


Figure FI-39. Location of streamflow reporting nodes (gauging stations, environmental sites, dummy nodes, and storage inflows) in the Fitzroy (WA) region. Note the region has no storage inflow streamflow reporting nodes

FI-3.7 Changes to flow regimes at environmental assets

Section 1.3 of the division-level Chapter 1 describes how environmental assets were shortlisted for assessment by this project. Four environmental assets have been shortlisted in the Fitzroy (WA) region: Roebuck Bay, Camballin Floodplain, Geikie Gorge and Windiana. The locations of these assets are shown in Figure FI-1 and the assets are characterised in Chapter FI-2.

This section presents the assessment of these shortlisted assets and reports metrics for those assets which have sufficient confidence in the modelled streamflow to enable analysis. Confidence in results for low flows and high flows was calculated separately on a scale of 1 to 5, with 1 indicating results with the highest confidence (as described in Section 2.2.6 of the division-level Chapter 2). Hydrological regime metrics (as defined in Section 2.5 of the division-level Chapter 2) for either low flows or high flows are reported only where confidence levels are 1, 2 or 3. If confidence levels in the low flows or high flows are ranked 4 or 5, results are not reported and are labelled NR (not reported).

Some of the assets in this region have multiple nodes at which streamflow modelling results are available. When reporting hydrological regime metrics for such assets a single node was selected. The selected node was that with the highest streamflow confidence level and the largest proportion of streamflow to the asset. Results for all nodes are presented in (McJannet et al., 2009).

In the absence of site-specific metrics for the Fitzroy (WA) region a set of standard metrics related to high and low flows have been utilised. However the conversion of these metrics into environmental impacts still requires development of quantitative relationships between flow and ecology.

FI-3.7.1 Standard metrics

Roebuck Bay

The surface water flow confidence levels for both high and low flows for all four Nodes entering Roebuck Bay are ranked unreliable (5) therefore they are of insufficient quality to allow environmental flow metrics to be calculated.

Geikie Gorge

The surface water flow confidence level for the selected reporting node for Geikie Gorge (see location on Figure FI-9) is considered moderately reliable (3) for both wet season flows and dry season flows (Table FI-15). Under Scenario A annual flow into this asset is dominated by wet season flows (98 percent) which have been 52 percent higher under Scenario B. Conversely dry season flows were 18 percent lower under Scenario B. Annual and seasonal flows do not change much from Scenario A under Scenario Cmid, but there is a large increase under Scenario Cwet (16 to 31 percent) and a large decrease under Scenario Cdry (30 to 45 percent). There are no development Scenarios for the area upstream of this asset.

The number of days when flow is less than the low flow threshold does not change much from Scenario A under Scenarios Cmid and Cwet, but there is a large increase under Scenario Cdry (Table FI-15). A similar pattern is seen in the number of days of zero flow. Under Scenario B the high flow threshold exceedance has been much more frequent than in Scenario A. There is little change in high flow threshold exceedance under Scenario Cmid compared to under Scenario A. Under Scenario Cwet there is a moderate increase in high flow exceedance from Scenario A; conversely there is a large decrease in high flow days under Scenario Cdry.

Camballin Floodplain (Le Livre Swamp System)

The surface water flow confidence level for the selected reporting node for Camballin Floodplain (see location on Figure FI-8) is considered moderately reliable (3) for wet season flows and unreliable (5) for dry season flows (Table FI-15). Under Scenario A annual flow into this asset is dominated by wet season flows (98 percent) which have been 58 percent higher under Scenario B. Annual and seasonal flows do not change much from Scenario A under Scenario Cmid, but there is a moderate increase under Scenario Cwet (16 to 17 percent) and a large decrease under Scenario Cdry (36 percent). There are no development Scenarios for the area upstream of this asset.

Under Scenario B the high flow threshold exceedance has been much more frequent than in Scenario A (Table FI-15). There is little change in high flow threshold exceedance under Scenario Cmid compared to under Scenario A. Under Scenario Cwet there is a moderate increase in high flow exceedance from Scenario A; conversely there is a large decrease in high flow days under Scenario Cdry. There are no low flow metrics reported for this asset.

Table FI-15. Standard metrics for changes to flow regime at environmental assets in the Fitzroy (WA) region under Scenario A and under scenarios B, C and D relative to Scenario A

Standard metrics	Units	A	B	Cwet	Cmid	Cdry	Dwet	Dmid	Ddry
			change from Scenario A						
Geikie Gorge - Node 1 (confidence level: low flow = 3, high flow = 3)									
Annual flow (mean)	GL	2290	+50%	+16%	-7%	-31%	nm	nm	nm
Wet season flow (mean)*	GL	2240	+52%	+16%	-7%	-30%	nm	nm	nm
Dry season flow (mean)**	GL	49.5	-18%	+31%	-3%	-45%	nm	nm	nm
Low flow threshold (discharge exceeded 90% of the time in Scenario A)	GL/d	0							
Number of days below low flow threshold (mean)	d/y	62.2	-25.5	-1.9	+2.4	+22	nm	nm	nm
Number of days of zero flow (mean)	d/y	62.2	-25.5	-1.9	+2.4	+22	nm	nm	nm
High flow threshold (discharge exceeded 5% of the time in Scenario A)	GL/d	34.5							
Number of days above high flow threshold (mean)	d/y	18.3	+13.2	+2.5	-0.9	-6.7	nm	nm	nm
Camballin Floodplain (Le Livre Swamp System) - Node 2 (confidence level: low flow = 5, high flow = 3)									
Annual flow (mean)	GL	7540	+56%	+17%	-6%	-36%	nm	nm	nm
Wet season flow (mean)*	GL	7380	+58%	+16%	-6%	-36%	nm	nm	nm
Dry season flow (mean)**	GL	NR	NR	NR	NR	NR	nm	nm	nm
Low flow threshold (discharge exceeded 90% of the time in Scenario A)	GL/d	NR							
Number of days below low flow threshold (mean)	d/y	NR	NR	NR	NR	NR	nm	nm	nm
Number of days of zero flow (mean)	d/y	NR	NR	NR	NR	NR	nm	nm	nm
High flow threshold (discharge exceeded 5% of the time in Scenario A)	GL/d	111							
Number of days above high flow threshold (mean)	d/y	18.3	+12.4	+2.1	-0.9	-7	nm	nm	nm
Windjana Gorge - Node 1 (confidence level: low flow = 5, high flow = 3)									
Annual flow (mean)	GL	366	+27%	+16%	-7%	-29%	nm	nm	nm
Wet season flow (mean)*	GL	354	+29%	+16%	-7%	-29%	nm	nm	nm
Dry season flow (mean)**	GL	NR	NR	NR	NR	NR	nm	nm	nm
Low flow threshold (discharge exceeded 90% of the time in Scenario A)	GL/d	NR							
Number of days below low flow threshold (mean)	d/y	NR	NR	NR	NR	NR	nm	nm	nm
Number of days of zero flow (mean)	d/y	NR	NR	NR	NR	NR	nm	nm	nm
High flow threshold (discharge exceeded 5% of the time in Scenario A)	GL/d	3.89							
Number of days above high flow threshold (mean)	d/y	18.3	+10	+1.5	-0.5	-6.6	nm	nm	nm

*Wet season covers the six months from November to April.
**Dry season covers the six months from May to October.
NR – metrics not reported because streamflow confidence level is ranked 4 or 5
nm – not modelled

Windjana Gorge

The surface water flow confidence level for the selected reporting node for Windjana Gorge (see location on Figure FI-10) is considered moderately reliable (3) for wet season flows and unreliable (5) for dry season flows (Table FI-15). Under Scenario A annual flow into this asset is dominated by wet season flows (97 percent) which have been 29 percent higher under Scenario B. Annual and seasonal flows do not change much from Scenario A under Scenario Cmid, but there is a moderate increase under Scenario Cwet (16 percent) and a moderate decrease under Scenario Cdry (29 percent). There are no development Scenarios for the area upstream of this asset.

Under Scenario B the high flow threshold exceedance has been much more frequent than in Scenario A (Table FI-15). There is little change in high flow threshold exceedance under Scenario Cmid compared to under Scenario A. Under Scenario Cwet there is a small increase in high flow exceedance from Scenario A; conversely there is a large decrease in high flow days under Scenario Cdry. There are no low flow metrics reported for this asset.

FI-3.7.2 Site-specific metrics

Table FI-16. Site-specific reported metrics for changes to flow regime at Camballin Barrage under Scenario A and under scenarios B, C and D relative to Scenario A

Reported metrics	Units	A	B	Cwet	Cmid	Cdry	Dwet	Dmid	Ddry
			change from Scenario A						
Camballin Floodplain - Fish passage across Camballin Barrage									
Number of days with flows above 8.0 GL/d (mean) *	d/y	69	+27.6	+3.9	-1.7	-15.9	nm	nm	nm
Number of days with flows above 28.8 GL/d (mean) **	d/y	42	+24.9	+3.3	-1.1	-12.3	nm	nm	nm

* Fish passage across barrage commences
** Fish passage across barrage unimpeded
nm – not modelled.

Camballin Floodplain (Le Livre Swamp System)

Note that results discussed in this section should be treated with some caution as the rating curve for this location is currently being refined.

At Camballin Barrage, which is located near the Camballin Floodplain environmental asset, environmental flow metrics have been defined by Morgan et al. (2005) which relate to fish passage across the barrage (Table FI-16). The first of these is when the water level is 1m above the Barrage, above which fish passage commences. This stage height corresponds to flow rate threshold of 8.0 GL/day. Morgan et al. (2005) also calculated the number of days when the Barrage was completely inundated and this occurred when the stage height was 2.3m above the Barrage, which corresponds to a flow threshold of 28.8 GL/d. Above this threshold fish passage was considered completely unimpeded.

The number of days when the flow is above the 8.0 GL/day threshold increased considerably under Scenario B (Table FI-16). There is little change to the exceedance of this flow threshold under Scenarios Cmid and Cwet, but there is a moderate decrease in this threshold exceedance under Scenario Cdry. The number of days when the flow is above the higher flow threshold of 28.8 GL/day threshold increased considerably under Scenarios B (Table FI-16). There is little change to the exceedance of this flow threshold under scenarios Cmid and Cwet, but there is a moderate decrease in this threshold exceedance under Scenario Cdry. Therefore fish passage across the barrage would be facilitated under Scenario B, but restricted under Scenario Cdry.

FI-3.8 References

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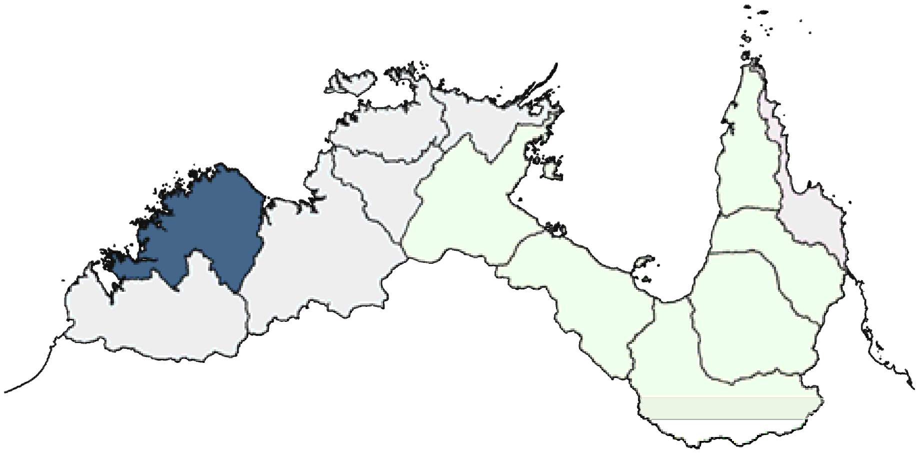
Water in the Kimberley region



KI-1 Water availability and demand in the Kimberley region

The first part of this report (the Preamble, Chapter 1 and Chapter 2) reports at the division level, including division-wide descriptions of climate and geology and methods which apply to all regions. Subsequent chapters report at the region level. In particular, Chapters KI-1, KI-2 and KI-3 focus on the Kimberley region (Figure KI-1).

This chapter summarises the water resources of the Kimberley region, using information from Chapter KI-2 and Chapter KI-3, and directly addresses the Terms of Reference, specifically terms 3, 4 and 5 as listed in the Preamble. Essentially, this chapter provides a synoptic view of the region and covers:

- regional observations
- water resource assessment
- seasonality of water resources
- surface–groundwater interaction
- changes to flow regime at environmental assets
- water storage options
- data and knowledge gaps.

For further details on the context of the region (physical and climate descriptions, hydrogeology and legislation) see Chapter KI-2. Region-specific methods and results are provided in Chapter KI-3. Modelling results are reported under climate and development scenarios as defined at the division level in Section 2.1 of Chapter 2.

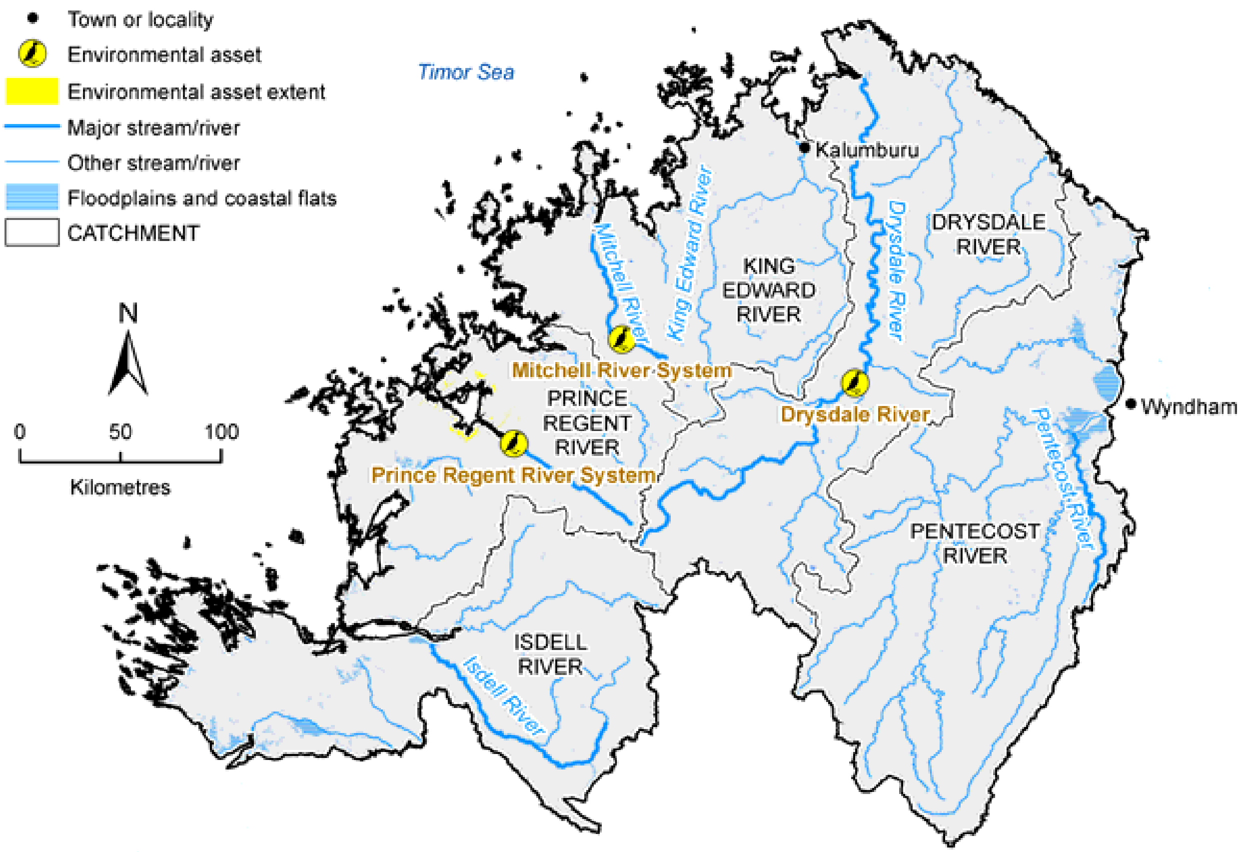


Figure KI-1. Major rivers, towns and location of assets selected for assessment of changes to hydrological regime in the Kimberley region

KI-1.1 Regional summary

This section summarises key modelling results from this project and provides other relevant water resource information as context about water availability and demand in the Kimberley region.

The historical (1930 to 2007) mean annual rainfall for the region is 950 mm. Mean annual areal potential evapotranspiration (APET) is 1994 mm. The mean annual runoff averaged over the modelled area of the Kimberley region is 152 mm, 16 percent of rainfall. These values are moderately high in comparison to other regions across northern Australia. Under the historical climate the mean annual streamflow over the Kimberley region is estimated to be 16,793 GL.

The Kimberley region has a high inter-annual variability in rainfall and hence runoff and recharge. Coefficients of variation are in the middle of the range of the regions across northern Australia and the region may experience long periods of many years that are considerably wetter or drier than others.

There is a strong seasonality in rainfall patterns, with 94 percent of rainfall falling in the wet season, between November and April, and a very high dry season (May to October) APET. The region has relatively high rainfall intensities, extremely high for the top 1 percent of events, and this is reflected in rapid runoff and a short lag between rainfall and runoff. Ninety-seven percent of runoff occurs within the months of December and April. There has been a slightly increasing amount and intensity of rainfall over the 1930 to 2007 period.

There is a strong north–south rainfall gradient and hence also runoff, with the runoff coefficient decreasing from 30 to 10 percent of precipitation in the same direction.

APET is annually greater than rainfall, and thus the region may be considered water-limited. The region is one of only a few, however, that is not water-limited throughout the entire year, with wet season rain exceeding APET, particularly towards the coast.

In the Kimberley region, the recent (1996 to 2007) climate record is statistically significantly wetter than the historical (1930 to 2007) record. Rainfall was 25 percent higher; runoff was 71 percent higher. It is likely that future (~2030) conditions will be similar to historical conditions, and future runoff and recharge will also be similar to historical levels, but lower than the recent past.

There is potential for surface water storage, with high flows and steep-sided valleys, though most catchments are relatively small and hence storages would not be very large. There is currently low demand, however, and costs would be high.

The fractured rock aquifers of the Kimberley region have good quality groundwater. However, bores are generally low yielding. Any future groundwater development in the Kimberley region will be limited by the low yields of fractured rock aquifers and not by the quality of groundwater.

At environmental assets, surface water flows are highly dominated by wet season flows with dry season flows only a small fraction of total annual flow. However, environmental assets are dependent on this strong seasonality and any significant changes in the frequency and duration of wet season high flows and dry season low flows are likely to have an environmental impact.

In the recent past there has been significantly more flow at most environmental assets. Annual and seasonal flows do not change much under the median future climate, hence there is little change in the high and low flow threshold exceedance under this scenario. There are large changes to the high flow threshold exceedance under the dry extreme future climate, which could have negative environmental impacts, and analysis suggests that there is likely to be a large increase in the number of days of zero flow under this scenario which could have undesirable environmental impacts. As major developments are not expected in the region, these scenarios do not consider the consequences of any future development.

The region is generally datapoor.

KI-1.2 Water resource assessment

Term of Reference 3a

KI-1.2.1 Under historical climate and current development

Term of Reference 3a (i)

Demand in the region for water resources is very low and the cost of harnessing a reliable surface water supply in the region is very high, requiring both a sufficiently-sized catchment and a structure that can pass large floods. Hence, there is little use of surface water in the region.

Under a continuation of the historical climate, mean annual diffuse groundwater recharge to the unconfined aquifers of the Kimberley region is likely to be similar to the historical (1930 to 2007) average rate. Whilst the current rate of groundwater extraction is unknown, it is likely to be negligible compared with the historical average recharge rate. Continued extraction at current levels under a historical climate would therefore have limited further impacts on the groundwater systems and the perennial rivers that rely on groundwater to sustain dry season flows (Table KI-1 and Figure KI-2).

Table KI-1. Estimated groundwater contribution (baseflow) to streamflow, modelled diffuse recharge and groundwater extraction for the Kimberley region under historical climate

Station	River	Station name	Annual BFI *	Dry season BFI *	Dry season baseflow *
					GL
804001	Isdell	Dales Yard	0.18	0.61	5.4
806001	Mitchell	Map Hill	0.20	0.53	4.9
806003	Crystal Ck	Crystal Head	0.07	0.20	0.1
806004	Carson	Old Theda	0.16	0.56	2.9
806005	Morgan	Moondoalnee (Theda)	0.22	0.61	4.1
806006	King Edward	Mt Reid	0.31	0.65	9.7
807001	Drysdale	Solea Falls (Horseshoe)	0.32	0.57	30.4
808001	Durack	Nettopus Pool Karunjie	0.21	0.31	1.0
		Historical recharge **	Estimated groundwater extraction		
		GL/y			
Entire Kimberley region		12,980	unknown		

* BFI (baseflow index) and baseflow volume derived from gauged data.
** Aggregated recharge from Zhang and Dawes (1998).

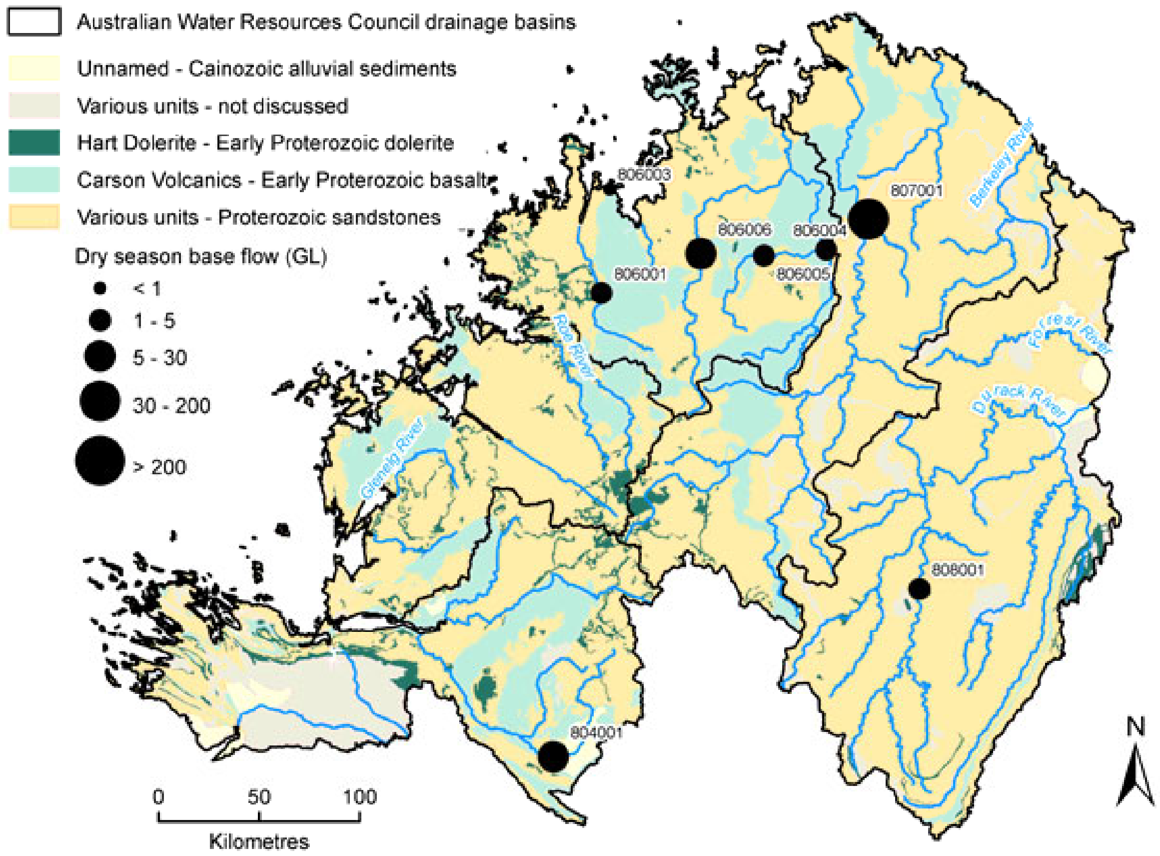


Figure KI-2. Surface geology of the Kimberley region with modelled mean dry season baseflow

KI-1.2.2 Under recent climate and current development

Term of Reference 3a (ii)

Under a recent climate, mean annual diffuse groundwater recharge to unconfined aquifers is estimated to be significantly higher than the historical (1930 to 2007) average rate in almost all areas of the region, except for the far north tip where a decrease has been estimated. It is likely, therefore, that groundwater levels and seasonal fluxes could increase under this scenario.

KI-1.2.3 Under future climate and current development

Term of Reference 3a (iii)

Under the future climate, mean annual diffuse groundwater recharge to unconfined aquifers may be slightly higher than the historical average rate across the entire Kimberley region.

KI-1.2.4 Under future climate and future development

Term of Reference 3a (iv)

The challenge for future groundwater development in this region is to ensure that extraction bores are placed a sufficient distance away from major rivers, particularly those that are perennial, so as to minimise the chance of depleting streamflow as a result of groundwater pumping.

KI-1.3 Changes to flow regime at environmental assets

Term of Reference 3b

Section 1.3 of the division-level Chapter 1 describes how environmental assets were shortlisted for assessment by this project. Three environmental assets were shortlisted for the Kimberley region: Drysdale River, Mitchell River System and Prince Regent River System. These assets are characterised in Chapter KI-2 and detailed results presented in Chapter KI-3.

In deciding whether it is feasible to report hydrological regime metrics for these shortlisted assets, it is important to consider the confidence levels in modelled streamflow (as described in Section 2.2.6 of the division-level Chapter 2). Confidence in results for low flows and high flows was calculated separately. Hydrological regime metrics (as defined in Section 2.5 of the division-level Chapter 2) for either low flows or high flows are reported only where confidence levels are sufficiently high. If confidence in the low flow or high flow is too low, metrics are not reported, and hence an important gap in our knowledge is identified.

Some of the assets in this region have multiple nodes at which streamflow modelling results are available. When reporting hydrological regime metrics for such assets a single node was selected. The selected node was that with the highest streamflow confidence level and the largest proportion of streamflow to the asset. The locations of nodes for each asset are shown on satellite images in Section KI-2.1.3. Results for all nodes are presented in McJannet et al. (2009).

Confidence in streamflow results was too poor to enable reporting of flow regime metrics at Prince Regent River System. Confidence was high for reporting high and low flow results for the Drysdale River and Mitchell River System. At these assets, annual flow is dominated by wet season flow, which has been as much as 70 percent higher than historical levels in the recent past. Dry season flows have also been much higher than the historical flows in the recent past. Future flows are likely to be similar to historical flows. Under a dry extreme future climate, flows are more than 30 percent lower than historical levels.

Zero flow days are expected to increase greatly under the dry extreme future climate at Drysdale River but are very rare at the Mitchell River System. The number of days modelled when flow is less than the low flow threshold increases moderately under the median future climate, but increases greatly under the dry extreme future climate.

Under the recent climate, high flows are approximately twice as frequent as under the historical climate at all sites. There is little change in high flow threshold exceedance under the median and wet extreme future climate, though under the dry extreme future climate a moderate increase is seen at all sites.

There is not expected to be any major future development in this region, hence this scenario was not analysed.

KI-1.4 Seasonality of water resources

Term of Reference 4

As for the rest of northern Australia, seasonality of rainfall – and hence runoff – is very high, with streamflow concentrated into incised, steep-sided valleys and producing very high flow rates. Shallow groundwater reserves are rapidly replenished, predominantly via stream-bed recharge, but also rapidly drain through the early part of the dry season, but also provide ongoing discharge to lower reaches, to generate significant baseflow in many rivers.

Under the historical climate, 95 percent of rainfall and 97 percent of runoff occurs during the wet season. Under the recent climate 94 percent of rainfall and 90 percent of runoff occurs during the wet season. Under the median future climate 93 percent of rainfall and 97 percent of runoff occurs during the wet season. Runoff is highest between January and March.

KI-1.5 Surface–groundwater interaction

Groundwater discharges to swamps, creeks and rivers throughout the year in the Kimberley region (Allen, 1966). The Drysdale, Isdell, King Edward and Mitchell rivers all have sustained baseflow during much of the dry season because of groundwater discharge (Figure KI-2). During the wet season, both intense and prolonged rainfall periods result in large volumes of surface water runoff and consequent flow in the tributaries and major rivers. It is likely that during the wet season, elevated river levels would lead to recharge of the aquifers that are either incised by or underlying the rivers.

KI-1.6 Water storage options

Term of Reference 5

KI-1.6.1 Surface water storages

There are no major water storages in the region. Demand in the region is very low and the cost of harnessing a reliable surface water supply in the region is very high due to the lack of infrastructure and remoteness and ruggedness of the region.

KI-1.6.2 Groundwater storages

Groundwater development in the Kimberley region is very low and estimated groundwater recharge rates are high, particularly in the northern half of the region. Under current development managed aquifer recharge (MAR) would have limited applicability as storages in the aquifers are likely to be at full capacity towards the end of the wet season when surface water is available for injection. Potential evapotranspiration exceeds rainfall for much of the year resulting in prolonged water-limited conditions. When water is not limited aquifers are expected to be at full capacity. Furthermore, the fractured rock aquifers that dominate the region are unlikely to be suitable for large-scale MAR schemes due to the heterogeneity and low storage capacity that is characteristic of these systems.

KI-1.7 Data gaps

Term of Reference 1e

Historical groundwater level and salinity monitoring data are very sparse for the Kimberley region. The absence of such data has meant that the conceptual models presented in this report are largely theoretical. Furthermore, until a comprehensive groundwater monitoring network is established and data are available, there can be no quantitative analysis of current or future impacts of groundwater development or climate change.

KI-1.8 Knowledge gaps

Term of Reference 1e

Only one of the environmental assets in this region has any site-specific metrics by which to gauge the potential impacts of future climate change and development. In the absence of site-specific metrics a set of standard metrics related to high flows and low flows have been utilised; however, the conversion of these metrics into environmental impacts still requires development of quantitative relationships between flow and specific ecological entities (for example, macrophyte populations, fish passage, faunal and floral habitats, etc.).

Flooding is an important factor that sustains many environmental assets and this occurs when the stream breaks out of its banks (a level known as bankfull stage or discharge). However, bankfull discharge is not known for many streams, nor is the dependence of area flooded on increasing stream depth, so it is difficult to predict when assets are inundated. Further information about bankfull stage and discharge are needed for most environmental assets.

Dry season flows are poorly understood in this region – therefore the ability to predict the potential impacts of the various scenarios on low or zero flows at environmental assets is very limited. Improved monitoring of low streamflow conditions is needed along with the development of hydrological models that combine surface and groundwater regimes. Further monitoring of groundwater levels is also required so that the potential impacts of climate change and development on groundwater-dependent ecosystems can be better understood.

Many environmental assets depend not simply on duration above or below certain flow levels, but on triggers (e.g. for reproduction or migration) set by the rate of change of flow. In addition, some environmental assets depend on the frequency and duration of events that occur less than annually (i.e. once every 5, 10 or 20 years or more). Further analysis is therefore required to look at how the timing, duration and rate of rise and fall in flow rates at critical times of the season will vary under the various scenarios.

KI-1.9 References

Allen AD (1966) The Hydrogeology of the Kimberley Plateau. Geological Survey of Western Australia. Record No. 1966/16.

McJannet DL, Wallace JW, Henderson A and McMahon J (2009) High and low flow regime changes at environmental assets across northern Australia under future climate and development scenarios. A report to the Australian Government from the CSIRO Northern Australian Sustainable Yields Project. CSIRO Water for a Healthy Country National Research Flagship, Division of Land and Water, Canberra. *In prep.*

Zhang L and Dawes W (1998) WAVES - An integrated energy and water balance model. Technical Report No. 31/98, CSIRO Land and Water.

KI-2 Contextual information for the Kimberley region

This chapter summarises the background information for the region, outlining existing knowledge of water resources and prior and current investigations relevant to the water resources of the region. This chapter also outlines the current and potential future legislation, water plans and other water resource management arrangements. This chapter is arranged into four sections:

- physical and climate descriptions
- data availability
- hydrogeology
- legislation, water plans and other arrangements.

KI-2.1 Overview of the region

KI-2.1.1 Geography and geology

The Kimberley region comprises the Australian Water Resources council river basins of the Isdell, Prince Regent, King Edward, Drysdale and Pentecost Rivers. The region covers 110,000 km^2 and is bounded to the south by the King Leopold Ranges and to the east by the Durack Range or the Halls Creek Orogenic Belt and the edge of the Kimberley plateau. A combination of high rainfall and a fractured dissected landscape results in thin, largely infertile, soils. The high rainfall and intense streamflow produce steep-sided valleys despite relatively low relief (906 m).

The region is dominated by a gently folded and warped Proterozoic sedimentary sequence, up to 5 km thick, of the Kimberley Basin. This sequence comprises sandstones with basalt flows and dolerite sills within (Gunn and Meixner, 1998) (Figure KI-3).

Skeletal sandy soils incompletely mantle sandstone boulder country, significant areas of volcanic and dolerite surfaces as well as lateritised upland with open forests, and alluvial floors along major river valleys.

The northern Mitchell subregion has a diverse array of exposed basement strata dissected by rivers, and a rugged sunken coastline, deeply embayed. The south Berkeley subregion is less dissected than the Mitchell, and is dominated by an upland of mainly Pentecost sandstones more continuously mantled by (sandy) soils supporting an open savanna woodland with few vine thickets.

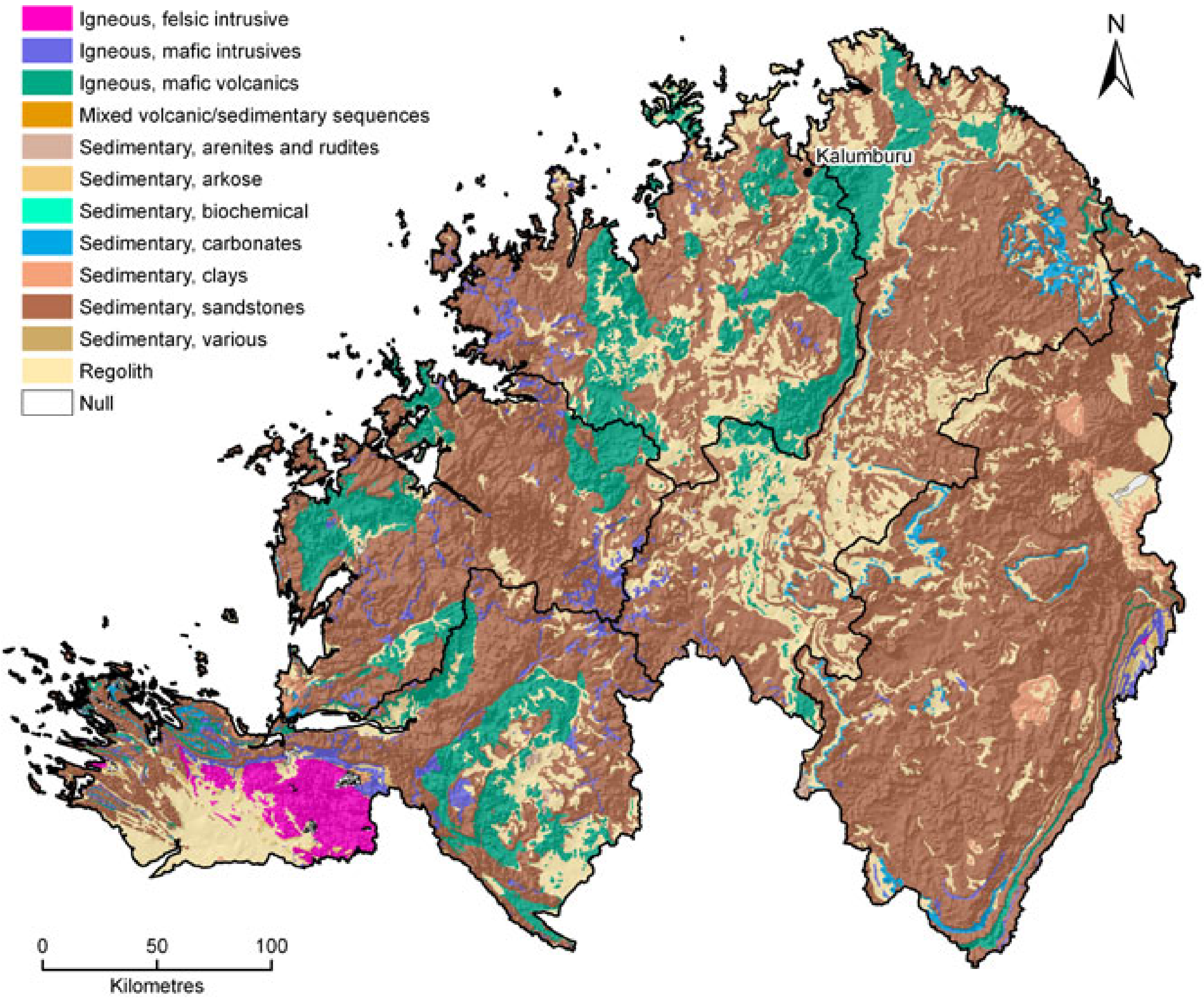


Figure KI-3. Surface geology of the Kimberley region overlaid on a relative relief surface

KI-2.1.2 Climate, vegetation and land use

The Kimberley region receives an average of 950 mm of rainfall over the September to August water year, most of which (898 mm) falls in the November to April wet season (Figure KI-4). Across the region there is a strong north–south gradient in annual rainfall, ranging from 1223 mm in the north to 628 mm in the south. Over the first half of the historical (1930 to 2007) period, annual rainfall has been relatively constant at around 750 mm. In the second half of the historical period, the mean rainfall increased to approximately 1050 mm. The highest yearly rainfall received was 1679 mm in 2000, and the lowest was 477 mm in 1936.

Areal potential evapotranspiration (APET) is very high across the region, averaging 1994 mm over a water year, and varies moderately across the seasons. APET generally remains higher than rainfall throughout the year resulting in year-round water-limited conditions to which the vegetation has adapted.

Variations of vegetation across the region (Figure KI-5) reflect the distribution of rainfall and soil types. Dense eucalypt woodlands, mangrove forest and rainforest remnants occur in the north. Savannah woodlands occur in the central area and sparse acacia scrub land and spinifex savannah in the south. Conservation reserves comprise almost two million hectares (Figure KI-6).

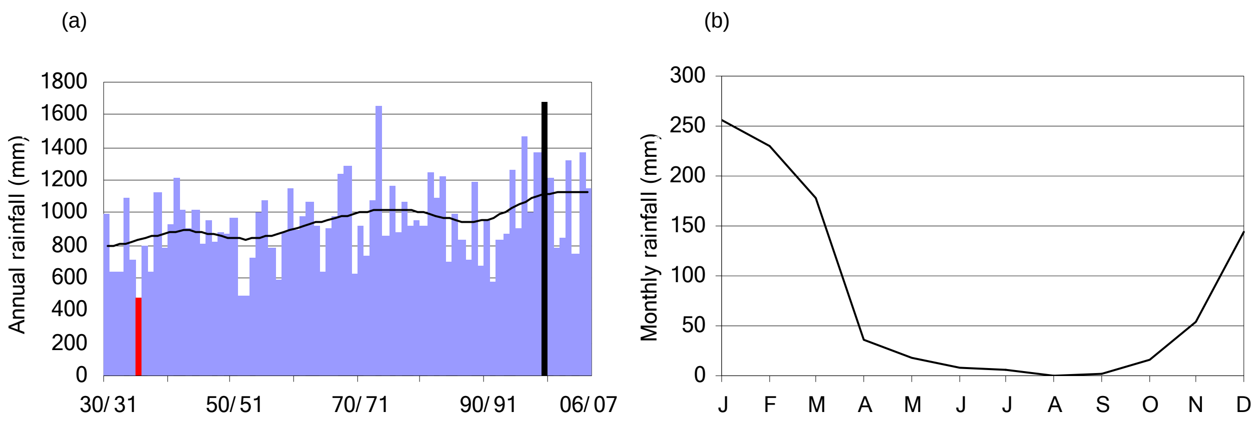


Figure KI-4. Historical (a) annual and (b) mean monthly rainfall averaged over the Kimberley region. The low-frequency smoothed line in (a) indicates longer term variability

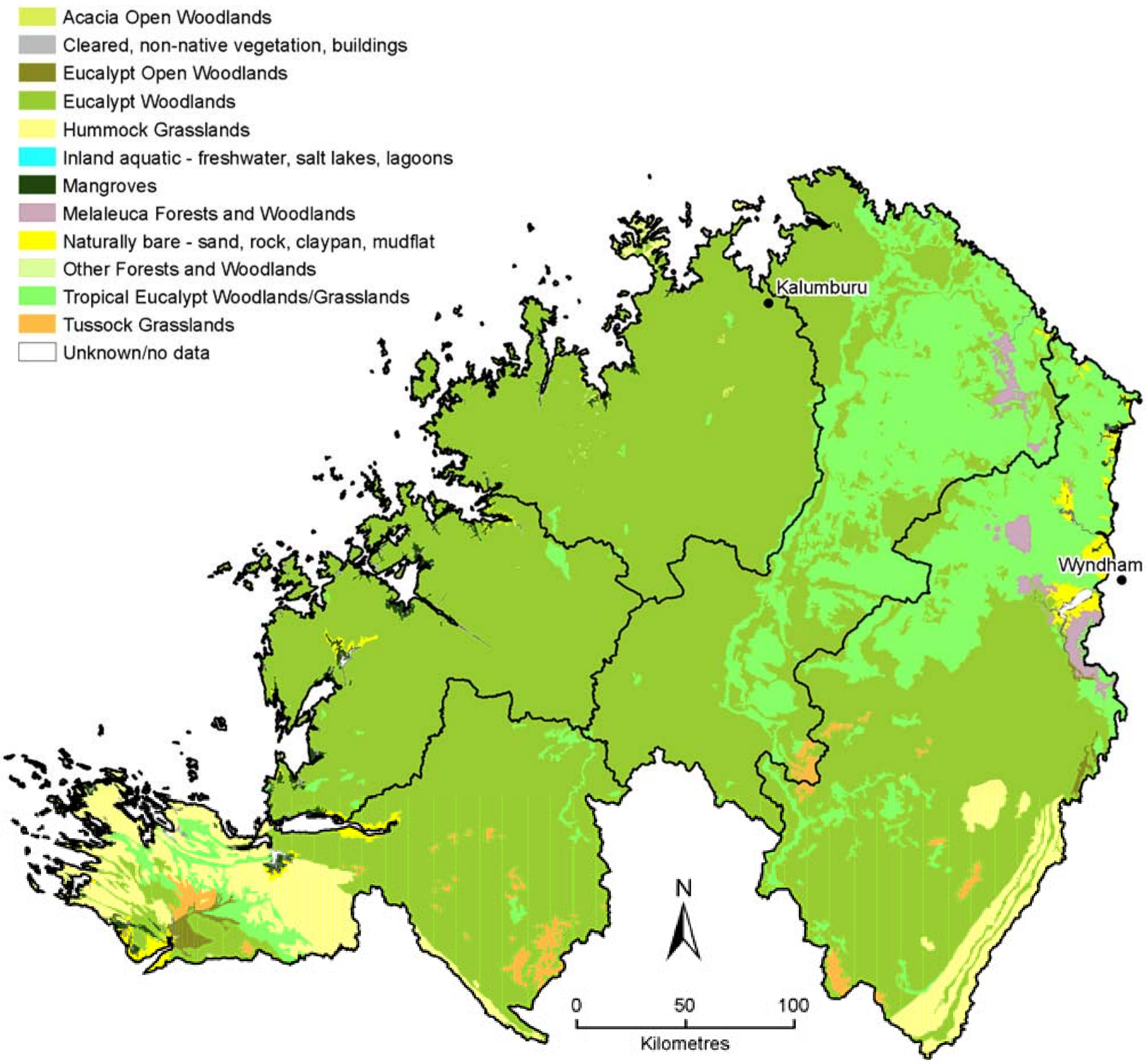


Figure KI-5. Map of current vegetation types across the Kimberley region (source DEWR, 2005)

The shallow sandy soils over Proterozoic siliceous sandstones support savannah woodland of Woollybutt and Darwin Stringy Bark rise over high Sorghum grasses and *Plectrachne schinzii* hummock grasses. The red and yellow earths mantling basic Proterozoic volcanics support savannah woodlands of *Eucalyptus tectifica* and *E. grandifolia* over high Sorghum grasses. Drainage lines support riparian closed forests of paperbark trees and *Pandanus*, while extensive mangroves occur in estuaries and sheltered embayments. Numerous small patches of monsoon rainforest are scattered through the district. These are the only occurrences of rainforests in Western Australia. They support a wide range of species of flora and associated fauna that do not occur elsewhere, and are of particular conservation significance.

Mangrove communities are a notable feature of the Kimberley coast, forming extensive low closed forests on tidal flats. These communities are more species rich than southern communities and are an important biological feature supporting diverse land and marine faunas, including many species dependent upon this habitat.

The predominance of grasses from a wide range of genera is also an important feature of the Kimberley flora.

The Kimberley was one of the earliest settled parts of Australia with the first arrivals landing about 40,000 years ago from the islands of what is now Indonesia. Alexander Forrest trekked across from the western coast to the Northern Territory in 1879. Forrest was the first European to discover and name the Kimberley district, as well as the Margaret and Ord rivers, the King Leopold Ranges, and the fertile area between the Fitzroy and Ord rivers. He subsequently set himself up as a land agent specialising in the region and was thus instrumental in the leasing of over 51,000,000 acres (210,000 km^2) in the region during 1883.

For the past century, the main land use in the Kimberley has been for pastoral activities. Currently, over half of the region is held under pastoral lease, comprising over 90 leases and carrying about half a million head of cattle (Figure KI-6).

The remaining land is either crown land, Indigenous reserve, conservation estate or freehold land in the major urban centres.

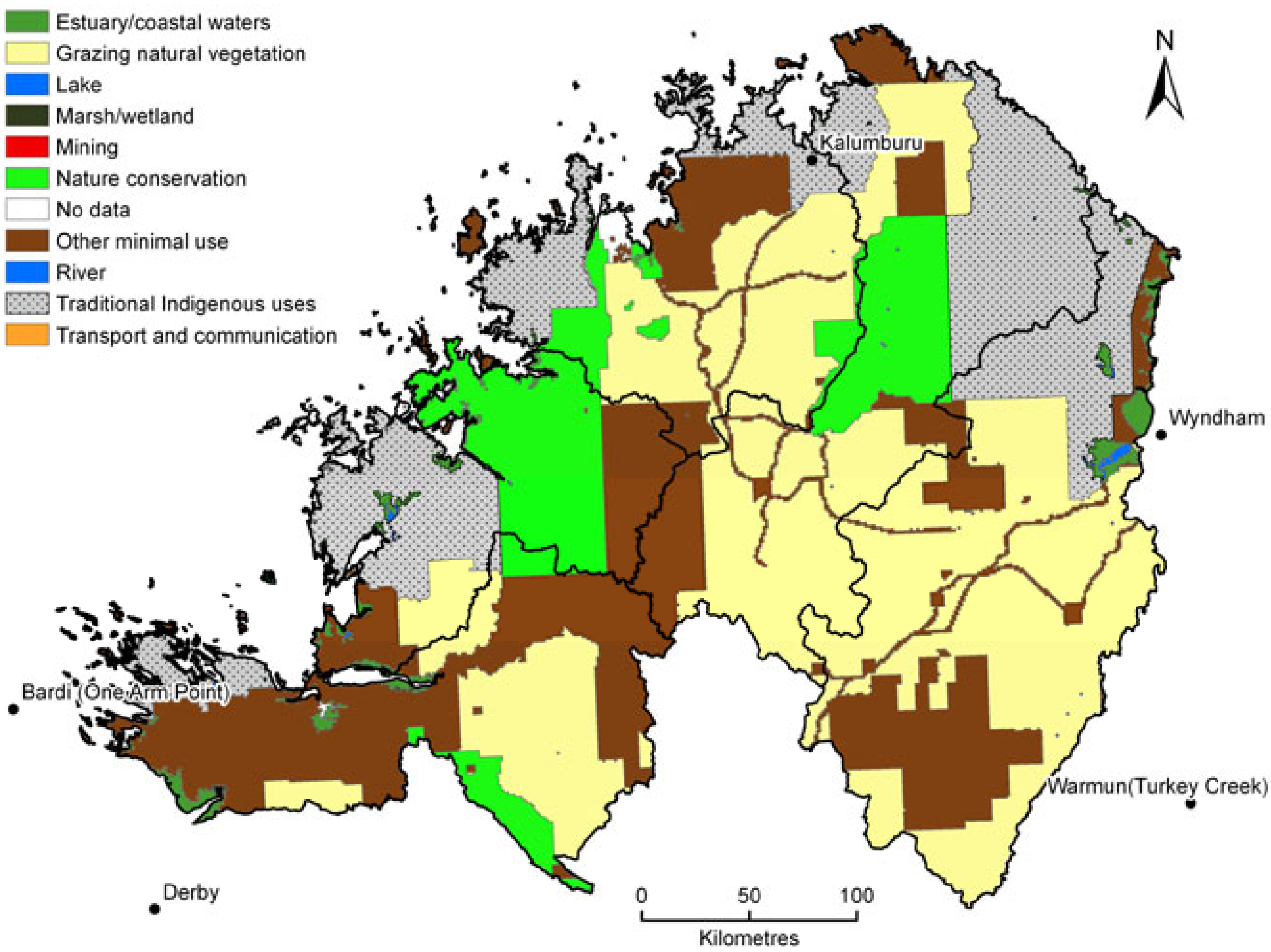


Figure KI-6. Map of dominant land uses of the Kimberley region (after BRS, 2002)

KI-2.1.3 Regional environmental asset description

Environmental assets were chosen from wetlands which are listed in the Directory of Important Wetlands in Australia (Environment Australia, 2001). From this directory, environmental assets were shortlisted for assessing changes to the hydrological regime under the climate and development scenarios. The selection of this shortlist was undertaken in consultation with state governments and the Australian Government through direct discussions and through internal reviews (see Section 1.3 in the division-level Chapter 1 for further detail).

All nationally, or internationally, important wetlands listed for the Kimberly region in the Directory of Important Wetlands in Australia (Environment Australia, 2001) are detailed in Table KI-2, with asterisks identifying the three shortlisted assets: Drysdale River, Mitchell River System and Prince Regent River System. The location of these shortlisted wetlands is shown in Figure KI-1. There are no wetlands classified as Ramsar sites in this region. Wetlands may be nationally or regionally significant depending on more locally specific criteria. All wetlands are important for a variety of ecological reasons or because they bear historical significance or have high cultural value, particularly to Indigenous people.

The following section characterises these shortlisted wetlands and is based largely on the description of these assets as outlined by Environment Australia (2001). Chapter KI-3 presents the assessment of those shortlisted assets, and reports hydrological regime metrics for those assets which have sufficient confidence in the modelled streamflow to enable analysis.

Table KI-2. List of Wetlands of National Significance located within the Kimberley region

Site code	Name	Area	Ramsar site
		ha	
WA062*	Drysdale River	5,670	No
WA063*	Mitchell River System	1,120	No
WA064*	Prince Regent River System	19,100	No

* Asterisk against the site code identifies those shortlisted for assessment of changes to hydrological regime.

Drysdale River

The Drysdale River site (Figure KI-7) is a good example of a permanent river of the bioregion and constitutes the largest system of river pools in the high rainfall north-west of the Kimberley. The site runs within or beside Drysdale River National Park. The site has an area of 5670 ha and an elevation ranging between approximately 80 and 310 m (Environment Australia, 2001). The site has 20 waterbird species that have been recorded, including four darters and cormorants and nine herons. The Drysdale system has the richest freshwater fish fauna (26 spp.) known in Western Australia. Three fish species are possibly endemic to the Drysdale River. The escarpment of the Drysdale River contains very important Indigenous art gallery sites.

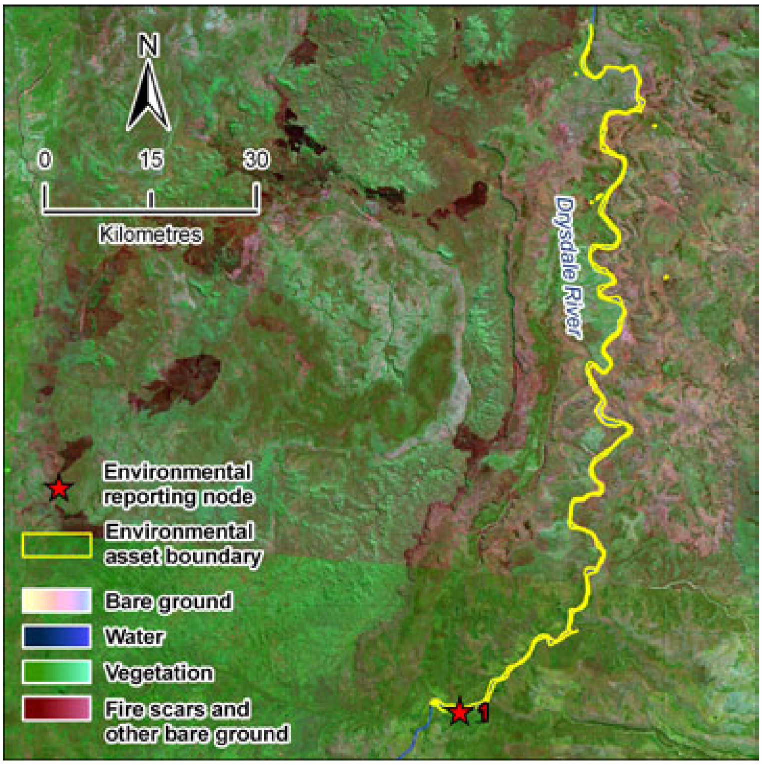


Figure KI-7. False colour satellite image of Drysdale River (derived from ACRES, 2000). Clouds may be visible in image

Mitchell River System

The Mitchell River System (Figure KI-8) is a good example of a complete, relatively small river system and estuary in the bioregion, with outstanding examples of escarpment waterfalls. The site comprises the entire Mitchell River drainage system and has an area of 1120 ha with an elevation between zero and 500 m above sea level (Environment Australia, 2001).

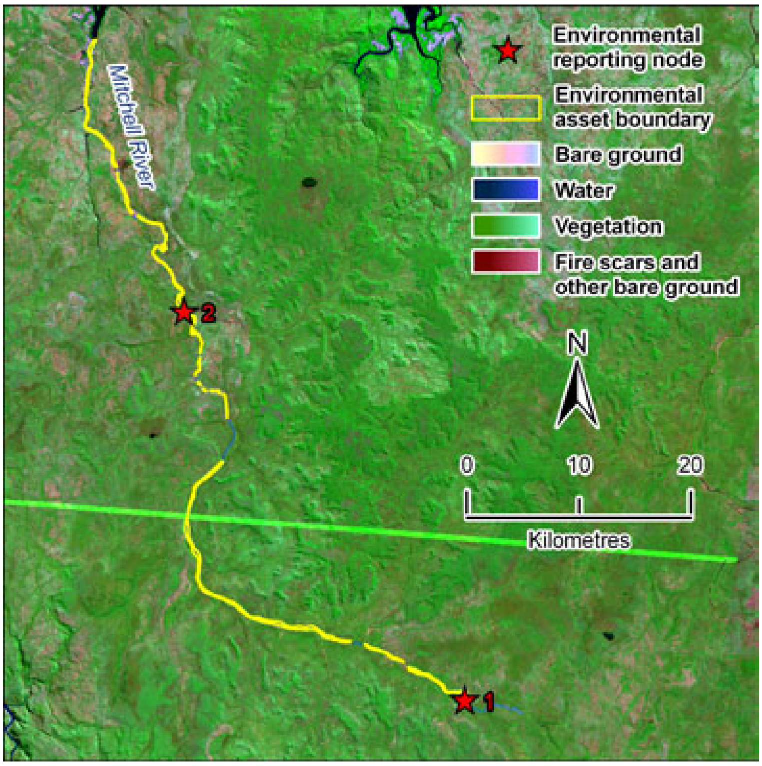


Figure KI-8. False colour satellite image of the Mitchell River System (derived from ACRES, 2000). Clouds may be visible in image

The site has notable terrestrial and aquatic flora including cycads and mangroves. Vegetation on Mitchell Plateau is dominated by eucalypts but *Livistona* sp. palms are common in the understorey and patches of rainforest occur near the escarpment (Burbidge et al., 1991; Johnstone, 1990).

The permanent fresh water and food resources of the site were valuable to Indigenous people in the past and some usage is likely to still occur (Environment Australia, 2001). Mitchell Falls are an increasingly popular tourist destination. The site's spectacular waterfalls are among the greatest aesthetic assets of the Kimberley. Most of the site's other wetlands are undisturbed and rarely visited (Environment Australia, 2001).

Prince Regent River System

The Prince Regent River System (Figure KI-9) is an outstanding example of a tropical estuary and river system incised in a plateau, and a good example of the mangrove-fringed embayments typical of the west coast of the bioregion. The site comprises the entire Prince Regent River System and large areas of mangrove on either side of the river mouth. The site has an area of 19,100 ha and has an elevation between zero and 779 m above sea level (Environment Australia, 2001).

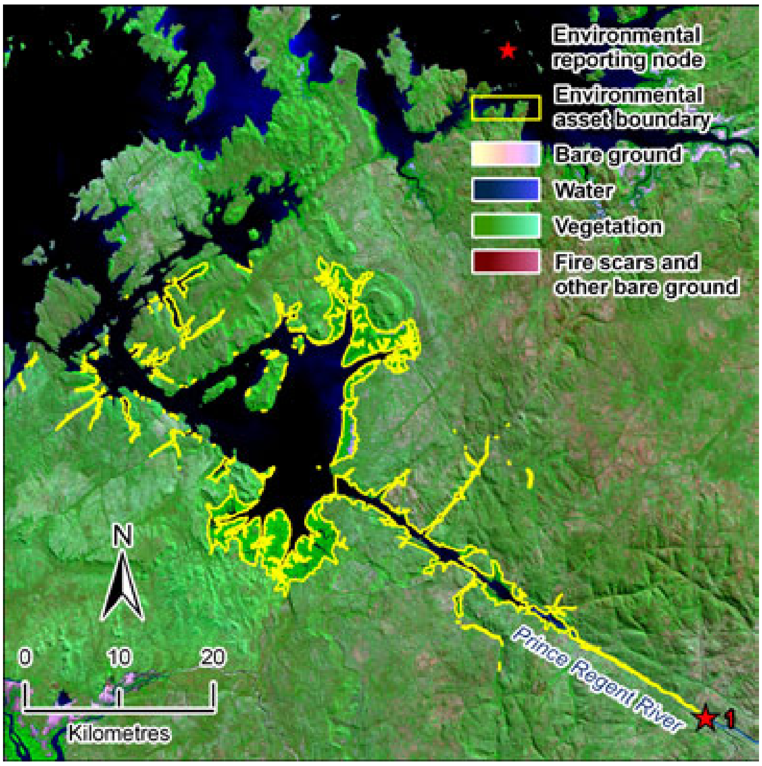


Figure KI-9. False colour satellite image of the Prince Regent River System (derived from ACRES, 2000). Clouds may be visible in image

At least ten mangrove species occur at the site (Environment Australia, 2001) and 15 waterbird species have been recorded. Both Freshwater and Saltwater Crocodiles occur, with the site including some of the most suitable and extensive breeding habitat for Saltwater Crocodile in Western Australia (Environment Australia, 2001). Indigenous cave paintings are situated in the reserve (Environment Australia, 2001). The area is becoming very popular for recreation, with access from the ocean by private and charter boats. Some of the most spectacular coastal scenery in Western Australia is found at the site.

KI-2.2 Data availability

KI-2.2.1 Climate

The rainfall-runoff modelling uses historical daily climate data (Scenario A) from the SILO database for the period 1 September 1930 to 31 August 2007 at 0.05 x 0.05 degree (~ 5 x 5 km) grid cells. Full details and characterisation of the SILO database are provided at the division level in Section 2.1 of Chapter 2. Scenario B and Scenario C climate data are rescaled versions of the Scenario A data; this is also discussed in Section 2.1 of Chapter 2.

KI-2.2.2 Surface water

Streamflow gauging stations are or have been located at 13 locations within the Kimberley region. Three of these gauging stations are either: (i) flood warning stations and measure stage height only, or (ii) have less than ten years of acceptable data. Of the remaining ten stations, four recorded more than half of their total volume of flow during events that exceed the maximum gauged stage height. Figure KI-10 shows the spatial distribution of good quality data (duration) and the proportion of flow above maximum gauged stage height (MGSH) (this assessment was only undertaken on stations with ten years or more data). In general the controls in the Kimberley region are good, with most gauging station sited on rock bars.

There are two gauging stations currently operating in the Kimberley region at a density of one station for every 54,900 km^2. This is the least number and lowest density of currently operating gauging stations of the 13 regions and is considerably below the Murray-Darling Basin average. For the 13 regions the median number of currently operating gauging stations per region is 12 and the median density of current gauging stations per region is one station for every 9700 km^2. The mean density of current stream gauging stations across the entire Murray-Darling Basin is one station for every 1300 km^2.

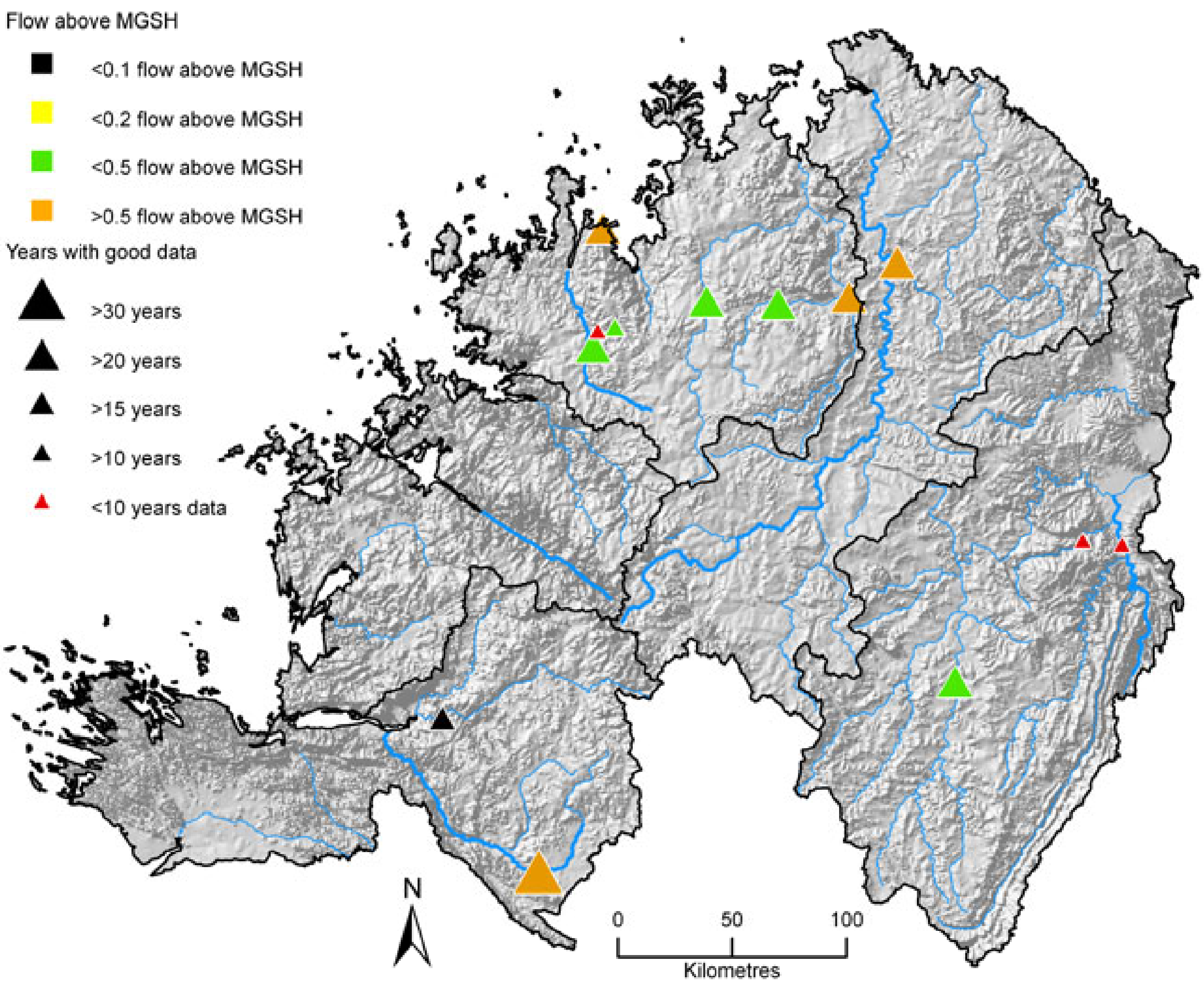


Figure KI-10. Location of streamflow gauging stations showing the proportion of flow above maximum gauged stage height across the Kimberley region, overlaid on a relative relief surface

KI-2.2.3 Groundwater

The Kimberley region contains a total of 70 registered groundwater bores. None of these bores have surveyed elevations that could enable watertable surfaces to be constructed for the main aquifers. There are 35 water level monitoring bores in the region; nine are historical and 26 are current.

KI-2.2.4 Data gaps

Historical groundwater level and salinity monitoring data are very sparse for the Kimberley region. The absence of such data has meant that the conceptual models presented in this report are largely theoretical. Furthermore, until a comprehensive groundwater monitoring network is established and data are available, there can be no quantitative analysis of current or future impacts of groundwater development or climate change.

KI-2.3 Hydrogeology

KI-2.3.1 Aquifer types

The Kimberley region is composed predominantly of Lower Proterozoic sandstones, basalt (Carson Volcanics) and dolerite (Hart Dolerite) as shown in Figure KI-2. Small, disconnected alluvial aquifers cover the remainder of the region, mostly bordering the larger rivers where they cross areas of low topographic relief.

Fractured rock aquifers

The sandstones, basalts and dolerites all contain fresh groundwater that is stored primarily in fractures, with watertables occurring at approximately 10 m below ground surface in flat country (Allen, 1966). Limited deep drilling information is available; however, it is likely that the vertical extent of these aquifers is significant. Changes in aquifer properties and salinity with depth are not widely known, although it is thought that salinity may increase with depth and if major faults are intersected, groundwater yields could potentially be high. Allen (1966) notes that the usual range for bore yields is from 0.6 to 1.9 L/second and that supplies exceeding 2.5 L/second are rare.

The Hart Dolerite and Carson Volcanics Basalt have been drilled for water supply more commonly than the sandstones since the soils associated with these units are more fertile than those of the sandstones, and they have been easier to drill (Passmore, 1967). Shallow bores (<20 m below ground surface) that are completed in the dolerite or basalt have yields typically around 1.9 L/second providing sufficient fractures have been intersected; numerous unsuccessful wells have also been drilled (Passmore, 1967). The Hart Dolerite aquifer is considered one of the best on the Kimberley Plateau while the Carson Volcanics basalt has more variable yields due to irregular fracturing (Allen, 1966).

Yields from wells completed in the sandstones are highly variable depending on the fractures intersected, but commonly range up to 2.5 L/second (Allen, 1966). Passmore (1967) has noted yields up to 9.3 L/second in some sandstone aquifers but comments that these regions have not been targetted for water supplies due to the difficulty of raising stock in sandstone country which have relatively poor soils. Fracture spacing is noted by Allen (1966) to be between 0.5 and 1.5 m for various sandstones of the Kimberley region.

Upper Proterozoic sediments cover a small area of the Kimberley region and are composed predominantly of shale with dolomite and dolomitic sandstones. The shales are not known to have significant fracturing while the dolomite is thought to be extensively jointed and may have dissolution features (Allen, 1966). The shales are of lesser groundwater potential due to their variable and generally lower yields (Allen, 1966) and higher salinities, particularly towards the end of groundwater flow paths (Passmore, 1967). The dolomite and dolomitic sandstone are considered to have reasonable groundwater potential depending on the density and characteristics of fractures intersected (Allen, 1966).

Alluvial aquifers

No regional-scale alluvial aquifers exist in the Kimberley region, but numerous small and disconnected aquifers are dotted along stretches of most of the major rivers (Allen, 1971; Derrick, 1969; Gellatly and Sofoulis, 1969; Plumb and Perry, 1971; Roberts and Perry, 1969; and Williams and Sofoulis, 1970). Allen (1966) suggests that alluvial aquifers exist more commonly along the interface of hard and soft formations (such as the King Leopold Sandstone and Carson Volcanics), as well as along the lower reaches of major rivers. He notes that most alluvial aquifers are small and isolated but that aquifers with a thickness of greater than 6 m have good potential for providing small supplies.

KI-2.3.2 Inter-aquifer connection and leakage

As described in Allen (1966) and Passmore (1967), it is thought that groundwater levels follow a subdued form of the topography with significant groundwater flow occurring only in the shallow parts of the aquifer, where fracture density is highest. Evidence of this shallow groundwater flow is in the form of both numerous springs and the perenniality of the major rivers in their lower reaches (Allen, 1966). If fracture sets extend to the base of the fractured rock units, it is likely that vertical leakage will occur between aquifers.

The potential for artesian conditions in deeper bores was discussed in a number of reports early in the last century, including the work of Jack (1906). In general it was thought that insufficient information on geological conditions would result in both uncertain results and problematic drilling. The concept, however, is based on the inference of deep flow paths and the potential for upward vertical leakage between geological units.

KI-2.3.3 Recharge, discharge and groundwater storage

Rapid recharge is thought to occur through the shallow skeletal soils and exposed fractured rock occurring across most of the Kimberley region (Allen, 1966). Recharge rates are thought to be low through clayey soils which have typically developed over areas of volcanic rocks and shales (Passmore, 1967). However preferential recharge is likely to occur early in the wet season through the cracks developed in the clays and then more slowly once the clays have swelled. Higher recharge rates are thought to occur in the fractured sandstone areas where more permeable soils exist and allow more rapid recharge to the fractured rock aquifers below. Passmore (1967) also notes that river recharge and leakage from thin alluvial aquifers may also be significant mechanisms for recharging the fractured rock aquifers. Recharge is thought to be greatest in the north-west of the region where rainfall is highest and decrease gradually towards the south-east.

Evapotranspiration is thought to be an important groundwater discharge mechanism since watertables are relatively shallow (typically shallower than 10 m below ground; Allen, 1966). Groundwater discharge through springs is also common in the Kimberley region, with numerous swampy areas and small permanent creeks being spring feed (Allen, 1966). The upper reaches of many major rivers host active groundwater springs, particularly in the Crosslands and Ellendale creeks which are tributaries to the Drysdale and Durack rivers respectively (Derrick, 1969). Allen (1966) also suggests that springs occur where rock sequences dip at 10 degrees or more, along small deeply incised tributaries and often on the contact between the King Leopold Sandstone and the Carson Volcanics basalt.

Groundwater discharge is responsible for maintaining permanent flows in the lower reaches of the major rivers of the Kimberley (Allen, 1966; Passmore, 1967). Upper reaches of the major rivers typically flow intermittently, and are reduced to isolated pools or dry riverbeds by the end of the dry season when groundwater levels fall below the river beds (Allen, 1966). There are however a number of rivers in the Kimberley region that have high volumes of dry season flow which is derived primarily from groundwater discharge (Table KI-1 and Figure KI-2).

Groundwater storage in the Kimberley Plateau has been estimated by Allen (1966) to be about 43,000 GL. This estimate was based on the assumption that open and frequent fracturing only exists in the upper 100 m of the aquifers and that little groundwater existed beyond this depth. It is likely, however, that groundwater does exist below 100 m and there may be high yielding zones along the interface between geological units.

KI-2.3.4 Groundwater quality

Groundwater across the Kimberley region is considered to be fresh and thus useful for most purposes (Allen, 1966; Passmore, 1967; Commander, pers. comm.). Groundwater salinity in the volcanic aquifers is reported to range from 300 to 1400 mg/L with an average of 440 mg/L (Allen, 1966; Passmore, 1967). Groundwater salinity for the alluvium and various sandstone aquifers ranges from 30 to 250 mg/L (Allen, 1966). The groundwater salinity in the Upper Proterozoic units (predominantly shales) are said to have values of less than 1000 mg/L near rivers and in areas more distant from rivers salinities could be greater than 3500 mg/L (Allen, 1966). There is very little recent groundwater salinity data; however the current groundwater salinity is thought generally to be less than 500 mg/L across much of the Kimberley region.

KI-2.4 Legislation, water plans and other arrangements

KI-2.4.1 Legislated water use, entitlements and purpose

In 1998, the Western Australia Department of Water commenced work on a *Kimberley Regional Water Allocation Plan*. This plan is still being developed and will provide a broad strategic plan establishing a Kimberley-wide (i.e. regional) framework to guide water allocation decisions and licensing policy for individual water resources or sub-regions (e.g. La Grange groundwater basin, the Ord River) within the Kimberley geographic extents. The department uses regional allocation plans to determine the priority environmental values and beneficial uses of surface and groundwater resources within a particular region. The *Kimberley Regional Water Allocation Plan* will provide a preliminary assessment of the amount of groundwater and surface water development that is considered to be ecologically sustainable after taking into account of ecological and social water values and will be subject to review by the Environmental Protection Agency. The *State Water Plan (2007)* provides a strategic framework to sustainably meet growing water demands.

There are no sub-region allocation plans for this region.

Current

Groundwater use in the Kimberley consists of a number of scattered pastoral bores and minor water supply bores for remote communities (Allen, 1966). Information from the Department of Water show two small allocations, one for Tablelands Station (18.25 ML/year) on the upper Chamberlain River and the other for Marunbabidi Community (4 ML/year) on the upper King Edward River.

Future

Tourism continues to increase through the region, but this has minimal water requirement at this stage. There is limited mining interest in the region (diamonds, bauxite) which are currently under evaluation. Indigenous values are high and pastoralism is likely to remain the main water user from local stock and domestic bores.

KI-2.4.2 Rivers and storages

Demand in the region is low and the cost of harnessing a reliable surface water supply in the region is very high due to the lack of infrastructure and remoteness and ruggedness of the region. A sufficiently-sized catchment would be required and most rivers in the region are short and deeply incised into the fractured rocks of the basement. The large flood events would also require expensive infrastructure to enable by-pass flow during extreme events. Hence, there are no water storages in the region.

KI-2.4.3 Unallocated water

There are currently no allocation limits on water in the region.

KI-2.4.4 Social and cultural considerations

There is no published literature describing the social or cultural values of this region. Anthropological studies for native title claims are likely to contain information on the significance of rivers and other assets to Indigenous groups, although these may be confidential.

Yu’s (2000) report provides a brief review of some anthropological literature relevant to the cultural significance of water to Indigenous people. Based on literary sources, she concludes that Indigenous concepts of serpents living in water-holes, rainmaking and ”living water” were found throughout much of Indigenous Australia (Yu, 2000). She noted that literature focusing on the water systems of the wet-dry tropical Kimberley region was scarce.

As part of the ongoing national 'Wild Rivers Project", the Western Australian Water and Rivers Commission has identified those rivers in Western Australia that remain in a 'pristine' or 'near pristine' condition. Of the 26 rivers in the state considered 'wild', 17 of them are located in the Kimberley region (i.e. the Timor Sea Drainage Division). Most of the identified wild rivers in the Kimberley are located in the remote and inaccessible north-west coastal region.

The Kimberley region has recently been declared for its heritage significance, with the West Kimberley, including about 22,500,000 ha, generally extending from Roebuck Bay in the west to the Hann River (including Drysdale River National Park) in the east, and from the Fitzroy River in the south to, and including, the Bonaparte and Buccaneer Archipelagos in the north, now listed on the National Heritage List.

KI-2.4.5 Changed diversion and extraction regimes

There are no diversion schemes, nor extraction regimes, in the region other than for local stock and domestic supply, including provision for fishing camps and tourism activities.

KI-2.4.6 Changed land use

There has been minimal land use change to the region. There is no expected change in the near future.

KI-2.4.7 Environmental constraints and implications of future development

The region has high conservation and Indigenous values. Any future development will managed using a precautionary approach. Environmental, water security and Indigenous needs will be recognised and will be guided by the *Kimberley Regional Water Allocation Plan*, currently under consideration.

KI-2.5 References

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KI-3 Water balance results for the Kimberley region

This chapter describes modelling results and the assessment of the water resources undertaken by this project for the Kimberley region. Detailed, quantified assessments are made where possible, and relevant, and confidence is estimated. Modelling results are reported under climate and development scenarios as defined at the division level in Section 2.1 of Chapter 2. This chapter is sub-divided into:

- climate
- recharge estimation
- conceptual groundwater models
- groundwater modelling results
- rainfall-runoff modelling results
- river system water balance
- changes to flow regimes at environmental assets.

KI-3.1 Climate

KI-3.1.1 Historical climate

The Kimberley region receives an average of 950 mm of rainfall over a September to August water year (Figure KI-11), most of which (898 mm) falls in the November to April wet season (Figure KI-12). Across the region there is a strong north–south gradient in annual rainfall (Figure KI-13), ranging from 1223 mm in the north to 628 mm in the south. Over the first half of the historical (1930 to 2007) period, rainfall has been relatively constant at around 750 mm. The second half of the period has seen an increase in mean rainfall to approximately 1050 mm. The highest yearly rainfall received was 1679 mm which fell in 2000, and the lowest was 477 mm in 1936.

Historical areal potential evapotranspiration (APET) is very high across the region, averaging 1994 mm over a water year (Figure KI-11), and varies moderately across the seasons (Figure KI-12). APET generally remains higher than rainfall throughout the year resulting in annually water-limited conditions.

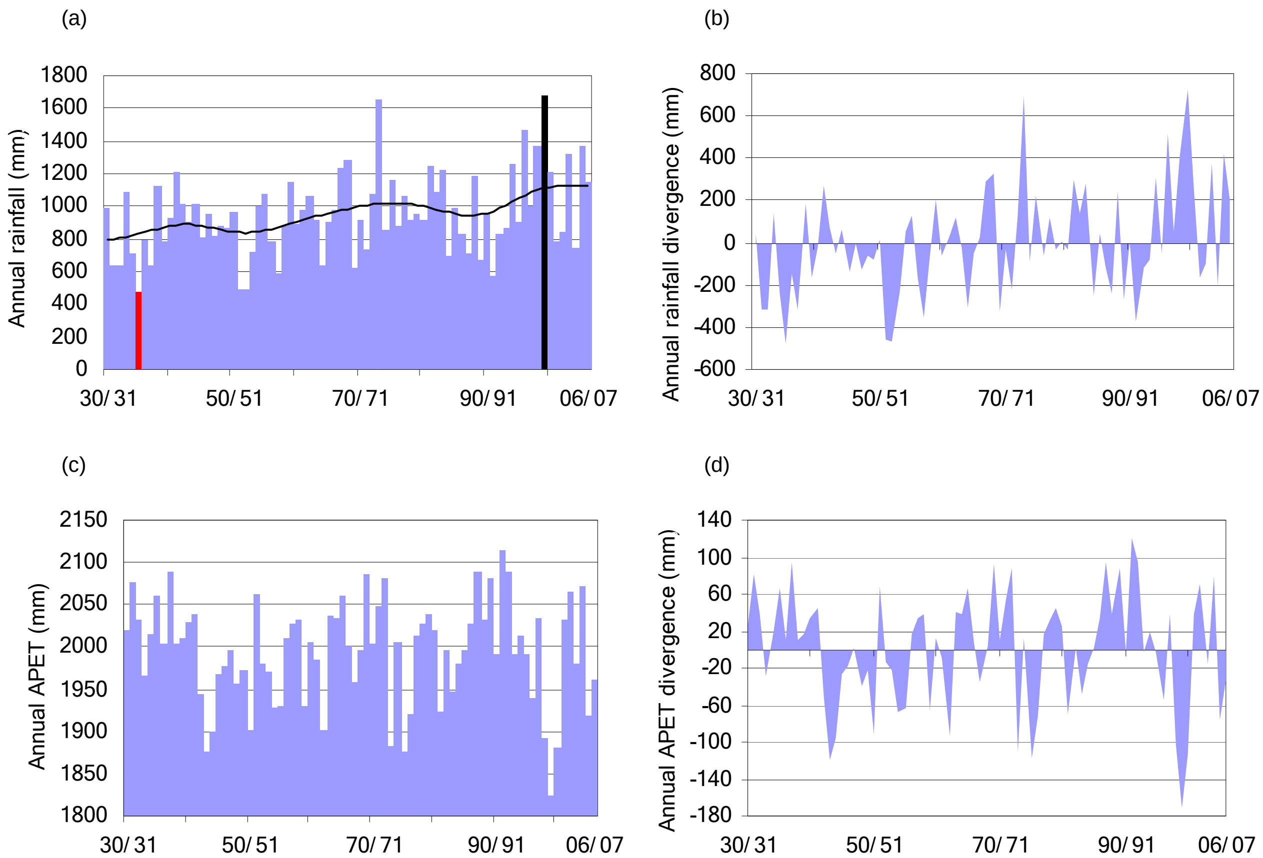


Figure KI-11. (a) Historical annual rainfall and (b) its divergence from the long-term mean; and (c) historical annual areal potential evapotranspiration and (d) its divergence from the long-term mean averaged over the Kimberley region. The low-frequency smoothed line in (a) indicates longer term variability

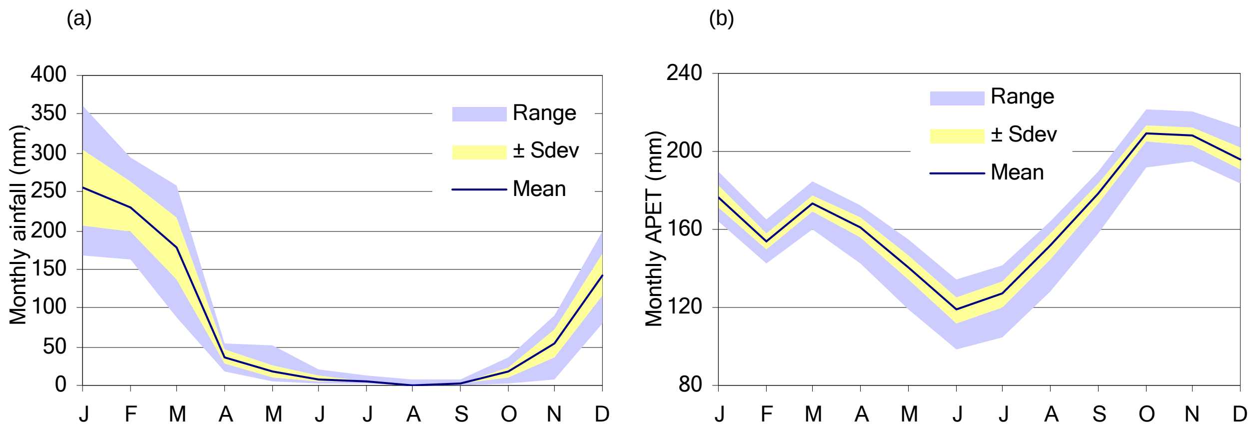


Figure KI-12. Historical mean monthly (a) rainfall and (b) areal potential evapotranspiration and their temporal variation (range and ± one standard deviation) averaged over the Kimberley region

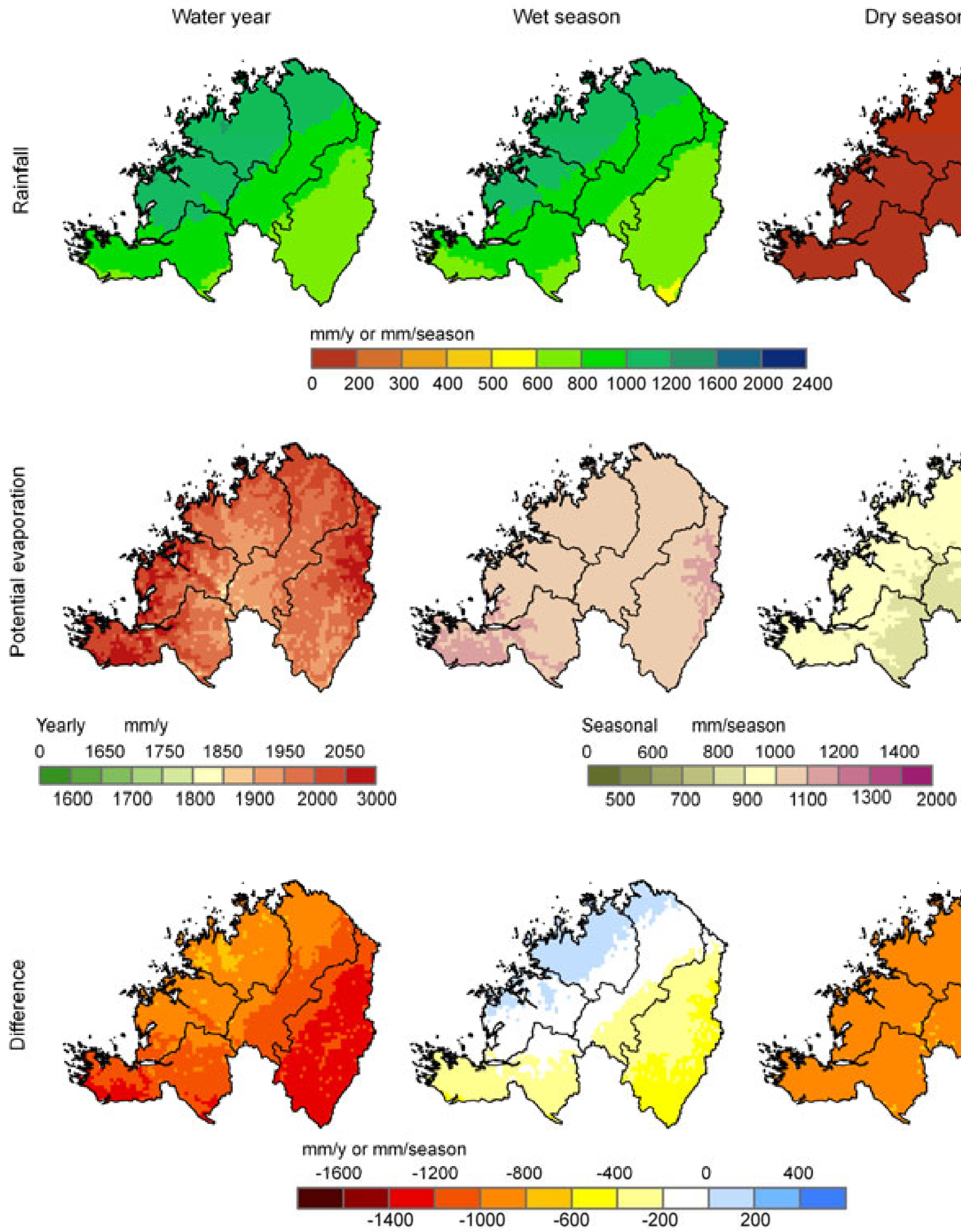


Figure KI-13. Spatial distribution of historical mean annual (water year), wet season and dry season rainfall and areal potential evapotranspiration (potential evaporation) and their difference (rainfall less areal potential evapotranspiration) across the Kimberley region

KI-3.1.2 Recent climate

Figure KI-14 compares recent (1996 to 2007) to historical (in this case the 66-year period from 1930 to 1996) mean annual rainfall for the Kimberley region. Across the whole region, recent rainfall is between 10 and 60 percent higher than historical rainfall – a statistically significant difference for the majority of the region.

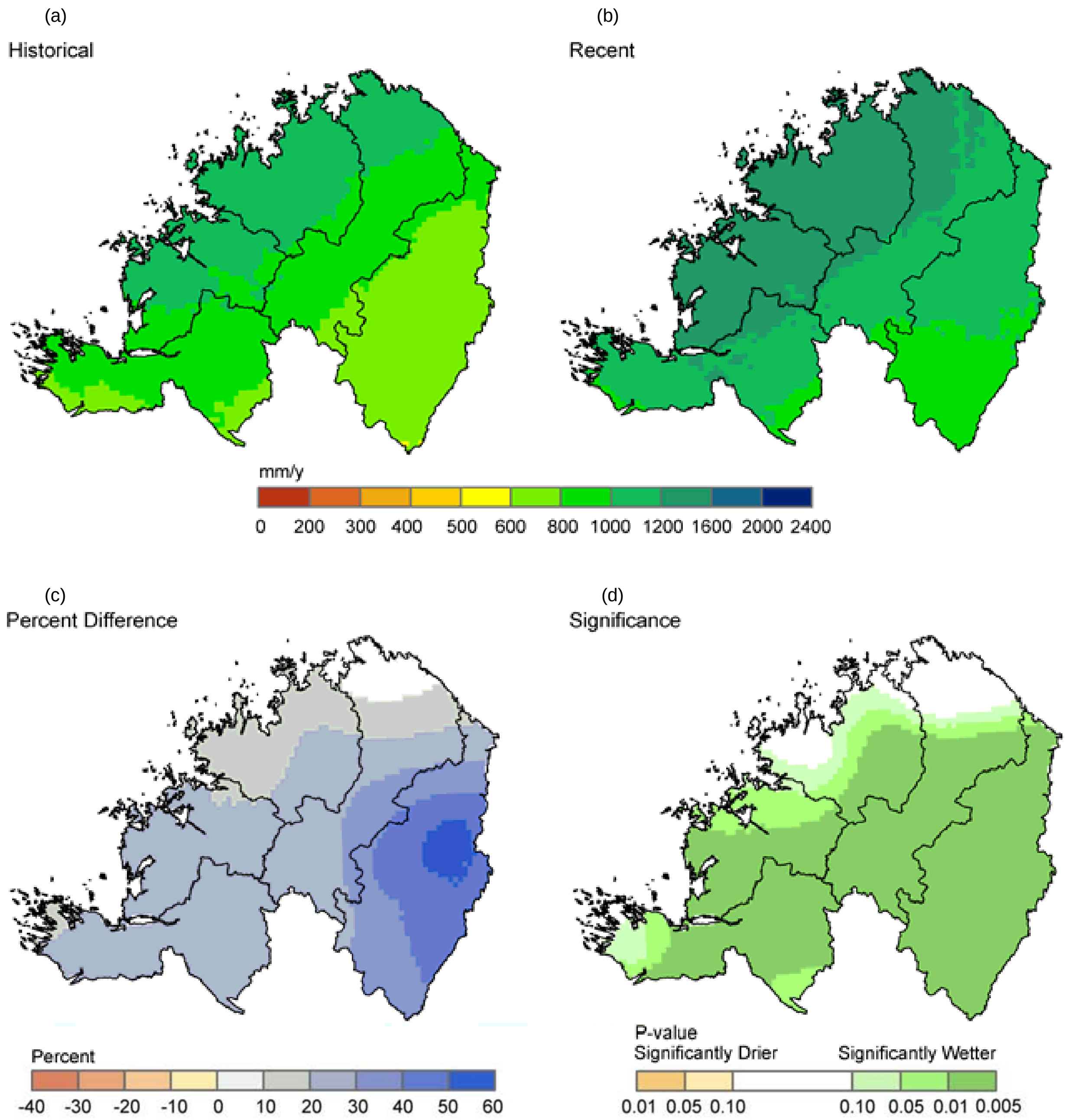


Figure KI-14. Spatial distribution of (a) historical and (b) recent mean annual rainfall; and (c) their relative percent difference and (d) the statistical significance of these differences across the Kimberley region. (Note that historical in this case is the 66-year period 1930 to 1996)

KI-3.1.3 Future climate

Under Scenario C annual rainfall varies between 819 mm and 1006 mm (Table KI-3) compared to the historical mean of 950 mm. Similarly, APET ranges between 2065 and 2076 mm compared to the historical mean of 1994 mm.

A total of 45 variants of Scenario C were modelled (15 global climate models (GCMs) for each of the high, medium and low global warming scenarios). Subsequently, results from an extreme 'wet', median and extreme 'dry' variant are shown (referred to as scenarios Cwet, Cmid and Cdry). Under Scenario Cwet annual rainfall and APET increase by 6 percent and 4 percent, respectively. Under Scenario Cmid annual rainfall increases by 1 percent and APET increases by 4 percent. Under Scenario Cdry annual rainfall decreases by 14 percent and APET increases by 4 percent.

Under Scenario Cmid long-term monthly averages of rainfall and APET do not differ much from historical values (Figure KI-15). Under Scenario Cmid rainfall lies well within the range in values from all 45 future climate variants. The seasonality of rainfall changes slightly only in that any changes in rainfall occur in the wet season. However there is appreciable variation in rainfall in the wet season months, varying by up to 50 mm/month. In contrast, the seasonality of APET remains the same as any changes occur uniformly across the year. Under Scenario Cmid APET lies near the middle of the range in values derived from all 45 future climate variants.

The spatial distributions of rainfall and APET under Scenario C are compared to the historical distribution in Figure KI-16 and Figure KI-17. Under Scenario C the strong north–south gradient in rainfall is retained, but with a southwards shift under Scenario Cwet and a northwards shift under Scenario Cdry. Under scenarios Cmid and Cdry the rainfall gradient changes due to relatively greater decreases in rainfall occurring along the northern coastlines compared to the south of the region. The spatial distribution of APET under Scenario C is similar to the highly regionalised historical distribution. The greatest changes to APET occur in the south and east of the region.

Table KI-3. Mean annual (water year), wet season and dry season rainfall and areal potential evapotranspiration averaged over the Kimberley region under historical climate and Scenario C

	Water year	Wet season	Dry season
	mm/y	mm/season	
Rainfall			
Historical	950	898	53
Cwet	1006	938	55
Cmid	959	894	53
Cdry	819	765	44
Areal potential evapotranspiration			
Historical	1994	1069	926
Cwet	2068	1102	963
Cmid	2065	1105	957
Cdry	2076	1114	959

* Note that the sum of the wet season and dry season values does not always equal the water year values because the combined wet season and dry season period (November to October) is different to the water year period (September to August).

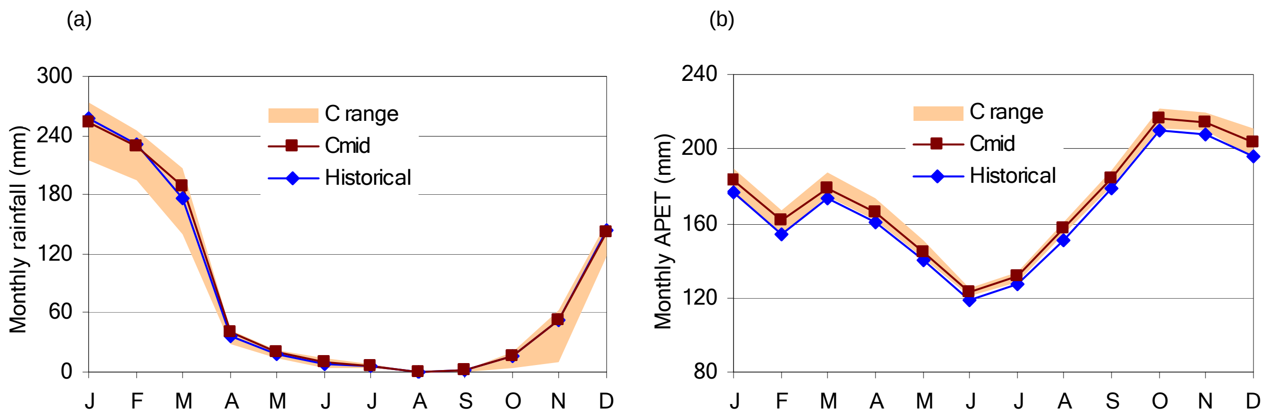


Figure KI-15. Mean monthly (a) rainfall and (b) areal potential evapotranspiration averaged over the Kimberley region under historical climate and Scenario C. (C range is the range under the 45 Scenario C simulations – the lower and upper limits in C range are therefore not the same as scenarios Cdry and Cwet)

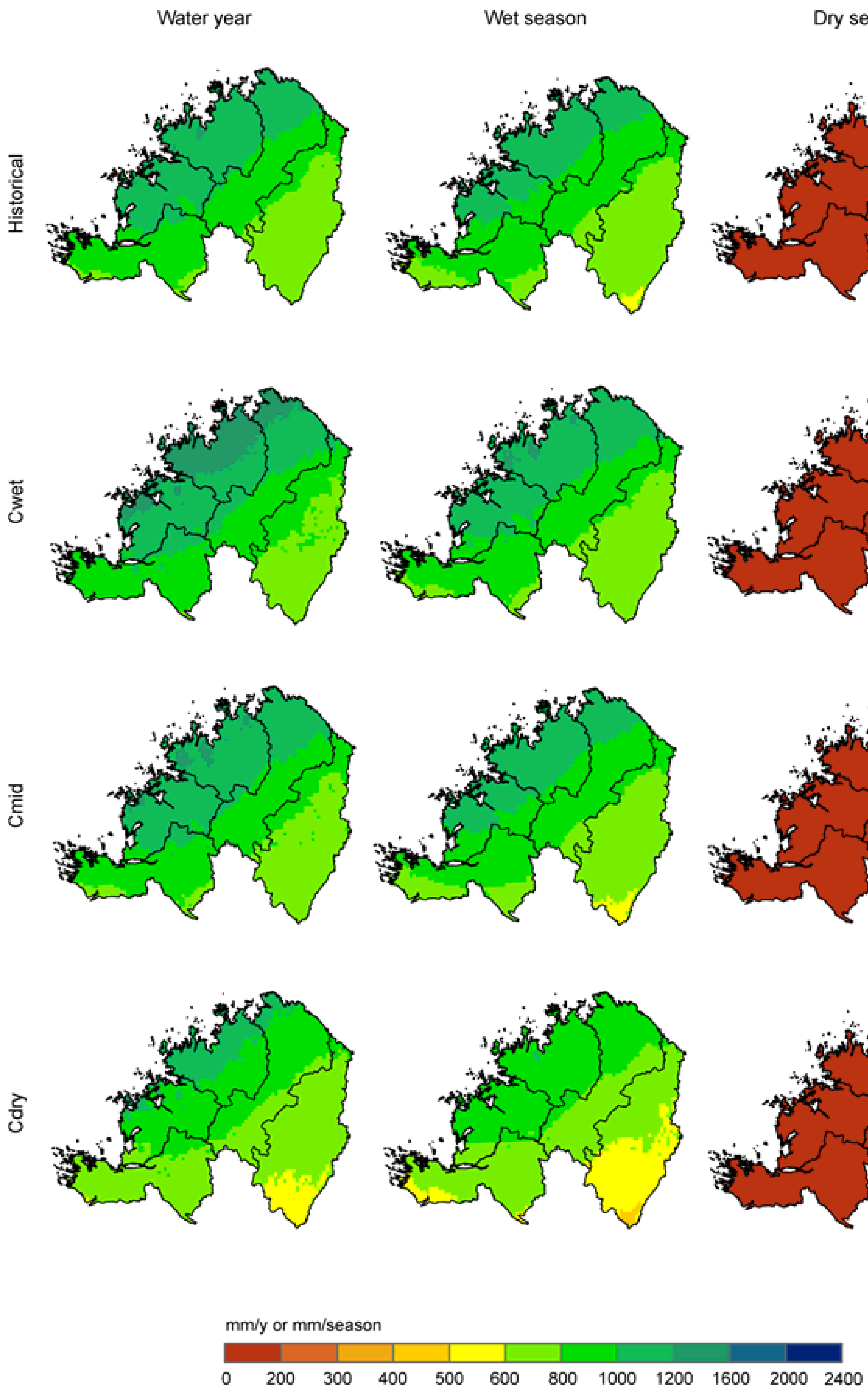


Figure KI-16. Spatial distribution of mean annual (water year), wet season and dry season rainfall across the Kimberley region under historical climate and Scenario C

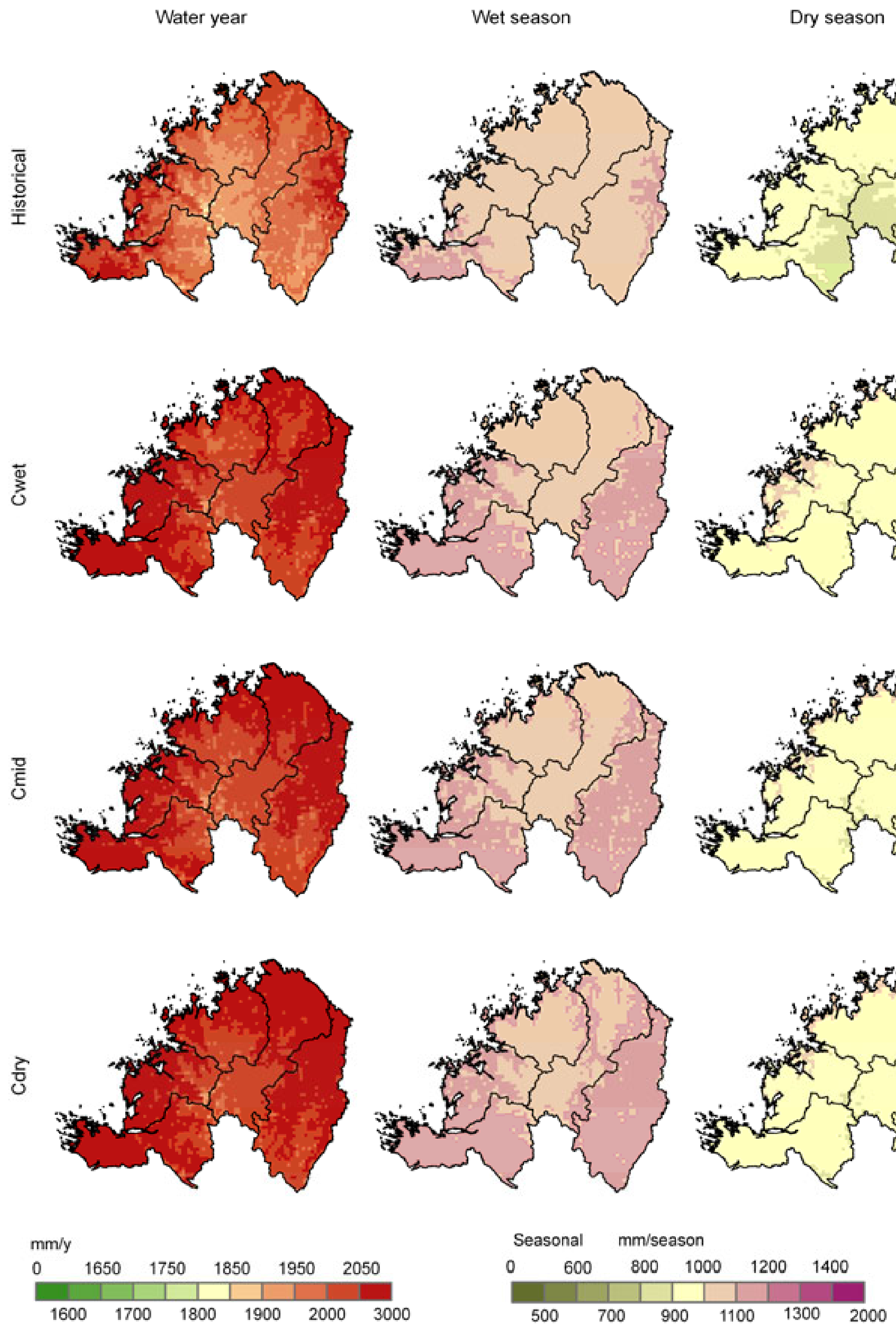


Figure KI-17. Spatial distribution of annual (water year), wet season and dry season areal potential evapotranspiration (potential evaporation) across the Kimberley region under historical climate and Scenario C

KI-3.1.4 Confidence levels

Analysis of confidence of the climate data is reported in Section 2.1.4 in the division-level Chapter 2.

KI-3.2 WAVES potential diffuse recharge estimations

The WAVES model (Zhang and Dawes, 1998) was used to estimate the change in groundwater recharge across the Kimberley region under a range of different climate scenarios. WAVES is a vertical recharge flux model that can model plant physiological feedbacks in response to increased CO_2, as well as modelling the water balance of different soil, vegetation and climate regimes. It was chosen for its balance in complexity between plant physiology and soil physics. It was also used to assess recharge for the Murray-Darling Basin Sustainable Yields Project (Crosbie et al., 2008).

KI-3.2.1 Under historical climate

Figure KI-18 shows the spatial distribution of calculated historical recharge for the Kimberley region, with calculated recharge greatest in the north-east and decreasing progressively to the south-west following the rainfall gradient. The historical record was assessed to establish any difference between wet and dry periods of recharge. A 23-year period was used, which allows the projection of recharge estimates to 2030 – in other words, to estimate recharge in 2030 assuming future climate is similar to historical climate (Scenario A).

For the three variants of Scenario A the recharge does change for the 23-year period when compared to the 77-year historical value (Table KI-4). Under a wet historical climate (Awet) the Kimberley region is calculated to have, on average, a 10 percent increase in recharge (i.e., a recharge scaling factor (RSF), averaged across the region, of 1.10). Under the median estimate of historical climate (Amid) the Kimberley region is calculated to have a 2 percent decrease in recharge that is quite uniform across the region. Under a dry historical climate (Adry) the Kimberley region is calculated to have a 13 percent decrease in recharge. Where unweathered bedrock outcrops occur, confidence in the modelled results is reduced. The locations of these outcrops in the Kimberley region are shown on the historical recharge map in Figure KI-18.

Table KI-4. Recharge scaling factors in the Kimberley region for scenarios A, B and C

Region	Awet	Amid	Adry	B	Cwet	Cmid	Cdry
Kimberley	1.10	0.98	0.87	1.33	1.21	1.08	0.91

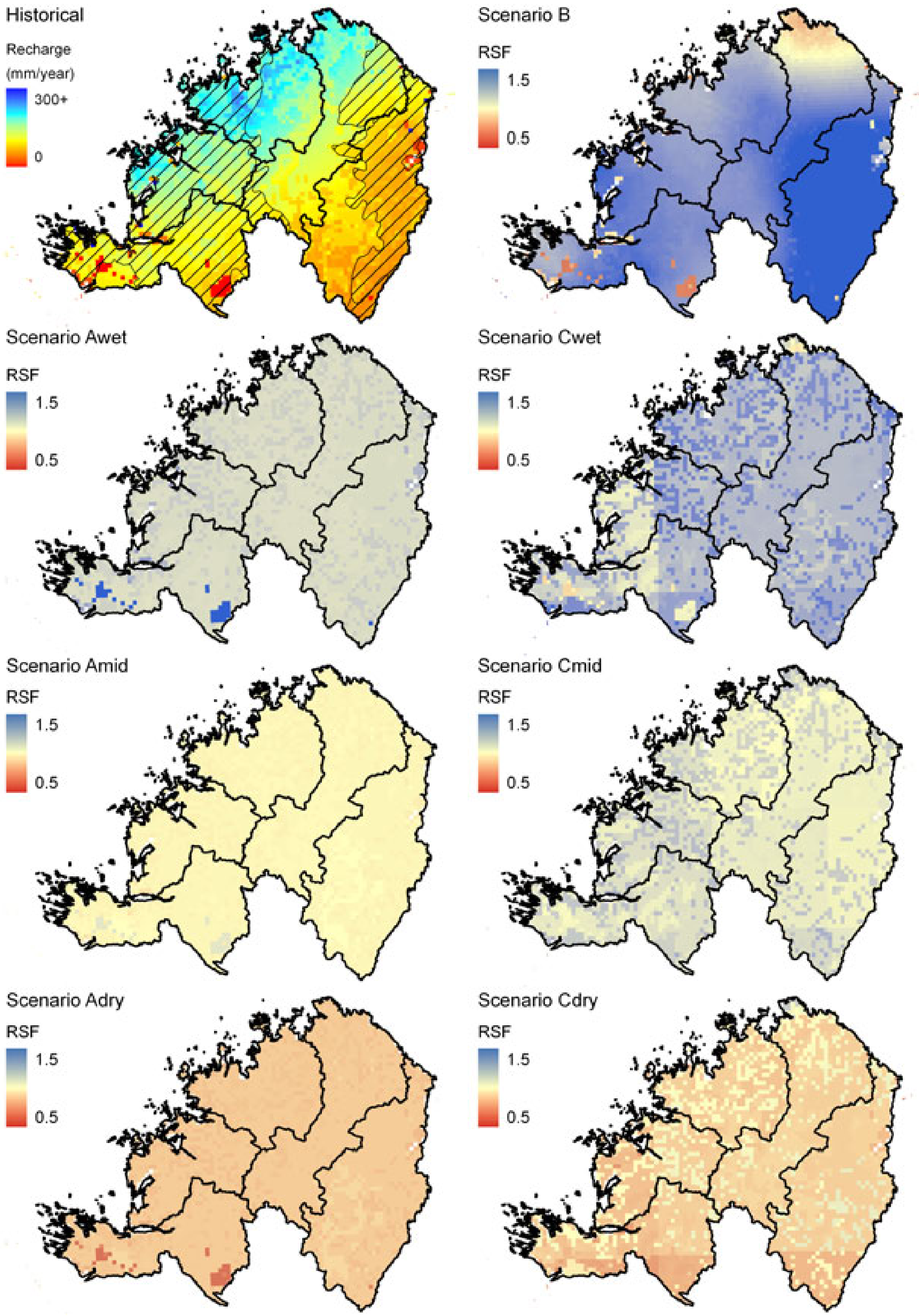


Figure KI-18. Spatial distribution of historical mean recharge rate; and recharge scaling factors in the Kimberley region for scenarios A, B and C. The hatched region on the historical recharge map identifies where unweathered bedrock outcrops occur

KI-3.2.2 Under recent climate

The recent (1996 to 2007) climate in the Kimberley region has been wetter than the historical (1930 to 2007) average and consequently the calculated recharge has seen an increase of 33 percent under Scenario B relative to Scenario A (Table KI-4). This increase has not been spatially uniform with the greatest increase in recharge in the west of the region and the north of the region shows a decrease in recharge (Figure KI-18).

KI-3.2.3 Under future climate

Figure KI-19 shows the percentage change in modelled mean annual recharge averaged over the Kimberley region under Scenario C relative to Scenario A for the 45 scenarios (15 GCMs for each of the high, medium and low global warming scenarios). The percentage change in the mean annual rainfall and recharge from the corresponding GCMs are also tabulated in Table KI-5. For the recharge projections from the GCM named ‘inmcm’, recharge is projected to decrease despite an increase in rainfall. This is because total rainfall is not the only climate variable that influences recharge. Daily rainfall intensity, temperature and CO_2 concentration are also important drivers (see Section 2.3.3 in the division-level Chapter 2), and specific situations can result in this counter-intuitive result. In particular, rainfall intensity is seen as a significant factor in this relationship.

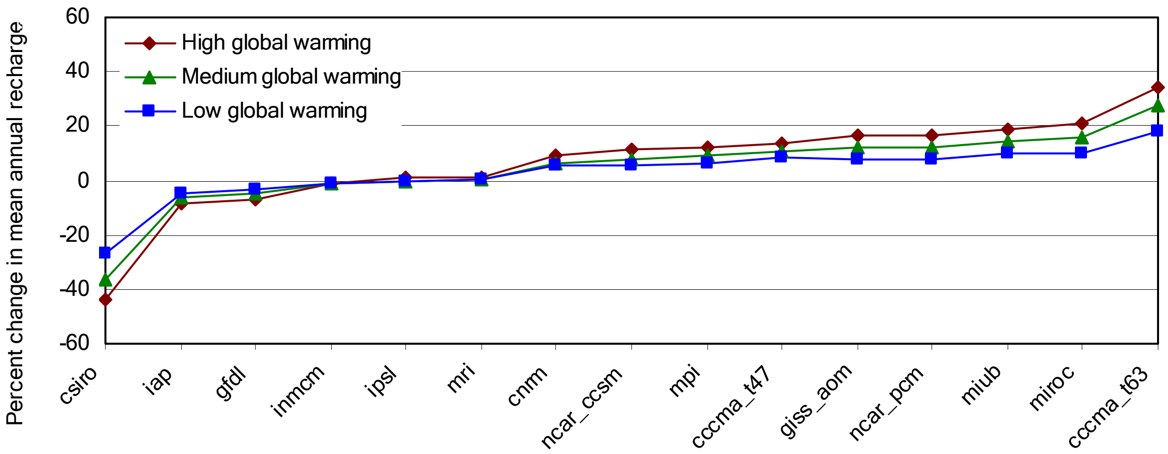


Figure KI-19. Percentage change in mean annual recharge under the 45 Scenario C simulations (15 global climate models and three global warming scenarios) relative to Scenario A recharge

Table KI-5. Summary results under the 45 Scenario C simulations (numbers show percentage change in mean annual rainfall and recharge under Scenario C relative to Scenario A)

High global warming			Medium global warming			Low global warming		
GCM	Rainfall	Recharge	GCM	Rainfall	Recharge	GCM	Rainfall	Recharge
csiro	-23%	-44%	csiro	-18%	-37%	csiro	-12%	-27%
iap	**-6%**	**-9%**	iap	-4%	-7%	iap	-3%	-5%
gfdl	-13%	-7%	gfdl	-10%	-5%	gfdl	-7%	-4%
inmcm	1%	-1%	inmcm	1%	-1%	inmcm	1%	-1%
ipsl	0%	1%	ipsl	0%	0%	ipsl	0%	0%
mri	0%	1%	mri	0%	1%	mri	0%	0%
cnrm	1%	9%	cnrm	1%	6%	cnrm	1%	5%
ncar_ccsm	4%	11%	**ncar_ccsm**	**3%**	**8%**	ncar_ccsm	2%	5%
mpi	1%	12%	mpi	1%	9%	mpi	1%	6%
cccma_t47	4%	14%	cccma_t47	3%	11%	cccma_t47	2%	8%
giss_aom	6%	16%	giss_aom	5%	12%	giss_aom	3%	8%
ncar_pcm	4%	16%	ncar_pcm	3%	12%	ncar_pcm	2%	8%
miub	2%	19%	miub	1%	14%	miub	1%	10%
miroc	**5%**	**21%**	miroc	4%	16%	miroc	3%	10%
cccma_t63	8%	34%	cccma_t63	6%	27%	cccma_t63	5%	18%

Under Scenario Cwet the Kimberley region is calculated to have an increase in recharge of 21 percent. Under Scenario Cmid the Kimberley region is calculated to have an increase in recharge of 8 percent. Under Scenario Cdry the Kimberley region is calculated to have a decrease in recharge of 9 percent.

KI-3.2.4 Confidence levels

The estimation of recharge from WAVES is only indicative of the actual recharge and has not been validated with field measurements. A steady state groundwater chloride mass balance has been conducted as an independent measure of recharge (Crosbie et al., 2009). The results in the Kimberley region show that the historical estimate of recharge using WAVES (120 mm/year) is less than the best estimate using the chloride mass balance (209 mm/year) but it is within the confidence limits of the chloride mass balance (51 to 424 mm/year).

KI-3.3 Conceptual groundwater models

Fractured rock aquifers across the Kimberley region, consisting of Lower Proterozoic sandstone, basalt and dolerite, are recharged directly following intense and prolonged rainfall events during the wet season as well as through river recharge when river levels are elevated. Shallow groundwater is likely to discharge locally to rivers towards the end of the wet season and early dry season, and small semi-permanent springs exist in some inland areas. Rivers do not receive prolonged groundwater discharge through the dry season in their upper reaches due to the generally low storage of the fractured rock aquifers. However river flow is maintained throughout the dry season in the lower reaches of some rivers due to regional groundwater discharge. Groundwater also discharges regionally via evapotranspiration where vegetation can access the water table and via throughflow towards the coast. Knowledge of groundwater in deeper aquifers is limited because the shallow groundwater is of good quality and has yields that meet existing demands.

KI-3.3.1 Baseflow indexing comparison with conceptual models

The annual baseflow index (BFI) values in the Kimberley region range from 0.07 to 0.32 with a median of 0.21 (n=8) (Table KI-1). All of the gauges on which analyses were performed are located towards the middle or lower reaches of the respective rivers. It is therefore likely that the rivers are receiving regional groundwater discharge in at least some of the dry season. This has a good correlation to the conceptual model developed for the region. The dry season baseflow volumes shown in Figure KI-2 are similar for all gauges except for the Drysdale River gauge which has a larger catchment area relative to the other gauges. A relatively high dry season baseflow (for location along river length) is seen in the Isdell River gauge which may be due to springs associated with the Carson Volcanics Basalt in the area. It is difficult to determine any relationship between BFI and dry season flows or any potential correlation to geology since gauges yield similar values and are located in similar fractured rock settings.

KI-3.4 Groundwater modelling results

The paucity of groundwater data and absence of an existing numerical model meant that a quantitative assessment of the water balance was not possible for the Kimberley region.

KI-3.5 Rainfall-runoff modelling results

In this section the term runoff is the sum of overland flow, interflow and baseflow. It is equivalent to streamflow expressed as a mm depth equivalent. All plots show data averaged over the modelled subcatchments of the Kimberley region. For this reason rainfall reported in this section may vary slightly from that reported elsewhere due to differences between the catchment boundaries (shown in Figure KI-1) and the DEM-derived catchment boundaries used here. In this section, where annual data are reported, years are represented by numbers 1 through 77. Consistently throughout this report, annual data are based on the water year (1 September to 31 August) and the dry season is defined as 1 May to 31 October. Unless stated otherwise scenarios Cwet, Cmid and Cdry are selected on the basis of the ranked mean annual runoff. For more details on methods refer to Section 2.2 of the division-level Chapter 2.

KI-3.5.1 Regional synopsis

The rainfall-runoff modelling estimates runoff in 0.05 degree grid cells in 48 subcatchments (Figure KI-20). Optimised parameter values from 12 calibration catchments are used. Ten of these calibration catchments are in the Kimberley region and two are in the Ord-Bonaparte region. The majority of the calibration catchments are situated away from the coastal fringes of the region.

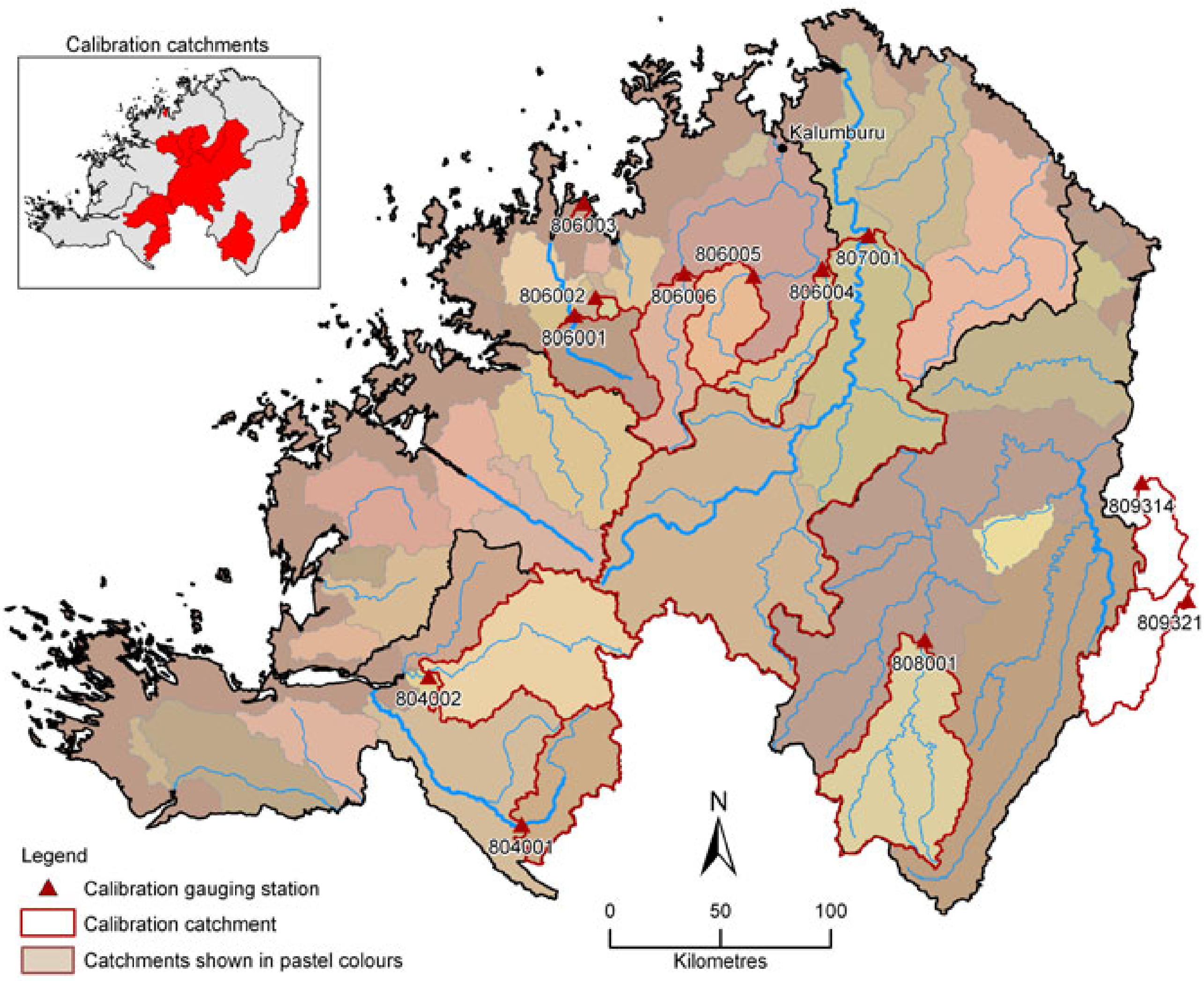


Figure KI-20. Map of the modelling subcatchments, calibration catchments and calibration gauging stations used for the Kimberley region with inset highlighting (in red) the extent of the calibration catchments

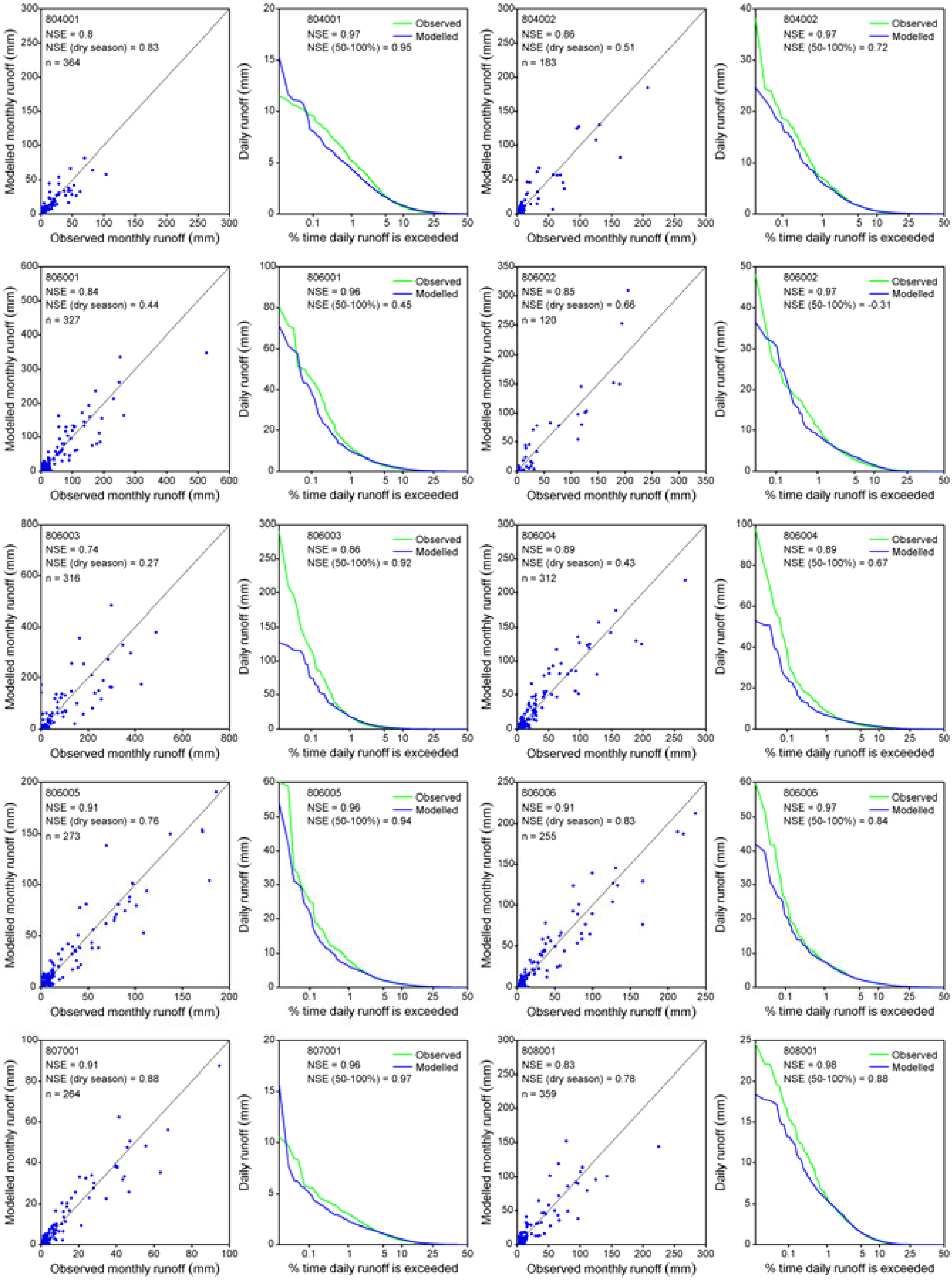
KI-3.5.2 Model calibration

Figure KI-21 compares the modelled and observed monthly runoff and the modelled and observed daily flow exceedance curves for the 12 calibration catchments. Nash-Sutcliffe efficiency (NSE) values provide a quantitative measure of how well simulated values match observed values. NSE values are described in more detail in Section 2.2.3 of the division-level Chapter 2. On the monthly plots NSE is the monthly Nash-Sutcliffe efficiency value and NSE (dry season) is the dry season monthly Nash-Sutcliffe efficiency value. On the daily flow exceedance plots, NSE is the daily flow exceedance curve Nash-Sutcliffe efficiency value and NSE (50 to 100 percent) is the lower half of the daily flow exeedance curve Nash-Sutcliffe efficiency value.

The results indicate that the ensemble calibration of the rainfall-runoff models Sacramento and IhacresClassic can reasonably reproduce the observed monthly runoff series (NSE values generally greater than 0.8) and the daily flow exceedance curve (NSE values generally greater than 0.9). The volumetric constraint used in the model calibration also ensures that the total modelled runoff is within 5 percent of the total observed runoff.

The calibration method places more importance on the simulation of high runoff, and therefore rainfall-runoff modelling of the medium and high runoff is considerably better than the modelling of low runoff. It should be noted, however, that while the relative difference between the observed and simulated low flow values may be large (which is what gives rise to the low monthly dry season NSE values for example), the absolute difference between the observed and simulated low flow values is generally small because both values are small. Nevertheless, an optimisation to reduce overall error variance can result in some underestimation of high runoff and overestimation of low runoff. This is evident in some of the scatter plots comparing the modelled and observed monthly runoff and many of the daily flow exceedance curves.

For the majority of calibration catchments the disagreement between the modelled and observed daily runoff curves is discernable for runoff that is exceeded less than 0.1 percent of the time. This is accentuated in the plots because of the linear scale on the y-axis and normal probability scale on the x-axis. In any case, the volumetric constraint used in the model calibration ensures that the total modelled runoff is always within 5 percent of the total observed runoff. As indicated by the relatively low NSE values for the lower half of the daily flow exceedance curve and monthly dry season there may be considerable disagreement between observed and modelled low flow values (i.e. cease-to-flow). Overall the monthly NSE values are considered sufficient for the general purposes of estimating long-term mean annual runoff.


804001
NSE = 0.8
NSE (dry season) = 0.83
n = 364
804001
NSE = 0.97
NSE (50-100%) = 0.95
804002
NSE = 0.86
NSE (dry season) = 0.51
n = 183
804002
NSE = 0.97
NSE (50-100%) = 0.72
806001
NSE = 0.84
NSE (dry season) = 0.44
n = 327
806001
NSE = 0.96
NSE (50-100%) = 0.45
806002
NSE = 0.85
NSE (dry season) = 0.66
n = 120
806002
NSE = 0.97
NSE (50-100%) = -0.31
806003
NSE = 0.74
NSE (dry season) = 0.27
n = 316
806003
NSE = 0.86
NSE (50-100%) = 0.92
806004
NSE = 0.89
NSE (dry season) = 0.43
n = 312
806004
NSE = 0.89
NSE (50-100%) = 0.67
806005
NSE = 0.91
NSE (dry season) = 0.76
n = 273
806005
NSE = 0.96
NSE (50-100%) = 0.94
806006
NSE = 0.91
NSE (dry season) = 0.83
n = 255
806006
NSE = 0.97
NSE (50-100%) = 0.84
807001
NSE = 0.91
NSE (dry season) = 0.88
n = 264
807001
NSE = 0.96
NSE (50-100%) = 0.97
808001
NSE = 0.83
NSE (dry season) = 0.78
n = 359
808001
NSE = 0.98
NSE (50-100%) = 0.88
Observed
Modelled
Modelled monthly runoff (mm)
Observed monthly runoff (mm)
Daily runoff (mm)
% time daily runoff is exceeded

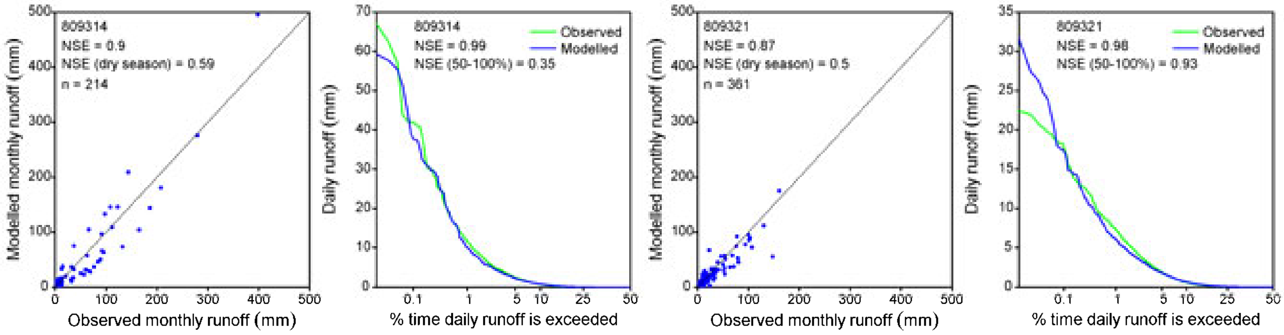


Figure KI-21. Modelled and observed monthly runoff and daily flow exceedance curve for each calibration catchment in the Kimberley region. (Red text denotes catchments that lie outside the region; blue text denotes catchments used for streamflow modelling only)

KI-3.5.3 Under historical climate

Figure KI-22 shows the spatial distribution of mean annual rainfall and runoff under Scenario A (averaged over 1930 to 2007) across the Kimberley region. Figure KI-23 shows the mean annual rainfall and runoff averaged over the region. The runoff grid extends outside of the AWRC boundary due to a discrepancy between it and the DEM-derived catchment boundary.

The mean annual rainfall and runoff averaged over the Kimberley region are 936 mm and 153 mm respectively. The mean wet season and dry season runoff averaged over the Kimberley region are 148 mm and 5 mm respectively.

In this project, all runoff grids are presented as long-term mean annual values. However the distributions of monthly and annual runoff data in northern Australia can be highly skewed; consequently the median and 10th and 90th percentile values spatially averaged over the region are also reported. The 10th percentile, median and 90th percentile annual runoff values across the Kimberley region are 311, 133 and 30 mm respectively. The median wet season and dry season runoff averaged over the Kimberley region are 129 mm and 4 mm respectively.

The mean annual rainfall varies from about 1200 mm in the north-west to 600 mm in the south-east. The mean annual runoff varies from over 400 mm in the central west to about 50 mm in the central Kimberley region i.e. the upper reaches of the Drysdale river (Figure KI-22). Runoff coefficients in the subcatchments vary from about 10 to 30 percent of rainfall. The majority of rainfall and runoff occurs during the wet season months December to April (Figure KI-24). Rainfall and runoff can vary considerably from year to year with long periods over several years or decades that are considerably wetter or drier than others (Figure KI-23). The coefficients of variation of annual rainfall and runoff averaged over the Kimberley region are 0.26 and 0.78 respectively.

The Kimberley is one of 13 regions which cover the three divisions studied in this project. Mean annual rainfall and runoff, as well as coefficients of variation, have been calculated for all of these 13 regions, and it is useful to compare the Kimberley results to results across all 13 regions. Across all 13 regions in this project 10th percentile, median and 90th percentile values are 1371, 936 and 595 mm respectively for mean annual rainfall and 374, 153 and 78 mm respectively for mean annual runoff. The mean annual rainfall (936 mm) and runoff (153 mm) averaged over the Kimberley region fall in the middle of this range. Across all 13 regions in this project the 10th percentile, median and 90th percentile values are 0.34, 0.26 and 0.19 respectively for the coefficient of variation of annual rainfall and 1.39, 0.69 and 0.48 for the coefficient of variation of runoff. The coefficients of variation of annual rainfall (0.26) and runoff (0.78) averaged over the Kimberley region fall within the middle of the values of the 13 reporting regions.

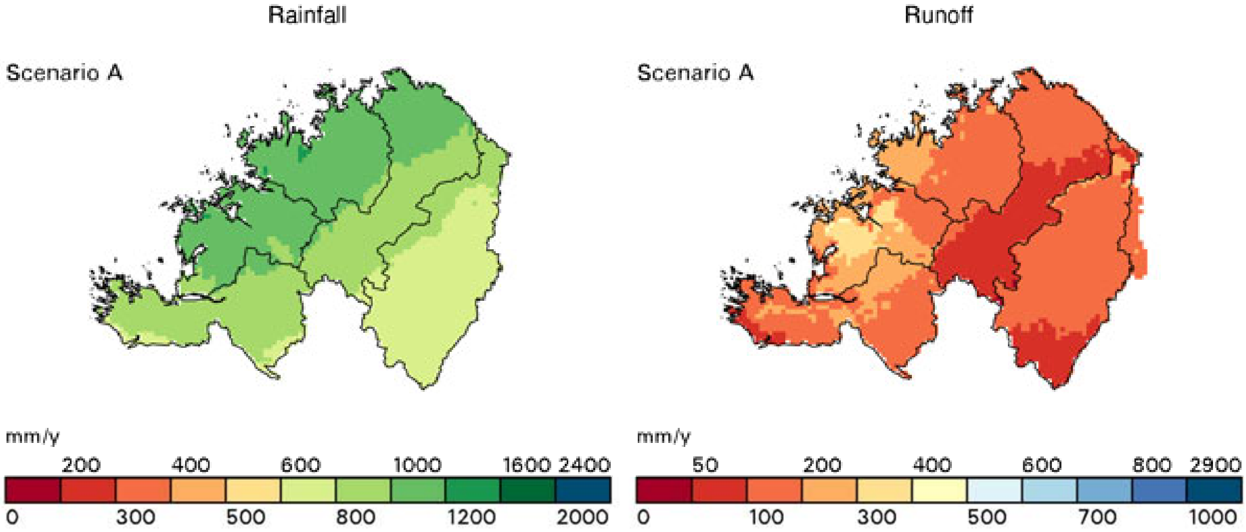


Figure KI-22. Spatial distribution of mean annual rainfall and modelled runoff across the Kimberley region under Scenario A

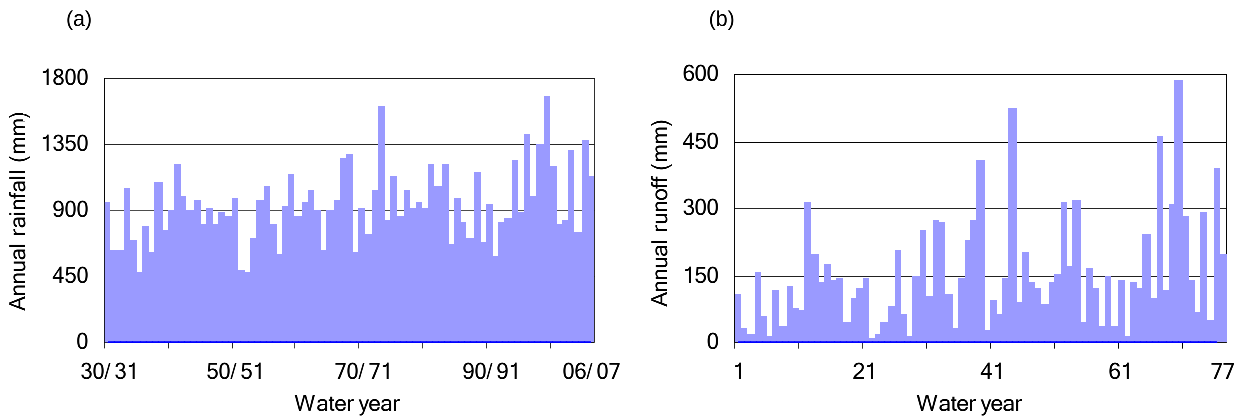


Figure KI-23. Mean annual (a) rainfall and (b) modelled runoff in the Kimberley region under Scenario A

Figure KI-24(a,b) shows the minimum and maximum monthly rainfall and runoff and the range of values between the 25th and 75th percentile monthly rainfall and runoff. Figure KI-24(c,d) shows the mean and median monthly flows and the range of values between the 25th and 75th percentile monthly rainfall and runoff. The large difference in the mean and median wet season monthly runoff values indicates that the distribution of monthly runoff in the Kimberley region is highly skewed.

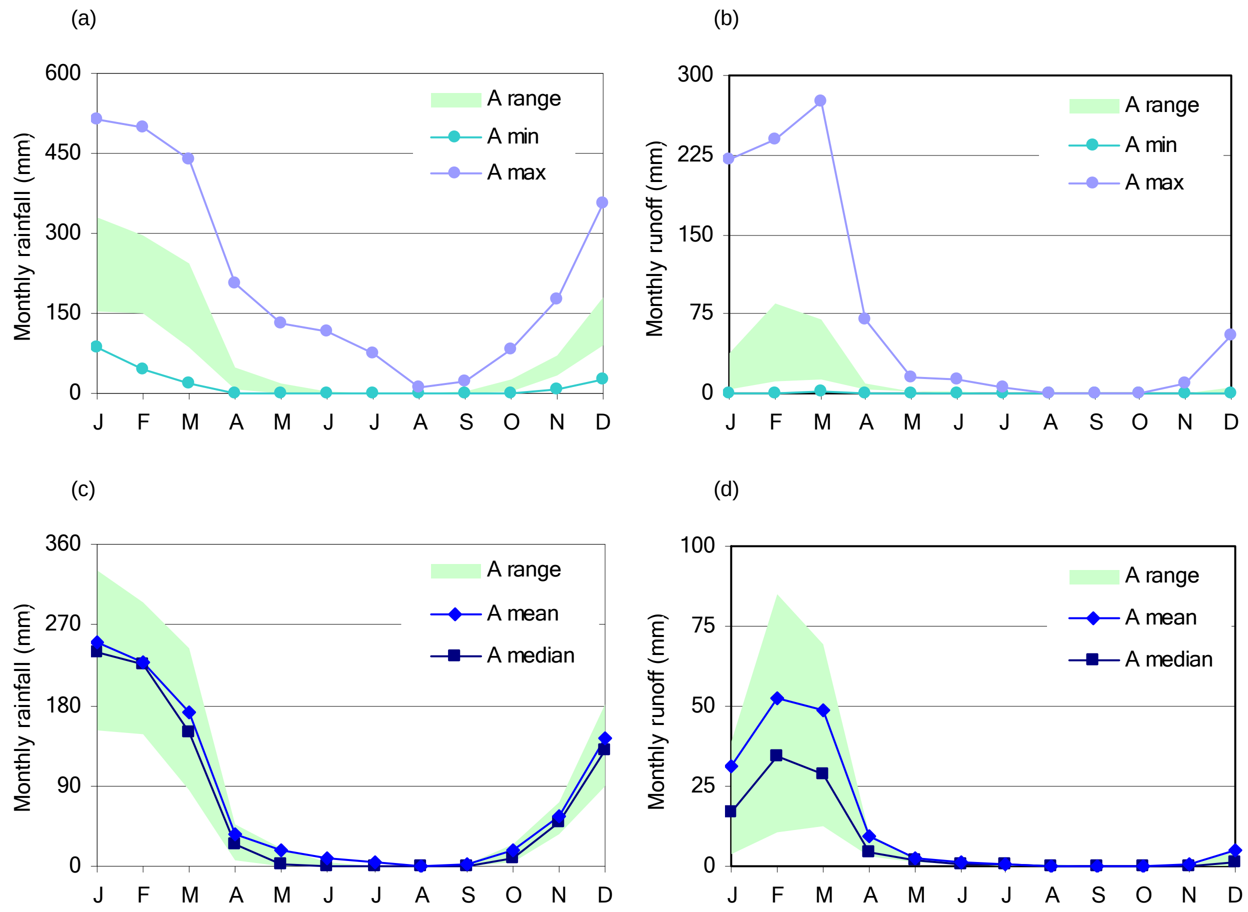


Figure KI-24. Minimum, maximum and A range monthly (a) rainfall and (b) modelled runoff; and mean, median and A range monthly (c) rainfall and (d) modelled runoff in the Kimberley region under Scenario A (A range is the 25th to 75th percentile monthly rainfall or runoff)

KI-3.5.4 Under recent climate

The mean annual rainfall and runoff under Scenario B (1996 to 2007) are 25 percent and 71 percent higher respectively than the historical (1930 to 2007) mean values. The spatial distribution of rainfall and runoff across the Kimberley region under Scenario B is shown in Figure KI-25.

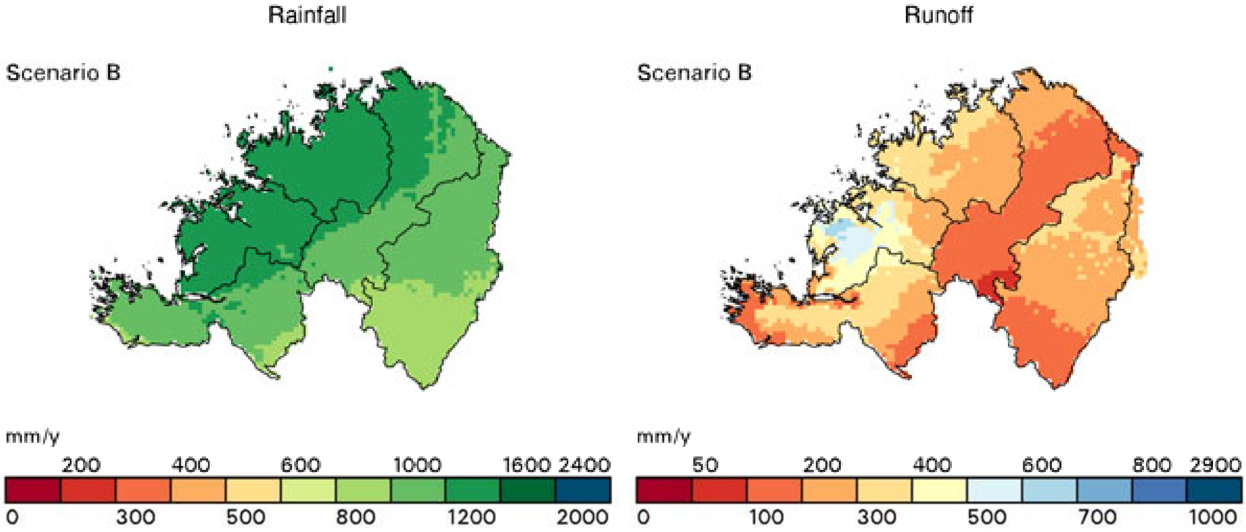


Figure KI-25. Spatial distribution of mean annual rainfall and runoff across the Kimberley region under Scenario B

KI-3.5.5 Under future climate

Figure KI-26 shows the percentage change in the mean annual runoff averaged over the Kimberley region under Scenario C relative to Scenario A for the 45 scenarios (15 global climate models (GCMs) for each of the high, medium and low global warming scenarios). The percentage change in the mean annual runoff and rainfall from the corresponding GCMs are also tabulated in Table KI-6.

The figure and table indicate that the potential impact of climate change on runoff can be very significant. Although there is considerable uncertainty in the estimates, the results indicate that runoff in ~2030 in the Kimberley region is as likely to increase as decrease. Rainfall-runoff modelling with climate change projections from eight of the GCMs shows a reduction in mean annual runoff, while rainfall-runoff modelling with climate change projections from seven of the GCMs shows an increase in mean annual runoff. The wide range of mean annual runoff values shown in Figure KI-26 and Table KI-6 is primarily due to the wide range of future projections of rainfall by the 15 GCMs.

Because of the large variation between GCM simulations and the method used to obtain the climate change scenarios, the biggest increase and biggest decrease in runoff come from the high global warming scenario. For the high global warming scenario, rainfall-runoff modelling with climate change projections from three of the GCMs indicates a decrease in mean annual runoff greater than 10 percent while rainfall-runoff modelling with climate change projections from two of the GCMs indicates an increase in mean annual runoff greater than 10 percent.

In subsequent reporting here and in other sections, only results from an extreme 'wet', 'mid' and extreme 'dry' variant are shown (referred to as scenarios Cwet, Cmid and Cdry). Under Scenario Cwet, results from the second highest increase in mean annual runoff from the high global warming scenario are used. Under Scenario Cdry, results from the second highest reduction in mean annual runoff from the high global warming scenario are used. Under Scenario Cmid, the median mean annual runoff results from the medium global warming scenario are used.

Under scenarios Cwet, Cmid and Cdry, mean annual runoff increases by 13 percent and decreases by 1 and 27 percent relative to Scenario A. By comparison, the range based on the low global warming scenario is a 4 to -16 percent change in mean annual runoff. Figure KI-27 shows the mean annual runoff across the Kimberley region under scenarios A and C. The linear discontinuities that are evident in Figure KI-27 are due to GCM grid cell boundaries.

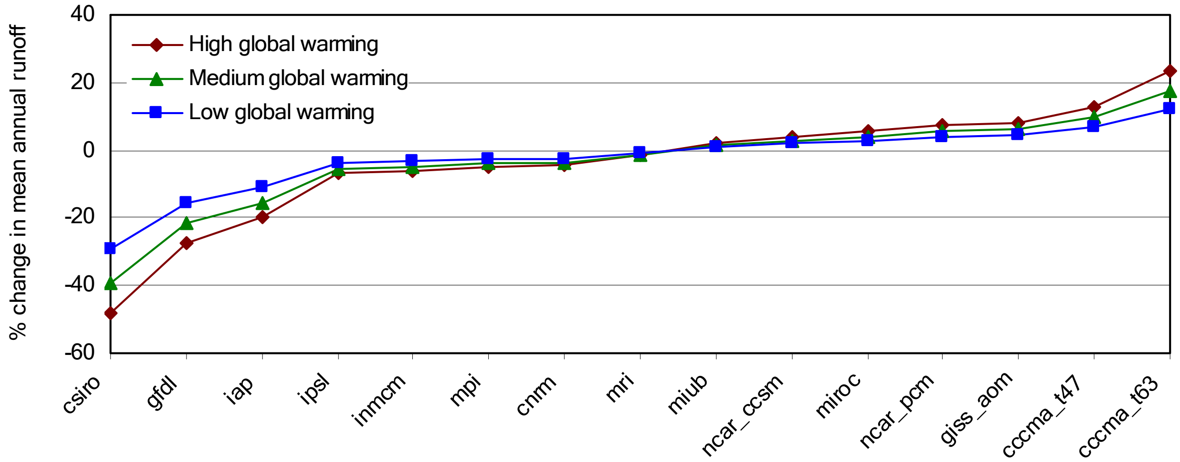


Figure KI-26. Percentage change in mean annual modelled runoff under the 45 Scenario C simulations (15 global climate models and three global warming scenarios) relative to Scenario A

Table KI-6. Summary results under the 45 Scenario C simulations for the modelled subcatchments in the Kimberley region (numbers show percentage change in mean annual rainfall and modelled runoff under Scenario C relative to Scenario A)

High global warming			Medium global warming			Low global warming		
GCM	Rainfall	Runoff	GCM	Rainfall	Runoff	GCM	Rainfall	Runoff
csiro	-23%	-48%	csiro	-18%	-39%	csiro	-13%	-29%
gfdl	**-14%**	**-27%**	gfdl	-11%	-22%	gfdl	-7%	-16%
iap	-6%	-20%	iap	-5%	-15%	iap	-3%	-11%
ipsl	-1%	-7%	ipsl	0%	-6%	ipsl	0%	-4%
inmcm	0%	-6%	inmcm	0%	-5%	inmcm	0%	-3%
mpi	1%	-5%	mpi	0%	-4%	mpi	0%	-3%
cnrm	1%	-5%	cnrm	1%	-4%	cnrm	1%	-3%
mri	0%	-1%	**mri**	**0%**	**-1%**	mri	0%	-1%
miub	1%	2%	miub	1%	2%	miub	1%	1%
ncar_ccsm	3%	4%	ncar_ccsm	3%	3%	ncar_ccsm	2%	2%
miroc	5%	5%	miroc	3%	4%	miroc	2%	3%
ncar_pcm	4%	8%	ncar_pcm	3%	6%	ncar_pcm	2%	4%
giss_aom	6%	8%	giss_aom	4%	6%	giss_aom	3%	4%
cccma_t47	**3%**	**13%**	cccma_t47	3%	10%	cccma_t47	2%	7%
cccma_t63	8%	23%	cccma_t63	6%	18%	cccma_t63	4%	12%

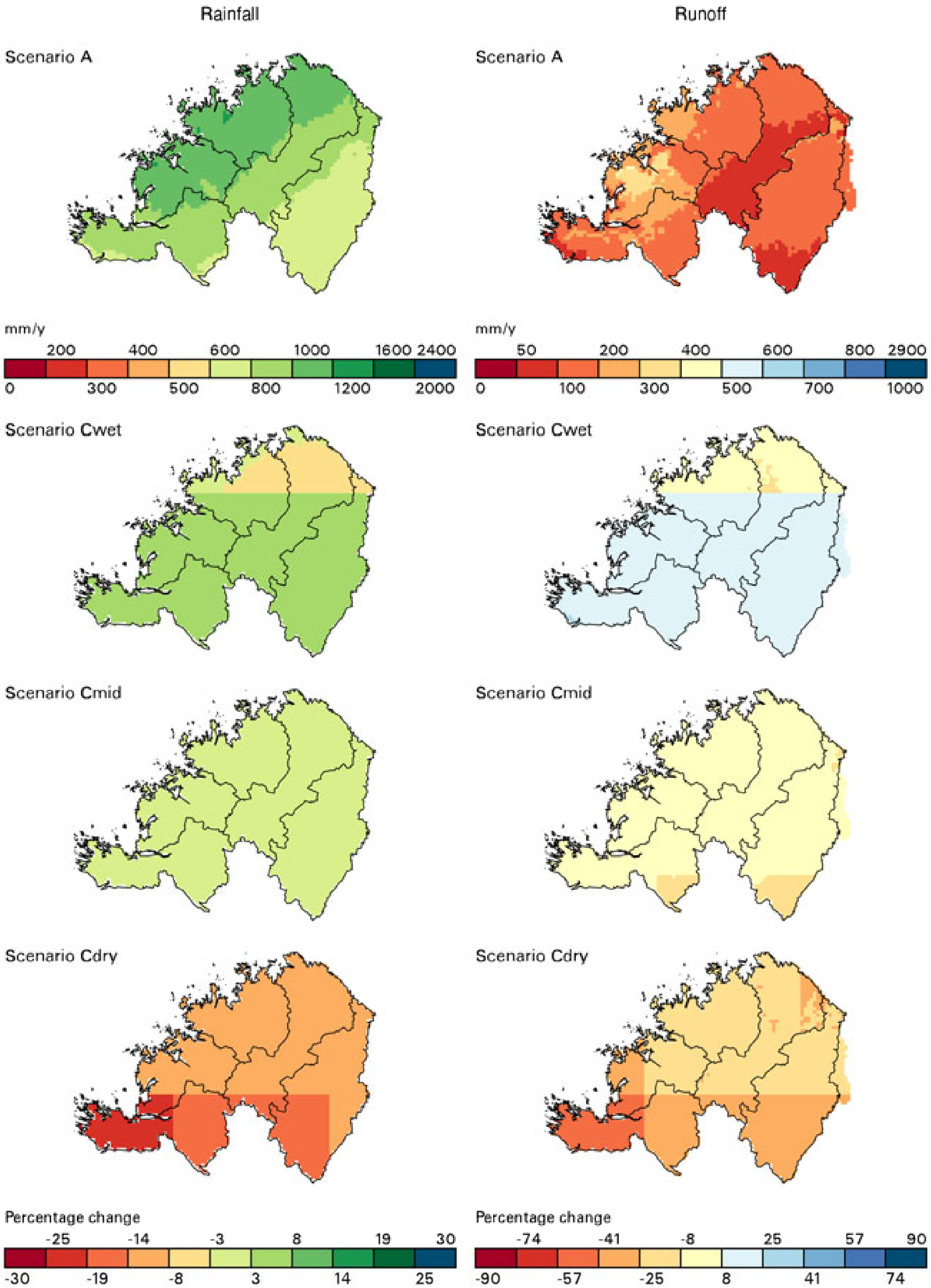


Figure KI-27. Spatial distribution of mean annual rainfall and modelled runoff across the Kimberley region under Scenario A and under Scenario C relative to Scenario A

KI-3.5.6 Summary results for all scenarios

Table KI-7 shows the mean annual rainfall, runoff and actual evapotranspiration under Scenario A averaged over the Kimberley region, and the percentage changes in the rainfall, runoff and actual evapotranspiration under scenarios B and C relative to Scenario A. The Cwet, Cmid and Cdry results are based on the mean annual runoff, and the rainfall changes shown in Table KI-7 are the changes in the mean annual value of the rainfall series used to obtain the runoff under scenarios Cwet, Cmid and Cdry. The changes in mean annual rainfall do not necessarily translate directly to the changes in mean annual runoff because of changes in seasonal and daily rainfall distributions and the relationship between rainfall and runoff is non-linear. The latter factor usually results in small changes in rainfall to be amplified in runoff (Table KI-6).

Figure KI-28 shows the mean monthly rainfall and runoff under scenarios A and C averaged over the 77 years for the region. Figure KI-29 shows the daily rainfall and flow exceedance curves under scenarios A and C averaged over the region. In Figure KI-28 Cmid is selected on a month-by-month basis, while in Figure KI-29 Cmid is selected for every day of the daily flow exceedence curve.

Table KI-7. Water balance over the entire Kimberley region under Scenario A and under scenarios B and C relative to Scenario A

Scenario	Rainfall	Runoff	Evapotranspiration
		mm	
A	936	153	784
		percent change from Scenario A	
B	25%	71%	16%
Cwet	3%	13%	1%
Cmid	0%	-1%	0%
Cdry	-14%	-27%	-11%

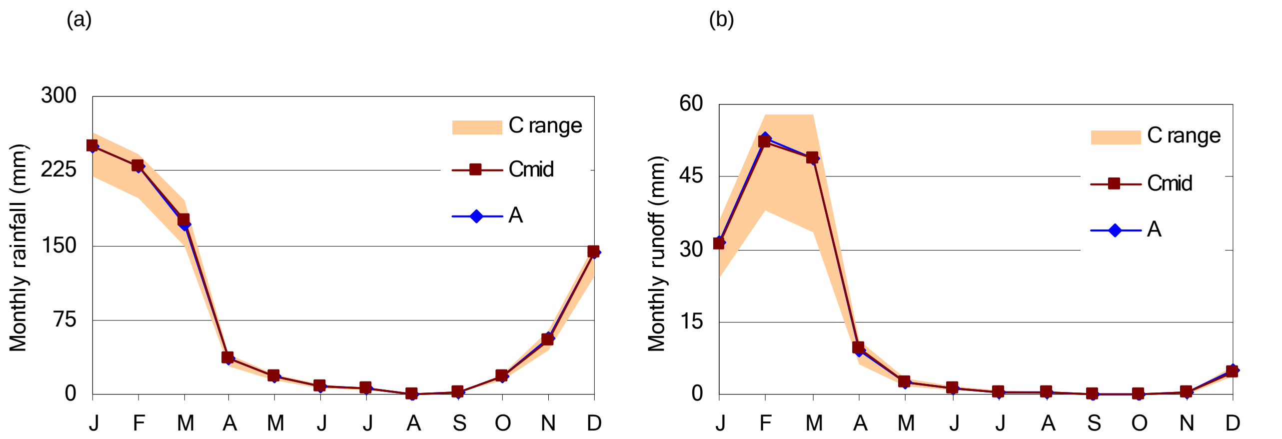


Figure KI-28. Mean monthly (a) rainfall and (b) modelled runoff in the Kimberley region under scenarios A and C. (C range is based on the consideration of each month separately – the lower and upper limits in C range are therefore not the same as scenarios Cdry and Cwet)

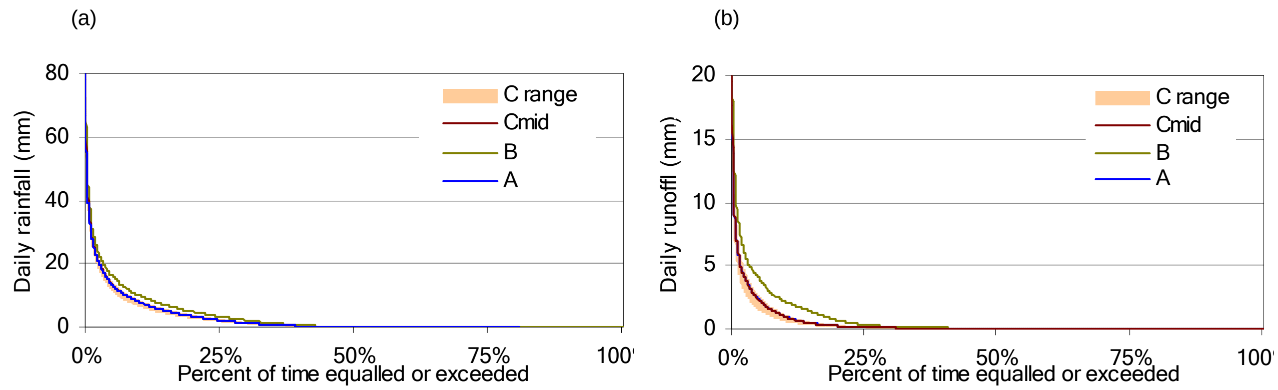


Figure KI-29. Daily flow exceedance curves for (a) rainfall and (b) runoff in the Kimberley region under scenarios A, B and C. (C range is based on the consideration of each month separately – the lower and upper limits in C range are therefore not the same as scenarios Cdry and Cwet)

KI-3.5.7 Confidence levels

The rainfall-runoff model verification analysis with data from 123 catchments from across all of northern Australia indicates that the mean annual runoff for ungauged catchments are under estimated or over estimated, when using optimised parameter values from a nearby catchment, by less than 20 percent in 40 percent of catchments and by less than 50 percent in 80 percent of the catchments. The level of confidence of the runoff estimates in the Kimberley region is varied. Along the coastal fringes of the region the level of confidence in the runoff estimates is low. Transposing parameters sets to the coastal catchments is problematic due to the lack of suitable donor catchments. Diagrams in Petheram et al. (2009) illustrate calibrated rainfall-runoff model parameter sets used to model streamflow in ungauged subcatchments in the Kimberley region. Rainfall stations are sparsely located across the Kimberley region, which contributes to the uncertainty of the rainfall-runoff modelling.

The level of confidence of the runoff estimates are highest in the central Kimberley region where there is a reasonable density of calibration catchments (Figure KI-20). The daily NSE value for Station 807001 is greater than 0.8. However the spatial distribution of runoff for this catchment appears to be different to the rest of the Kimberley region (Figure KI-22). A preliminary investigation by the Western Australia Department of Water suggests that there may be some uncertainty associated with the high end of the rating curve. However regional soil mapping also indicates there are deep sands located within the catchment. Due to the uncertainty associated with the runoff predictions from Station 807001, the high flow level of confidence was penalised two rankings (i.e. level 1 to level 3).

There is a high degree of confidence that dry season runoff in the Kimberley region is low because it is known that rainfall and baseflow are low during the dry season. The level of confidence for dry season flow map shown in Figure KI-30 provides a relative indication of how well dry season metrics, such as cease-to-flow, are simulated. Accurately predicting dry season flows in ungauged catchments in the Kimberley region is difficult as evident by Figure KI-30. There is a moderate level of confidence associated with dry season flows in the calibrated catchments in Kimberley region. A relatively large proportion of streamflow gauging stations have relatively stable low flow rating curves due to the prevalence of rock bar controls in the region.

Figure KI-30 shows the level of confidence in the modelling of the mid- to high runoff events (i.e. peak flows) and dry season runoff (respectively) for the subcatchments of the Kimberley region. It should be noted that these maps of level of confidence are not statistical confidence levels and are intended to only convey a broad reliability of prediction. The level of confidence in streamflow predictions will vary slightly from the level of confidence in runoff predictions shown below and as discussed in Section 2.2.6 of the division-level Chapter 2.

In summary the level of confidence in the long-term average monthly and annual results for the Kimberley region are low relative to other regions. As shown in Figure KI-30 however in many areas of the Kimberley region localised studies will require more detailed analysis than reported here and would most likely require the site to be visited and additional field measurements made.

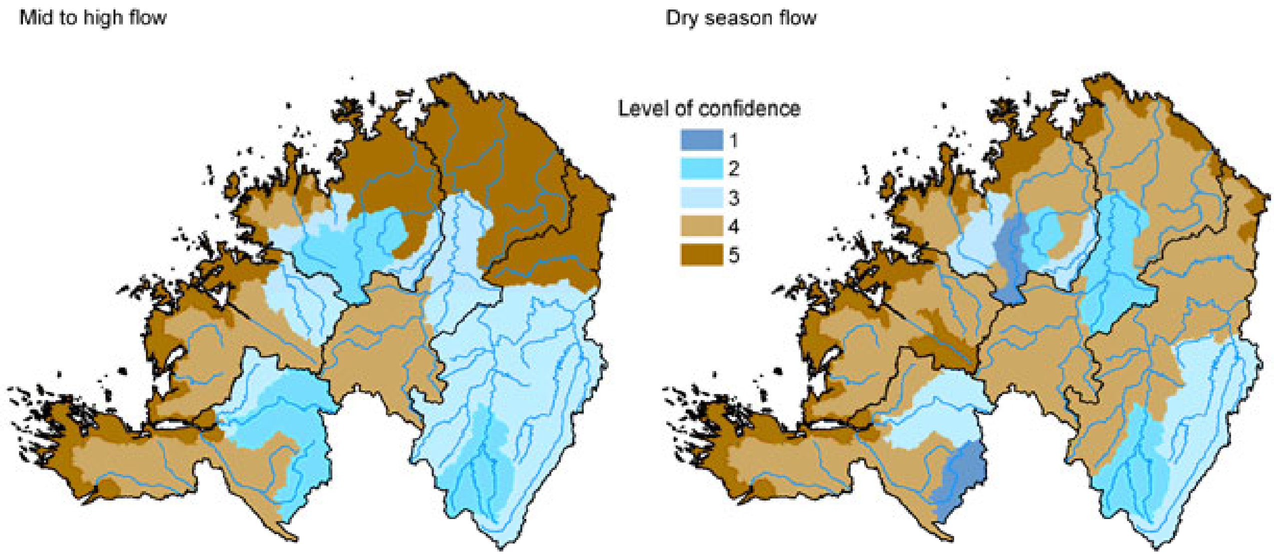


Figure KI-30. Level of confidence in the modelling of runoff for (a) mid- to high flow events and (b) monthly dry season flow events for the modelling subcatchments of the Kimberley region. 1 is the highest level of confidence, 5 is the lowest

KI-3.6 River system water balance

The Kimberley region is comprised of five AWRC river basins and has an area of 109,761 km^2. Under the historical climate the mean annual runoff across the region is 153 mm (Section KI-3.5.3), which equates to a mean annual streamflow across the region of 16,793 GL.

No information on infrastructure, water demand and water management and sharing rules or future development were available, and consequently there is no river modelling section to the Kimberley region report. Streamflow time series have been generated for each streamflow reporting node (SRN) based on the upstream grid cell rainfall-runoff simulations, as described in Section 2.2.5 of the division-level Chapter 2. The locations of these nodes are shown in Figure KI-31. Summary streamflow statistics for each SRN are reported in Petheram et al. (2009).

In addition to the streamflow time series generated by the rainfall-runoff model ensemble, a range of hydrological metrics computed using regression analysis are also available for each SRN (as described in Section 2.2.7 of the division-level Chapter 2). The complete set of results for the multiple regression analysis are reported in SKM (2009). The merit of each approach is discussed in Section 2.2.7 of the division-level Chapter 2.

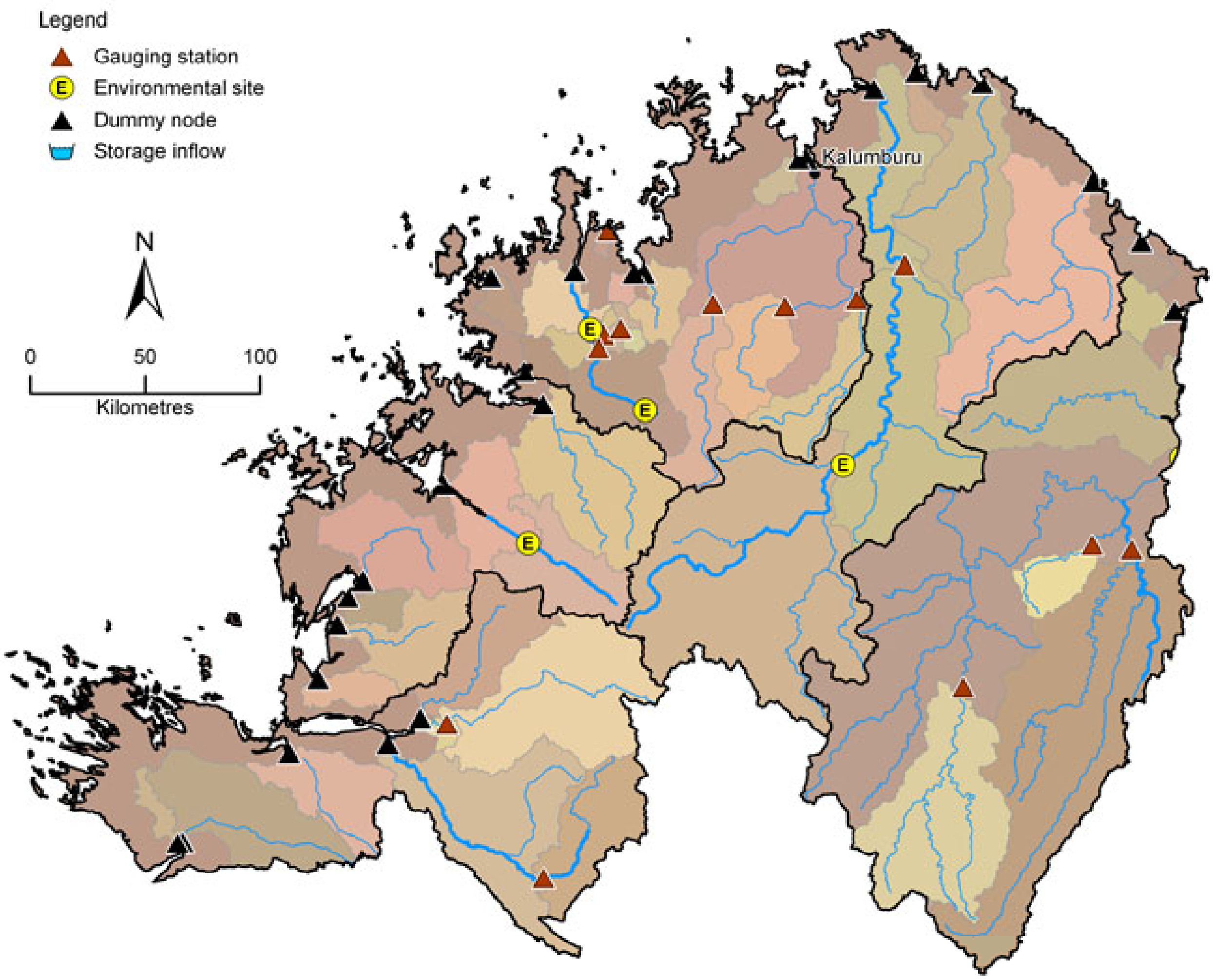


Figure KI-31. Location of streamflow reporting nodes (gauging stations, environmental sites, dummy nodes and storage inflows) in the Kimberley region. (Note there are no storage inflow streamflow reporting nodes in this region)

KI-3.7 Changes to flow regimes at environmental assets

Section 1.3 of the division-level Chapter 1 describes how environmental assets were shortlisted for assessment by this project. Three environmental assets have been shortlisted in the Kimberly region: Drysdale River, Mitchell River System and Prince Regent River System. The locations of these assets are shown in Figure KI-1 and the assets are characterised in Chapter KI-2.

This section presents the assessment of these shortlisted assets and reports metrics for those assets which have sufficient confidence in the modelled streamflow to enable analysis. Confidence in results for low flows and high flows was calculated separately on a scale of 1 to 5, with 1 indicating results with the highest confidence (as described in Section 2.2.6 of the division-level Chapter 2). Hydrological regime metrics (as defined in Section 2.5 of the division-level Chapter 2) for either low flows or high flows are reported only where confidence levels are 1, 2 or 3. If confidence levels in the low flows or high flows are ranked 4 or 5, results are not reported and are labelled NR (not reported).

Some of the assets in this region have multiple nodes at which streamflow modelling results are available. When reporting hydrological regime metrics for such assets a single node was selected. The selected node was that with the highest streamflow confidence level and the largest proportion of streamflow to the asset. Results for all nodes are presented in McJannet et al. (2009).

In the absence of site-specific metrics for the Kimberly region a set of standard metrics related to high an low flows have been utilised. However the conversion of these metrics into environmental impacts still requires development of quantitative relationships between flow and ecology.

KI-3.7.1 Standard metrics

Table KI-8. Standard metrics for changes to surface water flow regime at environmental assets in the Kimberley region

Standard metrics	Units	A	B	Cwet	Cmid	Cdry	Dwet	Dmid	Ddry
			change from Scenario A						
Drysdale River - Node 1 (confidence level: low flow = 3, high flow = 3)									
Annual flow (mean)	GL	667	+77%	+6%	-2%	-27%	nm	nm-	nm-
Wet season flow (mean)*	GL	637	+77%	+5%	-3%	-27%	nm	nm-	nm-
Dry season flow (mean)**	GL	29.8	+67%	+10%	+2%	-39%	nm	nm-	nm-
Low flow threshold (discharge exceeded 90% of the time in Scenario A)	GL/d	0.00012							
Number of days below low flow threshold (mean)	d/y	36.5	-29.8	-2.3	+3	+34.6	nm	nm-	nm-
Number of days of zero flow (mean)	d/y	32.7	-27.7	-2.1	+3	+33.8	nm	nm-	nm-
High flow threshold (discharge exceeded 5% of the time in Scenario A)	GL/d	10.7							
Number of days above high flow threshold (mean)	d/y	18.3	+20	+1.5	-0.7	-6.7	nm	nm-	nm-
Mitchell River System - Node 2 (confidence level: low flow = 3, high flow = 2)									
Annual flow (mean)	GL	382	+69%	+9%	-5%	-23%	nm	nm-	nm-
Wet season flow (mean)*	GL	370	+70%	+9%	-5%	-22%	nm	nm-	nm-
Dry season flow (mean)**	GL	11.9	+34%	+10%	-1%	-33%	nm	nm-	nm-
Low flow threshold (discharge exceeded 90% of the time in Scenario A)	GL/d	0.00774							
Number of days below low flow threshold (mean)	d/y	36.5	-35.2	-3.2	+11.2	+42	nm	nm-	nm-
Number of days of zero flow (mean)	d/y	1.17	+0.2	0	0	+0.3	nm	nm-	nm-
High flow threshold (discharge exceeded 5% of the time in Scenario A)	GL/d	5.55							
Number of days above high flow threshold (mean)	d/y	18.3	+15.2	+1.6	-1.1	-5.8	nm	nm-	nm-

* Wet season covers the six months from November to April.

** Dry season covers the six months from May to October.

NR – metrics not reported because streamflow confidence level is ranked 4 or 5.
nm – not modelled.

Drysdale River

The surface water flow confidence level for the selected reporting node for the Drysdale River (see location on Figure KI-7) is considered moderately reliable (3) for both wet season flows and dry season flows (Table KI-8). Under Scenario A annual flow into this asset is dominated by wet season flows (96 percent) which have been 77 percent higher under Scenario B. Dry season flows have also been 67 percent higher under Scenario B when compared to Scenario A. Annual and seasonal flows do not change much under scenarios Cmid and Cwet compared to Scenario A, but there are large decreases under Scenario Cdry (27 to 39 percent). There are no development scenarios for the area upstream of this asset.

Compared to under Scenario A the number of days when flow is less than the low flow threshold does not change very much under scenarios Cwet and Cmid, but there is a very large increase in low flow days under Scenario Cdry (Table KI-8). A similar pattern is seen in the number of days of zero flow. Under Scenario B the high flow threshold exceedance has been much more frequent than in Scenario A. There is little change in high flow threshold exceedance under scenarios Cmid and Cwet. Under Scenario Cdry there is a large decrease in high flow threshold exceedance from Scenario A.

Mitchell River System (WA)

The surface water flow confidence level for the selected reporting node for the Mitchell River System (WA) (see location on Figure KI-8) is considered fairly reliable (2) for wet season flows and moderately reliable (3) for dry season flows (Table KI-8). Under Scenario A annual flow into this asset is dominated by wet season flows (97 percent) which have been 70 percent higher under Scenario B. Dry season flows have also been 34 percent higher under Scenario B when compared to Scenario A. Annual and seasonal flows do not change much under scenarios Cmid and Cwet compared to Scenario A, but there are large decreases under Scenario Cdry (22 to 33 percent). There are no development scenarios for the area upstream of this asset.

Compared to under Scenario A the number of days when flow is less than the low flow threshold does not change very much under Scenario Cwet, but there is a large and very large increase in low flow days under scenarios Cmid and Cdry respectively (Table KI-8). A small number of zero flow days were recorded at this asset and this did not change much under any of the scenarios. Under Scenario B the high flow threshold exceedance has been much more frequent than underScenario A. There is little change in high flow threshold exceedance under scenarios Cmid and Cwet. Under Scenario Cdry there is a large decrease in high flow threshold exceedance from Scenario A.

Prince Regent River System

The surface water flow confidence level for this asset is 4 or 5 for both high flows and lows which is too unreliable to allow environmental flow metrics to be calculated for this asset.

KI-3.8 References

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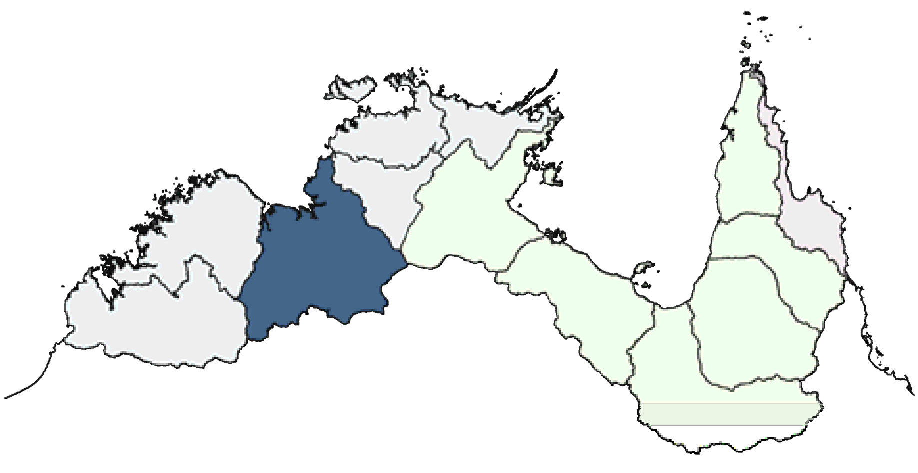
Water in the Ord-Bonaparte region



OB-1 Water availability and demand in the Ord-Bonaparte region

The first part of this report (the Preamble, Chapter 1 and Chapter 2) reports at the division level, including division-wide descriptions of climate and geology and methods which apply to all regions. Subsequent chapters report at the region level. In particular, Chapters OB-1, OB-2 and OB-3 focus on the Ord-Bonaparte region (Figure OB-1).

This chapter summarises the water resources of the Ord-Bonaparte region, using information from Chapter OB-2 and Chapter OB-3, and directly addresses the Terms of Reference, specifically terms 3, 4 and 5 as listed in the Preamble. Essentially, this chapter provides a synoptic view of the region and covers:

- regional observations
- water resource assessment
- seasonality of water resources
- surface–groundwater interaction
- changes to flow regime at environmental assets
- water storage options
- data and knowledge gaps.

For further details on the context of the region (physical and climate descriptions, hydrogeology and legislation) see Chapter OB-2. Region-specific methods and results are provided in Chapter OB-3. Modelling results are reported under climate and development scenarios as defined at the division level in Section 2.1 of Chapter 2.

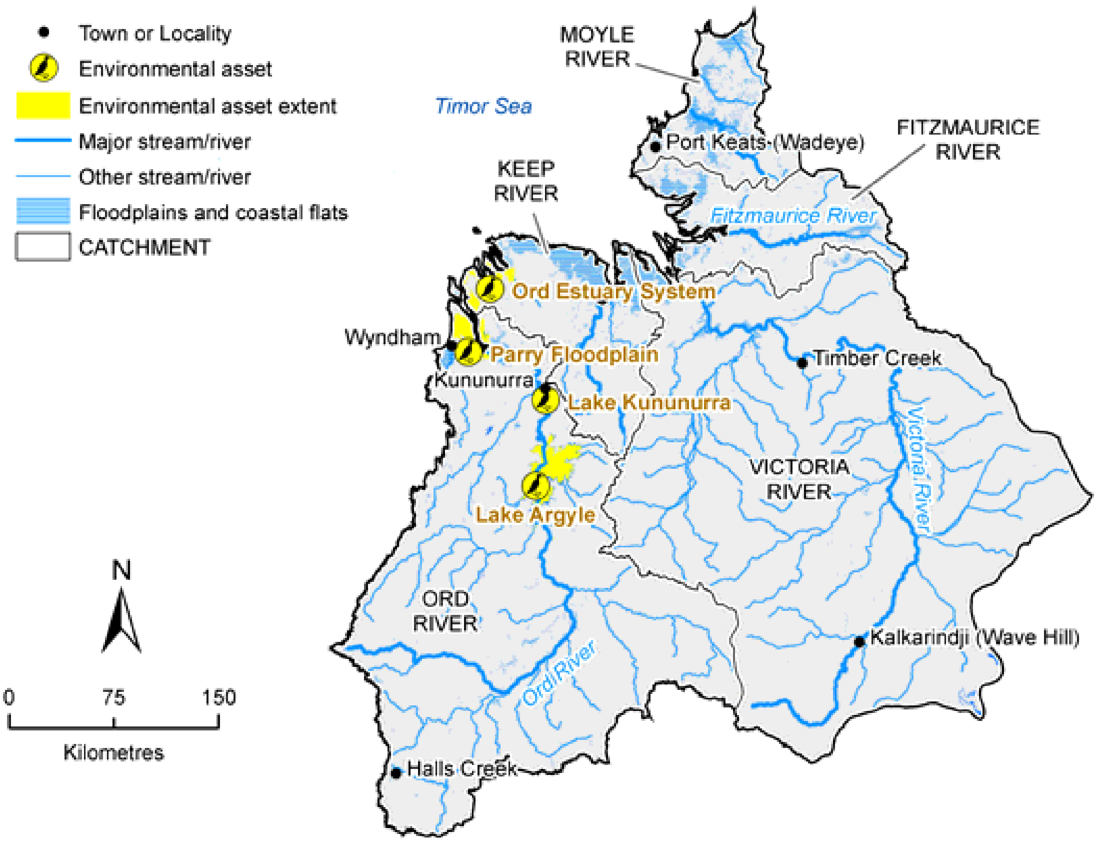


Figure OB-1. Major rivers, towns and location of environmental assets selected for assessment of changes to hydrological regime in the Ord-Bonaparte region

OB-1.1 Regional summary

This section summarises key modelling results from this project and provides other relevant water resource information as context about water availability and demand in the Ord-Bonaparte region.

The historical (1930 to 2007) mean annual rainfall for the region is 730 mm. Mean annual areal potential evapotranspiration (APET) is 1988 mm. The mean annual runoff averaged over the modelled area of the Ord-Bonaparte region is 112 mm, 15 percent of rainfall. These values are moderate in comparison to other regions across northern Australia. Under the historical climate the mean annual streamflow over the Ord-Bonaparte region is estimated to be 18,427 GL.

The Ord-Bonaparte region has a high inter-annual variability in rainfall and hence runoff and recharge. Relative to the rest of northern Australia, however, coefficients of variation are in the middle of the range of the regions across northern Australia and the region may experience long periods of many years that are considerably wetter or drier than others.

There is a strong seasonality in rainfall patterns, with 94 percent of rainfall falling in the wet season, between November and April, and a very high dry season (May to October) APET. The region has relatively high rainfall intensities, extremely high for the top 1 percent of events, and this is reflected in rapid runoff and a short lag between rainfall and runoff. Ninety-nine percent of runoff occurs within the months of December and April. There has been a slightly increasing amount and intensity of rainfall over the 1930 to 2007 period.

There is a strong north–south rainfall gradient and hence also runoff, with the runoff coefficient decreasing from 30 to 10 percent of precipitation in the same direction.

APET is annually greater than rainfall, and thus the region may be considered water-limited. The region has years when it is water-limited throughout the entire year, with APET exceeding rainfall even through the wet season.

The Ord-Bonaparte region has a recent (1996 to 2007) climate record that is statistically significantly wetter than the historical record. Rainfall was 26 percent higher; runoff was 56 percent higher. It is likely that future (~2030) conditions will be similar to historical conditions, and future runoff and recharge will also be similar to historical levels, but significantly lower than the recent past.

The water availability in the Ord catchment is 4257 GL/year. In the lower reaches of the Ord catchment there is a large carry-over storage, Lake Argyle, and a re-regulating structure, the Kununurra Diversion Dam. Lake Argyle has an active storage of 10,380 GL, which makes it the largest reservoir in northern Australia and the second largest reservoir by volume in Australia. Lake Argyle has a very high degree of regulation (0.8) as a consequence of having a large storage volume, high evaporative losses (about 2000 GL/year) and a relatively high level of use (57 percent under the historical climate). This has resulted in considerable changes to the behaviour of flow compared to the without-development scenario. Water products in the lower Ord catchment include hydroelectricity and irrigation water for the Ord River Irrigation Area. There are no major storages in the Victoria, Keep or Fitzmaurice river basins.

The major aquifers in the region with potential for development for irrigated agriculture occur in the northern sandstones. Strategies need to be implemented, however, to mitigate the impacts of groundwater accessions beneath the existing Ord River Irrigation Area and any areas proposed for future expansion. Potential for groundwater development of the fractured and karstic rock areas of the region is limited by variable salinity and potentially low recharge rates in some areas.

The Fitzmaurice River is the only naturally perennial river in the region where flow is sustained by groundwater discharge. Discharge of the Ord, downstream of Lake Argyle is now maintained through the dry season though releases from the dam.

In unregulated streams flows are highly dominated by wet season flows so dry season flows are only a small fraction of total annual flow. Downstream of Lake Kununurra, however, dry season flows are strongly augmented by water releases from the dam. These environmental flows are designed to sustain a wide range of ecological facets including fish, macrophytes and riparian vegetation. Under modelled future climate and development scenarios, periods of low environmental flow would be extended. This would be compensated through revision of storage release rules. In contrast, high flow environmental requirements will be met in all climate and development scenarios.

Other than the area downstream of the Argyle Dam, the region is generally datapoor.

OB-1.2 Water resource assessment

Term of Reference 3a

OB-1.2.1 Under historical climate and current development

Term of Reference 3a (i)

The mean annual rainfall and modelled runoff averaged over the Ord-Bonaparte region are 727 mm and 112 mm respectively. These values fall within the lower end of the range of values from the 13 regions.

The coefficients of variation of annual rainfall and runoff averaged over the Ord-Bonaparte region are 0.26 and 0.67 respectively. These values fall within the middle of the range of values from the 13 regions. The 10th, median and 90th percentile annual runoff values across the Ord-Bonaparte region are 208, 97 and 25 mm respectively.

Water availability for the Ord catchment is taken to be the inflows to Lake Argyle. For the Ord catchment the current average surface water availability is 4257 GL/year and on average about 348 GL/year (or 8 percent) of this water is diverted for irrigation. This is a relatively low level of development. However, if the water used for hydropower generation is also considered the level of use for the controlled releases is high at 57 percent under Scenario A.

Under a continuation of the historical climate, mean annual diffuse groundwater recharge to unconfined aquifers in the Ord-Bonaparte region is likely to be similar to the historical (1930 to 2007) average rate. Current groundwater extraction is estimated to be about 40 GL/year (Table OB-1). Continued extraction at this rate under an historical climate is therefore likely to continue current trends in groundwater resource condition. The most pronounced trend in the region at present is water table rise in the Ord River Irrigation Area; this trend is likely to continue until either a new state of equilibrium is achieved or management intervention occurs. Locally, salt accumulation is also a problem. There are local areas near Lake Kununurra where groundwater levels have been influenced by the (high) lake levels (relative to the original groundwater levels) and other local areas where the usual sub-surface gravels and sands (of high conductivity) are absent. In these latter areas, the usual lateral flow of groundwater away from recharge irrigated land recharge is limited. Generally, however, for the current Stage 1 areas as a whole, salinity risks are not high.

Table OB-1. Estimated groundwater contribution (baseflow) to streamflow, modelled diffuse recharge and groundwater extraction for the Ord-Bonaparte region under historical climate

Station	River	Station name	Annual BFI *	Dry season BFI *	Dry season baseflow *
					GL
809310	Ord	Bedford Downs	0.08	0.19	0.1
809314	King	Cockburn North	0.11	0.27	0.1
809315	Negri	Mistake Ck Homestead	0.14	0.62	5.6
809316	Ord	Old Ord Homestead	0.11	0.28	6.0
809317	Black Elvire R Trib	Koongie Park	0.02	0.03	0.0
809321	Dunham	Dunham Gorge	0.14	0.63	2.5
809322	Wilson	Odonnell Range	0.14	0.39	1.8
G8100225	Keep	Legune Rd Crossing.	0.08	0.37	0.4
G8110004	East Baines	Victoria HWY	0.20	0.73	4.7
G8110006	West Baines	Victoria HWY	0.12	0.35	1.8
G8110007	Victoria	Coolibah Homestead	0.13	0.38	19.8
G8110012	Timber Ck	2 Miles U/S Victoria Hwy	0.18	0.44	0.1
G8110014	Sullivan's Ck	U/S Fig Tree Yard	0.08	0.56	0.1
G8110110	Surprise Ck	V.R.D. Rd Crossing	0.06	0.40	0.0
G8110113	Victoria	Dashwood Crossing	0.01	0.26	5.4
G8110232	Wickham	Williams Crossing	0.30	0.72	13.0
G8110251	West Baines	Brumby Hill	0.16	0.69	0.4
		Historical recharge **	Estimated groundwater extraction		
		GL/y			
Entire Ord-Bonaparte region		11,410	40		

* BFI (baseflow index) and baseflow volume derived from gauged data.
** Aggregated recharge from Zhang and Dawes (1998).

OB-1.2.2 Under recent climate and current development

Term of Reference 3a (ii)

The mean annual rainfall and runoff under the recent (1996 to 2007) climate are 26 percent and 56 percent higher respectively than the historical (1930 to 2007) mean values.

Current mean annual surface water availability is 4257 GL and on average about 2425 GL/year (or 57 percent) of this water is used. This is a high level of development.

Under the recent climate, mean annual diffuse groundwater recharge is likely to be significantly higher than the historical average across most of the region. The only exception to this is in the far north-east where recharge is likely to be similar to the historical average, and in areas of vertosol soils where recharge is likely to be lower than the historical average. Continued groundwater extraction at current rates under a recent climate is likely to have similar impacts to those expected under an historical climate, except that greater recharge in some areas may serve to buffer the impacts of groundwater pumping on baseflow contributions to nearby rivers (Table OB-1).

OB-1.2.3 Under future climate and current development

Term of Reference 3a (iii)

Rainfall-runoff modelling with climate change projections from seven of the GCMs shows an increase in mean annual runoff, while rainfall-runoff modelling with climate change projections from six of the GCMs shows a decrease in mean annual runoff. Two of the GCMs show neither an increase nor decrease in mean annual runoff. For the high global warming scenario rainfall-runoff modelling with climate change projections from three of the GCMs indicates a decrease in mean annual runoff greater than 10 percent while rainfall-runoff modelling with climate change projections from three of the GCMs indicates an increase in mean annual runoff greater than 10 percent. Under scenarios Cwet, Cmid and Cdry, mean annual runoff increases by 32 and zero percent and decreases by 26 percent relative to Scenario A. By comparison, the range based on the low global warming scenario is a 17 to -15 percent change in mean annual runoff.

For the Ord catchment, under the median future climate there would be a 3 percent increase in water availability and no change to diversions for irrigation. Considering all water products the average annual controlled release would increase by 1 percent.

For the Ord catchment the climate extremes for 2030 indicate:

- under the wet extreme future climate, water availability increases 20 percent and there is no change to the diversions for irrigation. Average controlled releases increase 5 percent.
- under the dry extreme future climate, water availability decreases 21 percent and total diversions decrease 7 percent. Average controlled releases decrease 9 percent.

Under the future climate, mean annual diffuse groundwater recharge is likely to be slightly higher than the historical average across most of the region. With continued groundwater extraction at current rates the impacts of this increase in recharge are likely to be minimal.

OB-1.2.4 Under future climate and future development

Term of Reference 3a (iv)

For the Ord catchment, under the median future climate and future development there would be a 3 percent increase in water availability and a 113 percent increase to diversions for irrigation. Considering all water products the average annual controlled releases decreases by 4 percent.

For the Ord catchment the climate extremes for 2030 and future development indicate:

- under the wet extreme future climate and future development, water availability increases 20 percent and there is a 114 percent increase to the diversions for irrigation. Average controlled releases decrease 1 percent.
- under the dry extreme future climate, water availability decreases 21 percent and there is a 92 percent increase to the diversions for irrigation. Average controlled releases decrease 14 percent.

OB-1.3 Changes to flow regime at environmental assets

Term of Reference 3b

Section 1.3 of the division-level Chapter 1 describes how environmental assets were shortlisted for assessment by this project. Four environmental assets were shortlisted for the Ord-Bonaparte region: Lake Argyle, Lake Kununurra, Parry Floodplain and Ord Estuary System. Lake Argyle and Lake Kununurra are both artificially created wetlands. These assets are characterised in Chapter OB-2.

In deciding whether it is feasible to report hydrological regime metrics for these shortlisted assets, it is important to consider the confidence levels in modelled streamflow (as described in Section 2.2.6 of the division-level Chapter 2). Confidence in results for low flows and high flows was calculated separately. Hydrological regime metrics (as defined in Section 2.5 of the division-level Chapter 2) for either low flows or high flows are reported only where confidence levels are sufficiently high. If confidence in the low flow or high flow is too low, metrics are not reported, and hence an important gap in our knowledge is identified.

Some of the assets in this region have multiple nodes at which streamflow modelling results are available. When reporting hydrological regime metrics for such assets a single node was selected. The selected node was that with the highest streamflow confidence level and the largest proportion of streamflow to the asset. The locations of nodes for each asset are shown on satellite images in Section OB-2.1.3. Results for all nodes are presented in McJannet et al. (2009).

The surface water flow confidence levels for both high and low flows for the Ord Estuary System are ranked unreliable therefore they are of insufficient quality to allow environmental flow metrics to be calculated. Confidence in low flow metrics are ranked unreliable for Lake Argyle while no metrics were reported for Kununurra Diversion Dam as it is a managed storage which is operated in a narrow range of water levels from 41.1 to 41.7 m AHD with a target level of 41.5 m AHD.

Annual flow at all the remaining assets is dominated by wet season flow, which has been >65 percent higher than historical levels in the recent past. Dry season flows have been much greater that historical flows in the recent past. Future flows are likely to be similar to historical flows. Under a dry extreme future climate, flows are more that 20 percent lower than historical levels, while under a wet extreme future climate, flows are more that 20 percent higher than historical levels.

At the lower Ord River adjacent to the Parry floodplain, under the future climate with future development, results show moderate changes relative to the future climate with current development, indicating significant additional impact on the hydrological regime as a result of proposed development. Under the wetter conditions of the recent past, flows are maintained above the low flow and high flow thresholds calculated for the historical past for much more of the time.

Development appears to have the greatest effect on the low flow regime. It should be noted that due to the regulated nature of flows to location, there is an opportunity for dam managers to modify future release rules in order to balance the demands of agriculture, environmental flows and other uses.

The Department of Water, Western Australia have recognised the intrinsic ecological values of the region below the Ord River Dam and as such have developed an environmental water requirement regime based on the hydro-ecological flow requirements for the region downstream of the dam. The minimum environmental flow requirement for low flows was met at all times in the recent past and was not met on just 8 days per year under the historical past. There were 12 days/year below the threshold under future climate and this increased to an additional 23 days/year under the future climate with development. This implies that much of the change expected with regard to this flow metric may be attributed to the proposed development. Under the dry extreme future climate with development, flows were below minimum requirements for an additional 70 days per year. Current operating rules are able to be adapted to meet this low flow requirement if such conditions develop.

High flow environmental flow requirements for regular inundation of riparian zones and deep backwater pools as well as fish passage for the Lower Ord River were met for all the climate and development scenarios.

OB-1.4 Seasonality of water resources

Term of Reference 4

Approximately 94 percent of rainfall and 99 percent of runoff occurred during the wet season months under the historical climate. Under recent climate 94 percent of rainfall and 94 percent of runoff occurred during the wet season months. Under future climate in 2030 it is estimated that 95 percent of rainfall and 99 percent of runoff will occur during the wet season months. Runoff is highest in February and March.

OB-1.5 Surface–groundwater interaction

Term of Reference 4

During the wet season, intense and prolonged rainfall periods result in large volumes of runoff and consequent flow in the tributaries and major rivers (Figure OB-2). It is likely that during the wet season, elevated river levels would drive groundwater flows away from the river and hence recharge the nearby aquifers either directly or through near river alluvial sediments. In the dry season groundwater flows locally towards the rivers, and provides permanent flows in the lower reaches of some rivers. Baseflow surveys of the Fitzmaurice and Victoria Rivers for example, have been conducted at the end of the dry season and show the river flows are maintained by fresh groundwater (Power and Water Authority, 1987). Throughout most of the region however, groundwater levels fall below the river bed as the dry season progresses and river flows are only intermittent with some semi-permanent pools (Passmore, 1964).

Small springs occur in some parts of the region after average to above average rainfall years. Some have a small flow (<10 L/second) throughout the year. Most cease to flow early in the dry season. These springs often drain a very small area (less than 10 km^2) and, while they may be ecologically significant, are outside the scope of this discussion.

Reaches of rivers where significant groundwater discharge is known to occur are shown in Figure OB-2. The data used to compile this map represent a series of both below average and above average wet seasons. The flows are sustained by significant regional groundwater discharges from aquifers developed in the Cretaceous sediments (Fitzmaurice River) or Proterozoic carbonates (Wickham River).

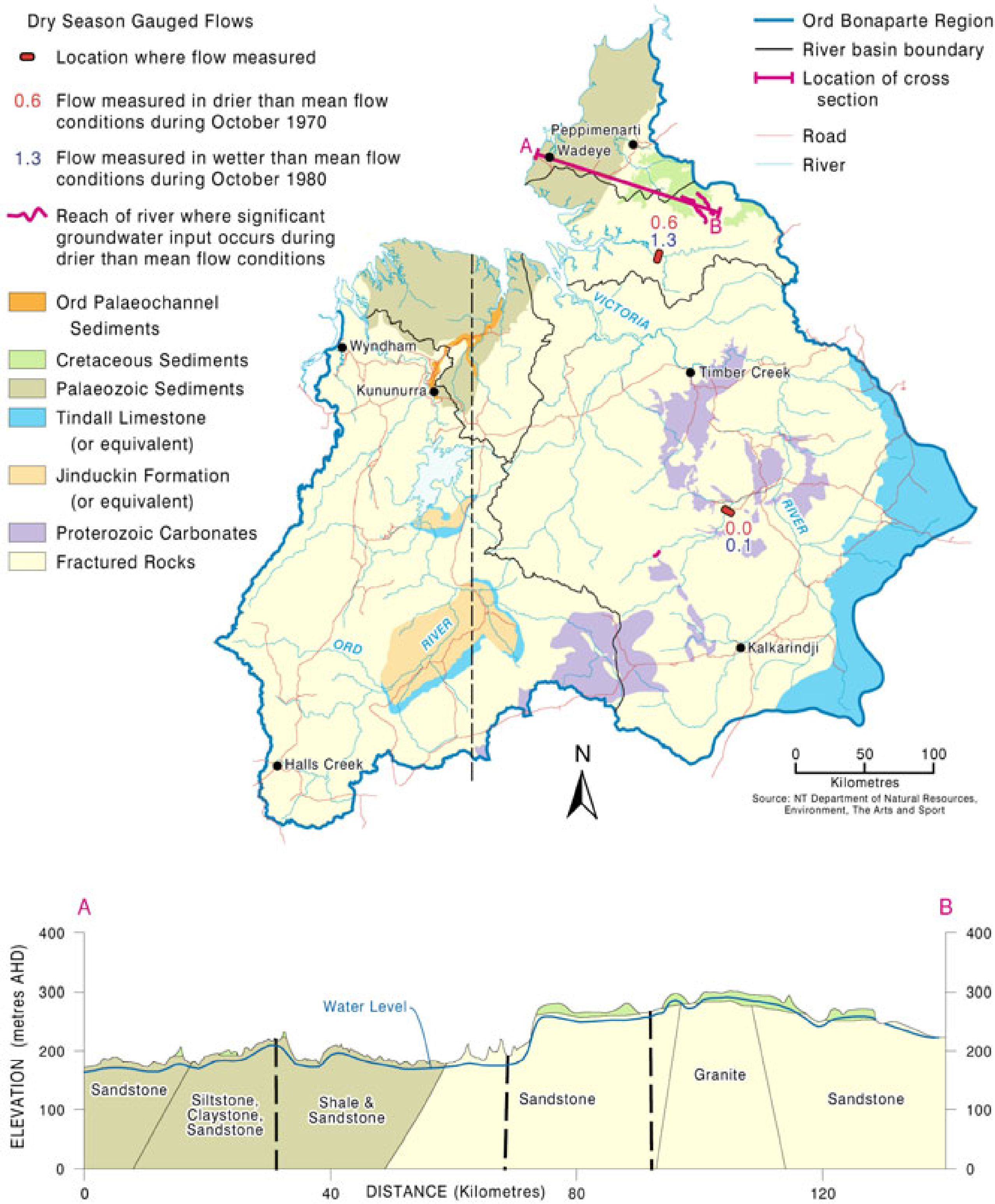


Figure OB-2. Hydrogeology of the Ord-Bonaparte region with dry season gauged flows (source NRETAS, 2009)

The amount of recharge to an aquifer system can be estimated from data on dry season flows (assuming total recharge is equivalent to total dry season stream flow, which may not always be appropriate). Detailed analysis of gauged dry season instantaneous flow data obtained since gauging station G8140232 was opened in 1967, was reported in Jackson and Jolly (2004). Flow and rainfall data were used in that study to predict regional groundwater discharges into the Wickham River. Predictions of groundwater inflow were typically in the range 0.1 to 1 m^3/second throughout the assessment period 1900 to 2003. The only two exceptions to this were in the early 1920s and early 1950s; predicted discharge decreased to approximately 0.01 m^3/second at the end of the 1954 dry season. The time series of predicted discharges were equated to a mean annual recharge rate of 15 mm/year for the period 1900 to 2003. The mean water year (September to August) rainfall for the same period was 645 mm/year.

Makin (1975), who researched the history of the Victoria River Downs Station on the Wickham River, stated that "*During the drought of the early 1950s, most of the springs on Victoria River Downs either dried up or were pugged up by thirsty cattle*." This is consistent with the predictions for groundwater discharge into the Wickham River made by Jackson and Jolly (2004) described above.

OB-1.6 Water storage options

Term of Reference 5

OB-1.6.1 Surface water storages

The Ord-Bonaparte region has two main storages, both located within the Ord River catchment. These are the Ord River Dam (11,000 GL) and the Kununurra diversion dam (108 GL), a re-regulating structure.

OB-1.6.2 Groundwater storages

Groundwater development in the Ord-Bonaparte region is low. Under current development managed aquifer recharge (MAR) would have limited applicability as storages in the local aquifers, particularly the Proterozoic carbonates, are likely to be at full capacity towards the end of the wet season when surface water is available for injection. Potential evaporation exceeds rainfall for most of the year resulting in near year-round water-limited conditions. When water is not limited aquifers are expected to be at full capacity. Therefore the only opportunity for MAR in the region is if future development leads to groundwater levels not fully recovering to the top of the aquifers each wet season.

OB-1.7 Data gaps

Term of Reference 1e

Streamflow gauging stations are or have been located at 63 locations within the Ord-Bonaparte region. However, 41 of these gauging stations are either: flood warning stations and measure stage height only, installed on irrigation drains in the Ord River Irrigation Area or have less than ten years of measured data. Overall, a large portion of the region is or has at some stage been gauged. However, Station 809302 at the Ord River Dam site was closed prior to construction of the dam. Currently a little over half of the contributing area to Lake Argyle is gauged. In the Victoria catchment station G811007 gauges a large proportion of the catchment. However, there are few suitable gauging stations nested within station G811007 to provide further information on the spatial distribution of runoff.

Gauging station coverage in the Ord-Bonaparte region is better than average for the project area, with twice the average number of the 13 regions and the median catchment area per gauge is ~70 percent of the median of the 13 regions of the project area. Most of the area, however, is gauged by only two gauging stations, one in the Ord and one in the Victoria river basin. Each of these catchments has an area of about 45,000 km^2. The large size of these catchments results in a lower level of confidence in rainfall-runoff model results.

The major aquifers with potential for development for irrigated agriculture occur in the Palaeozoic sediments. These aquifers are also a significant source of water for the extensive wetlands that occur adjacent to the Northern Territory's western coastline (e.g. the Moyle River floodplains). There is insufficient data available to develop a model for this extensive groundwater resource. A programme of work needs to be undertaken to obtain the data that will enable impact assessment models to be developed for these groundwater resources.

OB-1.8 Knowledge gaps

Term of Reference 1e

The Fitzmaurice River is the only perennial river in the Ord-Bonaparte region where flow is known to be sustained by groundwater discharge. A basic model such as that developed for the Katherine River (Daly region, Jolly et al., 2000a) and Goyder River (Arafura region, Williams et al., 2003) is required for the Fitzmaurice River. These models have been developed by determining potential water year recharge rates and relating the recharge to increases in groundwater derived river flow. This basic model is suitable for determining the natural long-term variability in dry season river flow but is not suitable for determining the impact a particular groundwater development (e.g. irrigated agriculture) will have on the river flow.

The development of these basic models is dependent on the availability of good quality dry season river flow data. Unfortunately, for most of the rivers the continuous river flow data being generated for river gauging stations is often so poor that it can not be used (the flow data is derived from measured river height data and a rating curve). This is the reason why only manually gauged river flow data was used in the development of the existing models for the Katherine and Goyder rivers. This is particularly the case for rivers where dry season flows are being sourced from aquifers developed in carbonate rocks. Olsen et al. (2004) assessed the accuracy of dry season flow data for seven streamflow gauging stations located in the catchment of the Daly River. They found that computer-generated streamflow was up to 40 percent higher or lower than manually gauged flows. They attributed the differences to the methodology used for the collection and processing of river discharge data, and identified the need to manually gauge dry season flows regularly and then use that data to generate synthetic dry season flow data. Gauging at six-weekly intervals was recommended.

Strategies need to be implemented to mitigate the impacts of groundwater accessions beneath the existing Ord River Irrigation Area and areas proposed for future expansion. These strategies must be based on the output of an aquifer simulation model for the entire Ord River Irrigation Area – current and proposed. Sufficient data exists for the development of these models.

The presence or absence of the Cretaceous sediments has a large impact on recharge to the karstic carbonate aquifers. Recharge via sinkholes to these karstic aquifers is important but has not yet been quantified. More work is required to understand this important recharge process and determine how it can be effectively incorporated into existing and future groundwater models.

The lower Ord River is the only area of this region to have any site-specific metrics by which to gauge the potential impacts of future climate change and development. In the absence of site-specific metrics on other rivers, a set of standard metrics related to high and low flows have been utilised; however, the conversion of these metrics into environmental impacts still requires development of quantitative relationships between flow and specific ecological entities (for example, macrophyte populations, fish passage, faunal and floral habitats, etc.).

Flooding is an important factor that sustains many environmental assets and this occurs when the stream breaks out of its banks (a level known as bankfull stage or discharge). However, bankfull discharge is not known for many streams, nor is the dependence of area flooded on increasing stream depth, so it is difficult to predict when assets are inundated. Further information about bankfull stage and discharge is needed for most environmental assets. The exception to this is for the lower Ord, below Lake Argyle, which has been the focus of extensive study and flow evaluation (e.g. Trayler et al., 2006; DoW, 2006).

Unregulated dry season flows are poorly understood in the this region therefore the ability to predict the potential impacts of the various scenarios on low or zero flows at environmental assets is very limited. Improved monitoring of low streamflow conditions is needed along with the development of hydrological models that combine surface and groundwater regimes. Further monitoring of groundwater levels is also required so that the potential impacts of climate change and development on groundwater-dependent ecosystems can be better understood.

Many environmental assets depend not simply on duration above or below certain flow levels, but on triggers (e.g. for reproduction or migration) set by the rate of change of flow. In addition, some environmental assets depend on the frequency and duration of events that occur less than annually (i.e. once every 5, 10 or 20 years or more). Further analysis is therefore required to look at how the timing, duration and rate of rise and fall in flow rates at critical times of the season will vary under the various scenarios.

OB-1.9 References

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OB-2 Contextual information for the Ord-Bonaparte region

This chapter summarises the background information for the region, outlining existing knowledge of water resources and prior and current investigations relevant to the water resources of the region. This chapter also outlines the current and potential future legislation, water plans and other water resource management arrangements. This chapter is arranged into four sections:

- physical and climate descriptions
- data availability
- hydrogeology
- legislation, water plans and other arrangements.

OB-2.1 Overview of the region

OB-2.1.1 Geography and geology

The geological history of the area is complex (Figure OB-3). Folding of the Early Proterozoic sediments of the Halls Creek Group into a zone of intense metamorphism formed the Halls Creek Mobile Zone. The sediments of the Victoria Basin are the oldest within the region, and significant aquifers occur within carbonate rocks of this basin. An aquifer within the Campbell Springs Dolomite contributes a small but significant baseflow to the upper reaches of the Wickham River (Jackson and Jolly, 2004).

The Victoria Basin is unconformably overlain by the Cambrian Antrim Plateau Continental Flood Basalt, sedimentary rocks of the Ord, Daly and Wiso basins and patchy cover of basin-margin Mesozoic sediments. Soon after the out flowing of basalt, the areas now known as the Ord, Daly and Wiso basins began to subside. A shallow sea formed and a sequence of dominantly carbonate rocks accumulated.

The evolution of the Palaeozoic Bonaparte Basin is tectonically linked to rifting events of the north-west Australian continental margin and periodic reactivation of the Halls Creek Mobile Zone faults, which influenced sedimentation. Sediments were deposited in the Upper Cambrian and Lower Ordovician via deposition of continental to shallow-marine clastics followed by marine carbonate and clastics. There followed deposition of deltaic sediments followed by shallow marine and continental sediments.

In the Early Cretaceous the sea again transgressed the region, depositing a sheet of predominantly sandy sediments followed by a layer of predominantly clayey sediments. That period was short lived and erosion again dominated until the present day. Cainozoic and Cretaceous sediments rest on a palaeo-topographic surface of Proterozoic and Palaeozoic sedimentary and volcanic rocks across the region.

The alluvial plains that cover an extensive area along the lower Moyle, Victoria and Keep rivers are underlain by primarily marine sediments that have been deposited since the end of the last ice age.

The current drainage system probably came into existence in the Cretaceous when uplift in the north resulted in a drainage divide between inland draining streams to the south and streams draining to the sea in the north.

The interior of the region is dominated by the Victoria River Plateau, a large highly dissected plateau up to about 350 m above sea level consisting of sandstone and other sediments. The Cambridge Gulf lowlands consist of more recently deposited Quaternary surface of marine sediments and alluvial plains. There are also some residual outcrops in these plains (Kerle, 1996).

Skeletal sandy soils occur on the rugged plateau but some of the major watercourses have broad, flat-bottomed alluvial valleys. On the coastal lowlands there are alluvial red earth and black soil plains (Kerle, 1996).

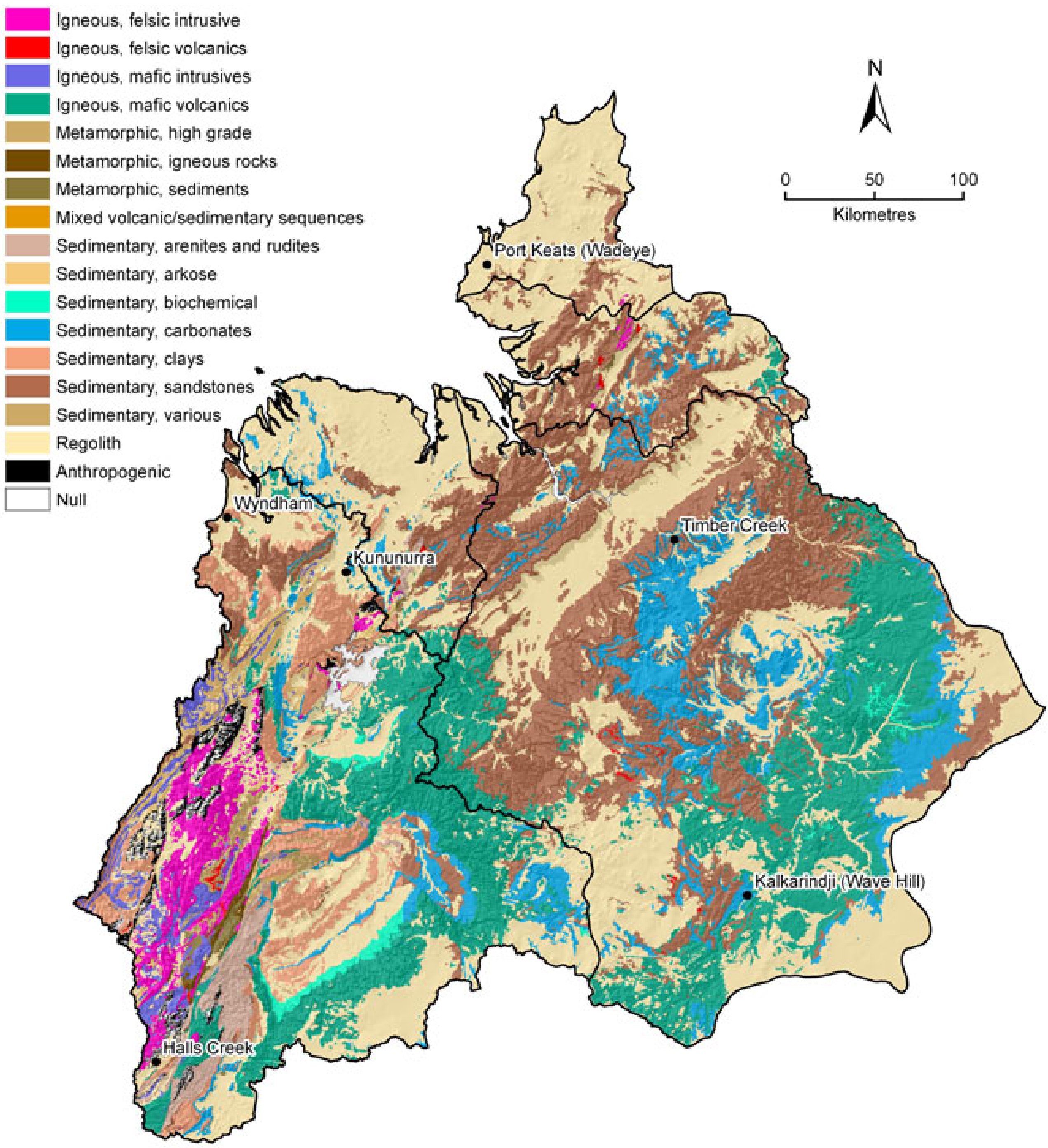

Figure OB-3. Surface geology of the Ord-Bonaparte region overlaid on a relative relief surface

OB-2.1.2 Climate, vegetation and land use

The Ord-Bonaparte region has a dry, warm monsoonal climate, which may be considered semi-arid. The region receives an average of 730 mm of rainfall over the September to August water year, most of which (689 mm) falls in the November to April wet season (Figure OB-4). Across the region there is a strong north–south gradient in annual rainfall, ranging from 1486 mm in the north to 441 mm in the south. Over the first half of the historical (1930 to 2007) period, rainfall has been relatively constant at around 600 mm. The second half of the historical period has seen an increase in mean rainfall to approximately 850 mm. The highest yearly rainfall was 1248 mm in 1974, and the lowest was 316 mm in 1952. Potential evapotranspiration (APET) is very high across the region, averaging 1988 mm over a water year, and varies moderately across the seasons. For most of the year APET remains higher than rainfall resulting in year-round water-limited conditions to which the vegetation has adapted.

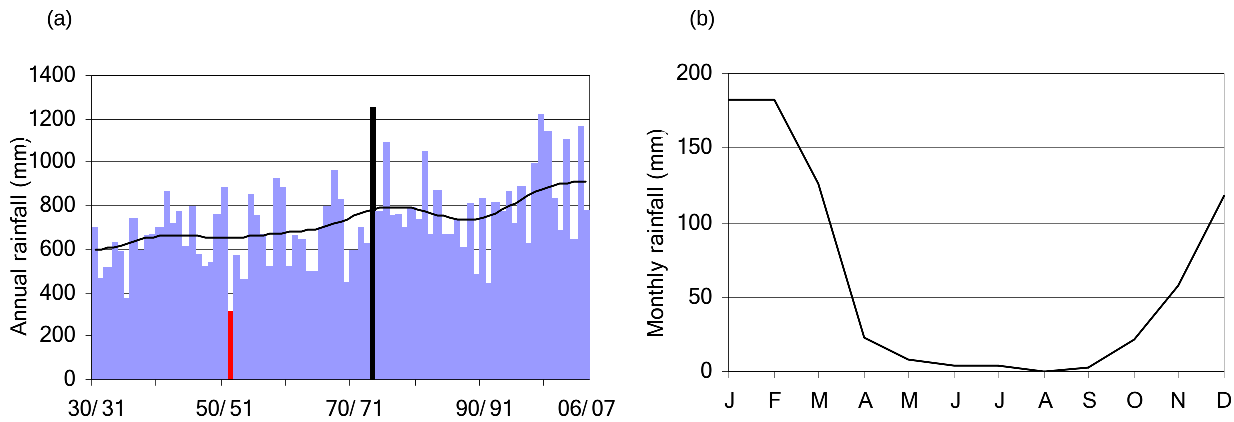

Figure OB-4. Historical (a) annual and (b) mean monthly rainfall averaged over the Ord-Bonaparte region. The low-frequency smoothed line in (a) indicates longer term variability

The bioregion contains two distinctive geomorphic units and four main drainage basins. The Ord River Floodplain and Lake Argyle and Kununurra are listed as Ramsar Wetlands of International Importance. The Ord River Floodplain is a large system of river, tidal mudflat and floodplain wetlands that supports mangroves, and a large numbers of waterbirds and Saltwater Crocodiles (*Crocodylus porosus*). Lake Argyle and Kununurra Ramsar site is large system of human-made reservoirs and associated wetlands used extensively by waterbirds, particularly during the dry season.

The vegetation of the region (Figure OB-5) comprises the Ord-Victoria Plains bioregion and consists of three main components largely determined by the underlying geology: (i) the Proterozoic and Phanerozoic ranges and scattered hills and mesas are mantled by shallow sand and loam soils which support *Triodia* hummock grasslands with sparse low trees; (ii) extensive plains underlain by the Cambrian volcanics and limestones have two main communities, with short grass (*Enneapogon* spp.) on dry calcareous soils and medium-height grassland communities (*Astrebla* and *Dichanthium*) on cracking clays; and (iii) in the south-west, younger bedrock is expressed as often lateritised upland sandplains with sparse trees. This component recurs as the Sturt Plateau Region in central Northern Territory.

In this region 1347 plant species have been recorded, including 39 rare and threatened species (Connors et. al., 1996). The most common vegetation communities are Eucalypt woodlands with tussock and hummock grass understorey. The vegetation communities, however, vary with the landforms, which include rocky country, undulating plains, watercourses and coastal areas.

On the rocky country on the southern portion of the Victoria Plateau there are low open woodland communities including Snappy Gum (*E. brevifolia*), Variable Barked Bloodwood (*Corymbia dichromophloia*) with Curly Spinifex (*Plectrachne pungens*) hummock grassland and a very sparse shrub layer. Darwin Woolly Butt (*E. miniata*) and Turkey Bush (*Calytrix exstipulata*) also occur in some areas.

In the north-east of the region there are two plant communities on the rocky country. One is a Salmon Gum (*E. tintinnans*), Variable Barked Bloodwood and Ironwood (*Erythophleum chlorostachys*) low woodland over Sorghum grassland. The other is taller woodland up to 14 m of Stringybark, Darwin Woolly Butt and Smooth-Stemmed Bloodwood (*Corymbia bleeseri*) with a sparse shrub layer over Sorghum grassland.

On the undulating plains woodland communities include Northern Box (*E. tectifica*) / Bloodwood (*Corymbia terminalis*) with White Grass (*Sehima nervosum*) and Golden Beard Grass (*Chrysopogon fallax*). In the north of the region Round Leaf Box (*E. latifolia*) occurs and the shrub layer includes palms and cycads.

Watercourses include Paperbarks (*Melaleuca minutifolia*), Coolibah (*E. microtheca*), and grassland of Golden Beard Grass and Blue Grass (*Dichanthium fecundum*) on the cracking clays.

Coastal communities include saline tidal flats with low chenopod shrubland (samphire) occurring between the sea and plains of Rice Grass (*Xerochloa* spp.). Patches of mangal low closed forest (mangroves) also occur along this section of the coast (Kerle, 1996). There are also pockets of monsoon vine thicket (Connors et. al., 1996).

The diversity of habitats in the bioregion is reflected by the diversity of bird species. Brown Honeyeaters and the Peaceful Dove are widespread. Patches of monsoon forest support species such as the Orange-Footed Scrub-Fowl

(*Magapodius reinwardt*) and Green-Backed Gerygone (*Gerygone chloronotus*). The endangered Gouldian Finch (*Erythrura gouldiae*) and the restricted Purple-Crowned Fairy-Wren (*Malurus coronatus*) occur within the bioregion (Kerle, 1996).

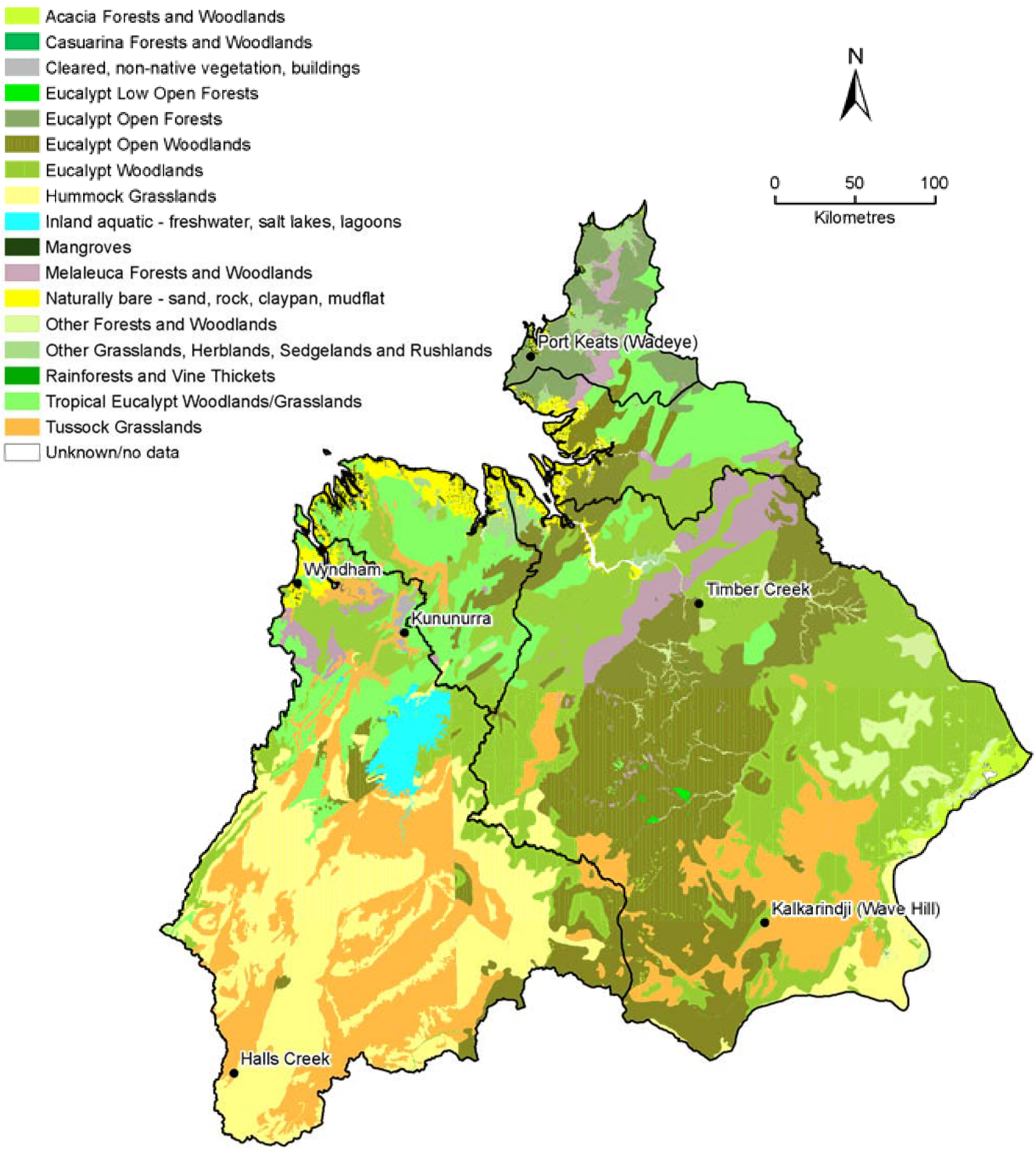

Figure OB-5. Map of current vegetation types across the Ord-Bonaparte region (source DEWR, 2005)

The region still retains over 99 percent native vegetation.

The only towns in the Ord-Bonaparte region are Kununurra, Halls Creek, Warmun, Peppiminarti, Wadeye, Kalkarindji, Dagaragu, Yarralin and Timber Creek. The total population living within the catchment is probably less than 20,000. The main activities occurring in the region are mining, irrigated agriculture, the pastoral industry, tourism and the operation of the Royal Australian Defence Force at Bradshaw.

Pastoralism is the dominant land use, with extensive cattle grazing, but large areas are devoted to horticulture associated with the Ord irrigation scheme (Figure OB-6) and military uses. There are significant areas of Indigenous land in this region. Tourism is a growing industry, with increasing use of four-wheel drive vehicles in rugged country. Attractions include Indigenous art sites and reserves such as Keep River and Gregory National Parks.

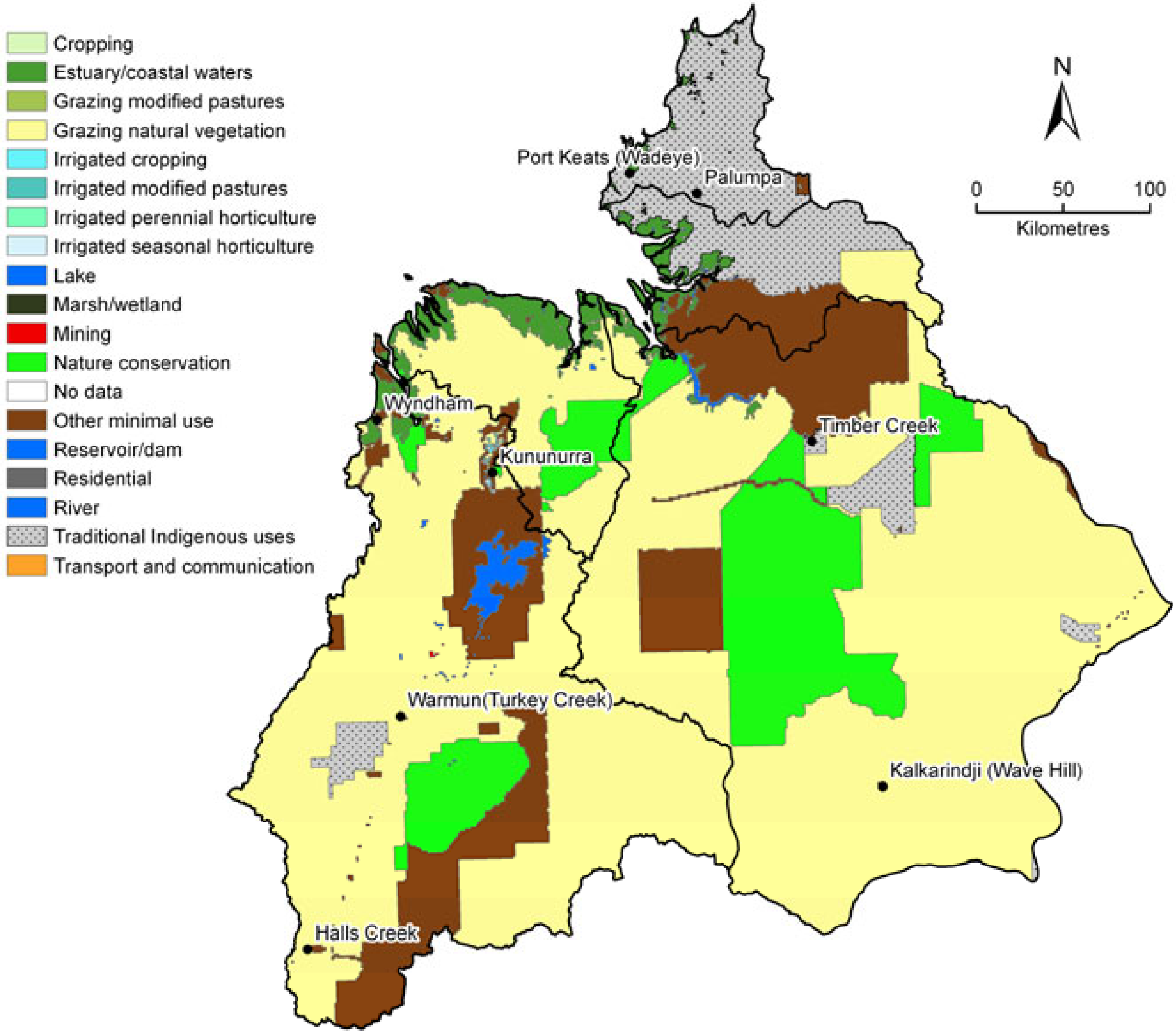

Figure OB-6. Map of dominant land uses of the Ord-Bonaparte region (after BRS, 2002)

OB-2.1.3 Regional environmental asset description

Environmental assets were chosen from wetlands which are listed in the Directory of Important Wetlands in Australia (Environment Australia, 2001). From this directory, environmental assets were shortlisted for assessing changes to the hydrological regime under the climate and development scenarios. The selection of this shortlist was undertaken in consultation with state governments and the Australian Government through direct discussions and through internal reviews (see Section 1.3 in the division-level Chapter 1 for further detail).

All nationally, or internationally, important wetlands listed for the Ord-Bonaparte region in the Directory of Important Wetlands in Australia (Environment Australia, 2001) are detailed in Table OB-2, with asterisks identifying the four shortlisted assets: Lake Argyle, Lake Kununurra, Parry Floodplain and Ord Estuary System. The location of these shortlisted wetlands is shown in Figure OB-1. These four wetlands are also Ramsar sites. Wetlands may be nationally or regionally significant depending on more locally specific criteria. All wetlands are important for a variety of ecological reasons or because they bear historical significance or have high cultural value, particularly to Indigenous people.

The following section characterises these shortlisted wetlands and is based largely on the description of these assets as outlined by Environment Australia (2001). Chapter OB-3 presents the assessment of those shortlisted assets, and reports hydrological regime metrics for those assets which have sufficient confidence in the modelled streamflow to enable analysis.

Table OB-2. List of Wetlands of National Significance located within the Ord-Bonaparte region

Site code	Name	Area	Ramsar site
		ha	
WA097 *	Lake Argyle	98,000	Yes
WA098 *	Lake Kununurra	2,500	Yes
WA100 *	Parry Floodplain	9,000	Yes
WA099 *	Ord Estuary System	94,700	Yes
NT033	Bradshaw Field Training Area	<10	No
NT030	Legune Wetlands	10,300	No
NT027	Moyle Floodplain and Hyland Bay System	74,700	No

* Asterisk against the site code identifies those shortlisted for assessment of changes to hydrological regime.

Lake Argyle

Lake Argyle (Figure OB-7) is a human-made wetland formed by the creation of a water storage. The site extends to the usual high water mark of Lake Argyle. The site has an area of 98,000 ha and an elevation ranging between 92.2 m (bottom of the spillway) and 97.3 m (high water mark of the largest recorded flood in 1992) (Environment Australia, 2001). It is a good example of an artificial freshwater lake in the Australian tropics, being the largest such lake in northern Australia. The site is listed jointly with Lake Kununurra as a Wetland of International Importance under the Ramsar Convention (Government of Western Australia, 1990).

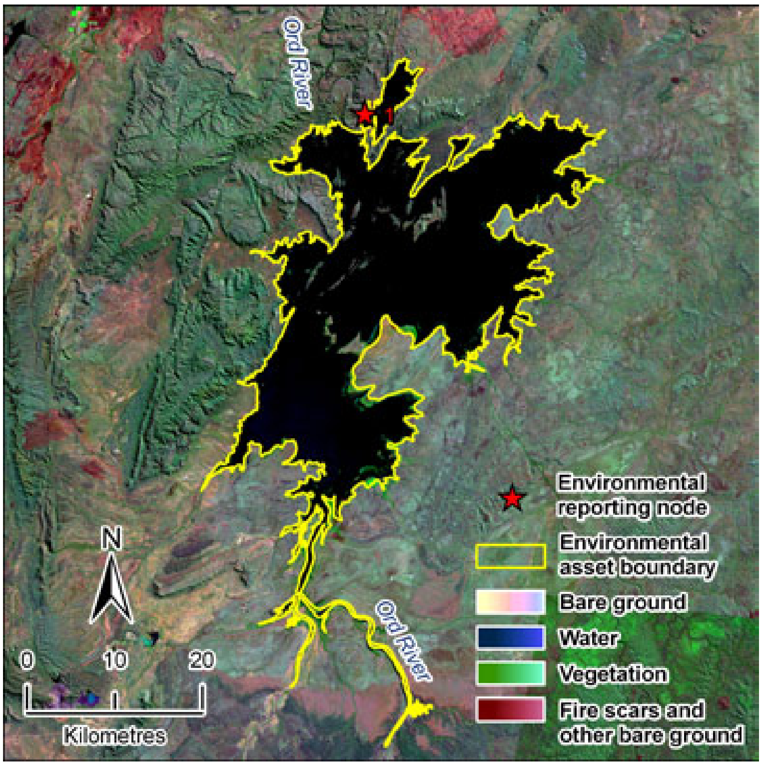

Figure OB-7. False colour satellite image of Lake Argyle (derived from ACRES, 2000). Clouds may be visible in image

The lake supports extensive mats of aquatic plants and large numbers of waterbird species. Both Australian species of crocodile and at least 15 fish species occur in the lake. Lake Argyle is a significant tourist destination and supports commercial boat tours and private recreational boating and fishing.

Lake Kununurra

Lake Kununurra (Figure OB-8) is formed by the Kununurra Diversion Dam on the Ord River near the town of Kununurra. It is a good example of an artificial tropical wetland system with extensive, permanently-inundated emergent vegetation. The site is listed, jointly with Lake Argyle, as a Wetland of International Importance under the Ramsar Convention (Government of Western Australia, 1990). The site comprises the drowned river channel and fringing swamps formed by flooding of surrounding dry land. The lake extends upstream to the Lake Argyle Dam. The site has an area of 2500 ha and an elevation ranging between approximately 40 and 60 m AHD (Environment Australia, 2001). The water level in Lake Kununurra is maintained in a narrow range of 41.1 to 41.7 m AHD (target of 41.5 m AHD) to facilitate diversion of water to the stage 1 areas of the Ord River Irrigation Area.

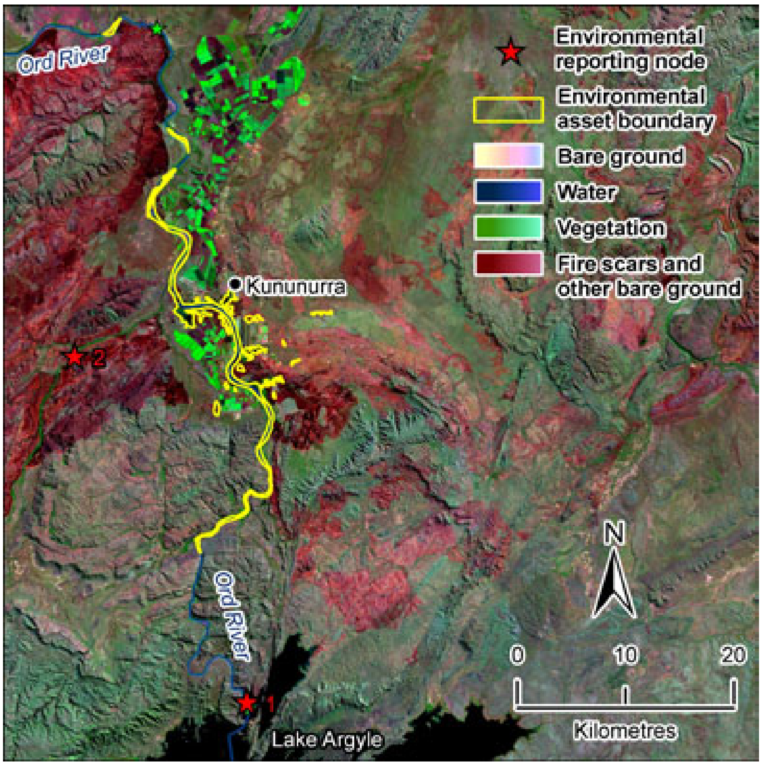

Figure OB-8. False colour satellite image of Lake Kununurra (derived from ACRES, 2000). Clouds may be visible in image

The Bulrush beds at this site are the most extensive in Western Australia outside the Swan Coastal Plain bioregion (WADCALM, 1990). The site supports colonies of Flying Fox and at least 15 species of freshwater fish. The site is a major breeding area for Freshwater Crocodiles. The lake is popular with local residents and tourists for swimming; recreational fishing and boating; charter boat and float-plane tours; and bird-watching.

Parry Floodplain

Parry Floodplain (Figure OB-9) is a good example of a tropical floodplain with permanent billabongs, seasonal marshes and wooded swamp. It is one of the few such floodplains of substantial area in Western Australia. It is listed jointly with the Ord Estuary System as a Wetland of International Importance under the Ramsar Convention (Government of Western Australia, 1990, 2000).The site has an area of 9000 ha and an elevation ranging between 5 and 10 m above sea level (Environment Australia, 2001). Since the construction of the Ord River Dam in 1972, the lower Ord River floods onto the Parry Floodplain much less frequently and most of the wet season runoff is generated from local creeks (e.g.

Wild Goose Creek, Parry Creek) which generate most flows and local flooding in this Ramsar wetland (Rodgers and Ruprecht, 2001). Overbank flows on the lower Ord River are now mainly a result of runoff from the catchment below the Ord River Dam (~10 percent of the previous total catchment), therefore the Parry Floodplain is now mainly fed by local inflow and local flooding, with much less frequent flooding from the lower Ord River.

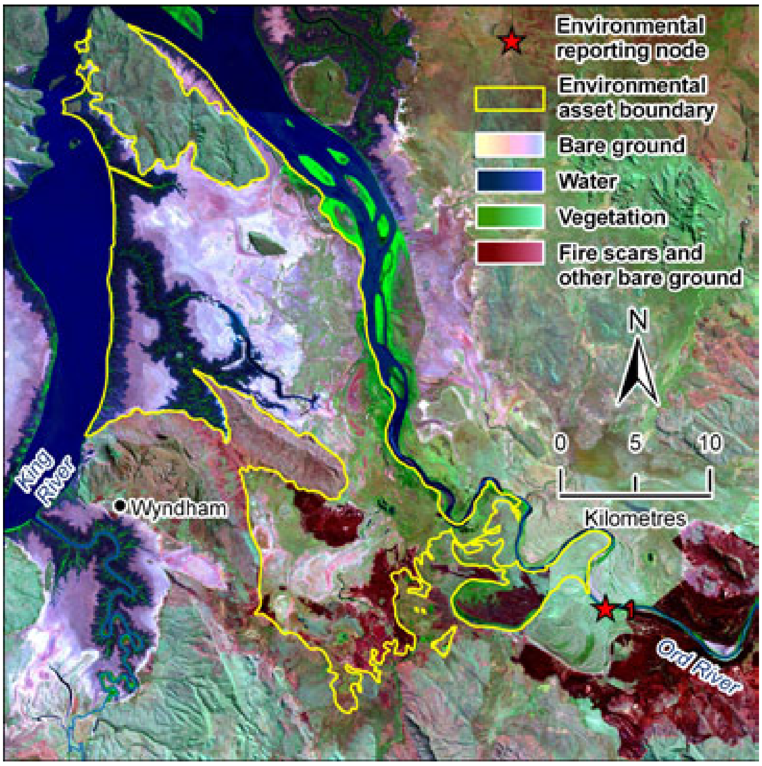

Figure OB-9. False colour satellite image of the Parry Floodplain (derived from ACRES, 2000). Clouds may be visible in image

The floodplain's herbland/grassland communities are the most extensive in Western Australia (Burbidge et al., 1991; WADCALM, 1990). Seventy-seven waterbird species have been recorded at the site (one of the highest totals in the Kimberley). The permanent freshwater and food resources of the site were valuable to Indigenous people. Areas of this site are popular picnic and bird-watching areas and the site in general is popular with tourists.

Ord Estuary System

The Ord Estuary System (Figure OB-10) is an outstanding example of an estuary system of tropical north-west Australia with the most extensive mudflat and tidal waterway complex in Western Australia. It is listed, jointly with Parry Floodplain, as a Wetland of International Importance under the Ramsar Convention (Government of Western Australia, 1990 2000). The Ord Estuary System has an area of 94,700 ha at an elevation at or near sea level (Environment Australia, 2001). This marine-dominated system experiences very large tides and as such changes in the flow regime of the Ord River are likely to have little impact on estuarine processes.

Many mangrove species have been recorded at the site. Substantial numbers of bird species have been observed. By virtue of the great extent of the mangrove area, the site constitutes a major nursery area for estuarine and marine fishes and crustaceans and supports a substantial population of Saltwater Crocodiles.

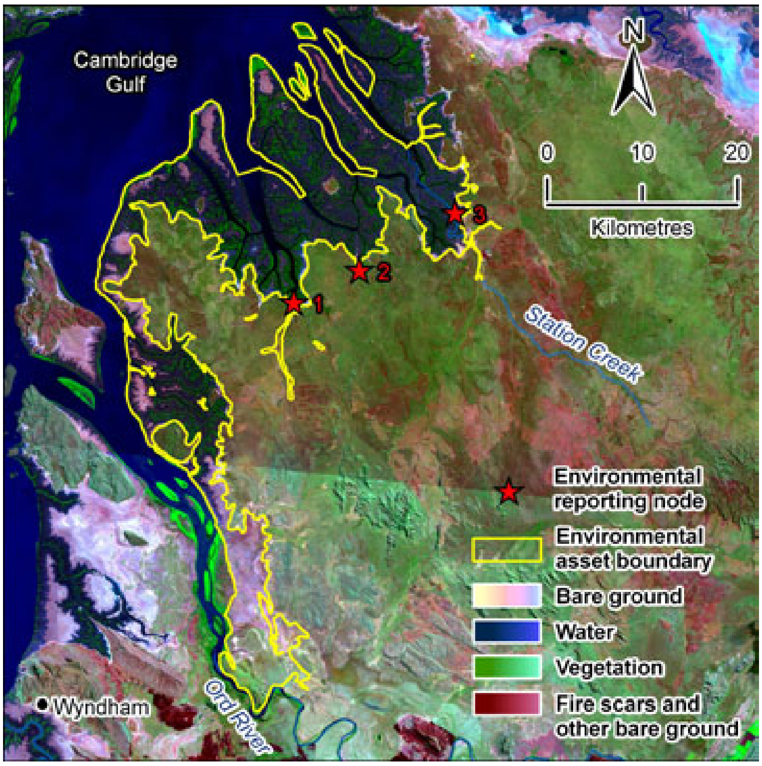

Figure OB-10. False colour satellite image of the Ord Estuary System (derived from ACRES, 2000). Clouds may be visible in image

OB-2.2 Data availability

OB-2.2.1 Climate

The rainfall-runoff modelling uses historical daily climate data (Scenario A) from the SILO database for the period 1 September 1930 to 31 August 2007 at 0.05 x 0.05 degree (~ 5 x 5 km) grid cells. Full details and characterisation of the SILO database are provided at the division level in Section 2.1 of Chapter 2. Scenario B and Scenario C climate data are rescaled versions of the Scenario A data; this is also discussed in Section 2.1 of Chapter 2.

OB-2.2.2 Surface water

Streamflow gauging stations are or have been located at 63 locations within the Ord-Bonaparte region. Forty-one of these gauging stations either: (i) are flood warning stations and measure stage height only, (ii) installed on irrigation drains in the Ord River Irrigation Area; or (iii) have less than ten years of measured data. Of the remaining 22 stations, eight recorded more than half of their total volume of flow during events that exceed the maximum gauged stage height. Figure OB-11 shows the spatial distribution of good quality data (duration) and the percentage of flow above maximum gauged stage height (MGSH) (this assessment was only undertaken on stations with ten years or more data). Prior to the development of the Ord Dam, inflows to Lake Argyle were assessed at Coolibah Pocket, gauge 809302 (catchment area of 45,195 km^2). Although this gauge has less than ten years of acceptable monthly data, the data are of relatively high quality. While the Victoria catchment has a low density of gauging stations, a large proportion of the catchment is gauged at Coolibah Homestead, G8110007 (catchment area of 44,900 km^2). This station has over 30 years of record and has a well-established rating curve.

There are 24 gauging stations currently operating in the Ord-Bonaparte region at a density of one gauge for every 6900 km^2. For the 13 regions the median number of currently operating gauging stations per region is 12 and the median density of gauging stations per region is one gauge for every 9700 km^2. The density of current gauging stations in the Ord-Bonaparte region is slightly higher than the median of the 13 regions across northern Australia and considerably lower than the Murray-Darling Basin average. The mean density of current stream gauging stations across the entire Murray-Darling Basin is one gauge for every 1300 km^2.

In Figure OB-11 the productive aquifer layer for the Northern Territory includes dolostone and limestone formations and Cretaceous sandstone formations. Consequently these productive aquifers exhibit a wide range of bore yields.

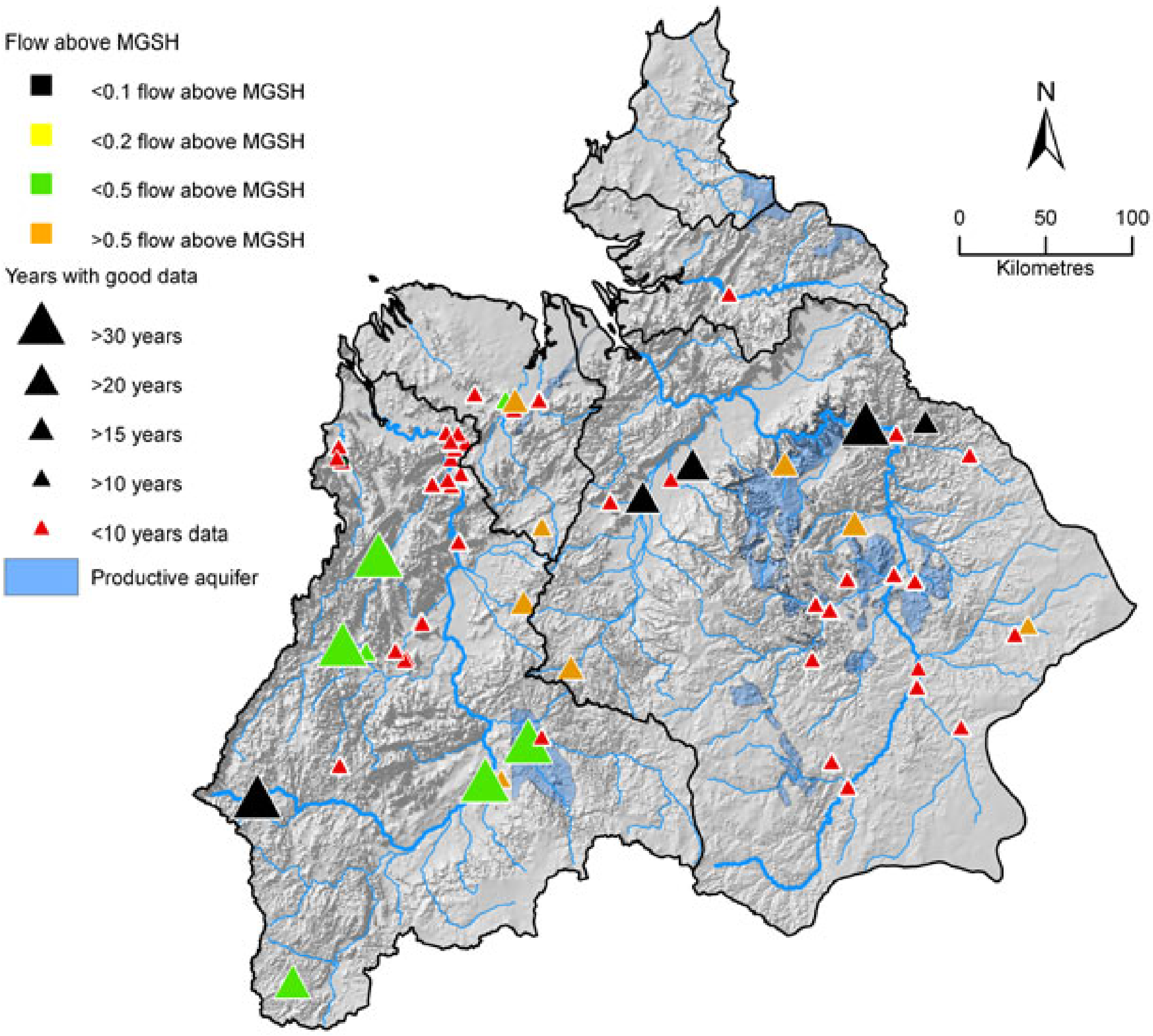

Figure OB-11. Location of streamflow gauging stations overlaid on a relative relief surface showing the proportion of gauges with flow above maximum gauged stage height across the Ord-Bonaparte region. Productive aquifer layer includes key dolostone, limestone and Cretaceous sandstone formations

OB-2.2.3 Groundwater

The Ord-Bonaparte region contains a total of 3353 registered groundwater bores. Of these, 368 have surveyed elevations that could enable watertable surfaces to be constructed for the main aquifers. However these bores are not necessarily monitored on a regular basis. There are 578 water level monitoring bores in the region; 209 are historical and 369 are current.

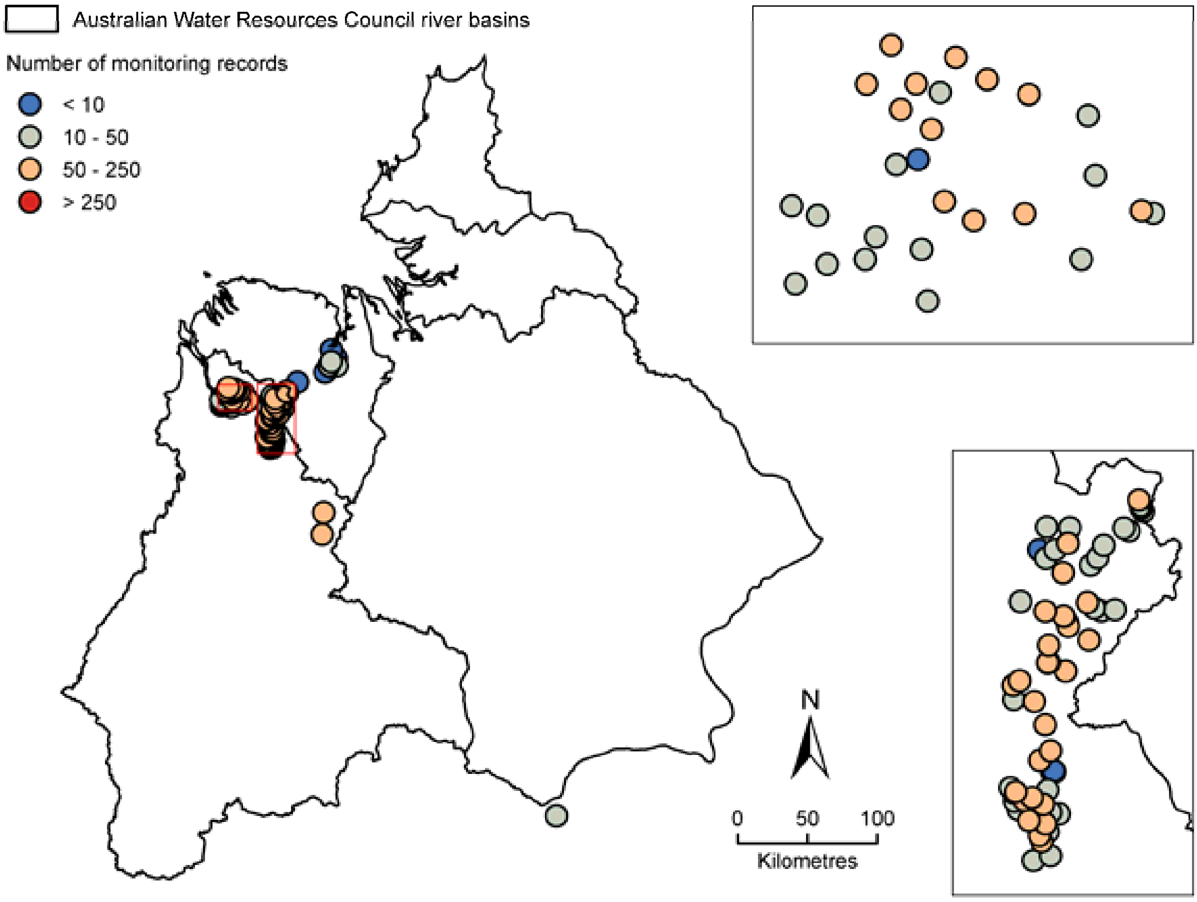

Figure OB-12. Current groundwater monitoring bores in the Ord-Bonaparte region

OB-2.2.4 Data gaps

The major aquifers with potential for development for irrigated agriculture occur in the Palaeozoic sediments. These aquifers are also a significant source of water for the extensive wetlands that occur adjacent to the Northern Territory's western coastline (e.g. the Moyle River floodplains). There is insufficient data available to develop a model for this extensive groundwater resource. A programme of work needs to be undertaken to obtain the data that will enable impact assessment models to be developed for these groundwater resources.

OB-2.3 Hydrogeology

This section describes the key sources of groundwater in the Ord-Bonaparte region. The description is primarily based on reports and water bore data held by the Northern Territory Government Department of Natural Resources, Environment, The Arts and Sport (NRETAS). The distribution of water bores in the region in 2008 is shown on Figure OB-13.

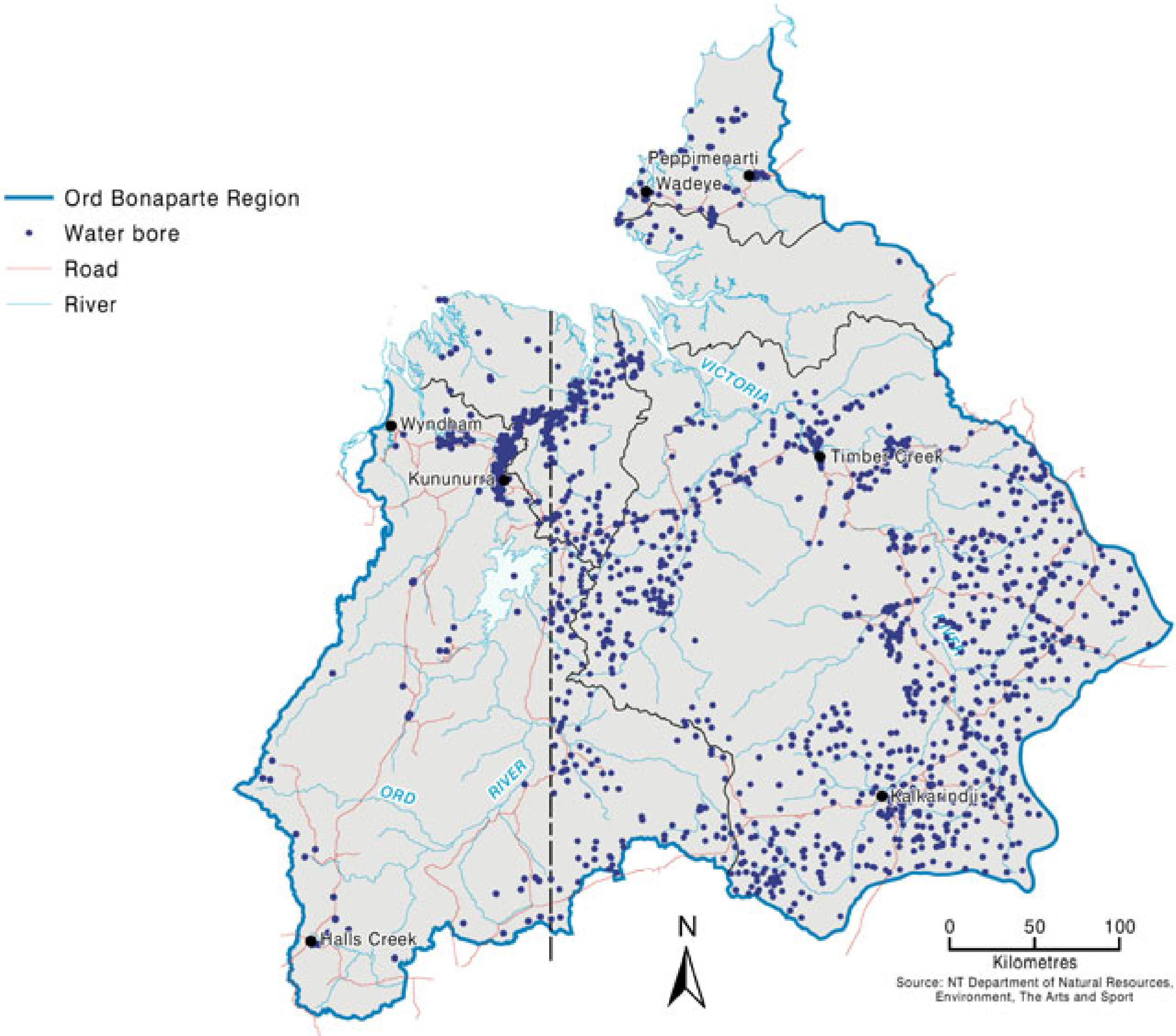

Figure OB-13. Location of groundwater bores in the Ord-Bonaparte region (source NRETAS, 2009)

OB-2.3.1 Aquifer types

There are four major aquifer types in the Ord-Bonaparte region, namely fractured rocks, karstic carbonate rocks, Palaeozoic and Cretaceous sediments, and Ord Palaeochannel Sediments. These types are briefly described below and their areal extent is shown on Figure OB-2.

Fractured rocks

A variety of Precambrian (older than 500 million years) rocks form the bedrock of the area. These are mainly sedimentary but also include granite and volcanic rocks. Sandstone, siltstone and greywacke are the main sedimentary rock types. In some areas they are flat-lying while in other areas they have been folded, faulted and show low grade metamorphism. In the Early Cambrian (500 million years ago) volcanic eruptions produced an extensive sheet of basalt flows known as the Antrim Plateau Volcanics. These cover a large portion of the Ord-Bonaparte region and underlie the land that has been most intensively developed by the pastoral industry.

Water is usually intersected in weathered fractured zones within the fractured rocks. Occasionally groundwater is intersected in the contact zone between flows of the basalt or at the unconformity between the basalt and the underlying Proterozoic sedimentary rocks.

Groundwater yields are controlled by the degree of fracturing of these units and are likely to be greater in areas located along large-scale joints and fault zones. Yields are noted to typically range from 55 to 110 m^3/day with up to 220 m^3/day found in some areas (Passmore, 1967). In the Ord Basin, Passmore (1967) notes that groundwater yields average 164 m^3/day, and have been found to be up to 330 m^3/day from a number of units. In the Victoria River District, yields from the Jasper Gorge Sandstone are found between 43 to 430 m^3/day and are of a similar range in Antrim Plateau Volcanics basalt (Sanders and Rajaratnam, 1994). Tickell and Rajaratnam (1998) report median airlift yields of 130, 170, 140 and 43 m^3/day for basalt, sandstone, dolomite and siltstone aquifers respectively in the Victoria River District.

Karstic carbonate rocks – Tindall Limestone (or equivalent), Jinduckin Formation (or equivalent) and Proterozoic carbonates

The most significant aquifers in the Top End of the Northern Territory occur within the carbonate rocks of the Ord, Daly and Wiso basins. These carbonate rocks extend across a large part of the Northern Territory and into Queensland (Figure OB-14). The Tindall Limestone (and equivalent Headley's Limestone) hosts widespread karstic aquifers. These aquifers have very high permeabilities due to an extensive network of interconnected solution cavities. The Jinduckin Formation (and equivalent Panton Formation and Nelson Shale) is mainly composed of siltstone. The formation contains thin, local aquifers in isolated limestone beds.

Lauritzen and Karp (1993) concluded that the Tindall Limestone karst aquifer developed before the Cretaceous period. The permeability of the karst aquifer has been further enhanced since then by the movement of acidic groundwater from the aquifer developed in the basal Cretaceous sandstone where it overlies the limestone.

Palaeozoic and Cretaceous sediments

Major aquifers occur over a large area in the north west of the Ord-Bonaparte region within Permian sandstones of the Bonaparte Basin (Haig and Matsuyama, 2003; Humphreys et al., 1995). While airlift yields in shallow bores average 170 m^3/day, yields are expected to be in excess of 840 m^3/day if bores were drilled deeper and appropriately screened (Tickell and Rajaratnam, 1998).

The Cretaceous Sandstone aquifer contributes a small but significant baseflow to the upper reaches of the Fitzmaurice and Moyle rivers. Over the region it normally occurs in rugged environments and hence no water bores have been drilled into it in the region.

Ord Palaeochannel sediments

Cainozoic sediments underlie part of the Keep River floodplain where expansion of the Ord River Irrigation Area is proposed to occur (see Section OB-2.4.1). These sediments comprise the palaeochannel sediments of the Ord River and Keep River. The deposition of these sediments is consistent with deposition in a fluvial environment, and many of the features of meandering rivers can be recognised (O'Boy et al., 2001). The sediments generally fine upwards. They comprise basal sands and gravels overlain by sand, red silty sand, and silt topped with black soil. The black cracking clay soils that cover most of the plains are fringed by sandy colluvial slopes of the surrounding hills. The sediments generally range up to 30 to 40 m in thickness. A significant aquifer occurs within the basal sands.

The sediments are typically categorised into four groups as described above, with yields of 432 to 2160 m^3/day for the basal sand and gravel; 43 to 432 m^3/day for sandy sediments; 4.3 to 43 m^3/day for sandy to silty sediments; and 0.43 to 4.3 m^3/day for clay to silty sediments (Smith, 2008).

Smaller alluvial deposits are located along the upper reaches of rivers traversing sandstone and granites; however these are not commonly extensive enough to provide large supplies (Passmore, 1964). Yields from smaller alluvial aquifers commonly range between 110 and 220 m^3/day (Passmore, 1967).

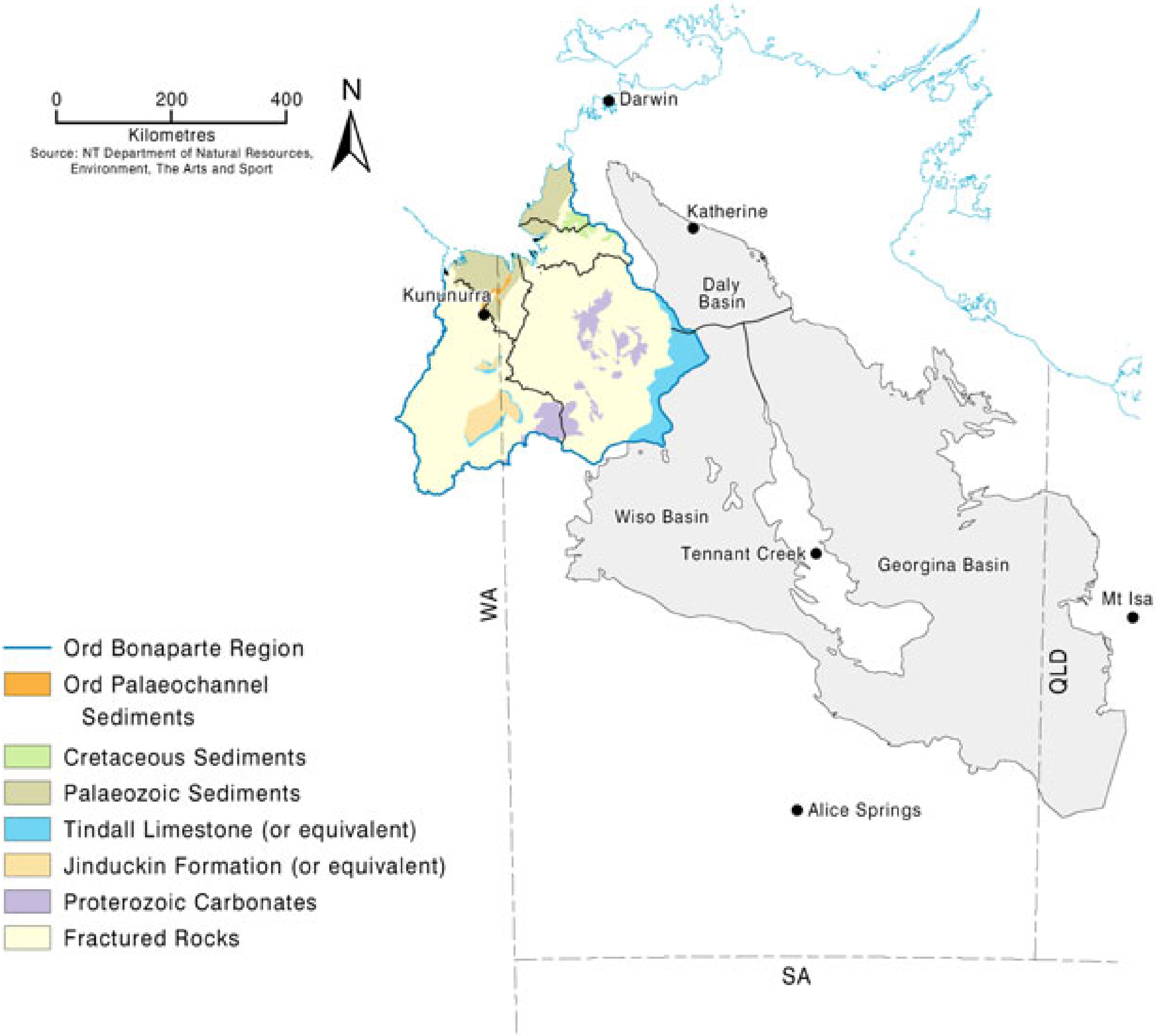

Figure OB-14. Location of Ord-Bonaparte region in relation to the Daly, Wiso and Georgina basins (source NRETAS, 2009)

OB-2.3.2 Inter-aquifer connection and leakage

The four major aquifer types in the region are not in hydraulic connection because they are separated by siltstone, claystone or shale (refer Figure OB-2).

The fractured rock aquifers may be in hydraulic connection with the aquifer developed in the basal sandstone of the Cretaceous sediments. This connection may be significant adjacent to the upper reaches of the Fitzmaurice River where spring discharge from the Cretaceous sandstone maintains the dry season river flow.

In the Ord River Irrigation Area there have been numerous hydrogeological investigations looking at the causes of groundwater accession since the mid-1960s, as described in O'Boy et al. (2001). However under natural conditions it is thought that groundwater levels would have been at, or slightly above, the bedrock leaving the alluvial sediments largely unsaturated, particularly in the dry season (O'Boy et al., 2001). Long-term pumping tests were conducted at rates in excess of 4000 m^3/day from the basal gravel sediments of the Ivanhoe plain by Smith et al. (2005) who found that there was significant connection with the overlying and less permeable, alluvial sediments. Where elevated groundwater levels exist in the alluvial aquifers, groundwater is thought to flow towards the Ord River and also vertically downwards to the more transmissive sediments and then horizontally, either towards the Ord River or the Keep River.

OB-2.3.3 Recharge, discharge and groundwater storage

Recharge occurs only in the wet season when rainfall intensity and duration is sufficient. Generally recharge leads to a rise in groundwater levels in the wet season and in the dry season the levels naturally fall as groundwater is either transpired or discharged to wetlands and rivers where it evaporates or is discharged to the sea. The amount and rate at which the groundwater levels rise and fall depends on the type, size and other physical properties of the aquifer as well as the amount of recharge. The recharge/discharge cycle that applies in the Ord-Bonaparte region is summarised in Figure OB-15.

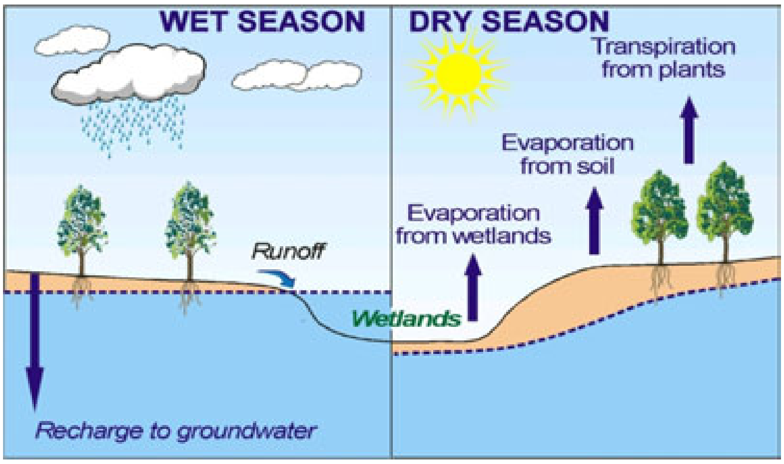

Figure OB-15. Schematic of the recharge and discharge cycle that applies in the Ord-Bonaparte region

Recharge beneath native vegetation is dominated by bypass flow and not diffuse movement through soil horizons. The most likely mechanism for this is via macro-pores (cracks and root holes in the soil).

Recharge rates will be higher in the north-east of the region in the Fitzmaurice and Moyle river basins due to higher rainfall. Passmore (1967) noted that river recharge and leakage from thin alluvial aquifers may also be significant mechanisms for recharging the fractured rock aquifers. Evapotranspiration is thought to be the primary discharge mechanism (Passmore, 1964; Tickell and Rajaratnam, 1998).

Springs in the Victoria River Basin commonly have flows ranging from seeps to 170 m^3/day (Tickell and Rajaratnam, 1998). Their occurrence is determined by a combination of the properties of the aquifer, landscape and aquifer location and geological features such as faults or contacts with impermeable units (Tickell and Rajaratnam, 1998). Spring flows depend on short-term rainfall patterns and are known to gradually decrease in discharge as the dry season progresses, often not being able to maintain permanent flows (Tickell and Rajaratnam, 1998). No estimate of groundwater storage has been made in the literature due to the complexity of the geology of the region.

Groundwater discharges that maintain perennial reaches of rivers within the Fitzmaurice, Moyle and Wickham rivers are important. Prior to 1988, the Northern Territory Government maintained river gauging stations on the Fitzmaurice and Moyle rivers that measured groundwater discharge to perennial reaches of rivers.

Small quantities of groundwater flow either into or out of the Ord-Bonaparte region across its boundary. It would be expected that over most of the region the inflows will balance the outflows and the net impact will not be significant. The only exception to this is the aquifer system that occurs in the Tindall Limestone which is located adjacent the eastern boundary of the region. This aquifer system discharges to the Flora River which is located in the Daly region to the immediate northeast of the Ord-Bonaparte region.

Specific comments relating to recharge and discharge for each of the four major aquifer types follow. The locations of monitoring bores and river gauging stations in the region that are referenced in the following sections are shown on Figure OB-2.

Fractured rocks

The hydrogeological characteristics of as the Antrim Plateau Volcanics have been documented in a report by Tickell and Rajaratnam (1998). Groundwater levels have been monitored in this formation at a number of sites on Rosewood Station since 1993. Tickell (1998) estimated recharge to the basalt aquifer over the period 1993 to 1998. His estimated recharge is compared to that of Jackson and Jolly (2004) for the Wickham River area over the same period in Table OB-3. The data shown in Table OB-3, which are supported by groundwater levels for bore RN028905 located near Rosewood Station (Figure OB-16), indicate that significant recharge is occurring to the basalt aquifer in most wet seasons. However there are wet seasons where minimal recharge appears to have occurred (e.g. 1997/98).

Table OB-3. Estimated recharge to the aquifer in the Antrim Plateau Volcanics

Year	Water year rainfall Rosewood	Estimated recharge Rosewood	Water year rainfall Wickham River area	Estimated recharge Wickham River area
	mm			
1993/94	719	29	914	67
1994/95	801	19	905	23
1995/96	631	3	1051	9
1996/97	904	79	972	70
1997/98	Not recorded	0	512	0

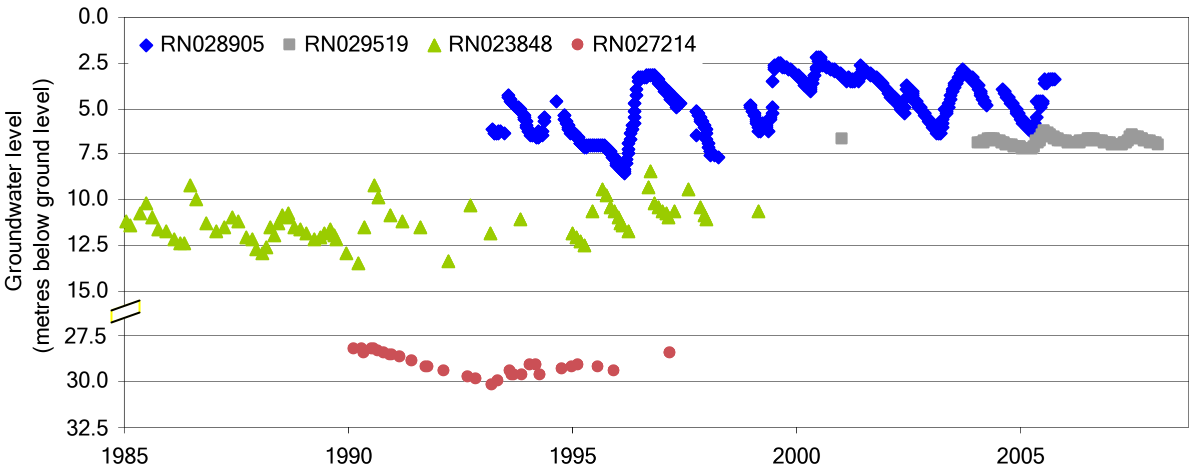

Figure OB-16. Observed groundwater levels for bore RN028905 in the Antrim Plateau Volcanics near Rosewood Station, bore RN023848 in the Proterozoic carbonate near Timber Creek, bore RN027214 in Palaeozoic sediments near Wadeye (Port Keats), and bore RN029519 in the Ord Palaeochannel Sediments beneath an undeveloped area

Karstic carbonate rocks – Tindall Limestone (or equivalent), Jinduckin Formation (or equivalent) and Proterozoic carbonates

There are only limited data available for groundwater levels in the Proterozoic carbonates. The data shown in Figure OB-16 for bore RN023848 located near Timber Creek indicates that significant recharge is occurring in most wet seasons. However there are wet seasons where minimal recharge appears to have occurred (e.g. 1989/1990).

Regional groundwater discharges from the aquifer developed in Proterozoic carbonates provide the dry season flow for the Wickham River and numerous small springs across the region. Jackson and Jolly (2004) estimated the potential recharge to carbonate aquifers in the Wickham River area for the period 1883 to 2003. They noted however that surface runoff was included in the figure derived for the potential recharge rate. Subsequent work has indicated that the estimated recharge rate should be approximately 40 percent of the potential recharge rate. Applying that relationship between potential and estimated recharge in the Wickham River area yields the relationship between rainfall and recharge shown in Figure OB-17.

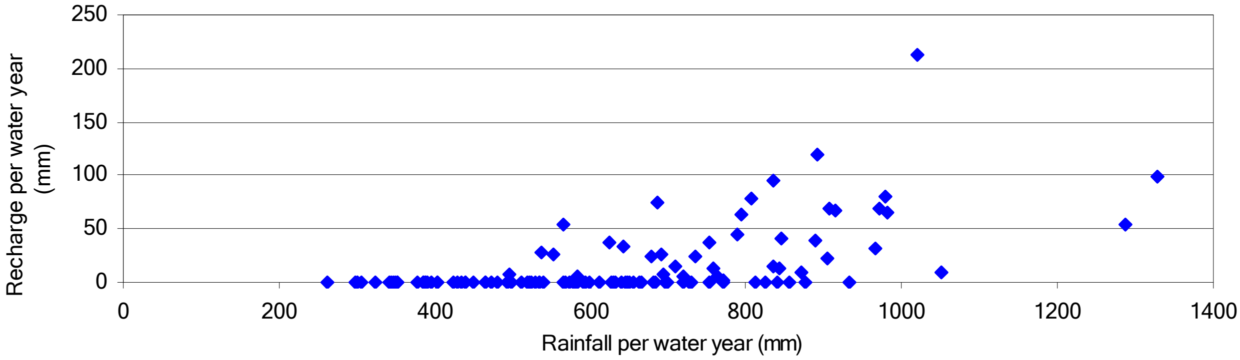

Figure OB-17. Estimated recharge for the Wickham River area

The Tindall Limestone (and equivalent) aquifer underlies such a large area that its recharge rate can vary significantly due both to the areal variability in rainfall and the presence or absence of Cretaceous sediments overlying it. However in this region no groundwater monitoring bores have been constructed to measure water levels in it. No information exists also for the formation in the south-western part of the region that is believed to be the equivalent of the Jinduckin Formation.

Palaeozoic and Cretaceous sediments

Changes in groundwater levels occur in response to changes in the amount of rainfall that recharges the aquifer each year. However there are no bores which monitor water level fluctuations in the Cretaceous sediments in the region. Regional groundwater discharges from the aquifer developed in the Cretaceous sediments, however, provides the dry season flow for the Fitzmaurice River and sections of the Moyle River. Dry season flow rates in rivers are dependent on the amount of rainfall that recharges the aquifer each year. The changing recharge rate to the Cretaceous sediments is reflected in the variation in dry season flow measured at gauge G8120220. This gauge is located on the Fitzmaurice River (Figure OB-18) and the data reflect an increase in recharge after 1979 compared to before 1974 (Figure OB-18).

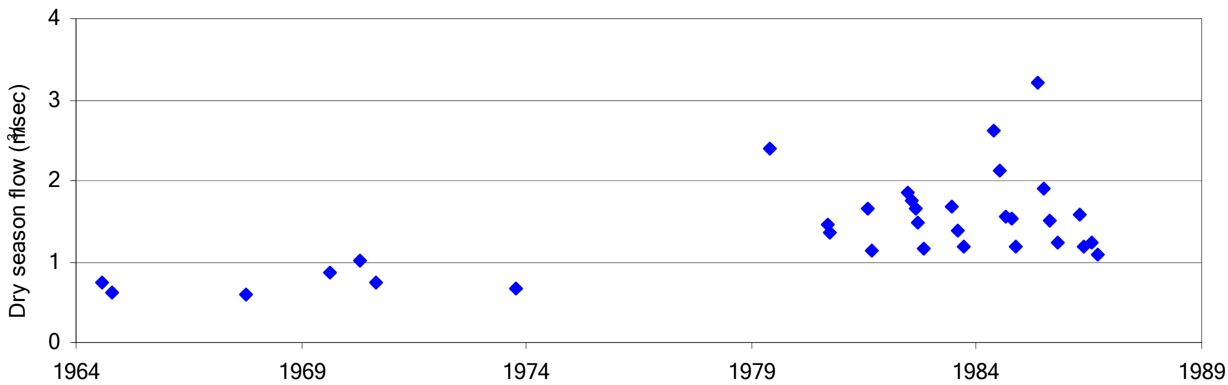

Figure OB-18. Gauged dry season flows at G8120220 on the Fitzmaurice River

There are some limited data available for groundwater levels in the Palaeozoic sediments. The data shown in Figure OB-16 for bore RN027214 located near Wadeye (Port Keats) indicate that significant recharge did not occur during the period from the beginning of 1991 to the end of 1993.

Ord Palaeochannel Sediments

Recharge to the aquifer in the Ord Palaeochannel Sediments that underlie the black soil plains of the lower Keep River has been investigated in a joint study between the Northern Territory Government and CSIRO. The area studied is proposed to be developed in a future extension of the Ord River Irrigation Area. The primary aim of the work was to identify the reason why the groundwater beneath the lower Keep River plain was saline. The study identified that recharge rates through the cracking black clay soils are low, probably of the order of 0.1 mm/year and that the salts in the unsaturated zone and groundwater were sourced from rainfall (Tickell et al., 2006). Their relatively high concentrations result from evaporative concentration of rain water (also causing the low recharge rates) and possibly from the upward movement of water and salts from the watertable driven by evapotranspiration. Recharge rates through the adjacent red brown earth soils and bedrock areas were estimated to be 7 and 45 mm/year respectively.

Groundwater levels for monitoring bore RN029519 located within the Keep River area are shown in Figure OB-16.

Humphreys et al. (1995) documented the results of the first numerical groundwater modelling undertaken for the Ord River Irrigation Area. They estimated that the likely recharge rate for areas of black cracking clay soil under irrigation would increase from near zero up to 73 mm/year. They identified that management of recharge would be required to minimise problems associated with rising groundwater levels. Subsequent groundwater modelling documented by Wesfarmers et al. (2000) predicted that leakage to groundwater from irrigated crop areas averaged 94 mm/year.

Smith et al. (2006) modelled the groundwater system in the palaeochannel sediments beneath the existing Ord River Irrigation Area. Their calibrated model water balance for the period 1975 to 2003 included an estimate of the cumulative groundwater storage. This storage term represents the difference between the groundwater stored in the aquifer in 1975 as compared to the amount stored at a later date. Smith et al. (2006) stated that the following features were evident from the water balance:

- Cumulative groundwater storage increased steadily up until 2001 due to the imbalance between net groundwater replenishment from rainfall and irrigation and net groundwater discharge.
- Groundwater storage decreased for the first time during 2002 and 2003 in response to decreased replenishment from rainfall, and increased groundwater discharge to the irrigation drain network.
- Inflow from Lake Kununurra to the Packsaddle aquifer was reduced to a relatively small component of the water balance by the late 1970s – by this time the watertable beneath Packsaddle Plain had risen considerably and the hydraulic gradient between the lake and aquifer had diminished.
- Inflow from Lake Kununurra to the Ivanhoe aquifer was approximately balanced by groundwater discharge from the aquifer to the Ord River.
- Leakage from the SP1 and M1 supply channels, and outflow through Cave Spring Gap, were relatively minor components of the model water balance.

Smith et al. (2006) also stated that the model water balance was consistent with the view that the storage capacities of the Packsaddle and Ivanhoe aquifers within the irrigation area were largely exhausted by the mid-1990s. They calculated that approximately 360 GL were added to storage between 1974 and 2001. This equates to a recharge rate of approximately 100 mm/year across the irrigation area.

Time series groundwater level data for a monitoring bore located within the existing irrigated area is shown in Figure OB-19.

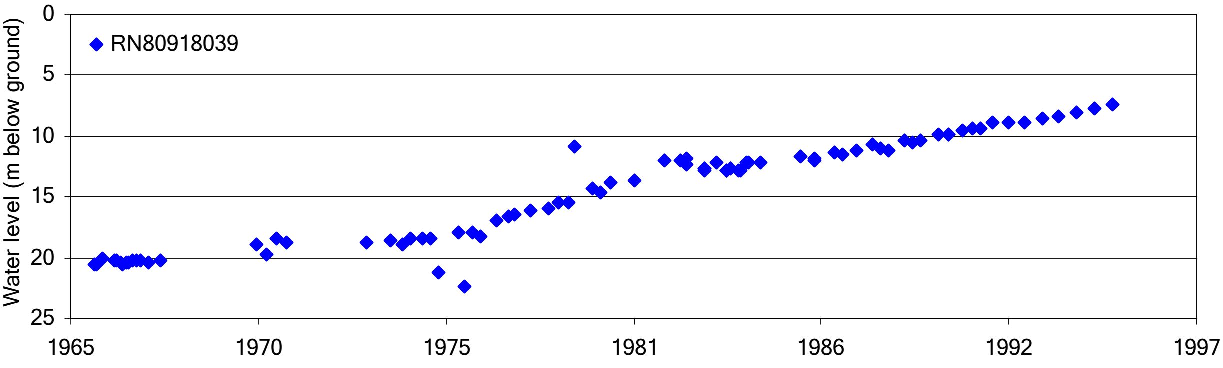

Figure OB-19. Observed groundwater level for monitoring bore 5F in the Ord River Irrigation Area

OB-2.3.4 Groundwater quality

The quality of most water sourced from the fractured rock aquifers across the Ord-Bonaparte region satisfy the drinking water guidelines (ADWG, 2004). Occasionally elevated levels of arsenic and fluoride pose a risk to human and animal health. Fluoride concentrations of up to 27 mg/L have been found in groundwater in the southern part of the region in Proterozoic sediments located immediately below the Antrim Plateau Volcanics. The fluoride is believed to be sourced from tuff in the Antrim Plateau Volcanics.

Groundwaters in the Tindall Limestone (and equivalent) and Proterozoic carbonates are slightly alkaline on average but pH can range from 6.4 to 8. Calcium, magnesium and bicarbonate are the dominant ions, while the salinity (as electrical conductivity) mostly falls within the range of 300 to 1500 µS/cm (Figure OB-20). Calcium, magnesium and bicarbonate ions show negligible geographic variation across the carbonate aquifer. They dissolve relatively easily from the limestone and dolomite and once saturation with respect to these minerals is reached, their concentrations rarely change. Hardness is normally high and will cause scale build-up in plumbing.

The Jinduckin Formation (and equivalent) is known to contain the evaporite minerals halite (NaCl) and anhydrite (calcium sulphate). Accordingly, groundwaters have calcium and sulphate as the dominant ions, while salinity (as electrical conductivity) typically ranges between 300 and 3000 µS/cm (Figure OB-20).

Groundwaters in the Palaeozoic and Cretaceous sediments are acidic with pH values of approximately 5. The salinity (as electrical conductivity) mostly ranges between 50 and 300 µS/cm.

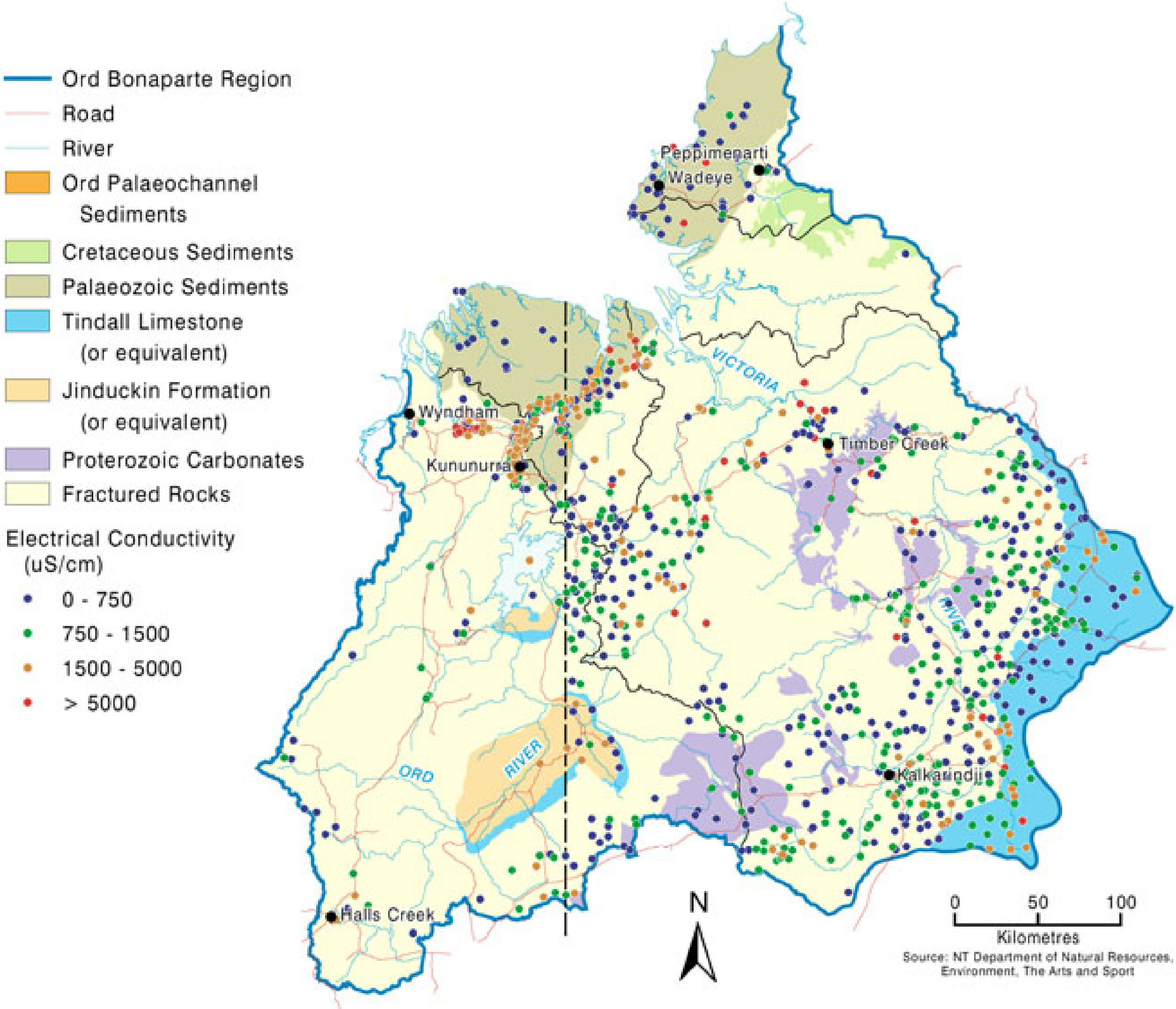

Figure OB-20. Groundwater electrical conductivity for bores in the Ord-Bonaparte region (source NRETAS, 2009)

It would be expected that shallow groundwater in the Ord River Irrigation Area has been affected by the change in recharge conditions due to irrigation. Electrical conductivity data for 20 bores for the period 1990 to 1996 (O'Boy et al., (2001) indicated that electrical conductivities decreased by an average of 25 percent between 1990 and 1996. However Smith et al. (2007) concluded that historical groundwater electrical conductivity measurements collected throughout the irrigation area since the early 1980s indicated no obvious trend in aquifer salinity during the past 23 years. A plot of time series electrical conductivity data for a typical shallow and deep monitoring site is shown in Figure OB-21.

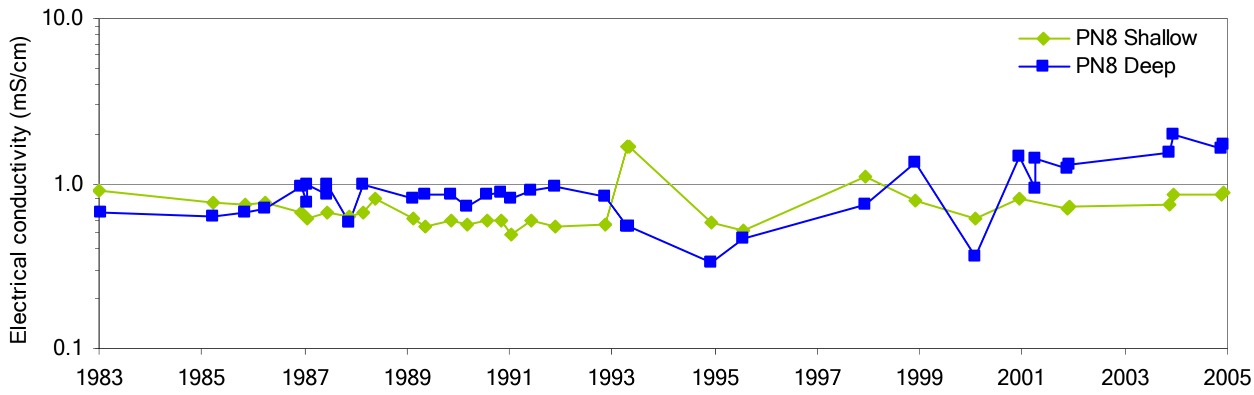

Figure OB-21. Electrical conductivity data for deep and shallow monitoring bores at site PN8

Smith et al. (2007) tested for a range of pesticides in groundwater beneath the ORIA. With the exception of Atrazine, all pesticides tested were below their analytical detection limits. Atrazine was detected in six (10 percent) of the groundwater samples at concentrations of less than 1 ug/L.

OB-2.4 Legislation, water plans and other arrangements

OB-2.4.1 Legislated water use, entitlements and purpose

Current

The Department of Water is the lead agency for the management of water resources in Western Australia and the *Rights in Water and Irrigation Act 1914* and the *Rights in Water Irrigation Regulations (2000)* provide the legislative basis for water resources management. The Department of Water prepares water management plans to specify how water resources are to be shared between the competing needs of the ecosystems, social expectations and public use within particular areas. Management plans establish sustainable diversion limits for particular water resources that define the water available for use. The limits are established by ensuring that sufficient water is retained in the resource to protect water-dependent ecosystems and to meet specific social needs. Within the Ord-Bonaparte region the only water management plan is for the lower Ord area and this describes how the waters of the Ord River are to be shared between the needs of the riverine environment of the lower Ord, and commercial water needs of irrigation and hydro-power generation over the coming years (DoW, 2006).

The first stage of the Ord River Irrigation Project commenced in the early 1960s with the construction of the Kununurra Diversion Dam and the completion of the first serviced farmlands to the east of the Ord River (Ivanhoe Plain). Stage 1 of the Ord River Irrigation Project was established by the mid-1970s after the construction of the Ord River Dam and completion of additional serviced farmlands to the west of the river (Packsaddle Plain).

Irrigated agriculture proved marginal in the Ord River Irrigation Area for the first two decades of operation. The Ord River Irrigation Area recovered slowly after the failure of cotton as a commercial crop in the mid-1970s. By the early 1990s sufficient confidence had returned in the future of the Ord River Irrigation Area for the Western Australian and Northern Territory governments to commence planning for the expansion of the Ord River Irrigation Area. In 1995 to 1996 the Ord River Dam Hydro-electric Power Station was constructed to supply electricity to the Argyle Diamond Mine and the towns of Kununurra and Wyndham.

In September 2004 the Ord Irrigation Cooperative was granted an average annual water entitlement of 335 GL/year. A further 46 other licences with a combined annual water entitlement of 23 GL/year have been granted in recent years. The additional licences have been issued to irrigators that pump directly from Lake Kununurra and the Ord River and for customers of the Water Corporation that pump from the M1 Channel.

Provision has been made to account for variations in water demand between annual periods by setting an annual allocation limit. This limit is set by the Department of Water during April each year. The amount of wet season rain is known at this time and the need to apply any water restrictions during the remainder of the annual period (the dry season) can be reliably assessed. In years when rainfall over the Stage 1 areas has been less than average, the annual allocation limit is greater than 335 GL/year. In years when the rainfall is above average, the annual allocation limit is less than 335 GL/year.

Groundwater use figures for the Ord-Bonaparte region were calculated for the Australian Water Resources 2000 Assessment. Use was estimated to be approximately 2 GL/year in 1983/84 and 10 GL/year in 1996/97.

Groundwater allocation data provided by the Western Australia Department of Water (2008) reveals there are currently seven groundwater allocations in the Ord River Basin totalling about 2800 ML/year. Small allocations are located in Alice Downs (1.5 ML/year), Purnululu National Park (4.5 ML/year) and multiple allocations around Halls Creek (sum of 70 ML/year) for a range of purposes, while larger public water supplies are sourced in Halls Creek (700 ML/year) and Kununurra (2000 ML/year). The bores at Kununurra are screened in the Ord alluvial aquifer while the other allocations are thought to be sourced from various volcanic and metamorphic fractured rock aquifers.

There are a number of remote communities in the Victoria, Fitzmaurice and Moyle river basins which have drinking water supplies sourced from groundwater. There are also over 600 stock water supply bores in the Victoria River Basin which are said to be pumping on average 170 m^3/day (Tickell and Rajaratnam, 1998). This amounts to approximately 19GL/year if it is assumed that groundwater is used for 6 months over the dry season. As at December 2008 no groundwater extraction licences had been issued in the Northern Territory portion of the Ord-Bonaparte region (NRETAS, 2008).

Future

The sustainable diversion limit for the Ord River between Lake Kununurra and Tarrara Bar (approximately 33 km downstream of the Kununurra Diversion Dam) is 750 GL/year. This diversion limit provides 350 GL/year for use on developed Stage 1 land and for minor demand growth in Stage 1 areas. The diversion limit also provides for an initial allocation of 400 GL/year for future demands in new areas. Future demands are expected to grow in increments, especially as the M2 Channel Supply Area (M2 Supply Area) is to be developed in stages, and new demands are not expected to exceed 400 GL/year for at least three years.

Further specification of these allocations and how water entitlements would be granted from these allocations is as follows. The 350 GL/year allocation for Stage 1 areas has two components. The first 250 GL/year is based on an expected annual reliability of 95 percent, and provides for historical use, corrected for required efficiency gains. The second 100 GL/year is based on an expected annual reliability of 90 percent, and provides for demand growth in Stage 1 areas (and assumes an increase of irrigated area from 3,800 ha to 6,000 ha).

The initial 400 GL/year allocation for future demand is based on an expected annual reliability of 95 percent. This allocation is more than sufficient to irrigate 14,800 ha of sugarcane (on 16,000 ha of farmland) given the evapotranspiration and rainfall conditions expected in the M2 Supply Area. Hence the allocation would support the staged development of at least 16,000 ha of serviced farmland in the M2 Supply Area (53 percent of the planned total of 30,064 ha). The allocation would support a larger farmland development if the area committed to growing sugarcane were reduced and replaced by a greater area of other crops with lower crop water requirements.

Applications for water entitlements under this allocation will be required when each new stage of the M2 Supply Area is to proceed or new demand develops. New water entitlements will be granted based on the area to be supplied, and the crop types or type of use planned. The entitlements could be issued with an expected annual reliability of up to 95 percent, depending on the reliability sought and the crop types or use planned. Efficient water management practices will be expected and will be a condition of granting the new entitlements. In the M2 Supply Area, this means the use of best irrigation practices, including automated control and scheduling systems for water distribution and on-farm water recycling facilities.

As provided for under the *Ord River Hydro Energy Project Agreement Act 1994*, the government will consult with Pacific Hydro Pty Ltd when an application for new water entitlements from the initial 400 GL/year allocation is received. New water release rules for the Ord River Dam Power Station will be developed to be compatible with the sum of existing and new water entitlements, if the application were granted (in whole or part). Final water release rules will be negotiated with Pacific Hydro Pty Ltd with the aim of ensuring sufficient water is available for the staged development of the M2 Supply Area, while protecting the commercial interests of the company. Current studies indicate that, if the initial 400 GL/year allocation were all granted as entitlements (at 95 percent reliability), compatible water release rules can be developed that would not significantly impact the company’s commercial interests. This was found to be the case even when the power demand on the station was assumed to be at or near the maximum output of the station.

OB-2.4.2 Rivers and storages

Construction of the Kununurra Diversion Dam and M1 Channel distribution system enabled the first water to be diverted from the Ord River in May 1963 and supplied to irrigation farmland on the black soils of the Ord River floodplain (the Ivanhoe Plain). The Kununurra Diversion Dam is a 20 m high structure that forms Lake Kununurra, holding water in the Ord River watercourse for approximately 50 km upstream. Lake Kununurra has a maximum storage of 101 GL (to the top of the dam’s gates at 41.76 m AHD) and enables water to be diverted to the current and planned irrigation areas of the Ord River Irrigation Project.

The Ord River Dam is located approximately 60 km upstream in the Carr Boyd Ranges, and provides the storage necessary to ensure a reliable water supply to the district. Construction of the Ord River Dam commenced in 1969, and the dam began to store water in Lake Argyle, the reservoir formed by the dam, in November 1971. Water levels in Lake Argyle reached the dam spillway (86.2 m AHD, storage 5800 GL) for the first time during the 1973/1974 wet season. Stage 19 of the Ord River Irrigation Project was effectively established in 1973, when construction of water distribution and drainage infrastructure, and serviced farmland to the west of the Ord River (Packsaddle Plain) was completed.

OB-2.4.3 Unallocated water

The Ord River Management Plan's (ORMP) interim environmental water provisions regime is designed to protect the environmental and social values of the lower Ord River under post-regulation conditions. Minor changes to instream habitat and riparian vegetation are likely when the additional allocations of this plan are implemented. However, these changes are expected to be small relative to changes caused by natural variations in wet season peak flows of the lower Ord River. These wet season peak flows are generated from the (effectively unregulated) catchment downstream of the Ord River Dam. Aquatic fauna should readily adapt to minor changes in river habitats and water quality of the lower Ord River is not expected to deteriorate under the EWP regime. More efficient irrigation practices in Stage 1 areas should reduce the biological loadings on the lower Ord River in the future. No significant changes are expected to the range of water levels of Lakes Kununurra and Argyle, or in the salinities of estuarine water in Cambridge Gulf. While the flood regime of the lower Ord River was substantially reduced by the construction of the Ord River Dam, the additional diversions allowed under the ORMP will not result in any significant further reduction in the flood regime. Consequently, no measurable impacts are expected on the Ramsar wetland values of the Parry's Lagoon Nature Reserve, the Ord floodplain, Lake Kununurra or Lake Argyle as a result of the provisions in this plan.

Ecological water requirement and environmental water provision for the lower Ord

Ecological water requirement is defined as the water regime needed to maintain ecological values of water-dependent ecosystems at a low level of risk. Environmental water provision is defined as the water regime provided as a result of the water allocation decision-making process taking into account ecological, social and economic impacts. They may meet in part or in full the ecological water requirements.

Braimbridge and Malseed (2007) recently revised the environmental water requirement of the lower Ord using the Flow Events Methods. Key aspects of the environmental water requirement for the lower Ord are summarised in Table OB-4 and Table OB-5. The environmental water provision for the lower Ord is described in Table OB-6.

Table OB-4. Lower Ord River environmental water requirement – continuous (non-event) flow regime

Period of year	Mean daily flow
	m^3/s
1 – 31 January	50
1 February to 31 March	57
1 – 30 April	53
1 - 15 May	48
16 May to 31 December	42

Table OB-5. Lower Ord River environmental water requirement – high flows expected in 80 percent of wet seasons

Daily flow	Number of days	Number of events
≥ 100 m^3/s	18	Not applicable
≥ 125 m^3/s	10	4
≥ 200 m^3/s	5	2
≥ 425 m^3/s	2	1

Table OB-6. Lower Ord River environmental water provision regime in relation to its environmental water requirement regime

Class of EWP* restriction	EWP as function of EWR** flow regime	Reliability (percentage of years level of EWP equalled or exceeded)
None	100%	88%
Class 1	88%	94%
Class 2	77%	100%

* EWP – environmental water provision
** EWR – environmental water requirement

OB-2.4.4 Social and cultural considerations

Indigenous values of the Ord River and wetlands were documented in 2003 by Barber and Rumley for the Water and Rivers Commission and in a workshop on Indigenous values of water convened by CSIRO in 2006 (Barber and Rumley, 2003; Jackson and Langton, 2006). This work describes the creation of hydrological features (waterholes, creeks, springs and portions of the river) by ancestral beings and the importance of these beliefs and understandings to the ceremonial and cultural life of the Miriuwung-Gajjerong native title holders. Barber and Rumley (2003) describe the Ord River and valley as a 'complex of cultural values': 'These values vary from location to location depending on the activity which occurred there during the Dreaming. The traditional owners believe that the Dreaming is both a continuing force, which began in the remote past and continues in the present and will continue in the future. In this respect the cultural values of the Ord River are considered to be ever-present. The Dreamings also created the cultural institutions which comprise the (native title holders') system of rights and interests which they hold to this day' (2003: 16). The traditional owners believe that through ritual activity they maintain the water sources in their country, particularly the seasonality of the wet and dry, tidal activity and seasonal flooding.

Changes experienced since the damming of the Ord River and the introduction of irrigated agriculture are also described by Barber and Rumley (2003), as are the impacts on Indigenous communities, particularly the effect of regulated stream flow on vegetation and patterns of access and resource use and the increased flows in the lower Ord.

A study by the Kimberley Land Council has further analysed the social and economic impacts of the Ord irrigation scheme on the social and economic life of Indigenous people in the region and on their values and use of water resources. These changes, as well as continuities with past spatial practices, are also addressed by Lane (2003), who contrasts the Indigenous and non-Indigenous land use practices in the Ord region (Lane, 2003, 2004). Indigenous economic, social and cultural reliance on waterholes and water places is evident in these reports and publications. Patterns of movement during the pastoral era before agricultural conversion were heavily influenced by the seasonal cycles of the monsoonal climate (Lane 2003).

The cultural and political significance of the Ord River system to the non-Indigenous community resident and non-resident has been analysed by a small number of social researchers during the past fifteen years (Head, 1999; Arthur, 1997; Lane, 2003, 2004). The damming of the Ord and the utilisation of water for agriculture are seen by many interviewed in these studies as very positive, resulting in improvements to productivity and regional wealth (Lane 2003). The Wetlands of International Importance downstream of the Ord diversion dam are now considered an environmental asset worthy of an environmental flow.

The *Ord River Water Management Plan (2006)* has a very brief section on social values referring to the significant recreational and tourism use of the lower Ord and the 'strong sense of community identity with the river'. Indigenous attachment is also described. This plan notes the dynamic character of social values in this recently transformed landscape: 'Current social values have largely arisen after the irrigation infrastructure was established and the subsequent establishment of the high dry season flows. These have become well established in the years since the Ord River dam was built' (*op cit.*). Social values were identified through a community reference panel workshop. Participants confirmed that a wide range of social and cultural values should be considered in water allocation decisions. The workshop recommended that water levels and flows could be maintained at current or slightly lower flows to satisfy most values and activities. Although the Management Plan observes the similarity between the community reference group recommendations and those of the scientific panel, Indigenous values were inconsistent to some extent because traditional owners placed a higher value on pre-dam low flows. The plan notes 'Because the waterway has already been modified, some of the cultural values have changed or been lost' (*op cit.*).

Indigenous views about desirable flow regimes of the lower Ord River were sought to assist the Department of Water to establish social water requirements. The Barber and Rumley (2003) report discussed above was the product of that inquiry.

OB-2.4.5 Changed diversion and extraction regimes

The sustainable diversion limit from the lower Ord River, downstream of House Roof Hill, is 115 GL/year. This allocation has an expected annual reliability of at least 95 percent (similar to the environmental water provision reliability) and is planned to supply future developments in the Mantinea Plain and Carlton Plain areas. Water entitlements will be granted up to the allocation limit, depending on the application(s) made, the areas to be supplied, and the uses and crop types proposed. The applicant(s) and irrigators will be required to establish efficient water distribution infrastructure and on-farm watering equipment and implement best irrigation practices.

Water released from Lake Argyle to generate hydro-electricity can also be diverted for irrigation at Lake Kununurra or used to contribute to environmental flows in the lower Ord River. However, when the hydro-electricity releases exceed the downstream water demands, the excess hydro-electricity releases become an additional draw on Lake Argyle and reduce water availability in subsequent years.

The excess of water demands for hydro-electricity over irrigation and environmental water demands, especially during the wet season, has been a central consideration in developing the allocations of this plan. Water Corporation's *Ord River Dam RiWI Act* licence also provides for the release of water through Pacific Hydro Pty Ltd's Ord River Dam Power Station for the generation of hydro-electricity. Currently, releases are made in accord with the existing water release principles of the *1994 Water Supply Agreement* between Pacific Hydro Pty Ltd and the Water Authority of Western Australia. New release rules have been developed to protect the reliability of Stage 1 allocations while the power station's annual electrical energy load exceeds the current minimum provision of 210 GWhrs/year, and before new generating capacity is constructed in the region. These changes are being negotiated with the company in accord with the provisions of the *Ord River Hydro Energy Project Agreement Act 1994* and will be implemented through revisions to Water Corporation's licence. Release rules will be updated as additional water entitlements are granted and Stage 2 irrigated areas developed.

The Department of Water will support proposals to generate hydroelectricity at the Kununurra Diversion Dam. The water available for electricity generation will be restricted to flows being released through the dam to meet the downstream environmental water provisions (EWP) flow regime or to discharge surplus inflows to the dam. This run of river provision excludes specific releases being made from either Lake Argyle or Lake Kununurra, for electricity generation at the Kununurra Diversion Dam. Consequently, the electricity able to be generated is directly dependent on the EWP regime for the lower Ord River. Under the interim EWP regime of this plan, an average of at least 50 GWhrs/year, depending on the design of the station, is potentially available. While additional electricity can be generated while water is not being diverted for the M2 Supply Area, the Department of Water will not guarantee a specified quantity of water for electricity generation at the Kununurra Diversion Dam.

OB-2.4.6 Changed land use

A major change in land use occurred in December 2001, when a joint venture of Wesfarmers, Marubeni and the Water Corporation withdrew from establishing 29,000 ha of sugarcane on 32,000 ha of new irrigated farmland, known as the M2 Supply Area. The last sugarcane was removed from the M1 Supply Area in 2008. This land is now slowly being replaced with high-value plantations, including sandalwood and mahogany.

Less than 1 percent of the region's native vegetation has been removed.

OB-2.4.7 Environmental considerations and implications of future development

The construction of the Ord River Dam has caused major changes to the flow regime of the Ord River. Prior to its construction, the Ord River flooded regularly, inundating large areas of its floodplain once in every two to three wet seasons. Most floods were sufficiently powerful to scour the riparian vegetation from banks of the river downstream of the Kununurra Diversion Dam. Flows receded rapidly following the wet season, ceasing by June in most dry seasons, with the river reducing to a series of unconnected pools. After construction of the Ord River Dam, wet season floods have been reduced by a factor of about ten and the river has continued to flow strongly throughout the dry season. Typical flow rates have increased from about zero to 50 m^3/second over the driest five months of the dry season.

These changes have altered the ecology of the lower Ord River, making it more like a river from the wet tropics, rather than the dry tropics of the Kimberley region. Reductions in the size and erosive power of floods has resulted in a more stable, dense band of riparian vegetation approximately 15 m wide along the water's edge within the main river channel. The permanent dry season flows have increased aquatic habitat and encouraged larger sized fish to develop in the lower Ord River than in nearby unregulated rivers, although the range of fish species found has remained very similar.

Maintaining sufficient instream habitat for invertebrates and fish during the dry season was the primary factor used to establish environmental water provisions for the lower Ord River. This was achieved by limiting the change in measures of dry season instream habitat, to levels considered of low ecological risk. Measures of instream habitat were determined over a range of flow regimes, including the flow rates considered typical of dry season conditions since the Ord River Dam was constructed (50 to 60 m^3/second). A flow regime was selected that limited occasions when instream habitat measures changed by more than 20 percent, relative to the habitat measures present at flow rates of 50 to 60 m^3/second.

Essential instream ecological processes and the biodiversity of the lower Ord River, which have characterised the riverine environment since the river has been regulated by the Ord River Dam, are to be protected by the following flow regime:

- When water levels in Lake Argyle are above 76 m AHD (expected 95 percent of the time), the lower Ord River is to be maintained at an average monthly flow rate of at least:
  - 45 m^3/second from the Dunham River confluence to House Roof Hill, and
  - 40 m^3/second downstream of House Roof Hill (approximately 58 km downstream of the Kununurra Diversion Dam).
- During drought periods when water levels in Lake Argyle are less than 76 m AHD (expected 5 percent of the time)
  - 35 m^3/second from the Dunham River confluence and House Roof Hill, and
  - 30 m^3/second downstream of House Roof Hill.

Restrictions on irrigation diversions and hydro-power generation will also apply during these periods of drought.

No significant increase is to be permitted in the regulation of the Dunham River tributary.

Responsibility for maintaining this environmental water provision has been assigned to the Water Corporation, under conditions of their *Rights in Water and Irrigation Act 1914* licence that specifies how the Ord River Dam and Kununurra Diversion Dam are to be operated.

OB-2.5 References

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OB-3 Water balance results for the Ord-Bonaparte region

This chapter describes modelling results and the assessment of the water resources undertaken by this project for the Ord-Bonaparte region. Detailed, quantified assessments are made where possible, and relevant, and confidence is estimated. Modelling results are reported under climate and development scenarios as defined at the division level in Section 2.1 of Chapter 2. This chapter is sub-divided into:

- climate
- recharge estimation
- conceptual groundwater models
- groundwater modelling results
- rainfall-runoff modelling results
- river system water balance
- changes to flow regimes at environmental assets.

OB-3.1 Climate

OB-3.1.1 Historical climate

The Ord-Bonaparte region receives an average of 730 mm of rainfall over a September to August water year (Figure OB-22), most of which (689 mm) falls in the November to April wet season (Figure OB-23). Across the region there is a strong north–south gradient in annual rainfall (Figure OB-24), ranging from 1486 mm in the north to 441 mm in the south. Over the first half of the historical (1930 to 2007) period, annual rainfall has been relatively constant at around 600 mm. The second half of the period has seen an increase in mean annual rainfall to approximately 850 mm. The highest yearly rainfall received was 1248 mm which fell in 1974, and the lowest was 316 mm in 1952.

Historical areal potential evapotranspiration (APET) is very high across the region, averaging 1988 mm over a water year (Figure OB-22), and varies moderately across the seasons (Figure OB-23). APET generally remains higher than rainfall throughout the year resulting in year-round water-limited conditions.

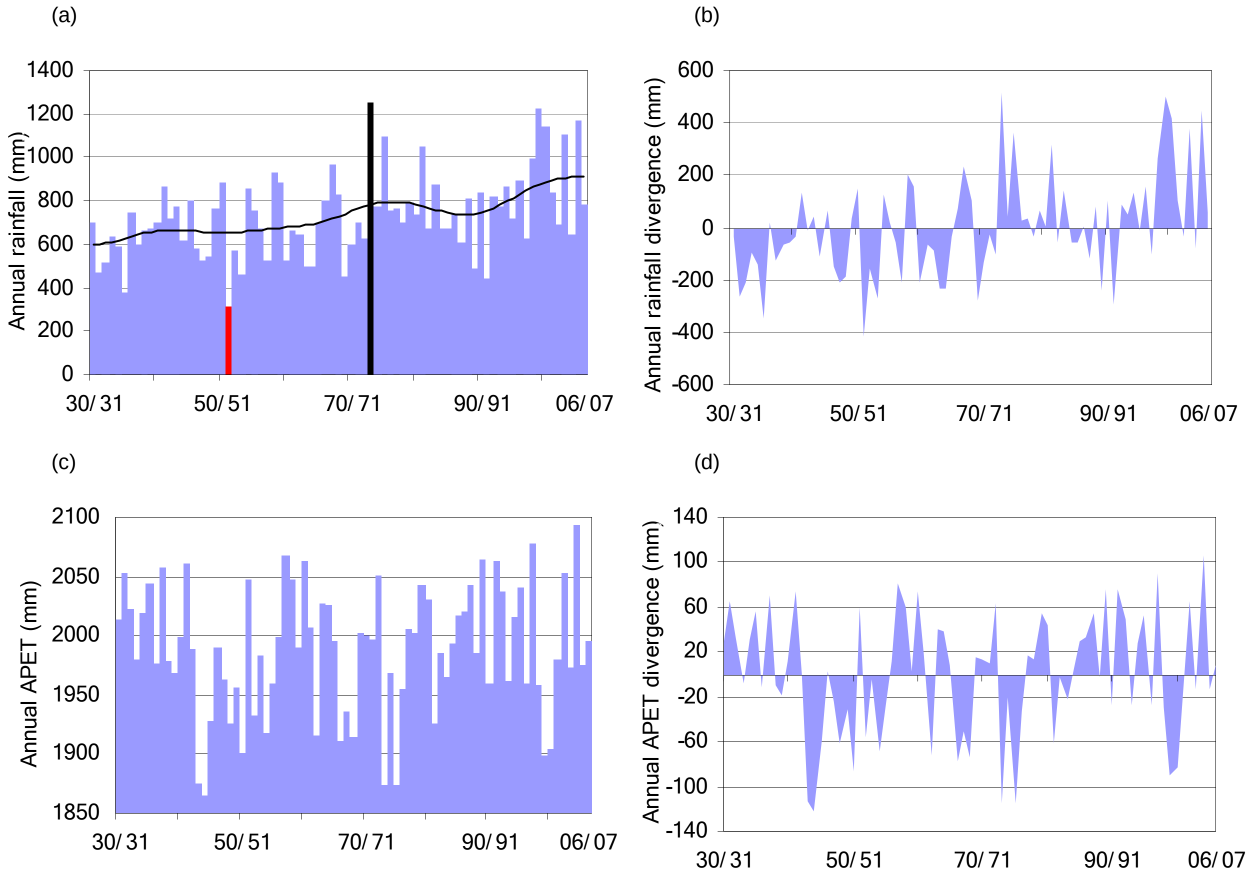


Figure OB-22. (a) Historical annual rainfall and (b) its divergence from the long-term mean; and (c) historical annual areal potential evapotranspiration and (d) its divergence from the long-term mean in the Ord-Bonaparte region under Scenario A. The low-frequency smoothed line in (a) indicates longer term variability

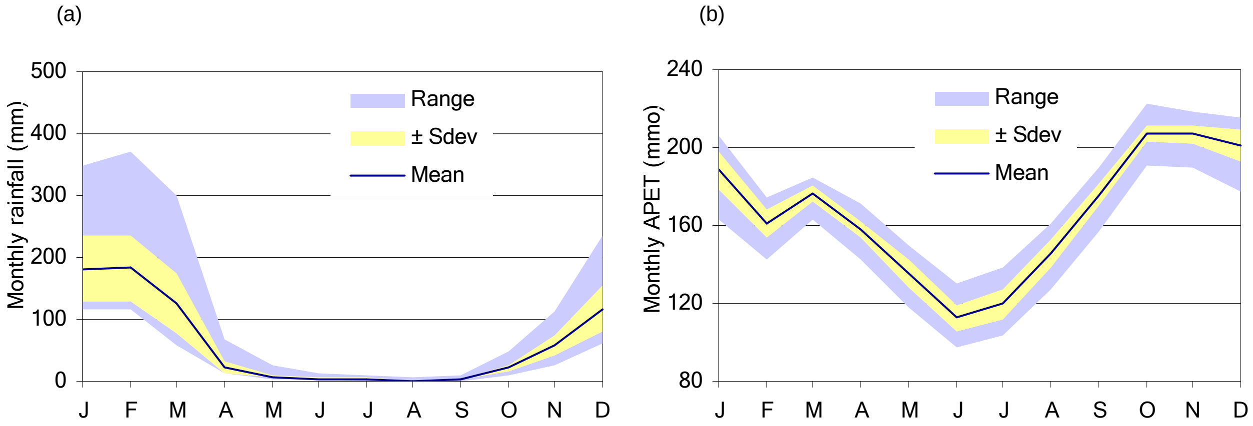


Figure OB-23. Historical mean monthly (a) rainfall and (b) areal potential evapotranspiration and their temporal variation (range and ± one standard deviation) in the Ord-Bonaparte region

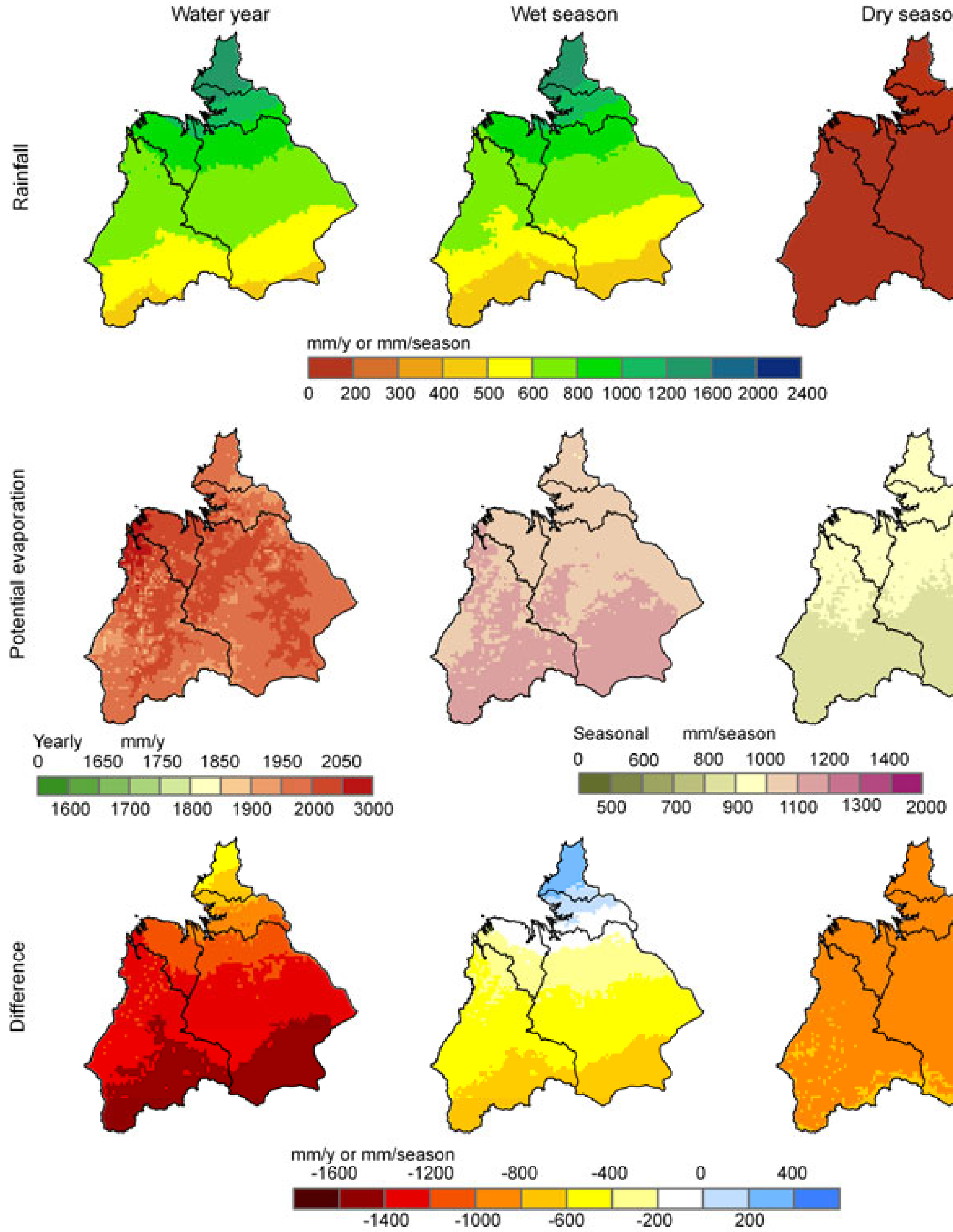


Figure OB-24. Spatial distribution of historical mean annual (water year), wet season and dry season rainfall and areal potential evapotranspiration (potential evaporation) and their difference (rainfall less areal potential evapotranspiration) across the Ord-Bonaparte region

OB-3.1.2 Recent climate

Figure OB-25 compares recent (1996 to 2007) to historical (in this case the 66-year period from 1930 to 1996) mean annual rainfall for the Ord-Bonaparte region. Across the whole region, recent rainfall is between 10 and 60 percent higher than historical rainfall – a statistically significant difference for the majority of the region.

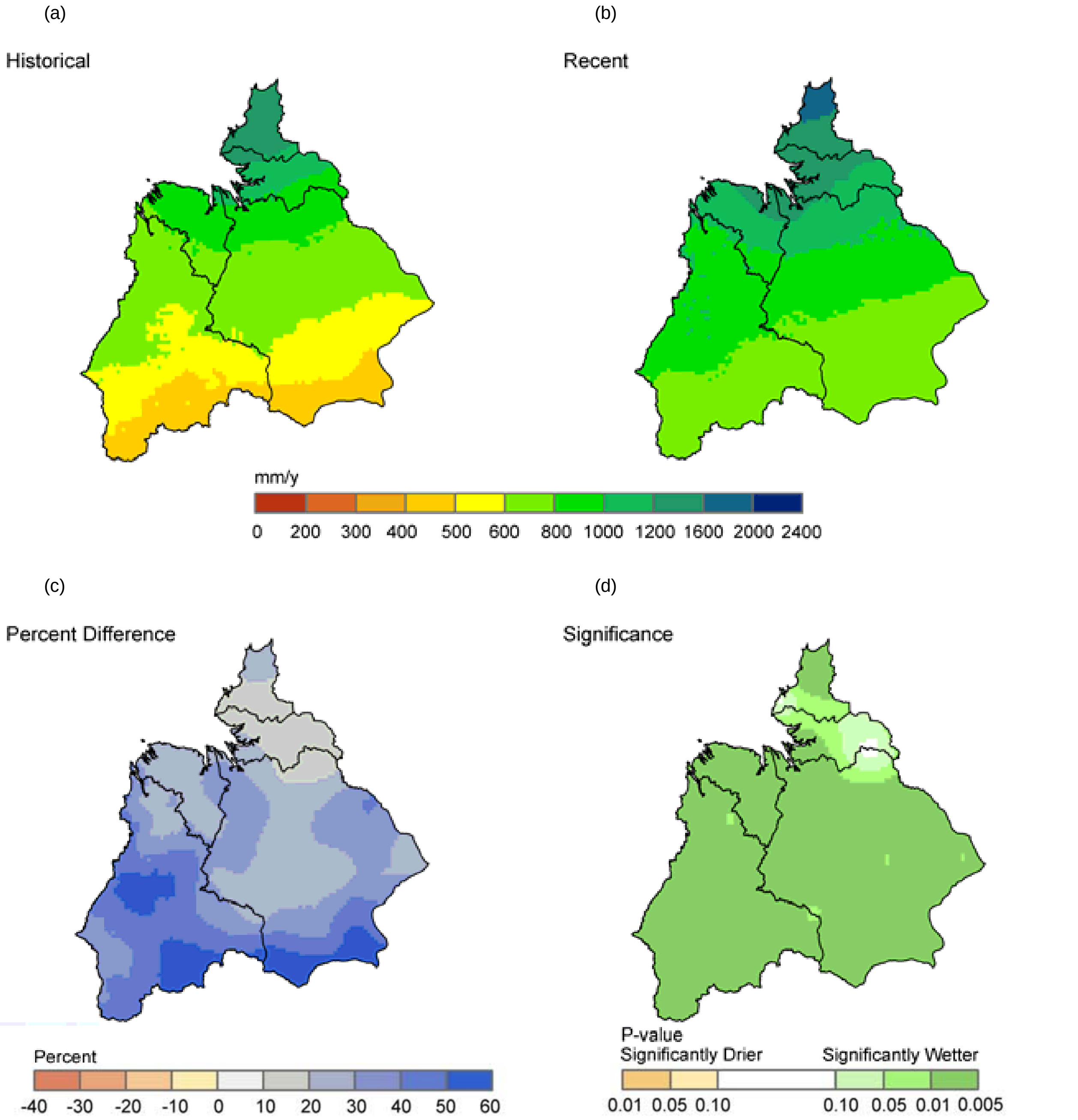


Figure OB-25. Spatial distribution of (a) historical and (b) recent mean annual rainfall ; and (c) their relative percent difference and (d) the statistical significance of these differences across the Ord-Bonaparte region

OB-3.1.3 Future climate

Under Scenario C annual rainfall varies between 632 and 798 mm (Table OB-7) compared to the historical mean of 730 mm. Similarly, APET ranges between 2037 and 2081 mm compared to the historical mean of 1988 mm.

A total of 45 variants of Scenario C were modelled (15 global climate models (GCMs) for each of the high, medium and low global warming scenarios). Subsequently, results from an extreme 'wet', median and extreme 'dry' variant are shown (referred to as scenarios Cwet, Cmid and Cdry). Under Scenario Cwet annual rainfall and APET increase by 9 percent and 3 percent, respectively. Under Scenario Cmid annual rainfall increases by 1 percent and APET increases by 2 percent. Under Scenario Cdry annual rainfall decreases by 13 percent and APET increases by 5 percent.

Under Scenario Cmid long-term monthly averages of rainfall and APET do not differ much from historical values (Figure OB-26). Under Scenario Cmid rainfall lies well within the range in values from all 45 future climate variants. The seasonality of rainfall changes slightly only in that any changes in rainfall occur in the wet season. However, there is appreciable variation in rainfall in the wet season months, varying by up to 75 mm/month. In contrast, the seasonality of APET remains the same as any changes occur uniformly across the year. APET is greater under Scenario C relative to historical values for every month of the year.

Table OB-7. Mean annual (water year), wet season and dry season rainfall and areal potential evapotranspiration in the Ord-Bonaparte region under historical climate and Scenario C

	Water year	Wet season	Dry season
	mm/y	mm/season	
Rainfall			
Historical	730	689	41
Cwet	798	747	41
Cmid	741	692	39
Cdry	632	587	37
Areal potential evapotranspiration			
Historical	1988	1092	896
Cwet	2054	1123	928
Cmid	2037	1117	917
Cdry	2081	1143	933

* Note that the sum of the wet season and dry season values does not always equal the water year values because the combined wet season and dry season period (November to October) is different to the water year period (September to August).

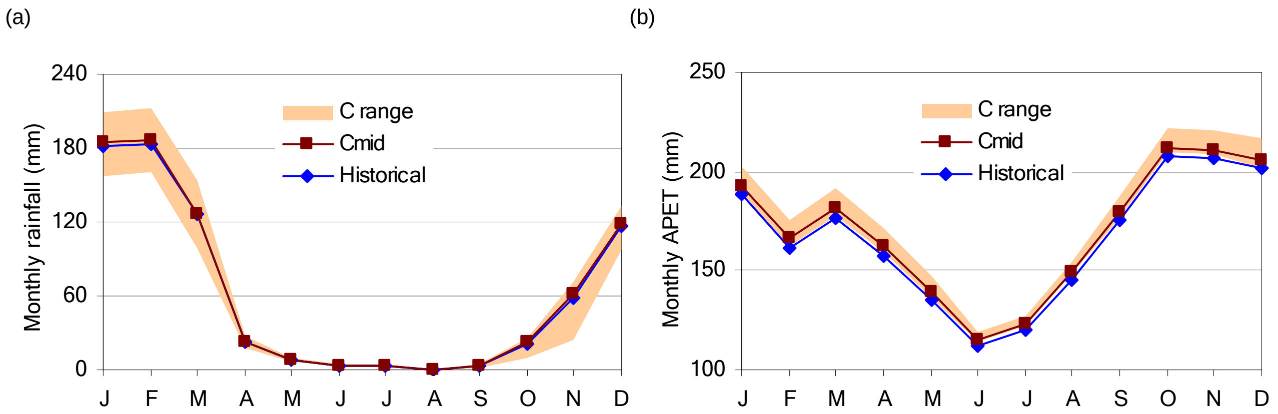


Figure OB-26. Mean monthly (a) rainfall and (b) potential evapotranspiration across the Ord-Bonaparte region under historical climate and Scenario C. (C range is pooled from the 45 Scenario C simulations (15 global climate models and three global warming scenarios) – the lower and upper limits in C range are therefore not the same as scenarios Cdry and Cwet)

OB-3.1.4 Confidence levels

Analysis of confidence of the climate data is reported in Section 2.1.4 in the division-level Chapter 2.

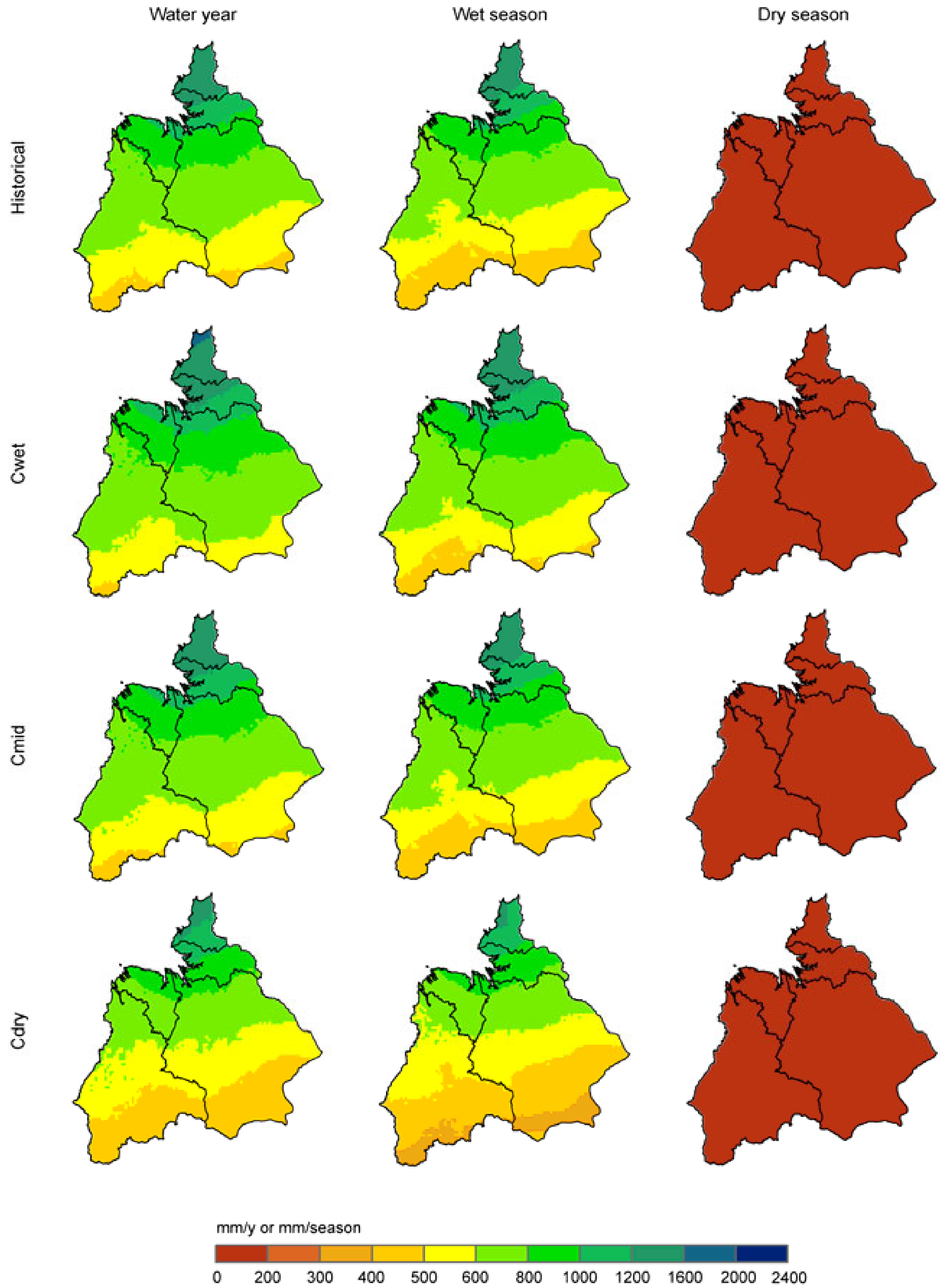


Figure OB-27. Spatial distribution of mean annual (water year), wet season and dry season rainfall across the Ord-Bonaparte region under historical climate and Scenario C

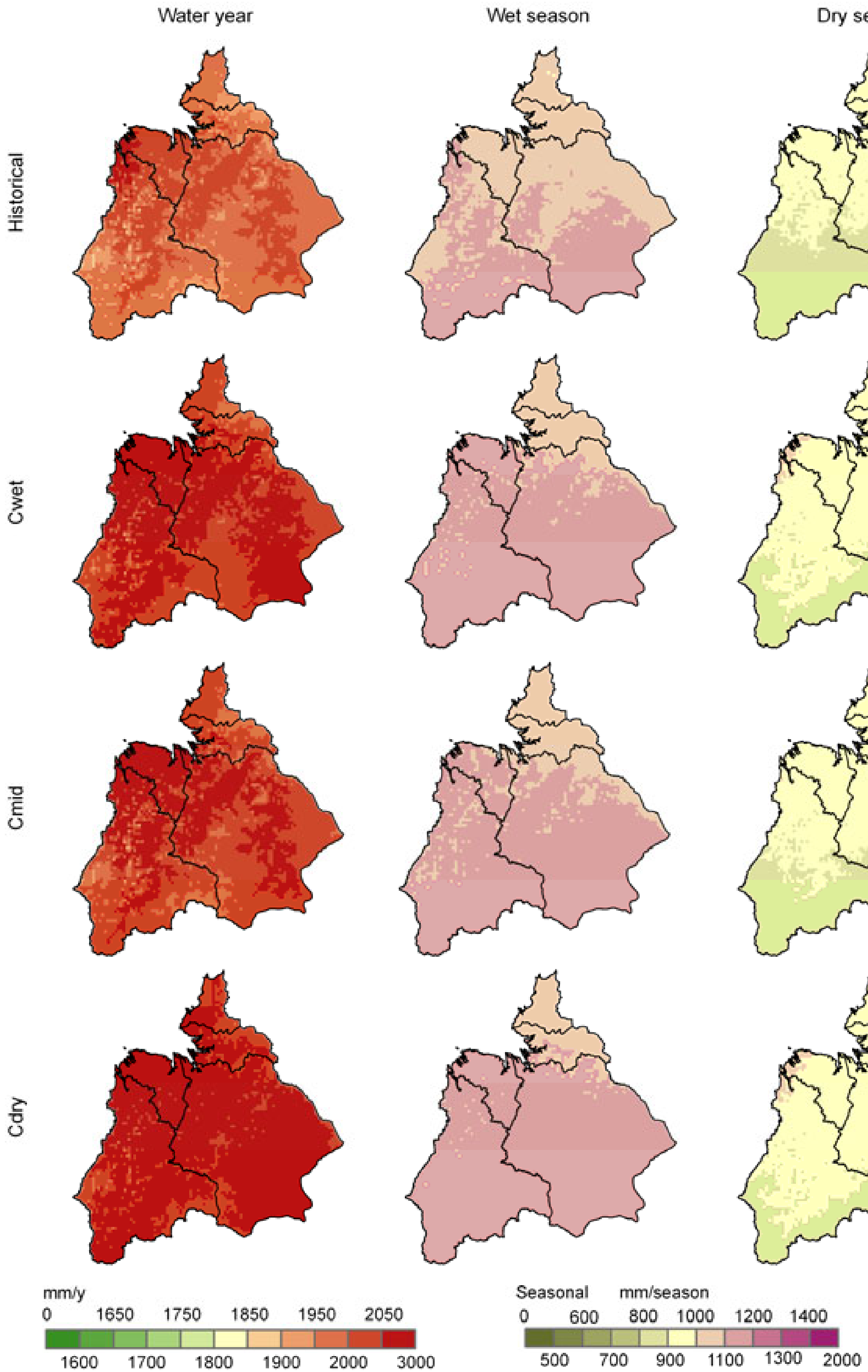


Figure OB-28. Spatial distribution of mean annual (water year), wet season and dry season areal potential evapotranspiration across the Ord-Bonaparte region under historical climate and Scenario C

OB-3.2 WAVES potential diffuse recharge estimations

The WAVES model (Zhang and Dawes, 1998) was used to estimate the change in groundwater recharge across the Ord-Bonaparte region under a range of different climate scenarios. WAVES is a vertical recharge flux model that can model plant physiological feedbacks in response to increased CO_2, as well as modelling the water balance of different soil, vegetation and climate regimes. It was chosen for its balance in complexity between plant physiology and soil physics. It was also used to assess recharge for the Murray-Darling Basin Sustainable Yields Project (Crosbie et al., 2008).

OB-3.2.1 Under historical climate

The calculated historical recharge for the Ord-Bonaparte region (Table OB-8) shows that recharge is greatest in the north and decreases progressively to the south following the rainfall gradient. The historical record was assessed to establish any difference between wet and dry periods of recharge. A 23-year period was used, which allows the projection of recharge estimates to 2030 – in other words, to estimate recharge in 2030 assuming future climate is similar to historical climate (Scenario A). Under a wet historical climate (Scenario Awet) the Ord-Bonaparte region is calculated to have an 11 percent increase in recharge. Under the median estimate of historical climate (Amid) the Ord-Bonaparte region is calculated to have a 3 percent decrease in recharge that is quite uniform across the region. Under a dry historical climate (Scenario Adry) the Ord-Bonaparte region is calculated to have a 14 percent decrease in recharge.

Where unweathered bedrock outcrops occur, confidence in the modelled results is reduced. The locations of these outcrops in the Ord-Bonaparte region are shown on the historical recharge map in Figure OB-29.

Table OB-8. Recharge scaling factors in the Ord-Bonaparte for scenarios A, B and C

Region	Awet	Amid	Adry	B	Cwet	Cmid	Cdry
Ord-Bonaparte	1.11	0.97	0.86	1.41	1.39	1.09	0.97

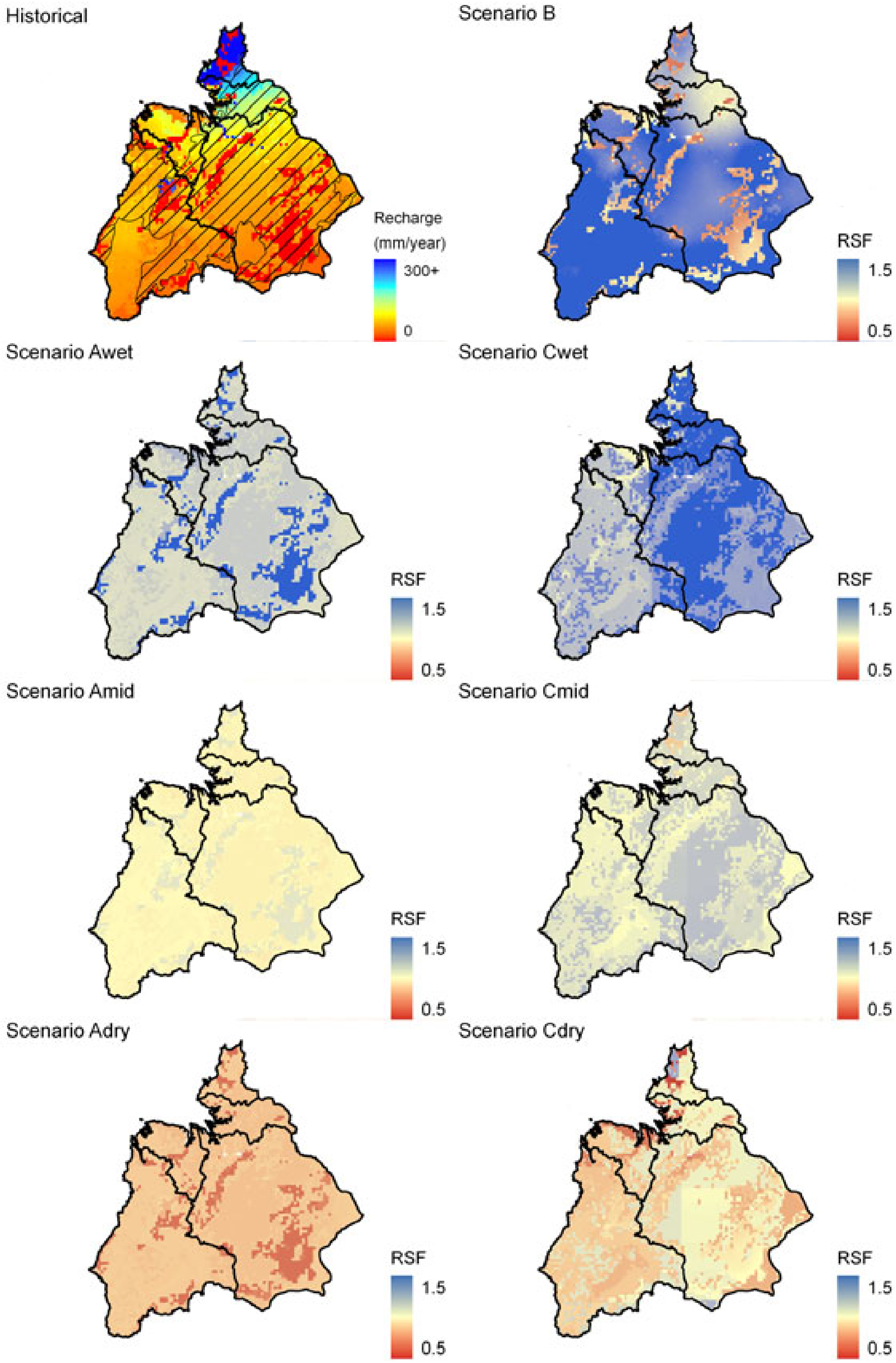


Figure OB-29. Spatial distribution of historical mean recharge rate; and recharge scaling factors in the Ord-Bonaparte region. The hatched region on the historical recharge map identifies where unweathered bedrock outcrops occur

OB-3.2.2 Under recent climate

The recent (1996 to 2007) climate in the Ord-Bonaparte region has been wetter than the historical average and consequently the calculated recharge has seen an increase of 41 percent under Scenario B relative to Scenario A (Table OB-8). This increase has not been spatially uniform with the greatest increases in recharge in the west of the region and areas on vertosol soils showing a decrease in recharge (Figure OB-29).

OB-3.2.3 Under future climate

Figure OB-30 shows the percentage change in modelled mean annual recharge averaged over the Ord-Bonaparte region under Scenario C relative to Scenario A for the 45 scenarios (15 GCMs for each of the high, medium and low global warming scenarios). The percentage change in the mean annual rainfall and recharge from the corresponding GCMs are also tabulated in Table OB-9. Under some scenarios the recharge is projected to increase despite a decrease in rainfall. This is because total rainfall is not the only climate variable that has an influence over recharge. Daily rainfall intensity, temperature and CO_2 concentration are also important drivers (see Section 2.3.3 in the division-level Chapter 2), and specific situations can result in this counter-intuitive result. In particular, rainfall intensity is seen as a significant factor in this relationship.

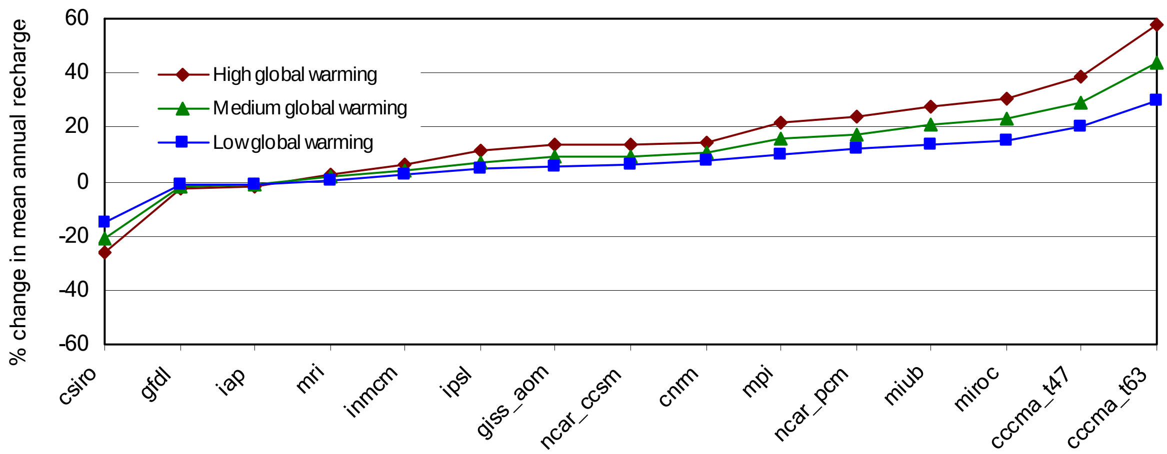


Figure OB-30. Percentage change in mean annual recharge under the 45 Scenario C simulations (15 global climate models and three global warming scenarios) relative to Scenario A recharge

Table OB-9. Summary results under 45 Scenario C simulations (numbers show percentage change in mean annual rainfall and recharge under Scenario C relative to Scenario A)

High global warming			Medium global warming			Low global warming		
GCM	Rainfall	Recharge	GCM	Rainfall	Recharge	GCM	Rainfall	Recharge
csiro	-18%	-26%	csiro	-14%	-21%	csiro	-10%	-15%
gfdl	**-13%**	**-3%**	gfdl	-10%	-2%	gfdl	-7%	-1%
iap	-5%	-2%	iap	-4%	-1%	iap	-3%	-1%
mri	-2%	3%	mri	-1%	2%	mri	-1%	1%
inmcm	2%	6%	inmcm	2%	4%	inmcm	1%	2%
ipsl	0%	11%	ipsl	0%	7%	ipsl	0%	5%
giss_aom	1%	13%	giss_aom	1%	9%	giss_aom	1%	5%
ncar_ccsm	3%	13%	**ncar_ccsm**	**2%**	**9%**	ncar_ccsm	2%	6%
cnrm	0%	14%	cnrm	0%	11%	cnrm	0%	8%
mpi	2%	21%	mpi	2%	16%	mpi	1%	10%
ncar_pcm	5%	24%	ncar_pcm	4%	17%	ncar_pcm	3%	12%
miub	3%	28%	miub	2%	21%	miub	2%	14%
miroc	7%	31%	miroc	6%	23%	miroc	4%	15%
cccma_t47	**10%**	**39%**	cccma_t47	7%	29%	cccma_t47	5%	21%
cccma_t63	14%	58%	cccma_t63	11%	44%	cccma_t63	8%	30%

Under Scenario Cwet the Ord-Bonaparte region is calculated to have an increase in recharge of 39 percent (less than the increase in recharge under Scenario B). Under Scenario Cmid the Ord-Bonaparte region is calculated to have an increase in recharge of 9 percent. Under Scenario Cdry the Ord-Bonaparte region is calculated to have a decrease in recharge of 3 percent.

OB-3.2.4 Confidence levels

The estimation of recharge from WAVES is only indicative of the actual recharge and has not been validated with field measurements. A steady state groundwater chloride mass balance has been conducted as an independent measure of recharge (Crosbie et al., 2009). The results in the Ord-Bonaparte region show that the historical estimate of recharge using WAVES (70 mm/year) is greater than the best estimate using the chloride mass balance (44 mm/year) but it is within the confidence limits of the chloride mass balance (5 to 112 mm/year).

OB-3.3 Conceptual groundwater models

OB-3.3.1 Fractured rocks

Relatively low annual rainfall and high potential evaporation means that recharge to the groundwater in fractured rock aquifers is likely to only occur after prolonged periods of intense rainfall in the wet season. Tickell (1998) assumed recharge only occurs when rainfall exceeds 100 mm per month. Jackson and Jolly (2004) assumed that recharge only occurs when a soil moisture deficit of 150 mm and a daily evapotranspiration rate of 7 mm are met and exceeded by rainfall. Recharge is more effective through sandy soils than black clay soils; the latter only being significant early in the wet season through cracks and preferential pathways before the clays swell. Aquifers are also locally recharged through either small alluvial aquifers or directly from the river when high flows or flooding occurs. Most of the area contains either basaltic or sandstone fractured rock aquifers which are thought to have relatively shallow groundwater flow systems. The main groundwater discharge process is through evapotranspiration. For rivers draining fractured rock aquifers in the region flows are reduced to disconnected semi-permanent pools and then dry river beds as the dry season progresses.

OB-3.3.2 Karstic carbonate rocks

Groundwater that recharges the Tindall Limestone in the south east of the Ord-Bonaparte region is primarily discharged to the Flora River, a major source of dry season flow into the Daly River. In other areas groundwater discharges to rivers are not enough in most years to maintain flow throughout the dry season.

Processes occurring in karstic carbonate rocks are similar to those for the fractured rocks. The main groundwater discharge processes are through evapotranspiration and spring discharge to rivers. River flows are maintained for different lengths of time by spring and diffuse groundwater discharge, but ultimately rivers are reduced to disconnected semi-permanent pools and then dry river beds as the dry season progresses, particularly in the middle and upper reaches. The only exception being the Wickham River which is perennial in periods of above average rainfall such as occurred since 1974. A conceptual model for the interconnection between the dolomite aquifer and the Wickham River is given in Figure OB-31.

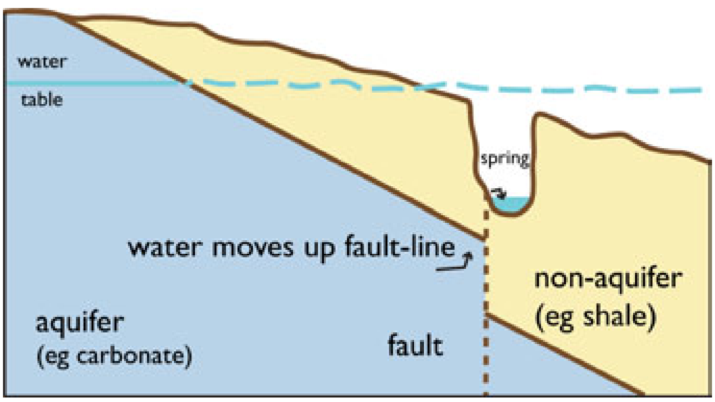


Figure OB-31. Schematic of conceptual model for groundwater discharge to the Wickham River

OB-3.3.3 Palaeozoic and Cretaceous sediments

Processes occurring in the Cretaceous sediments are similar to those for the fractured rocks. The main groundwater discharge processes are through evapotranspiration and spring discharge to rivers. River flows are maintained to varying degrees by the spring discharge.

This is the most common type of spring in the north of the Ord-Bonaparte region. It occurs where a layer of porous and permeable sandstone overlies a low permeability rock such as shale or granite (Figure OB-32). Water stored in the upper layer seeps out at the contact between the two rock types. This is generally in the form of a seepage zone or swampy area at the contact. Seepage over an area will eventually coalesce to form a river such as has occurred with the Fitzmaurice River.

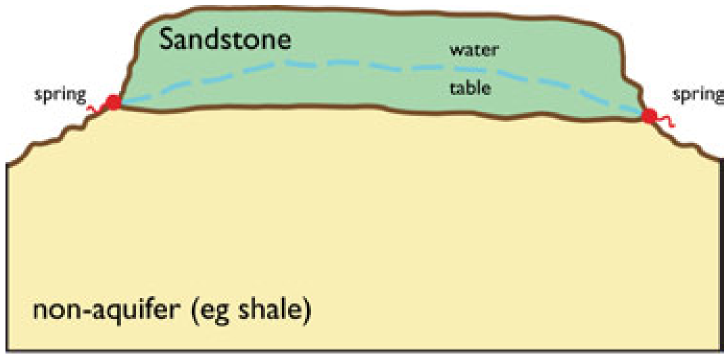


Figure OB-32. Schematic of conceptual model for groundwater discharge that provides the dry season flow for the Fitzmaurice River

OB-3.3.4 Palaeochannel sediments

The hydrogeology of Ord River Irrigation Area has been studied in detail over approximately the past 30 years, initially by Laws and George (1982), Laws (1991), Nixon (1995),Humphreys et al (1995), Tickell et al (2006) and others and then more recently through a number of technical reports by the CSIRO. Specific studies have been conducted on each of the alluvial plains currently irrigated (Ivanhoe and Packsaddle Plains) as well as the less developed areas (Carlton Plain, Mantinea Flats, Weaber Plain, Knox Creek Plain and Keep River Plain).

Under natural conditions, high rainfall and river flooding in the wet season would recharge the alluvial aquifer directly through the more permeable floodplain sediments. Significant river recharge would also occur through the incised banks during high river flows particularly where the basal sands and gravels are incised by the river. Bank storage and groundwater would return to the river as the floodwaters recede and the dry season progresses.

Currently, the influence of the permanent surface water feature in Lake Kununurra in addition to recharge from irrigation activities across the floodplain, have resulted in rising groundwater trends in the palaeochannel sediments. It was thought that the rate of subsurface drainage to the Ord River from the existing irrigation area would increase in response to the mounting hydraulic gradient in the aquifer, and the watertable would re-stabilise at a safe distance below ground surface. Smith et al. (2006) however have concluded that the degree of connectivity between the aquifer system beneath the irrigation area and the Ord River is much less than previously thought. Groundwater beneath a large part of Ivanhoe Plain does not drain effectively to the river and the aquifer has filled like a large subsurface reservoir. The watertable beneath Ivanhoe Plain has risen steadily by around 0.3 to 0.5 m/year (15 to 20 m in total) during the past 40 years and has now risen to within several metres of ground surface.

OB-3.3.5 Baseflow indexing comparison with conceptual models

The annual baseflow index (BFI) values in the Ord-Bonaparte region range from 0.01 to 0.30 with a median of 0.12 (n=17) as shown in Table OB-1. The higher value for the Wickham River gauge is thought to be due to discharge from the carbonate aquifer that the river intersects. The higher BFI values do not necessarily correlate to high dry season baseflows (Figure OB-2) relative to the other rivers, as is evident for the Timber Creek or West Baines River which have high BFIs and relatively low dry season baseflow. It is likely that the annual BFI values and dry season baseflow are related to a combination of factors including: geology; position in the hydrogeological setting; catchment area above gauge; groundwater basin area; and rainfall distribution. This analysis has a good correlation to the conceptual models developed for the region.

OB-3.4 Groundwater modelling results

OB-3.4.1 Historical groundwater balance

No attempt has been made to develop a detailed groundwater balance for the Ord-Bonaparte region due to the lack of data beyond the Ord River Irrigation Area. However the following general comments can be made.

- The main hydrological characteristic of this catchment is the great variability in rainfall from year to year, within a single year and over periods of years. This variability results in a similar great variability in both surface water runoff and groundwater recharge.
- The period of record for most gauging stations and groundwater monitoring points within the catchment is biased towards a period of above average rainfall (based on the existing rainfall data). This needs to be taken into consideration when analysing flow and recharge data.
- Evapotranspiration occurs from the trees and understorey; evaporation also occurs from the ground surface, shallow water tables and rivers. Data acquired by Hutley et al. (2001) suggest total evapotranspiration during the wet season for the Katherine area is 3.1 mm/day. Annual tree water use was estimated to be approximately 330 mm.
- Jolly et al. (2000) trialled a range of values for evapotranspiration for the recharge area for the Proterozoic carbonate aquifer in developing a model to predict historical groundwater fed flows in the Wickham River at gauge G8140232. A value of 150 mm was used for the maximum soil moisture deficit during development of the model. A value of 7 mm/day was chosen for wet season daily losses (primarily due to evapotranspiration and runoff) in the model as it yielded the best correlation between gauged and predicted groundwater fed river flows. Use of these values yielded a predicted mean estimated water year recharge rate of 15 mm/year. This compares to the use of 150 mm for the maximum soil moisture deficit and 5 mm per day wet season daily losses for similar models in the Daly region.
- Stewart and Zaar (1990) and O'Grady et al. (2002) reported dry season losses in flow rates in the Katherine and Daly Rivers (both in the adjacent Daly region) of 5 L/second/km length of river where groundwater inflow from and outflow to the river was deemed to be negligible due to the rivers incising very low permeability strata. The loss between where spring flow enters the Wickham River and the gauging station G8140232 equates to a loss of 7 L/second/km length of river.
- Smith et al. (2006) modelled the groundwater system in the palaeochannel sediments beneath the existing Ord River irrigation area. Their calibrated model for the period 1975 to 2003 provides the most rigorous water balance for this area to date.

OB-3.5 Rainfall-runoff modelling results

In this section the term runoff is the sum of overland flow, interflow and baseflow. It is equivalent to streamflow expressed as a mm depth equivalent. All plots show data averaged over the modelled subcatchments of the Ord-Bonaparte region. For this reason rainfall reported in this section may vary slightly from that reported elsewhere due to differences between the catchment boundaries (shown in Figure OB-1) and the DEM-derived catchment boundaries used here. In this section, where annual data are reported, years are represented by numbers 1 through 77. Consistently throughout this report, annual data are based on the water year (1 September to 31 August) and the dry season is defined as 1 May to 31 October. Unless stated otherwise scenarios Cwet, Cmid and Cdry are selected on the basis of the ranked mean annual runoff. For more details on methods refer to Section 2.2 of the division-level Chapter 2.

OB-3.5.1 Regional synopsis

The rainfall-runoff modelling estimates runoff in 0.05 degree grid cells in 118 subcatchments (Figure OB-33). Optimised parameter values from nine calibration catchments are used. All of the calibration catchments are located within the Ord-Bonaparte region, six in the Ord catchment and three in the Victoria catchment. While this is a relatively small number of calibration catchments for a large area, the gauging stations (some of which are no longer current) monitor a large proportion of the Ord-Bonaparte region.

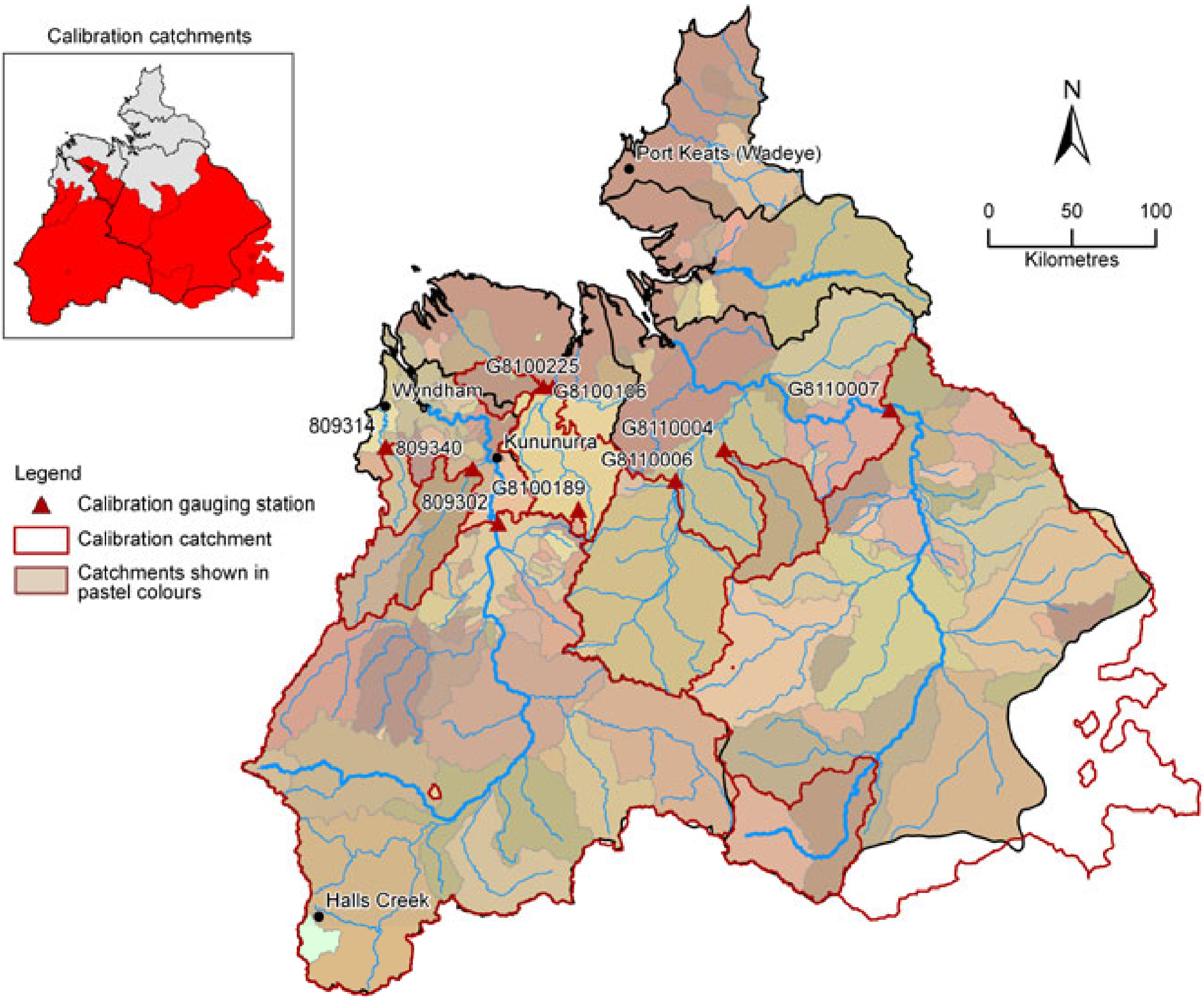


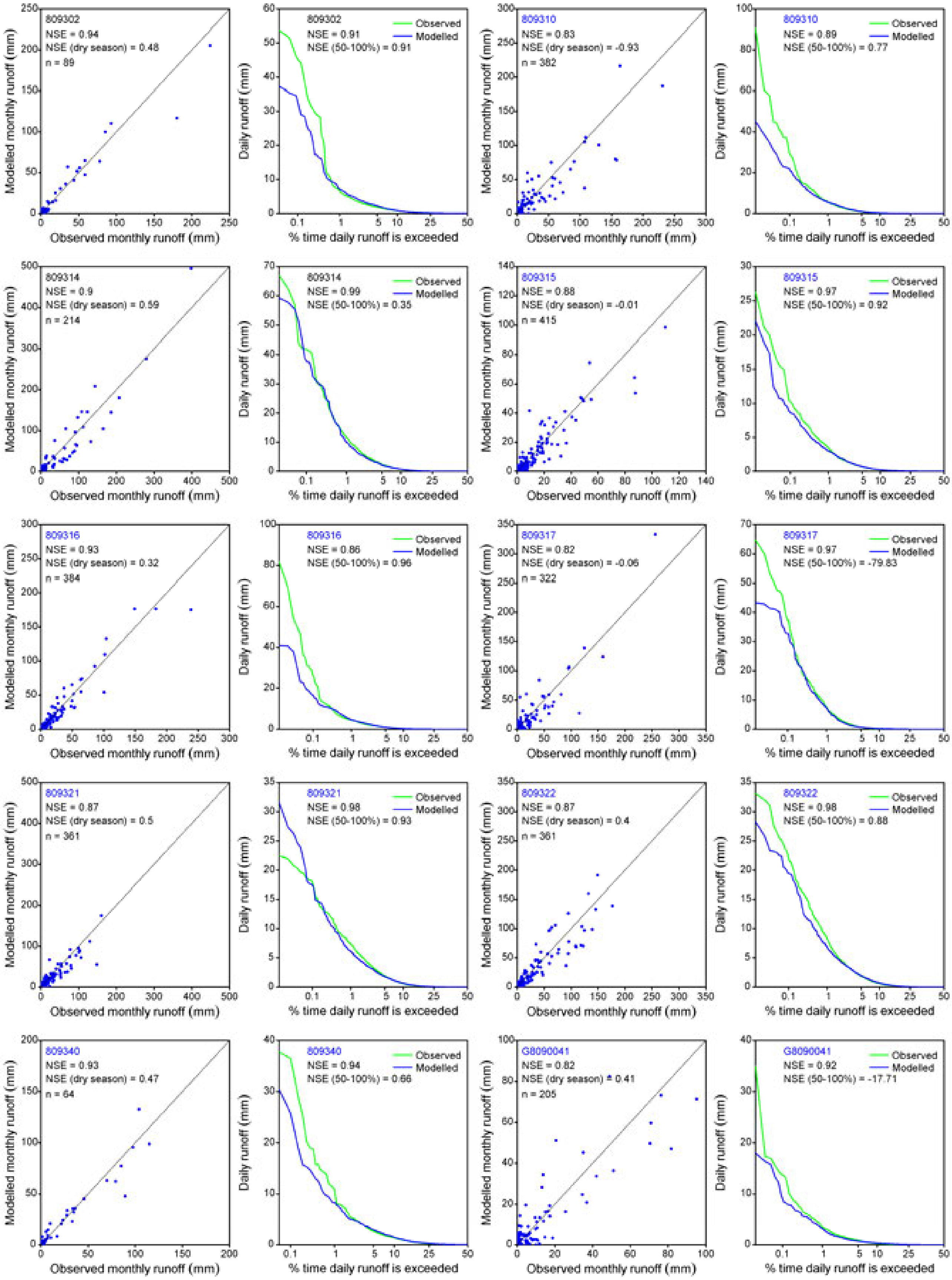
Figure OB-33. Map of the modelling subcatchments, calibration catchments and calibration gauging stations used for the Ord-Bonaparte region with inset highlighting (in red) the extent of the calibration catchments

OB-3.5.2 Model calibration

Figure OB-34 compares the modelled and observed monthly runoff and the modelled and observed daily flow exceedance curves for the nine calibration catchments. Nash-Sutcliffe efficiency (NSE) values provide a quantitative measure of how well simulated values match observed values. NSE values are described in more detail in Section 2.2.3 of the division-level Chapter 2. On the monthly plots NSE is the monthly Nash-Sutcliffe efficiency value and NSE (dry season) is the dry season monthly Nash-Sutcliffe efficiency value. On the daily flow exceedance plots, NSE is the daily flow exceedance curve Nash-Sutcliffe efficiency value and NSE (50 to 100 percent) is the lower half of the daily flow exeedance curve Nash-Sutcliffe efficiency value.

The results indicate that the ensemble calibration of the rainfall-runoff models Sacramento and IhacresClassic can reasonably reproduce the observed monthly runoff series (NSE values generally greater than 0.7) and the daily flow exceedance curve (NSE values generally greater than 0.9). The volumetric constraint used in the model calibration also ensures that the total modelled runoff is within 5 percent of the total observed runoff.

The calibration method places more importance on the simulation of high runoff, and therefore rainfall-runoff modelling of the medium and high runoff is considerably better than the modelling of low runoff. It should be noted, however, that while the relative difference between the observed and simulated low flow values may be large (which is what gives rise to the low monthly dry season NSE values for example), the absolute difference between the observed and simulated low flow values is generally small because both values are small. Nevertheless, an optimisation to reduce overall error variance can result in some underestimation of high runoff and overestimation of low runoff. This is evident in some of the scatter plots comparing the modelled and observed monthly runoff and many of the daily flow exceedance curves. For the majority of calibration catchments the disagreement between the modelled and observed daily runoff curves is discernable for runoff that is exceeded less than 1 percent of the time. This is accentuated in the plots because of the linear scale on the y-axis and normal probability scale on the x-axis. In any case, the volumetric constraint used in the model calibration ensures that the total modelled runoff is always within 5 percent of the total observed runoff. As indicated by the relatively low NSE values for the lower half of the daily flow exceedance curve and monthly dry season, there may be considerable disagreement between observed and modelled low flow values (i.e. cease-to-flow). Overall the monthly NSE values are considered sufficient for the general purposes of estimating long-term mean annual runoff.


809302
NSE = 0.94
NSE (dry season) = 0.48
n = 89
Modelled monthly runoff (mm)
Observed monthly runoff (mm)
809302
NSE = 0.91
NSE (50-100%) = 0.91
Observed
Modelled
Daily runoff (mm)
% time daily runoff is exceeded
809310
NSE = 0.83
NSE (dry season) = -0.93
n = 382
809310
NSE = 0.89
NSE (50-100%) = 0.77
809314
NSE = 0.9
NSE (dry season) = 0.59
n = 214
809314
NSE = 0.99
NSE (50-100%) = 0.35
809315
NSE = 0.88
NSE (dry season) = -0.01
n = 415
809315
NSE = 0.97
NSE (50-100%) = 0.92
809316
NSE = 0.93
NSE (dry season) = 0.32
n = 384
809316
NSE = 0.86
NSE (50-100%) = 0.96
809317
NSE = 0.82
NSE (dry season) = -0.06
n = 322
809317
NSE = 0.97
NSE (50-100%) = -79.83
809321
NSE = 0.87
NSE (dry season) = 0.5
n = 361
809321
NSE = 0.98
NSE (50-100%) = 0.93
809322
NSE = 0.87
NSE (dry season) = 0.4
n = 361
809322
NSE = 0.98
NSE (50-100%) = 0.88
809340
NSE = 0.93
NSE (dry season) = 0.47
n = 64
809340
NSE = 0.94
NSE (50-100%) = 0.66
G8090041
NSE = 0.82
NSE (dry season) = 0.41
n = 205
G8090041
NSE = 0.92
NSE (50-100%) = -17.71

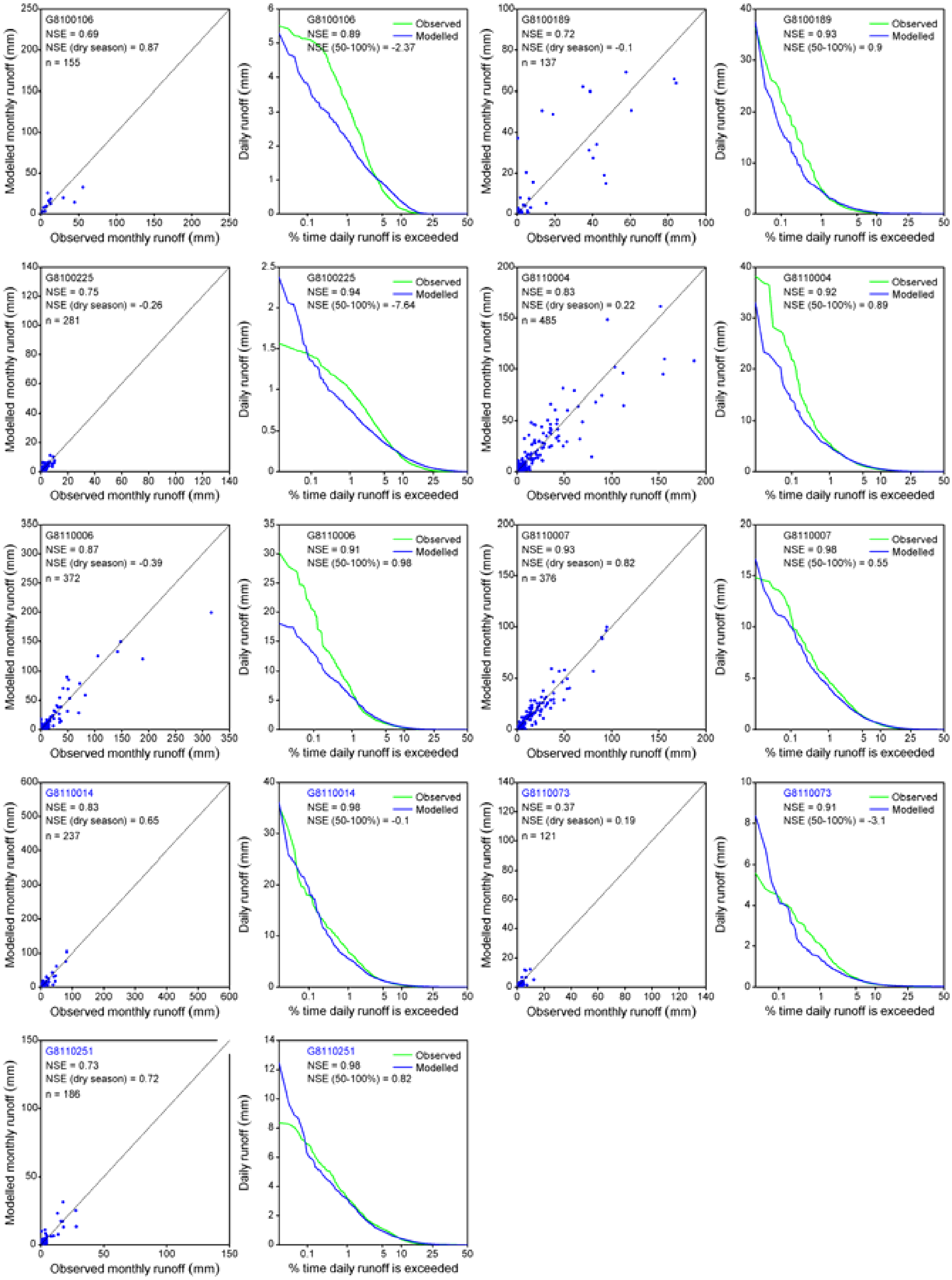


Figure OB-34. Modelled and observed monthly runoff and daily flow exceedance curve for each calibration catchment in the Ord-Bonaparte region. (Red text denotes catchments located outside the region; blue text denotes catchments used for streamflow modelling only)

OB-3.5.3 Under historical climate

Figure OB-35 shows the spatial distribution of mean annual rainfall and runoff under Scenario A (averaged over 1930 to 2007) across the Ord-Bonaparte region. Figure OB-36 shows the mean annual rainfall and runoff averaged over the region.

The mean annual rainfall and runoff averaged over the Ord-Bonaparte region are 727 mm and 112 mm respectively. The mean wet season and dry season runoff averaged over the Ord-Bonaparte region are 110 mm and 2 mm respectively.

In this project, all runoff grids are presented as long-term mean annual values. However, the distributions of monthly and annual runoff data in northern Australia are highly skewed; consequently the median and additional percentile values spatially averaged over the region are also reported. The 10th percentile, median and 90th percentile annual runoff values across the Ord-Bonaparte region are 208, 97 and 25 mm respectively. The median wet season and dry season runoff averaged over the Ord-Bonaparte region are 93 mm and 1 mm respectively.

The mean annual rainfall varies from over 1200 mm in the north to less than 500 mm in the south. The mean annual runoff varies from over 450 mm along the north-east coast to less than 50 mm in southern parts of the Victoria catchment (Figure OB-35). Runoff coefficients vary from about 5 to 30 percent of rainfall. The majority of rainfall and runoff occurs during the wet season months December to April (Figure OB-37). Rainfall and runoff can vary considerably from year to year with long periods over several years or decades that are considerably wetter or drier than others (Figure OB-36). The coefficients of variation of annual rainfall and runoff averaged over the Ord-Bonaparte region are 0.26 and 0.67 respectively.

The Ord-Bonaparte is one of 13 regions which cover the three divisions studied in this project. Mean annual rainfall and runoff, as well as coefficients of variation, have been calculated for all of these 13 regions, and it is useful to compare the Ord-Bonaparte results to results across all 13 regions. Across all 13 regions in this project, the 10th percentile, median and 90th percentile values are 1371, 936 and 595 mm respectively for mean annual rainfall and 374, 153 and 78 mm respectively for mean annual runoff. The mean annual rainfall (727 mm) and runoff (112 mm) averaged over the Ord-Bonaparte region fall in the lower end of this range. Across all 13 regions in this project, the 10th percentile, median and 90th percentile values are 0.34, 0.26 and 0.19 respectively for the coefficient of variation of annual rainfall and 1.39, 0.69 and 0.48 for the coefficient of variation of runoff. The coefficients of variation of annual rainfall (0.26) and runoff (0.67) averaged over the Ord-Bonaparte region fall within the middle of this range.

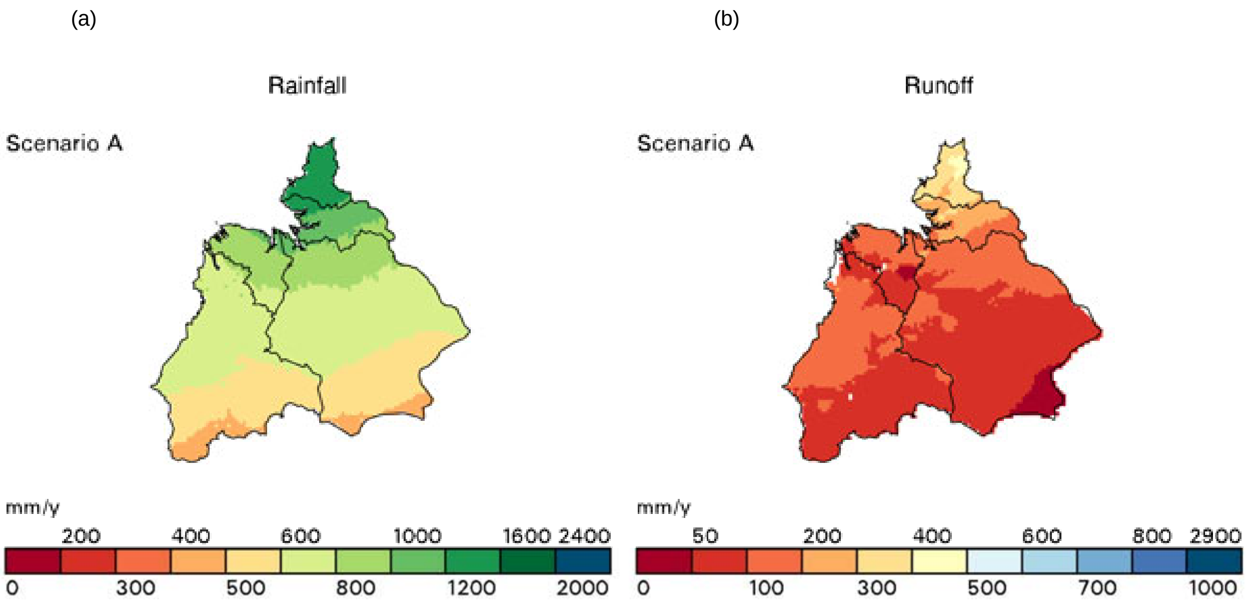


Figure OB-35. Spatial distribution of mean annual (a) rainfall and (b) modelled runoff across the Ord-Bonaparte region under Scenario A

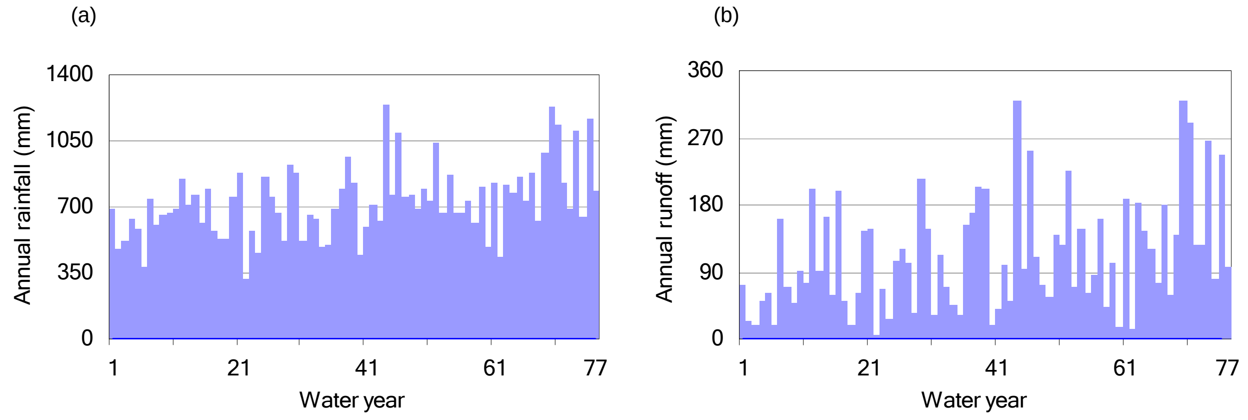


Figure OB-36. Mean annual (a) rainfall and (b) runoff in the Ord-Bonaparte region under Scenario A

Figure OB-37 shows the minimum and maximum monthly rainfall and runoff and the range of values between the 25th and 75th percentile monthly rainfall and runoff. Figure OB-37 shows the mean and median monthly flows and the range of values between the 25th and 75th percentile monthly rainfall and runoff. The large difference in the mean and median wet season monthly runoff values indicates that the distribution of monthly runoff in the Ord-Bonaparte region is highly skewed.

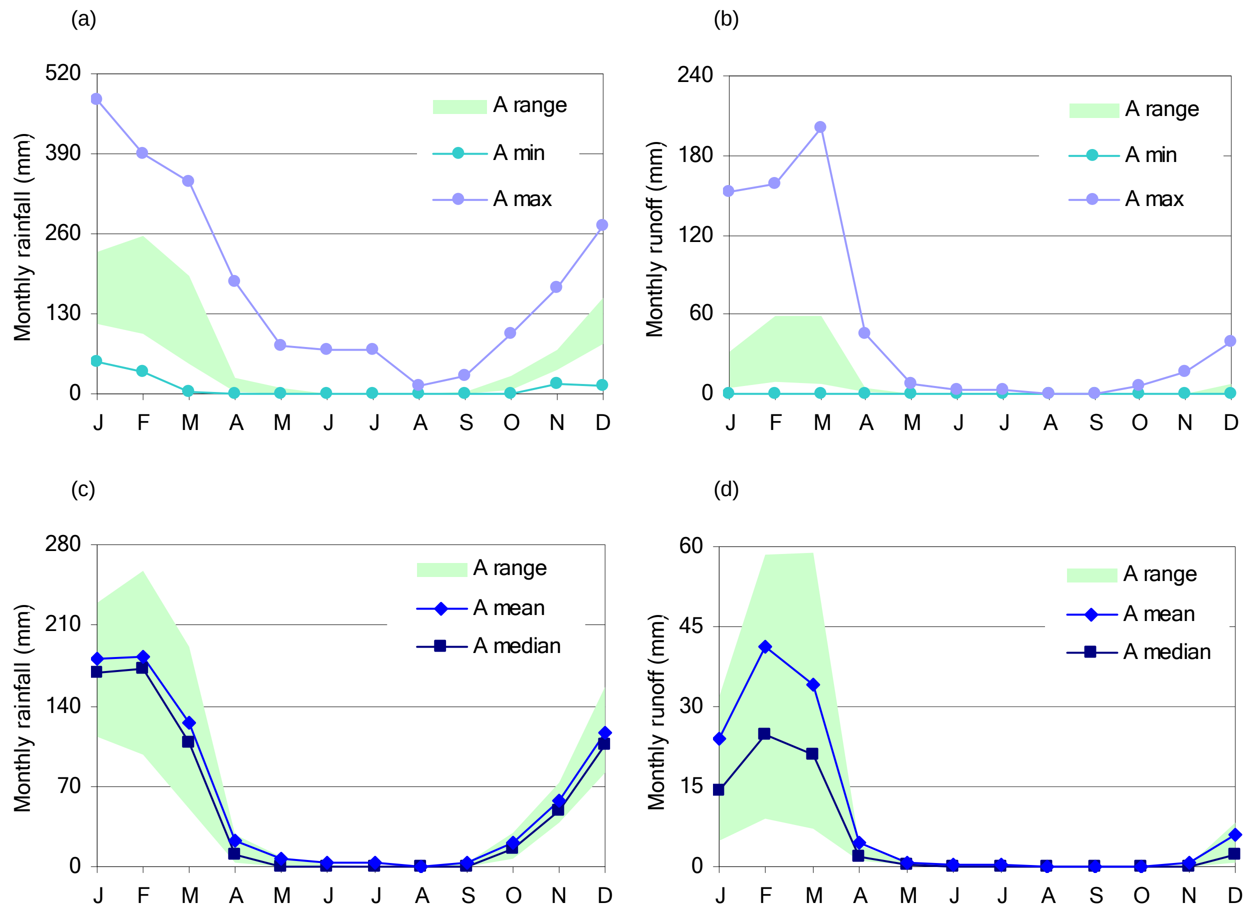


Figure OB-37. Minimum, maximum and A range monthly (a) rainfall and (b) modelled runoff; and mean, median and A range monthly (c) rainfall and (d) modelled runoff in the Ord-Bonaparte region under Scenario A (A range is the 25th to 75th percentile monthly rainfall or runoff)

OB-3.5.4 Under recent climate

The mean annual rainfall and runoff under Scenario B (1996 to 2007) are 26 percent and 56 percent higher respectively than the historical (1930 to 2007) mean values. The spatial distribution of rainfall and runoff across the Ord-Bonaparte region under Scenario B is shown in Figure OB-38.

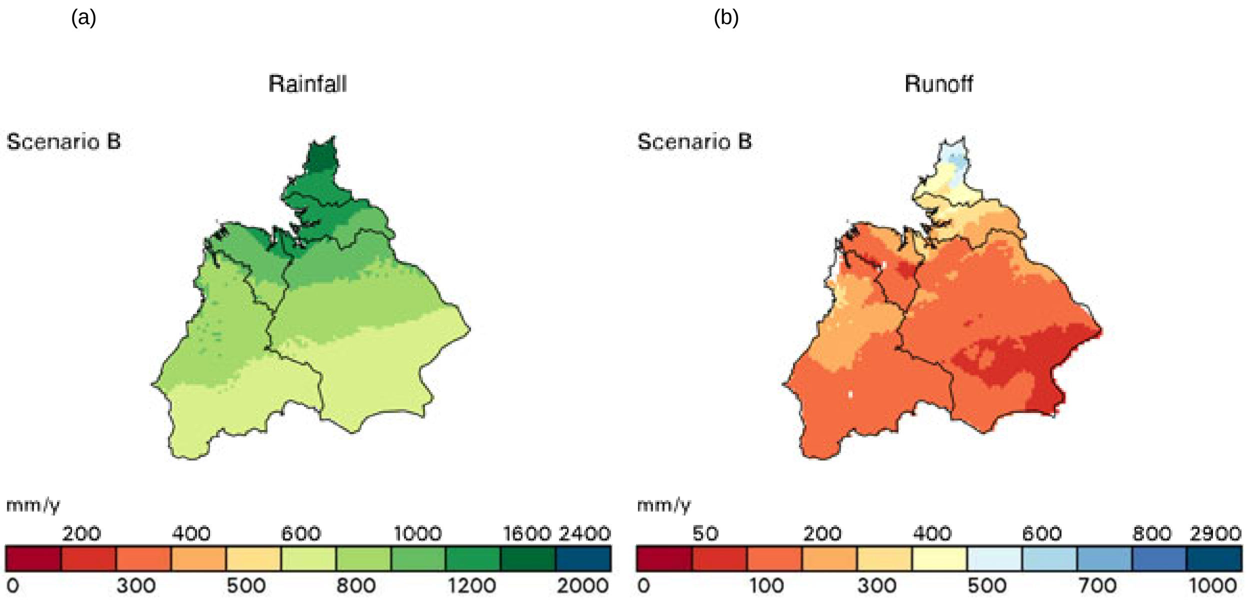


Figure OB-38. Spatial distribution of mean annual (a) rainfall and (b) modelled runoff across the Ord-Bonaparte region under Scenario B

OB-3.5.5 Under future climate

Figure OB-39 shows the percentage change in the mean annual runoff averaged over the Ord-Bonaparte region under Scenario C relative to Scenario A for the 45 scenarios (15 global climate models (GCMs) for each of the high, medium and low global warming scenarios). The percentage change in the mean annual runoff and rainfall from the corresponding GCMs are also tabulated in Table OB-10.

The figure and table indicate that the potential impact of climate change on runoff can be very significant. Although there is considerable uncertainty in the estimates, the results indicate that runoff in ~2030 in the Ord-Bonaparte region is as likely to increase as decrease. Rainfall-runoff modelling with climate change projections from seven of the GCMs shows an increase in mean annual runoff, while rainfall-runoff modelling with climate change projections from six of the GCMs shows a decrease in mean annual runoff. Two of the GCMs show neither an increase or decrease in mean annual runoff. The wide range of mean annual runoff values shown in Figure OB-39 and Table OB-10 is primarily due to the wide range of future projections of rainfall by the 15 GCMs.

Because of the large variation between GCM simulations and the method used to obtain the climate change scenarios, the biggest increase and biggest decrease in runoff come from the high global warming scenario. For the high global warming scenario, rainfall-runoff modelling with climate change projections from three of the GCMs indicates a decrease in mean annual runoff greater than 10 percent while rainfall-runoff modelling with climate change projections from three of the GCMs indicates an increase in mean annual runoff greater than 10 percent.

In subsequent reporting here and in other sections, only results from an extreme 'wet', 'mid' and extreme 'dry' variant are shown (referred to as scenarios Cwet, Cmid and Cdry). Under Scenario Cwet, results from the second highest increase in mean annual runoff from the high global warming scenario are used. Under Scenario Cdry, results from the second highest reduction in mean annual runoff from the high global warming scenario are used. Under Scenario Cmid, the median mean annual runoff results from the medium global warming scenario are used. These are shown in bold in Table OB-10.

Under scenarios Cwet, Cmid and Cdry, mean annual runoff increases by 32 and zero percent and decreases by 26 percent relative to Scenario A. By comparison, the range based on the low global warming scenario is a 17 to -15 percent change in mean annual runoff. Figure OB-40 shows the mean annual runoff across the Ord-Bonaparte region under scenarios A and C. The linear discontinuities that are evident in Figure OB-40 are due to GCM grid cell boundaries.

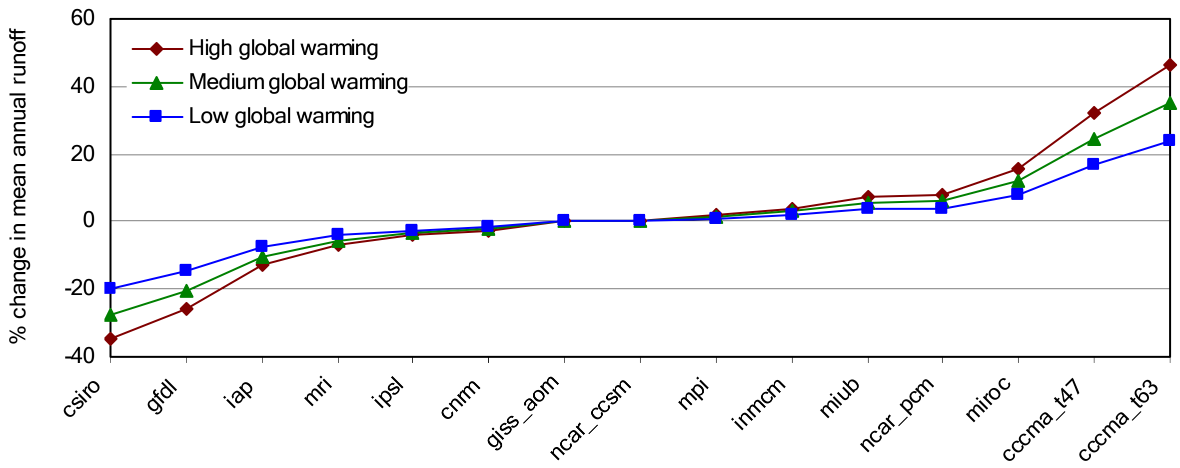


Figure OB-39. Percentage change in mean annual runoff under the 45 Scenario C simulations (15 global climate models and three global warming scenarios) relative to Scenario A

Table OB-10. Summary results under the 45 Scenario C simulations for the modelled subcatchment in the Ord-Bonaparte region (numbers show percentage change in mean annual rainfall and modelled runoff under Scenario C relative to Scenario A)

High global warming			Medium global warming			Low global warming		
GCM	Rainfall	Runoff	GCM	Rainfall	Runoff	GCM	Rainfall	Runoff
csiro	-18%	-34%	csiro	-14%	-28%	csiro	-10%	-20%
gfdl	**-14%**	**-26%**	gfdl	-10%	-20%	gfdl	-7%	-15%
iap	-6%	-13%	iap	-4%	-10%	iap	-3%	-7%
mri	-2%	-7%	mri	-2%	-5%	mri	-1%	-4%
ipsl	0%	-4%	ipsl	0%	-3%	ipsl	0%	-2%
cnrm	0%	-3%	cnrm	0%	-2%	cnrm	0%	-2%
giss_aom	1%	0%	giss_aom	1%	0%	giss_aom	0%	0%
ncar_ccsm	2%	0%	**ncar_ccsm**	**2%**	**0%**	ncar_ccsm	1%	0%
mpi	2%	2%	mpi	2%	2%	mpi	1%	1%
inmcm	2%	4%	inmcm	1%	3%	inmcm	1%	2%
miub	3%	7%	miub	2%	5%	miub	1%	4%
ncar_pcm	5%	8%	ncar_pcm	4%	6%	ncar_pcm	2%	4%
miroc	7%	16%	miroc	5%	12%	miroc	4%	8%
cccma_t47	**9%**	**32%**	cccma_t47	7%	24%	cccma_t47	5%	17%
cccma_t63	14%	46%	cccma_t63	10%	35%	cccma_t63	7%	24%

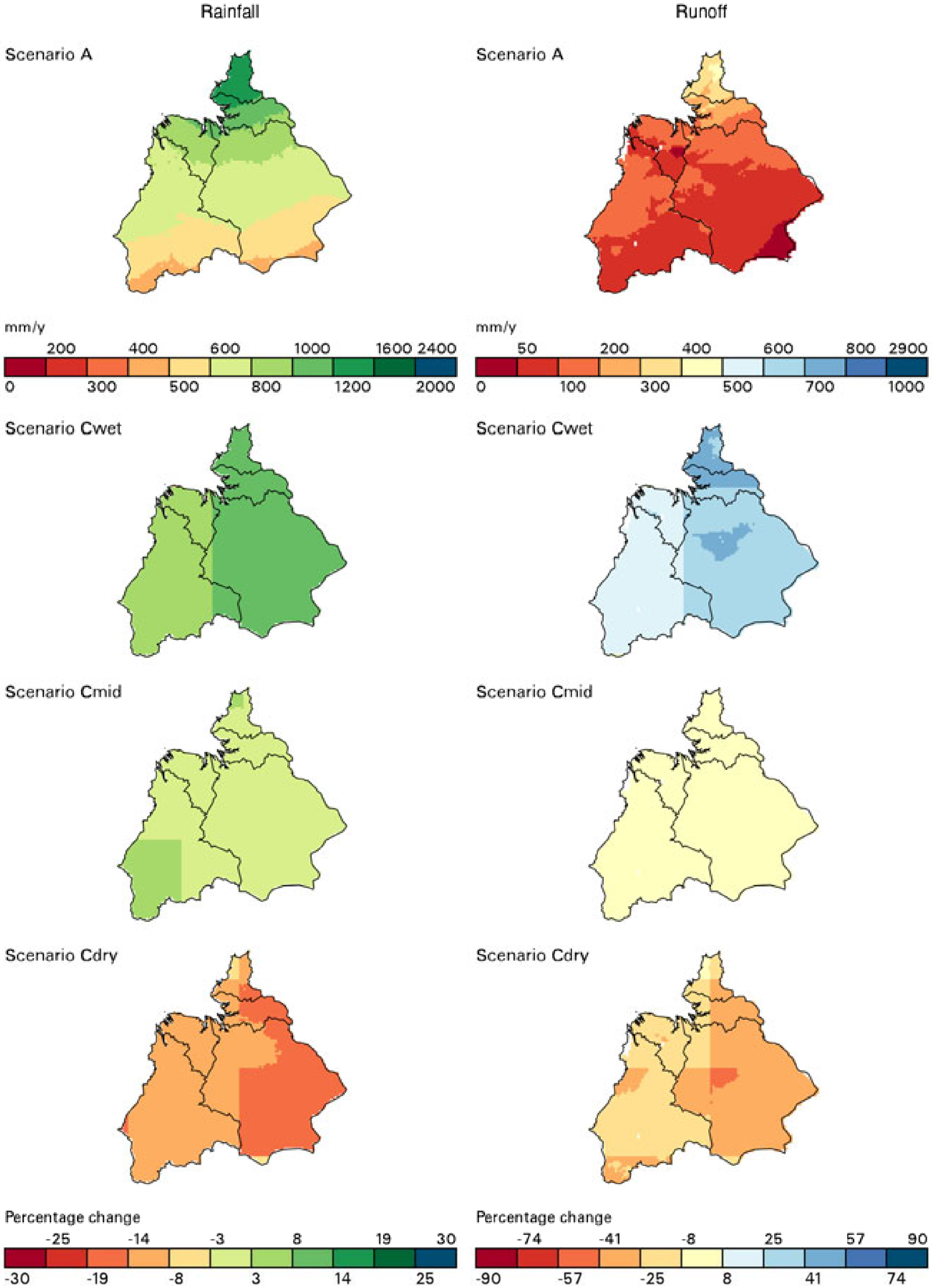


Figure OB-40. Spatial distribution of mean annual rainfall and modelled runoff across the Ord-Bonaparte region under Scenario A and under Scenario C relative to Scenario A

OB-3.5.6 Summary results for all scenarios

Table OB-11 shows the mean annual rainfall, runoff and actual evapotranspiration under Scenario A averaged over the Ord-Bonaparte region, and the percentage changes in the rainfall, runoff and actual evapotranspiration under scenarios B and C relative to Scenario A. The Cwet, Cmid and Cdry results are based on the mean annual runoff, and the rainfall changes shown in Table OB-11 are the changes in the mean annual value of the rainfall series used to obtain the runoff under scenarios Cwet, Cmid and Cdry. The changes in mean annual rainfall do not necessarily translate directly to the changes in mean annual runoff because of changes in seasonal and daily rainfall distributions and the relationship between rainfall and runoff is non-linear. The latter factor usually results in small changes in rainfall to be amplified in runoff (Table OB-10).

Figure OB-41 shows the mean monthly rainfall and runoff under scenarios A and C averaged over the 77 years for the region. Figure OB-42 shows the daily rainfall and flow exceedance curves under scenarios A and C averaged over the region. In Figure OB-41 Cwet, Cmid and Cdry are selected on a month-by-month basis, while in Figure OB-42 Cwet, Cmid and Cdry are selected for every day of the daily flow exceedance curve.

Table OB-11. Water balance over the entire Ord-Bonaparte region under Scenario A and under scenarios B and C relative to Scenario A

Scenario	Rainfall	Runoff	Evapotranspiration
		mm	
A	727	112	615
		percent change from Scenario A	
B	26%	56%	21%
Cwet	9%	32%	5%
Cmid	2%	0%	2%
Cdry	-14%	-26%	-11%

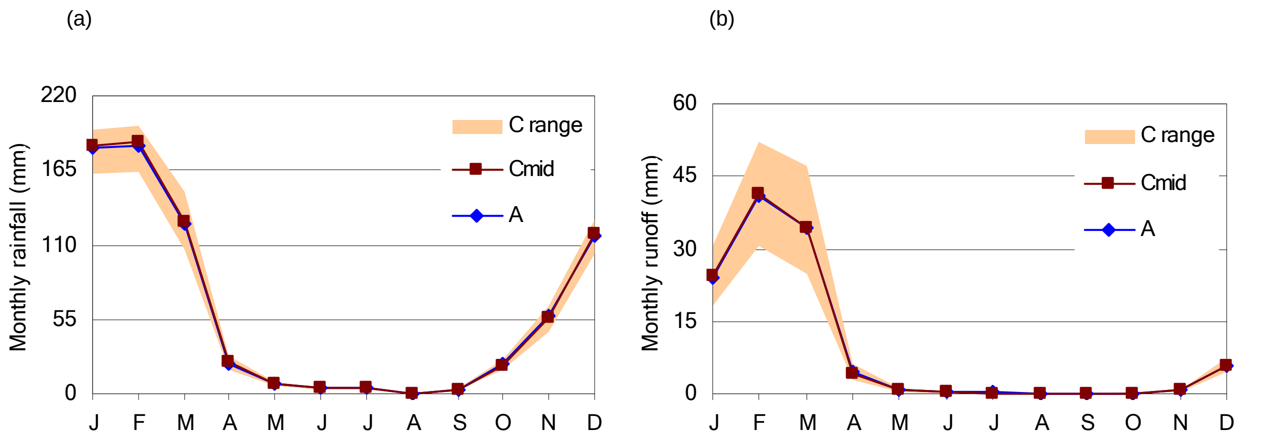


Figure OB-41. Mean monthly (a) rainfall and (b) modelled runoff in the Ord-Bonaparte region under scenarios A and C. (C range is based on the consideration of each rainfall and runoff percentile separately – the lower and upper limits in C range are therefore not the same as scenarios Cdry and Cwet)

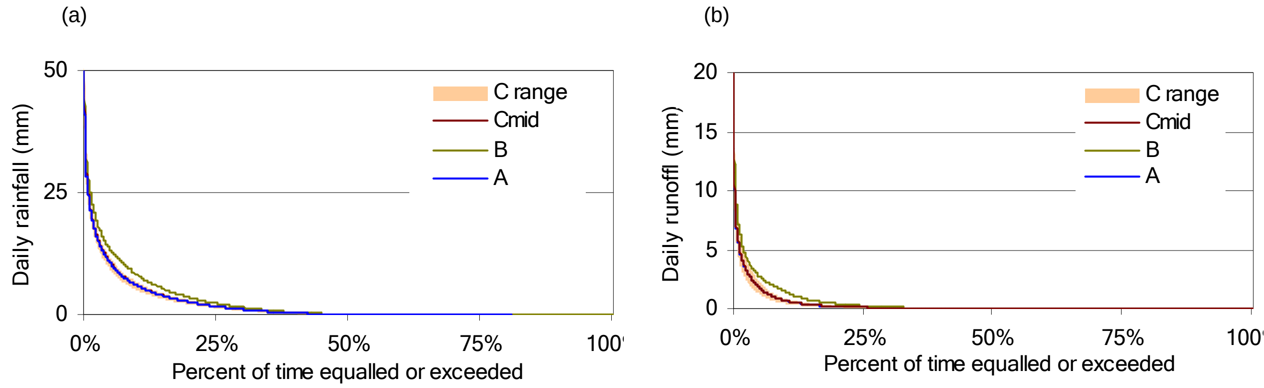


Figure OB-42. Daily flow exceedance curves for (a) rainfall and (b) modelled runoff in the Ord-Bonaparte region under scenarios A and C. (C range is based on the consideration of each rainfall and runoff percentile separately – the lower and upper limits in C range are therefore not the same as scenarios Cdry and Cwet)

OB-3.5.7 Confidence levels

The rainfall-runoff model verification analysis, with data from 123 catchments from across all of northern Australia, indicates that the mean annual runoff for ungauged catchments are under estimated or over estimated, when using optimised parameter values from a nearby catchment, by less than 20 percent in 40 percent of catchments and by less than 50 percent in 80 percent of the catchments. In the Ord-Bonaparte region, however, a large portion of the region has at some stage been gauged (Figure OB-33); consequently the level of confidence of the volume of water discharging from the region is relatively high. The main areas requiring donor parameter sets are the area downstream of Lake Argyle, the coastal regions and the ungauged subcatchments that lie to the north of the Victoria River. With no representative streamflow gauging stations from which to transpose parameters, runoff predictions in these areas have a low level of confidence. Diagrams in Petheram et al. (2009) illustrate which calibrated rainfall-runoff model parameter sets are used to model streamflow in the ungauged subcatchments in the Ord-Bonaparte region.

While a large portion of the region has at some stage been gauged most of this area is gauged by just two stations, one in the Ord (809302) and one in the Victoria (G8110007). Each of these stations has a catchment area of about 45,000 km^2. While the rainfall-runoff model ensemble exhibits reasonable skill at modelling streamflow at these stations (Figure OB-34), there is a lower degree of confidence associated with the runoff grid values within these catchments. This is because in large catchments rainfall-runoff models have a tendency to over predict runoff in wet areas and under predict runoff in dry areas. This additional uncertainty is reflected by a lower level of confidence for the mid to high flows for these stations than would be the case based on their daily NSE value (Figure OB-43). Further it should be noted that one of these stations (809302) only had about 9 years of acceptable monthly data. Fortunately the majority of wet seasons were recorded.

Based on the third version of the nine-second DEM, a large proportion of the Victoria catchment appears to extend outside of the Australian Water Resources Council (AWRC) basin boundary (Figure OB-33). While the DEM-derived catchment boundary is likely to be more accurate than the AWRC basin boundary, there is nevertheless uncertainty as to whether these relatively undefined lower reaches contribute flow to the Victoria River and, if so, during what size events.

There is a high degree of confidence that dry season runoff in the Ord-Bonaparte region is low because it is known that rainfall and baseflow are low during the dry season. The map of level of confidence for dry season flow shown in Figure OB-43 provides a relative indication of how well dry season metrics, such as cease-to-flow, are simulated.

Figure OB-43 shows the level of confidence in the modelling of the mid to high runoff events (i.e. peak flows) and dry season runoff (respectively) for the subcatchments of the Ord-Bonaparte region. It should be noted that these maps of level of confidence are not statistical confidence levels and are intended to only convey a broad reliability of prediction. The level of confidence in streamflow predictions will vary slightly from the level of confidence in runoff predictions shown below and as discussed in Section 2.2.6 of the division-level Chapter 2.

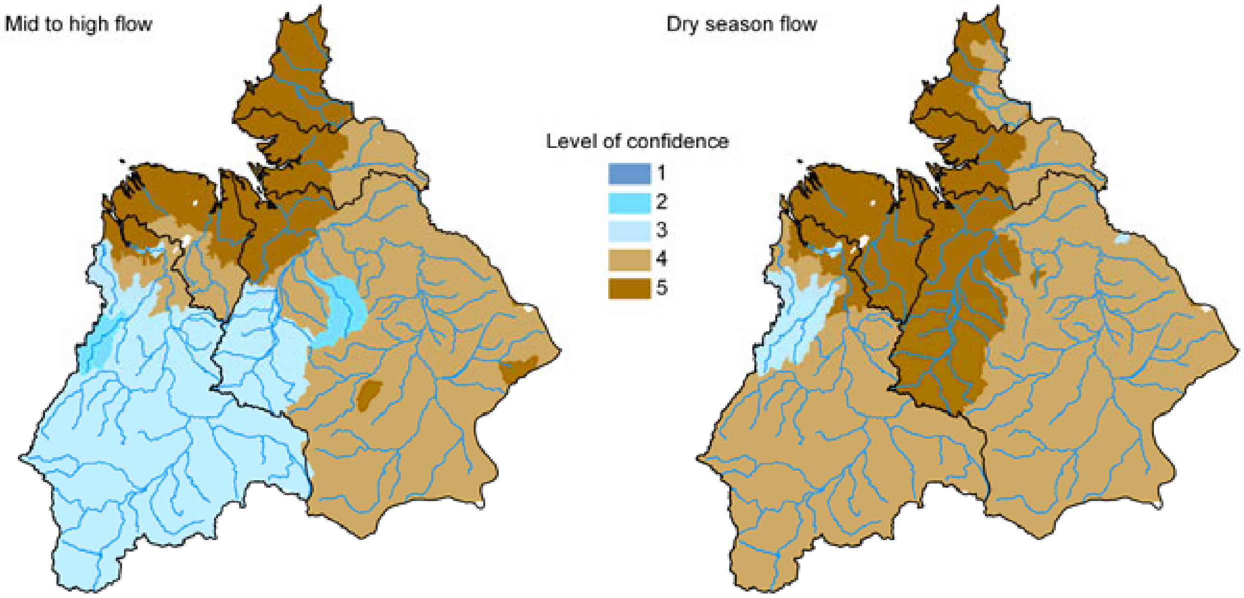


Figure OB-43. Level of confidence in the modelling of runoff for (a) mid- to high flow events and (b) monthly dry season flow events for the modelling subcatchments of the Ord-Bonaparte region. 1 is the highest level of confidence, 5 is the lowest

OB-3.6 River system water balance

The Ord-Bonaparte region is comprised of five AWRC river basins, the Ord, Keep, Victoria, Fitzmaurice and Moyle and has an area of 164,529 km^2. Under the historical climate the mean annual runoff across the region is 112 mm (Section OB-3.5.3), which equates to a mean annual streamflow across the region of 18,427 GL. The Ord is the only catchment represented by a river system model and is discussed in detail later in this section.

Keep, Victoria, Fitzmaurice and Moyle catchments

For the Keep, Victoria, Fitzmaurice and Moyle AWRC river basins no information on infrastructure, water demand and water management and sharing rules or future development were available, and consequently there is no river modelling section to the Ord-Bonaparte region report for these basins. Streamflow time series have been generated for each streamflow reporting node (SRN) based on the upstream grid cell rainfall-runoff simulations, as described in Section 2.2.5 of the division-level Chapter 2. The locations of these nodes are shown in Figure OB-44. Summary streamflow statistics for each SRN are reported in Petheram et al. (2009). In addition to the streamflow time series generated by the rainfall-runoff model ensemble, a range of hydrological metrics computed using multiple regression analysis is also available for each SRN (as described in Section 2.2.7 of the division-level Chapter 2). The complete set of results for the multiple regression analysis is reported in SKM (2009). The merit of each approach is discussed in Section 2.2.7 of the division-level Chapter 2.

The runoff time series generated in this project were used directly in the Ord River system model, hence SRN locations for the Ord catchment are also shown in Figure OB-44. In addition to time series of runoff, a range of hydrological metrics computed using regression analysis is available for each SRN. The merit of each approach is discussed in Section 2.2.6 of the division-level Chapter 2.

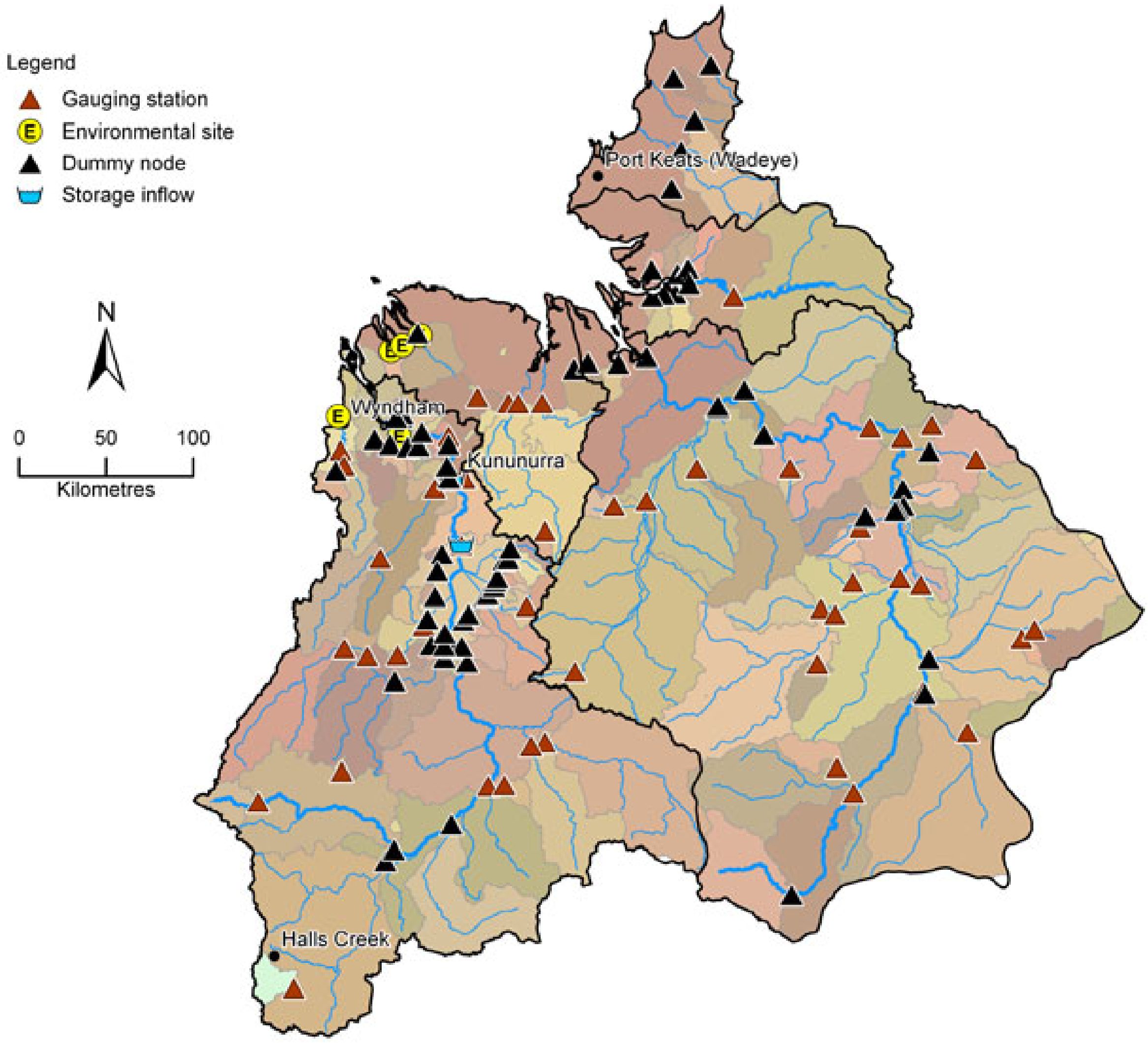


Figure OB-44. Location of streamflow reporting nodes in the Ord, Keep, Victoria, Fitzmaurice and Moyle catchments of the Ord-Bonaparte region

Ord catchment

General information about river modelling methods is presented at the division-level in Chapter 2. In that chapter, scenarios are defined in Section 2.1 and river modelling methods which apply to all regions are described in Section 2.2. The following section summarises this generic river modelling approach as applied to the Ord-Bonaparte region. The river modelling results for the Ord-Bonaparte river model are reported using a range of metrics, which were consistently applied across all regions. The use of a common set of metrics across the entire project area enables comparisons between regions.

In this section where annual data are reported, years are represented by numbers 1 through 77. Consistently throughout this report, annual data are based on the water year from 1 September to 31 August and the dry season is defined as 1 May to 31 October. Scenarios Cwet, Cmid and Cdry are selected on the basis of the ranked mean annual rainfall for the modelled subcatchments in Section OB-3.5.5.

River system models can be used to assess the implications of the changes in inflows on the reliability of water supply to users. They may also be used to support water management planning by assessing the trade-offs between supplies to various competing categories of users. These models describe infrastructure, water demands, and water management and sharing rules. Given the time constraints of the project, and the need to link the assessments to state water planning processes, it is necessary to use the river system models currently used by state agencies.

The Ord River and reservoir system is described by a numerical model using MIKE BASIN software (Danish Hydrologic Institute). The model was developed by the Western Australia Department of Water (DoW) to establish and refine operating rules for the Ord River Dam using an historical climate and streamflow dataset and a range of possible future development scenarios. Results from this model for the period from January 1906 to December 2004 were used to establish the operating rules and system targets for the Ord River Dam (ORD).

The MIKE BASIN model for the Ord has been used in this project to assess thirteen scenarios:

- Scenario A – historical climate sequence and current development
  This scenario incorporates the effects of current land use. Modelling commences on the 1 September 2007 and streamflow metrics are produced by modelling the 77-year historical climate sequence between 1 September 2007 and 31 August 2084. This scenario is used as a baseline for comparison with all other scenarios.
- Scenario AN – historical climate sequence and without-development
  Current levels of development such as public storages and demands are not considered when determining without-development conditions. Inflows were not modified for groundwater extraction, major land use change or farm dam development because the impact of these factors on catchment yields in this region is considered to be negligible. Without-development flows for the system were derived by adding the upstream catchment inflows for the Ord River, Kununurra River and Dunham River.
- Scenario BN – recent climate and without-development
  This scenario assuming without-development conditions (as per Scenario AN) and uses seven consecutive 11-year climate sequences between 1 September 1996 and 31 August 2007 to generate 77-year time series for runoff and climate. See Section 2.1.2 in the division-level Chapter 2 for more detail.
- Scenario CN – future climate and without-development
  Scenarios Cwet, Cmid and Cdry represent a range of future climate conditions assuming without-development conditions (as per Scenario AN).
- Scenario B – recent climate and current development
  This scenario incorporates the effects of current land use and uses seven consecutive 11-year climate sequences between 1 September 1996 and 31 August 2007 to generate 77-year time series for runoff and climate. See Section 2.1.2 in the division-level Chapter 2 for more detail.
- Scenario C – future climate and current development
  Scenarios Cwet, Cmid and Cdry represent a range of future climate conditions assuming current levels of development. Rainfall-runoff results from Section OB-3.5 were input directly into the MIKE BASIN model.
- Scenario D – future climate and 2030 development
  Scenarios Dwet, Dmid and Ddry represent a range of future climate conditions for a 2030 development scenario. The future development is representative of a 400 GL increase in allocation for the M2 irrigation area. Projections of commercial forestry and farm dams for 2030 are negligible and hence no adjustments were made to the Scenario C runoff time series.

The project scenario simulations use comparable but different initial conditions and inflow time series and a shorter simulation period than what was used by the DoW to establish reservoir operating rules and system targets. Results from these scenarios are not intended to be directly comparable with the department's simulations.

The changes in inflows between scenarios reported in this chapter differ from the changes in runoff reported in Section OB-3.5. These differences are due to difference in the methods by which the GCMs were ranked and difference in areas that are considered to contribute runoff to the surface water model. In Section OB-3.5 the entire region is considered while a subset of this area is considered here. The scenarios presented in this project may not eventuate but they encompass consequences that might arise if no management changes are made. Consequently results from this assessment are designed to highlight pressure points in the system, both now and in the future. This assessment does not elaborate on what management actions might be taken to address any of these pressure points. Where management changes to mitigate the effects of climate change have recently been implemented, the impacts of the changes predicted in this section may be an overestimate.

OB-3.6.1 Model configuration

Ord model description

The model extends from the Ord River Dam, which forms Lake Argyle, down to the confluence of the Ord and Dunham rivers. This area encapsulates the Ord River Irrigation Area and the Kununurra Diversion Dam, which forms Lake Kununurra. Inputs to the MIKE BASIN model include daily time series of runoff, rainfall and evaporation and water demand rules. The hydrological features of the Ord River system are described by daily time series of catchment runoff from the area upstream of the Ord River Dam, runoff from the area between the Ord River Dam and the Kununurra Diversion Dam, and runoff from the Dunham River (Figure OB-45). Spatially averaged daily time series of rainfall and evaporation data are used to compute the net evaporation from Lake Argyle and Lake Kununurra. Monthly irrigation demand over the Ord River Irrigation Area is varied for each scenario based on rainfall and evaporation data.

There are two major storages in the Ord system, the previously mentioned Ord River Dam and the Kununurra Diversion Dam. The Ord River Dam is the major storage providing water for various downstream users. It has an active storage of 10,380 GL (Table OB-12 presents details for the Ord River Dam). The Kununurra Diversion Dam is a re-regulating storage downstream of the Ord River Dam. It has an active storage volume of 105 GL, less than 1 percent of the Ord River Dam's active storage volume. The degree of regulation metric is defined in this project to be the sum of the net evaporation and controlled releases from the dam divided by the total inflows. Controlled releases include water for irrigation demands, for hydropower generation and for environmental water provisions, but exclude spills. The degree of regulation for the Ord River Dam is 0.8, which is very high. It is not appropriate to calculate the degree of regulation for the Kununurra Diversion Dam, which is a re-regulating structure.

The MIKE BASIN model includes three water users: (i) hydropower generation; (ii) irrigation; and (iii) environmental water provisions (EWP). Irrigation demands are represented on a monthly basis and environmental water provision on a daily basis. Hydropower demands at the Ord River Dam are specified as monthly power generation targets; the water required to produce these targets depends on water levels in Lake Argyle. The modelled water use configuration is summarised in Table OB-13. In this table the target power generation is the minimum commitment to be provided when Lake Argyle is above 78 m AHD.

The Ord River Dam operating rules were developed from results of simulations based on the Department of Water's 98-year historical climate and streamflow dataset. Rules were derived so that the following target outcomes were achieved as closely as possible:

- a 95 percent probability of supplying the full annual irrigation demand
- the minimum annual irrigation supply to be restricted to no less than 25 percent of demand
- a minimum water level in the reservoir of 70 m AHD.

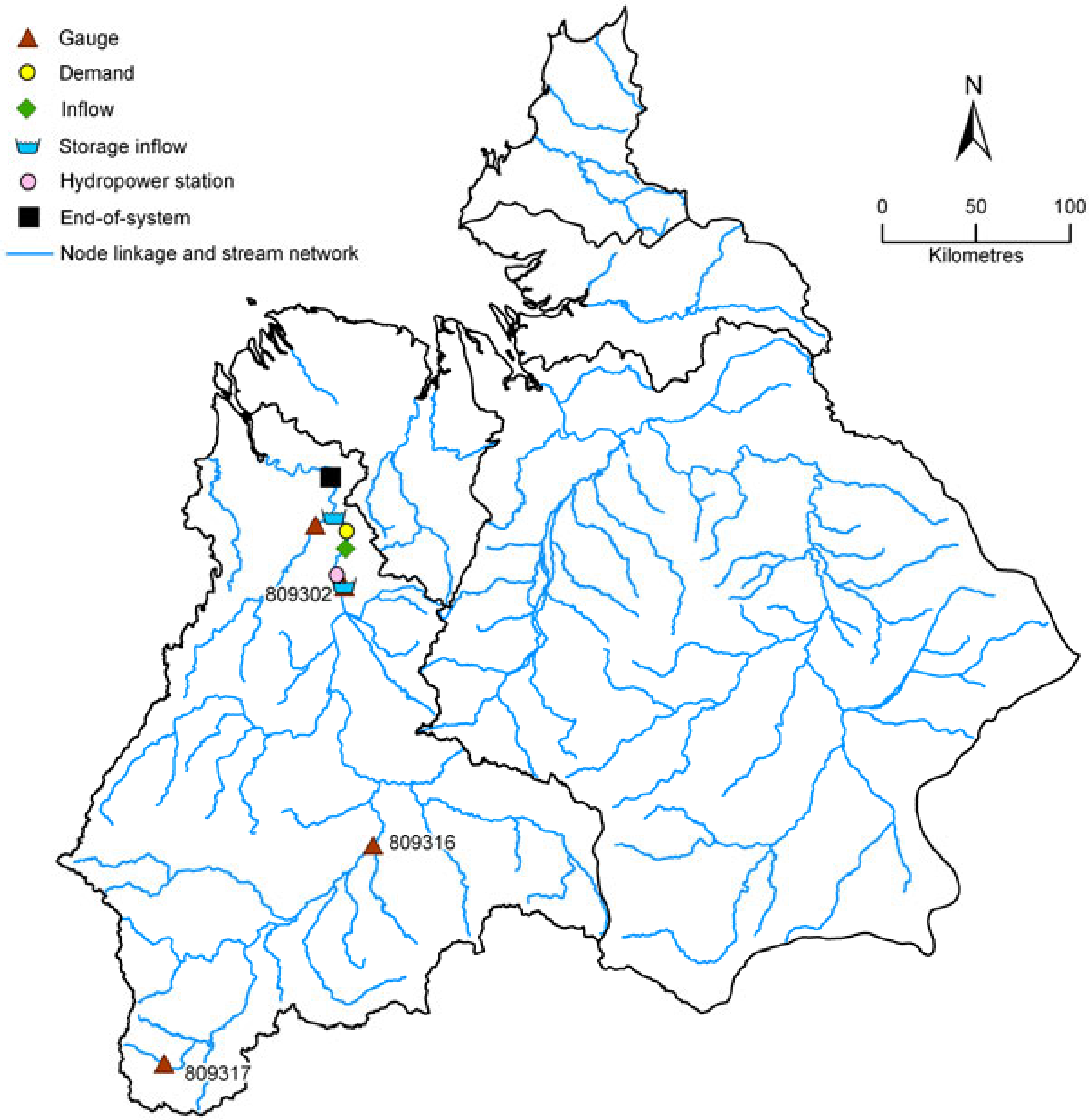


Figure OB-45. Schematic of the approximate location of gauging stations, main demand nodes and storages for the Ord system. The MIKE BASIN model extends from streamflow gauge 809302 to the end-of-system

Table OB-12. Major storage in the Ord river system model

	Active storage	Average annual Inflow	Average annual release	Average annual net evaporation	Degree of regulation
	GL	GL/y			
Major storage					
Ord River Dam	10,380	4257	2417	993	0.80

Table OB-13. Modelled water use configuration in the Ord system

Water users	Number of nodes	Allocation or Target	Model notes
Irrigation			
Current development	2	350 GL/y	Monthly demand for M1 and M1 growth areas
Future development	3	750 GL/y	Monthly demand for M1, M1 growth and M2 Irrigation
Hydropower	1	210 GWhr	Instream
Environmental water provision			Instream

Ecological water requirement and environmental water provision for the lower Ord

The environment water requirements and environment water provision for the lower Ord River are tabulated in Section OB- 2.4.3.

Ord model setup

Operating rules developed by DoW were applied to all of this project's scenarios. Rules and demands for the 350 GL allocation scenario have been applied to scenarios A, B and C, while rules for the future development, 750 GL/year, are used for Scenario D. All scenarios have been simulated with a starting water level in Ord River Dam of 91.35 m AHD, which is the level measured on 1 September 2007.

Without-development flows at the confluence of the Ord and Dunham rivers were derived by adding the catchment inflows to Lake Argyle and Lake Kununurra to the flows from the Dunham River.

Table OB-14 summarises the setup information for the Ord river system model.

Table OB-14. Ord river system model setup information

Model setup information		Version	Start date	End date
Ord	MIKE BASIN	2005	1/01/1906	31/12/2004
NASY simulation period				
	MIKE BASIN	2005	1/09/2007	31/08/2084
Modifications				
Data				
Inflows	Simulated runoff used			
Initial storage levels				
Ord River Dam	91.35 m AHD			
Kununurra Diversion Dam	41.9 m AHD			

OB-3.6.2 Ord system river water balance

The mass balance table (Table OB-15) shows volumetric components for Scenario A as GL/year, with all other scenarios presented as a percentage change from Scenario A. Mass balance includes the change in storage that is averaged over the 77-year period and is shown as GL/year.

Most of the inflows were based on data from a river gauge. The indirectly gauged inflows are from the area between the Ord River Dam and the Kununurra Diversion Dam. End-of-system flows are shown for the Ord River just below the confluence of the Ord and Dunham rivers (Figure OB-45).

Mass balance was checked by taking the difference between total inflows and outflows of the system. In all cases the mass balance variance was less than 1 percent of the inflows.

Table OB-15 shows that under scenarios Cwet and Cdry, inflows increase 19 percent and decrease 22 percent respectively. Compared to the change in inflows there is a larger change in flow at the end-of-system, a 27 percent decrease under Scenario Cdry. The impact to diversions is relatively small under Scenario C. Under scenarios Dwet, Dmid and Ddry, the additional irrigation water use results in an increase of 114, 113 and 98 percent change to diversions respectively. This assessment does not consider water products other than water that is diverted from the river. Results for all water users are reported in Section OB-3.6.5.

The large increase in inflows under Scenario B is due to the statistically significant increase in rainfall under the recent climate relative to the historical climate (Scenario A). This is clearly shown in Figure OB-25.

Net evaporation from Lake Argyle (Table OB-12) is a large proportion of the average annual inflow to the lake (approximately 23 percent) and controlled releases (approximately 41 percent).

Table OB-15. Ord river system model mean annual water balance under Scenario A and under scenarios B, C and D relative to Scenario A

	A	B	Cwet	Cmid	Cdry	Dwet	Dmid	Ddry
	GL/y							
Storage volume								
Change over period	5.8	5.8	8.7	4.0	-2.9	8.7	4.0	-1.7
	GL/y	percent change from Scenario A						
Inflows								
Subcatchments								
Gauged	4832.2	70%	19%	3%	-22%	19%	3%	-22%
Ungauged	115.8	62%	16%	3%	-21%	16%	3%	-21%
Sub-total	**4948.1**	**70%**	**19%**	**3%**	**-22%**	**19%**	**3%**	**-22%**
Diversions								
Irrigation	348.3	1%	1%	0%	-7%	114%	113%	92%
Sub-total	**348.3**	**1%**	**1%**	**0%**	**-7%**	**114%**	**113%**	**92%**
Outflows								
End-of-system flow	3593.8	95%	23%	3%	-27%	11%	-9%	-37%
Sub-total	**3593.8**	**95%**	**23%**	**3%**	**-27%**	**11%**	**-9%**	**-37%**
Net evaporation								
Lake Argyle	992.9	4%	11%	4%	-8%	15%	5%	-8%
KDD	17.9	-14%	3%	3%	16%	3%	3%	16%
Sub-total	**1010.7**	**4%**	**11%**	**4%**	**-8%**	**15%**	**5%**	**-7%**
Mass balance variance relative to total inflows (percent)								
	-0.2%	**-0.1%**	**-0.2%**	**-0.2%**	**-0.5%**	**-0.2%**	**0.2%**	**-0.7%**

OB-3.6.3 Ord system inflows

Inflows

Figure OB-46 presents a transect of inflows under without-development scenarios AN through CN, starting at 809317 (Koongie Park), which is upstream of Lake Argyle, down to the confluence of the Ord River and the Dunham River. Station 809302 is representative of the total inflows to Lake Argyle and the downstream of Kununurra Diversion Dam reach is representative of the mean annual flow immediately downstream of the Kununurra Diversion Dam. The end-of-system symbol shown in Figure OB-46 is located immediately downstream of the confluence of the Ord and Dunham rivers.

Under Scenario AN the maximum mean annual flow in the Ord River occurs at the confluence of the Ord and Dunham rivers and has a value of 4948 GL/year. Hence the Ord can be considered to be a gaining river system, which is typical of the majority of rivers in the Timor Sea and Gulf of Carpentaria drainage divisions.

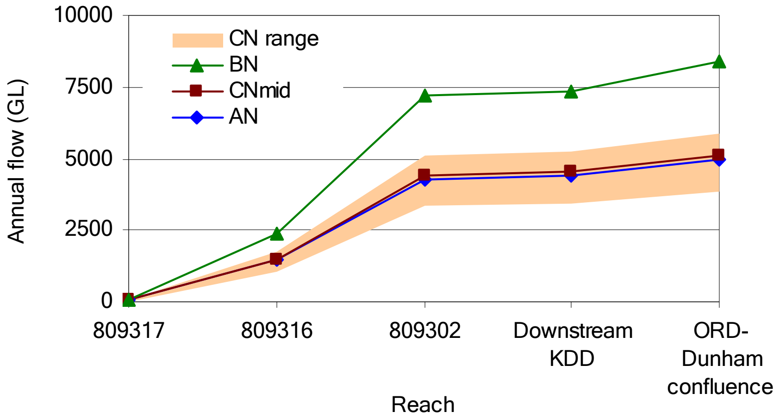


Figure OB-46. Transect of total mean annual river flow in the Ord system under scenarios AN, BN and CN (KDD is Kununurra Diversion Dam and ORD is Ord River Dam)

Water availability

In the Murray-Darling Basin Sustainable Yields Project, water availability was defined as the volume of water under the without-development scenario which occurs at the point of maximum mean annual flow along a river system. This generally occurred where a river system turned from a gaining reach to a losing reach. As shown in Figure OB-46 the Ord River is a gaining system. Hence the maximum mean annual flow occurs at the catchment outlet. However, end-of-system flow volumes are uncertain due to considerable ungauged flow contribution to these points. Further, in many river systems in northern Australia not all the water at the catchment outlet is available for consumptive use due to storage limitations. When computing water availability for this project ecological, social, cultural and economic values are not considered.

Within the Ord system water demands for irrigation and environmental water provisions are drawn from Lake Kununurra, which provides the head necessary to divert water to irrigation areas in the ORIA. Restriction policies for these demands are based on water levels in Lake Argyle, which is the main storage designed to supply water through drought periods. Hydropower demands are specified as monthly power generation targets; the water required to produce these targets also depends on water levels in Lake Argyle. Therefore for this region water availability is taken to be the inflow to Lake Argyle. These inflows are representative of those under Scenario AN as the contributing area upstream of Lake Argyle has negligible development that would impact on catchment yield.

A time series of annual surface water availability (Lake Argyle inflows) under Scenario AN is shown in Figure OB-47. The average annual water availability is 4257 GL/year. The lowest annual value is 172 GL in Year 6 of the simulation, and the highest annual water availability is 15,500 GL in Year 70. Figure OB-48 shows the difference in annual total surface water availability under Scenario CN relative to Scenario AN.

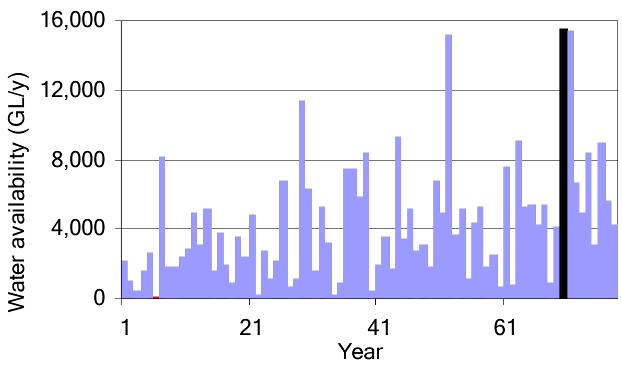


Figure OB-47. Annual water availability at the Ord River Dam (809302) under Scenario AN

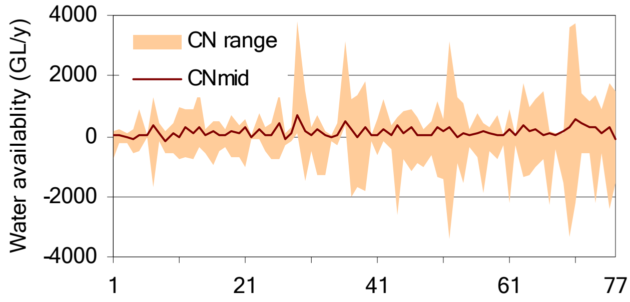


Figure OB-48. Annual water availability at the Ord River Dam (809302) under Scenario CN relative to Scenario AN

OB-3.6.4 Ord system storage behaviour

The modelled behaviour of major storages indicates how reliable the storage is during extended periods of low or no inflows. Table OB-16 provides indicators that show under each of the scenarios the lowest recorded storage volume and the corresponding year, and the average and maximum years between spills. A spill commences when the storage exceeds full supply volume and ends when the storage falls below 90 percent of full supply volume. The end condition is applied to remove the periods when the dam is close to full and oscillates between spilling and just below full which would otherwise distort the analysis. The period between spills is the length of time from when one spill ends (i.e. the storage falls below 90 percent of the fully supply volume) until the next spill commences (i.e. when the storage exceeds the full supply volume).

The minimum operating level is 70 m AHD or approximately 420 GL ±10 percent. Results in Table OB-16 show that this target is achieved for scenarios A, B Cwet, Cmid and Dwet. The time series of storage behaviour for Lake Argyle for the maximum period between spills under each of the scenarios is shown in Figure OB-49.

Despite a larger quantity of water diverted for irrigation under Scenario D compared to Scenario C, longer maximum years between spills and longer average years between spills are seen under Scenario Cwet compared to Scenario Dwet. This is most likely due to more severe restrictions on hydropower under Scenario D, which are intended to ensure there is sufficient water in the reservoir for irrigation during drought periods. As a consequence the water levels under Scenario D are higher than under Scenario C (Figure OB-49) and this results in more frequent spills under Scenario Dwet relative to Scenario Cwet. Higher water levels under Scenario Dwet relative to Scenario Cwet are also likely to be the reason for the higher net evaporation under Scenario Dwet in Table OB-15.

Table OB-16. Details of dam behaviour in the Ord system

Lake Argyle	A	B	Cwet	Cmid	Cdry	Dwet	Dmid	Ddry
	GL							
Minimum storage volume *	432.2	5,852.9	987.3	420.0	337.3	569.6	387.0	336.1
	Years							
Minimum storage year	7	3	7	7	7	7	7	7
Average years between spills	2.3	1.3	1.9	2.3	7.8	1.6	2.3	7.8
Maximum years between spills	28.4	2.5	14.4	28.4	28.6	12.5	28.4	29.5

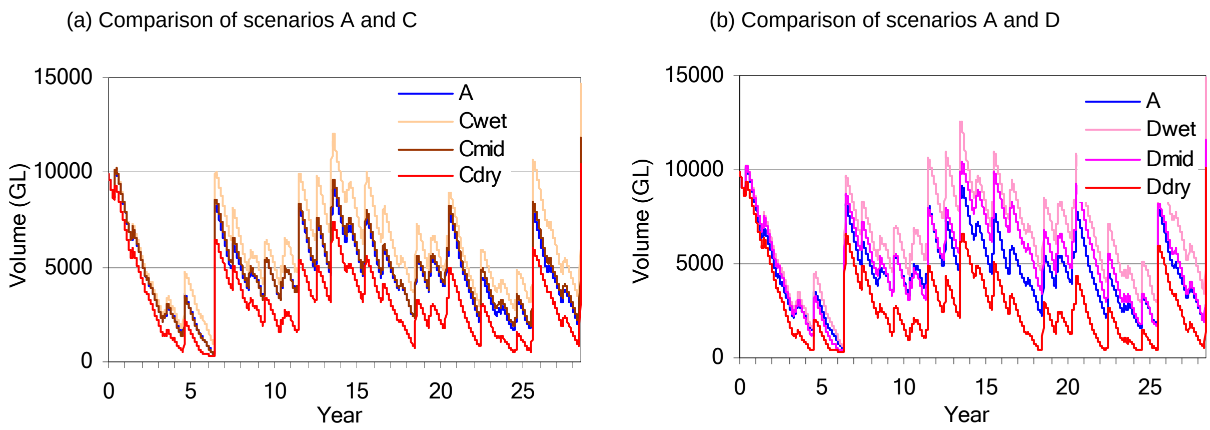


Figure OB-49. Storage behaviour over the maximum days between spills for Lake Argyle (a) under scenarios A and C and (b) under scenarios A and D

OB-3.6.5 Ord system water use

Water users

There are three water users in the Ord system – irrigation, hydropower generation and environmental water provisions. Table OB-17(a) shows average annual irrigation diversions for M1 irrigation area under Scenario A and under scenarios B, C and D relative to Scenario A. Table OB-17(b) shows average annual hydropower generation under Scenario A and under scenarios B, C and D relative to Scenario A. The environment receives water during periods of hydropower generation and at other times. Figure OB-50(a) shows the annual time series of irrigation diversions under Scenario A and under Scenario C relative to Scenario A.

The maximum and minimum diversions under Scenario A are 388.7 GL in Year 40 and 229.7 GL in Year 7 respectively. Figure OB-50(a) indicates there is little variation in irrigation diversions over the historic climate. In only a few years is irrigation supply severely restricted. As seen on Figure OB-50(b) restrictions for Years 6 and 7 are satisfied under Scenario Cwet.

Table OB-17. Change in water use under scenarios B, C and D relative to Scenario A: (a) diversions for M1 irrigation area, (b) hydropower generation

(a) Irrigation diversions

	A	B	Cwet	Cmid	Cdry	Dwet	Dmid	Ddry
	GL/y	percent change from Scenario A						
Ord River Irrigation Area (M1 only)	348.3	1%	1%	0%	-7%	0%	0%	-10%

(b) Hydropower generation

	A	B	Cwet	Cmid	Cdry	Dwet	Dmid	Ddry
	GWhr	percent change from Scenario A						
Hydropower	239.6	25%	8%	1%	-20%	3%	-3%	-22%

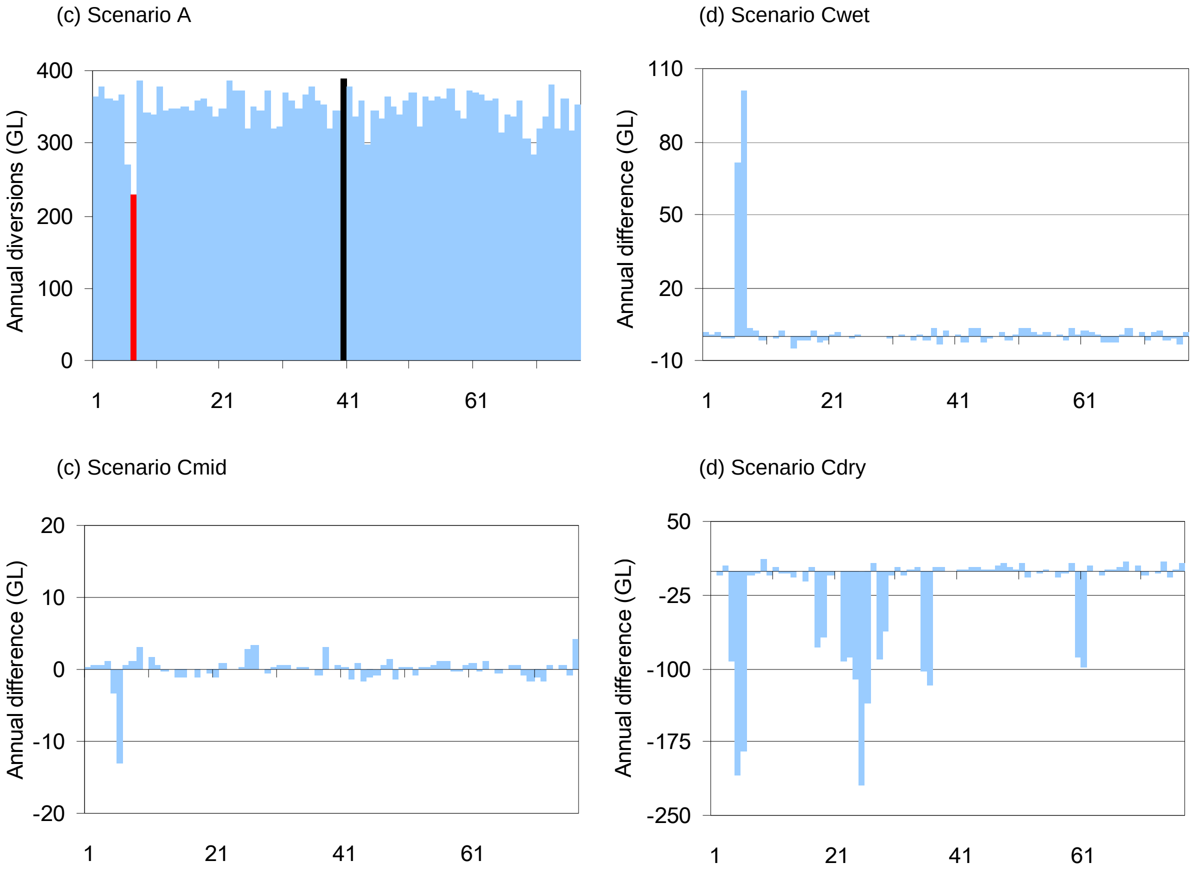


Figure OB-50. Total irrigation diversions in the Ord system under (a) Scenario A; and difference between irrigation diversions under Scenario A and under (b) Scenario Cwet, (c) Scenario Cmid, (d) Scenario Cdry

Figure OB-51 shows the annual time series of hydropower generation under Scenario A and under scenarios C and D relative to Scenario A. The maximum and minimum generation under Scenario A are 313.5 GWhr in Year 71 and 96.6 GWhr in Year 6 respectively.

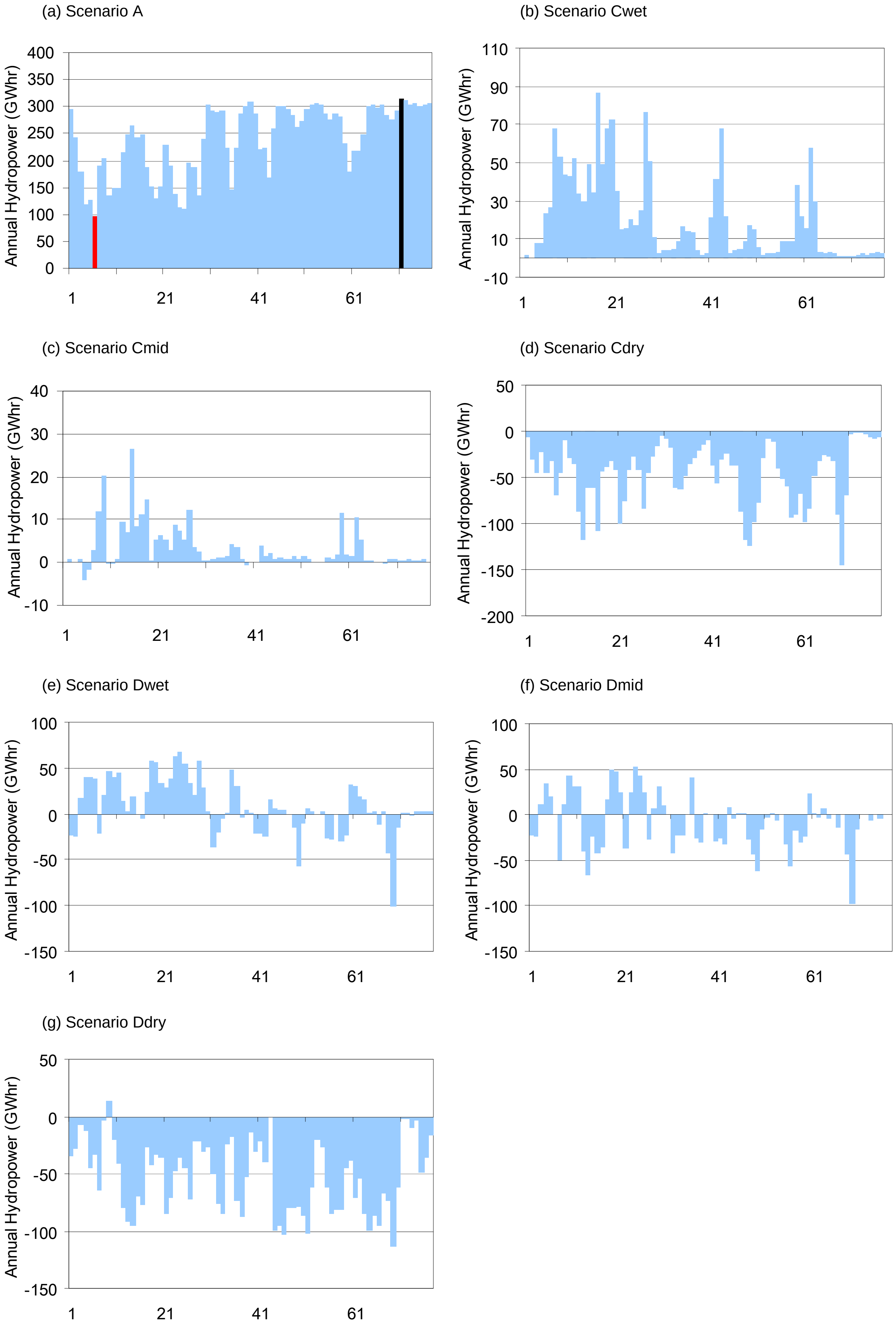


Figure OB-51. Hydropower generation in the Ord system under (a) Scenario A; and difference between irrigations diversions under Scenario A and under (b) Scenario Cwet, (c) Scenario Cmid, (d) Scenario Cdry, (e) Scenario Dwet, (f) Scenario Dmid, (g) Scenario Ddry

Level of use

The level of use metric used in this project is defined as the ratio of total water use to surface water availability. Total water use is presented for the Ord considering net volume of water diverted from the system (Table OB-18) and the total volume of controlled releases from Lake Argyle (Table OB-19). Controlled releases include water diverted for irrigation use and water used for hydropower generation and subsequently environmental water provisions.

Net diversions are used to reflect the change in mass balance of the system. They do not consider the difference in water quality that may exist between diversions and returns.

The level of use for water diverted from the Ord system is low for current irrigation allocations at 8 percent under Scenario A. This increases to 17 percent under Scenario Dmid for future irrigation allocations. If the water used for hydropower generation is also considered the level of use for the controlled releases (i.e. the sum of releases for diversions and hydropower generation) is high at 57 percent under Scenario A. Net evaporation and environmental water provision account for the difference between the degree of regulation of the Ord River Dam and the level of use.

Table OB-18. Relative level of use for irrigation diversions in the Ord system under scenarios A, B, C and D

	A	B	Cwet	Cmid	Cdry	Dwet	Dmid	Ddry
	GL/y							
Total surface water availability	4257	7173	5110	4396	3323	5110	4396	3323
Streamflow use	348	352	351	348	325	746	742	668
Sub-total	**348**	**352**	**351**	**348**	**325**	**746**	**742**	**668**
	percent							
Relative level of use	8%	5%	7%	8%	10%	15%	17%	20%

Table OB-19. Relative level of use for controlled releases from Lake Argyle in the Ord system under scenarios A, B, C and D

	A	B	Cwet	Cmid	Cdry	Dwet	Dmid	Ddry
	GL/y							
Total surface water availability	4257	7173	5110	4396	3323	5110	4396	3323
Controlled releases	2417	2766	2541	2438	2115	2403	2329	2070
Sub-total	**2417**	**2766**	**2541**	**2438**	**2115**	**2403**	**2329**	**2070**
	percent							
Relative level of use	57%	39%	50%	55%	64%	47%	53%	62%

Use during dry periods

Table OB-20 shows the average annual irrigation diversions and the annual irrigation diversions for the lowest 1-, 3- and 5-year periods under Scenario A and the percentage change from Scenario A under each other scenario. The results in Table OB-20 indicate the relative impact on surface water use during dry periods is greatest for a 1-year period.

Table OB-20. Indicators of diversions in the Ord system during dry periods under scenarios A, B C and D

Annual diversion (M1 only)	A	B	Cwet	Cmid	Cdry	Dwet	Dmid	Ddry
	GL/y	percent change from Scenario A						
Lowest 1-year period	230	30%	24%	0%	-63%	12%	-20%	-77%
Lowest 3-year period	288	11%	5%	-2%	-46%	5%	-10%	-56%
Lowest 5-year period	314	8%	3%	-1%	-30%	3%	-5%	-46%
Average	348	1%	1%	0%	-7%	0%	0%	-10%

Table OB-21 shows the average annual hydropower generation as well as the lowest 1-, 3- and 5-year periods under Scenario A and the percentage change from Scenario A under each other scenario. These figures indicate the change in hydropower generation is relatively consistent for the three time periods considered, except for scenario B, Cwet and Dwet.

Table OB-21. Indicators of hydropower generation in the Ord system during dry periods under scenarios A, B, C and D

Annual hydropower generation	A	B	Cwet	Cmid	Cdry	Dwet	Dmid	Ddry
	GWhr	percent change from Scenario A						
Lowest 1-year period	97	184%	24%	-2%	-33%	40%	0%	-35%
Lowest 3-year period	114	148%	11%	-1%	-29%	35%	12%	-32%
Lowest 5-year period	143	105%	9%	0%	-33%	16%	2%	-33%
Average	240	25%	8%	1%	-20%	3%	-3%	-22%

Reliability

In Table OB-22 the reliability of supply for water products is presented as the ratio of average annual diversions and power generation to annual allocation and targets under Scenario A and the percent change under scenarios B, C and D relative to Scenario A. The results indicate that reliability of supply for water products is good for all scenarios.

Table OB-22. Average reliability of water products in the Ord system under scenarios A, B, C and D

	A			B	Cwet	Cmid	Cdry	Dwet	Dmid	Ddry
Irrigation										
	Allocation	Average annual diversions	fraction diverted per 1ML allocated	percent change from Scenario A						
M1	350.0 GL/y	348.3 GL/y	1.00 GL/y	1%	1%	0%	-7%	0%	0%	-10%
				percent difference to Allocation						
M1 and M2	750.0							99%	99%	89%
Hydropower generation										
	Target	Average annual power generation	fraction of target	percent change from Scenario A						
Hydropower	210.0 GWhr	239.6 GWhr	1.14	25%	8%	1%	-20%	3%	-3%	-22%

OB-3.6.6 Ord system river flow behaviour

There are many ways of considering the flow characteristics in river systems. For this report two different indicators are provided: daily flow exceedance and seasonal plot. These are considered at the junction of the Ord and Dunham rivers (the modelled end-of-system). Figure OB-52 shows the flow exceedance curves at the end-of-system.

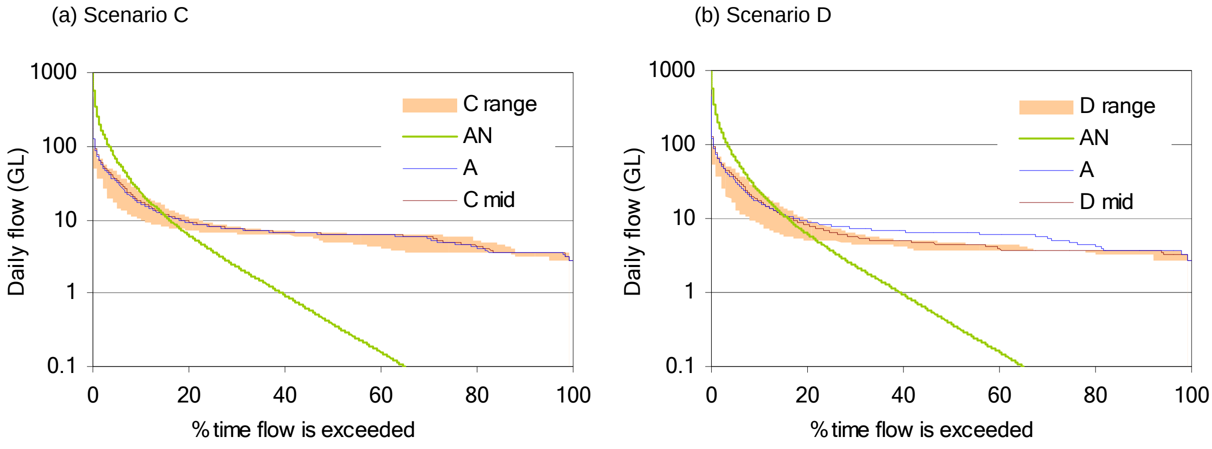


Figure OB-52. Daily flow exceedance curves for the Ord end-of-system under scenarios AN, A, C and D

Figure OB-53 gives the mean monthly flow under scenarios AN, A, C and D at the end-of-system. They show a strong seasonality reflecting the wet and dry seasons. There is a noticeable change in both the timing and quantity of water for the without-development scenario (Scenario AN), the current development scenarios (scenarios A and C), and the future development scenario (Scenario D). Figure OB-52 and Figure OB-53 indicate that the peak daily and monthly flows have decreased, while the low flows and dry season flows have increased as a result of development. Where once the river was ephemeral it is now perennial. These results indicate that the impoundment of water by the Ord River Dam and Kununurra Diversion Dam has resulted in a far greater change to the flow regime at the end-of-system than the climate change projections examined in this project. The Scenario A results presented here confirm the historical changes previously reported by Rodgers et al. (2000) and the Ord River Management Plan (2006).

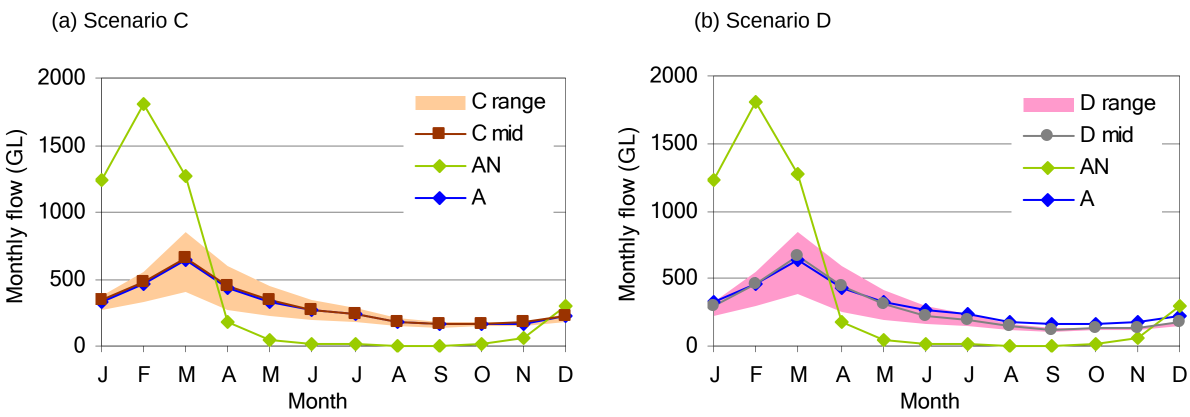


Figure OB-53. Mean monthly flow at the Ord end-of-system under scenarios AN, A, C and D

OB-3.6.7 Ord system share of water resource

Non-diverted water shares

Non-diverted water is defined as that water which is not diverted for consumptive use.

There are several ways of considering the relative level of impact on non-diverted water. Table OB-23 presents two indicators for relative impact on non-diverted water:

- the average annual non-diverted water as a proportion of the available water
- average annual non-diverted for each scenario compared with average annual non-diverted under Scenario A.

Non-diverted water is defined here as the total available water minus the sum of the water diverted for irrigation and the net evaporation from Lake Argyle and Lake Kununurra.

Table OB-23. Relative level of non-diverted water in the Ord system under scenarios A, B, C and D

Ord	A	B	Cwet	Cmid	Cdry	Dwet	Dmid	Ddry
	percent							
Non-diverted water as a percentage of total available water	68%	80%	71%	68%	62%	63%	59%	52%
Non-diverted share relative to Scenario A non-diverted share	100%	199%	125%	103%	71%	111%	90%	59%

Combined water shares

Figure OB-54 combines the results from the water availability, water balance and non-diverted water. The size of the bars indicates total water availability and the subdivision of the bars indicates the diverted and non-diverted fractions.

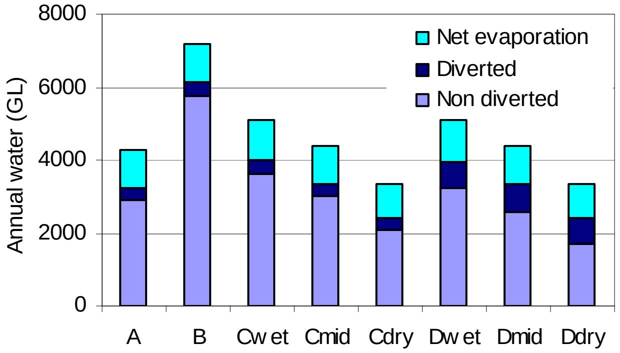


Figure OB-54. Comparison of diverted and non-diverted shares of water in the Ord system under scenarios A, B, C and D

OB-3.7 Changes to flow regimes at environmental assets

Section 1.3 of the division-level Chapter 1 describes how environmental assets were shortlisted for assessment by this project. Four environmental assets have been shortlisted in the Ord-Bonaparte region: Lake Argyle, Lake Kununurra, Parry Floodplain and Ord Estuary System. The locations of these assets are shown in Figure OB-1 and the assets are characterised in Chapter OB-2.

This section presents the assessment of these shortlisted assets and reports metrics for those assets which have sufficient confidence in the modelled streamflow to enable analysis. Confidence in results for low flows and high flows was calculated separately on a scale of 1 to 5, with 1 indicating results with the highest confidence (as described in Section 2.2.6 of the division-level Chapter 2). Hydrological regime metrics (as defined in Section 2.5 of the division-level Chapter 2) for either low flows or high flows are reported only where confidence levels are 1, 2 or 3. If confidence levels in the low flows or high flows are ranked 4 or 5, results are not reported and are labelled NR (not reported).

Some of the assets in this region have multiple nodes at which streamflow modelling results are available. When reporting hydrological regime metrics for such assets a single node was selected. The selected node was that with the highest streamflow confidence level and the largest proportion of streamflow to the asset. Results for all nodes are presented in McJannet et al. (2009).

In the absence of site-specific metrics for the Ord-Bonaparte region a set of standard metrics related to high and low flows have been utilised. However the conversion of these metrics into environmental impacts still requires development of quantitative relationships between flow and ecology.

OB-3.7.1 Standard metrics

Table OB-24. Standard metrics for changes to surface water flow regime at environmental assets in the Ord-Bonaparte region

Standard metrics	Units	A	B	Cwet	Cmid	Cdry	Dwet	Dmid	Ddry
			change from Scenario A						
Lake Argyle - Node 1 (confidence level: low flow = 4, high flow = 3)									
Annual flow (mean)	GL	4260	+69%	+20%	+3%	-22%	nm	nm	nm
Wet season flow (mean)*	GL	4180	+68%	+20%	+4%	-22%	nm	nm	nm
Dry season flow (mean)**	GL	NR	NR	NR	NR	NR	nm	nm	nm
Low flow threshold (discharge exceeded 90% of the time in Scenario A)	GL/d	NR							
Number of days below low flow threshold (mean)	d/y	NR	NR	NR	NR	NR	nm	nm	nm
Number of days of zero flow (mean)	d/y	NR	NR	NR	NR	NR	nm	nm	nm
High flow threshold (discharge exceeded 5% of the time in Scenario A)	GL/d	54							
Number of days above high flow threshold (mean)	d/y	18.3	+12.2	+2.6	+0.4	-4.6	nm	nm	nm
Parry Floodplain - Node 1 (confidence level: low flow = <3, high flow = <3)									
Annual flow (mean)	GL	3590	+95%	+23%	+3%	-27%	+11%	-9%	-37%
Wet season flow (mean)*	GL	2250	+103%	+24%	+4%	-29%	+17%	-3%	-37%
Dry season flow (mean)**	GL	1340	+81%	+21%	+2%	-25%	+1%	-17%	-38%
Low flow threshold (discharge exceeded 90% of the time in Scenario A)	GL/d	3.63							
Number of days below low flow threshold (mean)	d/y	8.1	-8.1	-4.3	-1.3	+44.6	-1.4	-14.6	+70.4
Number of days of zero flow (mean)	d/y	0.013	0	0	0	+0.2	0	0	+0.2
High flow threshold (discharge exceeded 5% of the time in Scenario A)	GL/d	32.3							
Number of days above high flow threshold (mean)	d/y	18.3	+45.1	+11.2	+1.8	-9.2	+12.2	+2.5	-9.1

*Wet season covers the six months from November to April.

**Dry season covers the six months from May to October.

NR – metrics not reported because streamflow confidence level is ranked 4 or 5
nm – not modelled.

Lake Argyle

The surface water flow confidence level for the selected reporting node for Lake Argyle (see location on Figure OB-7) is considered fairly reliable (3) for wet season flows and unreliable (4) for dry season flows (Table OB-24). Under Scenario A annual flow into this asset is highly dominated by wet season flows (98 percent) which have been 68 percent higher under Scenario B. Annual and wet seasonal flows do not change much under Scenario Cmid when compared to Scenario A. There are moderate decreases in wet season flow under Scenario Cdry (22 percent) when compared to Scenario A and moderate increases under Scenario Cwet (20 percent). There are no development scenarios for the area upstream of this asset.

Under Scenario B the high flow threshold exceedance has been much more frequent than in Scenario A. There is little change in high flow threshold exceedance under Scenario Cmid. Under Scenario Cwet high flow exceedance increases moderately from Scenario A; conversely, there is a moderate decrease in high flow days under the Scenario Cdry.

Lake Kununurra

Kununurra Diversion Dam (see location on Figure OB-8) is operated with the aim of maintaining the water level in the lake at as close to 41.9 m AHD as possible. The reservoir is operated to maintain this level to enable water to be gravity fed through most of the irrigation district. As a result of the management procedure the level in Kununurra Diversion Dam is a relatively stable system which will vary little across scenarios. Of more interest are the changes to assets downstream of the storage and these will be discussed for the Parry Floodplain (standard metrics) and Lake Kununurra asset below the dam wall (site-specific metrics) below.

Parry Floodplain

The surface water flow confidence level for the selected reporting node for Parry Floodplain (see location on Figure OB-9) is considered fairly reliable or better (<3) for both wet season flows and dry season flows (Table OB-24). The selected reporting node is representative of the conditions experienced in the lower Ord River which, since the construction of the Ord River Dam, only contributes significant flood water to the Parry Floodplain during very large floods. While this river is adjacent to the defined boundaries of this asset it should be noted that much of the wet season runoff and flooding generated at this asset comes from the local creeks that drain this sub-catchment area. This fact, coupled with the regulated nature of flows in the Ord River below the Ord River Dam requires that caution be exercised in the interpretation of results for this asset.

Under Scenario A annual flow into this asset is more evenly distributed between the wet season (63 percent) and the dry season (37 percent), because the dry season flows are sustained by water releases from the Kununurra Dam. Under Scenario B flows have been around twice those under Scenarios A. Annual and wet seasonal flows do not change much under Scenario Cmid when compared to Scenario A, but there are moderate decreases in flow (25 to 29 percent) under Scenario Cdry and moderate increases in flow under Scenario Cwet (21 to 24 percent). Some increase in the number of days with flows less than the minimum (EWR) threshold is to be expected when more water is being diverted under scenario D. The number of days this occurred in all but scenarios Cdry and Ddry were less than considered acceptable by the DoW's expert panel advising on the lower Ord's EWP regime. The increase for scenario Dmid was greater than the increase estimated by DoW in their simulations of the same development (by about 3 days/year over the common years simulated). This difference is considered minor for the following reasons. Minimum flow metrics such as these are sensitive to the critically dry inflow years used in the simulations and the operating rules developed from them. Other aspects of the two sets of simulations are also different, and as noted before, make them not directly comparable. Nevertheless, DoW consider that the operating rules used in these simulations could be readily fine tuned to ensure minimum thresholds in the Lower Ord River are adequately maintained under scenarios Cmid and Dmid. Operating rules would require additional modification if the dry climate conditions (of scenarios Cdry and Ddry) developed over the next 20 years.

Under the wetter conditions of Scenario B flows are maintained above the low flow threshold calculated for Scenario A at all times. The number of days when flow is less than the low flow threshold does not change very much under Scenarios Cmid and Cwet when compared to Scenario A, but there is a large increase in low flow days under Scenario Cdry (Table OB-24). Zero flow days are very rare at this asset and this does not change much under any of the scenarios. Adding the upstream development plans to the climate scenarios has a very large effect on the number of days below the low flow threshold under Scenario Dmid and Dwet. It should be noted that due to the regulated nature of the flows to this reporting node, there is an opportunity for dam managers to modify future release rules in order to balance the demands of agriculture, environmental flows and other uses.

Under Scenario B the high flow threshold exceedance has been much more frequent than under Scenario A. There is little change in high flow threshold exceedance under Scenario Cmid. Conversely, under Scenario Cwet and Cdry there are very large increases and decreases respectively in the high flow threshold exceedance.

Ord Estuary System

The surface water flow confidence levels for both high and low flows for all three nodes entering the Ord Estuary System are ranked unreliable (5) therefore they are of insufficient quality to allow environmental flow metrics to be calculated.

OB-3.7.2 Site-specific metrics

Table OB-25. Site-specific reported metrics for changes to flow regime at Lake Kununurra

Reported metrics	Units	A	B	Cwet	Cmid	Cdry	Dwet	Dmid	Ddry
		change from Scenario A							
Lower Ord downstream of Lake Kununurra – Node 2 (confidence level: low flow = <3, high flow = <3)									
Number of days with flows below 3.63 GL/d (mean) (1)	d/y	8.1	-8.1	-4.3	-1.3	+44.6	-1.4	+14.6	+70.4
Number of days with flows above 10.80 GL/d (mean) (2)	d/y	58	+80.7	+16.2	+2.6	-25.7	+10.3	-2.6	-30.8
Number of days with flows above 36.72 GL/d (mean) (3)	d/y	15	+43	+10.5	+1.7	-7.8	+11.5	+2.5	-7.2

(1) Threshold for fish and macrophyte habitat requirements

(2) Threshold for deep backwater habitat and flooded riparian benches

(3) Threshold for fish passage by migratory species

Lower Ord downstream of Lake Kununurra

The environmental flow requirements of the lower Ord River downstream of the Kununurra Diversion Dam have been defined by Braimbridge and Malseed (2007), based on the hydro-ecological studies of this river reach by Trayler et al. (2006). They recommend that a low flow threshold of 42 m^3/second (3.63 GL/day) should be sustained throughout the dry season in order to meet the environmental flow requirements for fish and macrophyte habitats and pools for algal production. In the same river reach, high flow thresholds are also recommended, including the maintenance of wet season flows in excess of 125 m^3/second (10.8 GL/day) for at least 10 days per year in order to sustain regular inundation of riparian zones and deep backwater pools. To maintain fish passage an even higher wet season flow threshold is recommended, i.e. 425 m^3/second (36.7 GL/day) for at least 2 days per year. The Department of Water, Western Australia have recognised the intrinsic ecological values of the region below the Ord River Dam and as such have developed an environmental water requirement regime based on the flow requirements defined by Braimbridge and Malseed (2007). It should be noted that the low flow threshold of Braimbridge and Malseed (2007) is the same as the minimum environmental flow release from the Kununurra Diversion Dam during the dry season months under conditions of no water restrictions. The environmental flow release is progressively reduced under Level 1 and 2 water restrictions for the irrigation area. For Level 1 and Level 2 water restrictions the minimum environmental flow release is reduced to 37 m^3/second and 32.3 m^3/second, respectively. Being a managed system the opportunity exists in the future to modify release rules for the storage in order to deal with changing water resource conditions.

Table OB-25 shows how these site-specific metrics changed under the various scenarios. Under Scenario A, on average, flow is below the low flow threshold of 42 m^3/second (3.63 GL/day) on just 8 days/year. Under Scenario B flow is never under this threshold and Scenario Cmid shows little change when compared to Scenario A. However, there is a large increase in low flow days under Scenario Cdry when compared to Scenario A. Under Scenario D the combined climate and development results in even longer periods below the suggested low flow threshold when compared to scenario A. While there were an additional 4 days/year below the threshold under Scenario Cmid, this increased to an additional 15 days/year under Scenario Dmid. This implies that much of the change to be expected with regard to this flow metric are attributed to the proposed development. Current operating rules will require adaption if such conditions develop.

The effect of the various scenarios on the Braimbridge and Malseed (2007) high flow thresholds are also shown in Table OB-25. Their first high flow threshold 125 m^3/second (10.8 GL/day) is exceeded for much more than the minimum 10 day requirement in all scenarios, despite the large changes in high flow threshold exceedance that occurs between scenarios. The same is true for the second high flow threshold 425 m^3/second (36.7 GL/day), which is exceeded for much more than the minimum 2 days required to maintain fish passage. This implies that regular inundation of riparian zones and deep backwater pools as well as fish passage for migratory species is maintained in all the climate and development scenarios.

OB-3.8 References

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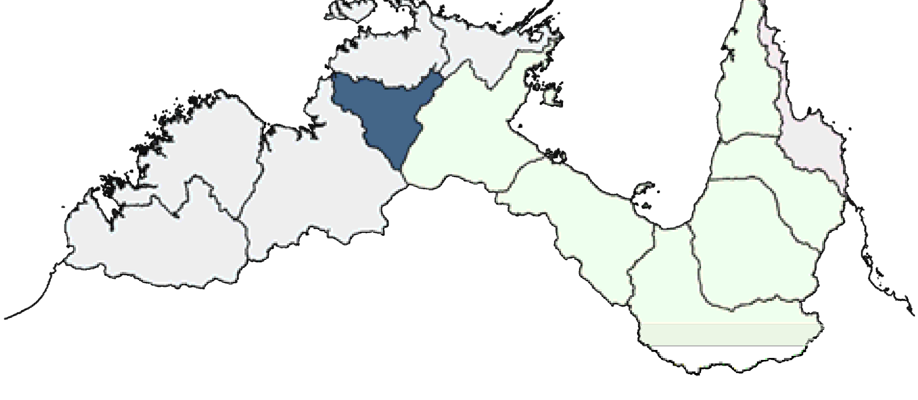
Water in the Daly region



DA-1 Water availability and demand in the Daly region

The first part of this report (the Preamble, Chapter 1 and Chapter 2) reports at the division level, including division-wide descriptions of climate and geology and methods which apply to all regions. Subsequent chapters report at the region level. In particular, Chapters DA-1, DA-2 and DA-3 focus on the Daly region (Figure DA-1).

This chapter summarises the water resources of the Daly region, using information from Chapter DA-2 and Chapter DA-3, and directly addresses the Terms of Reference, specifically terms 3, 4 and 5 as listed in the Preamble. Essentially, this chapter provides a synoptic view of the region and covers:

- regional observations
- water resource assessment
- seasonality of water resources
- surface–groundwater interaction
- changes to flow regime at environmental assets
- water storage options
- data and knowledge gaps.

For further details on the context of the region (physical and climate descriptions, hydrogeology and legislation) see Chapter DA-2. Region-specific methods and results are provided in Chapter DA-3. Modelling results are reported under climate and development scenarios as defined at the division level in Section 2.1 of Chapter 2.

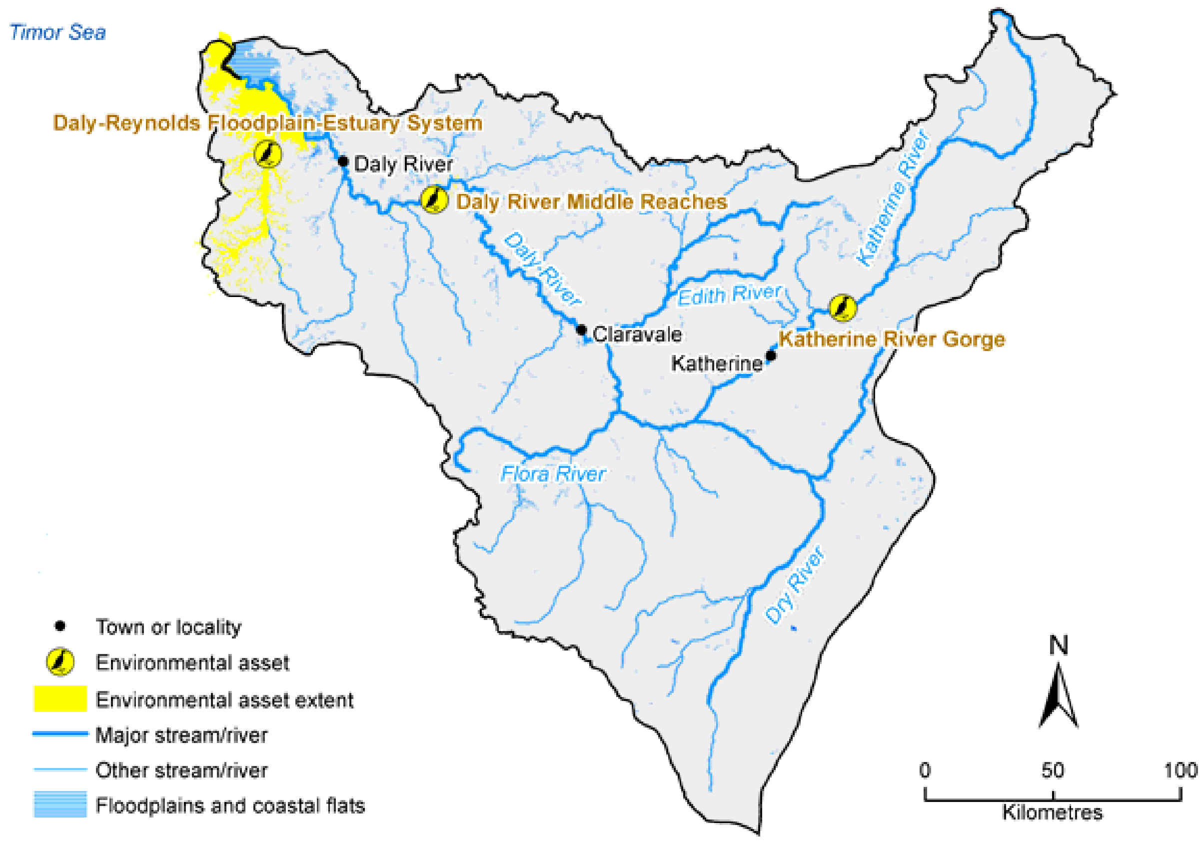


Figure DA-1. Major rivers, towns and location of assets selected for assessment of changes to hydrological regime in the Daly region

DA-1.1 Regional summary

These regional observations summarise key modelling results and other relevant water resource information about the Daly region.

The Daly region has a high inter-annual variability in rainfall and hence also runoff and groundwater recharge. Coefficients of variation are typical of those in northern Australia.

There is an extreme seasonality in rainfall patterns, with 95 percent (975 mm) of rainfall falling in the wet season between November and May, but also a very high wet season potential evapotranspiration (APET) (1015 mm). The region has a high rainfall intensity (mean >8 mm/rain day), and hence rapid runoff and short lag between rainfall and runoff with a slightly increasing amount and intensity of rainfall over the period from 1930 to 2007. Annually APET (1942 mm) is greater than rainfall (1019 mm) and thus the region is water-limited; in other words there is more energy available to remove water than there is water available to be removed. The region is generally datapoor.

The Daly region has a recent (1996 to 2007) climate record that is statistically significantly wetter than the historical (1930 to 2007) record: recent rainfall was 25 percent higher; runoff was 66 percent higher. It is likely, however, that future (~2030) conditions will be similar to historical conditions; hence, future runoff and recharge is also expected to be similar to historical levels, and lower than the recent past.

There is a strong north–south rainfall gradient producing more runoff (35 percent) towards the estuary and less (3 percent) inland. Lower reaches are flood determined and dominated and estuaries experience significant tidal ranges. There are few opportunities for surface water storage. Mean annual runoff is 159 mm, 15 percent of rainfall. Under the historical climate the mean annual streamflow over the Daly region is estimated to be 8,653 GL.

Groundwater is a dynamic resource, with large seasonal fluctuations in storage, and an intricate interaction with surface waters. The region is flood dependent in the wet and groundwater dependent in the dry. The region has a number of perennial rivers, supporting endemic wildlife and irrigation development. The main aquifers are carbonate-rich and are characterised by karstic features.

Modelled diffuse groundwater recharge has been significantly higher recently than under the historical climate, particularly in the western half of the region. Despite this increase in recharge, median groundwater levels rise by only a maximum of several metres (compared to the historical median) under current development. Groundwater discharge from the Tindall Limestone into the Katherine River is likely to decrease slightly, while discharge from the Oolloo Dolostone to the Daly River and its tributaries is likely to increase. There are strong (>10m) seasonal variations in water table depth.

Under the future climate, mean annual diffuse groundwater recharge is likely to be higher than the historical mean, but median groundwater levels for the Tindall Limestone around Katherine are slightly lower than the historical median levels, due to an expected increase in extraction. This is also reflected in lower groundwater discharge (a decrease of between 14 and 22 GL/year) to rivers under the future (wetter) climate. For the Oolloo Dolostone, however, median groundwater levels are similar to historical values, but discharge to rivers is harder to predict, ranging from a possible increase of up to 60 GL/year to a decrease of 43 GL/year.

At environmental assets, annual surface water flows are highly dominated by wet season events and dry season flows are only a small fraction of total annual flow. Dry season flows, however, are dominated by groundwater discharge, and environmental assets depend on this strong seasonality. Any significant changes in the frequency and duration of wet season high flows and dry season low flows are likely to have an environmental impact. In the recent past there has been significantly more flow, with fewer low flow days and more high flow days. There are no days of zero flow under any scenario at the assets investigated by this project. There are large changes to the high flow threshold exceedance under the wet extreme and dry extreme future climate, which could have negative environmental impacts.

Analysis of site-specific metrics at the Daly River Middle Reaches environmental asset showed no threat to the specified minimum environmental flow requirement for transpiration of riparian vegetation under any scenario. Under the dry extreme future climate, with both current and proposed future development, there is a increase in the mean annual number of days in which flows are below the optimal threshold for nesting success for Pig-Nosed Turtles (*Carettochelys* *insculpta*) and for *Vallisneria nana* beds, suggesting that under such scenarios, the survival of these species is threatened.

DA-1.2 Water resource assessment

Term of Reference 3a

DA-1.2.1 Under historical climate and current development

Term of Reference 3a (i)

Mean annual rainfall for the Daly region is 1019 mm, with a standard deviation of 189 mm. Maximum recorded rainfall was 1640 mm in 1974; the lowest was 498 mm in 1952. Mean annual areal potential evapotranspiration (APET) is 1942 mm, with a relatively small variation (standard deviation of 29 mm). Highest APET occurred in 1998 (2064 mm); lowest in 1945 (1752 mm). Rainfall and runoff generation both decline with distance from the coast but otherwise show little spatial variation.

Based on the rainfall-runoff modelling, the mean annual rainfall and runoff averaged over the modelled Daly region are 1027 mm and 159 mm, respectively. These values fall within the middle of the range of values from the 13 regions. The coefficients of variation of annual rainfall and runoff averaged over the Daly region are 0.22 and 0.69 respectively. These values fall within the middle of the range of values from the 13 regions. The 10^{th} percentile, median and 90^{th} percentile annual runoff values across the Daly region are 314, 135 and 43 mm respectively.

Rainfall is very seasonal, with 95 percent falling during the wet season, and runoff is highest in January and February.

Water availability in the Daly is taken to be at streamflow gauge G8140040. Average surface water availability under the median historical climate is 8184 GL/year. There are no large storages or surface water diversions in the Daly region.

Under a continued historical climate, mean annual diffuse groundwater recharge to unconfined aquifers in the Daly region is likely to be similar to the historical (1930 to 2007) average value. Current groundwater extraction in the region is estimated to be in excess of 30 GL/year (Table DA-1). Groundwater levels, seasonal fluctuations and hence rates of discharge to the Daly River and some of its tributaries are similar to current conditions under a continued historical climate and current levels of development. The only likely change is that the impacts of current groundwater pumping on streamflow in nearby rivers would become more pronounced over time.

Table DA-1. Estimated groundwater contribution (baseflow) to streamflow, modelled diffuse recharge and groundwater extraction for the Daly region under historical climate

Station	River	Station name	Annual BFI *	Dry season BFI *	Dry season baseflow *
					GL
G8140001	Katherine	Railway Br	0.28	0.80	66.2
G8140003	Daly	Police Stn	0.47	0.95	1267.7
G8140008	Fergusson	Old Railway Br	0.16	0.47	1.1
G8140011	Dry	Manbulloo Boundary	0.15	0.13	0.5
G8140040	Daly	Mount Nancar	0.37	0.83	446.2
G8140041	Daly	Gourley	0.36	0.86	294.2
G8140042	Daly	2KM D/S of Beeboom	0.38	0.86	418.3
G8140063	Douglas	D/S Old Douglas H/S	0.36	0.85	14.4
G8140067	Daly	U/S Dorisvale Crossing	0.26	0.77	144.6
G8140152	Edith	Dam Site	0.17	0.64	1.9
G8140158	McAdden Ck	Dam Site	0.17	0.66	0.3
G8140159	Seventeen Mile C	Waterfall View	0.33	0.84	9.6
G8140161	Green Ant Ck	Tipperary	0.29	0.76	4.0
		Historical recharge **	Estimated groundwater extraction		
		GL/y			
Entire Daly region		8,140			>30

* BFI (baseflow index) and baseflow volume derived from gauged data.
** Aggregated region recharge from Zhang and Dawes (1998).

DA-1.2.2 Under recent climate and current development

Term of Reference 3a (ii)

The mean annual rainfall and runoff under the recent (1996 to 2007) climate are 25 percent and 66 percent higher respectively than the historical (1930 to 2007) mean values.

Under the recent climate, mean annual diffuse groundwater recharge is likely to be significantly higher than the historical average value, particularly in the western half of the Daly region. Despite this increase in recharge, median groundwater levels only rise by a maximum of several metres (compared to the historical median) under current development. With current development, groundwater discharge from the Tindall Limestone into the Katherine River is likely to decrease slightly, while discharge from the Oolloo Dolostone to the Daly River and its tributaries is likely to increase. Mean annual groundwater discharge from the Tindall Limestone decreases relative to the historical value despite increased recharge because of a 23-fold increase in extraction between the two simulation periods. Licensed extraction from the Oolloo Dolostone around Daly River is currently less than 60 percent of the volume from the Tindall Limestone around Katherine. Under this extraction regime, an increase in discharge is expected under a recent climate scenario.

DA-1.2.3 Under future climate and current development

Term of Reference 3a (iii)

Rainfall-runoff modelling with climate change projections from five of the GCMs shows a reduction in mean annual runoff, while rainfall-runoff modelling with climate change projections from ten of the GCMs shows an increase in mean annual runoff. Under the high global warming scenario, rainfall-runoff modelling with climate change projections from three of the GCMs indicates a decrease in mean annual runoff greater than 10 percent while rainfall-runoff modelling with climate change projections from four of the GCMs indicates an increase in mean annual runoff greater than 10 percent. Under the wet extreme, median and dry extreme future climate, mean annual runoff increases by 34 and 1 percent and decreases by 29 percent, respectively, relative to the historical climate. By comparison, the range based on the low global warming scenario is a 18 to -17 percent change in mean annual runoff.

Under the median future climate water availability reduces 1 percent.

The climate extremes for 2030 indicate:

- under the wet extreme future climate, water availability increases 32 percent
- under the dry extreme future climate, water availability decreases 32 percent.

Under the future climate, mean annual diffuse groundwater recharge is likely to be significantly higher than the historical average value over most of the region.

DA-1.2.4 Under future climate and future development

Term of Reference 3a (iv)

Although diffuse recharge is likely to increase under the future climate, potential future groundwater development causes median groundwater levels to generally be lower than the historical values at key reporting sites in the main carbonate aquifers. These declines in groundwater level result in significantly reduced groundwater discharge to rivers; on average between 14 and 22 GL/year less discharge would occur from the Tindall Limestone into the Katherine River around Katherine compared to the historical value. The range of possible changes to groundwater discharge from the Oolloo Dolostone under this scenario are far greater, with a mean annual increase of up to 60 GL/year under a wet extreme future climate and a decrease of up to 43 GL/year under a dry extreme future climate. Under a median future climate groundwater discharge decreases by about 9 GL/year.

DA-1.3 Changes to flow regime at environmental assets

Term of Reference 3b

DA-1.3.1 Surface water metrics

Section 1.3 of the division-level Chapter 1 describes how environmental assets were shortlisted for assessment by this project. Three environmental assets were shortlisted for the Daly region: Daly River Middle Reaches, Daly-Reynolds Floodplain-Estuary System, and Katherine Gorge. These assets are characterised in Chapter DA-2.

In deciding whether it is feasible to report hydrological regime metrics for these shortlisted assets, it is important to consider the confidence levels in modelled streamflow (as described in Section 2.2.6 of the division-level Chapter 2). Confidence in results for low flows and high flows was calculated separately. Hydrological regime metrics (as defined in Section 2.5 of the division-level Chapter 2) for either low flows or high flows are reported only where confidence levels are sufficiently high. If confidence in the low flow or high flow is too low, metrics are not reported, and hence an important gap in our knowledge is identified.

Unlike other regions, the Daly region is represented with an existing, calibrated, regional-scale, FEFLOW numerical groundwater flow model coupled to a calibrated MIKE11 surface water model. Confidence in results is sufficiently high to report metrics at all environmental assets.

Annual flow at all three assets is dominated by wet season flow, which has been as much as three times higher than historical levels in the recent past. Dry season flows have been twice the historical flows in the recent past. Future flows are likely to be similar to historical flows, though under the wet extreme future climate, flows are similar to the recent regime. Under a dry extreme future climate, flows are 30 percent lower than historical levels.

Flow continues year-round under all scenarios modelled for all sites. Under all future climate scenarios, low flow and high flow metrics change at each site, but the changes are different at each site and thus it is difficult to summarise as general trends.

Within the Daly-Reynolds Floodplain-Estuary System and Daly River Middle Reaches, the number of days when flow is less than the low flow threshold decreases moderately under future scenarios, but increases in the Katherine River Gorge, moderately under current development, doubling under future development. It should be noted however that the reporting node for Katherine Gorge is 25 km downstream of the gorge itself near the town of Katherine where flows will be affected by local extractions. There are large increases in low flow days under the dry extreme future climate and large decreases under the wet extreme future climate. These increases are accentuated under future development for the area downstream of Katherine Gorge indicating quite severe changes to the hydrological regime due to the development in this scenario, despite the development occurring downstream of the gorge.

Under the recent climate, high flows are more than twice as frequent as under the historical climate at all sites. There is little change in high flow threshold exceedance under the median future climate and current development, though under the wet extreme future climate a large increase is seen at all sites and under the dry extreme future climate a moderate decrease is seen. Under the future climate with future development, all sites show little change relative to the future climate with current development, indicating little additional impact on the hydrological regime as a result of proposed development.

Development appears to have the greatest effect on the low flow regime.

DA-1.3.2 Groundwater metrics

Groundwater metrics can be determined at two of the environmental asset sites: Daly River Middle Reaches and Daly-Reynolds Floodplain-Estuary System. Annual groundwater flow to the river at all asset sites is dominated by dry season flow (65 percent of annual flow), and this has been 35 percent higher under the recent climate than under the historical climate. Wet season flows have been 12 to 17 percent lower recently. There is little modelled change under future scenarios, but under the wet extreme future climate, moderate increases are expected, while small decreases are expected under the dry extreme future climate. With future development, these changes trend to lower flows, due to the additional development.

There is a large increase in the number of days below the low flow threshold under the recent climate and only small changes to the number of days below the low flow threshold under all other scenarios. In the case of groundwater flow the low flow threshold is not necessarily a metric of dry season conditions. In fact, negative groundwater flows occur during the peak of the wet season when surface water flows, and hence the hydraulic head, are high. In this case an increase in the number of days below the low flow threshold indicates wetter conditions under recent climate.

Under the recent climate the high flow threshold is exceeded four times as frequently as under historical conditions. There is only a small change in high flow threshold exceedance under median future climate, while under the wet extreme future climate high flow exceedance increases greatly and under the dry extreme future climate there is a small decrease in high flow days. There is less of an exceedance of the high flow threshold under the wet extreme climate with future development and a decrease in high flow threshold exceedance under the dry extreme climate with future development. These changes indicate additional flow decreases under development scenarios.

Under the recent climate, dry season groundwater depth (metres below soil surface) at the Daly River Middle Reaches decreases by 1.1 m relative to historical levels. Thus, the groundwater will be closer to the surface and these changes would be likely to better sustain groundwater-dependent ecosystems of this floodplain. Very little change in groundwater depth occurs under the median future climate, with moderately shallower groundwater depth (0.7 m closer to the surface) under the wet extreme climate and marginally deeper groundwater depth (0.3 m deeper) under the dry extreme climate. The same changes to groundwater depth were shown under future climate with and without future development, indicating no additional impact on watertable level at this asset with proposed future development.

There were no modelled groundwater depth results for any other assets in this region.

DA-1.3.3 Site-specific metrics

Oolloo Crossing

Within the Daly River Middle Reaches, at Oolloo Crossing, environmental flow metrics have been defined by Erskine et al. (2003; 2004) which relate to habitat suitability for key plant and animal species. The first of these is a threshold of 1.037 GL/day. This is the recommended minimum flow threshold for Pig-Nosed Turtles (*Carettochelys insculpta*) and *Vallisneria nana*. Under the historical climate there is an average of 151 days/year when conditions are below this identified threshold. There is little change to the number of days below the threshold under future climate, with or without future development. This number decreases greatly under recent climate and under the wet extreme future climate. Under the dry extreme future climate there is a significant increase (>30 percent) in the number of days below the identified threshold. These changes would result in a reduction in the number of *V. nana* beds and a decline in the nesting success of the Pig-Nosed Turtle.

The minimum flow requirement to maintain transpiration requirements of riparian vegetation has been reported by Erskine et al. (2003) to be 0.17 GL/day at the Oolloo Crossing gauge. The flow threshold analysis showed that flow levels were maintained above this level under all scenarios, so there is likely to be little or no impact of climate or development on transpiration of riparian vegetation at this asset.

DA-1.4 Seasonality of water resources

Term of Reference 4

Approximately 95 percent of rainfall and 94 percent of runoff occurred during the wet season months under the historical climate. Under recent climate 96 percent of rainfall and 85 percent of runoff occurred during the wet season months. Under future climate in 2030 it is estimated that 96 percent of rainfall and 94 percent of runoff occurs during the wet season months. Runoff is highest in February and March.

The Daly region experiences significant dry season streamflow (6 percent of annual flow), indicating the river is gaining from groundwater discharge. The level of use expressed as a percentage of dry season flow is 12 percent use under current conditions, possibly increasing to over 20 percent under future development scenarios.

DA-1.5 Surface–groundwater interaction

Term of Reference 4

The main aquifers in the Daly region extend beyond the boundaries of the Daly River catchment, and hence beyond the boundaries of the Daly region. Small quantities of groundwater, therefore, flow across the boundaries of the Daly region. Over most of the catchment, inflows will balance the outflows and the net impact will not be significant. The only exception is the aquifer system that provides the source of dry season flow in the Flora River. Approximately 50 percent of the groundwater-fed flow in the Flora River is sourced from recharge outside the Daly region. This recharge occurs within the Daly and Wiso basins to the south.

Small springs occur throughout the region, often providing low flow (<10 L/second) for much of the year. Many springs cease-to-flow early in the dry season. These springs often drain a very small area (less than 10 km^2) and, while they may be ecologically significant, are outside the scope of this discussion.

Data on reaches of rivers where significant groundwater discharges occur are given in Figure DA-3. These are indicated by instantaneous flow rates measured for various locations in the Daly River catchment towards the end of the dry season (Figure DA-2). The data show that flow at these locations occurs regardless of the previous season's flow or rainfall. That is, flow will occur after a series of below average, average or above average wet seasons. These flows are sustained by significant regional groundwater discharges from karstic aquifers developed in the Tindall Limestone and the Oolloo Dolostone (Figure DA-2).

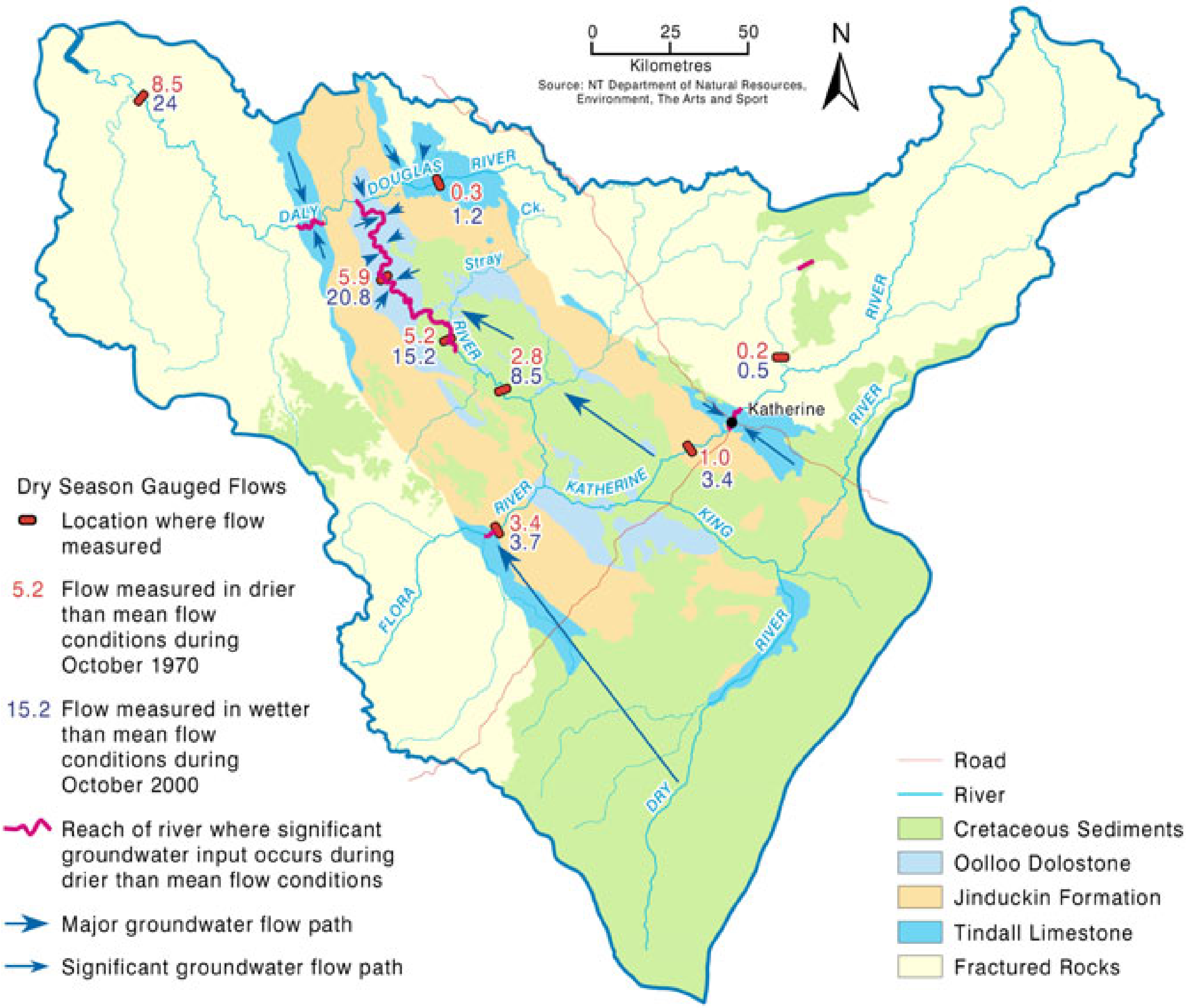


Figure DA-2. Hydrogeology of the Daly region showing reaches of rivers where significant groundwater input occurs (derived from map provided by NRETAS, 2009)

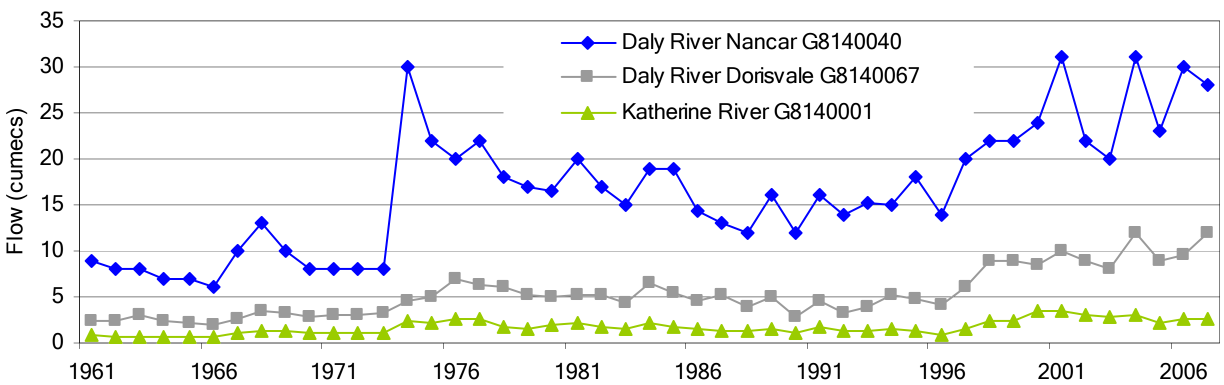


Figure DA-3. Discharge at gauging stations G8140001, G8140067 and G8140040 in the Daly Region for each year of record

DA-1.6 Water storage options

Term of Reference 5

DA-1.6.1 Surface water storages

There is currently no significant (>250 ML) surface water storage within the catchment.

DA-1.6.2 Groundwater storages

In the Daly region sites that might be investigated for a managed aquifer recharge (MAR) scheme would include the upper reaches of the King River, treating it and then injecting it into the Tindall Limestone aquifer and adjacent to the Katherine River in the vicinity of its junction with the King River. The targeted aquifer in both cases would be the Oolloo Dolostone, and the location would be in areas where there is capacity for artificial storage in the aquifer at the end of each wet season.

DA-1.7 Data gaps

Term of Reference 1e

Relative to other regions in the Timor Sea Drainage Division there are a large number of streamflow gauging stations with good quality data in the Daly. However, these stations tend to be concentrated in the northern half of the Daly region. To the south of the Daly River there are relatively few good quality stations and consequently the spatial distribution of runoff in these areas is relatively low.

Diffuse groundwater recharge is estimated through modelling. Validation of recharge for different soils, vegetation types and climate regimes requires field validation. Total water flux measurements are currently underway in the Daly region (Hutley et al., 2008), but are limited in spatial extent. Ongoing measurements are required across a broad range of landscapes.

Groundwater monitoring bores are concentrated along the Daly River. There are few bores in the north-east, or south of the region. This includes the region of the important Oolloo Dolostone and is a limitation on the development of the Oolloo Dolostone groundwater model.

The lack of metered groundwater extraction data for irrigated agriculture is a limitation of the existing groundwater model for the Tindall Limestone.

DA-1.8 Knowledge gaps

Term of Reference 1e

Applying rainfall-runoff models in the dolomitic limestone environments like the Daly catchment can be problematic where there are good connections between the surface and groundwater systems and water can bypass gauging stations, thus violating model assumptions (unless the modifications to the model structure have been made). It is also problematic in areas like the Dry River where the undefined nature of the flow regime, in some parts of the catchment, means that more runoff may be generated than is measured at the gauge. This is evident by the considerably lower measured runoff in the Dry River as compared to neighbouring regions.

The major aquifers in the region are the Tindall Limestone and Oolloo Dolostone. These aquifers are the targets for sourcing water for large-scale irrigated agricultural developments. They are also the source of dry season flows for the Katherine, Flora, Douglas and Daly rivers. An aquifer simulation model exists for these aquifers. However work is required to address the following weaknesses in the model:

- While recharge is currently assumed to be diffuse in the model, bypass flow via macropores/sinkholes is known to be a dominant recharge mechanism. The importance of this mechanism should to be quantified.
- The Cretaceous sediments unconformably overlie the Tindall Limestone and Oolloo Dolostone over most of the Daly Basin. The occurrence of the sediments is known to significantly reduce recharge to aquifers in the Tindall Limestone and Oolloo Dolostone. More work is required to quantify this reduction.

- Groundwater discharge from the Cretaceous sediments – above ground to Seventeen Mile Creek and below ground to the Tindall Limestone in the headwaters of the King River – is believed to be the source of most of the dry season flow to the Katherine River during very dry periods. More work is required to model the groundwater processes at these locations.

The presence or absence of the Cretaceous sediments has a large impact on recharge to the karstic carbonate aquifers. Recharge via sinkholes to these karstic aquifers is important but has not yet been quantified. More work is required to understand this important recharge process and determine how it can be effectively incorporated into existing and future groundwater models.

Better quantification of river–aquifer interactions is required, particularly with respect to the flows from the river to the groundwater system.

The dry season flow characteristics of the Flora River should be determined. The Flora River provides most of the dry season flow in the upper reaches of the Daly River during very dry periods. However the quality of the dry season flow data at the gauge on this river is very poor.

Environmental thresholds are necessary for habitats in addition to the Daly River Middle Reaches. None of the other environmental assets in this region have any site-specific metrics by which to gauge the potential impacts of future climate change and development. In the absence of site-specific metrics a set of standard metrics related to high and low flows have been utilised. However, the conversion of these metrics into environmental impacts still requires development of quantitative relationships between flow and specific ecological entities (for example, macrophyte populations, fish passage, faunal and floral habitats, etc.).

Flooding is an important factor that sustains many environmental assets and this occurs when the stream breaks out of its banks (a level known as bankfull stage or discharge). However, bankfull discharge is not known for many streams, nor is the dependence of area flooded on increasing stream depth, so it is difficult to predict when assets are inundated. Further information about bankfull stage and discharge are needed for most environmental assets.

Dry season flows are poorly understood in this region therefore the ability to predict the potential impacts of climate and development on low or zero flows at environmental assets is very limited. Improved monitoring of low streamflow conditions is needed along with the development of hydrological models that combine surface and groundwater regimes. Further monitoring of groundwater levels is also required so that the potential impacts of climate change and development on groundwater-dependent ecosystems can be better understood.

Many environmental assets depend not simply on duration above or below certain flow levels, but on triggers (e.g. for reproduction or migration) set by the rate of change of flow. In addition, some environmental assets depend on the frequency and duration of events that occur less than annually (i.e. once every 5, 10 or 20 years or more). Further analysis is therefore required to look at how the timing, duration and rate of rise and fall in flow rates at critical times of the season will vary under the various scenarios.

DA-1.9 References

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DA-2 Contextual information for the Daly region

This chapter summarises the background information for the region, outlining existing knowledge of water resources and prior and current investigations relevant to the water resources of the region. This chapter also outlines the current and potential future legislation, water plans and other water resource management arrangements. This chapter is arranged into four sections:

- overview of the region: physical and climate descriptions
- data availability
- hydrogeology
- legislation, water plans and other arrangements.

DA-2.1 Overview of the region

DA-2.1.1 Geography and geology

A variety of Precambrian (older than 500 million years) rocks form the bedrock of the area (Figure DA-4). These are mainly sedimentary but also include granite and volcanic rocks. Sandstone, siltstone and greywacke are the main sedimentary rock types. In some areas they are flat-lying while in other areas they have been folded, faulted and show low grade metamorphism.

In the Early Cambrian (500 million years ago) volcanic eruptions produced an extensive sheet of basalt flows, now known as the Antrim Plateau Volcanics. These cover a large portion of the project area, particularly south of Katherine. Soon after the out-flowing of basalt, the area now known as the Daly Basin (Figure DA-5) began to subside. A shallow sea formed and a sequence of dominantly carbonate rocks accumulated between about 500 and 450 million years ago.

Once the sea retreated there was a long period when erosion dominated and no deposition occurred. It was not until the Early Cretaceous (120 million years ago) that the sea again encroached on the area, depositing a sheet of clay and sand. That period was short lived and erosion again dominated until the present day. The only exception is a narrow and discontinuous alluvial plain along the Daly and Katherine rivers where sand, silt and clay have accumulated in recent times.

The current drainage system probably came into existence in the Cretaceous when uplift across northern Australia resulted in a drainage divide between inland draining streams to the south and streams draining to the sea in the north. The Daly River flows from the foothills of Arnhem Land, 320 km north-west into the Timor Sea at Anson Bay, although estuarine conditions exist for the last 65 km where the river leaves the elevated land of Mount Haywood, Mount Boulder and Mount Nancar.

The Daly River is one of the largest perennial rivers of northern Australia, with a catchment area of just over 53,000 km^2. Dry season flow is dominated by input from groundwater from two underlying limestone aquifers which have an intervening siltstone aquitard. The catchment contains a number of important rivers, including the Katherine, Flora, Edith and Douglas rivers, which have tourism and conservation value.

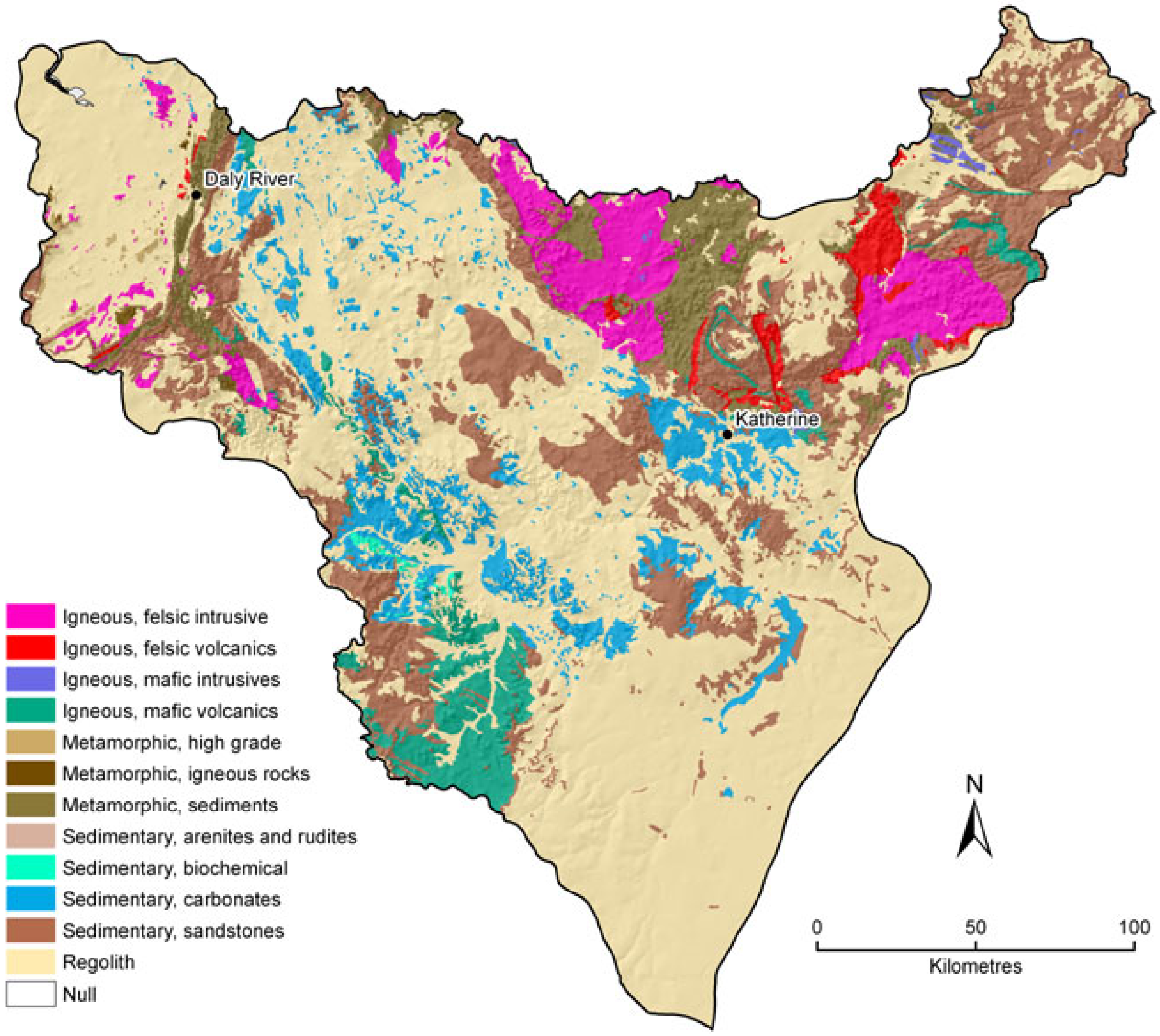


Figure DA-4. Surface geology of the Daly region overlaid on a relative relief surface

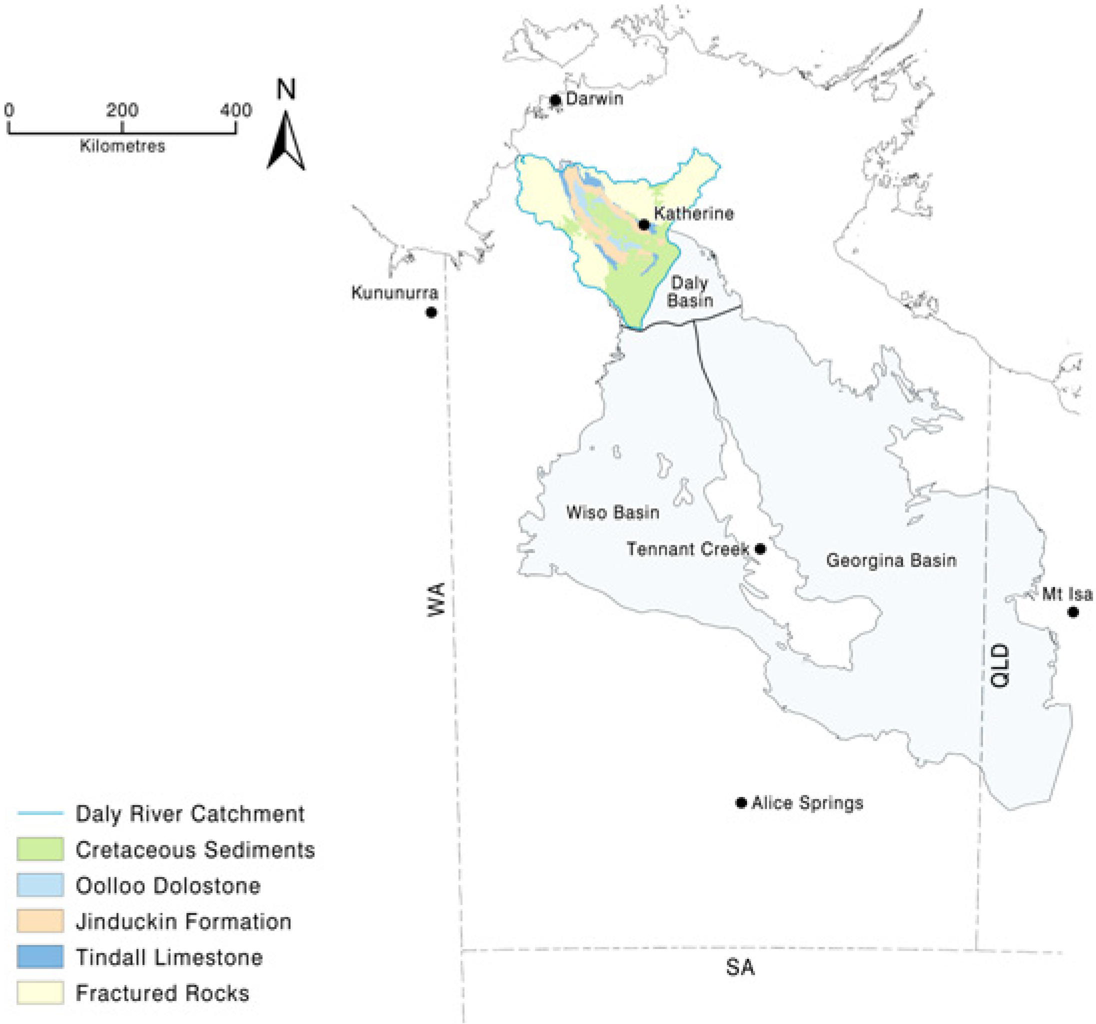
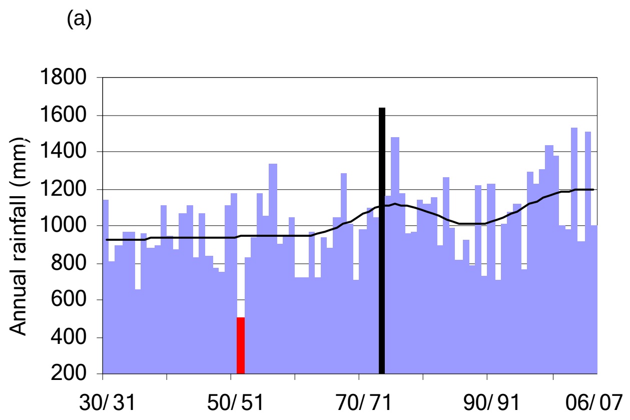


Figure DA-5. Location of Daly, Wiso and Georgina basins (modified from map supplied by the Northern Territory Department of Natural Resources, Environment, The Arts and Sport)

DA-2.1.2 Climate, vegetation and land use

The Daly region receives an average of 1020 mm of rainfall over the September to August water year, most of which (975 mm) falls in the November to April wet season. Across the region there is a north–south gradient in annual rainfall, ranging from 1485 mm in the north to 670 mm in the south. Annual rainfall has been steadily increasing throughout the historical (1930 to 2007) period, from an average of around 560 mm to 1230 mm. The highest yearly rainfall received was 1640 mm which fell in 1974, and the lowest was 500 mm in 1952.

Areal potential evapotranspiration (APET) is very high across the region, averaging 1940 mm over a water year, and varies little across the seasons. APET is higher than rainfall throughout most of the year, resulting in almost year-round water-limited conditions. From January until March, however, conditions may be energy-limited, meaning rainfall has relatively less effect on actual evapotranspiration rates. The vegetation of the region has adapted to such cyclical variations in moisture availability.



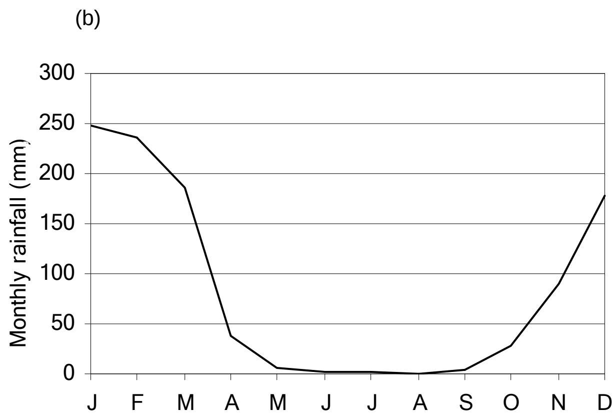


Figure DA-6. Historical (a) annual and (b) mean monthly rainfall averaged over the Daly region The low-frequency smoothed line in (a) indicates the longer term variability

The region is characterised by extensive open eucalypt woodlands (Figure DA-7), dominated by Northern Box (*E. tectifica*) and Round-Leaved Bloodwood (*E. latifolia*) with sorghum grassland understorey.

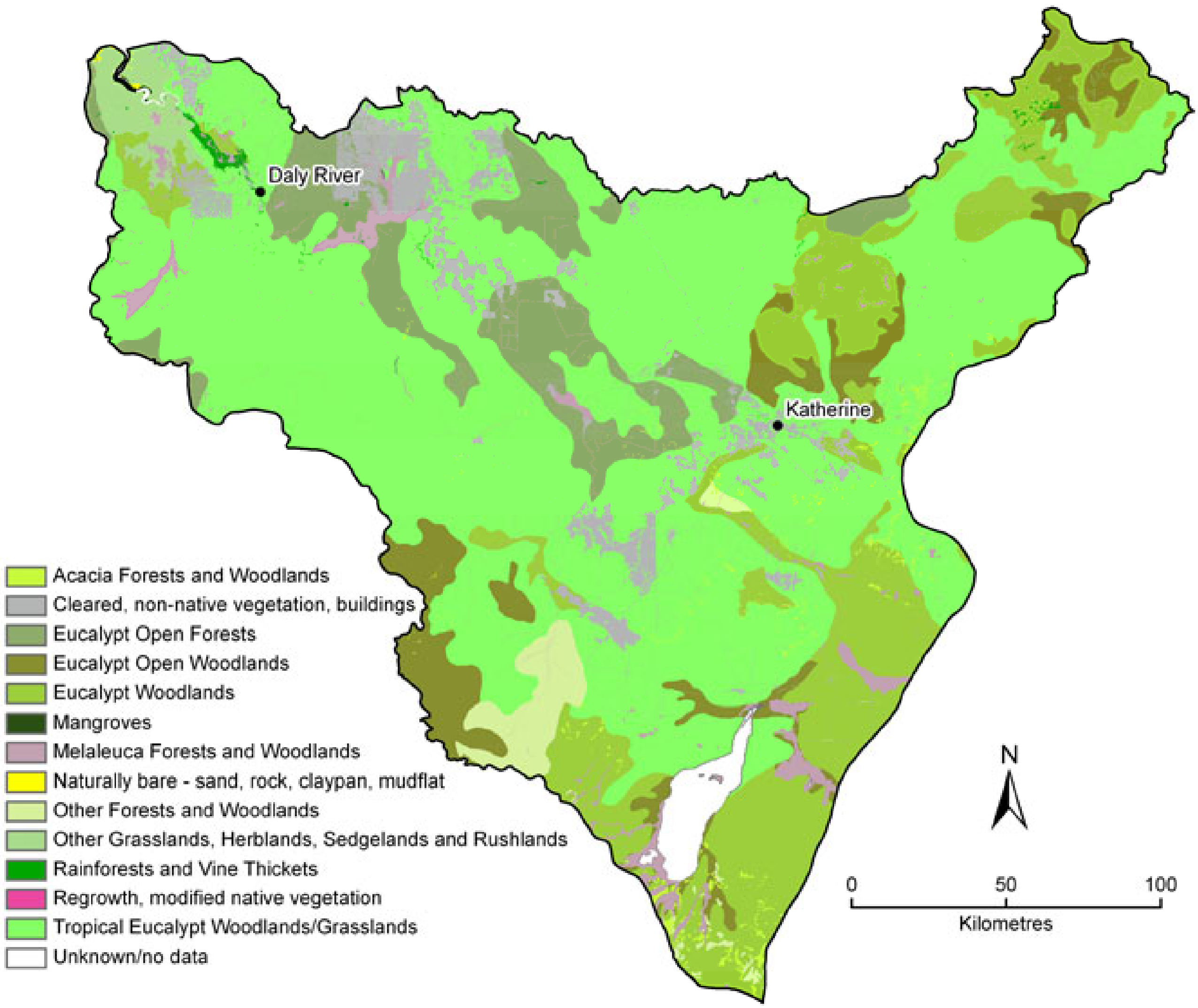


Figure DA-7. Map of current vegetation types across the Daly region (source DEWR, 2005)

The region was first explored by Europeans in 1865, and underwent initial development due to discovery of copper in 1883 and discovery of gold during the construction of the overland telegraph between Adelaide and Darwin. Activity waned in the 1900s, but pastoralism took over and the region now supports extensive grazing lands and local peanut and tobacco farming. Across the region, less than 0.4 percent is currently under intensive agriculture. Currently land clearing for the catchment downstream of Katherine is restricted and continuously reviewed. Significant areas are under perpetual pastoral lease, crown lease reserve and Indigenous land (Figure DA-8).

The only towns in the Daly River catchment are Katherine, Pine Creek and Naiyu (Daly River), and the total population living within the catchment is less than 10,000. The main activity is operation of the Royal Australian Air Force Base at Tindall, near Katherine. Irrigation is becoming increasingly important. Other activities include tourism, mining and grazing.

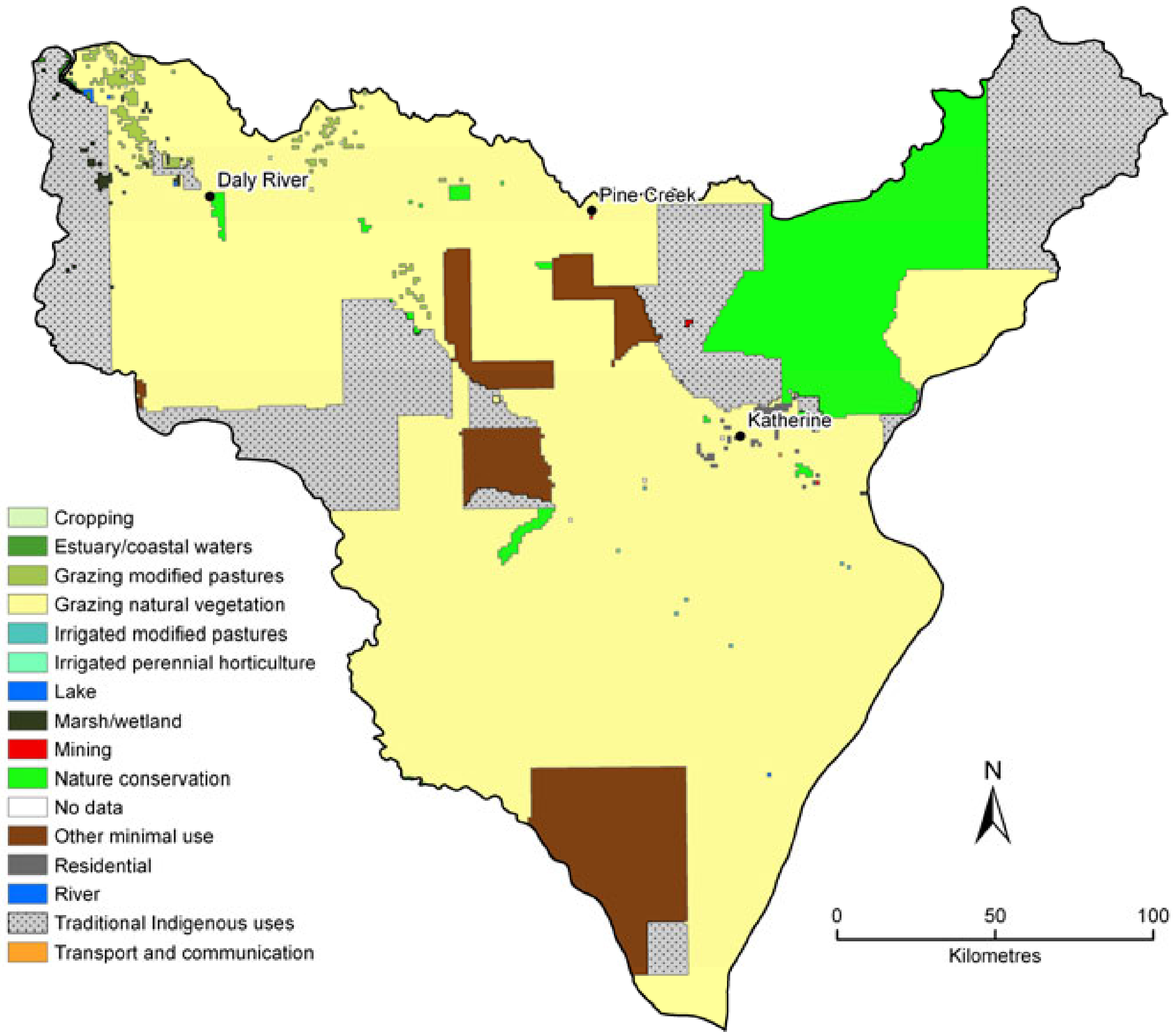


Figure DA-8. Map of dominant land uses of the Daly region (after BRS, 2002)

DA-2.1.3 Regional environmental asset description

Environmental assets were chosen from wetlands which are listed in the Directory of Important Wetlands in Australia (Environment Australia, 2001). From this directory, environmental assets were shortlisted for assessing changes to the hydrological regime under the climate and development scenarios. The selection of this shortlist was undertaken in consultation with state governments and the Federal Government through direct discussions and through internal reviews (see Section 1.3 in the division-level Chapter 1 for further detail).

All nationally, or internationally, important wetlands listed for the Daly region in the Directory of Important Wetlands in Australia (Environment Australia, 2001) are detailed in Table DA-2, with asterisks identifying the three shortlisted assets: Daly River Middle Reaches, Daly-Reynolds, Floodplain-Estuary System, and Katherine Gorge. The location of these shortlisted wetlands is shown in Figure DA-1. There are no wetlands classified as Ramsar sites in this region. Wetlands may be nationally or regionally significant depending on more locally specific criteria. All wetlands are important for a variety of ecological reasons or because they bear historical significance or have high cultural value, particularly to Indigenous people.

The following section characterises these shortlisted wetlands and is based largely on the description of these assets as outlined by Environment Australia (2001). Chapter DA-3 presents the assessment of those shortlisted assets, and reports hydrological regime metrics for those assets which have sufficient confidence in the modelled streamflow to enable analysis.

Table DA-2. List of Wetlands of National Significance located within the Daly region

Site code	Name	Area	Ramsar site
		ha	
NT001 *	Daly River Middle Reaches	1,470	No
NT024 *	Daly-Reynolds Floodplain-Estuary System	159,000	No
NT018 *	Katherine River Gorge	354	No

* Asset has been selected for detailed reporting.

Daly River Middle Reaches

The Daly River system has been identified as being of national significance due to a range of aquatic environmental assets (Begg et al., 2001; Blanch, 2005; Erskine et al., 2003). The river is perennial and has the highest baseflow of all the rivers in the Northern Territory due to discharge from limestone aquifers. These hydrological characteristics have led to some very significant environmental assets, particularly in the middle reaches of the Daly River. The Daly River Middle Reaches includes the reaches of the Daly River from the junction of Stray Creek (upstream of Oolloo Crossing) downstream to Daly River (Policeman's) Crossing. The asset as defined by Environment Australia (2001) includes the main channel and billabongs and swamps within 1 km of the channel (Figure DA-10).

The river reach is permanent and billabongs are generally seasonal except for deeper channels. During the wet season, floodwaters sometimes extend 1 to 2 km from the main channel. The Daly River Middle Reaches are a major breeding and dry season habitat for Freshwater Turtles (five species, notably the Pig-Nosed Turtle (*Carettochelys insculpta*) (Figure DA-9), fishes, and Freshwater Crocodile. Also found in this area are rare species of shark and sawfish (Blanch, 2005; Erskine et al., 2003). The Daly River Middle Reaches include many popular destinations for recreational fishing, swimming, boating and camping.

Figure DA-9. Pig-nosed turtle (*Carettochelys insculpta*)

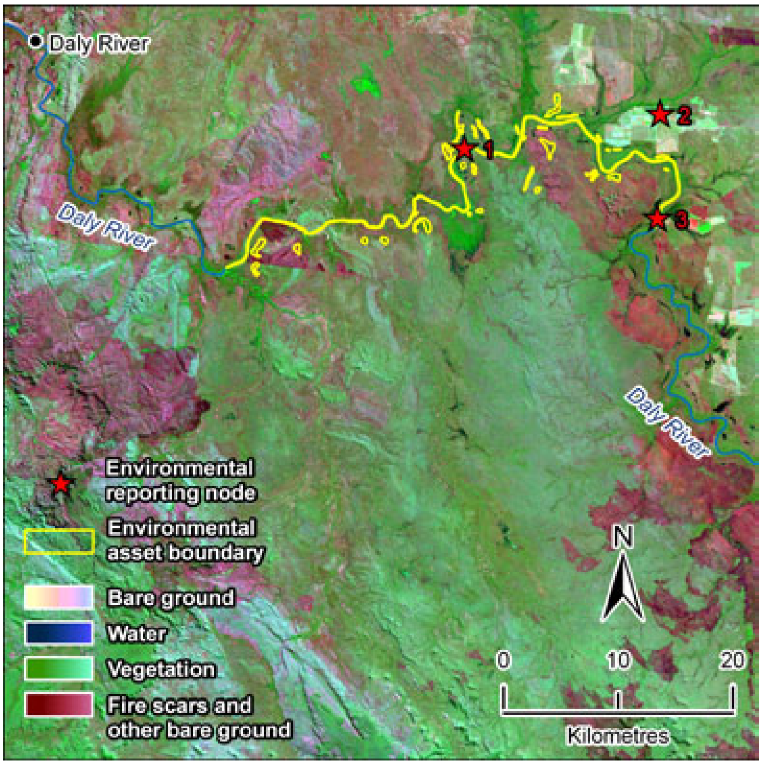


Figure DA-10. False colour satellite image of Daly River Middle Reaches (source ACRES, 2000). Clouds may be visible in image

Daly-Reynolds Floodplain-Estuary System

The Daly-Reynolds Floodplain-Estuary system covers an area of 1590 km^2 and includes the entire floodplain and estuary of the Daly River (Figure DA-11). The system represents one of the largest floodplains in the Northern Territory and it contains a diverse mixture of wetland types (van Dam et al., 2008). These include estuarine mudflats, marshes and mangroves as well as freshwater wetlands and seasonally flooded swamps and forests. A more comprehensive description of the major wetland types in the Daly Basin is given by Begg et al. (2001). The Daly's estuary and lower floodplain wetlands support a number of significant waterbird breeding sites. For example (Blanch, 2005) report that the area is the most significant place for waterbirds between Darwin and the Moyle River, containing 14 feeding and six breeding sites that can host over 30,000 waterbirds in a single season. There are also numerous species of freshwater and estuarine fish (48 species compared to 33 for the whole Murray-Darling Basin, which has an area 19 times larger than the Daly Basin) and it is considered the best barramundi fishing river in Australia (Blanch, 2005). The river also has important marine influence, since its discharge to the Timor Sea is the second highest of any Australian river.

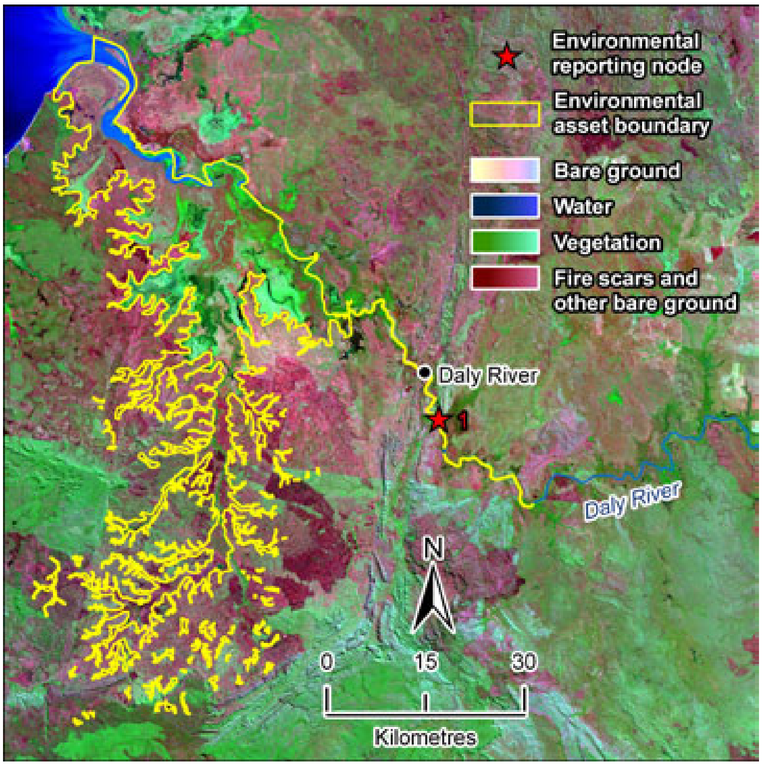


Figure DA-11. False colour satellite image of the Daly-Reynolds Floodplain-Estuary System (source: ACRES, 2000). Clouds may be visible in image

Katherine River Gorge

The Katherine River flows into the Daly River near Claravale and contributes approximately 40 percent to the mean annual flow of the Daly River (Begg et al., 2001). The Katherine River basin has the second highest number of wetlands in the Daly Basin and also contains the Katherine River Gorge (Figure DA-12) which is listed as one of the Nationally Important Wetlands in Australia. Katherine Gorge has near-vertical rock walls and is a major dry season refuge for aquatic fauna, particularly fish, freshwater crocodiles and turtles. Katherine Gorge is located within the Nitmiluk National Park and is the site of significant Indigenous rock art; two major sites (Barraway and Gunbokmo) occur in the gorge. The permanent waters were and are often frequented by Indigenous people. The national park is an immensely popular national and international tourist destination and visitor use of the gorge generates substantial income in the Katherine area. Canoeing, swimming, camping and fishing are permitted in parts of the gorge system. The gorge has spectacular sheer rock faces more than 50 m high along much of its length; these contrast markedly with the still deep waters, plunging waterfalls (in wet season), riverside greenery and abundant (mostly arboreal) bird-life.

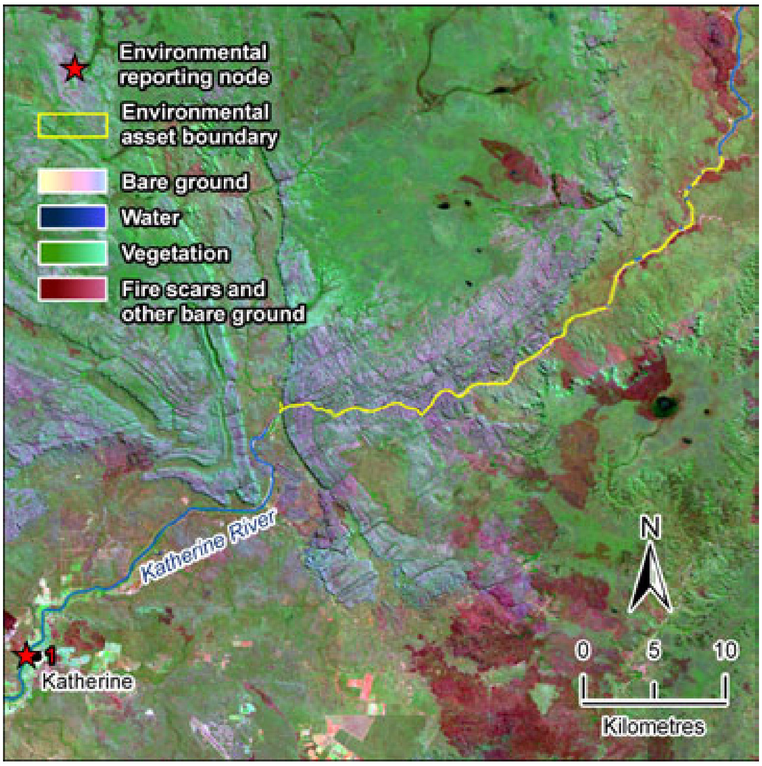


Figure DA-12. False colour satellite image of the Katherine River Gorge (source ACRES, 2000). Clouds may be visible in image

Aquatic reptiles occurring at the site include Freshwater Crocodile, Freshwater Snake and turtles. Twenty frog species have been recorded in the national park. A rich fish fauna exists; fishes which may be found in Katherine River based on literature and Northern Territory Museum collection records number 46 species.

DA-2.2 Data availability

DA-2.2.1 Climate

The rainfall-runoff modelling uses historical daily climate data (Scenario A) from the SILO database for the period 1 September 1930 to 31 August 2007 at 0.05 x 0.05 degree (~ 5 x 5 km) grid cells. Full details and characterisation of the SILO database are provided at the division level in Section 2.1 of Chapter 2. Scenario B and Scenario C climate data are rescaled versions of the Scenario A data; this is also discussed in Section 2.1 of Chapter 2.

DA-2.2.2 Surface water

Streamflow gauging stations are or have been located at 32 locations within the Daly region. Seventeen of these gauging stations either (i) are flood warning stations and measure stage height only; or (ii) have less than ten years of measured data. Of the remaining stations, two recorded more than half of their total volume of flow during events that exceed the maximum gauged stage height (MGSH). Gauge G8140040, located within a natural constriction in the lower reaches of the Daly, gauges an area of approximately 47,100 km^2. This gauge provides high quality measurements on the volume of water being discharged from the Daly catchment. Interpreting low flow measurements in reaches that flow through carbonate rock can be confounded by the build up of tufa dams during the dry season and their occasional breakdown during the wet season. There is no instream dam or notable river extraction in the Daly and consequently all gauging stations are considered unimpeded.

There are 16 gauging stations currently operating in the Daly region at a density of one gauge for every 3,400 km^2. For the 13 regions the median number of currently operating gauging stations per region is 12 and the median density of current gauging stations per region is one gauge for every 9700 km^2. Although the Daly region has a high density of current gauging stations relative to other regions in northern Australia, the density is low relative to the MDB average. The mean density of current stream gauging stations across the entire MDB is one gauge for every 1,300 km^2.

In Figure DA-13 the productive aquifer layer for the Northern Territory includes key dolostone and limestone formations and Cretaceous sandstone formations. Consequently these productive aquifers exhibit a wide range of bore yields.

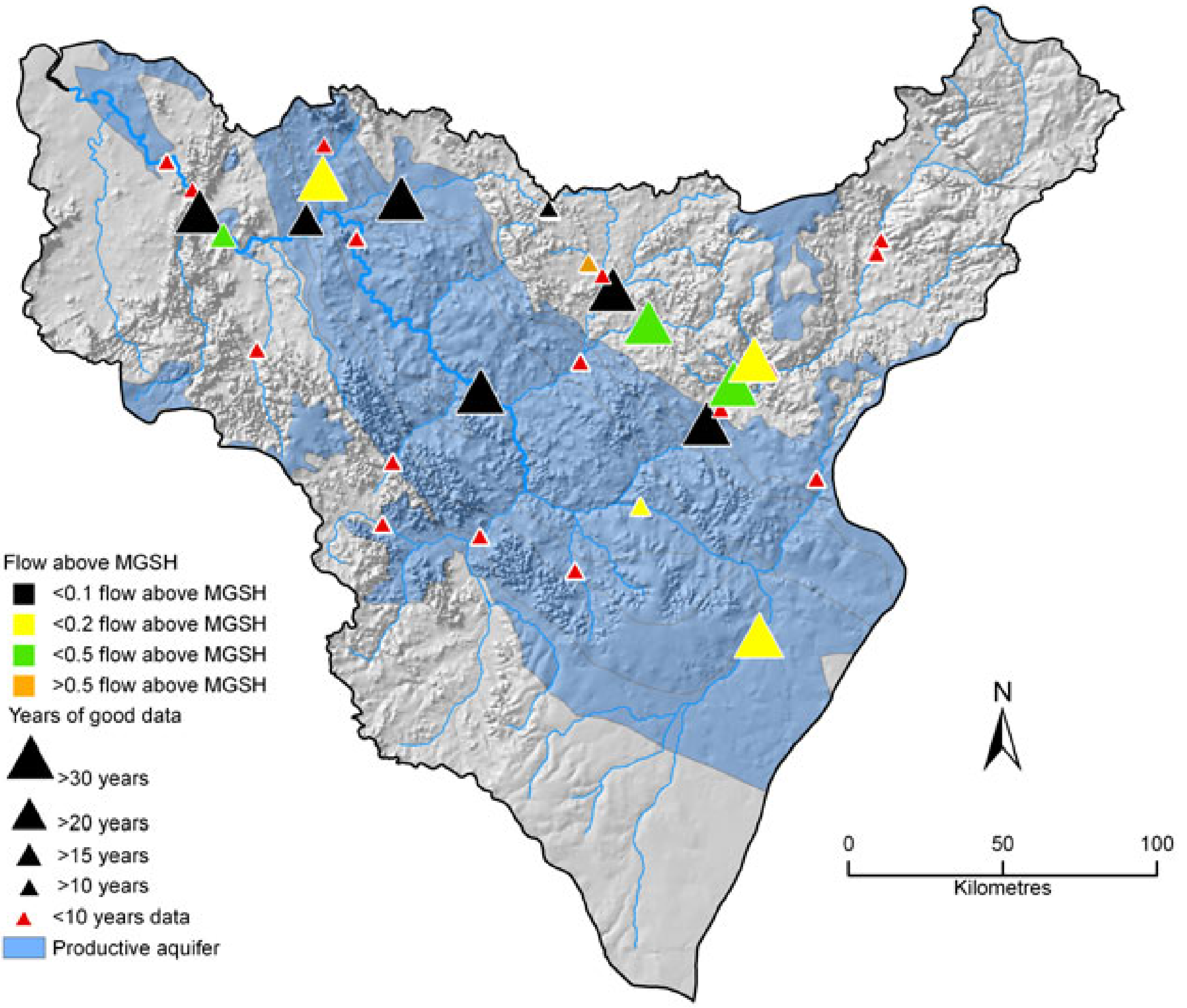


Figure DA-13. Location of streamflow gauging stations overlaid on a relative relief surface showing the proportion of gauges with flow above maximum gauged stage height across the Daly region. Productive aquifer layer includes key dolostone, limestone and Cretaceous sandstone formations

DA-2.2.3 Groundwater

The Daly region contains a total 2188 registered groundwater bores. 166 of these bores have surveyed elevations that could enable watertable surfaces to be constructed for the main aquifers. However these bores are not necessarily monitored on a regular basis. There are 173 water level monitoring bores in the region; 92 are historical and 81 are current (Figure DA-14).

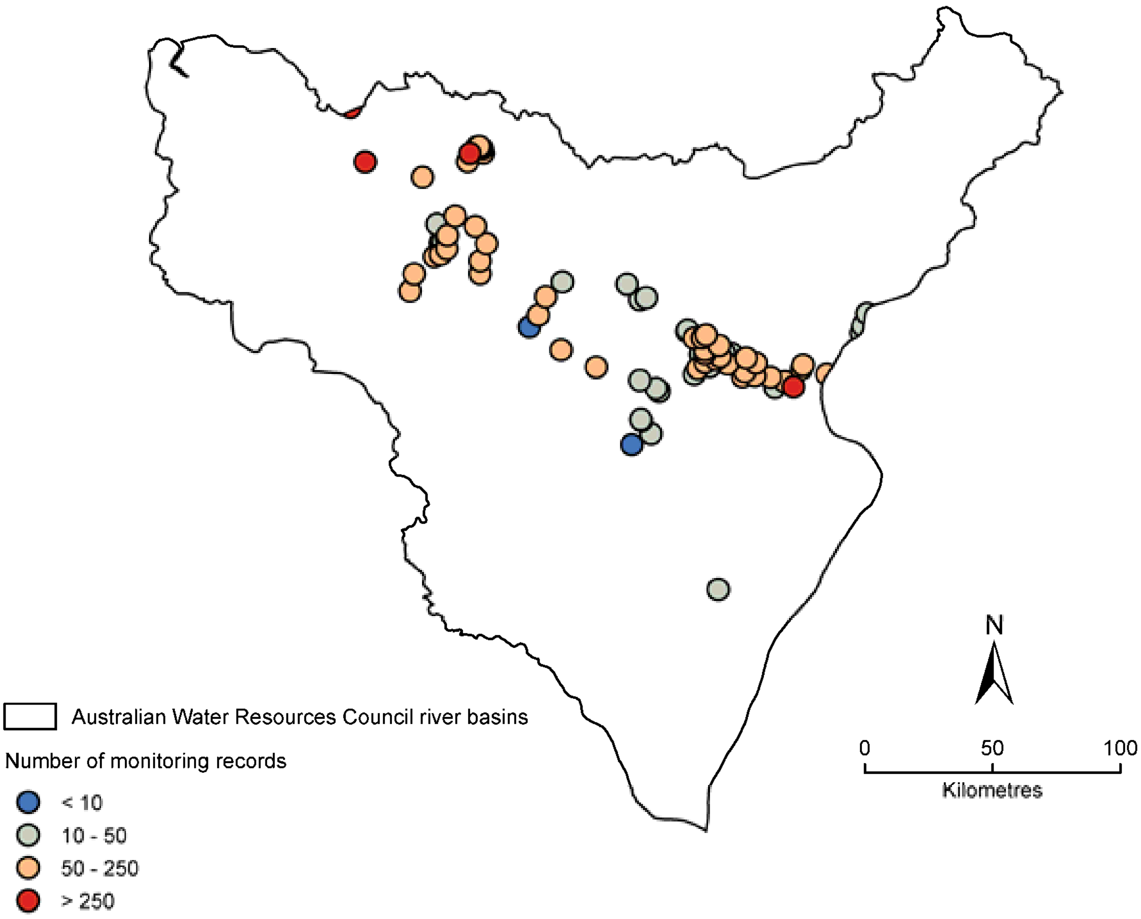


Figure DA-14. Current groundwater monitoring bores in the Daly region

DA-2.2.4 Data gaps

The lack of metered groundwater extraction data for irrigated agriculture is a limitation of the existing groundwater model for the Tindall Limestone.

DA-2.3 Hydrogeology

This section describes the key sources of groundwater in the Daly region. The description is primarily based on reports and water bore data held by the Northern Territory Department of Natural Resources, Environment, The Arts and Sport (NRETAS). Maps in this section were modified from data provided by NRETAS. The distribution of groundwater bores in the region in 2004 is shown on Figure DA-15.

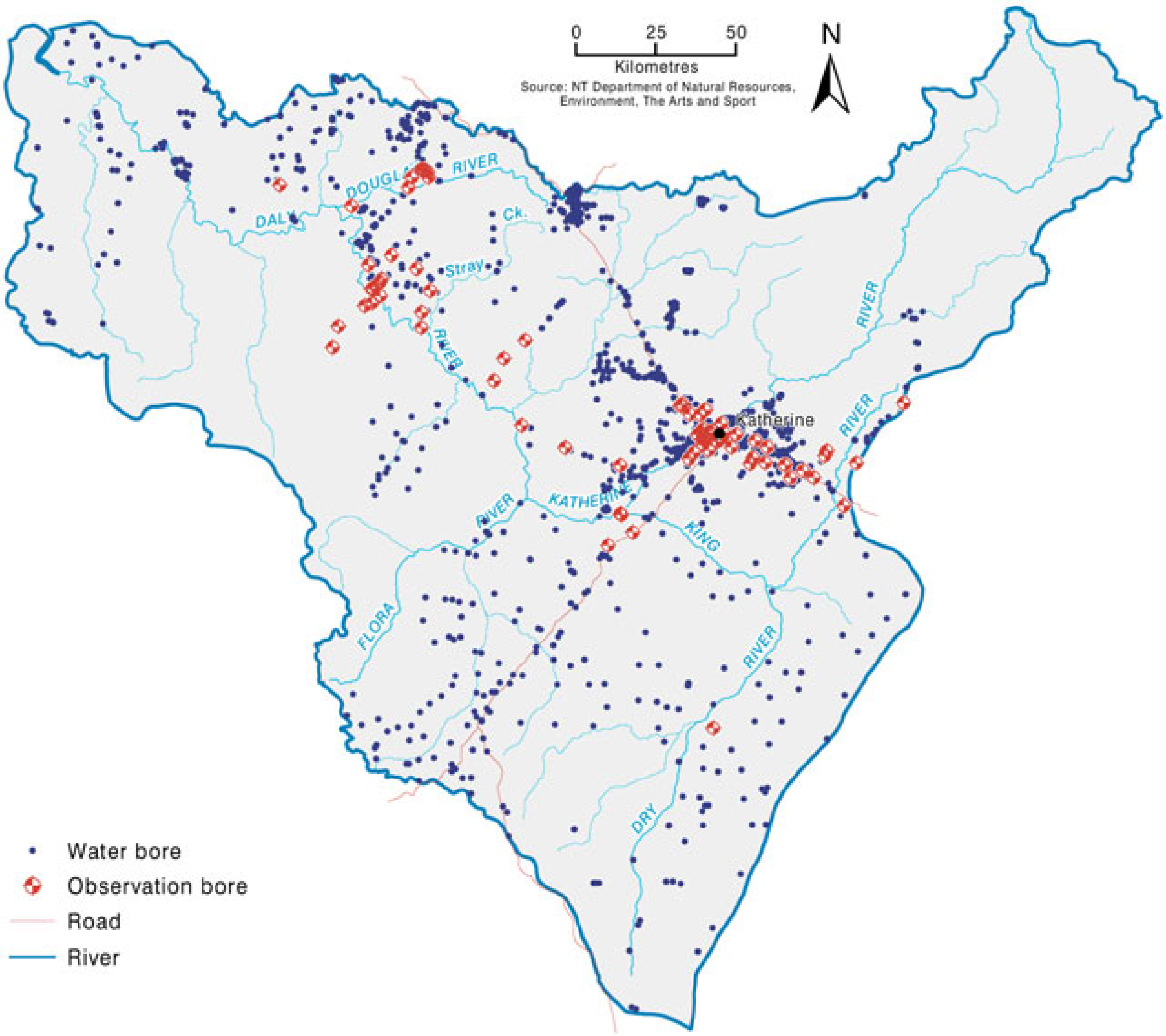


Figure DA-15. Location of groundwater bores in the Daly region (map provided by NRETAS, 2009)

DA-2.3.1 Aquifer types

There are three major aquifer types in the Daly River catchment: fractured bedrock, karstic carbonate rocks and Cretaceous sediments. These types are briefly described below and their areal extent is shown in Figure DA-2.

Fractured rocks

A variety of Precambrian (older than 500 million years) rocks form the bedrock of the area. These are mainly sedimentary but also include granite and volcanic rocks. Sandstone, siltstone and greywacke are the main sedimentary rock types. In some areas they are flat-lying while in other areas they have been folded, faulted and show low grade metamorphism. They form minor aquifers in the region.

In the Early Cambrian (500 million years ago) volcanic eruptions produced an extensive sheet of basalt flows, now known as the Antrim Plateau Volcanics. These cover a large portion of the project area, particularly south of Katherine.

Karstic carbonate rock – Tindall Limestone, Jinduckin Formation and Oolloo Dolostone

The major aquifers in the region occur within the carbonate rocks of the Daly Basin. These carbonate rocks are part of an extensive area of carbonate rocks that extend across a large part of the Northern Territory and into Queensland (Figure DA-2). The Tindall Limestone and the Oolloo Dolostone host widespread karstic aquifers. These aquifers have very high permeabilities due to an extensive network of interconnected solution cavities. The Jinduckin Formation is mainly composed of siltstone. The formation contains thin, local aquifers in isolated limestone beds.

Lauritzen and Karp (1993) concluded that the Tindall Limestone karst aquifer developed before the Cretaceous period. The permeability of the karst aquifer has been further enhanced since then by the movement of acidic groundwater from the aquifer developed in the basal Cretaceous sandstone where it overlies the limestone. It is believed that the karst aquifer in the Oolloo Dolostone developed in a similar way.

The Tindall Limestone karst aquifer is the main contributor to baseflow in the Katherine and Flora rivers. The Cretaceous Sandstone aquifer contributes a small but significant baseflow to the upper reaches of the Katherine River. The Oolloo Dolostone karst aquifer is the main contributor to baseflow in the Daly River. The Tindall Limestone karst aquifer contributes a small but significant baseflow to the Douglas River and the lower reaches of the Daly River. These two aquifers are also the aquifers of most interest to irrigators as they occur beneath land suitable for irrigation and can yield high flow rates (greater than 50 L/sec per bore) from relatively shallow depths.

Cretaceous sediments

A sheet of predominantly sandy sediments overlain by a layer of predominantly clayey sediments constitute shallow aquifers that can be locally important sources for dry season discharge to rivers (Skwarko, 1966). Above these, a narrow and discontinuous alluvial plain of sand, silt and clay has accumulated along the Daly and Katherine rivers since the end of the last ice age.

DA-2.3.2 Inter-aquifer connection and leakage

The major aquifers in the region, the Tindall Limestone and the Oolloo Dolostone, are not in hydraulic connection because they are separated by the Jinduckin Formation which is mainly composed of siltstone (refer Figure DA-2). This lack of connection has been confirmed by water quality data obtained from bores that have intersected the confined aquifer in the upper unit of the Tindall Limestone that occurs beneath the Jinduckin Formation. The salinity of the water from the high yielding confined Tindall Limestone aquifer is much lower than that of the low yielding aquifers intersected in the Jinduckin Formation.

The Tindall Limestone and the Oolloo Dolostone, however, are in hydraulic connection with the aquifer developed in the basal sandstone of the Cretaceous sediments. This connection is believed to be particularly important adjacent to the upper reaches of the King River where it is believed that subsurface discharge from the Cretaceous sandstone aquifer into the Tindall karst aquifer maintains a significant proportion of dry season flow into the Katherine River during extended dry period such as occurred in the 1960s and early 1970s (Yin Foo, 1985).

DA-2.3.3 Recharge, discharge and groundwater storage

Recharge occurs only in the wet season when rainfall intensity and duration is sufficient. Recharge leads to a rise in groundwater levels. In the dry season the levels fall as groundwater is either transpired or discharged to wetlands and rivers where it evaporates or is discharged to the sea. The amount and rate at which the groundwater levels rise and fall depend on the type, size and other physical properties of the aquifer, as well as the amount of recharge. The recharge-discharge cycle that applies in the Daly River catchment is summarised in Figure DA-16.

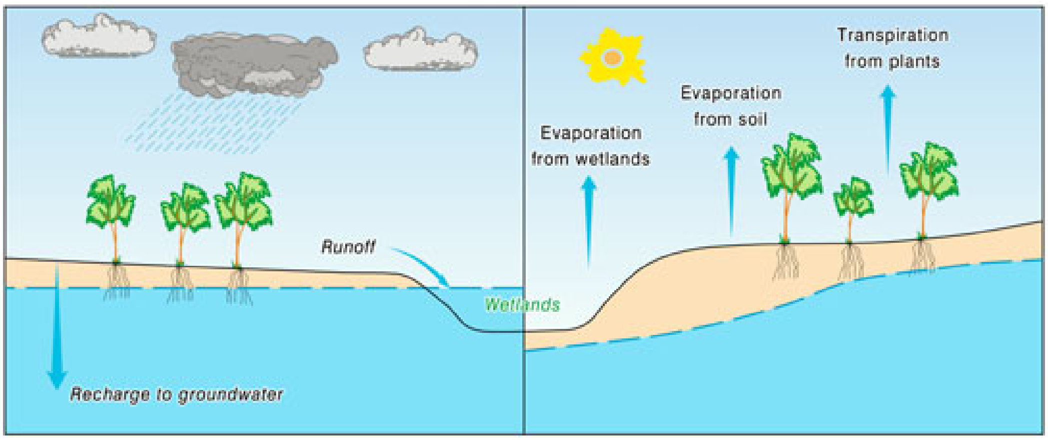


Figure DA-16. Schematic of the recharge and discharge cycle that applies in the Daly region. Note that where rivers are perennial, the groundwater level is maintained above the base of the river during the dry season (right image).

Recharge beneath native vegetation is dominated by bypass flow, not slow movement through soil horizons. The most likely mechanism for this is via stream sinks, sinkholes and/or macropores (cracks and root holes in the soil). While stream sinks have been located over the Tindall Limestone they are not a prominent feature of the landscape over other formations such as the Oolloo Dolostone. Water chemistry was used to estimate that recharge over uncleared land over the Oolloo Dolostone in the Douglas/Daly region was made up of approximately 30 percent diffuse recharge and 70 percent bypass recharge.

Jolly et al. (2000) documented a method to predict the estimated annual potential recharge rate in the Katherine area. They noted however that surface runoff was included in the figure derived for the potential recharge rate. The figures derived have been adjusted to better reflect recharge rates by using runoff data for a nearby gauging station GS8140158 that has minimal groundwater-derived flow. G8140158 is located on Macadam Creek within 20 km of G8140001. The resulting relationship between rainfall and estimated recharge is plotted in Figure DA-17.

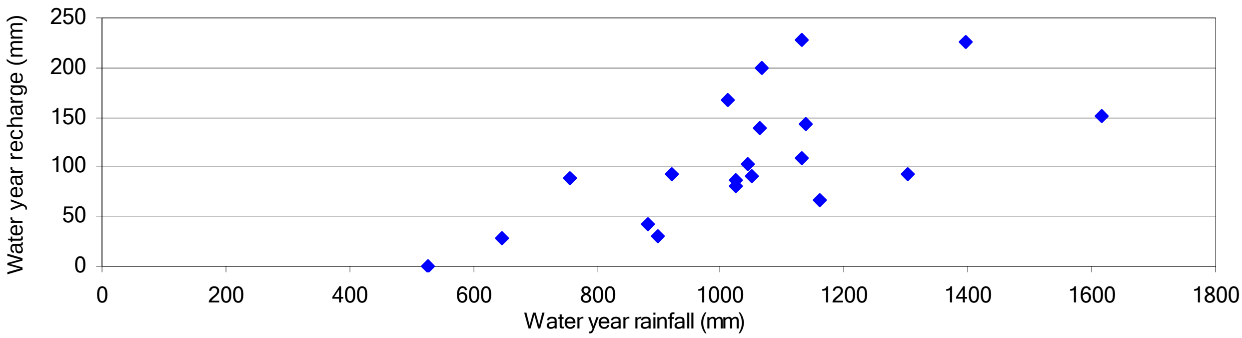


Figure DA-17. Recharge in the Katherine area of the Daly region

Groundwater discharge occurs across the basin mostly as evapotranspiration. Jolly (2000) estimated that on average evapotranspiration accounted for more than 85 percent of discharge across the catchment. Groundwater discharges that maintain perennial reaches of rivers within the Daly River catchment are important. The most visible of these discharges take the form of springs, on or adjacent to the banks of rivers such as the Katherine, Flora, Douglas and Daly rivers. Most discharge, however, occurs as diffuse discharge through the beds of rivers. The Northern Territory Government maintains a network of river gauging stations in the Daly River catchment that measure groundwater discharge to perennial reaches of rivers.

Specific comments relating to recharge to each of the three major aquifers follow. The locations of monitoring bores and river gauging stations in the Daly River catchment that are referenced in the following sections are shown on Figure DA-18.

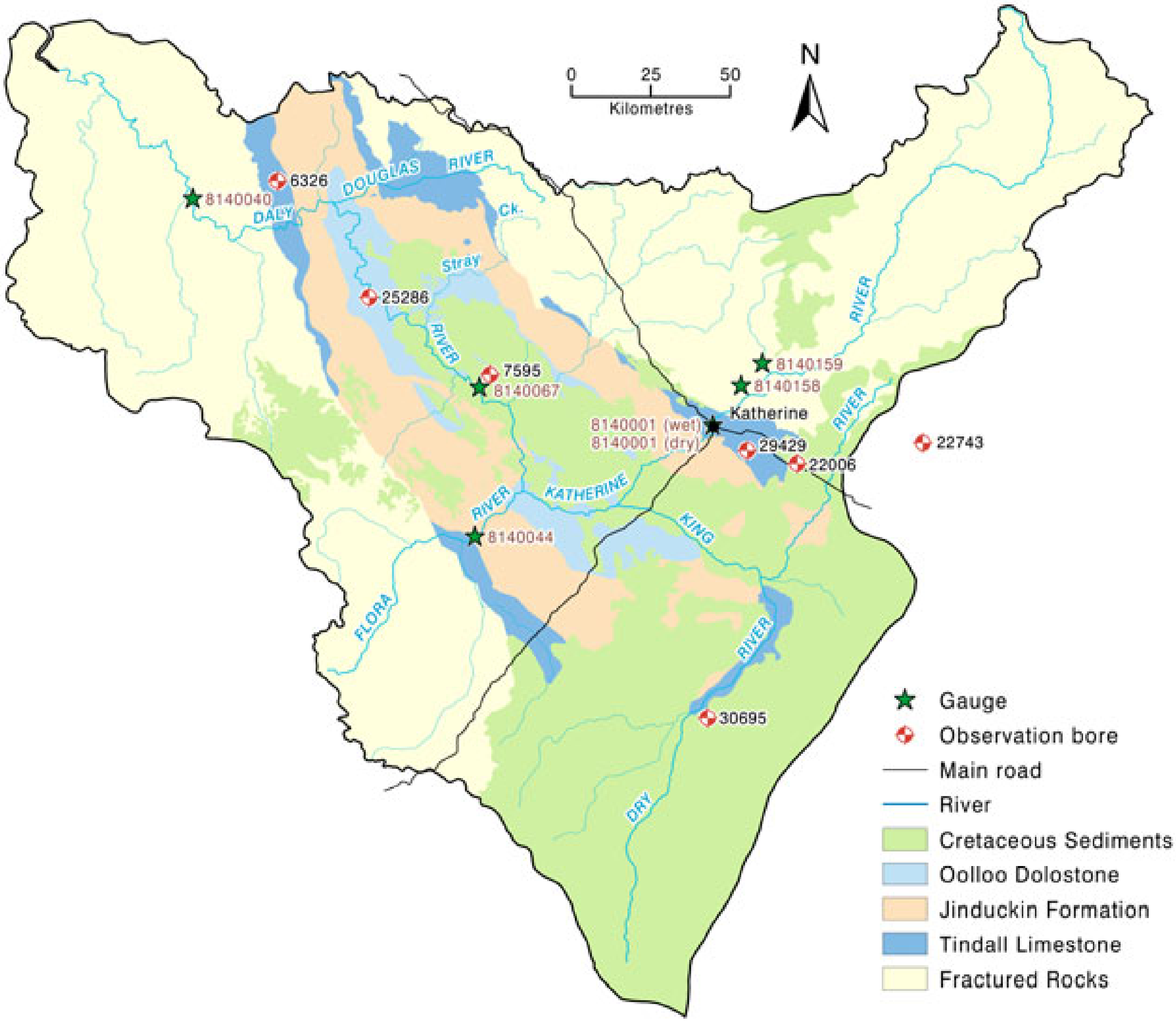


Figure DA-18. Location of monitoring bores and gauging stations referred to in this report (map provided by NRETAS, 2009)

Cretaceous sediments

Regional groundwater discharges from the aquifer developed in these sediments provide the dry season flow for Seventeen Mile Creek. This creek maintains the water level in the first pool in Katherine Gorge and provides the source of most of Katherine's water supply via Donkey Camp pool. The aquifer also provides recharge regionally to aquifers developed in the Tindall Limestone and Oolloo Dolostone.

Changes in dry season flow rates occur in response to changes in the amount of rainfall that recharges the aquifer each year. The changing recharge rate is reflected in the variation in water level measured in monitoring bores intersecting the aquifer. Figure DA-18 contains a plot of data for bore RN022743 which is located near the King River. The data indicate that annual recharge rates vary from zero to about 350 mm. Low water levels correspond to the period when flows were at their lowest at G8140159, higher water levels to higher flows.

This aquifer also is the source of water for many spring-fed rainforest patches in the vicinity of the upper reaches of the King River.

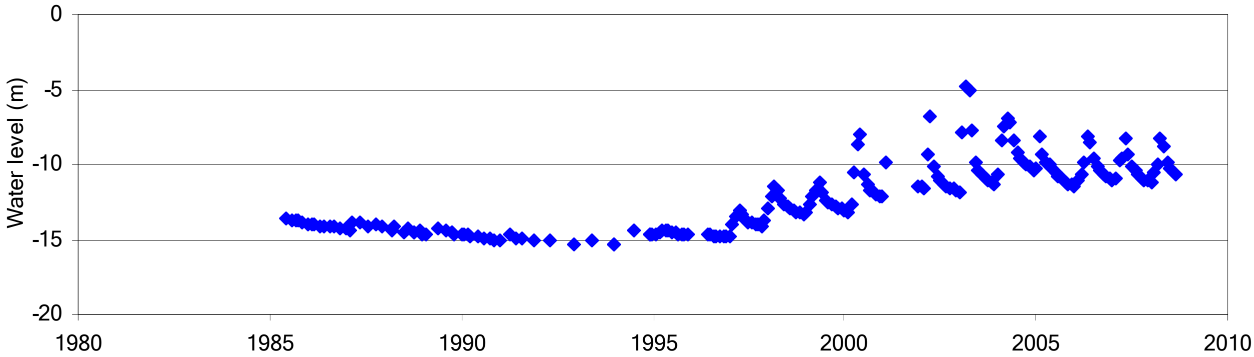


Figure DA-19. Observed groundwater level in bore RN022743 in the Daly region

Tindall Limestone

Regional groundwater discharges from the karst aquifer developed in the Tindall Limestone provide most of the dry season flow for the Katherine, Flora and Douglas rivers. They also provide a significant proportion of the flow in the Daly River. In dry periods such as the 1960s and early 1970s discharge from the Tindall Limestone into the Flora River was critical to maintaining the perenniality of all of the Daly River. The groundwater catchment of the Flora River extends into the Wiso Basin for more than 200 km outside of the surface water catchment of the Daly River (Yin Foo and Matthews, 2000).

As the Tindall Limestone aquifer underlies such a large area, its recharge rate can vary significantly due both to the areal variability in rainfall and the presence or absence of Cretaceous sediments overlying it. Figure DA-20 and Figure DA-21 indicate that variability. While significant rises and falls in water levels in wetter than average rainfall years occur in bores RN006326 and RN029429 which monitor the aquifer where it outcrops, these rises and falls are much smaller in bores RN022006 and RN030695 where the aquifer is covered by Cretaceous sediments.

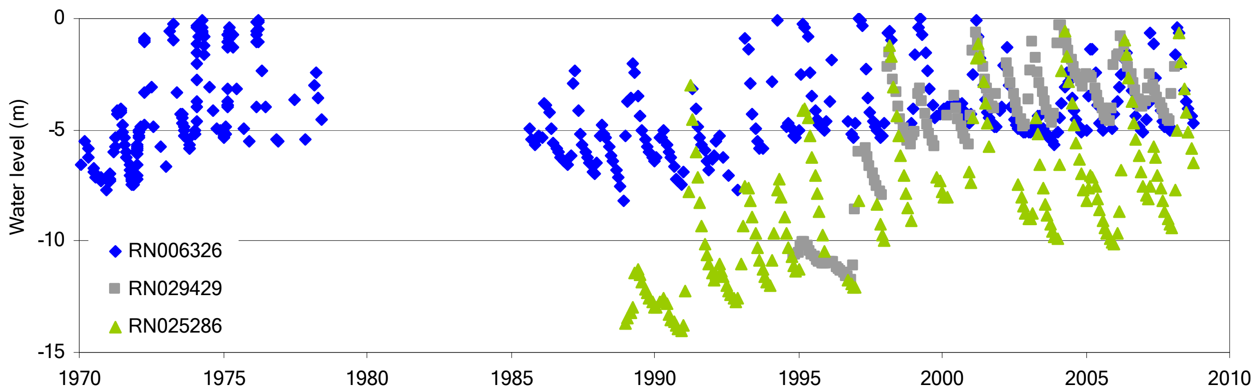


Figure DA-20. Observed groundwater levels in bores RN006326, RN025286 and RN029429 in the Daly region

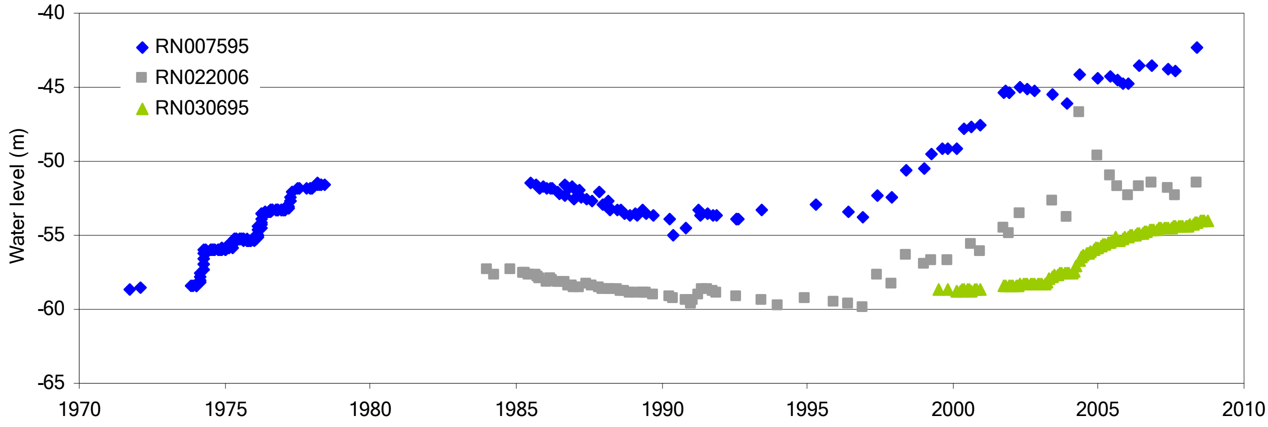


Figure DA-21. Observed groundwater levels in bores RN007595, RN022006 and RN030695 in the Daly region

The long-term variability in regional groundwater discharge rates from the karst aquifer developed in the Tindall Limestone is shown on Figure DA-3. The end-of-dry-season flow rates for G8140001 and G8140067 reflect the discharge from the Tindall Limestone aquifers. In recent times discharges have been up to five times greater than they were in the 1960s and early 1970s.

A plot of the lowest flow in the Katherine River at gauging station G8140001 and cumulative deviation from mean annual rainfall for Katherine are shown on Figure DA-3. The plot indicates that the low baseflows in the 1960s and early 1970s occurred after a long period of below average rainfall, while the very high baseflows that have occurred since 1996 have coincided with a period of above average rainfall.

Oolloo Dolostone

Regional groundwater discharges from the karst aquifer in the Oolloo Dolostone provide most of the dry season flow for the Daly River.

Recharge to the aquifer in the Oolloo Dolostone is dependent on the presence or absence of Cretaceous sediments overlying it. Figure DA-20 and Figure DA-21 indicate that variability. While significant rises and falls in water levels in wetter than average rainfall years occur in bore RN025286 which monitors the aquifer where it outcrops, these fluctuations are much smaller in bore RN007595 where the aquifer is covered by Cretaceous sediments.

Where the Oolloo Dolostone outcrops annual watertable rises of up to 8 m occur. Where this formation is covered by Cretaceous sandstone annual watertable rises of up to 2 m occur. This indicates that about four times as much water is recharging and discharging from the aquifer where the Oolloo Dolostone outcrops. The mean annual recharge rate for the period shown has been determined to be approximately 150 mm where the Oolloo Dolostone outcrops and about 40 mm where it is covered by Cretaceous sandstone.

The long-term variability in regional groundwater discharge rates from the karst aquifer developed in the Oolloo Dolostone is shown on Figure DA-3. The end-of-dry-season flow rates for the Daly River as measured at G8140040 reflect the discharge from the Oolloo Dolostone aquifer. In recent times discharges have been up to five times greater than they were in the 1960s and early 1970s.

A plot of the water levels in bore RN007595 and cumulative deviation from mean annual for Katherine are shown on Figure DA-21. The plot indicates that the low water levels and baseflows in the 1960s and early 1970s occurred after a long period of below average rainfalls, while the very high baseflows in the Daly River that have occurred since 1996 (as shown in Figure DA-17) have coincided with a period of above average rainfall.

DA-2.3.4 Groundwater quality

Most water from the fractured rock aquifers across the Daly River catchment fall within acceptable drinking water guidelines (ADWG, 2004). Occasionally elevated levels of arsenic are an issue.

Groundwaters in the Tindall Limestone and Oolloo Dolostone (for locations see Figure DA-2) are slightly alkaline on average, but pH can range from slightly acid (pH=6.4) to slightly alkaline (pH=8). Calcium, magnesium and bicarbonate are the dominant ions and salinities (measured as electrical conductivity) range between 300 and 1500 µS/cm (Figure DA-22). Calcium, magnesium and bicarbonate ions do not show much geographic variation, reflecting the relative ease with which they dissolve from the limestone and dolomite. Hardness is high and will cause scale build-up in plumbing.

Groundwaters in the Jinduckin Formation are known to contain the evaporite minerals halite (sodium chloride) and anhydrite (calcium sulphate). These were deposited when the sediments were laid down. Calcium and sulphate are the dominant ions in these groundwaters, which have salinities ranging between 300 and 3000 µS/cm (Figure DA-22).

Elevated levels of the naturally occurring radioactive isotope radium-226 (^{226}Ra) have been measured in many water bores in the Katherine area (Qureshi and Martin, 1996). Some of these exceed the guidelines (ADWG, 2004) for drinking water. High levels are restricted to areas where the Tindall aquifer is confined by the Jinduckin Formation and are found within 20 m of the contact between the two formations. The source of the radium is unclear, but is postulated to be the Jinduckin Formation.

Groundwaters in the Cretaceous sediments are acidic with pH ~5. Salinities are low and mostly range between 50 and 100 µS/cm.

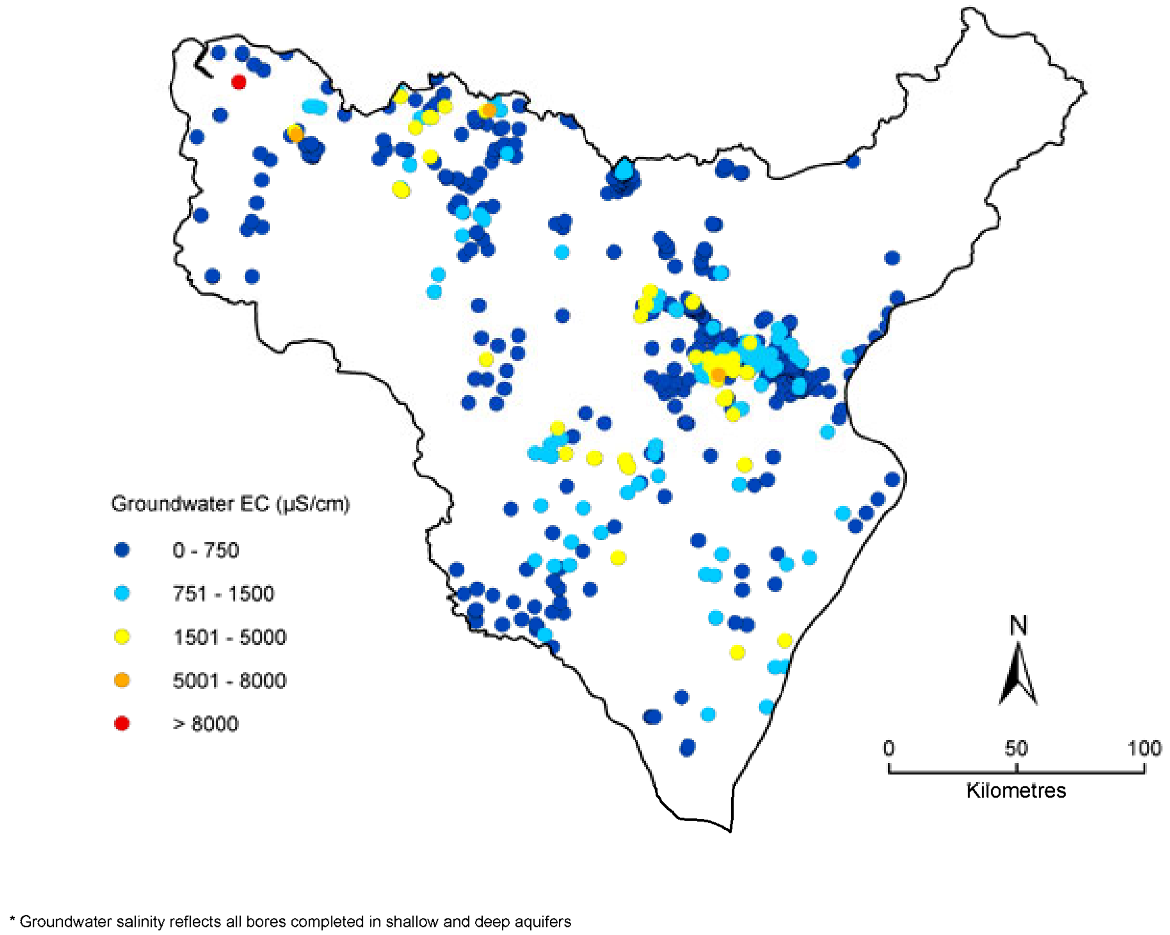


Figure DA-22. Groundwater electrical conductivity for bores in the Daly region

DA-2.4 Legislation, water plans and other arrangements

DA-2.4.1 Legislated water use, entitlements and purpose

The Northern Territory manages its water resources through a regulatory framework that includes the *Water Act 1992*, the Water Regulations and a series of water allocation plans in preparation. According to the *Water Act 1992*, the Crown owns all surface and groundwater – a situation unique to Australian water law (O'Donnell 2002). Water is allocated to consumptive uses which are licensed (for industry such as horticulture and public water supplies) and non-consumptive use that includes the environment and other public benefits that are not licensed. The Northern Territory's water policy framework is not well developed with only one plan completed. Recently recommendations have been made to introduce more transparent policies and guidelines, including for Indigenous access to water. Legislation applying to water allocation and management is in the process of review and revision.

The only water allocation plan currently written is the *Katherine Draft Water Allocation Plan (Tindall Limestone Aquifer)* (NRETA, 2008). The allocation limits in this plan are: dry season 87 percent environment and 13 percent consumptive pool; wet season 70 percent environment and 30 percent consumptive pool (NRETAS, 2008a).

The Daly Basin has been selected by the Northern Territory Government for major agricultural development which will intensify the current pastoral use by land subdivision, large-scale clearance of native vegetation and land modification.

The extraction limit which makes up the consumptive pool for the Tindall Limestone Aquifer is dynamic and will vary from year to year. This results from variable annual recharge to the Tindall Limestone Aquifer and strong and variable connectivity between the Tindall Limestone Aquifer and the Katherine River. The Katherine River baseflow is dominated by water discharged from the Tindall Limestone Aquifer.

The extraction limit for the Tindall Limestone Aquifer will be determined annually, based on its modelled discharge to the Katherine River.

Work is currently being carried out by NRETAS to assess potential allocation limits for the Oolloo aquifer.

Groundwater use figures for the Daly Basin were calculated for the Australian Water Resources 2000 Assessment (AWR, 2000). Use was approximately 20 GL/year. Groundwater use in the catchment in 2000 outside of the basin was probably less than 1 GL/year.

Groundwater use figures for the Tindall Limestone in the Katherine area are available for 1984, 2000, 2003 and 2008. Note that these figures are estimated as there is no requirement for all bores to be equipped with a meter. In 1984 groundwater use from the Tindall Limestone in the Katherine area was estimated to be approximately 1 GL/year. In 2000 groundwater use had increased to approximately 13 GL/year. In 2003 that figure had increased to 19.5 GL/year: 13.7 for agriculture; 2.7 for rural, stock and domestic; 1.7 for public water supply; and 1.4 for industry. In 2008 groundwater use was estimated to be 27.9 GL/year (excluding rural, stock and domestic use): 12.5 for agriculture; 0.8 for public water supply; and 1.2 for industry.

Groundwater use figures for the Tindall Limestone for the remainder of the Daly River catchment are available for two years, 2000 and 2003. In 2000 use was estimated at 0.5 GL/year. In 2003 use was estimated at 1.7 GL/year.

Groundwater use figures for the Jinduckin Formation are only available for 2000. In 2000 use was estimated at 4.5 GL/year.

Groundwater use figures for the Oolloo Dolostone are available for two years, 2000 and 2003. Note that these figures are estimated as there is no requirement for all bores to be equipped with a meter. In 2000 groundwater use from the Oolloo Dolostone was estimated to be approximately 1.7 GL/year. In 2003 groundwater use (predominantly in the Katherine area, Figure DA-23) had increased to approximately 10.6 GL/year: 9.8 for agriculture; 0.7 for rural, stock and domestic; and 0.1 for industry.

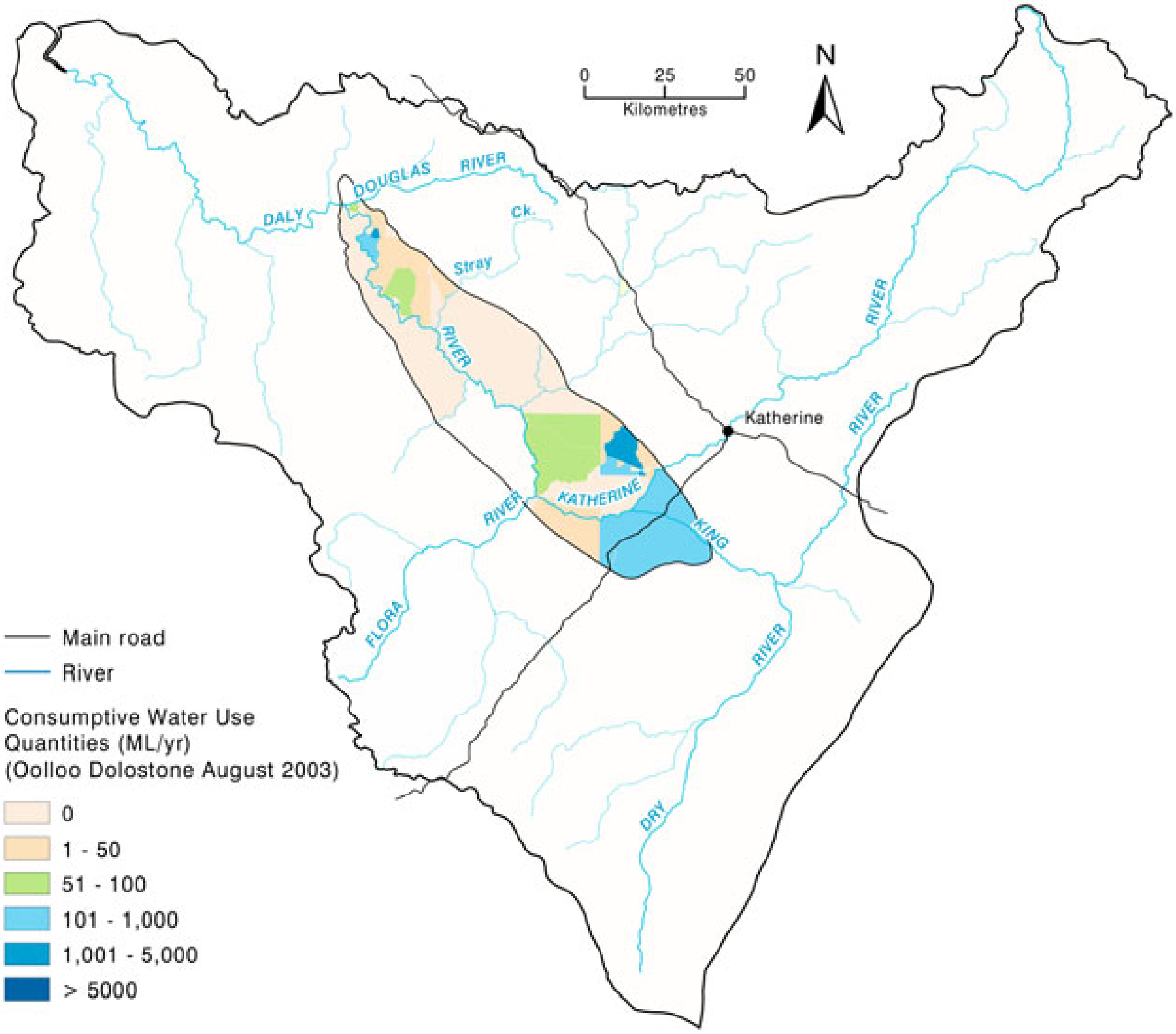


Figure DA-23. Water use from the Oolloo Dolostone aquifer (Source: Northern Territory Government, August 2003)

DA-2.4.2 Rivers and storages

There are numerous small storages on the rivers of the Daly region. Most are natural pools, but some have been augmented with structures to increase holding capacity. An important small storage occurs upstream of Katherine, on the Katherine River at Donkey Camp Pools (near gauge 814058 on Figure DA-18). In 1992, Donkey Camp Weir was constructed, raising the naturally occurring pool by 1.5m in response to expected growth of Katherine and the neighbouring Tindall Air Force Base. An annual safe (99.9 precent) yield of 5,650 ML has been determined (SKM, 2005), with existing annual licensed volume for extractions of 4,500 ML. Demand, however, rarely exceeds 12 kL/day during the dry season and 6 kL/day during the wet season (<3 ML/year).

DA-2.4.3 Unallocated water

The water policy framework in the Northern Territory is not well developed and the legislation has no objects or principles to guide the development of a water allocation plan. Sustainability is introduced through the concept of ‘beneficial use’. Through the public declaration of beneficial uses, management goals are set for a water control district to determine how and why community sectors and government want to protect, manage and use the water resource. According to the *Northern Territory Water Act 1992*, cultural beneficial uses are defined as aesthetic, recreational and cultural needs. These needs cover those expressed by the Indigenous and non-Indigenous communities. It is assumed that the cultural beneficial uses are to be met by instream flow and that they are of a non-consumptive nature, i.e. their satisfaction does not require water extraction.

Strategic Indigenous Reserve is set at 25 percent of total consumptive pool. This is expected to equate to about 20 GL/year for the Tindall Limestone aquifer while the Oolloo Dolostone aquifer is expected to be fully allocated once entitlements are met.

DA-2.4.4 Social and cultural considerations

A number of small Indigenous settlements are found in the area where at least ten Indigenous language groups comprise approximately a quarter of the total population and own approximately 30 percent of the land-base (Jackson, 2005).

The river is highly valued by a range of sectors for its constant flow, and for the provision of breeding areas, habitat and refuge for important aquatic populations of fishes, turtles, waterbirds and crocodiles. Recreation values are also significant with the Daly described in public discourse as a ‘Territory icon’ which affords fishers and campers the space to enjoy nature and ‘escape from the daily routine’ (Young, *cited in* Jackson, 2005). The hot climate, dry for many months of the year, and the limited recreational opportunities in many of the more remote regions, result in a high appreciation for the recreational value of rivers and waterbodies.

The Daly River has been described as a ‘significant ceremonial track’ by John Daly, Deputy Chairman of the Northern Land Council, the statutory authority representing the traditional owners of the region (Jackson, 2005). Impacts on the water table are perceived as a threat to the numerous sacred sites associated with the river. John Daly states that: “water usage as planned will not only expose these sites visually, but will also make them prone to destruction” (*op cit.*).

A preliminary report on the Indigenous cultural values in 2004 found that water – its origins, features and appropriate use – is highly significant to the way of life, sense of identity, economy and cosmology of the Indigenous language groups (Jackson, 2004). The qualities of water that have a sense of the sacred, embody life and generate feelings of belonging and identity were all given as important in consultations with Indigenous groups over land use, water abstraction and socio-ecological impacts.

Many of the sacred sites are associated with river, their tributaries and water dependent ecosystems, such as billabongs in the Daly River region. Sacred sites are landscape features “created either by the metamorphosis of Dreamtime figures, into rocks, boulders, trees, etc., or by the action of such an ancestor, or ancestors, sometimes when interacting with each other” (Jackson, 2005). Some of those ancestors were species that one would automatically associate with water - black water hens, barramundi, frogs, freshwater sharks, crocodiles or bamboo (*ibid.*).

Hydrological processes are recognised as important to the health of the region’s ecosystems by Indigenous people consulted during the study (Jackson, 2004). This is consistent with reports from the Fitzroy region of the Kimberley, where:

“… the importance of hydrology ‘driving’ ecology is not lost on the Indigenous people. They are fully aware of the importance of flood flows and much of their hunting culture seems to associate a large flood with environmental ‘health’ of the river, particularly of the permanent pools” (Storey, et al., 2001).

River flow is considered vital to the character of the river and the dependent wildlife. Activities that might stop river flow and disturb movement of fish and turtle, for instance, are seen in a negative light. Climatic variations are also of considerable interest to Indigenous traditional owners. One respondent wished to see dry years used as the basis for calculations of water availability to ensure that long-term fluctuations in rainfall were taken into account (Jackson, 2004). Wetlands in the traditional estates of the groups consulted were perceived to be sensitive to changes in groundwater levels from water abstraction. Jessie Brown, a Wardaman woman notes: “These two billabongs [on Florina station] are full all year around from the groundwater. Lilly root and fish depend on water. There’s a Dreaming in the centre of the water”.

Vibrant traditional narratives describe the creation of water features, such as the Flora River springs which are an important recharge site for the Daly River throughout the year. Wardaman people ascribe the functioning of the Flora spring system to a grasshopper lying under the ground ‘pumping’ the water out into the river (Jackson, 2004).

Cooper and Jackson (2008) undertook a study of the cultural significance of the groundwater resources of the Tindall Limestone aquifer. The major regional centre of Katherine is the Northern Territory’s third largest town, with a population of approximately 9,000, a quarter of whom are Indigenous (Cooper and Jackson, 2008). There are seven Indigenous communities within the town and nearby surrounds, ranging in population from about 10 to 300 residents. The region comprises land tenures associated with the most intensive current and future water usage in the Northern Territory's Top End. These include residential, industrial, commercial horticultural, farming and pastoral uses. The region also relies economically on tourism, focused on Nitmiluk National Park (Katherine Gorge) and other permanent waters of the spring-fed Katherine/Daly River system, including Edith Falls and the Flora River Nature Reserve.

The headwaters of the Katherine River lie in the escarpment country of Arnhem Land and Nitmiluk and Kakadu National Parks to the north. The Katherine River is subject to high wet season flows with occasional serious flooding. Groundwater discharge from aquifers sustains dry season base-flows in parts of these river systems. The Tindall Limestone Aquifer is the most substantial and reliable groundwater resource within the study area and its discharge sustains the important ecological, cultural and economic values associated with the Katherine river system. Maintenance of these base-flows is therefore a priority water management objective.

The report documented the social arrangements, customary relationships and cultural practices relating to water, and documents Indigenous knowledge of groundwater and surface water sources held by Indigenous cultural groups in the vicinity of Katherine (Jackson and Cooper, 2008). It also addresses the impediments to continued customary use of water sources, how rights to water and management responsibilities are conceived and applied in context of the land use history of the area, as well as present and future economic and commercial use of water supplies. An emphasis on the environmental management and governance frameworks affecting water management is especially relevant to the case study because of recent increases in the commercial demand for water and the imminent introduction of water trading as a new resource allocation mechanism governed by a water allocation plan.

Indigenous rights and interests in water in the study area are in part a product of the history of Indigenous and colonial occupation and use of land, which has been influenced by a number of environmental, cultural and historical factors. Such factors include the ecological and related cultural values of significant riverine environments, such as the Katherine River system, pastoral and mining development; development of the town of Katherine, and the regional movement of Indigenous people to the area. The groundwater-fed Katherine and Flora rivers are both examples of ecologically-rich ecosystems that are correspondingly rich in the occurrence of Indigenous cultural sites and patterns of occupation and use. This richness has continued to influence the residential patterns of local Indigenous people. The present locations of the permanent Indigenous communities are all within such zones, and despite the fact that their development as permanent communities has been influenced by non-Indigenous settlement; they are all on or adjacent to important cultural sites of longstanding significance. That is, they represent instances of customary use of the land. Certain land and waters within the Katherine Water Control District are subject to a current native title claim, and in claim documentation, fishing and hunting in those waters are given as incidents of the customary rights and continuity of occupation asserted by claimants (*ibid.)*.

A significant portion of the report is devoted to describing the cultural context and significance of water. As a fundamental aspect of land and ecosystems, water is integral to the lives and beliefs of Indigenous groups in the Katherine area. However while distinct and, indeed, profoundly important aspects of cultural practices and beliefs relating to water exist, it is difficult and perhaps unwise to attempt to abstract such practices and beliefs from the broader processes and institutions that shape and give meaning to Indigenous cultures and to the social arrangements, lived experience and relationships to land of Indigenous people (*ibid.)*.

Cultural practices relating to water include talking to country, 'watering' strangers and others, restrictions on behaviour and activities, protecting others from harm and management and protection of sites. These practices are a consequence of belief in the continuing spiritual presence in the landscape of creation beings as well as more recent remembered and unremembered ancestors, or 'old people', returned to their countries as spirits. The animating spirits that become children are also believed to enter their mothers from water.

Indigenous groups have deep cultural connections to water sources in the study area, including customary rights of ownership and custodianship of cultural water sources. Significant cultural water sites within the study area include rivers and creeks and their associated features, including gorges, waterfalls, plunge pools, waterholes, billabongs and springs; and areas away from river and creek beds such as seasonally inundated swampy areas and isolated rockholes and springs. Importantly, such connection and cultural rights extend beyond surface waters to the underground waters, including the waters of the Tindall Limestone Aquifer. The study finds that the underground waters are themselves significant and feature in Indigenous ritual knowledge. This is an important issue that remains largely unaddressed in management and planning contexts, including in relation to heritage protection and the current water planning processes.

The traditional owners of the study area have sought formal registration of a number of sites under the Sacred Sites Act. There are approximately 25 registered sites within the study area that include culturally-significant water features. Formal mechanisms for the protection and management of cultural sites are described and questions are raised about the application of Northern Territory heritage law and Commonwealth native title law to the extraction or consumption of groundwater.

DA-2.4.5 Changed diversion and extraction regimes

There are no surface water diversions in the region.

In recognition of the intimate connection of groundwater from the Tindall aquifer with surface water in the Katherine River, the Draft Water Allocation Plan for the Tindall Limestone Aquifer (2008) will provide a target base flow to the Katherine River to provide water for environmental, indigenous cultural and other instream public benefit outcomes. Due to annual climatic variability, an extraction limit is calculated each year. The extraction limit is the total volume of water that may be extracted under licences for the water accounting year.

The extraction limit is calculated annually prior to the commencement of the water accounting year on 1 May. The Tindall Limestone groundwater model is used to predict recharge based on the previous wet season rainfall and subsequently the river flow that will occur in the Katherine River late in the dry season. In years when recharge is poor and discharge to the river is consequently low, the extraction limit may need to be reduced to ensure discharge from the aquifer is sufficient to maintain river flows throughout the dry season.

The extraction limit under the Plan allows for a flexible water extraction regime based on actual availability of water from year to year. The extraction limit ranges from 4,340 ML/yr during very dry years, gradually increasing through to 34,171ML/year in very wet years. The minimum extraction limit is sufficient to provide for essential public water supply and rural stock and domestic requirements, whilst the maximum extraction limit is equivalent to the total volume of water allocated under licences.

DA-2.4.6 Changed land use

Adaptive management is a major feature of the draft Plan in that announced allocations are based on an extraction limit that varies with annual climatic conditions. Additionally, the draft Plan stipulates a monitoring program that seeks to assess the adequacy of the Plan's strategies in achieving its objectives.

Current valid licences in the Plan area for agriculture have a combined total volume of 18,750ML/year. A desktop mapping assessment utilising GIS and imagery captured in 2006, was undertaken by NRETAS to determine the current level of agricultural development within the Plan area (NRETAS 2008b). The assessment assumed the full development of all tree crops and represents the maximum water use requirements of all irrigated crops planted in 2006. The assessed maximum requirement at 2006 development is 12,500ML/year.

The draft Plan allows for new and expanding agriculture over the next 10 years in the Katherine region. Future water requirements for agriculture were assessed via a framework developed in consultation with industry and the Katherine Water Advisory Committee. Future water requirements for agriculture were assessed at 34,171ML/year in 2018. In the draft Plan, water is assigned for future agriculture and industry development according to two different licence security levels, 23,862 in high security and 8,433ML/year in low security.

Additional expansion in the region is expected to require other minor increases in licenses, for public water supply, aquaculture, industry and rural stock and domestic. Total increases for these licenses are not expected to be more than 2,000 ML/year.

DA-2.4.7 Environmental considerations and implications of future development

A guideline for water allocation across the Northern Territory is to designate 80 percent of the consumptive pool for the environment and 20 percent for consumptive use throughout the year. This applies to water from either surface or groundwater sources. This guideline is adopted in the absence of a water allocation plan.

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DA-3 Water balance results for the Daly region

This chapter describes modelling results and the assessment of the water resources undertaken by this project for the Daly region. Detailed, quantified assessments are made where possible, and relevant, and confidence is estimated. Modelling results are reported under climate and development scenarios as defined at the division level in Section 2.1 of Chapter 2. This chapter is sub-divided into:

- climate
- recharge estimation
- conceptual groundwater models
- groundwater modelling results
- rainfall-runoff modelling results
- river system water balance
- changes to flow regimes at environmental assets.

DA-3.1 Climate

DA-3.1.1 Historical climate

The Daly region receives an average of 1019 mm of rainfall over a September to August water year (Figure DA-24), most of which (975 mm) falls in the November to April wet season (Figure DA-25). Across the region there is a strong north–south gradient in annual rainfall (Figure DA-26) ranging from 1493 mm in the north to 667 mm in the south. Over the first part of the historical (1930 to 2007) period, annual rainfall has been relatively constant at around 920 mm. However, the past four or so decades has seen an slow increase in mean rainfall. The highest annual rainfall was 1640 mm which fell in 1974, and the lowest was 498 mm in 1952.

Historical areal potential evapotranspiration (APET) is very high across the region, averaging 1942 mm over a water year (Figure DA-24), and varies moderately across the seasons (Figure DA-25). APET generally remains higher than rainfall throughout most of the year resulting in water-limited conditions. The exception to this is January to March, when more rain falls than can potentially be evaporated.

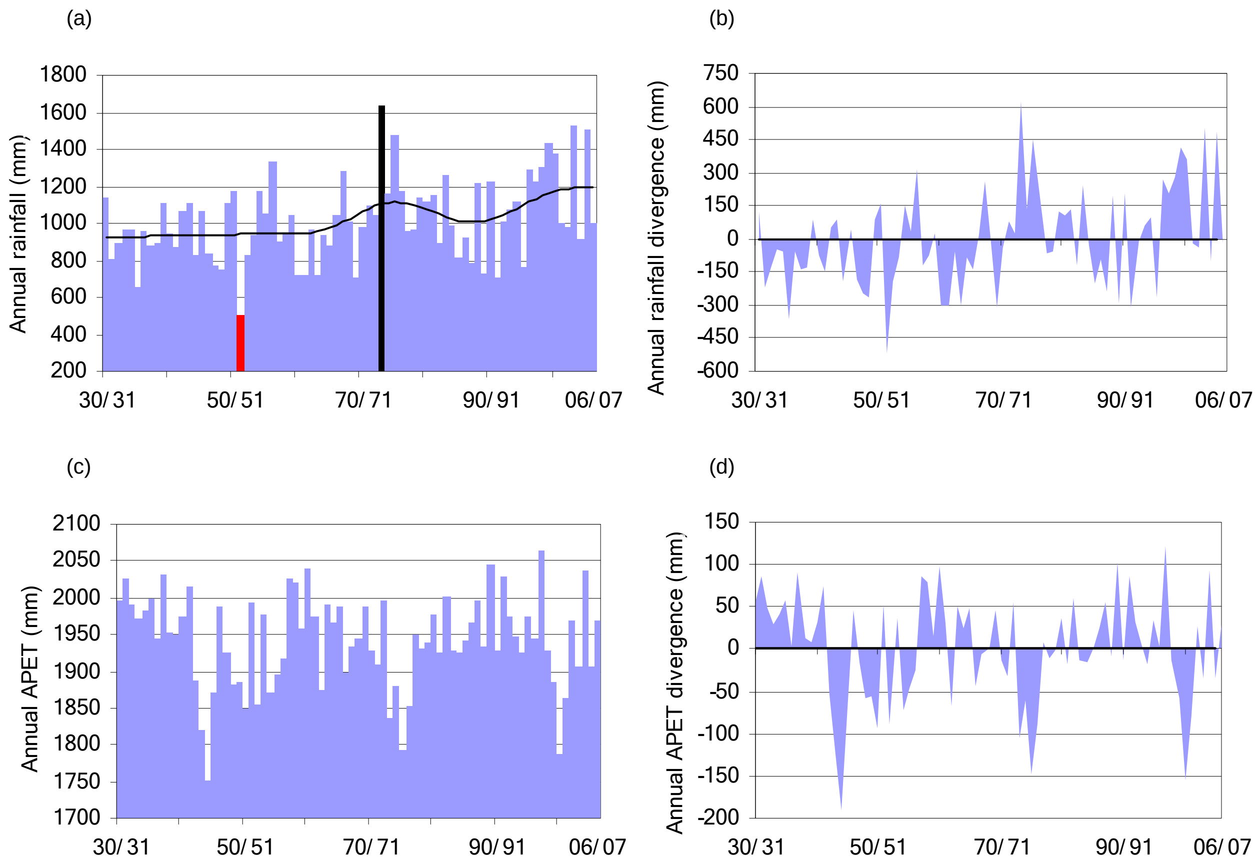


Figure DA-24. (a) Historical annual rainfall and (b) its divergence from the long-term mean; and (c) historical annual areal potential evapotranspiration and (d) its divergence from the long-term mean averaged over the Daly region. The low-frequency smoothed line in (a) indicates longer term variability

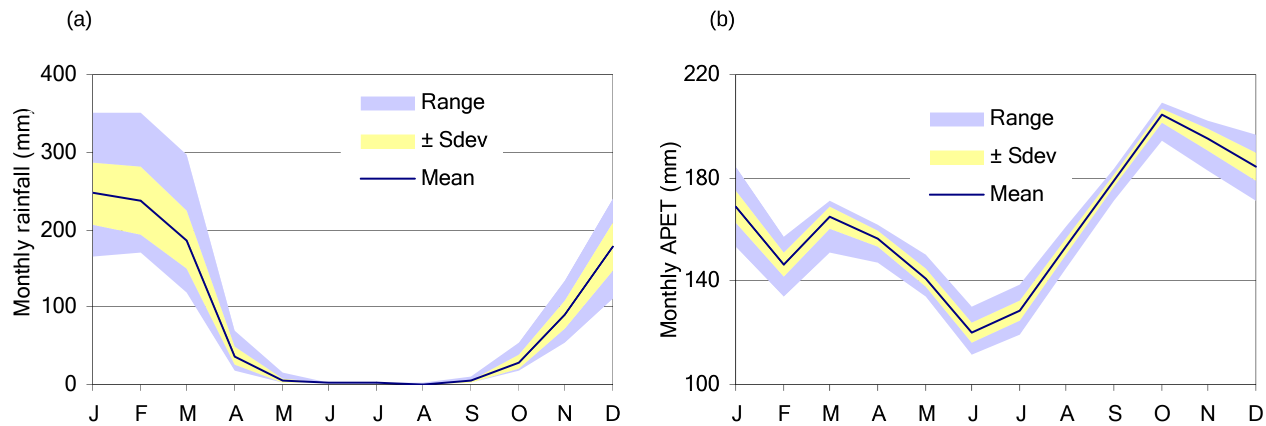


Figure DA-25. Historical mean monthly (a) rainfall and (b) areal potential evapotranspiration and their temporal variation (range and ± one standard deviation) averaged over the Daly region

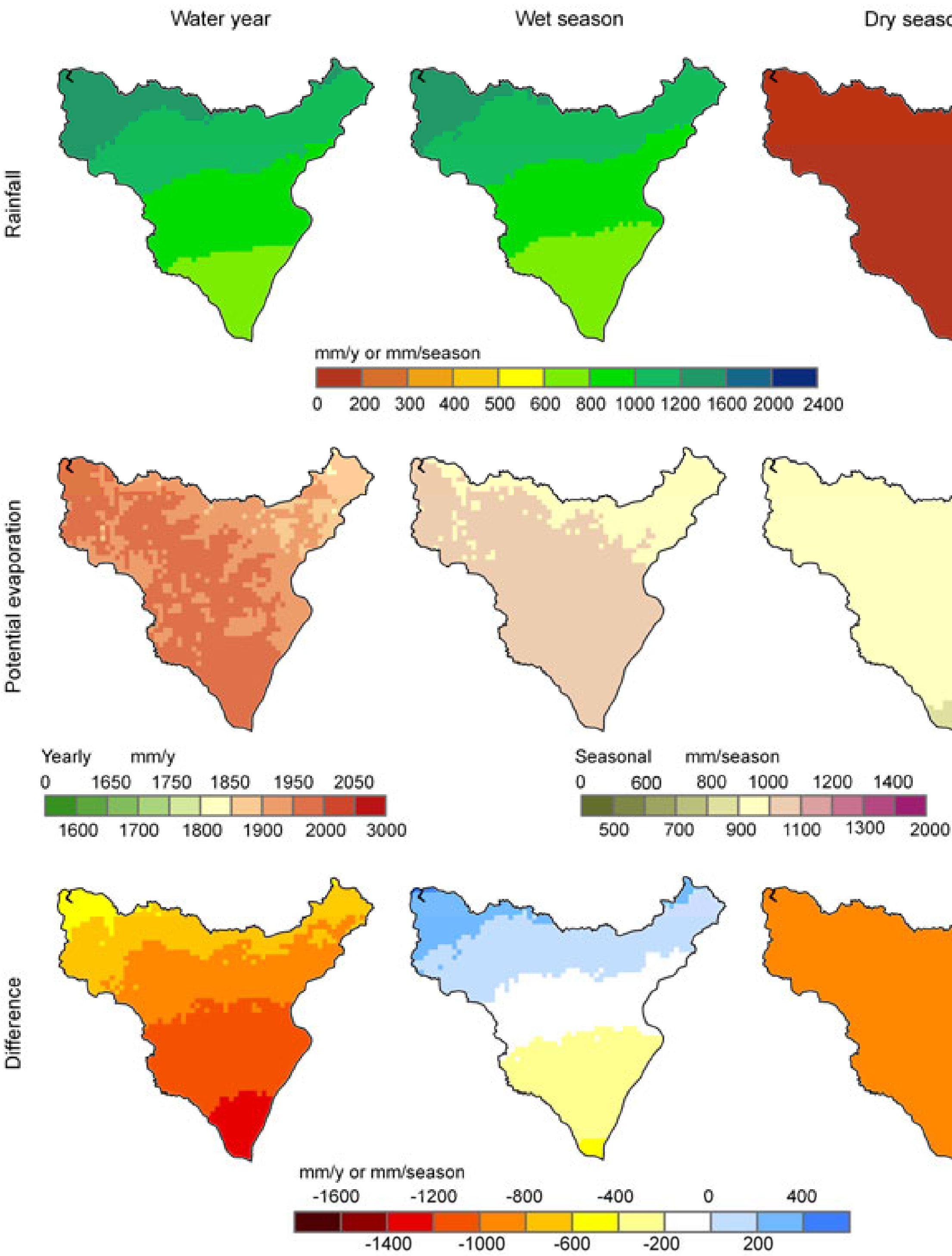


Figure DA-26. Spatial distribution of historical mean annual (water year), wet season and dry season rainfall and areal potential evapotranspiration (potential evaporation) and their difference (rainfall less areal potential evapotranspiration) across the Daly region

DA-3.1.2 Recent climate

Figure DA-27 compares recent (1996 to 2007) to historical (in this case the 66-year period 1930 to 1996) mean annual rainfall for the Daly region. Across the whole region, recent rainfall is up to 50 percent higher than historical rainfall – a statistically significant difference for the majority of the region. Rainfall has increased most in the west of the region over the project period.

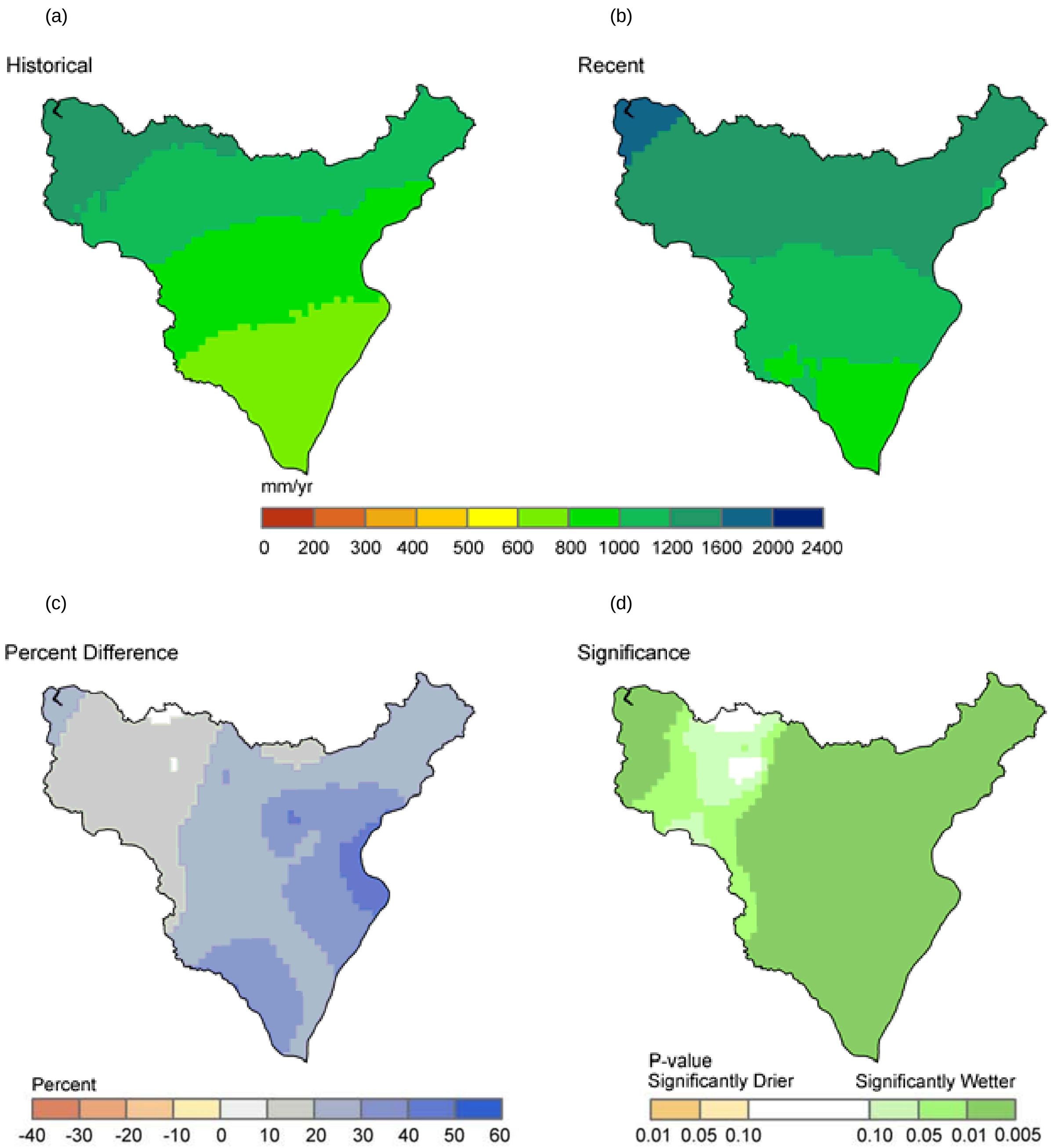


Figure DA-27. Spatial distribution of (a) historical and (b) recent mean annual rainfall; and (c) their relative percent difference and (d) the statistical significance of these differences across the Daly region. (Note that historical in this case is the 66-year period 1930 to 1996)

DA-3.1.3 Future climate

Under Scenario C annual rainfall varies between 892 and 1131 mm (Table DA-3) compared to the historical mean of 1019 mm. Similarly, APET ranges between 1967 and 2069 mm compared to the historical mean of 1942 mm.

A total of 45 variants of Scenario C were modelled (15 global climate models (GCMs) for each of the high, medium and low global warming scenarios). Subsequently, results from an extreme 'wet', median and extreme 'dry' variant are shown (referred to as scenarios Cwet, Cmid and Cdry). Under Scenario Cwet annual rainfall and APET increase by 11 percent and 1 percent, respectively. Under Scenario Cmid annual rainfall and APET increase by 1 percent and 3 percent. Under Scenario Cdry annual rainfall decreases by 13 percent and APET increases by 7 percent.

Under Scenario Cmid long-term monthly averages of rainfall and APET do not differ much from historical values (Figure DA-28). Rainfall under Scenario Cmid lies well within the predicted range in values from all 45 future climate variants. The seasonality of rainfall is expected to change little under Scenario Cmid but APET is expected to be consistently higher than historical values. In fact, all projections of future APET are higher than historical values for all months of the year.

The spatial distributions of rainfall and APET under Scenario C are compared to the historical distribution in Figure DA-29 and Figure DA-30. Under Scenario C the strong north–south gradient in rainfall is retained in the wet season, but with a southwards shift under Scenario Cwet and a northwards shift under Scenario Cdry. The spatial distribution of APET under Scenario C is similar to the highly regionalised historical distribution. The greatest changes to APET occur in the south of the region.

Table DA-3. Mean annual (water year), wet season and dry season rainfall and areal potential evapotranspiration averaged over the Daly region under historical climate and Scenario C

Scenario	Water year*	Wet season	Dry season
	mm/y	mm/season	
Rainfall			
Historical	1019	975	44
Cwet	1131	1057	63
Cmid	1032	978	44
Cdry	892	856	26
Areal potential evapotranspiration			
Historical	1942	1015	927
Cwet	1967	1017	949
Cmid	2003	1045	957
Cdry	2069	1088	979

* Note that the sum of the wet season and dry season values does not always equal the water year values because the combined wet season and dry season period (November to October) is different to the water year period (September to August).

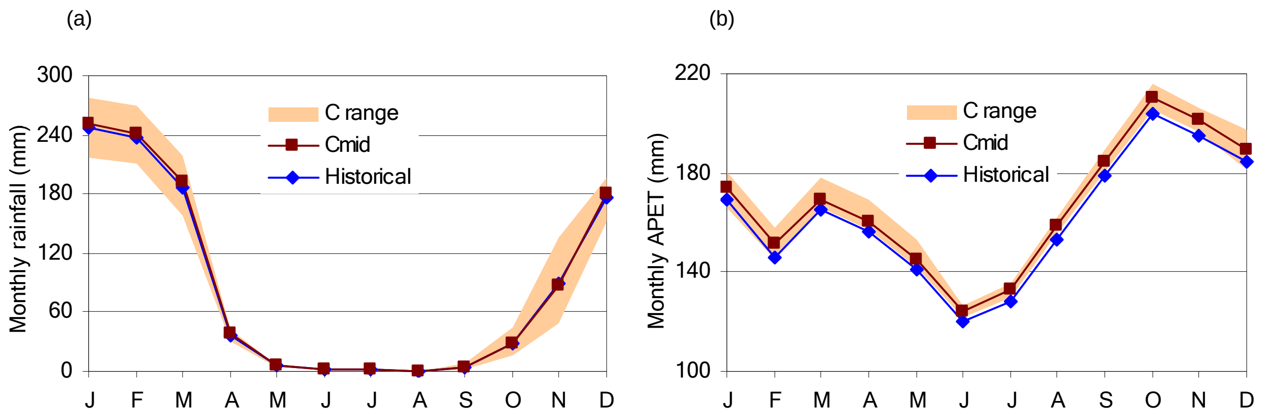


Figure DA-28. Mean monthly (a) rainfall and (b) areal potential evapotranspiration averaged over the Daly region under historical climate and Scenario C. (C range is the range under the 45 Scenario C simulations – the lower and upper limits in C range are therefore not the same as scenarios Cdry and Cwet)

DA-3.1.4 Confidence levels

Analysis of confidence of the climate data is reported in Section 2.1.4 of the division-level Chapter 2.

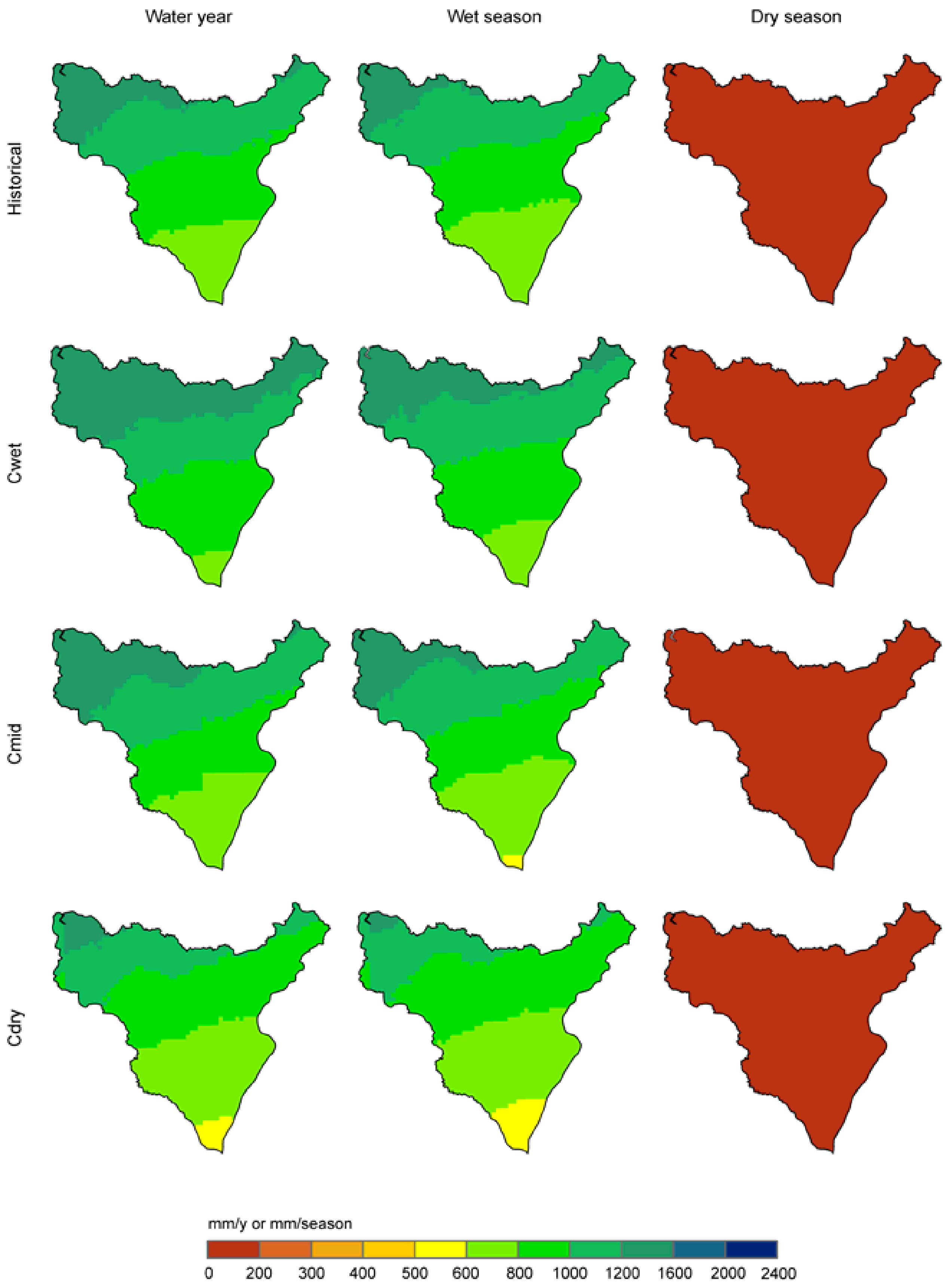


Figure DA-29. Spatial distribution of mean annual (water year), wet season and dry season rainfall across the Daly region under historical climate and Scenario C

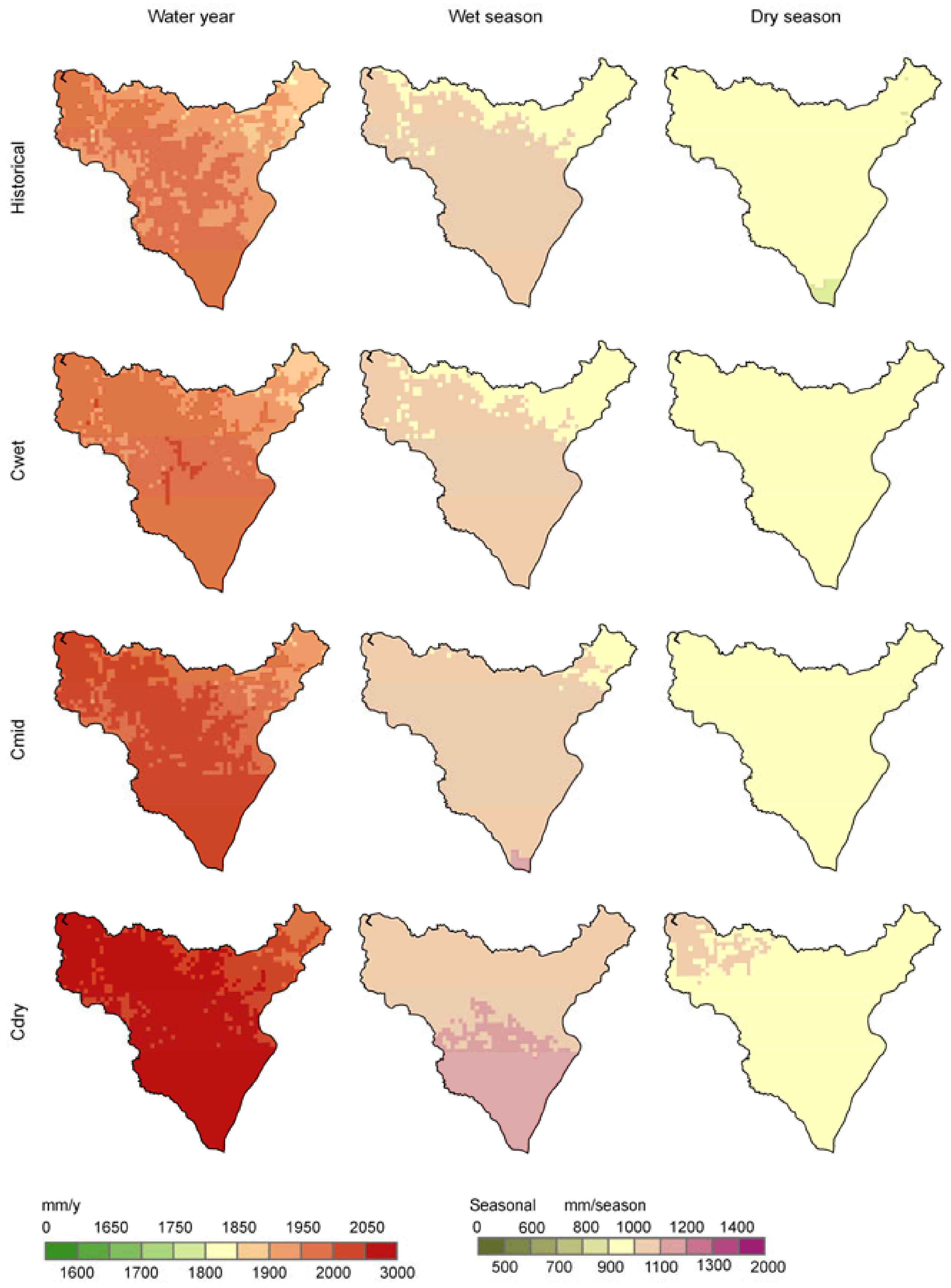


Figure DA-30. Spatial distribution of mean annual (water year), wet season and dry season areal potential evapotranspiration across the Daly region under historical climate and Scenario C

DA-3.2 WAVES potential diffuse recharge estimations

The WAVES model (Zhang and Dawes, 1998) was used to estimate the change in groundwater recharge across the Daly region under a range of different climate scenarios. WAVES is a vertical recharge flux model that has the capability to model plant physiological feedbacks in response to increased CO_2, as well as modelling the water balance based on different soil, vegetation and climate regimes. This model has been chosen for its balance in complexity between plant physiology and soil physics. This model was also chosen to assess recharge for the Murray-Darling Basin Sustainable Yields Project (Crosbie et al., 2008).

DA-3.2.1 Under historical climate

The historical (1930 to 2007) modelled recharge in the Daly region is around the median of all regions studied within the project. Recharge is lowest on the vertosols near the river and highest in the north-east of the region where the rainfall is greater (Figure DA-31). The historical record was assessed to establish any difference between wet and dry periods of recharge. A 23-year period was used, which allows the projection of recharge estimates to 2030 – in other words, to estimate recharge in 2030 assuming future climate is similar to historical climate (Scenario A). Under the three variants of Scenario A the recharge does change for a 23-year period compared to the recharge under the historical climate. For the recharge that is exceeded in 90 percent of 23-year periods (Scenario Awet), recharge is on average 11 percent greater that the historical average (that is, a recharge scaling factor (RSF) of 1.11). For the recharge that is exceeded in 50 percent of 23-year periods (Scenario Amid), recharge is on average 3 percent lower than the historical average (RSF=0.97). For the recharge that is exceeded in 10 percent of 23-year periods (Scenario Adry), recharge is on average 14 percent lower than the historical average (RSF=0.86) (Table DA-4).

Where unweathered bedrock outcrops occur, confidence in the modelled results is reduced. The locations of these outcrops in the Daly region are shown on the historical recharge map in Figure DA-31.

Table DA-4. Recharge scaling factors in the Daly region for scenarios A, B and C

Region	Awet	Amid	Adry	B	Cwet	Cmid	Cdry
Daly	1.11	0.97	0.86	1.25	1.38	1.13	0.98

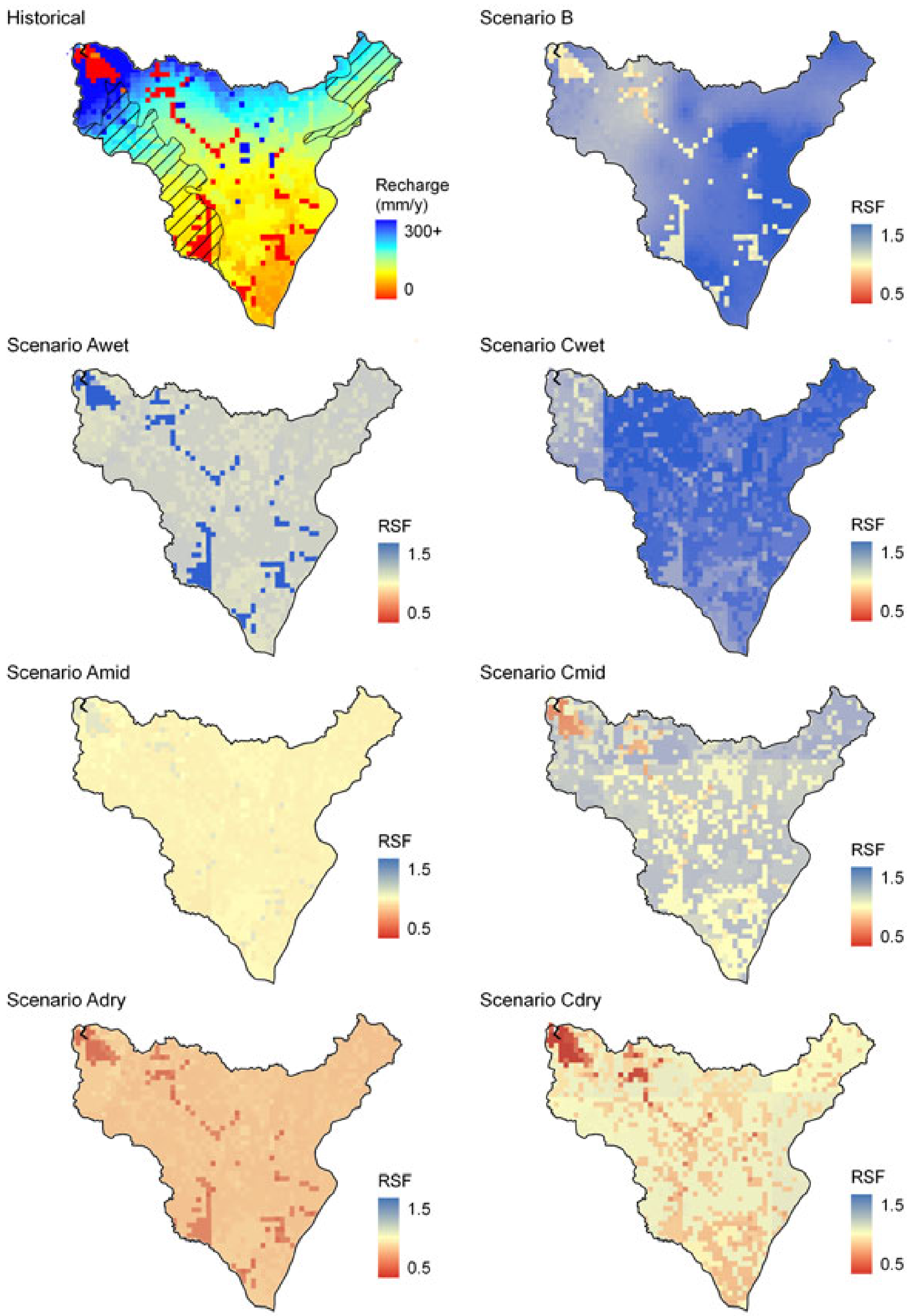


Figure DA-31. Spatial distribution of historical mean recharge rate; and recharge scaling factors in the Daly region for scenarios A, B and C. The hatched region on the historical recharge map identifies where unweathered bedrock outcrops occur

DA-3.2.2 Under recent climate

The recent (1997 to 2006) climate in the Daly region has been wetter than the historical (1930 to 2007) average and consequently the calculated recharge increases 25 percent under Scenario B relative to Scenario A (Table DA-4). This increase has not been spatially uniform with the greatest change in recharge in the east of the catchment (Figure DA-31).

DA-3.2.3 Under future climate

Figure DA-32 shows the percentage change in modelled mean annual recharge averaged over the Daly region under Scenario C relative to Scenario A for 45 scenarios (15 GCMs for each of the high, medium and low global warming scenarios). The percentage change in the mean annual rainfall and recharge from the corresponding GCMs are also tabulated in Table DA-5. Under some scenarios the recharge is projected to increase despite a decrease in rainfall. This is because total rainfall is not the only climate variable that has an influence over recharge. Daily rainfall intensity, temperature and CO_2 concentration are also important drivers (see Section 2.3.3 in the division-level Chapter 2), and specific situations can result in this counter-intuitive result. In particular, rainfall intensity is seen as a significant factor in this relationship.

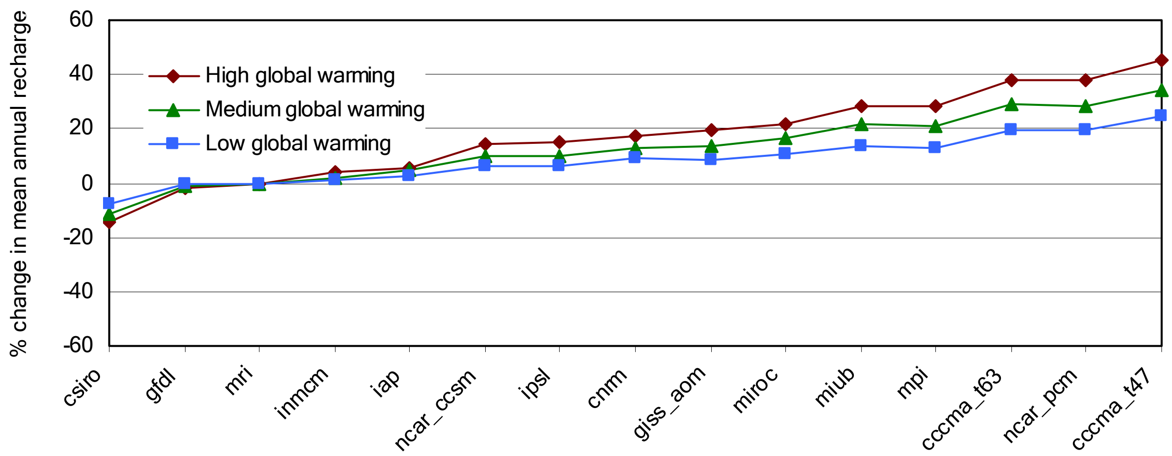


Figure DA-32. Percentage change in mean annual recharge under the 45 Scenario C simulations (15 global climate models and three global warming scenarios) relative to Scenario A recharge

Table DA-5. Summary results under 45 Scenario C simulations (numbers show percentage change in mean annual rainfall and recharge under Scenario C relative to Scenario A)

High global warming			Medium global warming			Low global warming		
GCM	Rainfall	Recharge	GCM	Rainfall	Recharge	GCM	Rainfall	Recharge
csiro	-12%	-14%	csiro	-10%	-12%	csiro	-7%	-8%
gfdl	**-14%**	**-2%**	gfdl	-11%	-1%	gfdl	-7%	-1%
mri	-4%	0%	mri	-3%	0%	mri	-2%	-1%
inmcm	0%	4%	inmcm	0%	2%	inmcm	0%	1%
iap	-2%	6%	iap	-2%	5%	iap	-1%	3%
ncar_ccsm	3%	14%	ncar_ccsm	2%	10%	ncar_ccsm	2%	7%
ipsl	1%	15%	ipsl	1%	10%	ipsl	1%	6%
cnrm	1%	17%	**cnrm**	**1%**	**13%**	cnrm	1%	9%
giss_aom	2%	20%	giss_aom	1%	13%	giss_aom	1%	9%
miroc	4%	22%	miroc	3%	17%	miroc	2%	11%
miub	3%	28%	miub	2%	21%	miub	2%	14%
mpi	2%	29%	mpi	2%	21%	mpi	1%	13%
cccma_t63	9%	38%	cccma_t63	7%	29%	cccma_t63	5%	20%
ncar_pcm	**11%**	**38%**	ncar_pcm	8%	28%	ncar_pcm	6%	20%
cccma_t47	12%	45%	cccma_t47	9%	34%	cccma_t47	6%	24%

Under Scenario Cwet recharge increases 38 percent reasonably uniformly across the region. Under Scenario Cmid recharge increases 13 percent, although the north-west of the region is calculated to have a small decrease in recharge. Under Scenario Cdry recharge decreases overall 2 percent with the greatest decrease in the north-west.

DA-3.2.4 Confidence levels

The estimation of recharge from WAVES, as done here, is only indicative of the actual recharge and has not been validated with field measurements. A steady state groundwater chloride mass balance was conducted as an independent measure of recharge (Crosbie et al., 2009). The results in the Daly show that the historical estimate of recharge using WAVES (153 mm/year) is toward the upper end of the range of estimates made using the chloride mass balance (10 to 158 mm/year). The WAVES estimate is considerably higher than the best estimate using the chloride mass balance (64 mm/year).

DA-3.3 Conceptual groundwater models

The major hydrogeological feature of the Daly region is the Cambrian-Ordovician Daly Basin comprising the Tindall Limestone, Jinduckin Formation and the Oolloo Dolostone. Early Cretaceous rocks overlie much of the Oolloo Dolostone and large areas of the Tindall Limestone to the south-east (Figure DA-2).

The aquifers of the Oolloo Dolostone and the Tindall Limestone are typical of karstic aquifers where chemical weathering has produced widespread secondary porosity and permeability in the carbonates. The carbonate aquifers are expected to have greatest permeability within the weathered zone, up to a maximum of 200 m below the surface. The karstic nature of the aquifers means that on a local scale groundwater flow is via preferential pathways. However, on a basin-wide scale the aquifers are considered to behave as an equivalent porous media with very high transmissivities (5000 m^2/day for the Tindall and 10,000 m^2/day for the Oolloo) and relatively low storage with estimates ranging from 0.01 to 0.07.

The Jinduckin Formation overlies the Tindall Limestone and underlies the Oolloo Dolostone. Aquifers are only sparsely developed in this formation. The bulk of the formation is shale and siltstone with little fractured porosity. Minor cavernous and fractured rock aquifers are developed in the thicker dolostone beds. There are few aquifers in the upper part of the formation directly beneath the Oolloo Dolostone. The Jinduckin Formation confines the Tindall Limestone and it is in these areas that the groundwater is considered to be 'dead water', with the majority of the inputs/outputs of the system occurring in the unconfined regions of the Tindall Limestone at the edges of the Daly Basin.

The Cretaceous rocks consist predominantly of clay, claystone and sandy clay with lesser sandstone, sand and clayey sand. The thickest accumulations are preserved along the axis of the Daly Basin running from the north side of the King River down to the north-east side of the Daly River as far as Stray Creek (Tickell, 2002b). The main influence of the Cretaceous sediments is to reduce the recharge to the Oolloo Dolostone aquifer. The impact of reduced recharge depends on the lithology of the unit, which is predominantly clay/clayey sand, and on the subdued response of groundwater hydrographs for the bores located in areas where Cretaceous rocks cover the underlying carbonate aquifer. Water balance and hydrograph analysis indicates that recharge is approximately 25 percent of the recharge observed in areas with outcropping carbonates.

Recharge is via four mechanisms. The first is through direct recharge where water is added to the groundwater in excess of soil moisture deficits and evapotranspiration. This is the dominant mechanism in areas with Cretaceous cover. The second is through macropores where precipitation is preferentially 'channelled' through the unsaturated zone with limited interaction. The third mechanism is through localised indirect recharge where surface water can be channelled into karstic features such as dolines where it recharges the groundwater with virtually no interaction with the unsaturated zone. The fourth mechanism is when the stage height of the river exceeds the adjacent groundwater level in the aquifer. This is thought to be a minor component of the overall water budget.

The second mechanism (i.e. macropore flow) is thought to dominate in the Oolloo Dolostone, as there are few doline features in this formation. However, chloride mass balance analysis indicates that up to 75 percent of the water recharging the aquifer does not have appreciable interaction with the unsaturated zone.

Recharge to the groundwater of the Tindall Limestone is thought to be dominated by the second and third mechanisms, with considerable recharge occurring during exceptionally wet years when surface water flow is intercepted by the numerous dolines in the Katherine River area.

On a basin scale the groundwater flow within the Oolloo Dolostone is from the south-east to the north-west; locally the flow is to the Daly River. The majority of groundwater discharged to the Daly River from the Oolloo Dolostone occurs downstream of the gauging station at Dorisvale (G8140067).

The amount of recharge to an aquifer system can also be determined from data on dry season flows. Detailed analysis of gauged dry season instantaneous flow data for each year for which adequate records exist for gauging station G8140001 was reported by Jolly et al. (2000). The work was undertaken as it was recognised on examination of Katherine's rainfall record that the flow records for gauging stations in the Daly River catchment were biased towards above average rainfall years (Figure DA-33). These flow and rainfall data were used to predict regional groundwater discharges at G8140001 for the full period of Katherine's rainfall record (Jolly et al., 2000). The predicted discharges and gauged discharges are plotted on Figure DA-34. The predicted discharges were estimated to equate to a mean annual recharge rate of 90 mm for the period. This recharge rate applies to the relatively small area of outcropping Tindall Limestone in the Katherine area.

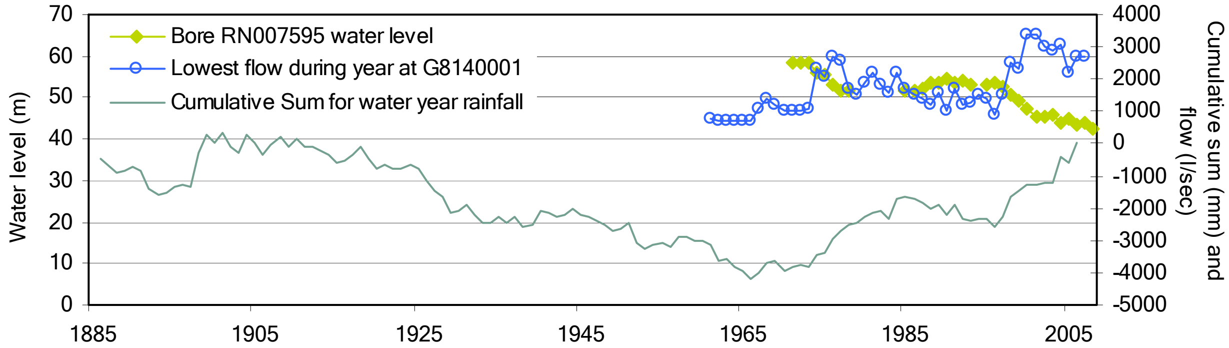


Figure DA-33. Discharge at gauging station G8140001 in the Daly region, with cumulative deviation from mean rainfall and water levels in nearby bore for each year of record

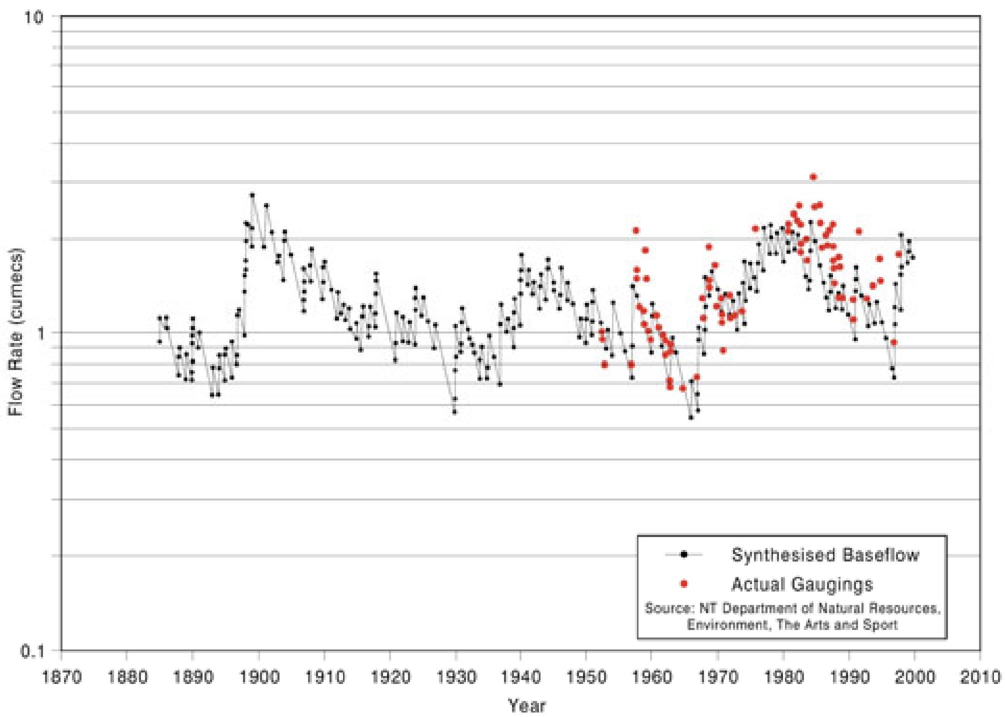


Figure DA-34. Flows from groundwater to river at gauging station G8140001 in the Daly region (after Jolly et al., 2000)

The technique gave a good match for data obtained in average and drier than average rainfall years. The technique, however, under estimated flow values in wetter years, because in higher rainfall years sinkholes become an important recharge source. The analysis undertaken by Jolly et al. (2000) assumed that diffuse recharge was the only source. Lauritzen and Karp (1993) identified seven sinkholes that act as stream sinks into the Tindall Limestone within 30 km of the Katherine River. Inspection of Figure DA-33 and Figure DA-34 provides confidence that the flow records for gauging stations in the Daly River catchment, while biased towards above average rainfall years, have captured groundwater discharge flow data for the full range of rainfall/recharge/discharge conditions likely to occur in the Daly River catchment.

The groundwater flow within the Tindall Limestone is from the south to the north where it discharges to the Katherine River, Flora River, Douglas River and Daly River along the bed of rivers and via discrete springs. Major discharges occur along the Flora River as it intercepts the much larger groundwater flows from the Wiso Basin. A smaller scale sub-basin is evident in the Katherine River area where a groundwater divide occurs roughly coincident with surface water catchment divide of the King River. Groundwater flow is towards the Katherine River from the divide to the south-east and from the area to the south-east of the Edith River. Similar small-scale sub-basins discharge into the Douglas River and Daly River.

Minor discharge from the groundwater is also through evapotranspiration from the riparian zone along the rivers.

DA-3.4 Groundwater modelling results

DA-3.4.1 Historical groundwater balance

The various components of the water balance, as they apply to the Daly region, are:

- inflow – rainfall recharge, inflows from adjacent aquifers
- outflow – discharge to rivers, evaporation and transpiration, groundwater pumping
- storage – unsaturated and saturated zones.

The main hydrological characteristic of this catchment is the great variability in rainfall from year to year, within a single year and over periods of years. This variability results in a similar great variability in both surface water runoff and groundwater recharge.

The period of record for most gauging stations and groundwater monitoring points within the catchment is biased towards a period of above average rainfall (based on the existing rainfall data). This needs to be considered when analysing flow and recharge data.

Evapotranspiration occurs from the trees, understorey, the ground surface and rivers. Data acquired by Hutley et al. (2001) suggest total evapotranspiration during the wet season for the Katherine area averages 3.1 mm/day. Annual tree water use, however, was estimated to be approximately 150 mm, suggesting a high water use from other evapotranspiration sources. Wet season pan evaporation rates averaged about 5.5 mm/day.

Jolly (2000) trialled a range of values for evapotranspiration for the recharge area for the Tindall Limestone aquifer in developing a model to predict historical groundwater-fed flows in the Katherine River at G8140001. A value of 150 mm was used for the maximum soil moisture deficit (difference between saturated and free draining moisture content of the profile above the watertable) during development of the model. A range of values was trialled for wet season daily losses (primarily due to evapotranspiration). A value of 5 mm/day was chosen in the model as it yielded the best correlation between gauged and predicted groundwater-fed river flows. Use of these values yielded a predicted mean annual potential recharge rate of 225 mm. This is considerably higher than the 90 mm estimated from the flow record. This difference is due to runoff being included in the figure derived for the potential recharge rate. Runoff data however exists for a nearby gauging station GS8140158 that has minimal groundwater-derived flow. G8140158 is located on Macadam Creek within 20 km of G8140001. Analysis of that data indicates that runoff is approximately 60 percent of the potential recharge rate calculated by Jolly (2000). If this figure was subtracted from the predicted mean annual potential recharge rate, the value for the mean annual recharge would be 90 mm.

Stewart et al. (1990) and O’Grady et al. (2002) reported late dry season losses in flow rates in the Katherine and Daly rivers ranging between 2.9 and 5 L/second/km length of river. The higher (5 L/second/km) values were determined for stretches of the Katherine and Daly rivers where groundwater inflow from and outflow to the river was deemed to be negligible due to the rivers incising very low permeability strata. The lower value (2.9 L/second/km) was calculated over a stretch of the Katherine River where the river was likely to be gaining inflow from the limestone strata incised by the river. These losses in flow rate were attributed to evaporation losses from the rivers and transpiration from their riparian zones.

Jolly et al. (2000) attempted to evaluate the amount of water lost via evapotranspiration from creeks, rivers, wetlands and their riparian zones. An allowance has to be made for additions to or losses from groundwater storage. However, the data contained in the table indicates the variability in the amount available each year.

No detailed work has been undertaken to quantify groundwater storage. Jolly (2000) estimated the amount of water in storage beneath the ground surface in the Daly Region based primarily on his extensive knowledge of the project area. The following estimates of storage have been extracted from his report.

The amount of water stored above the watertable varies according to the type of strata and the season. All strata in the catchment (Figure DA-2) have negligible primary porosity except where they have been extremely weathered. Based on data from boreholes drilled in the catchment it is probable that the average depth of this extremely weathered zone averages about 20 m. In most aquifers in the project area seasonal watertable fluctuations occur in this zone. However the change from unsaturated to saturated conditions usually results from the addition of only a small amount of water (up to 5 percent by volume) due to the clayey nature of most of the extremely weathered strata. The average water content of this 20 m zone would be expected to be about 25 percent by volume.

The porosity, and hence water content, of the strata below 20 m depends on the amount of weathered fractures or voids. The occurrence of these weathered fractures or voids depends on the composition of the strata in which they occur. The consistent factor for each type of strata is that the number of weathered fractures or voids decreases with depth. Averaged over the catchment, weathered fractures or voids would occupy about 2 percent by volume of the strata above 100 m depth and negligible amounts below 100 m.

Based on the above assumptions, the following estimates have been derived for the amounts of water stored in the various parts of the profile over the 52,600 km^2 of the Daly region:

- volume of water stored above and below the watertable is 350,000 GL
- volume of free draining water stored in the extremely weathered zone is 50,000 GL
- volume of adsorbed water stored in the extremely weathered zone is 220,000 GL
- volume of free draining water stored in the weathered zone is 80,000 GL
- mean volume of water added as recharge each year is 5000 GL.

DA-3.4.2 Groundwater model development

The Daly Basin groundwater/surface water model is based on a three-dimensional finite-element framework developed in the FEFLOW simulation code consisting of two layers, with the upper layer coupled to a MIKE11 river model which uses an implicit, finite difference scheme for the computation of unsteady one-dimensional flows in rivers and estuaries (DHI, 2005). The model was originally designed to examine the effects of groundwater extraction on river flows for the Tindall Limestone in the Katherine River area and the Oolloo Dolostone.

The FEFLOW model encompasses an area of approximately 159,000 km^2 and includes the entire extent of the Tindall Limestone in the Daly Basin and its equivalents in the northern Wiso Basin and northern Georgina Basin (Figure DA-5). The outer boundary of the basin and the model is considered no-flow.

Both of the major aquifers in the Daly Basin are karstic and are dominated by secondary porosity/permeability due to chemical weathering. For simplicity the system has been modelled as an equivalent porous media using calibrated regional aquifer parameters to reproduce the regional groundwater levels and observed discharge to the rivers.

The dominant recharge mechanism in the areas of outcropping Tindall Limestone and Oolloo Dolostone is via preferential pathways. This mechanism, however, is not well understood and is poorly represented numerically. Recharge was therefore estimated as diffuse recharge using a simple soil moisture deficit model using rainfall and estimated evapotranspiration. Comparison to groundwater level hydrographs and gauged flows, however, shows that this methodology does not quantifiably reproduce increases in recharge during wetter periods. Recent estimates of recharge have been determined using MIKE SHE which enables a more process-based estimate of recharge to be calculated including an estimate of bypass flow. Recharge is also expected during periods when the river stage height is greater than the groundwater level adjacent to the river where the river overlies the aquifers and the model simulates this process.

Recharge is applied to the model according to recharge zones. Each recharge zone was determined primarily from the underlying geology. The input recharge for this project was generated from the WAVES modelling and scaled to match the calibrated groundwater model recharge.

The groundwater model includes boundary conditions that define the interaction between the rivers and the groundwater system (transfer boundary nodes). The transfer in/out rates vary spatially across the model domain. Extraction for stock and domestic and horticultural use is simulated from the model domain via well boundary nodes.

The model was calibrated to match historical groundwater discharge and groundwater levels in monitoring bores in the area of the Tindall Limestone that contributes discharge to the Katherine River and the entire Oolloo Dolostone (refer. Figure DA-35) The rest of the model domain was calibrated to match steady state conditions and act as boundary conditions for the transient areas within the model domain.

The MIKE11 model encompasses the entire Daly River catchment (refer Figure DA-35). The upstream model boundaries to the surface water model consist of rainfall-runoff from the catchments using the NAM module within MIKE11. The conceptual NAM model treats each catchment as a single unit, allowing some of the model parameters to be evaluated from physical catchment data.

The calibration of the MIKE11 model involved adjusting the rainfall-runoff model parameters to ensure that recorded channel discharges estimates within the river system were simulated adequately. The simulated water levels were then calibrated to recorded levels by adjustment of the channel roughness parameter (Manning's 'n' parameter). The channel roughness was modified both laterally across the section and longitudinally down the river system.

Interaction between the groundwater and surface water model occurs where the MIKE11 channels are coupled to the FEFLOW transfer boundary conditions. The current understanding of the interaction between the river and aquifer is poor and it is assumed that the transfer rate in/out are equal.

Evapotranspiration from the riparian zone is estimated at approximately 3 mm/day. The evapotranspiration has not been explicitly considered in the FEFLOW model; however, evaporation is removed from the river via the coupled MIKE11 model using daily pan evaporation to simulate loss fluxes.

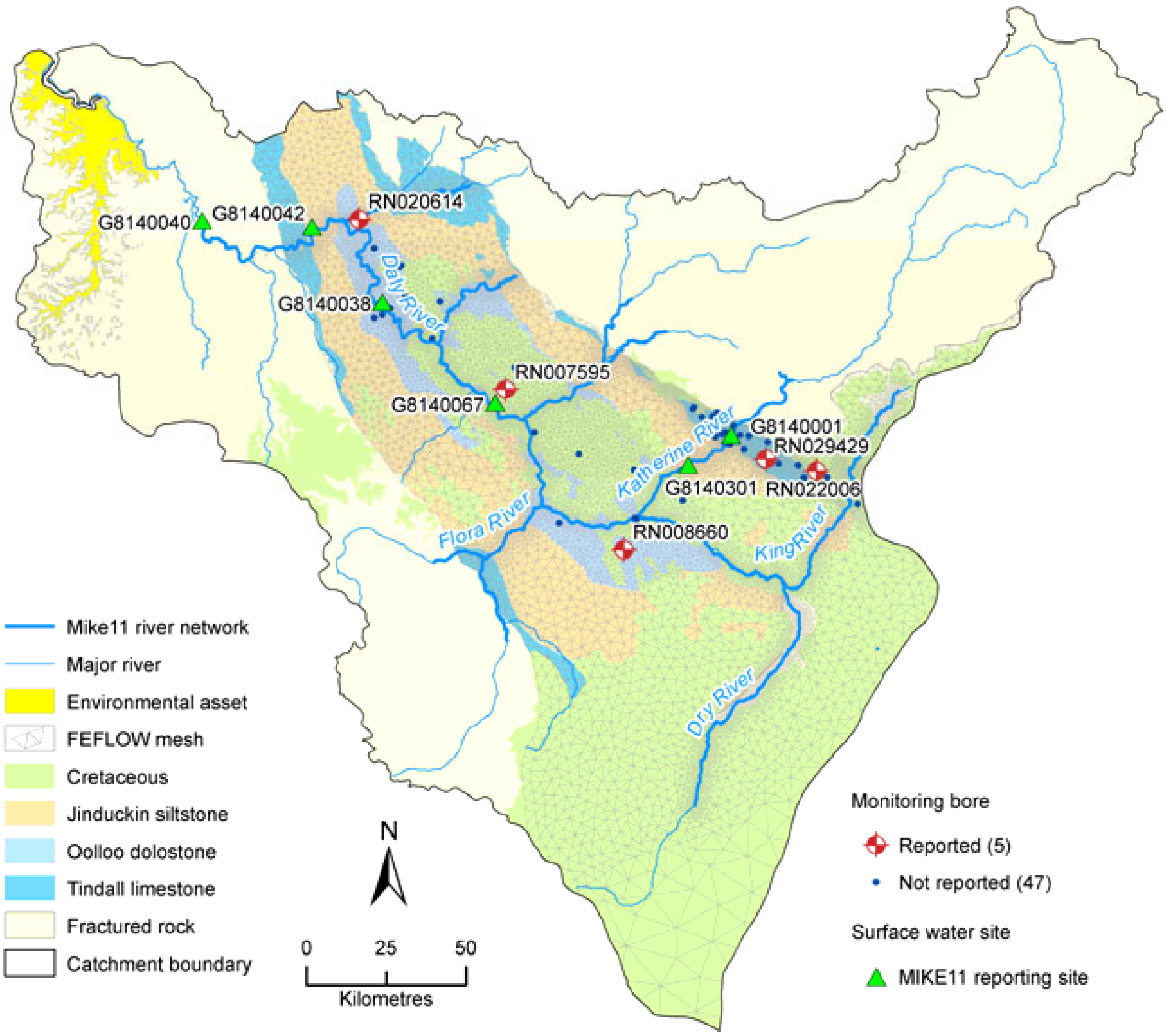


Figure DA-35. Groundwater and surface water model reporting sites for the Daly region

The coupled MIKE11-FEFLOW models were employed in the Northern Australia Sustainable Yields Project to evaluate water availability under each of the four scenarios A, B, C and D. Further details of model design and scenario implementation are provided in Knapton et al. (2009).

In the following sections, model-derived water levels are reported for five groundwater sites and three surface water sites (Figure DA-35). Two of the groundwater reporting sites are located within the Tindall Limestone in the Katherine River area representing areas with outcropping Tindall Limestone (RN029429) and where Cretaceous cover exists (RN022006). Three sites are located in the Oolloo Dolostone. Two are in areas where the dolostone outcrops (RN008660 and RN020614) and one where the Cretaceous cover exists (RN007595). The surface water sites are located at existing gauge stations and represent the total discharge from the Tindall Limestone in the Katherine River area (G8140301), the mid-reaches of the Daly River (G8140067) and the lower reaches of the Daly River (G8140040).

Model water balances are reported for two areas within the model domain: one corresponding to the area of unconfined Tindall Limestone that discharges to the Katherine River and the other area covering the entirety of the Oolloo Dolostone.

DA-3.4.3 Under historical climate

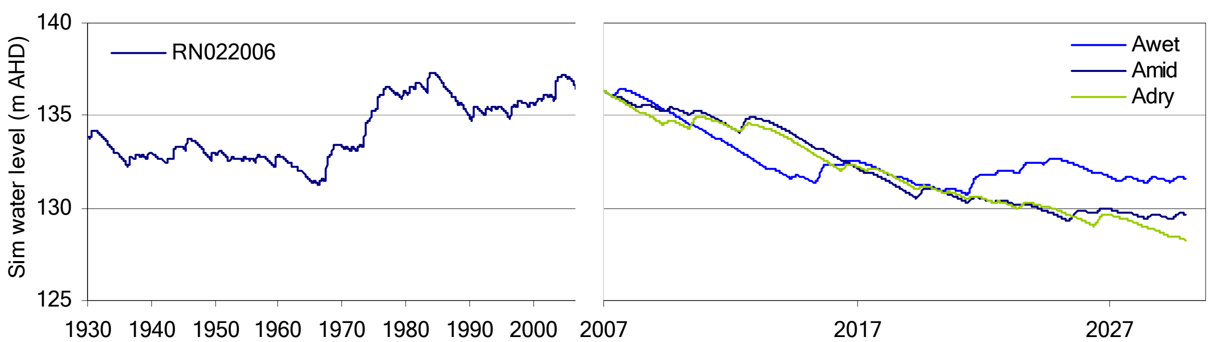
Under the historical climate (1930 to 2007) groundwater levels trended upward at each of the five reporting sites (Figure DA-36). The mean annual water balances for the historical record (Table DA-6 and Table DA-7) indicate that the model is in dynamic equilibrium with the differences between inputs and outputs ranging from 1 to 3 percent of the inputs. Median water levels for the entire 77-year period at each reporting site are presented in Table DA-8.

The groundwater level hydrographs reflect the different recharge conditions prevailing in the vicinity of each of the reporting sites (Figure DA-36). Bores RN029429, RN08660 and RN020614 are all located in areas where the carbonate aquifers outcrop; they all exhibit a more ‘peaky’ response and have considerably higher dynamic range than bores RN022006 and RN007595 which are located in areas overlain by Cretaceous cover. Bore RN020614 is close to the Daly River (Figure DA-35) and the groundwater hydrograph reflects the connectivity of the surface water and the groundwater. The lower level of the hydrograph is controlled by the water level in the river during the dry season resulting in a relatively steady trend in the overall level.

Modelling completed by Knapton (2006) indicates that in the case of the Tindall Limestone aquifer in the Katherine area there is a time lag between the commencement of extraction and the impacts of extraction on the discharge at the river. Bores sited more than 20 km from the river can expect to only have 50 to 60 percent of their extraction rate impact upon the river after a 20- to 30-year period.

Three 23-year periods were selected to represent natural variability under Scenario A: Adry (01 September 1940 to 31 August 1963), Amid (1 September 1978 to 31 August 2001), and Awet (01 September 1959 to 31 August 1982). Time series corresponding to these periods were clipped from the historical sequence and transposed to the new period from 01 September 2007 to 31 August 2030 for both the WAVES groundwater recharge time series and the NAM runoff time series.

(a)



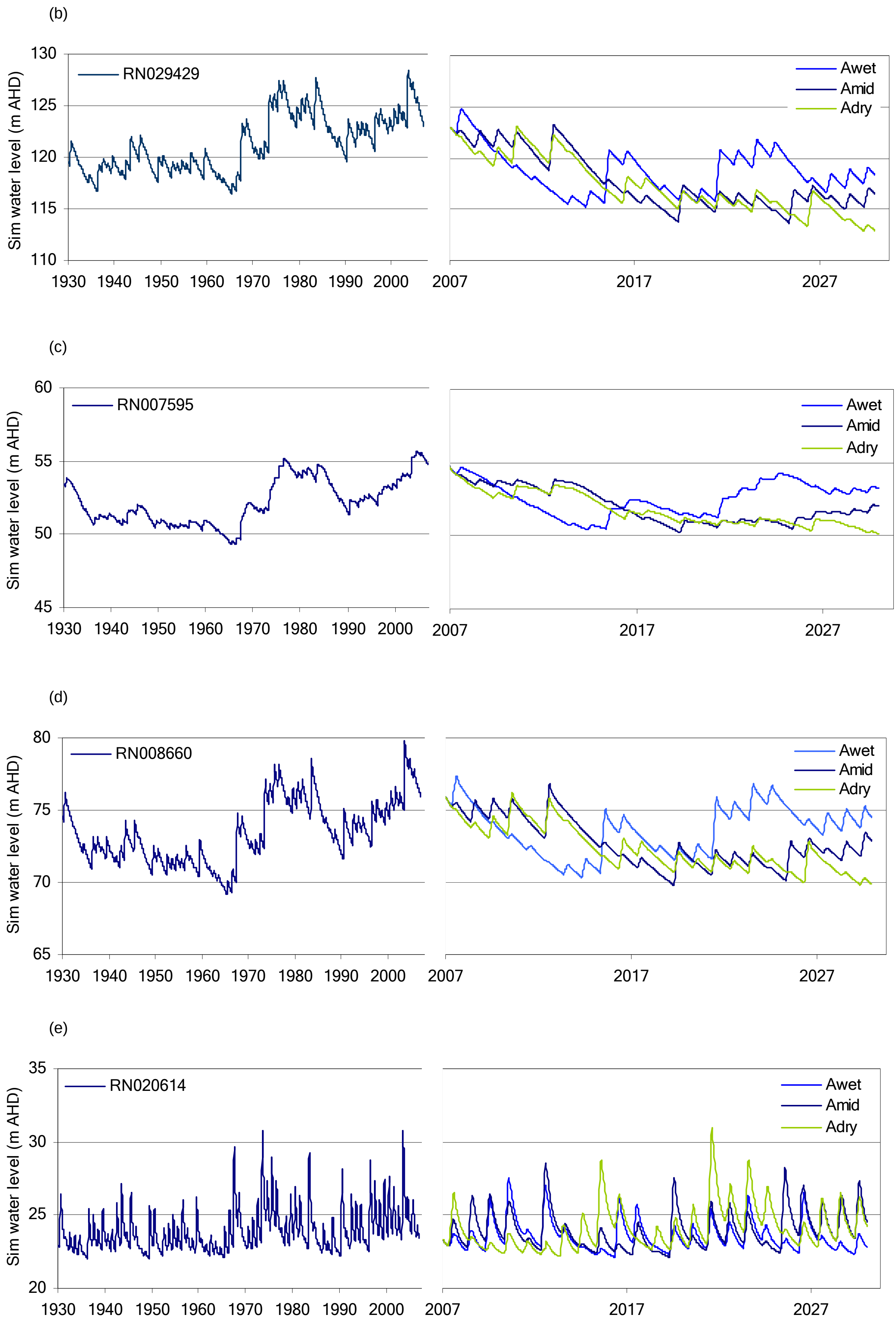


Figure DA-36. Simulated groundwater levels for selected observation bores in the Daly region for the warm-up period and Scenario A forecast

Table DA-6. Mean annual water balance for the Tindall Limestone in the Katherine River area under scenarios A, B, C and D

	Ahis	Awet	Amid	Adry	B	B'	C'wet	C'mid	C'dry	D'wet	D'mid	D'dry
	GL/y											
Recharge (gains)												
Rainfall	40.3	44.9	39.5	34.9	60.6	60.7	55.7	43.5	38.7	55.8	43.4	38.5
Cretaceous	3.8	4.5	4.7	4.7	3.5	3.5	4.0	4.6	4.9	4.0	4.6	5.0
From river	0.4	0.5	1.0	0.5	1.1	2.1	0.9	0.9	0.7	1.7	1.9	1.8
Sub-total	**44.5**	**49.9**	**45.1**	**40.1**	**65.3**	**66.3**	**60.6**	**49.1**	**44.3**	**61.6**	**49.9**	**45.2**
Discharge (losses)												
Extraction	-1.2	-27.9	-27.9	-27.9	-27.9	-27.9	-27.9	-27.9	-27.9	-35.8	-35.8	-35.8
To rivers	-42.0	-29.8	-27.9	-26.6	-38.6	-39.5	-34.0	-28.7	-26.0	-28.0	-22.7	-20.0
Sub-total	**-43.2**	**-57.7**	**-55.8**	**-54.5**	**-66.5**	**-67.4**	**-61.9**	**-56.6**	**-53.8**	**-63.8**	**-58.5**	**-55.8**
Change	1.3	-7.8	-10.7	-14.4	-1.3	-1.1	-1.3	-7.6	-9.5	-2.3	-8.6	-10.6

Table DA-7. Mean annual water balance for the Oolloo Dolostone under scenarios A, B, C and D

	Ahis	Awet	Amid	Adry	B	B'	C'wet	C'mid	C'dry	D'wet	D'mid	D'dry
	GL/y											
Recharge (gains)												
Rainfall	286.6	320.9	282.9	250.1	342.2	342.9	403.7	308.9	272.0	405.0	308.7	271.2
From river	39.9	41.2	47.2	31.1	54.9	86.2	44.9	44.8	39.4	46.7	46.6	41.7
Sub-total	**326.6**	**362.1**	**330.2**	**281.2**	**397.2**	**429.0**	**448.6**	**353.7**	**311.4**	**451.7**	**355.3**	**312.9**
Discharge (losses)												
Extraction	0.0	-16.8	-16.8	-16.8	-16.8	-16.8	-16.8	-16.8	-16.8	-43.8	-43.8	-43.8
To rivers	-331.4	-351.5	-327.2	-306.4	-388.7	-416.4	-403.2	-335.6	-301.7	-391.3	-322.2	-288.2
Sub-total	**-331.4**	**-368.3**	**-344.1**	**-323.2**	**-405.5**	**-433.2**	**-420.0**	**-352.5**	**-318.5**	**-435.2**	**-366.0**	**-332.1**
Change	-4.8	-6.1	-13.9	-42.0	-8.4	-4.1	28.5	1.2	-7.2	16.5	-10.7	-19.1

Table DA-8. Median water levels at selected monitoring sites under scenarios A, B, C and D

Bore	Ahis	Awet	Amid	Adry	B	B'	C'wet	C'mid	C'dry	D'wet	D'mid	D'dry
	m AHD											
RN029429	121.0	118.4	116.6	116.5	122.8	123.0	120.4	117.3	116.1	118.7	115.4	114.3
RN022006	133.6	132.1	131.3	131.7	136.1	136.1	133.5	131.5	130.3	133.3	131.3	130.2
RN007595	51.9	52.6	51.6	51.3	54.0	54.5	53.6	52.0	51.2	51.8	49.6	48.9
RN008660	73.1	73.9	72.3	71.9	76.0	76.6	74.8	73.0	71.8	70.4	67.9	67.0
RN020614	23.6	23.7	23.6	23.3	24.2	24.6	24.2	23.7	23.3	24.3	23.7	23.3

Under Adry average annual recharge reduces 16 percent (after scaling) compared to the historical period. The water balance under this scenario (Table DA-6 and Table DA-7) indicates that the sum of discharge to the river and extraction is greater than the recharge, so water is being lost from storage. The hydrographs reflect this deficit with falling trends in both the Katherine and Oolloo areas (Figure DA-36). Median groundwater levels (Table DA-8) also reflect the loss of groundwater from storage. Based on the continuing downward trend of all hydrographs it is expected that a new dynamic equilibrium is not met during the 23-year period but would occur within 5 to 7 years after 2030. Discharge to the Katherine River and the Daly River also continues to decline throughout the scenario (data not shown) reflecting the continued reduction in groundwater heads.

Under Amid average annual recharge reduces 3 to 4 percent compared to the historical period. Because the last decade of the modelled historical recharge time series was relatively high compared with earlier periods in the record, the initial groundwater levels for the start of the Scenario A simulations were high. As a result, groundwater levels typically drop from the start of the simulation until a new dynamic equilibrium level is reached after approximately 10 to 15 years (Figure DA-36).

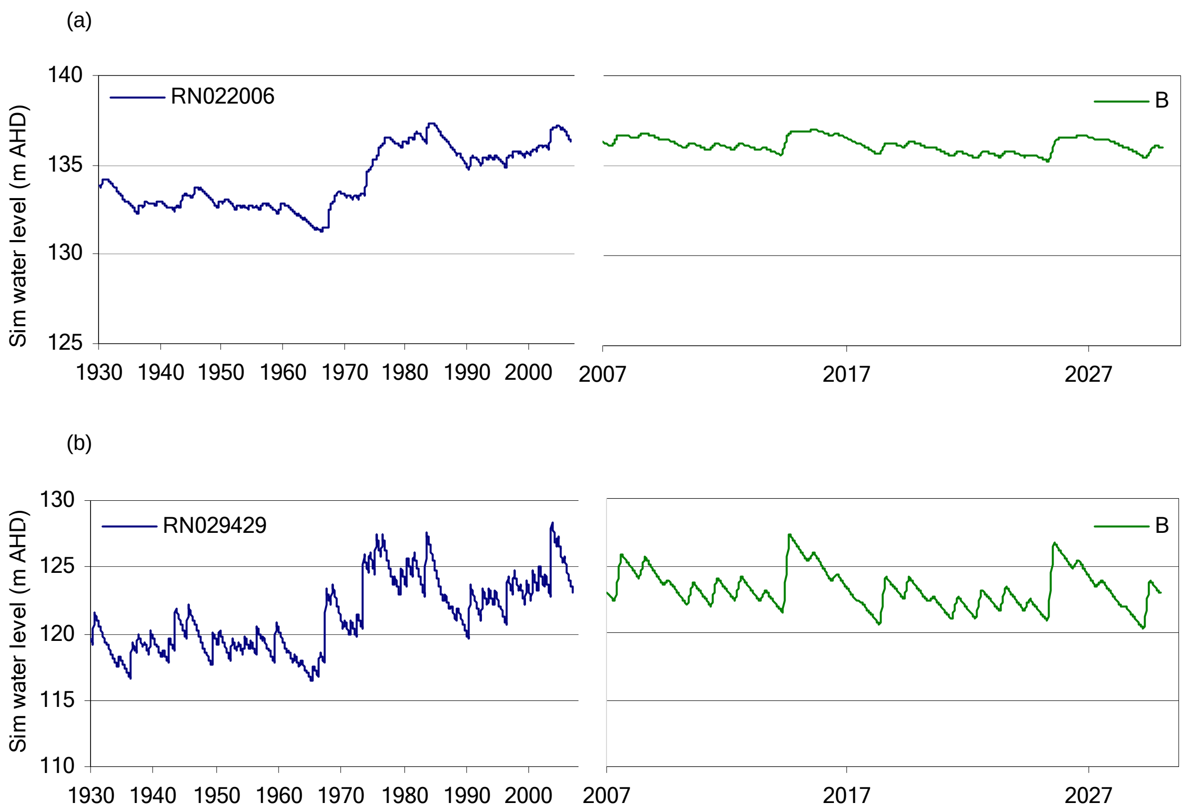
Under Awet average annual recharge increases 9 percent (after scaling) compared to the historical period. The elevated groundwater levels at the end of the historical period can not be sustained under this variant of Scenario A and a new equilibrium level is reached after approximately 5 to 10 years (Figure DA-36).

DA-3.4.4 Under recent climate

Scenario B uses the climate data from 01 September 1996 to 31 August 2007 to generate the WAVES recharge and NAM runoff data. The resulting recharge and runoff data were repeated three times to synthesise 33 years of data; 23 years of model results are presented here to enable reporting out to 2030.

Under Scenario B average annual recharge increases 48 percent in the Katherine River area and 16 percent in the Oolloo area, both compared to the historical record. The groundwater system should be in dynamic equilibrium given that it repeats the preceding 11 years; however the hydrographs for bores RN29429 and RN22006 in the Katherine River area (Figure DA-37) show a subtle downward trend. This is likely due to the intensive groundwater extraction occurring nearby.

Scenario B' is a variant of Scenario B that uses the same WAVES recharge time series, but the NAM runoff data are scaled to the Sacramento model results employed in the surface water analysis. This represents a 47 percent increase in recharge in the Katherine River area and a 15 percent increase in recharge in the Oolloo area. The main difference from the Scenario B simulation is that more groundwater recharge from the river and discharge to the river occurs as a result of the higher river levels generated through the Sacramento model.



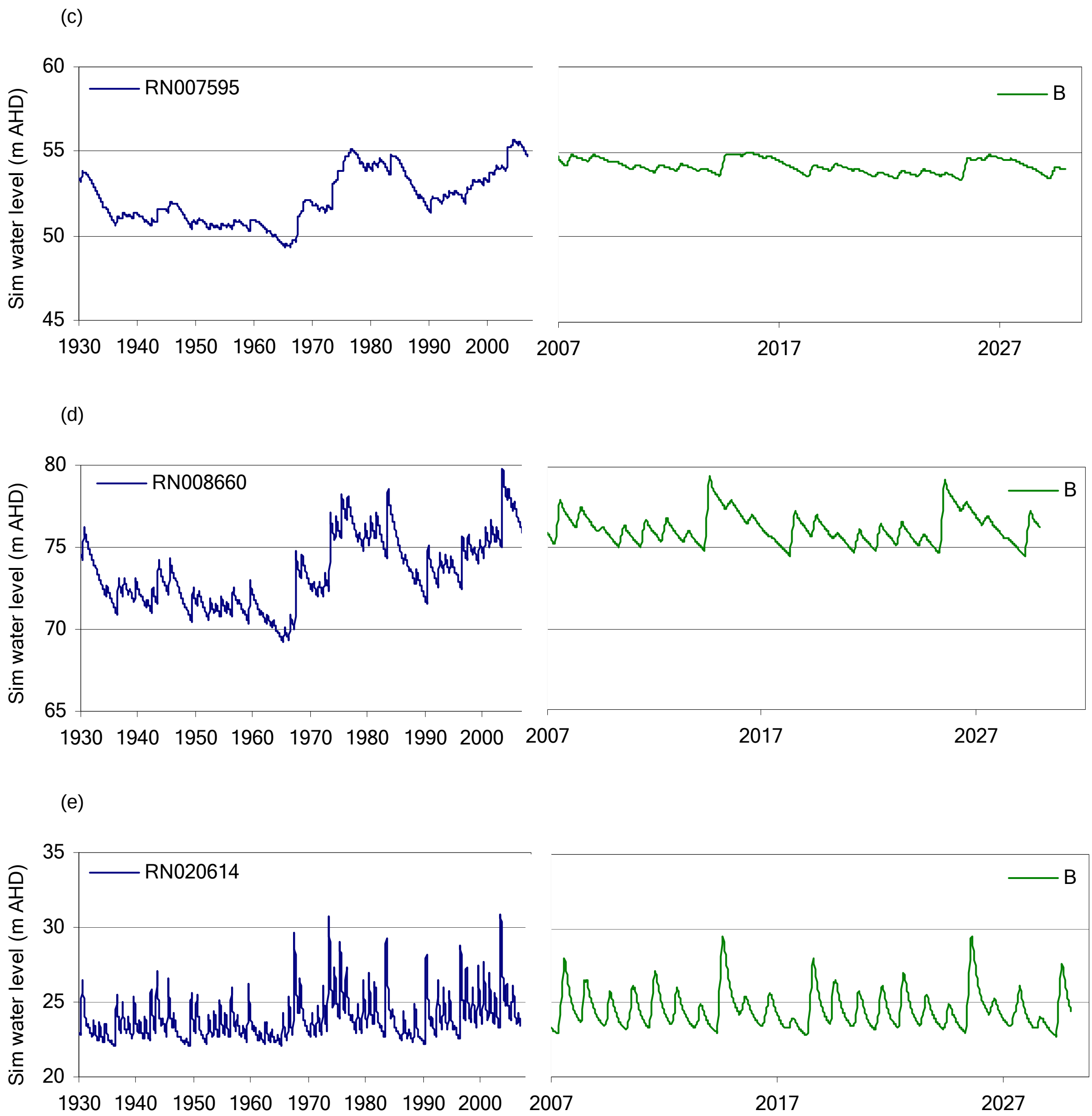


Figure DA-37. Simulated groundwater levels for selected observation bores in the Daly region for the warm-up period and Scenario B forecast

DA-3.4.5 Under future climate

Two future climate scenarios were modelled, one with current groundwater development (Scenario C) and the other with potential future groundwater development (Scenario D). Both use the same GCM climate data to generate the WAVES recharge and NAM runoff data. As in Scenario B' the NAM runoff data for scenarios C and D was scaled to the Sacramento model results employed in the surface water analysis by adopting the GCM results that were used to generate the WAVES recharge. Under the three variants of scenarios C' and D' (wet, mid and dry) there are changes in the average annual recharge of approximately -3 percent, 10 percent and 42 percent compared to Scenario Amid.

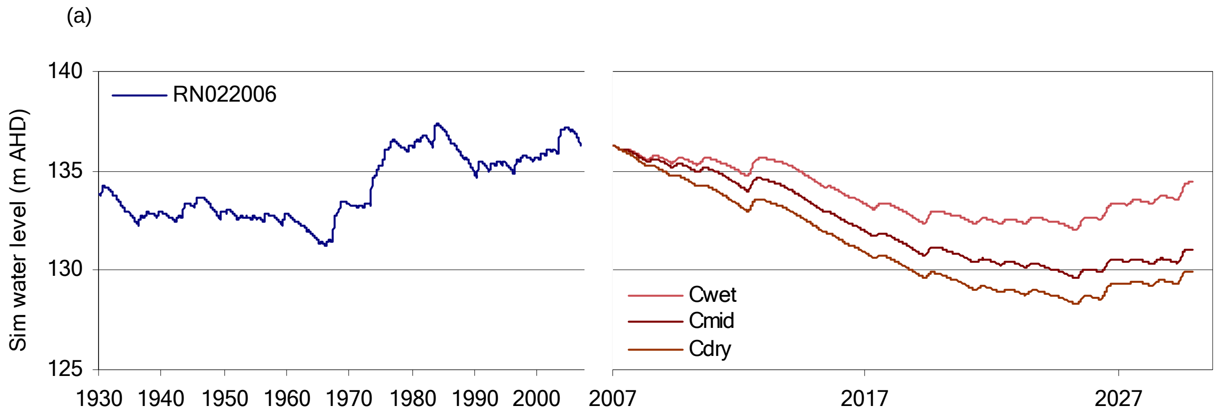
Scenario C' uses the scaled recharge and runoff and the current entitlements. Scenario D' uses the same recharge and runoff time series as Scenario C' but the future entitlements for groundwater extraction. A comparison of the total extraction for the Katherine and Oolloo areas implemented in the model for the various scenarios is presented in Table DA-9. In the Katherine area under Scenario D' extraction increases 7.9 GL/year or 28 percent over the total of 27.9 GL/year under Scenario C'. In the Oolloo area under Scenario D' extraction increases 37 GL/year or 160 percent over the figure of 16.8 GL/year under Scenario C'.

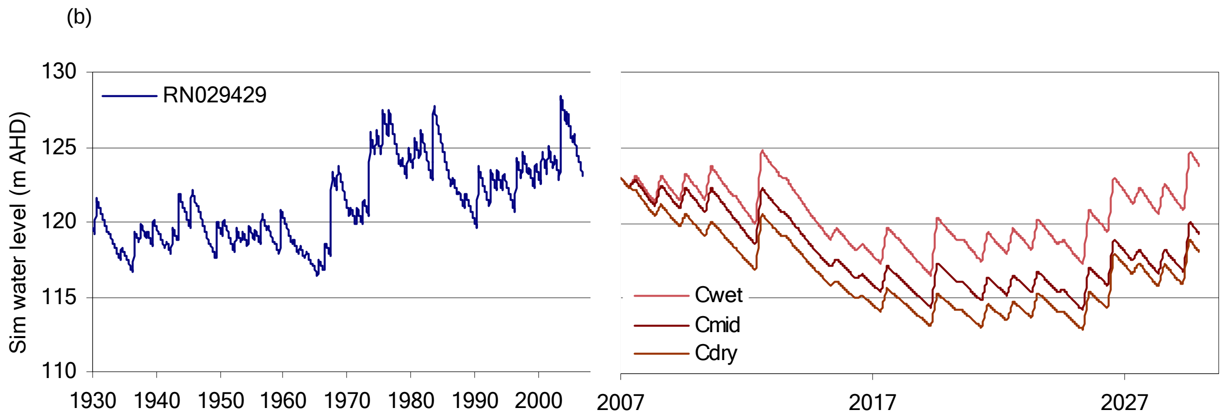
Table DA-9. Average annual extraction for the Katherine and Oolloo reporting areas of the Daly River Basin under scenarios A, B, C and D

Area	Ahis	A	B	B'	C'	D'
	GL/y					
Katherine	-1.2	-27.9	-27.9	-27.9	-27.9	-35.8
Oolloo	0.0	-16.8	-16.8	-16.8	-16.8	-43.8
Total	**-1.2**	**-44.7**	**-44.7**	**-44.7**	**-44.7**	**-79.6**

Simulated groundwater levels under Scenarios C' and D' are presented in hydrographs in Figure DA-38 and Figure DA-39 respectively. Median groundwater levels for the simulation period are also provided in Table DA-8. The Scenario C' forecasts are very similar to those under Scenario A (Figure DA-36). However, the individual groundwater level hydrographs for each of the three variants of scenarios C' and D' show much greater similarity than those under Scenario A. This reflects the methodology used to generate the three recharge time series for each scenario. The groundwater level hydrographs respond in a manner that would be expected for the three variants, that is, the wet variant results in the highest groundwater levels, the dry variant results in the lowest groundwater levels and the mid variant results in groundwater levels somewhere between the two extremes. Based on the groundwater level hydrographs both scenarios appear to reach dynamic equilibrium after approximately 10 to 15 years.

Groundwater levels under Scenario C' are generally comparable to or higher than under Scenario Amid. In contrast the water levels under Scenario D' are generally lower than those under Scenario Amid except at bore RN022006. The groundwater levels for the Oolloo Dolostone aquifer are most notably affected and reflect the significant increase in extraction.





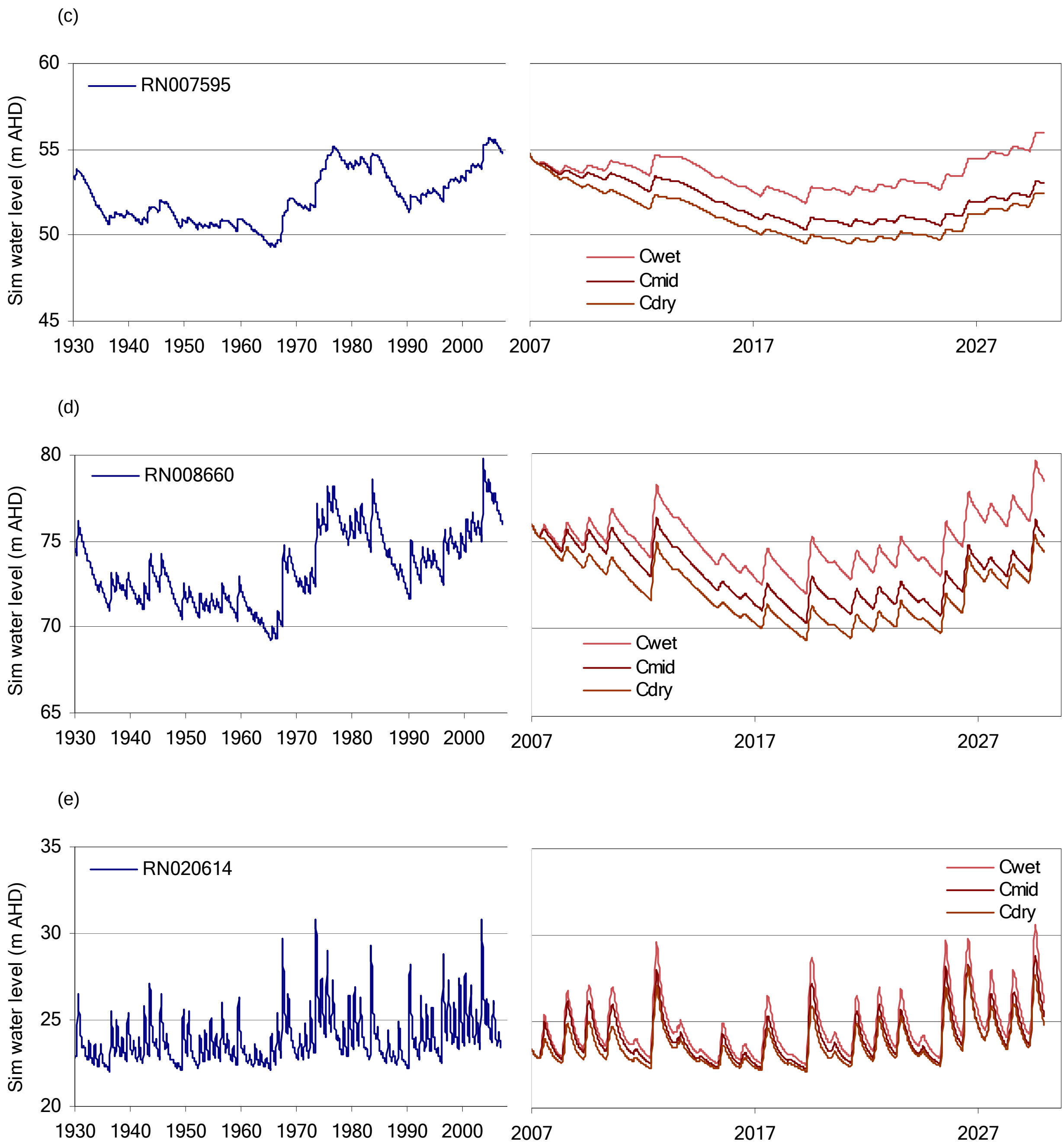
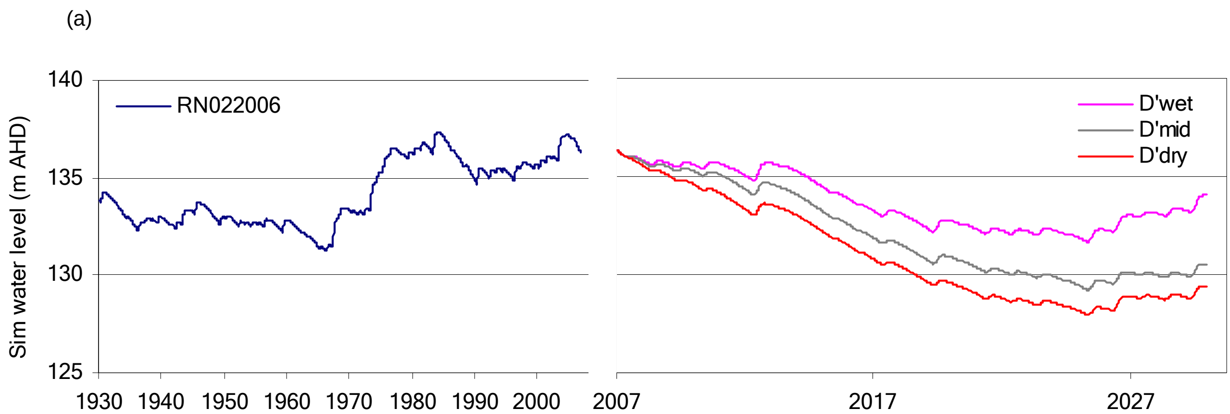


Figure DA-38. Simulated groundwater levels for five bores in the Daly region for the warm-up period and Scenario C forecast



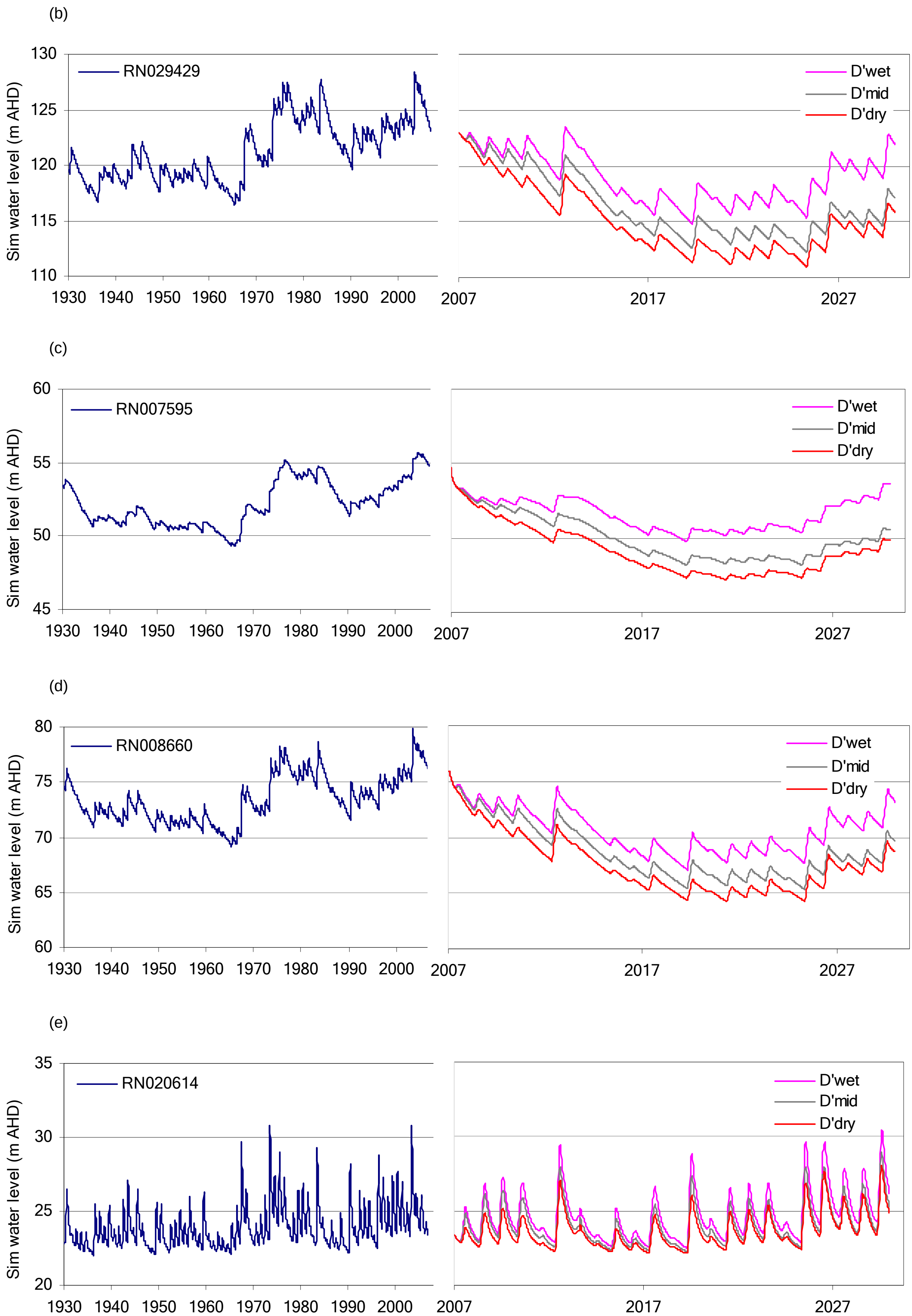


Figure DA-39. Simulated groundwater levels for five bores in the Daly region for the warm-up period and Scenario D forecast

The water balances for the Katherine and Oolloo areas under scenarios C’ and D’ are presented in Table DA-6 and Table DA-7. The water balance for the Katherine area shows an increase in the imbalance of the system between the two scenarios by 1 GL/year for all of the scenario variants due to the increase in extraction. The water balances for the Oolloo Dolostone aquifer also reflect the increased extraction with an increase in the imbalance of approximately 12 GL/year between scenarios C’ and D’.

In the Katherine area discharge to the Katherine River decreases by approximately 6 GL/year between the two scenarios; this volume equates to a reduction of 23 percent, 21 percent and 18 percent from the discharge reported under scenarios C’dry, C’mid and C’wet respectively. In the Oolloo area there is a 12 to 13 GL/year reduction in discharge to the Daly River which is a reduction of 4 percent, 4 percent and 3 percent from the discharge reported under scenarios C’dry, C’mid and C’wet respectively. However, despite this decrease in discharge there is only a 1 to 2 GL/year increase in the recharge from the river to the aquifers in both areas.

DA-3.4.6 Water quality

In the Daly region, baseflow contributions from groundwater support surface water flows during the dry season. The groundwater in this region is extremely fresh, with more than 80 percent of all groundwater samples having electrical conductivities less than 1000 µS/cm. Increases or decreases in groundwater discharge, slight increases in groundwater salinity or minor contaminant introduction (i.e. fertilizers, agrochemicals) to the aquifer systems may harmfully impact the unique ecosystems of the Daly River and its tributaries.

Groundwater chemistry data for 1640 samples collected from the Oolloo, Jinduckin and Tindall formations were interpreted to better understand the geochemistry of these systems. Particular focus was placed on determining solute sources and solute mobility both within and between these aquifer units. Groundwater in the Oolloo and Tindall formations has the lowest total dissolved solids (TDS), with major element composition dominated by calcium (Ca^{2+}) and bicarbonate (HCO_3^-). Ca/HCO_3 molar ratios of about 0.5 and HCO_3^-/Cl ratios greater than 10 indicate that solutes in these aquifer units are sourced from carbonate mineral weathering. Higher groundwater salinities occur in the Jinduckin Formation where major element compositions are dominated by Ca^{2+} and sulphate (SO_4^{2-}). The evaporite mineral anhydrite ($CaSO_4$) is common in this formation and Ca/SO_4 molar ratios trending towards 1 for higher salinity (TDS) samples indicate that dissolution of calcium- and sulphate-bearing minerals (likely anhydrite) accounts for the higher TDS (mg/L) values in groundwater sampled from this formation. Groundwater chemistry data for the overlying Oolloo and underlying Tindall Formation suggests some degree of connectivity (i.e. mixing) with the Jinduckin Formation. This has direct consequences on the mobility of contaminants (fertilizers and agrochemicals) as all three units outcrop the surface within the Daly region. Contaminants, especially nitrate, if introduced into one aquifer unit have the potential to migrate into an adjacent unit(s) and potentially into surface water systems.

Increases in the availability of nitrogen are generally followed by decreases in biodiversity of ecosystems. In addition to fertilizer application, nitrogen availability can be increased by biomass burning and land clearing. Ammonium and nitrate concentrations of unsaturated zone soil water were measured by Wilson et al. (2006) in the Douglas Daly region. Ammonium concentrations (1 to 14 mg/L) peaked in near surface soils and were attributed to decomposition of organic mater. Unsaturated zone nitrate concentrations >5 mg/L were reported from 2 to 5 m beneath recently cleared land that had not yet been fertilized. This suggests that the NO_3^- may have been sourced from the oxidation of soil organic nitrogen through either biomass burning and/or land clearing then displaced downward by the enhanced recharge. Globally, these processes are thought to mobilise over 60 million metric tons of nitrogen from the soil zone (<1 m) per year (Vitousek et al., 1997). Although soil water solute data are very limited, the presence of nitrate beneath cleared land, whereas little to no nitrate was present beneath uncleared land, suggests that natural soil nitrogen may be mobilised following clearing and could be transported by the groundwater systems to the surface water ecosystems of the Daly region. Nitrate (NO_3^-) concentrations are reported for 26 percent and 28 percent of the groundwater sampled from the Oolloo and Tindall formations, respectively. NO_3^- concentrations are only reported for 12 percent of the groundwater sampled from the Jinduckin Formation. NO_3^- levels range from zero to 11 mg/L (median 2 mg/L) for the Oolloo, zero to 40 mg/L (median 1 mg/L) for the Jinduckin and zero to 26 mg/L (median 1 mg/L) for the Tindall formations. Eight percent of the total number of samples analysed for NO_3^- had concentrations that exceeded the 5 mg/L limit set by the Australian and New Zealand Environment and Conservation Council (ANZECC) guideline for long-term environmental sustainability.

The mobility of nitrate in the subsurface is highly dependent on the geochemical conditions of the groundwater system. The presence of electron donors such as dissolved organic carbon (DOC), Mn^{2+}, Fe^{2+} or S^{2-} creates thermodynamically favourable conditions for the reduction of NO_3^- to N_2 or NH_4^+. However, elevated dissolved oxygen (DO) may decrease nitrate attenuation as oxygen is the more thermodynamically favoured electron acceptor than NO_3^-. Of the common electron donors in natural waters, only iron (reported as total iron, which is the total of Fe^{2+} and Fe^{3+}) is reported for 70 percent of the groundwater sampled from the Oolloo, Jinduckin and Tindall formations. Groundwater sampled from the Jinduckin Formation exhibited the highest total iron concentrations, which ranged from zero to 128 mg/L (median 0.8 mg/L). This is in contrast to the Oolloo and Tindall where total iron ranged from zero to 20 mg/L (median 0.5 mg/L) and zero to 89 mg/L (median 0.3 mg/L), respectively. No measurements exist for DO, Mn^{2+} or S^{2-} concentrations in groundwater. Therefore it is not possible to assess the nitrate attenuation capacity of the aquifer systems in the Daly region. However, from the existing data, the higher total iron levels in groundwater sampled from the Jinduckin Formation suggest that this aquifer unit has a greater nitrate reduction capacity than the Oolloo of Tindall aquifers.

DA-3.4.7 Confidence levels

Current limitations of the coupled Daly Basin model are:

- The recharge and runoff components of the surface water budget are not interlinked. The water budget for the various components indicate that they are, however, relatively consistent.
- Recharge is assumed to be diffuse; however, bypass flow via macropores/sinkholes is known to be a dominant recharge mechanism. It is expected that for the years with above average rainfall that the WAVES recharge will under estimate actual recharge.
- Areas where the Tindall Limestone is confined by the Jinduckin Formation are not adequately represented. Development of groundwater resources in regions where bores access groundwater in the Tindall Limestone beneath the Jinduckin Formation cannot be assessed. The model currently assumes that storage loss results in a direct reduction in groundwater level in the unconfined areas of each aquifer.
- Actual river–aquifer interactions are poorly understood, especially with respect to the flows from the river to the groundwater system.

Greater knowledge of the redox conditions in the Oolloo, Jinduckin and Tindall aquifer units is required to assess the nitrate attenuation capacity of these systems. Field measurements of Eh, dissolved oxygen, ferrous iron, manganese and sulphide are needed to establish the presence of suitable electron donors for nitrate reduction to N_2 or ammonium (NH_4^+).

DA-3.5 Rainfall-runoff modelling results

In this section the term runoff is the sum of overland flow, interflow and baseflow. It is equivalent to streamflow expressed as a mm depth equivalent. All plots show data averaged over the modelled subcatchments of the Daly region. For this reason rainfall reported in this section may vary slightly from that reported elsewhere due to differences between the catchment boundaries (shown in Figure DA-1) and the DEM-derived catchment boundaries used here. In this section, where annual data are reported years are represented by numbers 1 through 77. Consistently throughout this report, annual data are based on the water year (1 September to 31 August) and the dry season is defined as 1 May to 31 October. Unless stated otherwise scenarios Cwet, Cmid and Cdry are selected on the basis of the ranked mean annual runoff. For more details on methods refer to Section 2.2 of the division-level Chapter 2.

DA-3.5.1 Regional synopsis

The rainfall-runoff modelling estimates runoff in 0.05 degree grid cells in 15 subcatchments (Figure DA-40). Subcatchments correspond to those used in the MIKE11 river modelling (Section DA-3.6). Optimised parameter values from nine calibration catchments are used. Eight of these calibration catchments are in the Daly region and one is to the north in the Van Diemen region. There is a reasonably good distribution of station in the Daly region, although there tends to be more stations in the north than the south. Stations G8140040 and G8140067 are calibrated to the residual flow (i.e. the difference in flow between the upstream stations and the downstream station) using monthly streamflow data as described in Section 2.2.2 in the division-level Chapter 2. In the south-eastern portion of the Daly region a discrepancy between the Australian Water Resources Council (AWRC) river basin boundary layer and the DEM-derived catchment boundaries is evident (Figure DA-40).

DA-3.5.2 Model calibration

Figure DA-41 compares the modelled and observed monthly runoff and the modelled and observed daily flow exceedance curves for the eight calibration catchments. Nash-Sutcliffe efficiency (NSE) values provide a quantitative measure of how well simulated values match observed values. NSE values are described in more detail in Section 2.2.3 of the division-level Chapter 2. On the monthly plots NSE is the monthly Nash-Sutcliffe efficiency value and NSE (dry season) is the dry season monthly Nash-Sutcliffe efficiency value. On the daily flow exceedance plots, NSE is the daily flow exceedance curve Nash-Sutcliffe efficiency value and NSE (50 to 100 percent) is the lower half of the daily flow exceedance curve Nash-Sutcliffe efficiency value.

The results indicate that the ensemble calibration can reasonably reproduce the observed monthly runoff series (NSE values generally greater than 0.9) and the daily flow exceedance curve (NSE values generally greater than 0.95). The volumetric constraint used in the model calibration also ensures that the total modelled runoff is within 5 percent of the total observed runoff.

The calibration method places more importance on the simulation of high runoff, and therefore rainfall-runoff modelling of the medium and high runoff is considerably better than the modelling of low runoff. It should be noted, however, that while the relative difference between the observed and simulated low flow values may be large (which is what gives rise to the low monthly dry season NSE values for example), the absolute difference between the observed and simulated low flow values is generally small because both values are small. Nevertheless, an optimisation to reduce overall error variance can result in some underestimation of high runoff and overestimation of low runoff. This is evident in some of the scatter plots comparing the modelled and observed monthly runoff and many of the daily flow exceedance curves. For the majority of calibration catchments the disagreement between the modelled and observed daily runoff curves is discernable for runoff that is exceeded less than 1 percent of the time. This is accentuated in the plots because of the linear scale on the y-axis and normal probability scale on the x-axis. In any case, the volumetric constraint used in the model calibration ensures that the total modelled runoff is always within 5 percent of the total observed runoff. As indicated by the relatively low NSE values for the lower half of the daily flow exceedance curve and monthly dry season, there may be considerable disagreement between observed and modelled low flow values (i.e. cease-to-flow).

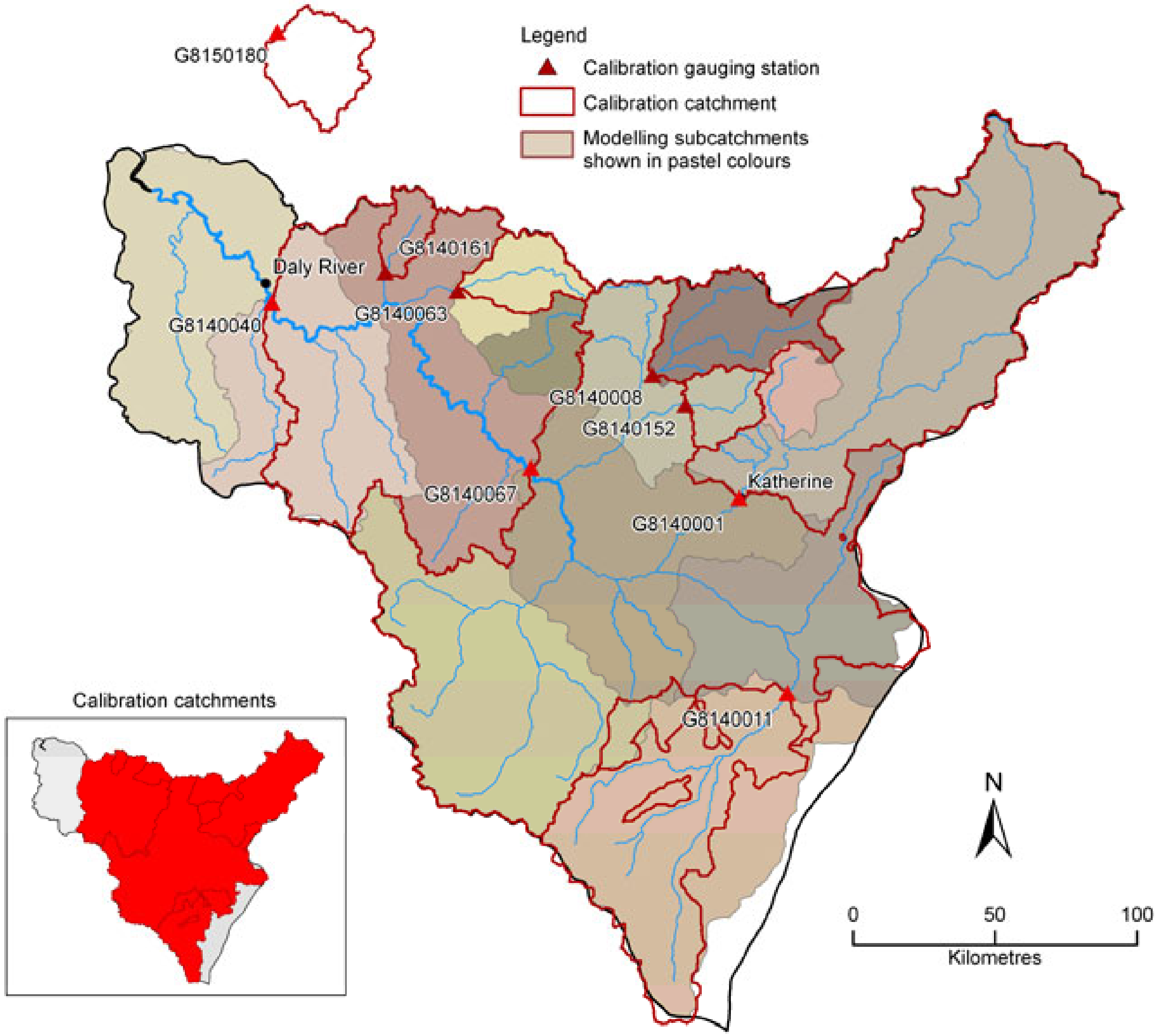


Figure DA-40. Map of the modelling subcatchments, calibration catchments and calibration gauging stations fused or the Daly region with inset highlighting (in red) the extent of the calibration catchments

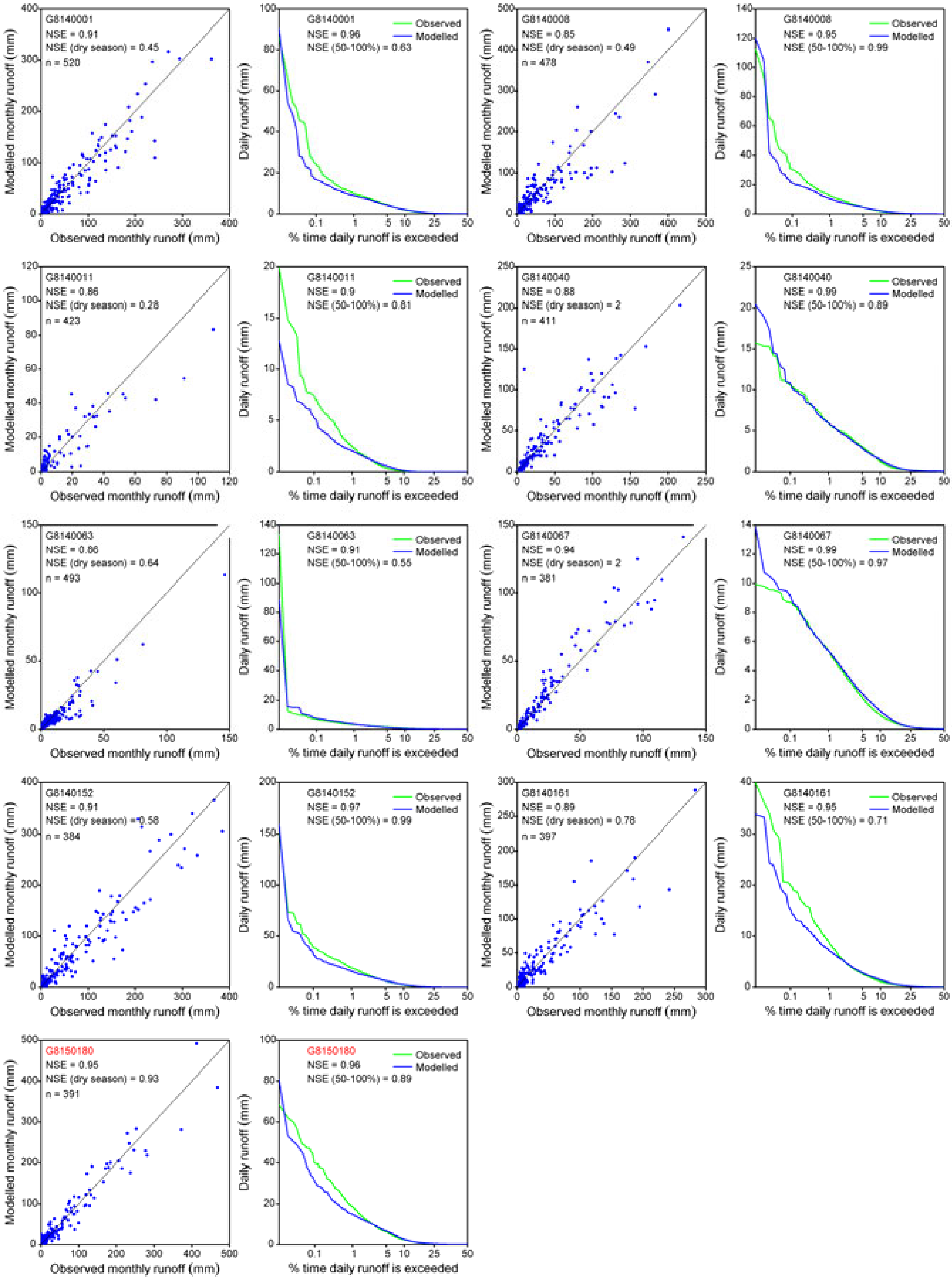


Figure DA-41. Modelled and observed monthly runoff and daily flow exceedance curve for each calibration catchment in the Daly region. (Red text denotes catchments located outside the region; blue text denotes catchments used for surface water modelling only)

DA-3.5.3 Under historical climate

Figure DA-42 shows the spatial distribution of mean annual rainfall and runoff under Scenario A (averaged over 1930 to 2007) across the Daly region. Figure DA-43 shows the mean annual rainfall and runoff averaged over the region. The blank space in the runoff grid is due to a discrepancy between the AWRC river basin boundaries and the DEM-derived catchment boundaries.

The mean annual rainfall and runoff averaged over the averaged over the Daly region are 1027 mm and 159 mm respectively. The mean wet season and dry season runoff averaged over the Daly region are 149 mm and 10 mm respectively.

In this project, all runoff grids are presented as long-term mean annual values. However, the distributions of monthly and annual runoff data in northern Australia are highly skewed; consequently the median and additional percentile values spatially averaged over the region are also reported. The 10th percentile, median and 90th percentile annual runoff values across the Daly region are 314, 135 and 43 mm respectively. The median wet season and dry season runoff averaged over the Daly region are 127 mm and 9 mm respectively.

The mean annual rainfall varies from about 1500 mm in the north-east to 700 mm in the south-east. Upstream of the lowest gauge in the catchment (G8140040 at Mount Nancar), the mean annual runoff varies from over 300 mm in the upper reaches of the Katherine River to less than 30 mm in the Dry River (Figure DA-42). Runoff coefficients in the Daly region vary from 3 percent to about 30 percent of rainfall. The majority of rainfall and runoff occurs during the wet season months December to April (Figure DA-43). Rainfall and runoff can vary considerably from year to year with long periods over several years or decades that are considerably wetter or drier than others (Figure DA-43). The coefficients of variation of annual rainfall and runoff averaged over the Daly region are 0.22 and 0.69 respectively.

The Daly is one of 13 regions which cover the three divisions studied in this project. Mean annual rainfall and runoff, as well as coefficients of variation, have been calculated for all of these 13 regions, and it is useful to compare the Daly results to results across all 13 regions. Across all 13 regions in this project 10th percentile, median and 90th percentile values are 1371, 936 and 595 mm respectively for mean annual rainfall and 374, 153 and 78 mm respectively for mean annual runoff. The mean annual rainfall (1027 mm) and runoff (159 mm) averaged over the Daly region fall in the middle of this range. Across all 13 regions in this project the 10th, median and 90th percentile values are 0.34, 0.26 and 0.19 respectively for the coefficient of variation of annual rainfall and 1.39, 0.69 and 0.48 for the coefficient of variation of runoff. The coefficient of variation of annual rainfall (0.22) and runoff (0.69) averaged over the Daly region are in the middle of this range.

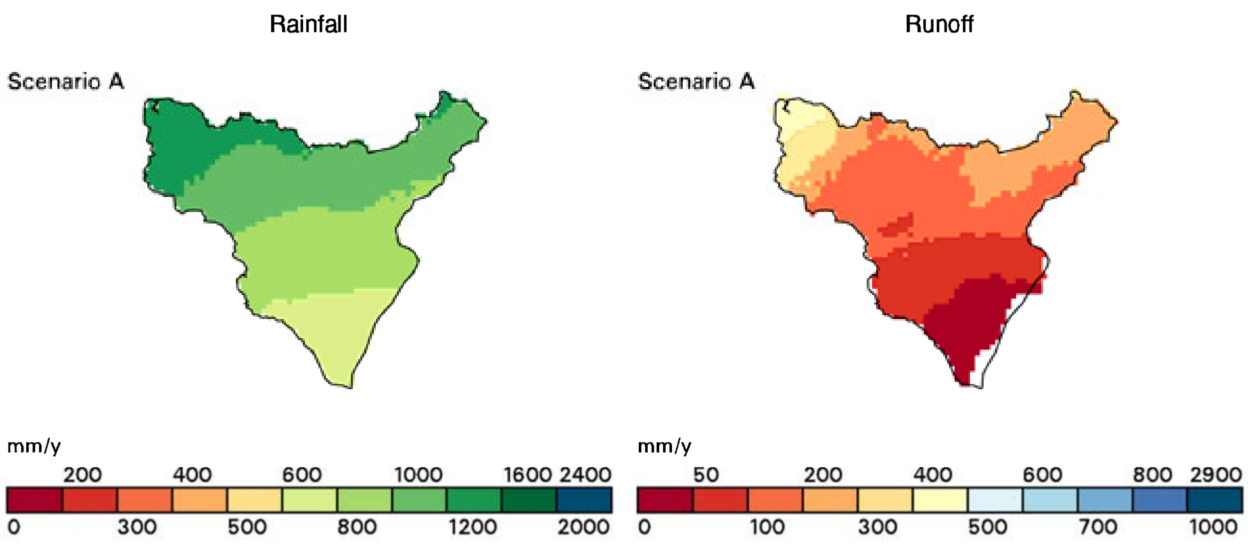


Figure DA-42. Spatial distribution of mean annual rainfall and modelled runoff across the Daly region under Scenario A

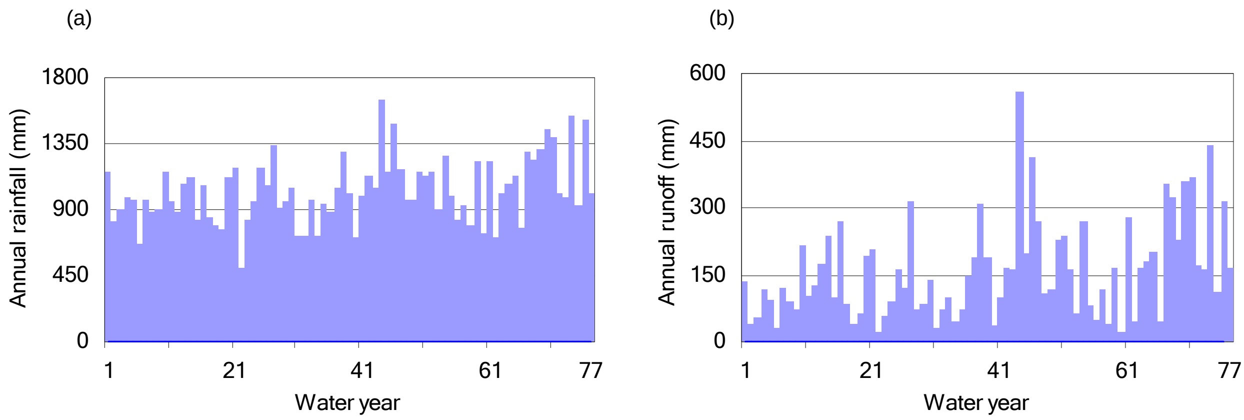


Figure DA-43. Mean annual (a) rainfall and (b) modelled runoff in the Daly region under Scenario A

Figure DA-44(a,b) shows the minimum and maximum monthly rainfall and runoff and the range of values between the 25th and 75th percentile monthly rainfall and runoff. Figure DA-44(c,d) shows the mean and median monthly flows and the range of values between the 25th and 75th percentile monthly rainfall and runoff. The large difference in the mean and median wet season monthly runoff values indicates that the distribution of monthly runoff in the Daly region is highly skewed.

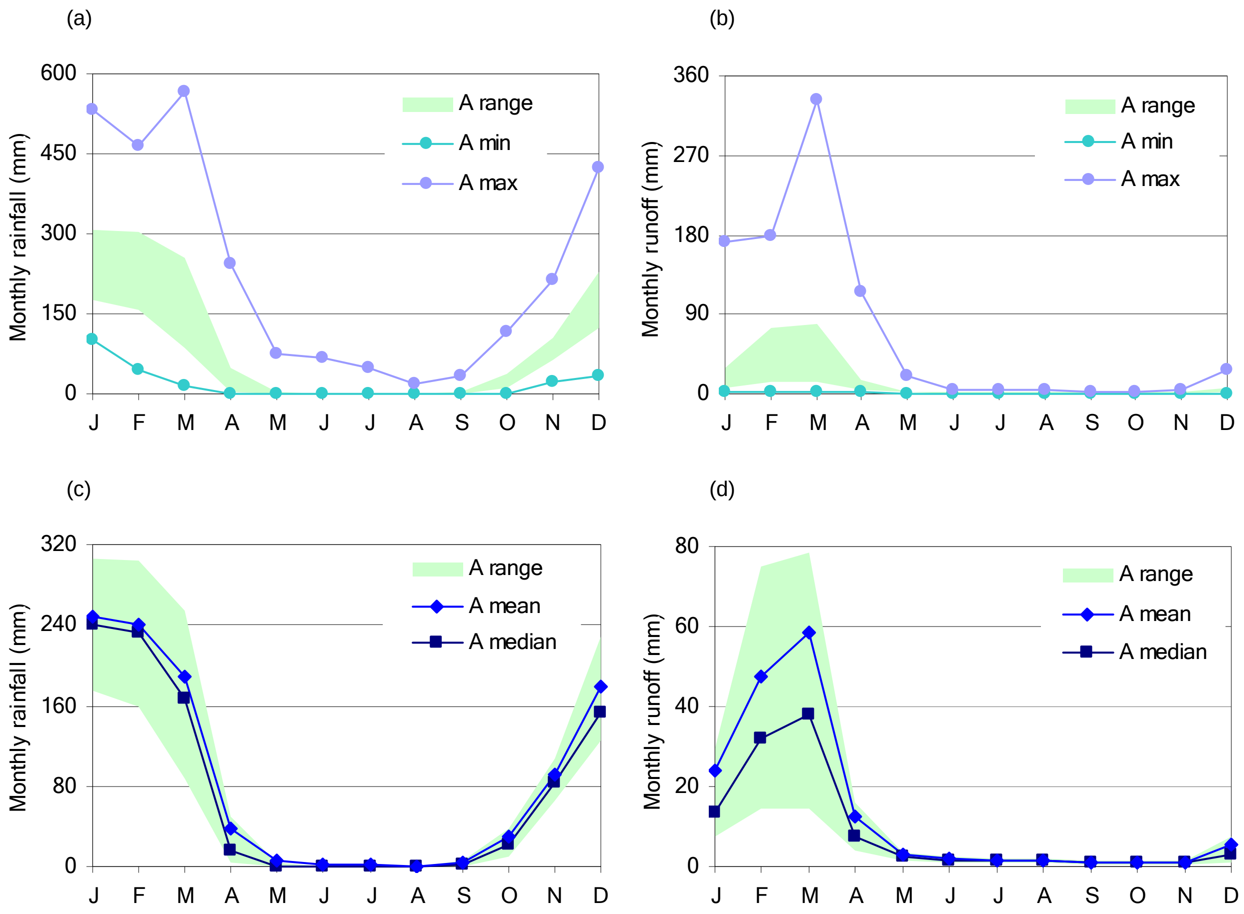


Figure DA-44. Minimum, maximum and A range monthly (a) rainfall and (b) modelled runoff; and mean, median and A range monthly (c) rainfall and (d) modelled runoff in the Daly region under Scenario A (A range is the 25th to 75th percentile monthly rainfall or runoff)

DA-3.5.4 Under recent climate

The mean annual rainfall and runoff under Scenario B (1996 to 2007) are 20 percent and 71 percent higher respectively than the historical (1930 to 2007) mean values. The spatial distribution of rainfall and runoff across the Daly region under Scenario B is shown in Figure DA-45.

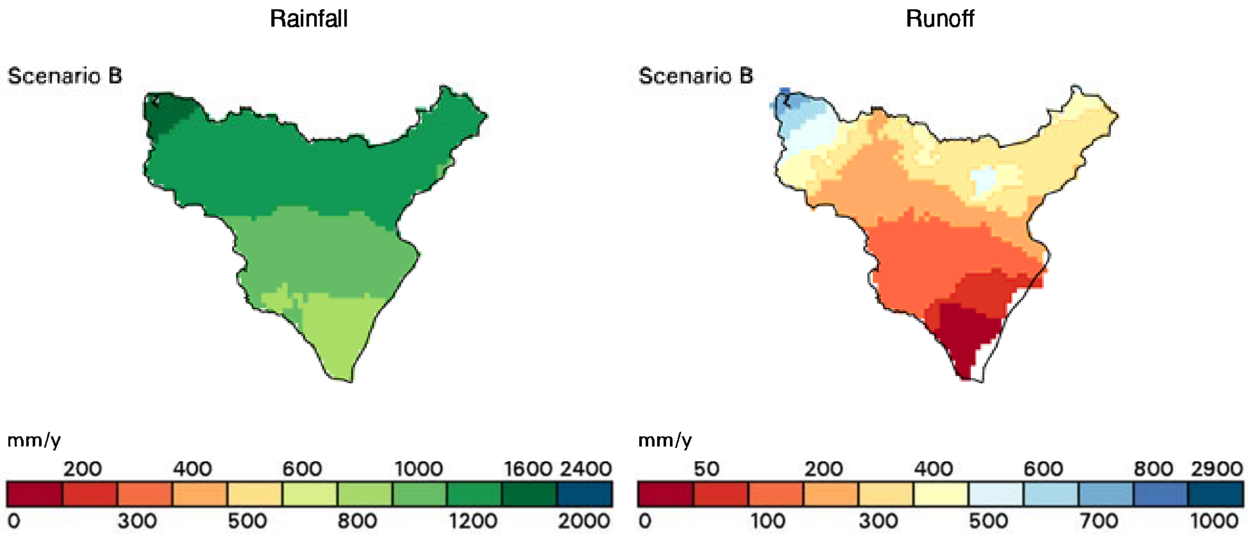


Figure DA-45. Spatial distribution of mean annual rainfall and modelled runoff across the Daly region under Scenario B

DA-3.5.5 Under future climate

Figure DA-46 shows the percentage change in the mean annual runoff averaged over the Daly region under Scenario C relative to Scenario A for the 45 scenarios (15 GCMs for each of the high, medium and low global warming scenarios). The percentage change in the mean annual runoff and rainfall from the corresponding GCMs are also tabulated in Table DA-10.

The figure and table indicate that the potential impact of climate change on runoff can be very significant. Although there is considerable uncertainty in the estimates, the results indicate that runoff in ~2030 in the Daly region is more likely to increase than decrease. Rainfall-runoff modelling with climate change projections from five of the GCMs shows a reduction in mean annual runoff, while rainfall-runoff modelling with climate change projections from ten of the GCMs shows an increase in mean annual runoff. The wide range of mean annual runoff values shown in Figure DA-46 and Table DA-10 is primarily due to the wide range of future projections of rainfall by the 15 GCMs.

Because of the large variation between GCM simulations and the method used to obtain the climate change scenarios, the biggest increase and biggest decrease in runoff come from the high global warming scenario. For the high global warming scenario, rainfall-runoff modelling with climate change projections from three of the GCMs indicates a decrease in mean annual runoff greater than 10 percent while rainfall-runoff modelling with climate change projections from four of the GCMs indicates an increase in mean annual runoff greater than 10 percent.

In subsequent reporting here and in other sections, only results from an extreme 'wet', 'mid' and extreme 'dry' variant are shown (referred to as scenarios Cwet, Cmid and Cdry). Under Scenario Cwet, results from the second highest increase in mean annual runoff from the high global warming scenario are used. Under Scenario Cdry, results from the second highest reduction in mean annual runoff from the high global warming scenario are used. Under Scenario Cmid, the median mean annual runoff results from the medium global warming scenario are used. These are shown in bold in Table DA-10.

Under scenarios Cwet, Cmid and Cdry, mean annual runoff increases by 34 and 1 percent and decreases by 29 percent, respectively, relative to Scenario A. By comparison, the range based on the low global warming scenario is a 18 to -17 percent change in mean annual runoff. Figure DA-47 shows the mean annual runoff across the Daly region under scenarios A and C. The linear discontinuities that are evident in Figure DA-47 are due to GCM grid cell boundaries.

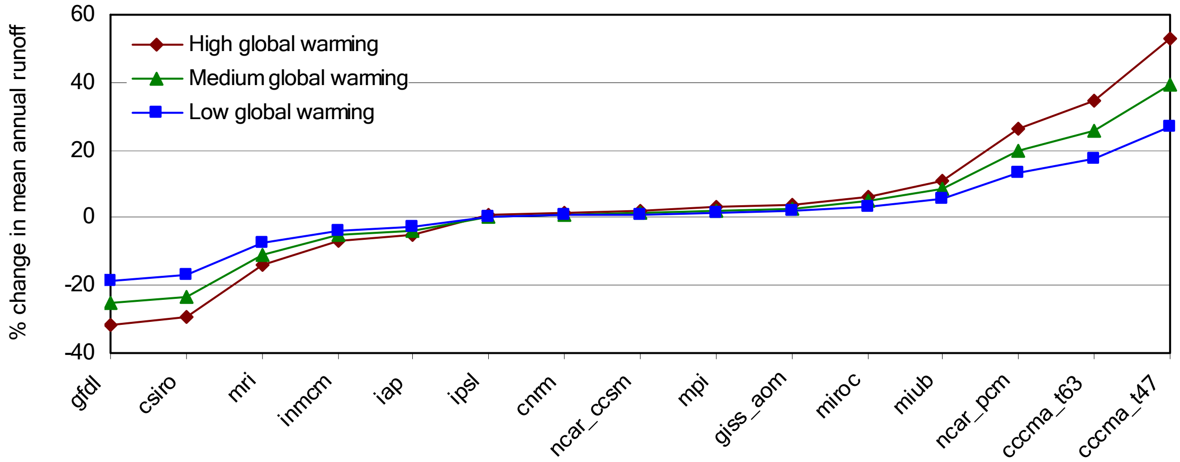


Figure DA-46. Percentage change in mean annual modelled runoff under the 45 Scenario C simulations (15 global climate models and three global warming scenarios) relative to Scenario A

Table DA-10. Summary results under the 45 Scenario C simulations for the modelled subcatchments in the Daly region (numbers show percentage change in mean annual rainfall and runoff under Scenario C relative to Scenario A)

High global warming			Medium global warming			Low global warming		
GCM	Rainfall	Runoff	GCM	Rainfall	Runoff	GCM	Rainfall	Runoff
gfdl	-14%	-32%	gfdl	-11%	-25%	gfdl	-7%	-18%
csiro	**-13%**	**-29%**	csiro	-10%	-24%	csiro	-7%	-17%
mri	-4%	-14%	mri	-3%	-11%	mri	-2%	-8%
inmcm	0%	-7%	inmcm	0%	-5%	inmcm	0%	-4%
iap	-3%	-5%	iap	-2%	-4%	iap	-1%	-3%
ipsl	1%	1%	ipsl	1%	0%	ipsl	1%	0%
cnrm	1%	1%	cnrm	1%	1%	cnrm	1%	1%
ncar_ccsm	3%	2%	**ncar_ccsm**	**2%**	**1%**	ncar_ccsm	1%	1%
mpi	2%	3%	mpi	2%	2%	mpi	1%	1%
giss_aom	2%	4%	giss_aom	1%	3%	giss_aom	1%	2%
miroc	4%	6%	miroc	3%	5%	miroc	2%	3%
miub	3%	11%	miub	2%	8%	miub	2%	6%
ncar_pcm	11%	27%	ncar_pcm	8%	20%	ncar_pcm	6%	14%
cccma_t63	**9%**	**34%**	cccma_t63	7%	26%	cccma_t63	5%	18%
cccma_t47	11%	53%	cccma_t47	9%	40%	cccma_t47	6%	27%

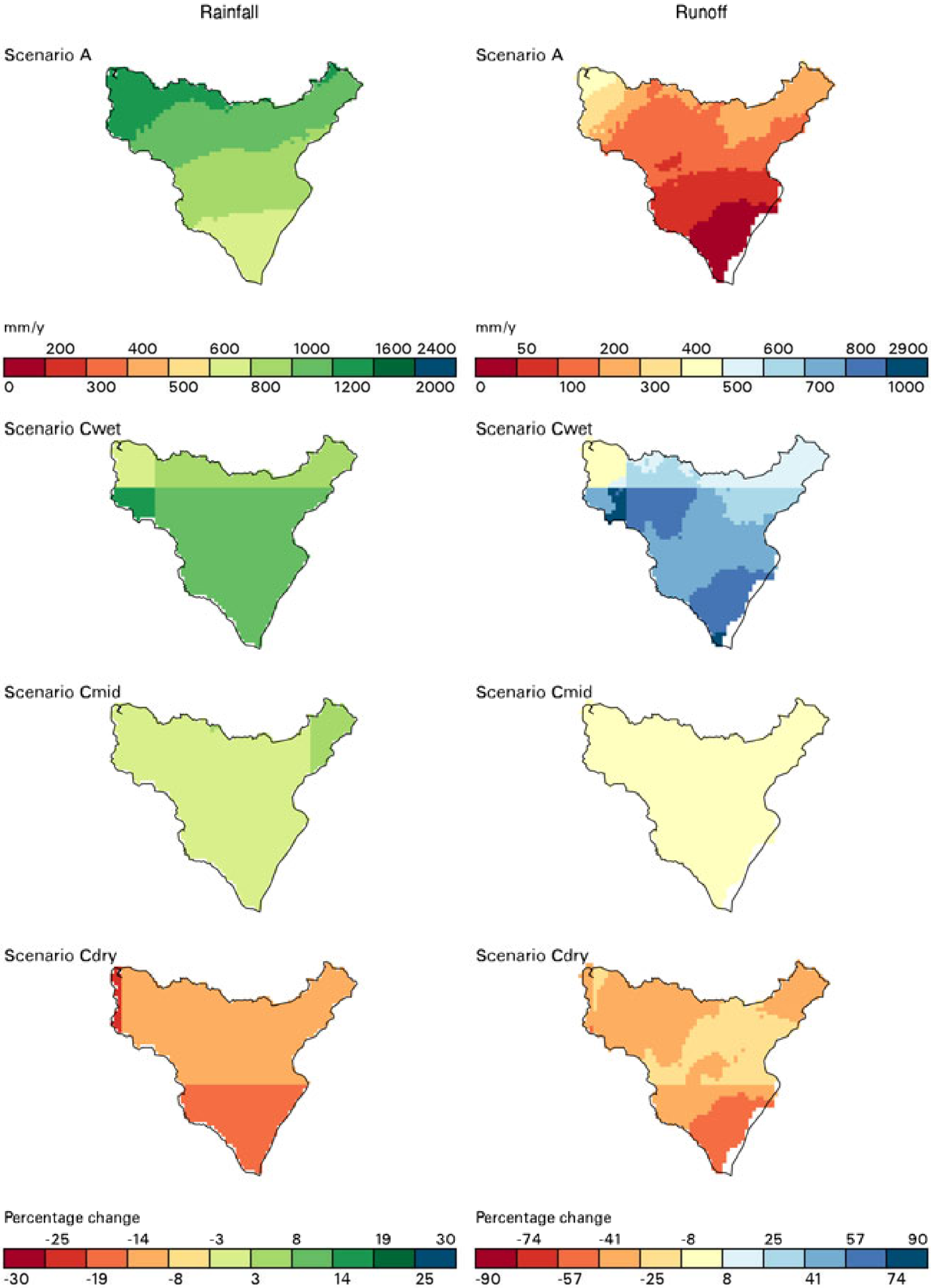


Figure DA-47. Spatial distribution of mean annual rainfall and runoff across the Daly region under scenarios A and C

DA-3.5.6 Summary results for all scenarios

Table DA-11 shows the mean annual rainfall, runoff and actual evapotranspiration under Scenario A averaged over the Daly region, and the percentage changes under scenarios B and C relative to Scenario A. The Cwet, Cmid and Cdry results are based on the mean annual runoff, and the rainfall changes shown in Table DA-11 are the changes in the mean annual value of the rainfall series used to obtain the runoff under scenarios Cwet, Cmid and Cdry. The changes in mean annual rainfall do not necessarily translate directly to the changes in mean annual runoff because of changes in seasonal and daily rainfall distributions and the relationship between rainfall and runoff is non-linear. The latter factor usually results in small changes in rainfall to be amplified in runoff (Table DA-10).

Figure DA-48 shows the mean monthly rainfall and runoff under scenarios A and C averaged over 1930 to 2007 for the region. Figure DA-49 shows the daily rainfall and flow exceedance curves under scenarios A and C averaged over the region. In Figure DA-48 Cwet, Cmid and Cdry are selected on a month-by-month basis, while in Figure DA-49 Cwet, Cmid and Cdry are selected for every day of the daily flow exceedance curve.

Table DA-11. Water balance over the entire Daly region under scenarios A, B and C

Scenario	Rainfall	Runoff	Evapotranspiration
		mm	
A	1027	159	868
		percent change from Scenario A	
B	21%	72%	11%
Cwet	9%	34%	4%
Cmid	2%	1%	2%
Cdry	-13%	-29%	-10%

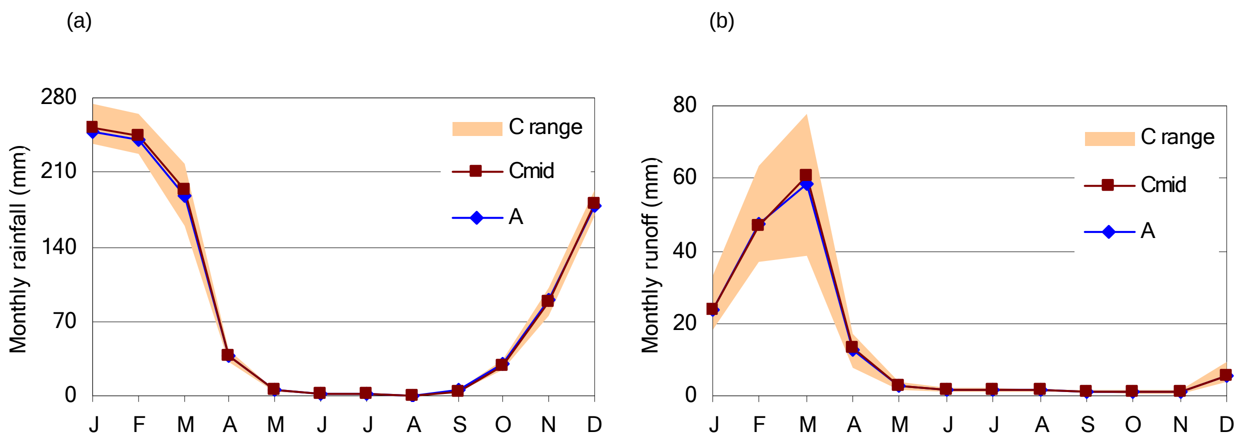
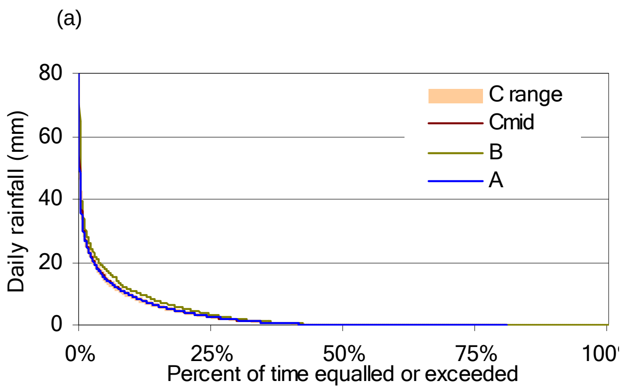


Figure DA-48. Mean monthly (a) rainfall and (b) modelled runoff in the Daly region under scenarios A and C



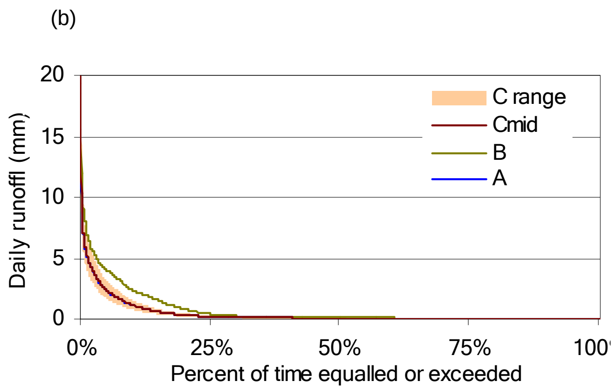


Figure DA-49. Daily flow exceedance curves for (a) rainfall and (b) runoff in the Daly region under scenarios A and C

DA-3.5.7 Confidence levels

The rainfall-runoff model verification analysis with data from 123 catchments from across all of northern Australia indicates that the mean annual runoff for ungauged catchments are under estimated or over estimated, when using optimised parameter values from a nearby catchment, by less than 20 percent in 40 percent of catchments and by less than 50 percent in 80 percent of the catchments. However, in the Daly region, with the exception of the coastal floodplain area, it was not necessary to regionalise model parameters because stations in the middle (G8140067) and lower reaches (G8410040) were used to model the residual flow (difference between upstream stations and downstream station) as described in Section 2.2.2.

However, difficulties remain. For example, applying rainfall-runoff models in the dolomitic limestone environments like the Daly catchment can be problematic where there are good connections between the surface and groundwater systems and water can bypass gauging stations, thus violating model assumptions (unless the modifications to the model structure have been made). There was little information to suggest at which stations this may occur. Rainfall-runoff modelling can also be problematic in areas like the Dry River where the undefined nature of flow in some parts of the catchment means that more runoff may be generated than is measured at the gauge. This is evident by the considerably lower mapped runoff in the Dry River compared to neighbouring regions (i.e. the Dry River subcatchment has a runoff coefficient of 3 percent compared to at least 10 percent elsewhere).

Nevertheless the relatively high density of gauging stations in the Daly catchment means that there is a relatively high degree of confidence associated with the monthly and total flow volumes. In particular the level of confidence in the monthly and annual volumes of streamflow discharged from the Daly River is relatively high due to the high quality gauging station at Mount Nancar (G8140040), conveniently located in the lower reaches, where the Daly River flows through the Mount Nancar range (Figure DA-40). Despite stations G8140040 and G8140067 being calibrated to monthly flow data they have relatively high daily NSE values (0.63 and 0.75 respectively).

Runoff estimates tend to be better in the northern regions than the southern regions, where there is a greater concentration of gauging stations. Consequently the level of confidence in the spatial distribution of runoff in these areas is relatively low (Figure DA-50). Downstream of the Mount Nancar gauge there is a low degree of confidence in the spatial distribution of runoff, although there is a relatively high degree of confidence in the streamflow volumes due to the gauge at Mount Nancar. While the area downstream of the Mount Nancar gauge constitutes a relatively small portion of the entire area of the Daly region, the lower reaches of the Daly River have considerable ecological value.

The level of confidence associated with dry season flow projections in the Daly region is lower than the mid to high flow projections because the groundwater-fed dry season flows are best modelled using models that better represent groundwater processes (e.g. FEFLOW). Nevertheless the mean annual dry season value runoff computed using the rainfall-runoff models compares favourably to the MIKE11-FEFLOW model (Section DA-3.6) for the 77-year Scenario A sequence.

Figure DA-50 shows the level of confidence in the modelling of the mid to high runoff events (i.e. peak flows) and dry season runoff (respectively) for the subcatchments of the Daly region. It should be noted that these maps of level of confidence are not statistical confidence levels and are intended to only convey a broad reliability of prediction. The level of confidence in streamflow predictions will vary slightly from the level of confidence in runoff predictions shown below and as discussed in Section 2.2.6 of the division-level Chapter 2.

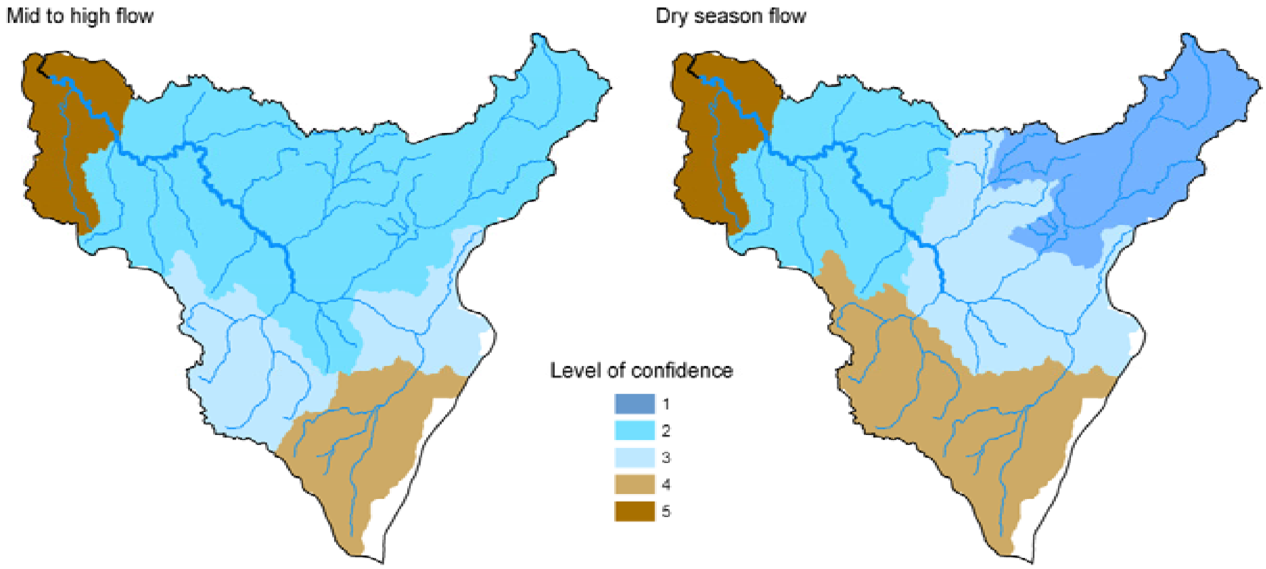


Figure DA-50. Level of confidence of the modelling of runoff for (a) mid- to high flow events and (b) monthly dry season flow events for the modelling subcatchments of the Daly region. 1 is the highest level of confidence, 5 is the lowest

DA-3.6 River system water balance

General information about river modelling methods is presented at the division level in Chapter 2. In that chapter, scenarios are defined in Section 2.1 and river modelling methods which apply to all regions are described in Section 2.2. The following section summarises this generic river modelling approach as applied to the Daly region. The river modelling results for the Daly River model is reported using a subset of metrics, which were applied across all regions. A subset of metrics is reported here because there are no instream or large storages or surface water diversions in the Daly River catchment, which meant that many of the metrics reported in the river modelling sections elsewhere are redundant in the Daly.

River system models can be used to assess the implications of the changes in inflows on the reliability of water supply to users. They may also be used to support water management planning by assessing the trade-offs between supplies to various competing categories of users. These models describe infrastructure, water demands, and water management and sharing rules under a full use of existing entitlements case. Given the time constraints of the project, and the need to link the assessments to state water planning processes, it is necessary to use the river system models currently used by state agencies.

The strong connectivity of the groundwater and surface water systems in the Daly region requires a models that can simulate the groundwater and surface water systems and the interactions between them. For the Daly region there is a calibrated coupled MIKE11-FEFLOW model (Knapton 2006). This model is discussed in detail in Section DA-3.4 and results for groundwater level simulations and water balances for the Tindall Limestone and Oolloo Dolostone aquifers are provided. It should be noted that the MIKE11 model is a flood routing, hydrodynamic model, not specially designed for water resource assessment purposes. In the case of the Daly catchment, however, there are no instream or large storages or surface water diversions. Should storages be constructed in the future and water diverted from the river, then it may be necessary to use an alternative model. This section presents the results of river flow behaviour in the Daly River.

Because development in the Daly River is predominantly based on groundwater extraction and key questions about current and future development are largely based on groundwater extraction rates and their impact on dry season flow, scenarios for the Daly were developed using the forecasting approach used by the groundwater modelling components of this project. This approach adopted 23-year input sequences to forecast groundwater levels in 2030 (Section 2.3 of the division-level Chapter 2). However, instead of ranking the GCM recharge values to select the GCMs that correspond to scenarios Cwet, Cmid and Cdry (as was done in DA-3.5.4), in this section the GCMs were selected on the basis of ranked rainfall. For these reasons the scenarios for the Daly described below are not consistent with those described in other sections of this report . In the Northern Australia Sustainable Yields Project the river system modelling for the Daly region consists of eight scenarios:

- Scenario Amid – historical climate and current development
  This scenario assumes current level of groundwater development and uses recharge and runoff data from a 23-year period corresponding to 1 September 1978 to 31 August 2001. This period was selected as being the median 23-year period from the 77-year historical sequence (1 September 1930 to 31 August 2007). There are no large surface water diversions in the Daly. See Section DA-3.4.3 for more detail on this scenario. This scenario is used as a baseline for comparison with all other scenarios.

- Scenario B – recent climate and current development
  This scenario assumes current level of groundwater development and uses climate data from 1 September 1996 to 31 August 2007 to generate a 23-year sequence of recharge and runoff data, i.e. to 2030. See Section DA-3.4.4 for more detail on this scenario.

- Scenario C – future climate and current development
  Scenarios Cwet, Cmid and Cdry represent a range of future climate conditions that are derived by adjusting the historical climate and flow inputs used in Scenario A. The level of development for Scenario C is the current level of groundwater development, i.e. the same as for Scenario Amid. See Section DA-3.4.5 for more detail on this scenario.

- Scenario D – future climate and 2030 development scenario
  Scenarios Dwet, Dmid and Ddry represent a range of future climate conditions that are derived by adjusting the historical climate and flow inputs used in Scenario A. For this scenario groundwater extraction increases 7.9 GL/year. The level of development for Scenario D assumes the full use of existing entitlements, i.e. the same as for Scenario Amid.

It should be noted that results presented by the Northern Territory Department of Natural Resources, Environment, The Arts and Sport (e.g. Knapton, 2006) may differ from numbers published in this report due to the different modelling period, different initial conditions and development conditions.

The changes in inflows between scenarios reported in this chapter differ from the changes in runoff reported in Section DA-3.5. These differences are due to difference in the methods by which the GCMs were ranked and different time periods of analysis. The scenarios presented in this project may not eventuate but they encompass consequences that might arise if no management changes are made. Consequently results from this assessment are designed to highlight pressure points in the system, both now and in the future. This assessment does not elaborate on what management actions might be taken to address any of these pressure points. Where management changes to mitigate the effects of climate change have recently been implemented, the impacts of the changes predicted in this section may be an overestimate.

DA-3.6.1 River model configuration

Daly model description

The Daly Basin groundwater/surface water model is based on a three-dimensional finite-element framework developed in the FEFLOW simulation code consisting of two layers, with the upper layer coupled to a MIKE11 river model which uses an implicit, finite difference scheme for the computation of unsteady one-dimensional flows in rivers and estuaries (DHI, 2005). The key streamflow gauging stations used to construct the MIKE11 river model are shown in Figure DA-51. The initial inflows to the MIKE11 river model were generated using the NAM model (DHI, 2005). There are no instream or large storages in the Daly region.

Daly model setup

In contrast to the other river modelling sections – which looked at indicators of flow, water storage and diversions over 77-year sequences – the Daly model was run using 23-year climate sequences from 1 September 2007 to 31 August 2030. This approach, while different to the river modelling scenarios described in the other project regions, is consistent with the forecasting approach used by the groundwater modelling components of this project. Consequently in this section, where mean annual values are provided they have been averaged over a 23-year period, not a 77-year period.

A more detailed description of the model and modelling methods are provided in Section DA-3.4 and Knapton (2009).

Table DA-12. Daly River model setup information

Model setup information		Version	Start date	End date
Daly	MIKE11-FEFLOW model		01/09/2007	31/08/2030
Connection				
None				
Baseline models				
Warm-up period			01/09/1930	31/08/2007
Daly	MIKE11-FEFLOW model		01/09/2007	31/08/2030
Connection				
Modifications				
Data	No data extension required			
Inflows	No adjustment to Scenario A			

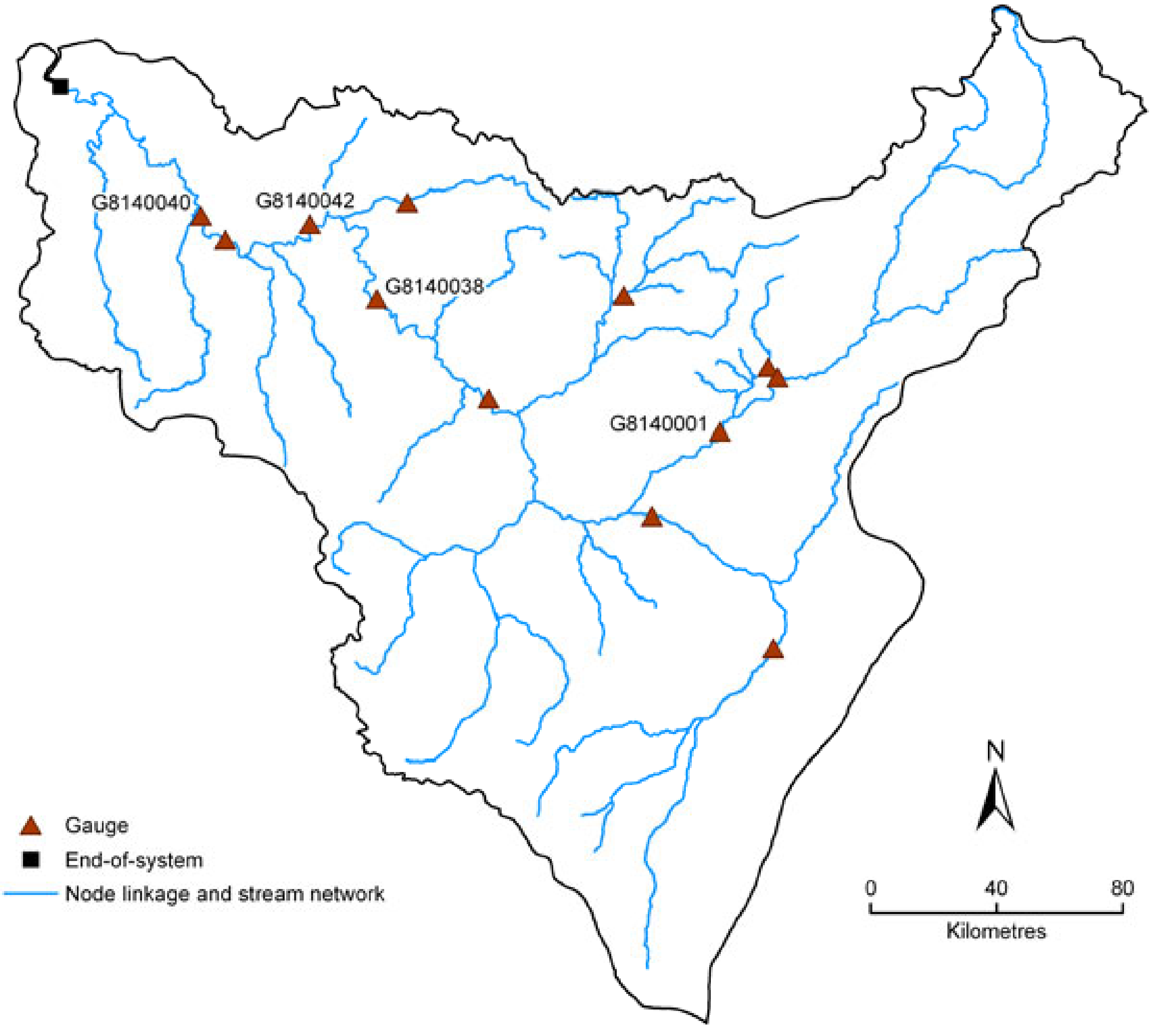


Figure DA-51. Location of key gauging stations used to calibrate the MIKE11 model

DA-3.6.2 River system water balance

Groundwater levels and water balances for the Tindall Limestone and Oolloo Dolostone aquifers are provided in Sections DA-3.4.3 to DA-3.4.7. There are no large storages or surface water diversions in the Daly region.

DA-3.6.3 Inflows

Figure DA-52 compares the mean flow at various stations along the Daly River under different scenarios. Figure DA-52(a) illustrates that the Daly River is a gaining catchment, which means that the mean annual flow increases with distance downstream. The maximum average annual mainstream gauged flow occurs at the last gauge G8140040 (Daly River at Mount Nancar) with a value of 8184 GL/year under Scenario Amid.

Figure DA-52(b) illustrates the mean flow during the dry season at various stations along the Daly River under scenarios Amid, B and C. Dry season flow increases with distance downstream, indicating that considerable groundwater discharge to the river occurs between each of these stations. The maximum average dry season flow at G8140040 is 363 GL/year under Scenario Amid.

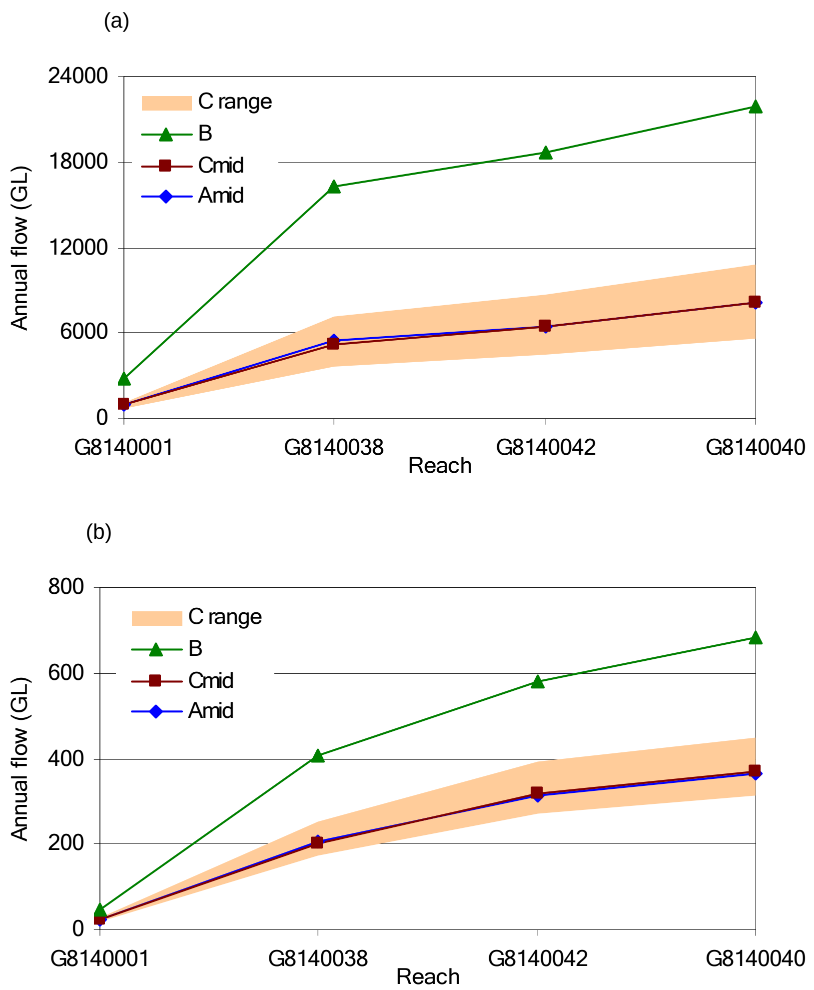


Figure DA-52. Transect of (a) total river flow and (b) total river flow during the dry season under scenarios Amid, B and C

There is negligible difference in mean annual flow in 2030 under Scenario C and Scenario D, even though the latter had increased groundwater extraction. This is most likely due to (i) the time lag between groundwater pumping and impact on discharge to the river; and (ii) the relocation of groundwater pumping bores away from the river under Scenario D. It is likely that in the future beyond 2030, the mean annual flow under Scenario D will decrease relative to Scenario C as increased groundwater pumping reduces discharge to the Daly River.

Water availability

In the Murray-Darling Basin Sustainable Yields Project water availability was defined as the volume of water under the without-development scenario which occurs at the point of maximum mean annual flow along a river system. This occurred where a river system turned from a gaining reach to a losing reach. The major rivers in northern Australia are, however, gaining systems. In other words, their highest mean annual flow occurs at their end-of-system. However end-of-system flow volumes are uncertain due to considerable ungauged flow contribution to these points. For this reason water availability is defined in this project as the volume of water under the without-development scenario which occurs at the gauged point of maximum mean annual flow along a river system. In the Daly this occurs at G8140040 (Figure DA-53). The term ‘water availability’ does not mean that all this water is available for consumptive use, because no assessment of potential surface water storages were made in this project. It does, however, provide a point of reference for comparing one scenario with another and is a volume against which the level of consumptive use (i.e. diversions/extractions) can be compared. When computing water availability for this project ecological, social, cultural and economic values are not considered.

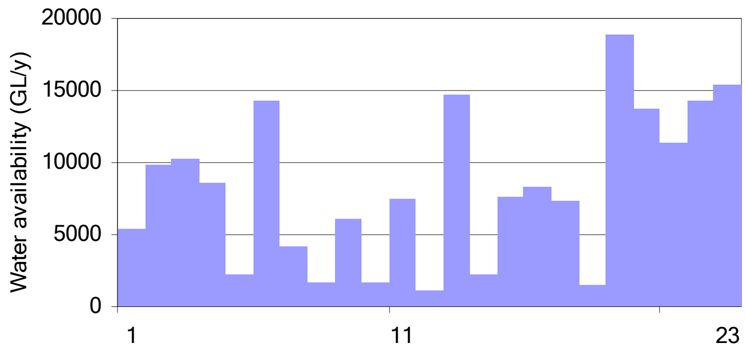


Figure DA-53. Water availability under Scenario Amid

DA-3.6.4 Storage behaviour

There are no large storages in the Daly region.

DA-3.6.5 Consumptive water use

There are no surface water diversions in the Daly region.

In this section the level of groundwater use is expressed as a percentage of surface water availability. Table DA-13 shows the level of groundwater use relative to the total surface water availability at G8140040. When compared to the total surface water availability the relative level of use is very low, typically less than 1 percent.

Table DA-13. Level of use relative to total surface water availability at G8140040 under scenarios A, B, C and D

	A	B	Cwet	Cmid	Cdry	Dwet	Dmid	Ddry
	GL/y							
Total surface water availability	8184	21,947	10841	8095	5556	10,903	8134	5536
Groundwater use	45	45	45	45	45	80	80	80
	percent							
Relative level of use	0.5%	0.2%	0.4%	0.6%	0.8%	0.7%	1.0%	1.4%

However, groundwater extraction can lead to a reduction in groundwater discharge to a river, most notably during the dry season. Table DA-14 shows the level of groundwater use relative to the surface water availability at G8140040 during the dry season. When the level of groundwater use is compared to surface water availability during the dry season the relative level of use increases substantially.

Table DA-14. Level of use relative to surface water availability at G8140040 during the dry season under scenarios A, B, C and D

	A	B	Cwet	Cmid	Cdry	Dwet	Dmid	Ddry
	GL/y							
Total surface water availability during dry season	363	685	450	369	315	452	368	305
Groundwater use	45	45	45	45	45	80	80	80
	percent							
Relative level of use	12.3%	6.5%	9.9%	12.1%	14.2%	17.6%	21.6%	26.1%

The impact of current and projected groundwater extractions on discharge to and from the river are discussed in more detail in Section DA-3.4.

DA-3.6.6 River flow behaviour

There are many ways of considering the flow characteristic in river systems. For this report three different indicators are provided: daily flow exceedance, seasonal plot and daily event frequency. Figure DA-54(a) shows the flow exceedance curves at G8140040. Figure DA-54(b) gives the mean monthly flow under scenarios Amid and C at G8140040. They show a strong seasonality reflecting the wet and dry seasons. The percentage of time that flow occurs under these scenarios is presented in Table DA-15.

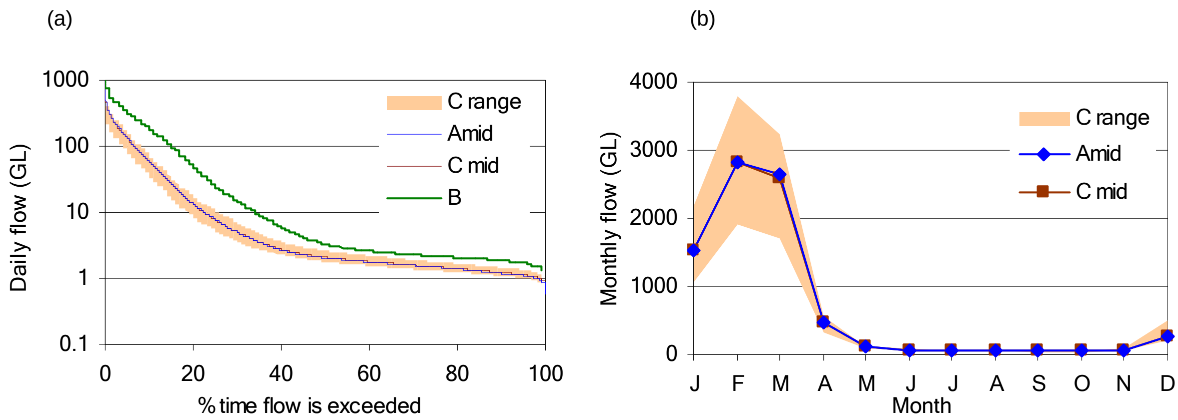


Figure DA-54 (a) Daily flow exceedance curves and (b) monthly flow for the Daly region at G8140040 under scenarios Amid, B and C. Scenario B is not shown in (b)

Table DA-15. Percentage of time flow at Daly G8140040 is greater than 2 GL/day

Catchment	Amid	B	Cwet	Cmid	Cdry
Daly	52%	84%	67%	53%	45%

DA-3.6.7 Share of water resource

This section is not relevant to the Daly region.

DA-3.7 Changes to flow regimes at environmental assets

Section 1.3 of the division-level Chapter 1 describes how environmental assets were shortlisted for assessment by this project. Three environmental assets have been shortlisted in the Daly region: Daly River Middle Reaches, Daly-Reynolds, Floodplain-Estuary System, and Katherine Gorge. The locations of these assets are shown in Figure DA-1 and the assets are characterised in Chapter DA-2.

This section presents the assessment of these shortlisted assets and reports metrics for those assets which have sufficient confidence in the modelled streamflow to enable analysis. Confidence in results for low flows and high flows was calculated separately on a scale of 1 to 5, with 1 indicating results with the highest confidence (as described in Section 2.2.6 of the division-level Chapter 2). Hydrological regime metrics (as defined in Section 2.5 of the division-level Chapter 2) for either low flows or high flows are reported only where confidence levels are 1, 2 or 3. If confidence levels in the low flows or high flows are ranked 4 or 5, results are not reported and are labelled NR (not reported).

Some of the assets in this region have multiple nodes at which streamflow modelling results are available. When reporting hydrological regime metrics for such assets a single node was selected. The selected node was that with the highest streamflow confidence level and the largest proportion of streamflow to the asset. Results for all nodes are presented in McJannet et al. (2009).

In the absence of site-specific metrics for the Daly region a set of standard metrics related to high and low flows have been utilised. However the conversion of these metrics into environmental impacts still requires development of quantitative relationships between flow and ecology.

DA-3.7.1 Standard metrics

Unlike other regions, almost the entire Daly region is represented with an existing, calibrated, regional-scale, FEFLOW numerical groundwater flow model coupled to a calibrated MIKE11 surface water model. Comparison of scenarios using this modelling approach is over a 23-year period rather than the 77-year period used in other modelling approaches (see Chapter 2 for full descriptions). This model has been calibrated against existing gauges and developed over a number of years. Confidence in results, therefore, is considered high enough (i.e. <3) to report standard metrics at all three environmental assets (Table DA-16).

Daly River Middle Reaches

Under Scenario A annual flow at the selected node for this asset (see location on Figure DA-10) is dominated by wet season flows (95 percent) which are 191 percent higher under Scenario B (Table DA-16). Dry season flows are also 87 percent higher under Scenario B. Annual and seasonal flows do not change much under Scenario Cmid when compared to Scenario A, but there are large increases under Scenario Cwet (26 to 34 percent) and moderate decreases under Scenario Cdry (13 to 32 percent). Changes to annual and seasonal flows under scenarios Dwet, Dmid and Ddry when compared to Scenario A are similar to those under Scenario C, indicating very little additional impact on the hydrological regime as a result of proposed development. Slight increases in flow under scenario D as compared to scenario C are possibly the result of changes to the location of major groundwater extraction between these scenarios. Under Scenario C many of the pumping bores are in an area where there is very good connection between the river and the aquifer. Under Scenario D the majority of extraction occurs where there is less connectivity between the aquifer and the river (for more details refer to Section DA-3.4.5).

The number of days when flow is less than the low flow threshold decreases moderately under Scenario Cmid compared to Scenario A, but there is a large increase in low flow days under Scenario Cdry and a large decrease in low flow days under Scenario Cwet (Table DA-16). The number of days when flow is less than the low flow threshold also decreases moderately under Scenario Dmid when compared to Scenario A. Scenario Dwet is similar to Cwet indicating little impact from proposed development, but there is a larger increase in low flow days under Scenario Ddry when compared to Scenario Cdry. There were no zero flow days at this asset under any scenario.

Under Scenario B high flows have been much more frequent than under Scenario A. Compared to Scenario A there is little change in high flow threshold exceedance under Scenario Cmid. Under Scenario Cwet high flow exceedance increases moderately from Scenario A; conversely, there is a large decrease in high flow days under Scenario Cdry.

Changes to high flow threshold exceedance under scenarios Dwet, Dmid and Ddry are similar to those under Scenario C indicating very little additional impact on hydrological regime due to proposed development.

Daly-Reynolds Floodplain-Estuary System

Under Scenario A annual flow at the selected node for this asset (see location on Figure DA-11) is dominated by wet season flows (96 percent) which are 172 percent higher under Scenario B (Table DA-16). Dry season flows are also 89 percent higher under Scenario B when compared to Scenario A. Annual and seasonal flows do not change much under Scenario Cmid when compared to Scenario A, but there are large increases under Scenario Cwet (24 to 33 percent) and moderate decreases under Scenario Cdry (13 to 33 percent). Changes to annual and seasonal flows under scenarios Dwet, Dmid and Ddry compared to Scenario A are similar to those under Scenario C, indicating very little additional impact on hydrological regime due to proposed development. Slight increases in flow under scenario D as compared to scenario C are possibly the result of changes to the location of major groundwater extraction between these scenarios. Under Scenario C many of the pumping bores are in an area where there is very good connection between the river and the aquifer. Under Scenario D the majority of extraction occurs where there is less connectivity between the aquifer and the river (for more details refer to Section DA-3.4.5).

The number of days when flow is less than the low flow threshold under Scenario A decreases moderately under scenarios Cmid or Dmid, but there is a large increase in low flow days under Scenario Cdry and a doubling under Scenario Ddry. Conversely, there are large decreases in low flow days under scenarios Cwet and Dwet when compared to Scenario A(Table DA-16). Scenario Dwet shows very little difference from Scenario Cwet indicating little impact from proposed development, but there is a larger increase in low flow days under Scenario Ddry when compared to Scenario Cdry. There were no zero flow days at this asset under any scenario.

Under Scenario B high flows are more than twice as frequent as under Scenario A. There is little change in high flow threshold exceedance under Scenario Cmid. Under Scenario Cwet high flow exceedance shows a moderate increase from Scenario A; conversely, there is a moderate decrease in high flow days under Scenario Cdry. Changes to high flow threshold exceedance under scenarios Dwet, Dmid and Ddry are similar to those under Scenario C, indicating little additional impact on the hydrological regime as a result of proposed development.

Table DA-16. Standard metrics for changes to flow regime at environmental assets in the Daly region under scenarios A, B, C and D

Standard metrics	Units	A	B	Cwet	Cmid	Cdry	Dwet	Dmid	Ddry
			change from Scenario A						
Daly River Middle Reaches - Node 1 (confidence level: low flow = <3, high flow = <3)									
Annual flow (mean)	GL	6520	+186%	+34%	-1%	-31%	+34%	0%	-32%
Wet season flow (mean)*	GL	6210	+191%	+34%	-1%	-32%	+35%	-1%	-32%
Dry season flow (mean)**	GL	311	+87%	+26%	+2%	-13%	+26%	+2%	-16%
Low flow threshold (discharge exceeded 90% of the time in Scenario A)	GL/d	1.04							
Number of days below low flow threshold (mean)	d/y	36.6	-36.2	-31.9	-6.7	+27.4	-31.1	-5.8	+38.3
Number of days of zero flow (mean)	d/y	0	0	0	0	0	0	0	0
High flow threshold (discharge exceeded 5% of the time in Scenario A)	GL/d	108							
Number of days above high flow threshold (mean)	d/y	18.3	+31.6	+5.4	-0.4	-7.7	+5.7	-0.3	-7.7
Daly-Reynolds Floodplain-Estuary System - Node 1 (confidence level: low flow = <3, high flow = <3)									
Annual flow (mean)	GL	8180	+168%	+32%	-1%	-32%	+33%	-1%	-32%
Wet season flow (mean)*	GL	7820	+172%	+33%	-1%	-33%	+34%	-1%	-33%
Dry season flow (mean)**	GL	363	+89%	+24%	+2%	-13%	+25%	+1%	-16%
Low flow threshold (discharge exceeded 90% of the time in Scenario A)	GL/d	1.19							
Number of days below low flow threshold (mean)	d/y	36.6	-36.1	-31.7	-7.2	+25.5	-30.6	-6.3	+35.3
Number of days of zero flow (mean)	d/y	0	0	0	0	0	0	0	0
High flow threshold (discharge exceeded 5% of the time in Scenario A)	GL/d	135							
Number of days above high flow threshold (mean)	d/y	18.3	+29.7	+5.7	-0.2	-8.2	+5.9	0	-8.2
Katherine River Gorge - Node 1 (confidence level: low flow = <3, high flow = <3)									
Annual flow (mean)	GL	920	+200%	+26%	+1%	-23%	+26%	+0%	-23%
Wet season flow (mean)*	GL	898	+202%	+26%	+1%	-23%	+26%	+1%	-23%
Dry season flow (mean)**	GL	22.1	+115%	+18%	-3%	-21%	+11%	-10%	-28%
Low flow threshold (discharge exceeded 90% of the time in Scenario A)	GL/d	0.0569							
Number of days below low flow threshold (mean)	d/y	36.6	-36.3	-29.4	+4.8	+47.4	-9.9	+35	+79.3
Number of days of zero flow (mean)	d/y	0	0	0	0	0	0	0	0
High flow threshold (discharge exceeded 5% of the time in Scenario A)	GL/d	14.9							
Number of days above high flow threshold (mean)	d/y	18.3	+32.5	+4.4	+0.1	-4.5	+4.4	+0.1	-4.4

*Wet season covers the six months from November to April.

**Dry season covers the six months from May to October.

NR – metrics not reported because streamflow confidence level is ranked 4 or 5.

Katherine Gorge

The Katherine River Gorge is located outside the bounds of the coupled groundwater and surface model for the Daly region however model results are available at the town of Katherine (Gauge no. G814001 indicated by node 1 on Figure DA-11) which is about 25km downstream of the gorge itself. While results are reported for this downstream node it should be noted that they do not represent conditions in the gorge itself. The area around Katherine also supports some agriculture which is expected to be developed further in the near future so these impacts will be seen under Scenario D results.

Under Scenario A annual flow at the selected node for this asset (see location on Figure DA-11) is dominated by wet season flows (98 percent) which are 202 percent higher under Scenario B (Table DA-16). Dry season flows are also 115 percent higher than Scenario A under Scenario B. Annual and seasonal flows do not change much under Scenario Cmid when compared to Scenario A, but there are moderate increases under Scenario Cwet (18 to 26 percent) and moderate decreases under Scenario Cdry (21 to 23 percent). Changes to annual and seasonal flows under scenarios Dwet and Dmid compared to Scenario A are similar to those under scenarios Cwet and Cmid, indicating little additional impact (~7 percent) on the hydrological regime due to proposed development. However, comparison of scenarios C and D indicates that development results in lower dry season flows.

Compared to Scenario A the number of days when flow is less than the low flow threshold increases moderately under Scenario Cmid, but there is a doubling of this threshold exceedance under Scenario Dmid. There are even larger increases in low flow days under scenarios Cdry and Ddry, the latter being over three times that under Scenario A. There is also a large decrease in low flow days under Scenario Cwet when compared to Scenario A (Table DA-16). There is a much larger increase in low flow days under Scenario Ddry when compared to Scenario Cdry indicating drier conditions which push the flow below the low flow threshold of scenario A much more often. There are no zero flow days at this asset under any scenario.

Under Scenario B high flows are more than twice as frequent as under Scenario A. There is little change in high flow threshold exceedance under Scenario Cmid when compared to Scenario A. Under Scenario Cwet high flow exceedance increases moderately from Scenario A; conversely, there is a moderate decrease in high flow days under Scenario Cdry. Changes to high flow threshold exceedance under scenarios Dwet, Dmid and Ddry are very similar to those under Scenario C, indicating little additional impact on high flows due to proposed development. For this asset development appears to have the most effect on the low flow regime.

DA-3.7.2 Groundwater metrics

Table DA-17. Metrics for changes to groundwater regime at environmental assets in the Daly region

Groundwater metrics	Units	A	B	Cwet	Cmid	Cdry	Dwet	Dmid	Ddry
			change from Scenario A						
Daly River Middle Reaches									
Annual groundwater flow (mean)	GL	410	+19%	+26%	+4%	-5%	+21%	-1%	-11%
Wet season groundwater flow (mean)*	GL	126	-17%	+33%	+7%	+1%	+24%	-2%	-9%
Dry season groundwater flow (mean)**	GL	283	+35%	+23%	+3%	-8%	+19%	-1%	-12%
Low flow threshold (groundwater discharge exceeded 90% of the time in Scenario A)	GL/d	0.0488							
Number of days below low flow threshold (mean)	d/y	36.6	+14.5	-3.2	-1.3	-3	-0.9	+0.7	+0.7
High flow threshold (groundwater discharge exceeded 5% of the time in Scenario A)	GL/d	2.19							
Number of days above high flow threshold (mean)	d/y	18.3	+58.6	+42.6	+4.2	-5.6	+34.6	-0.8	-8.8
Dry season depth to groundwater (mean)*** Monitoring Well - RN020614	m	19	-1.1	-0.7	-0.1	+0.3	-0.7	-0.1	+0.3
Daly-Reynolds Floodplain-Estuary System									
Annual groundwater flow (mean)	GL	493	+17%	+25%	+4%	-5%	+21%	0%	-10%
Wet season groundwater flow (mean)*	GL	172	-12%	+33%	+7%	+1%	+26%	+1%	-6%
Dry season groundwater flow (mean)**	GL	320	+33%	+22%	+3%	-8%	+19%	-1%	-12%
Low flow threshold (groundwater discharge exceeded 90% of the time in Scenario A)	GL/d	0.368							
Number of days below low flow threshold (mean)	d/y	36.6	+15.4	-5.3	-1.8	-3.3	-3.9	-0.3	-0.6
High flow threshold (groundwater discharge exceeded 5% of the time in Scenario A)	GL/d	2.47							
Number of days above high flow threshold (mean)	d/y	18.3	+57.6	+43	+5	-5.7	+36.2	-0.5	-8.8
Dry season depth to groundwater (mean)***	m	-	-	-	-	-	-	-	-

*Wet season covers the six months from November to April.

**Dry season covers the six months from May to October.

***A negative change in depth from Scenario A indicates that the watertable is closer to the surface.

Daly River Middle Reaches

Under Scenario A annual groundwater flow to the Daly River Middle Reaches (node 1 on Figure DA-10) is dominated by dry season flows (65 percent) which are 35 percent higher under Scenario B (Table DA-17). Wet season flows are 17 percent lower under Scenario B than those under Scenario A. Annual and seasonal flows do not change much under Scenario Cmid when compared to Scenario A, but there are moderate increases under Scenario Cwet (23 to 33 percent) and small changes under Scenario Cdry. Changes to annual and seasonal flows under Scenario Dwet show less of an increase than Scenario Cwet when compared to Scenario A. Changes to annual and seasonal flows under Scenario

Ddry show more of a decrease when compared to Scenario A than Scenario Cdry; these changes are indicative of additional flow decreases under development scenarios.

There is a large increase in the number of days below the low flow threshold under Scenario B when compared to Scenario A and only small changes to the number of days below the low flow threshold for all other scenarios. In the case of groundwater flow the low flow threshold is not necessarily a metric of dry season conditions. In fact, negative groundwater flows occur during the peak of the wet season when surface water flows, and hence the hydraulic head, are high. In this case an increase in the number of days below the low flow threshold is an indication of wetter conditions under Scenario B as compared to Scenario A.

Under Scenario B the high flow threshold is exceeded four times as frequently as under Scenario A. Compared to Scenario A there is only a small change in high flow threshold exceedance under scenarios Cmid and Dmid. Under Scenario Cwet high flow exceedance increases greatly from Scenario A; conversely, there is a small decrease in high flow days under scenarios Cdry and Ddry. Changes to the exceedance of the high flow threshold under Scenario Dwet when compared to Scenario A show less of an increase than under Scenario Cwet while changes under Scenario Ddry show more of a decrease than under Scenario Cdry; these changes are indicative of additional flow decreases under development scenarios.

Under Scenario B mean dry season groundwater depth (metres below soil surface) decreased by 1.1 m when compared to Scenario A (refer to node 3 on Figure DA-10 for location). Thus, the groundwater will be closer to the surface and these changes would be likely to better sustain groundwater-dependent ecosystems of this floodplain. Very little change in groundwater depth occurs under scenarios Cmid and Dmid as compared to Scenario A. Under Scenario Cwet groundwater depth is 0.7 m closer to the surface than under Scenario A and under Scenario Cdry groundwater depth increased by 0.3 m. The same changes to groundwater depth occur under scenarios C and D indicating no additional impact on watertable level at this asset with proposed future development.

Daly-Reynolds Floodplain-Estuary System

Under Scenario A annual groundwater flow to the Daly River Middle Reaches at the selected node (see location on Figure DA-11) is dominated by dry season flows (65 percent) which are 33 percent higher under Scenario B (Table DA-17). Wet season flows are 12 percent lower under Scenario B when compared to Scenario A. Annual and seasonal flows do not change much from Scenario A under Scenario Cmid, but there are moderate increases under Scenario Cwet (23 to 33 percent) and small changes under Scenario Cdry. Changes to annual and seasonal flows under Scenario Dwet when compared to Scenario A show less of an increase than under Scenario Cwet while changes under Scenario Ddry show more of a decrease than under Scenario Cdry; these changes are indicative of additional flow decreases under development scenarios.

Compared to Scenario A there is a large increase in the number of days below the low flow threshold under Scenario B and only small changes to the number of days below the low flow threshold for all other scenarios. In the case of groundwater flow the low flow threshold is not necessarily a metric of dry season conditions. In fact, negative groundwater flows occur during the peak of the wet season when surface water flows, and hence the hydraulic head, are high. In this case an increase in the number of days below the low flow threshold when compared to Scenario A is an indication of wetter conditions under Scenario B.

Under Scenario B the high flow threshold is exceeded four times as frequently as that for Scenario A. Compared to Scenario A there is little change in high flow threshold exceedance under Scenario Cmid and Dmid. Under Scenario Cwet high flow exceedance increases greatly from Scenario A; conversely, there is a small decrease in high flow days under scenarios Cdry and Ddry. Changes to the exceedance of the high flow threshold under Scenario Dwet compared to Scenario A show less of an increase than Scenario Cwet while changes under Scenario Ddry show more of a decrease than under Scenario Cdry; these changes are indicative of additional flow decreases under development scenarios.

There were no modelled groundwater depth results available for this asset.

DA-3.7.3 Site-specific metrics

Daly River Middle Reaches (Oolloo Crossing)

At Oolloo Crossing, which falls within the bounds of the Daly River Middle Reaches (node 3 on Figure DA-10), environmental flow metrics have been defined by Erskine et al. (2003; 2004) which relate to habitat suitability for key plant and animal species. The first of these is a threshold of 1.037 GL/day, which is the minimum recommended flow threshold for Pig-Nosed Turtles (*Carettochelys insculpta*) and *Vallisneria nana* beds. Under Scenario A there is an average of 151 days per year when conditions are below the threshold (Table DA-18). This number decreases greatly under scenarios B, Cwet and Dwet. There is little change to the number of days below the identified threshold under scenarios Cmid and Dmid. The greatest increase in days below the threshold for the nesting success of the Pig-Nosed Turtle and the number of *V. nana* beds is under scenarios Cdry and Ddry with 30 and 37 percent increases, respectively. These changes would result in a reduction in the number of *V. nana* beds and a decline in the nesting success of the Pig-Nosed Turtle.

The minimum flow requirement to maintain transpiration requirements of riparian vegetation has been reported by Erskine et al. (2003) to be 0.17 GL/day at the Oolloo Crossing gauge. The flow threshold analysis showed that flow levels were maintained above this level under all scenarios (Table DA-18), so there is likely to be little or no impact of climate or development on transpiration of riparian vegetation at this asset.

Table DA-18. Site-specific reported metrics for changes to flow regime at Daly River Middle Reaches

Reported metrics	A	B	Cwet	Cmid	Cdry	Dwet	Dmid	Ddry
	d/y	d/y (change from Scenario A)						
Daly River Middle Reaches - Pig-Nosed Turtle nesting habitat suitability and *V. nana* bed occurrence								
Number of days with flows below identified threshold (mean)*	151	-139.6	-49.1	+9.8	+45.3	-47.7	+13.4	+56.3
Daly River Middle Reaches - Riparian vegetation water requirement								
Number of days with flows below identified threshold (mean)**	0	0	0	0	0	0	0	0

*Pig-Nosed Turtle nesting habitat threshold = 1.037 GL/day (see text for explanation).

**Riparian vegetation threshold = 0.17 GL/day (see text for explanation).

DA-3.8 References

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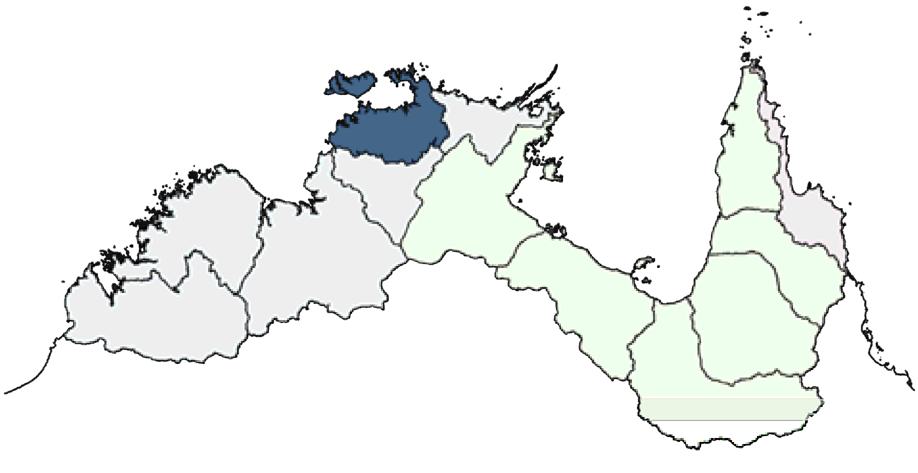
Water in the Van Diemen region



VD-1 Water availability and demand in the Van Diemen region

The first part of this report (the Preamble, Chapter 1 and Chapter 2) reports at the division level, including division-wide descriptions of climate and geology and methods which apply to all regions. Subsequent chapters report at the region level. In particular, Chapters VD-1, VD-2 and VD-3 focus on the Van Diemen region (Figure VD-1).

This chapter summarises the water resources of the Van Diemen region, using information from Chapter VD-2 and Chapter VD-3, and directly addresses the Terms of Reference, specifically terms 3, 4 and 5 as listed in the Preamble. Essentially, this chapter provides a synoptic view of the region and covers:

- regional observations
- water resource assessment
- seasonality of water resources
- surface–groundwater interaction
- changes to flow regime at environmental assets
- water storage options
- data and knowledge gaps.

For further details on the context of the region (physical and climate descriptions, hydrogeology and legislation) see Chapter VD-2. Region-specific methods and results are provided in Chapter VD-3. Modelling results are reported under climate and development scenarios as defined at the division level in Section 2.1 of Chapter 2.

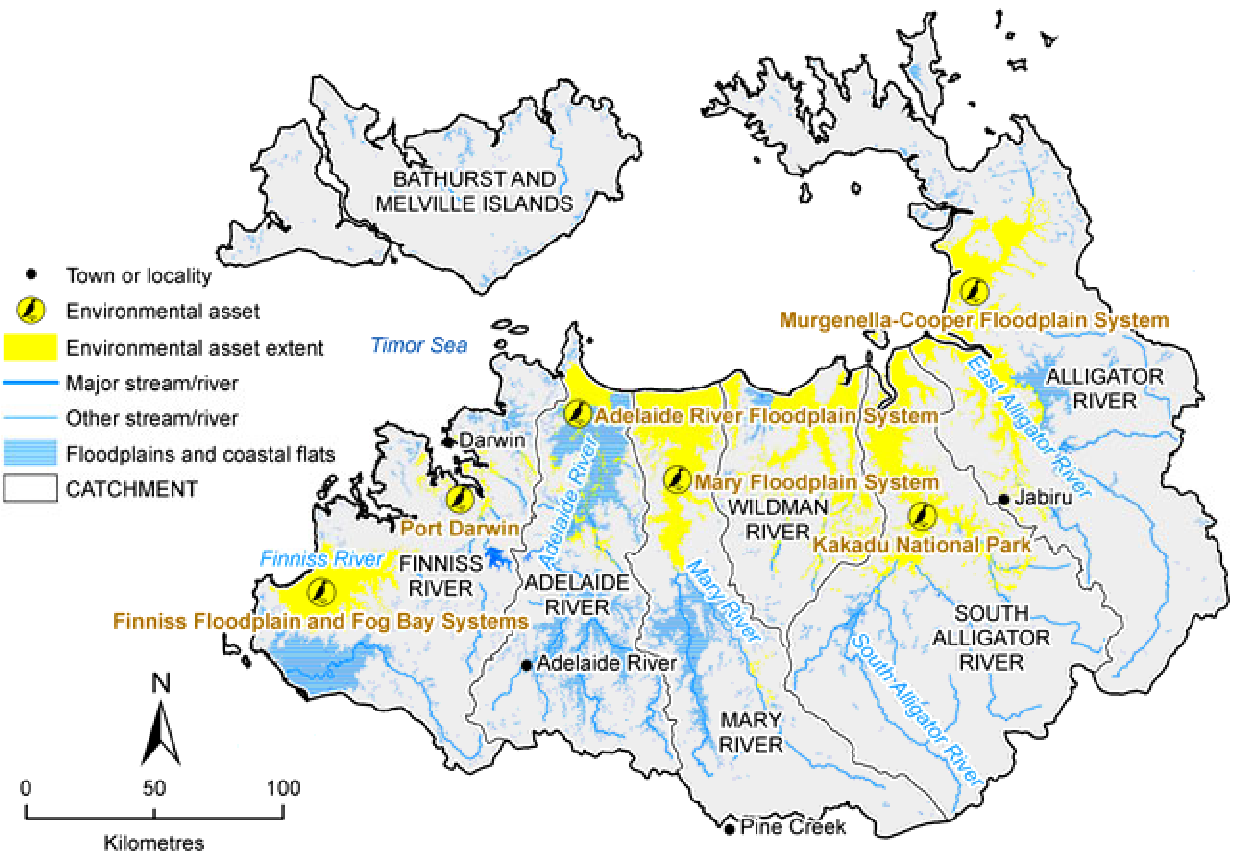


Figure VD-1. Major rivers, towns and location of environmental assets selected for assessment of changes to hydrological regime in the Van Diemen region

VD-1.1 Regional summary

This section summarises key modelling results from this project and provides other relevant water resource information as context about water availability and demand in the Van Diemen region.

The historical (1930 to 2007) mean annual rainfall in the region is 1390 mm. Mean annual areal potential evapotranspiration (APET) is 1936 mm. The mean annual runoff averaged over the modelled area of the Van Diemen region is 375 mm, 27 percent of rainfall. These values are amongst the highest across northern Australia. Under the historical climate the mean annual streamflow over the Van Diemen region is estimated to be 25,345 GL.

The Van Diemen region has a high inter-annual variability in rainfall and hence runoff and recharge. Relative to the rest of northern Australia, however, coefficients of variation are among the lowest of the regions but still reflect multiple consecutive years of significantly below, or above, average rainfall.

There is a strong seasonality in rainfall patterns, with 95 percent of rainfall falling in the wet season, between November and April, and a very high dry season (May to October) APET. The region has relatively high rainfall intensities, extremely high for the top 1 percent of events, and this is reflected in rapid runoff and a short lag between rainfall and runoff. Ninety-six percent of runoff occurs within the months of December and April. There has been a slightly increasing amount and intensity of rainfall over the 1930 to 2007 period.

There is a strong north–south rainfall gradient and hence also runoff, with the runoff coefficient decreasing from 40 to 15 percent of precipitation in the same direction.

APET is annually greater than rainfall, and thus the region may be considered water-limited. The region is one of only a few, however, that is not water-limited throughout the entire year, with wet season rain exceeding APET, particularly towards the coast.

In the Van Diemen region, the recent (1996 to 2007) climate record is statistically significantly wetter than the historical (1930 to 2007) record. Rainfall was 16 percent higher; runoff was 44 percent higher. It is likely that future (~2030) conditions will be similar to historical conditions, and future runoff and recharge will also be similar to historical levels, but lower than in the recent past.

There are opportunities for surface water storage in the area to the south of Darwin on the Finniss and Adelaide rivers. These sources are currently under investigation by Power and Water Corporation for long-term future development. Lower reaches of many of the rivers of the region are flood determined and dominated and estuaries may experience high tidal ranges.

The major aquifers in the region have been developed in the Proterozoic carbonates and Cretaceous and Palaeozoic sediments. Groundwater is being extracted from the Proterozoic carbonate aquifers in the Darwin Rural Area. Current dry season extraction from the bores of the Darwin Rural Area is close to the long-term extraction limit and these aquifers exhibit strong seasonal variability with groundwater levels currently rising and falling by up to 17 m/year. Whilst the shallow systems will fill during the wet season, during dry periods the level of use will not be able to be sustained by the resource.

This is one of only a few regions where a significant proportion of public groundwater use is metered. Very little private groundwater use, however, is metered across the region.

The aquifers in the Proterozoic carbonates and Cretaceous sediments are the source of dry season flow in the perennial reaches of rivers in the Van Diemen region. Discharge is highly localised and coincides with limited outcrop regions of these aquifers. If future demand for water extraction increases in the vicinity of the discharge areas, there will be significant impact on the dry season flow downstream of these areas. Management of releases from the Darwin River Dam, however, ensures perennial flow to the Darwin River.

At environmental assets, flows are highly dominated by wet season flows, with dry season flows only a small fraction of total annual flow. However, environmental assets are adapted to this strong seasonality and any significant changes in the frequency and duration of wet season high flows and dry season low flows are likely to have an environmental impact.

In the recent past there has been significantly more flow, with fewer low flow days and more high flow days than historically. Under the median future climate, annual and seasonal flows do not change much; hence there is little change in the high and low flow threshold exceedance. In contrast, there are large changes to the high flow threshold exceedance under the wet extreme and dry extreme future climates and this could have negative environmental impacts. At assets where zero flow is rare there is not much change to this metric under any of the scenarios, hence ecological assets attuned to zero flow conditions should not be greatly affected. However, other assets do have significant periods of zero flow each year and this period changes significantly under dry and wet extreme future climates. Ecological assets that depend on the current zero flow periods may therefore be negatively impacted under these scenarios.

Away from the Darwin Rural Area, the region is generally datapoor, though locally good information is available (e.g. Jabiru).

VD-1.2 Water resource assessment

Term of Reference 3a

VD-1.2.1 Under historical climate and current development

Term of Reference 3a (i)

The mean annual rainfall and runoff averaged over the Van Diemen region are 1386 mm and 375 mm respectively. The mean annual rainfall and runoff averaged over the Van Diemen region fall at the upper end of the range of values from the 13 regions. The coefficients of variation of annual rainfall and runoff averaged over the Van Diemen region are 0.18 and 0.49 respectively. The coefficients of variation of annual rainfall and runoff averaged over the Van Diemen region are among the lowest of the 13 regions. The 10^{th} percentile, median and 90^{th} percentile annual runoff values across the Van Diemen region are 640, 345 and 158 mm respectively.

Under a continued historical climate, mean annual diffuse groundwater recharge to unconfined aquifers in the Van Diemen region is likely to be similar to the historical (1930 to 2007) average value. Current groundwater extraction is estimated to be in excess of 36 GL/year (Table VD-1) and much of this is sourced from within the Darwin Rural Area – McMinn's – Howard East Section horticultural area. Dry season minimum groundwater levels for the dolomite aquifer in this area have been declining for many years, and modelling undertaken for this project predicts these trends will continue under an historical climate with the current level of development. One particular concern is that predicted groundwater levels around Lambells' Lagoon bore LL24714 regularly approach mean sea level throughout the simulation period (2007 to 2030).

Table VD-1. Estimated groundwater contribution (baseflow) to streamflow, modelled diffuse recharge and groundwater extraction for the Van Diemen region under historical climate

Station	River	Station name	Annual BFI *	Dry season BFI *	Dry season baseflow *
					GL
G8150010	Finniss	Batchelor Damsite	0.25	0.61	2.5
G8150018	Elizabeth	Stuart HWY	0.26	0.41	0.7
G8150096	Carawarra Ck	Cox Peninsula	0.38	0.62	1.3
G8150097	East Finniss	Rum Jungle +Ansto Eb4	0.28	0.37	0.2
G8150098	Blackmore	Tumbling Waters	0.18	0.34	0.3
G8150127	Rapid Ck	D/S McMillans Rd	0.35	0.61	0.6
G8150179	Howard	Koolpinyah Stockyard	0.34	0.54	1.9
G8150180	Finniss	Gitchams	0.19	0.59	8.0
G8170002	Adelaide	Railway Br	0.26	0.52	5.8
G8170005	Adelaide site 13	U/S Marrakai Crossing	0.24	0.47	6.2
G8170006	Br Ck	U/S Railway	0.15	0.62	0.3
G8170011	Manton Dam	Dam Intake Tower	0.22	0.29	1.9
G8170033	Manton	Acacia Gap	0.11	0.27	0.3
G8170066	Coomalie Ck	Stuart HWY	0.38	0.72	1.6
G8170075	Manton	U/S Manton Dam	0.24	0.64	0.4
G8170084	Adelaide	Tortilla Flats	0.21	0.46	4.6
G8170085	Acacia Ck	Stuart HWY	0.24	0.50	0.1
G8180026	Mary	El Sherana Rd Crossing	0.20	0.85	13.8
G8180035	Mary	Mount Bundey	0.23	0.35	12.0
G8180059	Mary	U/S of ?	0.28	0.43	54.1
G8180065	Opium Ck	Old Point Stuart Rd Xing	0.40	0.77	1.1
G8180069	McKinlay	near Burrundie	0.07	0.25	0.2
G8190001	West Alligator	U/S Arnhem HWY	0.20	0.38	0.5
G8200044	Goodparla Ck	Coirwong Gorge	0.05	0.35	0.0
G8200045	South Alligator	El Sherana (C)	0.23	0.72	7.0
G8200112	Nourlangie Ck	Kakadu HWY	0.15	0.39	6.6
G8210009	Magela Ck	D/S Jabiru	0.23	0.43	1.4
G8210017	Magela Ck Plains	Jabiluka Billabong	0.26	0.52	5.0
		Historical recharge **	Estimated groundwater extraction		
		GL/y			
Entire Van Diemen region		19,990			36.7

* BFI (baseflow index) and baseflow volume derived from gauged data.
** Aggregated recharge from Zhang and Dawes (1998).

VD-1.2.2 Under recent climate and current development

Term of Reference 3a (ii)

The mean annual rainfall and runoff under the recent (1996 to 2007) climate are 16 percent and 44 percent higher respectively than the historical (1930 to 2007) mean values.

Under the recent climate, mean annual diffuse groundwater recharge is likely to be similar to or slightly higher than the historical average value over most of the region, particularly in the far south-east corner. An exception to this trend is where vertosol soils exist in which case recharge is likely to be lower. Despite the increase in recharge, model predictions for the dolomite aquifer in the Darwin Rural Area – McMinn's – Howard East Section suggest groundwater levels are likely to exhibit greater seasonal fluctuations under a recent climate with current development, but that the recently observed declines in groundwater level may reach a new state of dynamic equilibrium by 2030.

VD-1.2.3 Under future climate and current development

Term of Reference 3a (iii)

Rainfall-runoff modelling with climate change projections from seven of the GCMs shows a reduction in mean annual runoff, while rainfall-runoff modelling with climate change projections from eight of the GCMs shows an increase in mean annual runoff. Under the high global warming scenario, rainfall-runoff modelling with climate change projections from four of the GCMs indicates a decrease in mean annual runoff greater than 10 percent while rainfall-runoff modelling with climate change projections from three of the GCMs indicates an increase in mean annual runoff greater than 10 percent. Under scenarios Cwet, Cmid and Cdry, mean annual runoff increases by 24 and 1 percent and decreases by 25 percent percent relative to Scenario A. By comparison, the range based on the low global warming scenario is a 12 to -15 percent change in mean annual runoff.

Under the future climate, mean annual diffuse groundwater recharge is likely to be higher than the historical mean value over most over the region, except in the far west where it is likely to be similar to the historical average and where vertosol soils exist. Model predictions for the dolomite aquifer in the Darwin Rural Area – McMinn's – Howard East Section suggest groundwater levels will continue to decline under this scenario, and that the magnitude of decline may be as much as 5 to 10 m in the McMinn's area. Furthermore, the predicted groundwater levels for bore LL24714 at Lambells Lagoon regularly approach mean sea level during the simulation period (2007 to 2030).

VD-1.2.4 Under future climate and future development

Term of Reference 3b

No simulations of future groundwater development were performed for the Darwin Rural Area – McMinn's – Howard East Section as the Proterozoic carbonate aquifers in this area are already considered to be in a state of overdraw. The challenge for future groundwater development elsewhere in the Van Diemen region is to locate extraction bores a sufficient distance away from the major perennial rivers, so that groundwater pumping has minimal impacts to dry season baseflow contributions to these rivers (Table VD-1).

VD-1.3 Changes to flow regime at environmental assets

Term of Reference 3a (iv)

Section 1.3 of the division-level Chapter 1 describes how environmental assets were shortlisted for assessment by this project. Six environmental assets were shortlisted for the Van Diemen region: Murgenella-Cooper Floodplain System, Kakadu National Park, Adelaide River Floodplain System, Finniss Floodplain and Fog Bay Systems, Mary Floodplain System and Port Darwin. These assets are characterised in Chapter VD-2.

In deciding whether it is feasible to report hydrological regime metrics for these shortlisted assets, it is important to consider the confidence levels in modelled streamflow (as described in Section 2.2.6 of the division-level Chapter 2). Confidence in results for low flows and high flows was calculated separately. Hydrological regime metrics (as defined in Section 2.5 of the division-level Chapter 2) for either low flows or high flows are reported only where confidence levels are sufficiently high. If confidence in the low flow or high flow is too low, metrics are not reported, and hence an important gap in our knowledge is identified.

Some of the assets in this region have multiple nodes at which streamflow modelling results are available. When reporting hydrological regime metrics for such assets a single node was selected. The selected node was that with the highest streamflow confidence level and the largest proportion of streamflow to the asset. The locations of nodes for each asset are shown on satellite images in Section VD-2.1.3. Results for all nodes are presented in McJannet et al. (2009).

Of the six assets selected in this region there was sufficient confidence in high flows and low flows to report results for all but the Adelaide River Floodplain System. For this asset, confidence in low flow was too poor to present results.

At all assets, annual flow is dominated by wet season flow. Under the recent climate, wet season flow has increased dramatically (e.g. by 65 percent for Finniss Floodplain and Fog Bay System and by 53 percent for the Kakadu National Park). Dry season flows under the recent climate have increased by similar magnitudes at all assets except at the Mary Floodplain System where it increased by 125 percent.

There is little to moderate increase in flow under the future climate with moderate increases and decreases in flow under the wet extreme and dry extreme future climates, respectively.

Zero flow days occur at all assets but are rare. This is little change to the number of days of zero flow under the future climate; however, there is a large change under the dry extreme future climate.

Under the recent climate the high flow threshold exceedance has been much more frequent than under the historical climate. Under the wet extreme future climate there is a moderate increase in the number of days of high flow exceedance.

VD-1.4 Seasonality of water resources

Term of Reference 4

Approximately 95 percent of rainfall and 96 percent of runoff occurred during the wet season months under the historical climate. Under recent climate 96 percent of rainfall and 96 percent of runoff occurred during the wet season months. Under future climate in 2030 it is estimated that 96 percent of rainfall and 97 percent of runoff will occur during the wet season months. Runoff is highest in February and March.

VD-1.5 Surface–groundwater interaction

Term of Reference 4

Figure VD-2 shows reaches of rivers where significant groundwater discharge is known to occur towards the end of the dry season. The data used to compile this map represents gauged instantaneous flows after a series of below average and above average wet seasons. These flows are sustained by significant regional groundwater discharges from aquifers developed in karstic rocks and Cretaceous sediments. Perennial reaches of rivers where dry season flow is sourced from karstic rocks are the Berry Creek and Howard River. Perennial reaches of rivers where dry season flow is sourced from Cretaceous sediments are the Mary, South Alligator and Howard rivers, as well as Bluewater, Taracumbi and Takamprimili creeks.

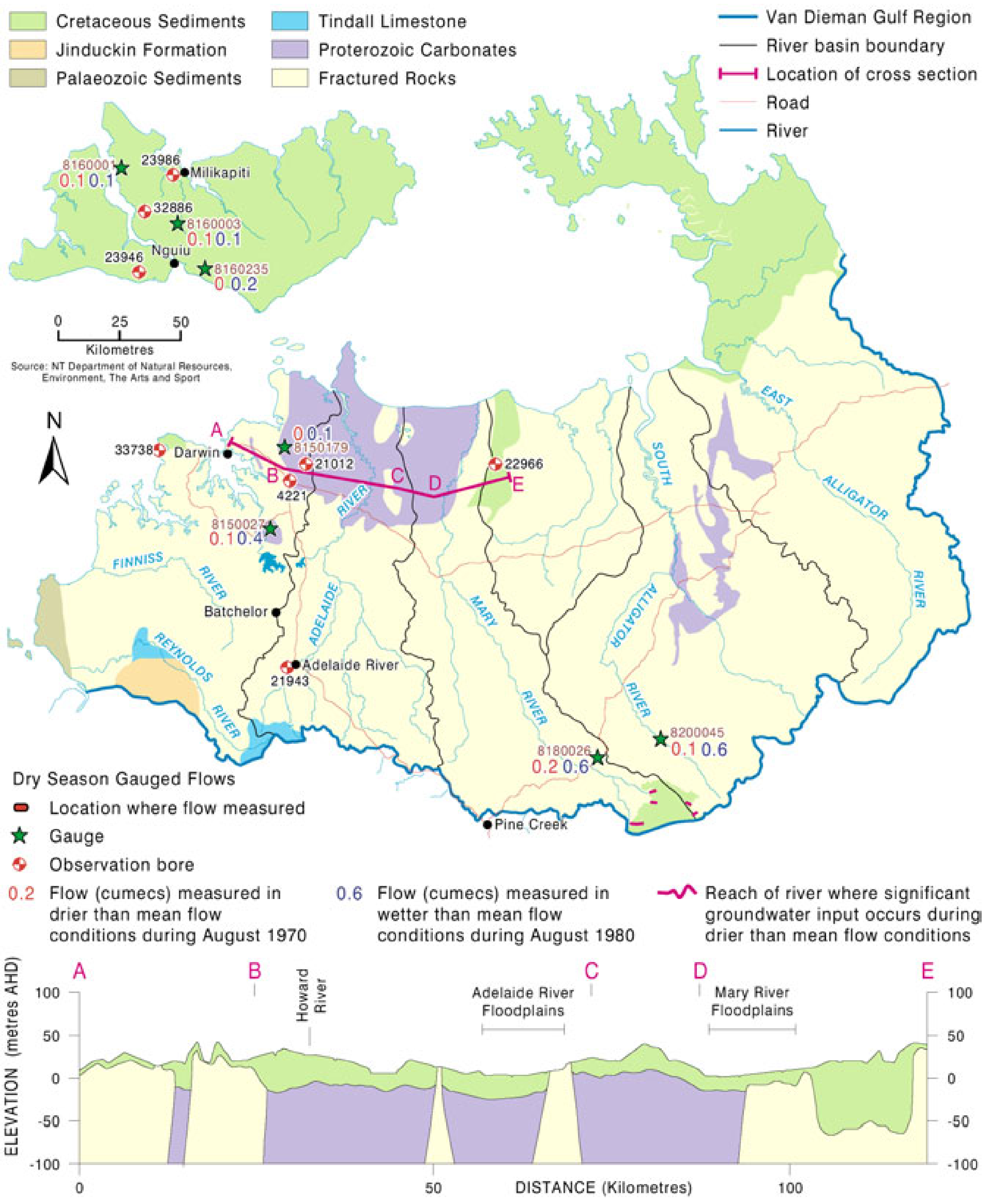


Figure VD-2. Hydrogeology of the Van Diemen region with dry season gauged flows (map provided by NRETAS, 2009)

The amount of recharge to an aquifer system can be estimated from data on dry season flows, assuming all recharge ultimately leaves the aquifer through discharge to streams within the following dry season. Jolly et al. (2000) conducted a detailed analysis of gauged dry season instantaneous flow data for gauge G8150027. The work was undertaken because it was recognised that the flow records for gauging stations in the region were biased towards above average rainfall years. Flow and rainfall data were used to predict regional groundwater discharges at gauge G8150027 for the full period of rainfall record. The modelled discharge fluxes for the period 1900 to 1999 and gauged flows are plotted in Figure VD-3.

The technique gave a good match for gauged data. The existing flow records, while biased towards above average rainfall years, have captured groundwater discharge data over a large range of conditions that are likely to occur in the Arafura region (Figure VD-3).

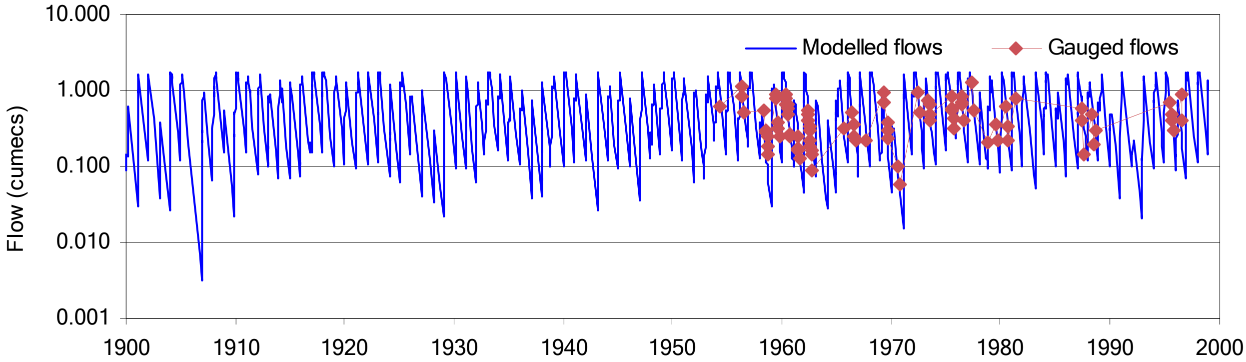


Figure VD-3. Modelled dry season flows at G815027 in Berry Creek in the Van Diemen region

Tien (2002) applied the same technique to model spring flow at Howard Springs, a popular tourist attraction near Darwin. The modelled groundwater discharge fluxes for the period 1870 to 2000 and gauged flows are plotted on Figure VD-4. The technique also gave a good match for gauged data at this location.

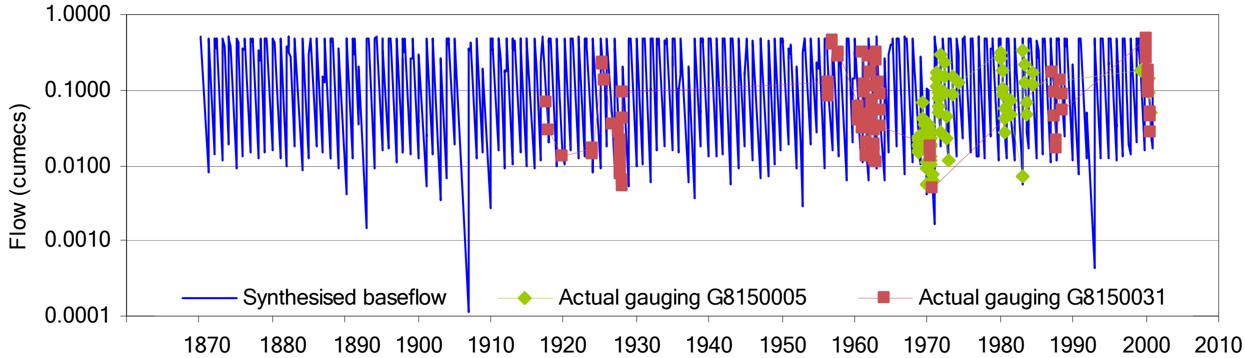


Figure VD-4. Modelled flows at Howard Springs 1970 to 2000

VD-1.6 Water storage options

Term of Reference 5

VD-1.6.1 Surface water storages

The Darwin River Dam is the only large reservoir in the Van Diemen region. The degree of regulation for the Darwin River Dam is high (0.66). The relative level of use under Scenario A is high (37 percent). Under the high global warming scenario the relative level of use falls to 28 percent, while under the low global warming scenario the relative level of use rises to 43 percent.

VD-1.6.2 Groundwater storages

Groundwater development is very intensive in some localised parts of the Van Diemen region, particularly the Darwin Rural Area. Managed aquifer recharge (MAR) may have potential to mitigate declining trends in storage of the Proterozoic carbonate aquifers in these areas. That is, there is often some sub-surface storage capacity towards the end of the wet season when surface water is available for injection. However, the extensive laterite that covers these areas would preclude the use of infiltration pits for MAR. Instead, any potential future scheme would need to use injection wells to recharge the aquifer, the costs of which may be prohibitive for irrigation.

VD-1.7 Data gaps

Term of Reference 1e

The extraction of groundwater from the Proterozoic carbonate aquifers in the Darwin Rural Area results in fluctuations in groundwater levels by up to 17 m/year (currently). Modelling has identified that during dry periods current extraction will not be able to be sustained by the resource. The accuracy of the model has been constrained by the lack of metered groundwater extraction data for private bores across the region. Groundwater use for community and town water supply purposes is, however, metered.

VD-1.8 Knowledge gaps

Term of Reference 1e

None of the environmental assets in this region have any site-specific metrics by which to gauge the potential impacts of future climate change and development. In the absence of site-specific metrics a set of standard metrics related to high flows and low flows have been utilised. However, the conversion of these metrics into environmental impacts still requires development of quantitative relationships between flow and specific ecological entities (for example, macrophyte populations, fish passage, faunal and floral habitats, etc.).

Flooding is an important factor that sustains many environmental assets and this occurs when the stream breaks out of its banks (a level known as bankfull stage or discharge). However, bankfull discharge is not known for many streams, nor is the dependence of area flooded on increasing stream depth, so it is difficult to predict when assets are inundated. Further information about bankfull stage and discharge are needed for most environmental assets.

Dry season flows are poorly understood in this region therefore the ability to predict the potential impacts of the various scenarios on low or zero flows at environmental assets is very limited. Improved monitoring of low streamflow conditions is needed along with the development of hydrological models that combine surface and groundwater regimes. Further monitoring of groundwater levels is also required so that the potential impacts of climate change and development on groundwater-dependent ecosystems can be better understood.

Many environmental assets depend not simply on duration above or below certain flow levels, but on triggers (e.g. for reproduction or migration) set by the rate of change of flow. In addition, some environmental assets depend on the frequency and duration of events that occur less than annually (i.e. once every 5, 10 or 20 years or more). Further analysis is therefore required to look at how the timing, duration and rate of rise and fall in flow rates at critical times of the season varies under the various scenarios.

VD-1.9 References

Jolly P, Sutcliffe E and Jolly I (2000) Prediction of Springflows at GS 8150027 on Berry Creek for the Period 1870 to 1999. Report No WRD00023 Department of Lands, Planning and Environment, Darwin

McJannet DL, Wallace JW, Henderson A and McMahon J (2009) High and low flow regime changes at environmental assets across northern Australia under future climate and development scenarios. CSIRO Water for a Healthy Country Flagship, Canberra. *In prep.*

Tien AT (2002) Hydrology and Water Quality at Howard Springs Nature Park, Northern Australia. Master of Natural Resources Research Report, University of New England, Armidale, Australia

Zhang L and Dawes W (1998) WAVES - An integrated energy and water balance model. Technical Report No. 31/98, CSIRO Land and Water.

VD-2 Contextual information for the Van Diemen region

This chapter summarises the background information for the region, outlining existing knowledge of water resources and prior and current investigations relevant to the water resources of the region. This chapter also outlines the current and potential future legislation, water plans and other water resource management arrangements. This chapter is arranged into four sections:

- physical and climate descriptions
- data availability
- hydrogeology
- legislation, water plans and other arrangements.

VD-2.1 Overview of the region

VD-2.1.1 Geography and geology

The Pine Creek Orogen underlies most of the region (Figure VD-5). It consists of multiple sequences of deformed and metamorphosed Palaeoproterozoic successions underlain by Archaean (2,500-4,560 million year old) granites and gneisses. The Pine Creek Orogen hosts over a thousand mineral occurrences and is the most prospective province of the Northern Territory. The region contains approximately 20 percent of the world's low-cost uranium resource and has a significant potential for gold.

The Daly Basin underlies a small area in the south west of the region. It contains the lower Palaeozoic Daly River Group, comprising, in ascending order, the marine Tindall Limestone and the peritidal Jinduckin Formation.

The Palaeozoic Bonaparte Basin also underlies a small area in the south-west corner of the region. In the region the sediments are of Permian age and are mainly sandstones.

In the Early Cretaceous the sea encroached on the interior of the region, depositing a sheet of predominantly sandy sediments followed by a layer of predominantly clayey sediments (Walpole et al, 1968). That period was short lived and erosion has again dominated until the present day. Cainozoic and Cretaceous sediments rest on a palaeo-topographic surface of Proterozoic and Palaeozoic sedimentary and volcanic rocks across the region.

The on shore Money Shoal Basin primarily occurs adjacent to the northern edge of the mainland and it also underlies the Tiwi Islands. It is relatively undeformed and is composed primarily of Cretaceous aged sediments. The basin contains mildly deformed, largely flat-lying sediments; these consist of Cretaceous successions of marine and continental clastics, predominantly sandstones with minor coals, shales, claystones and marls. Money Shoal Basin strata overlie Proterozoic strata of the Pine Creek Orogen.

The current drainage system probably came into existence in the Cretaceous when uplift in the north of the Northern Territory resulted in a drainage divide between inland draining streams to the south and streams draining to the sea in the north. Hilly and rugged ridges alternate with undulating plains and alluvial plains. Major rivers which drain to the north coast include the Finniss, Adelaide, Mary, Wildman, South Alligator and East Alligator.

The alluvial floodplains that cover an extensive area along the coastal northern edge of the region are underlain largely by marine sediments that have been deposited in the last 10,000 years since the end of the ice age.

Kakadu National Park covers most of the Wildman and South Alligator rivers and part of the East Alligator River and is a RAMSAR area of international importance for its wetlands as breeding sites for migratory birds and is one of four Australian sites included on the World Heritage List for both outstanding cultural and natural values.

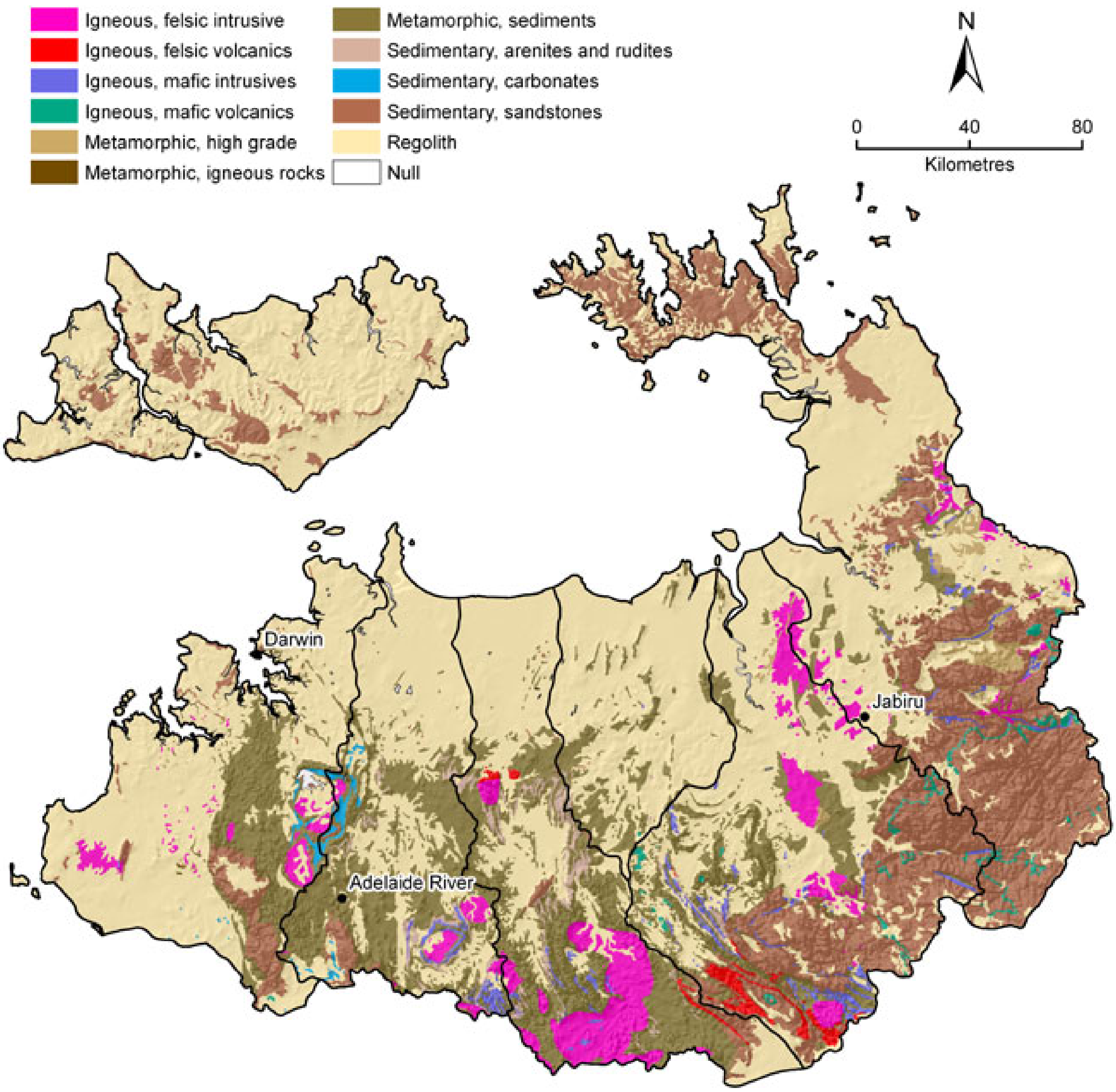


Figure VD-5. Surface geology of the Van Diemen region overlaid on a relative relief surface

VD-2.1.2 Climate, vegetation and land use

The Van Diemen region receives an average of 1390 mm of rainfall over the September to August water year, most of which (1327 mm) falls in the November to April wet season (Figure VD-6). Across the region there is a strong north–south gradient in annual rainfall, ranging from 1695 mm in the north to 1155 mm in the south. Over the historical (1930 to 2007) period, annual rainfall has been gradually increasing from an initial average of around 1100 mm to approximately 1400 mm later in the period. The highest yearly rainfall received was 1942 mm which fell in 2000, and the lowest was 765 mm in 1952.

Areal potential evapotranspiration (APET) is very high across the region, averaging 1936 mm over a water year, and varies moderately across the seasons. APET generally remains higher than rainfall from April until November resulting in water-limited conditions over these months. Between December and March conditions are energy-limited, meaning more rain falls than can potentially be evaporated.

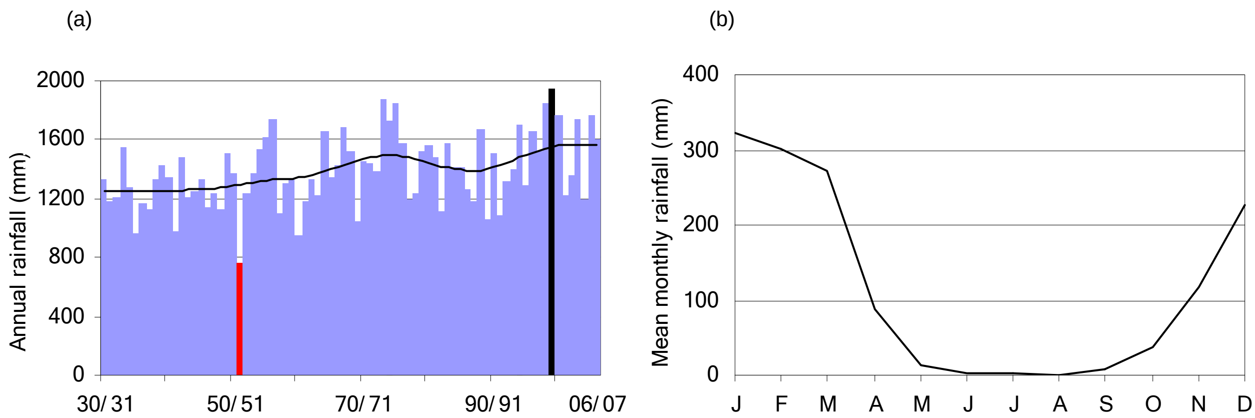


Figure VD-6. Historical (a) annual and (b) mean monthly rainfall averaged over the Van Diemen region

The most extensive vegetation (Figure VD-7) of this region is eucalypt open forest, typically co-dominated by darwin stringybark (*Eucalyptus tetrodonta*) and darwin woollybutt (*E.miniata*), but with smaller areas of bloodwood woodlands (variably dominated by *Corymbia tectifica, C. grandifolia, C. confertiflora, C. dichromophloia* and *C. latifolia*), intermixed with paperbark woodlands on drainage depressions and in riparian areas, and small patches of monsoon rainforest (typically in springs and on rocky hillslopes topographically protected from fire). Connors et al. (1996) listed 1,713 plant species across the region.

VD-2.1.3 Land use

The region comprises pastoral leasehold (mostly cattle), conservation reserves and Aboriginal freehold and also contains the most intensively developed and settled part of the Northern Territory, including the city of Darwin and surrounding urban developments and horticultural developments (mostly fruit trees) on the fringe of the city (Figure VD-8).

Lands reserved for conservation within the region include Litchfield National Park, Kakadu National Park, Mary River Conservation Reserve and Manton Dam Recreation Area (Connors et. al., 1996).

Aboriginal people continue to live throughout the region and have strong traditional ties with the land. There are many documented sites of significance, and Aboriginal association with the land has been recognised by successful land claims and joint management of Kakadu and Nitmiluk National Parks. Aboriginal land management includes traditional hunting, pastoralism, horticulture, tourism and fire management.

There are several large mining ventures mostly for gold, lead-zinc and uranium within the bioregion.

Tourism is a major industry in the region, particularly to Kakadu, Litchfield and Nitmiluk National Parks.

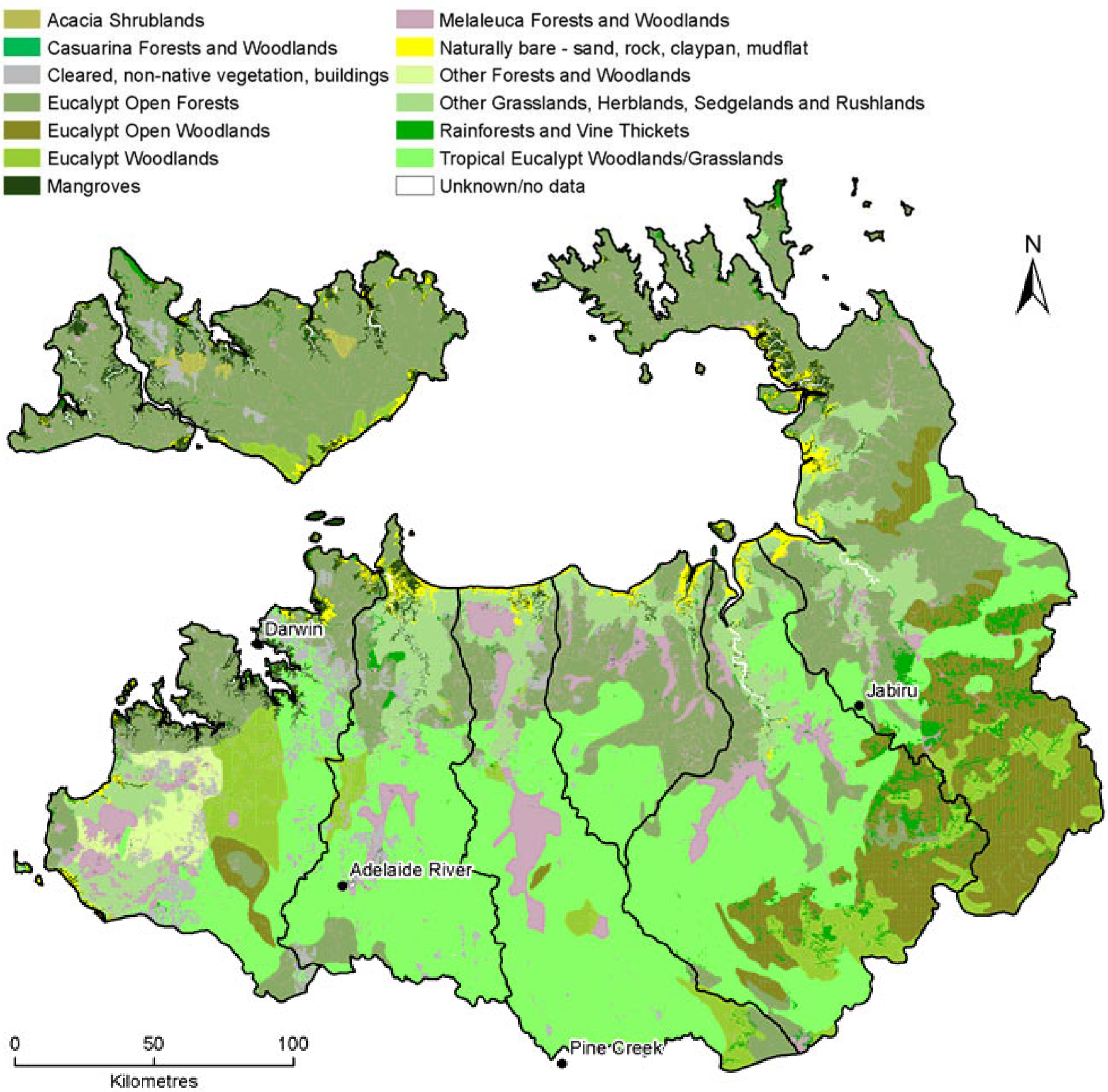


Figure VD-7. Map of current vegetation types across the Van Diemen region (source DEWR, 2005)

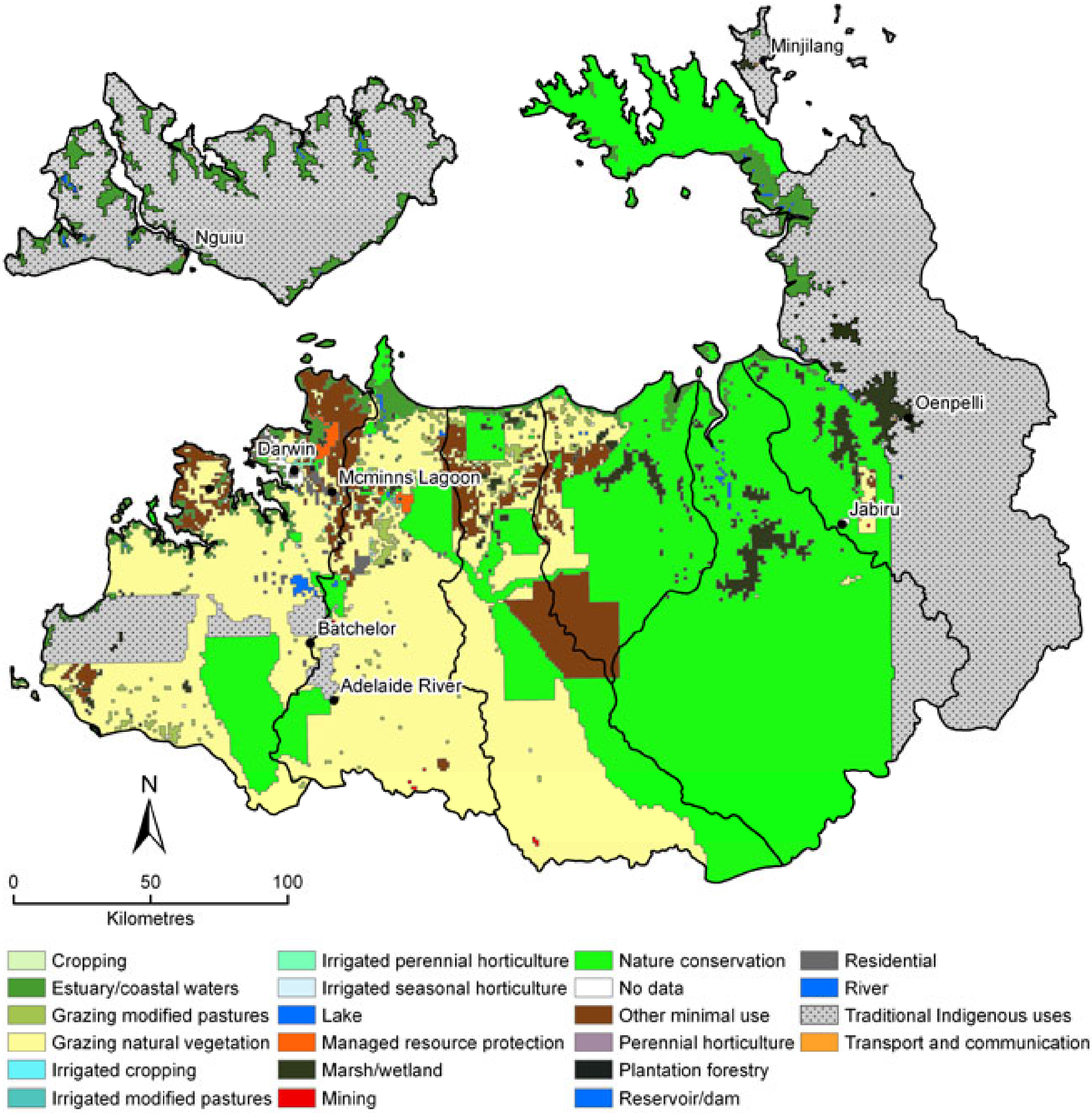


Figure VD-8. Map of dominant land uses of the Van Diemen region (after BRS, 2002)

VD-2.1.4 Regional environmental asset description

Environmental assets were chosen from wetlands which are listed in the Directory of Important Wetlands in Australia (Environment Australia, 2001). From this directory, environmental assets were shortlisted for assessing changes to the hydrological regime under the climate and development scenarios. The selection of this shortlist was undertaken in consultation with state governments and the Australian Government through direct discussions and through internal reviews (see Section 1.3 in the division-level Chapter 1 for further detail).

All nationally, or internationally, important wetlands listed for the Van Diemen region in the Directory of Important Wetlands in Australia (Environment Australia, 2001) are detailed in Table VD-2, with asterisks identifying the six shortlisted assets: Murgnella-Cooper Floodplain System, Kakadu National Park, Adelaide River Floodplain System, Finniss Floodplain and Fog Bay Systems, Mary Floodplain System and Port Darwin. The location of these shortlisted wetlands is shown in Figure VD-1. There are no wetlands classified as Ramsar sites in this region. Wetlands may be nationally or regionally significant depending on more locally specific criteria. All wetlands are important for a variety of ecological reasons or because they bear historical significance or have high cultural value, particularly to Indigenous people.

The following section characterises these shortlisted wetlands and is based largely on the description of these assets as outlined by Environment Australia (2001). Chapter VD-3 presents the assessment of those shortlisted assets, and reports hydrological regime metrics for those assets which have sufficient confidence in the modelled streamflow to enable analysis.

Table VD-2. List of Wetlands of National Significance located within the Van Diemen region

Site code	Name	Area	Ramsar site
		ha	
NT023	Cobourg Peninsula System	254,000	Yes
NT028 *	Murgenella-Cooper Floodplain System	81,500	Yes
NT017 *	Kakadu National Park	233,000	Yes
NT020 *	Adelaide River Floodplain System	134,000	No
NT025 *	Finniss Floodplain and Fog Bay Systems	81,300	No
NT026 *	Mary Floodplain System	128,000	No
NT031	Mount Bundey Training Area - Mary River Floodplain	<10	No
NT029 *	Port Darwin	48,800	No
NT032	Shoal Bay - Micket Creek	<10	No

* Asterisk against the site code identifies those selected for assessment of changes to hydrological regime.

Murgenella-Cooper Floodplain System

The Murgenella-Cooper Floodplain System (Figure VD-9) is characterised by marine and coastal zone wetlands and inland wetlands. The site has an elevation ranging between 1 and 7 m above sea level and is a good example of a floodplain-tidal wetland system of the Top End Region which has a relatively low volume of freshwater inflow (Environment Australia, 2001).

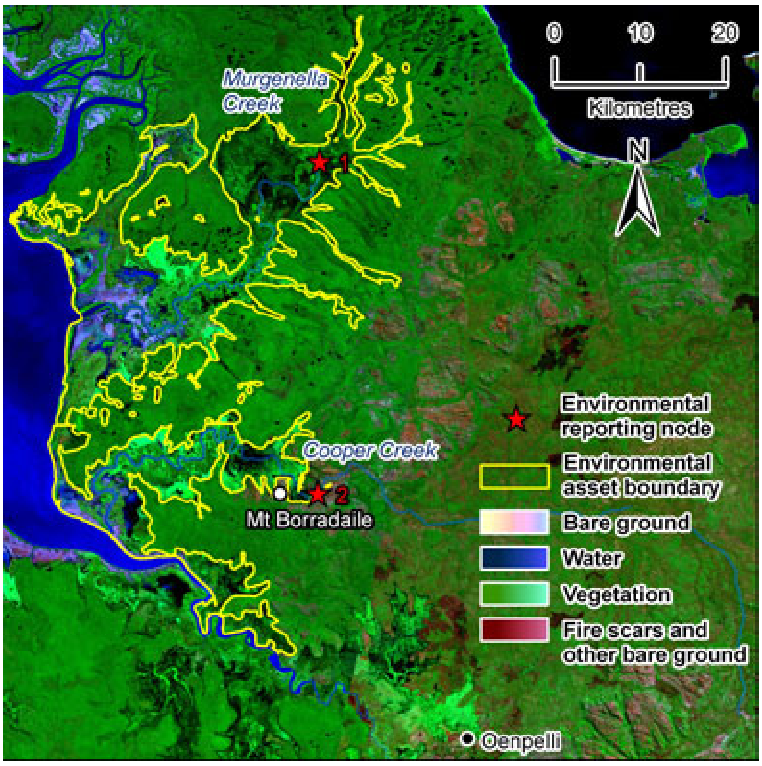


Figure VD-9. False colour satellite image of the Murgenella-Cooper Floodplain System (derived from ACRES, 2000). Clouds may be visible in image

Magpie Goose breeds extensively on both Murgenella and Cooper Floodplains. Mudflats and saline coastal flats of the site are used at times by more than 10,000 shorebirds as a migration stop-over. Major dry season concentrations of waterbirds occur on the Cooper Floodplain (up to approximately 100,000) and counts of up to 17,000 "waders" have been recorded.

An Indigenous community (Oenpelli) is located 33 km from the site and some traditional use of the wetlands is still practised. Significant Indigenous rock art occurs at Mt Borradaile (Environment Australia, 2001). Commercial fishing occurs at the coast.

Kakadu National Park

Kakadu National Park (Figure VD-10) is a national icon and is characterised by marine and coastal wetlands, and inland wetlands. Amongst a large list of aquatic environments are marine waters, subtidal aquatic beds, mud and sand flats; tidal marshes and permanent and seasonal rivers and streams (Environment Australia, 2001). Kakadu National Park contains part or all of the catchments of two large and two smaller river systems, including a mosaic of contiguous wetlands associated with them. The wetlands and their catchments encompass sandstone plateau communities, escarpments, lowland open forest and woodland savanna, seasonal floodplains, tidal flats, estuaries, and offshore islands.

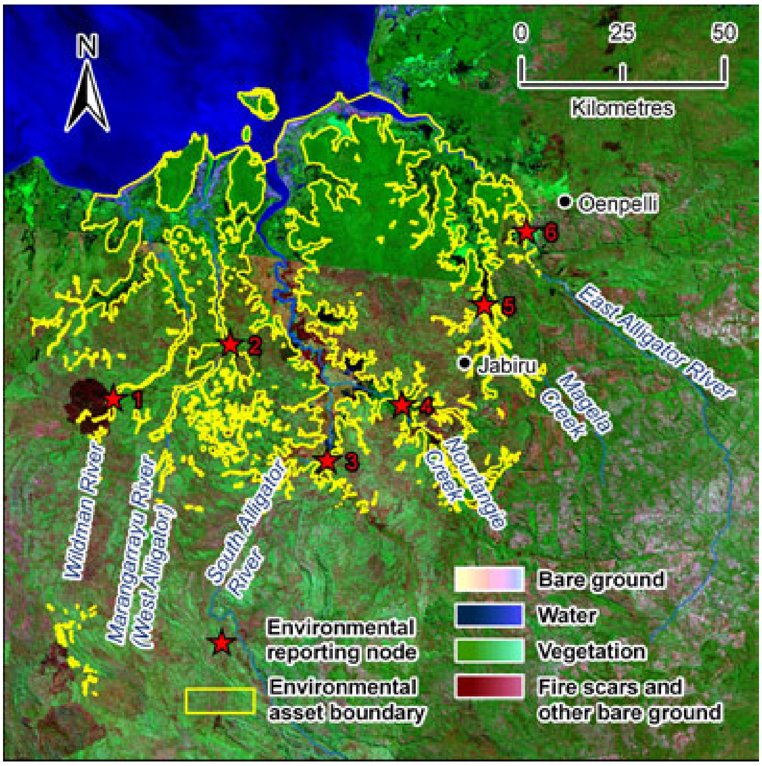


Figure VD-10. False colour satellite image of Kakadu National Park (derived from ACRES, 2000). Clouds may be visible in image

The floodplains and other wetlands of the Kakadu National Park support about three million waterbirds. Large populations of many other vertebrate and invertebrate species are also found. The site has an area of 233,000 ha and an elevation ranging between zero and 400 m above sea level (Environment Australia, 2001). The Kakadu wetlands are significant for a number of reasons, including their diversity, the flora and fauna they support, and their ongoing importance to the traditional owners of the area. High values are perceived nationally and internationally for conservation, mining, tourism, education and research. Indigenous sacred sites and art sites are found throughout the park and are important to continuing Indigenous culture (Environment Australia, 2001). In recognition of the conservation significance of the area, Kakadu National Park is listed under the Ramsar Convention. The international significance of the region is also recognised by the fact that it is a proclaimed World Heritage Area.

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Adelaide River Floodplain System

The Adelaide River Floodplain System (Figure VD-11) is a good example of a major floodplain-tidal wetland system typical of the Top End Region. The site has an area of 134,000 ha and an elevation ranging between zero and 6 m above sea level (Environment Australia, 2001). Notable features include one of the largest blocks of mangrove associated with a Top End floodplain, a tightly meandering major tidal river, the largest floodplain lake in the Top End (Environment Australia, 2001).

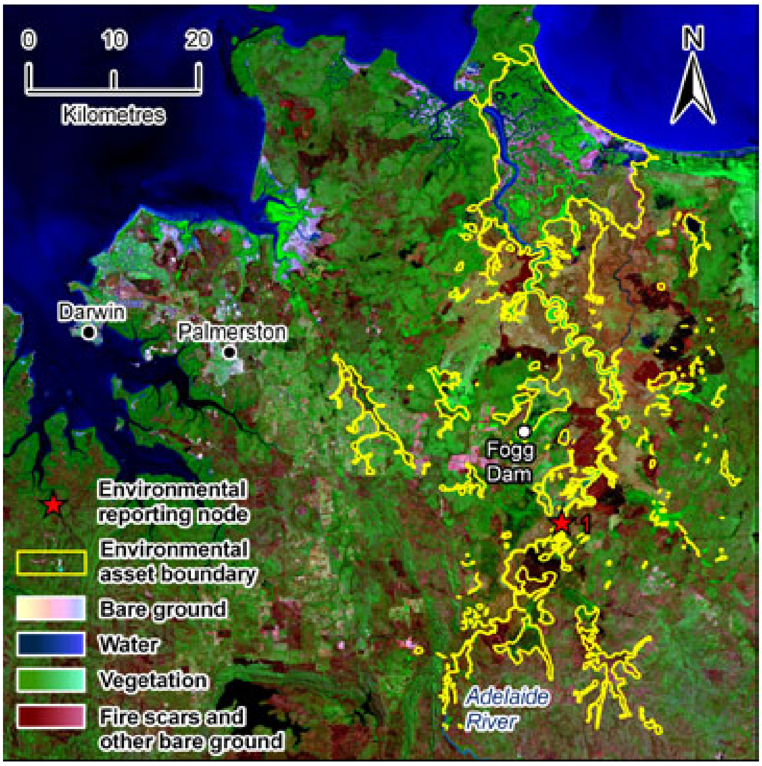

Figure VD-11. False colour satellite image of the Adelaide River Floodplain System (derived from ACRES, 2000). Clouds may be visible in image

The highest known density of breeding by the magpie Goose occurs at this site. The site supports at least two major waterbird breeding rookeries. Coastal mudflats and nearby areas are important migration stop-over areas, supporting in the order of 10,000 shorebirds on the floodplain at times before the wet season sets in (Environment Australia, 2001). Saltwater Crocodile and Freshwater Crocodile occur at the site.

The site includes registered Indigenous sites and supports several pastoral enterprises and commercial boat tours. Saltwater Crocodile eggs are harvested commercially in areas of this site to support of a significant part of the crocodile farming industry. The lower estuaries support major barramundi and mud crab fisheries. Adelaide River is popular for barramundi fishing, boating, nature study (especially bird-watching at Fogg Dam) and boat tours (especially for crocodile viewing).

Finniss Floodplain and Fog Bay System

The Finniss Floodplain and Fog Bay system (Figure VD-12) is a beach-fringed, curved bay with continuous intertidal mudflats, and a modified but relatively intact floodplain with extensive paperbark swamps. The site has an area of 81,300 ha and an elevation a few metres above sea level (Environment Australia, 2001).

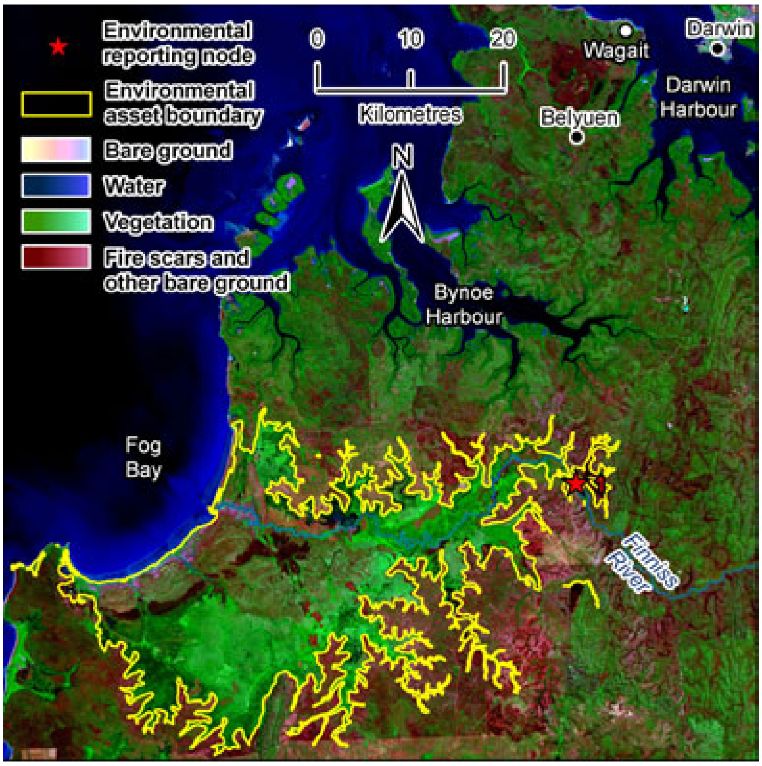

Figure VD-12. False colour satellite image of the Finniss Floodplain and Fog Bay System (derived from ACRES, 2000). Clouds may be visible in image

The site supports some of the best floating mat vegetation communities in the NT. In excess of 25,000 migrant shorebirds have been recorded using the area as a migration stop-over. Dugong and Indo-pacific Humpback Dolphin regularly occur in the south-west of Fog Bay (Environment Australia, 2001). The permanent floodplain billabongs in the north-east of the site are a major breeding area for Saltwater and Freshwater Crocodiles (Hill and Webb, 1982; Webb et al., 1983; Wood and Bonnin, 1987; Ottley).

An Indigenous community (Wagait) is located at the edge of the site and semi-traditional use of the wetlands is still practised (Environment Australia, 2001). Commercial activities in the area include a pastoral grazing enterprise on the floodplain, commercial fishing near the river mouth, and harvesting of Saltwater Crocodile eggs from floating mat swamps. A major harvest of banana prawn occurs in Fog Bay.

Mary Floodplain System

The Mary Floodplain System (Figure VD-13) is a good example of a major floodplain-tidal wetland system typical of the Top End Region, but unusual in lacking a coherent river channel or major river estuary. The site has an area of 126,000 ha and an elevation ranging between zero and 10 m above sea level (Environment Australia, 2001). The site includes some of the largest areas of wooded swamp (apart from Arafura Swamp) in the Northern Territory, and features a complex network of channels and billabongs. The unusual morphology of the plain contributes to rapid overtopping of levees and inundation of huge seasonal wetlands, even in years of relatively low rainfalls. Drainage rates are also lower than many other systems, such as the Adelaide River, so that the site provides greater areas of wetland habitats over a relatively extended period.

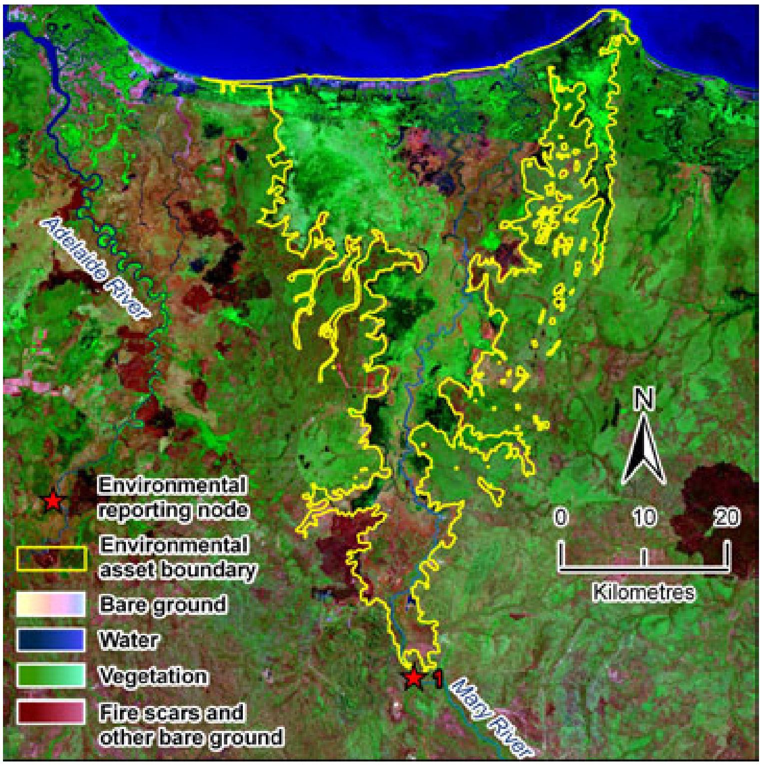

Figure VD-13. False colour satellite image of the Mary Floodplain System (derived from ACRES, 2000). Clouds may be visible in image

The site includes the highest known breeding concentration of sea-eagles in the Northern Territory (Environment Australia, 2001). The mudflats and coastal flats support at least several thousand migrant shorebirds at times (Environment Australia, 2001). During synchronous flowering of melaleuca swamp forests at this site, fruit bats in numbers in the order of 250,000 have been observed.

A number of registered Indigenous sites exist on the floodplain (Environment Australia, 2001). The site supports several pastoral (buffalo, cattle) grazing enterprises and commercial wildlife tours. The site (river and estuaries) is the most popular area for amateur fishing of barramundi in the Northern Territory. Recreation sites exist at seven points and development of additional facilities and opportunities for wildlife observation, boating, fishing, camping and picnicking have been proposed (Environment Australia, 2001).

Port Darwin

Port Darwin (Figure VD-14) is a good example of a shallow branching embayment of the Top End Region and supports one of the largest discrete areas of mangrove swamp in the Northern Territory. The mangrove communities of this site are the most extensive and species-rich of any Northern Territory embayment (Wightman, 1989). This site is characterised by marine and costal zone wetlands. The site has an area of 21,900 ha and an elevation at sea level (Environment Australia, 2001).

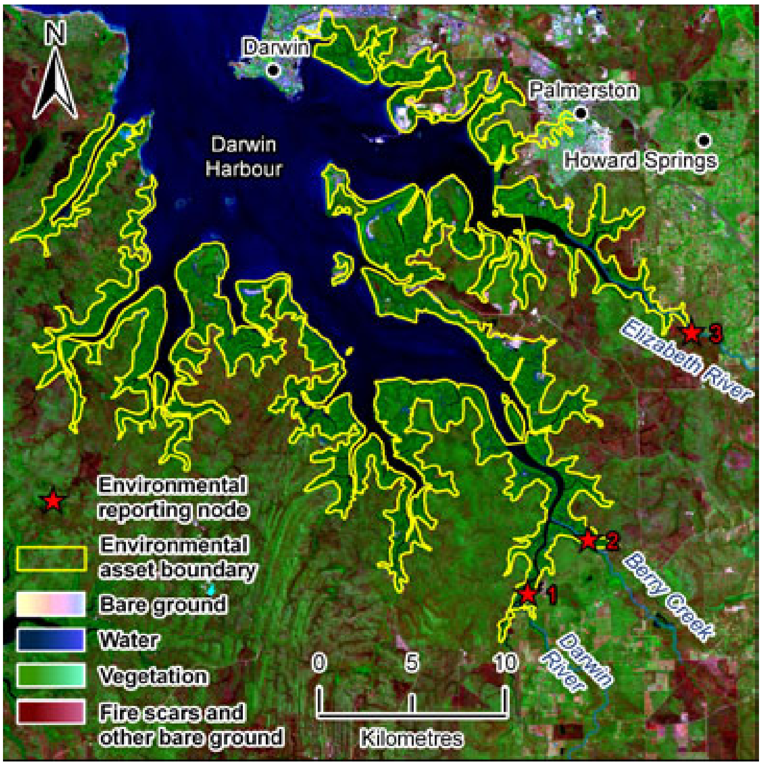

Figure VD-14. False colour satellite image of Port Darwin (derived from ACRES, 2000). Clouds may be visible in image

At least 15 migrant shorebird species use the site as a migration stop-over, most of them probably on a regular basis. Dolphins and turtles are commonly seen. The mangroves and shallows are an important nursery area for fish, crabs, prawns and other marine fauna (Environment Australia, 2001).

The annual cycle of hunting and gathering of the Larrakia Indigenous people includes the site, where a wide variety of meat and vegetable foods are procured (Environment Australia, 2001). The site is used for commercial fishing pearl culturing, aquaculture, port facilities and industry, and tourism.

VD-2.2 Data availability

VD-2.2.1 Climate

The rainfall-runoff modelling uses historical daily climate data (Scenario A) from the SILO database for the period 1 September 1930 to 31 August 2007 at 0.05 x 0.05 degree (~ 5 x 5 km) grid cells. Full details and characterisation of the SILO database are provided at the division level in Section 2.1 of Chapter 2. Scenario B and Scenario C climate data are rescaled versions of the Scenario A data; this is also discussed in Section 2.1 of Chapter 2.

VD-2.2.2 Surface water

Streamflow gauging stations are or have been located at 97 locations within the Van Diemen region. About two-thirds of these gauging stations (65) are either: flood warning stations and measure stage height only, or have less than ten years of measured data. Of the remaining 32 stations, five recorded more than half of their total volume of flow during events that exceed the maximum gauged stage height. Figure AR-7 shows the spatial distribution of good quality data (duration) and the percentage of flow above maximum gauged stage height (MGSH) (this assessment was only undertaken on stations with ten years or more data). The greatest concentration of current streamflow gauging stations is in the western part of the Van Diemen region, which is proximal to Darwin.

There are 37 gauging stations currently operating in the Van Diemen Gulf region at density of one gauge for every 1,800 km^2. The Van Diemen Gulf region has the greatest number and density of currently operating gauging stations of the 13 regions. For the 13 regions the median number of currently operating gauging stations per region is 12 and the median density of current gauging stations per region is one gauge for every 9700 km^2. The Van Diemen region has the highest density of current gauging stations of all 13 regions across northern Australia. The density of current stations is comparable to the MDB average. The mean density of current stream gauging stations across the entire MDB is one gauge for every 1,300 km^2.

In Figure VD-15 the productive aquifer layer for the Northern Territory includes dolostone and limestone formations and Cretaceous sandstone formations. Consequently these productive aquifers exhibit a wide range of bore yields.

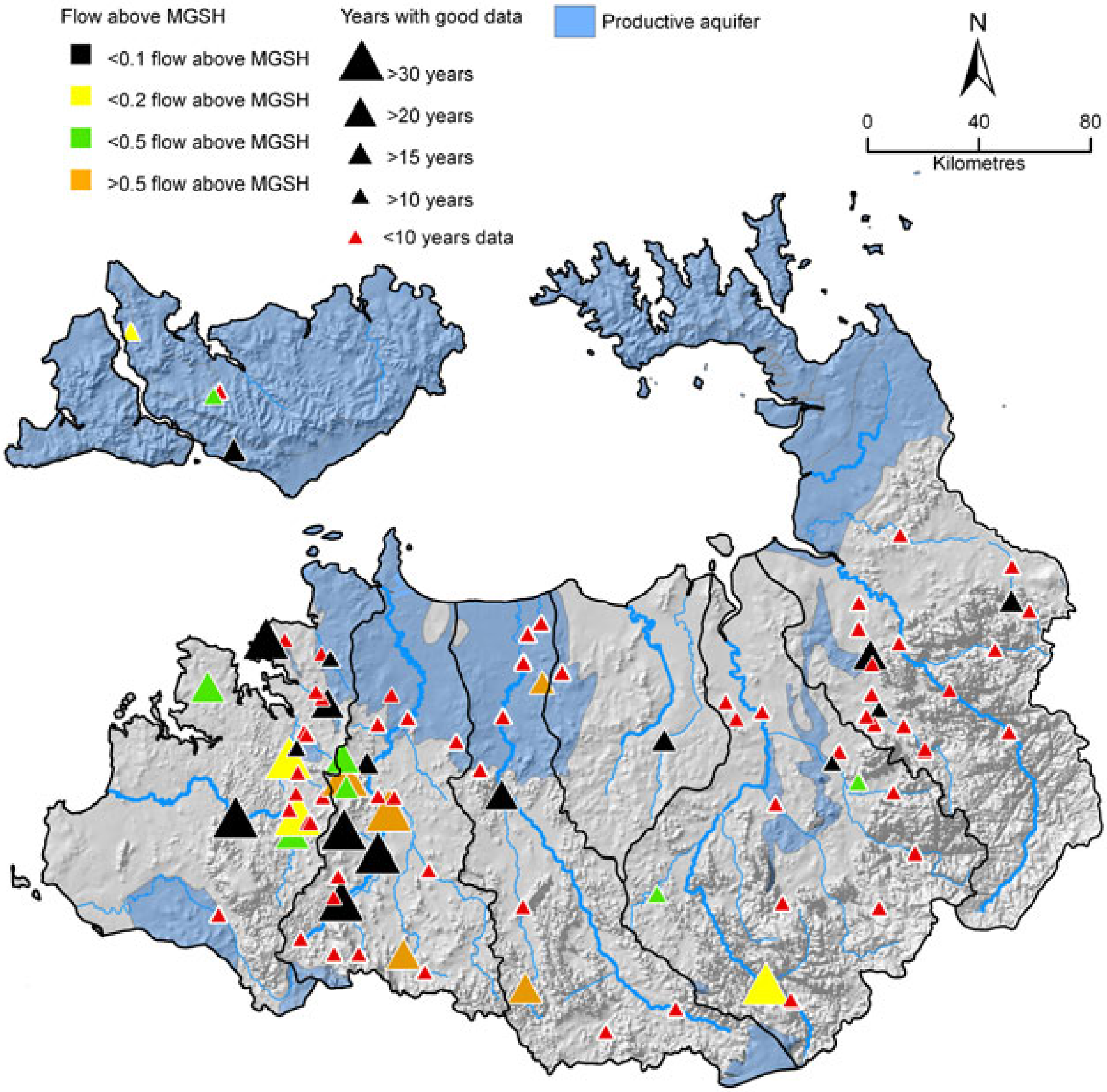

Figure VD-15. Location of streamflow gauging stations overlaid on a relative relief surface showing the proportion of gauges with flow above maximum gauged stage height across the Van Diemen region. Productive aquifer layer includes key dolostone, limestone and Cretaceous sandstone formations

VD-2.2.3 Groundwater

The Van Diemen region contains a total 11,623 registered groundwater bores. Of these, 943 have surveyed elevations that could enable water table surfaces to be constructed for the main aquifers. However these bores are not necessarily monitored on a regular basis. There are 990 water level monitoring bores in the region; 794 are historical and 196 are current (Figure VD-17).

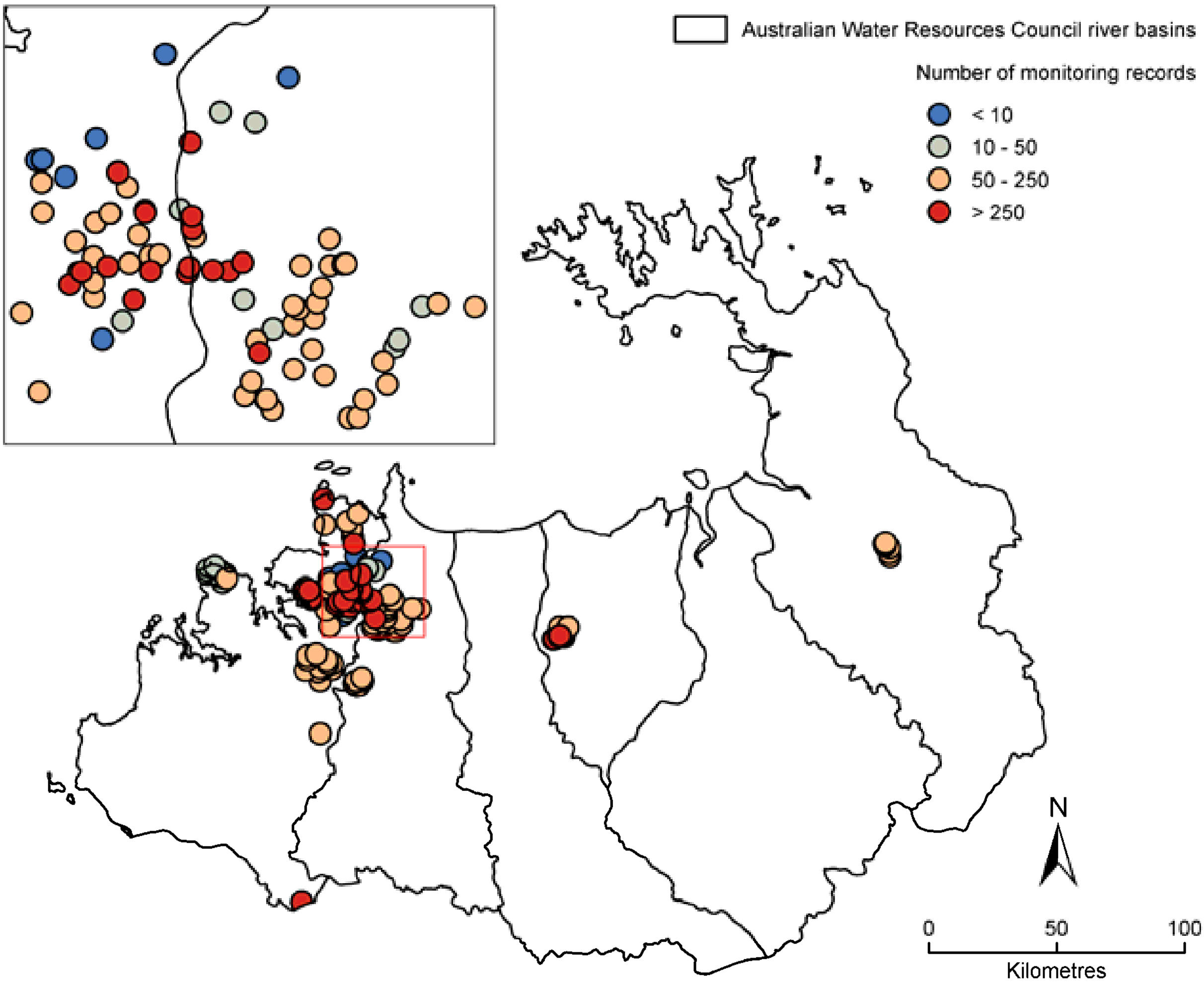

Figure VD-16. Current groundwater monitoring bores in the Van Diemen region

VD-2.2.4 Data gaps

Groundwater being extracted from the Proterozoic carbonate aquifers in the Darwin Rural Area is resulting in groundwater levels currently fluctuating by up to 17 m/year. During dry periods modelling has identified that current extraction will not be able to be sustained by the resource. The accuracy of the model has been constrained by the lack of metered groundwater extraction data for private bores across the region. Groundwater use for community and town water supply purposes is however metered.

The main aquifers with potential for development for irrigated agriculture are the Cretaceous and Palaeozoic sediments. These aquifers are believed to be a significant source of water for the extensive wetlands that occur adjacent to the coastline. There is insufficient data available to develop a model for these extensive groundwater resources. A programme of work needs to be undertaken to obtain the data that will enable impact assessment models to be developed for these groundwater resources. This is particularly the case for the Tiwi Islands where a large forestry development is occurring.

VD-2.3 Hydrogeology

This section describes the key sources of groundwater in the Van Diemen region. The descriptions are primarily based on reports and water bore data held by the Northern Territory Government Department of Natural Resources, Environment, The Arts and Sports (NRETAS). Specific details on the hydrogeology and recharge/discharge characteristics of what is known as the Darwin Rural Area – McMinn's – Howard East Section groundwater system are provided in Sections VD-2.3.2 and VD-2.3.4 (respectively) as this area contains the most intensive groundwater development in the Van Diemen region and accordingly was modelled for the current project.

The distribution of water bores in the region in 2008 is shown on Figure VD-17.

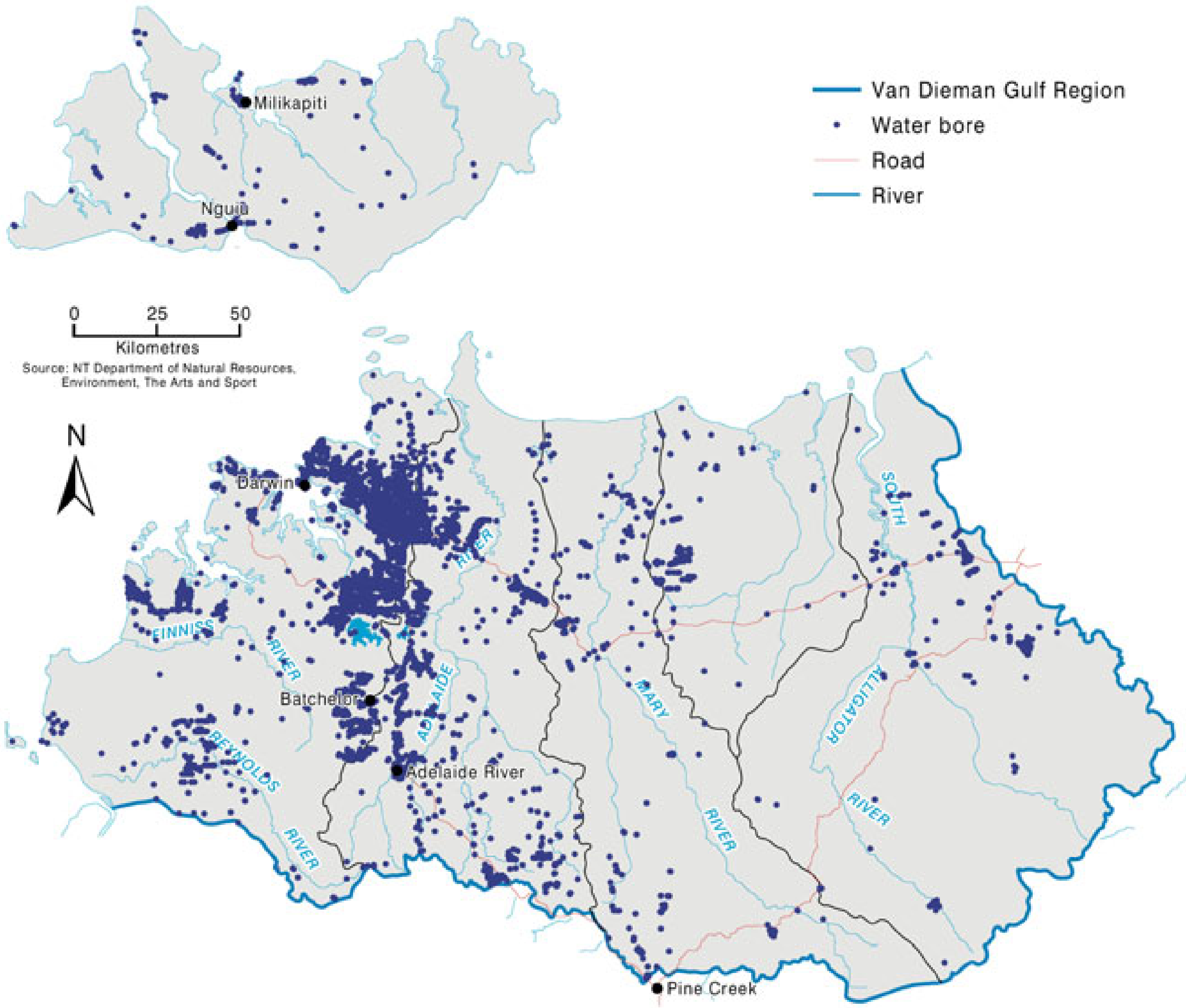

Figure VD-17. Location of groundwater bores in the Van Diemen region (map provided by NRETAS, 2009)

VD-2.3.1 Aquifer types

There are three major aquifer types in the Van Diemen region. These types are fractured rocks, karstic carbonate rocks and Cretaceous and Palaeozoic sediments; all of which are briefly described below and their areal extent is shown on Figure VD-21.

Fractured rocks

A variety of Precambrian (older than 500 million years) rocks form the bedrock of the area. These are mainly sedimentary but also include granite and volcanic rocks. Sandstone, siltstone and greywacke are the main sedimentary rock types. In some areas they are flat-lying while in other areas they have been folded, faulted and show low grade metamorphism.

Water is usually intersected in weathered fractured zones within the fractured rocks. Groundwater yields are controlled by the degree of fracturing of these units and are likely to be greater in areas located along large scale joints and fault zones.

Karstic carbonate rock – Proterozoic carbonates, Tindall Limestone and Jinduckin Formation

The major karstic aquifer in the region occurs within the Proterozoic carbonates. This aquifer contributes dry season spring flows to Berry and Howard Springs, both popular dry season attractions located close to Darwin.

Aquifers in the south west of the region occur within the carbonate rocks of the Daly Basin. These carbonate rocks are part of an extensive area of carbonate rocks comprising the Daly, Wiso and Georgina Basins that extend across a large part of the Northern Territory and into Queensland. The Tindall Limestone elsewhere in the Daly Basin hosts widespread karstic aquifers. These aquifers have very high permeabilities due to an extensive network of interconnected solution cavities. However in the Van Diemen region bore yields are not as high as encountered in the Daly region, probably because in the northern part of the Daly Basin the Tindall Limestone contains a higher proportion of siltstone than it does in the south. The Jinduckin Formation is mainly composed of siltstone. The formation contains thin, local aquifers in isolated limestone beds.

Cretaceous and Palaeozoic sediments

A significant aquifer occurs over a small area in the south west of the Van Diemen region within Palaeozoic sandstones of the Bonaparte Basin (Richardson, 1996).

The Cretaceous sediments form a mantle of lateritised claystone and sandstone covering much of the area before thickening to the north as they dip beneath the Tiwi Islands. On Figure VD-2 the sediments have only been mapped where it is expected that they form the major aquifer at that locality. However they overlie the karstic rock aquifers over much of the region. The beds are sub-horizontal and may be divided into an upper claystone and siltstone unit and a basal sandstone unit. Outcrop is generally sparse due to the soft nature of the rock but in places silicification has altered them to porcellanite and quartzite.

In the central coastal area between Darwin and the Mary River the Cretaceous sediments are usually finer than to the east, west and south. In the area between the Mary and Wildman River sequences of very permable sandstone have been intersected. In the south the sediments provide significant dry season flows to the headwaters of the Mary and South Alligator Rivers.

Under the Tiwi Islands the sediments comprise a sequence that is over 700 m thick. A thin basal sandstone less than 50 m thick unconformably overlies Proterozoic basement rock. This basal sandstone is overlain by up to 500 m of impermeable mudstone which is overlain by up to 150 m of sediments comprising a basal 20 to 50 m thick sandstone member, overlain by 50 to 80 m of mudstone, overlain again by sandstone. The Cretaceous sandstone that overlies the thick mudstone sequence contributes significant dry season flows to many rivers on the Tiwi Islands.

VD-2.3.2 Darwin Rural Area – McMinn's – Howard East Section

The area approximately 25 km to the east and south-east of Darwin and Palmerston hosts significant rural residential and horticultural development. These areas include localities such as Humpty Doo, Howard Springs and Berry Springs. Groundwater resources are important to these areas. The sub-area of the overall Darwin Rural area is known as the Darwin Rural Area – McMinn's – Howard East Section.

The major hydrogeological features of the Darwin Rural Area – McMinn's – Howard East Section groundwater system are (Figure VD-18):

- a laterite aquifer extending generally from the surface (down to approximately 30 m with greatest permeability in the upper 12 m overlying a siliceous layer of porcellanite) into less weathered Cretaceous age sediments
- cretaceous age sediments of the Bathurst Island Formation between the base of the laterite and a transitional zone of cherty, quartz rich, sandy and gravelly material over the fractured dolomite
- a transitional zone between the lower Cretaceous age sediments and the underlying fractured Proterozoic age Koolpinyah Dolomite, including deeply weathered dolomite and cherty, gravel and sandy material that generally included the basal conglomerate of the Darwin Member of the Bathurst Island Formation (this effectively provides the underlying dolomite aquifer with the capacity to 'store' water)
- a fractured dolomite beneath the transitional zone including some schistose facies overlying at depth less fractured / permeable dolomite
- effective hydrogeological basement consisting of Archean to Early Proterozoic age metamorphic rocks and granites.

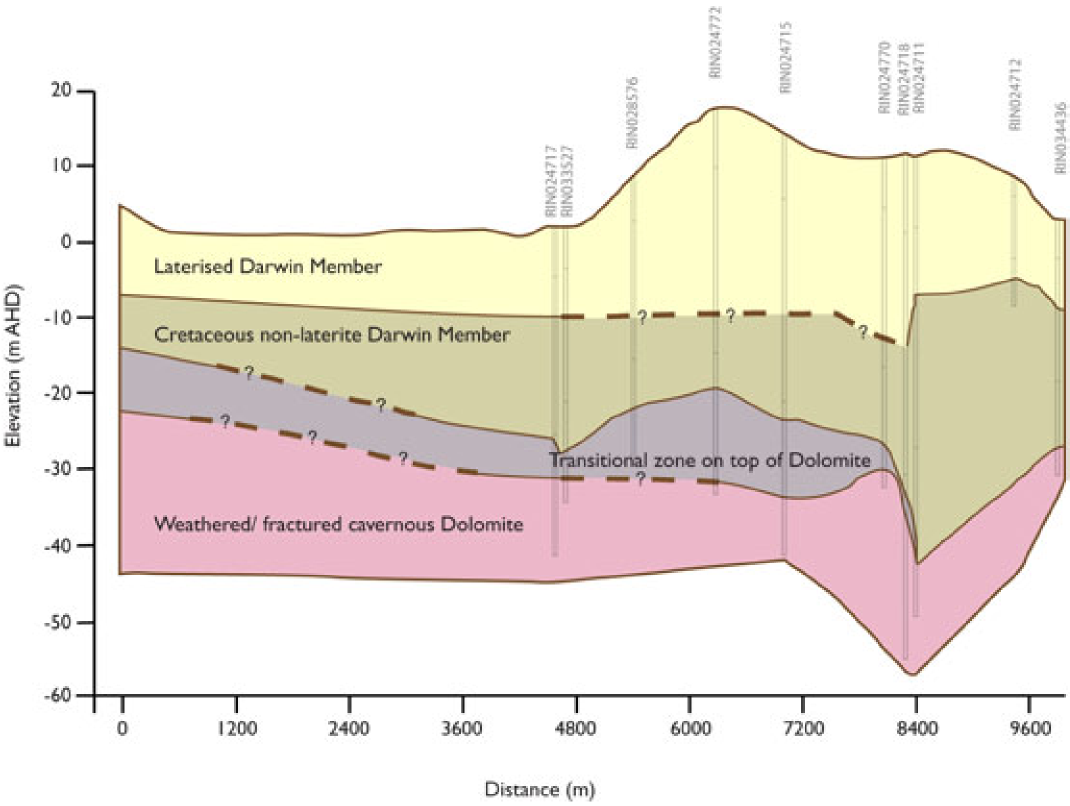

Figure VD-18. Schematic hydrogeological section through Lambell's Lagoon area of Darwin Rural Area – McMinn's – Howard East Section groundwater system (after EHA, 2007)

The outcrop of the Wildman Siltstone constitutes the western boundary of the aquifer system, however there is some dispute regarding the continuity of the Koolpinyah Dolomite across the Adelaide River, with a north-south trending fault mapped by Jolly and Yin Foo (1988) west of Fogg Dam being suggested as a suitable eastern model boundary.

The aquifer developed in the Koolpinyah Dolomite has significant spatial variation in permeability due to folding and subsequent weathering of the schistose units of the formation. The cavernous dolomite is best described as the water transmission zone and most high yielding bores in the area target this zone as it has the best potential to provide silt and sand free water at the required pumping rates.

Test pumping data has enabled the estimation of aquifer storage coefficients for the Koolpinyah Dolomite ranging from 6.9×10^{-5} to 1.25×10^{-2}, and aquifer transmissivity ranges for the Koolpinyah Dolomite:

- Gunn Point area – 80 to 890 m^2/day
- Lambell's Lagoon area – 1160 to 9000 m^2/day
- McMinn's area – 175 to 4200 m^2/day.

VD-2.3.3 Inter-aquifer connection and leakage

In the Van Diemen region there may be connection between the fractured rock aquifers and the basal sandstone of the Cretaceous Sediments in some locations.

VD-2.3.4 Recharge, discharge and groundwater storage

Recharge occurs only in the wet season when rainfall intensity and duration is sufficient. Recharge leads to a rise in groundwater levels. In the dry season the levels naturally fall as groundwater is either transpired or discharged to wetlands and rivers where it evaporates or is discharged to the sea. The amount and rate at which the groundwater levels rise and fall depends on the type, size and other physical properties of the aquifer, as well as the amount of recharge. The recharge/discharge cycle that applies in the Van Diemen region is summarised in Figure VD-19.

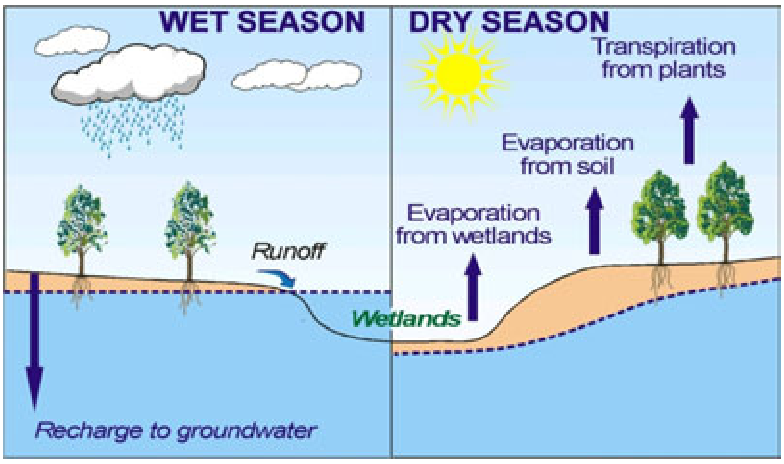

Figure VD-19. Schematic of the recharge and discharge cycle that applies in the Van Diemen region

Recharge beneath native vegetation is dominated by bypass flow and not diffuse movement through soil horizons. The most likely mechanism for this is via macro-pores such as cracks and root holes in the soil. Sinkholes have been located over the Proterozoic carbonates.

Jolly et al. (2000) evaluated the annual recharge rate to the area providing spring flow to the lower reaches of Berry Creek. The recharge data indicated that in a number of the years, a significant proportion of the potential annual recharge is 'rejected' because the aquifer is fully recharged (ie groundwater levels are above ground level in the area where the aquifer is being recharged). In the 21-year period 1961 to 1981 it was likely that this occurred in 11 wet seasons.

Groundwater discharge occurs across the region mostly as evaporation and transpiration (ET). Groundwater discharges that maintain perennial reaches of rivers within the region are important. The most visible of these discharges take the form of springs on or adjacent to the banks of rivers such as the Mary and South Alligator, and Berry and Bluewater Creeks. However the majority of discharge occurs as diffuse discharge through the beds of rivers.

Specific comments relating to recharge and discharge for each of the three major aquifer types, and then specifically for the Darwin Rural Area – McMinn's – Howard East Section now follows. The locations of monitoring bores and river gauging stations that are referenced in the following sections are shown on Figure VD-18.

Fractured rocks

A number of the towns in the region obtain their water supply from aquifers developed in sandstone of Proterozoic age. The sandstone has been fractured and extensively weathered to depths of up to 100 m. The time series groundwater level data shown in Figure VD-20 is for bore RN021943 located at Adelaide River.

The recharge rate is reflected in the variation in water level measured in monitoring bores intersecting the aquifer. Over the period of record the annual variation in water level ranged from 3.5 to 7 m. The average rise was approximately 5 m.

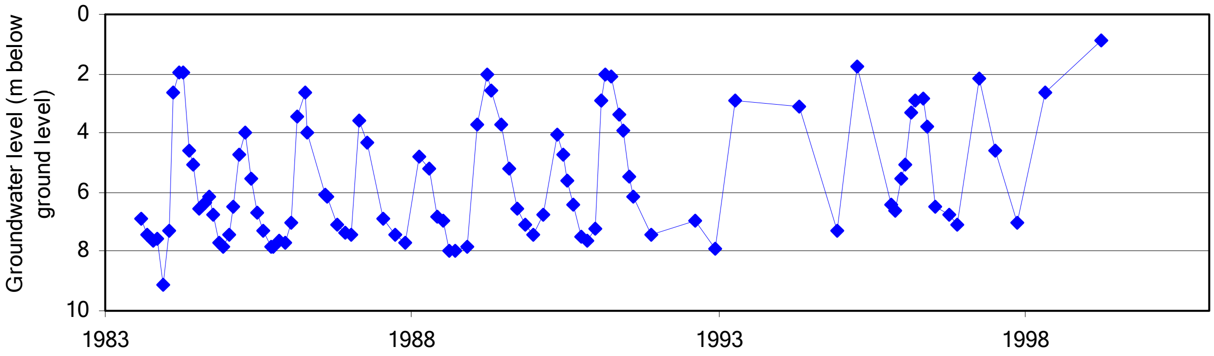

Figure VD-20. Observed groundwater levels in monitoring bore RN021943 in the fractured rock aquifer within the Van Diemen region

Proterozoic carbonates

There is considerable data available across the region for groundwater levels in the Proterozoic Carbonates. The data shown in Figure VD-21 is for monitoring bores RN004221 and RN021012 located in the Proterozoic carbonates near the Howard River. The aquifer in this area is exploited by many small rural land holders as a domestic water supply. It is also exploited for irrigation and is used as a water supply for Darwin.

Prior to 1985 there was little development in the region. This is reflected in the hydrographs for both bores. Since 1985 significant exploitation of the aquifer has occurred in the area surrounding monitoring bore RN004221, leading to large seasonal fluctuations in groundwater level. Bore RN021012 is located in an area that has not yet been developed.

The recharge rate and use is reflected in the variation in water level measured in the monitoring bores. Over the 45-year period of record the pre-development annual variation in water level ranged from 5 to 8 m. Since development has occurred the annual variation in water level in bore RN004221 has increased to approximately 17 m.

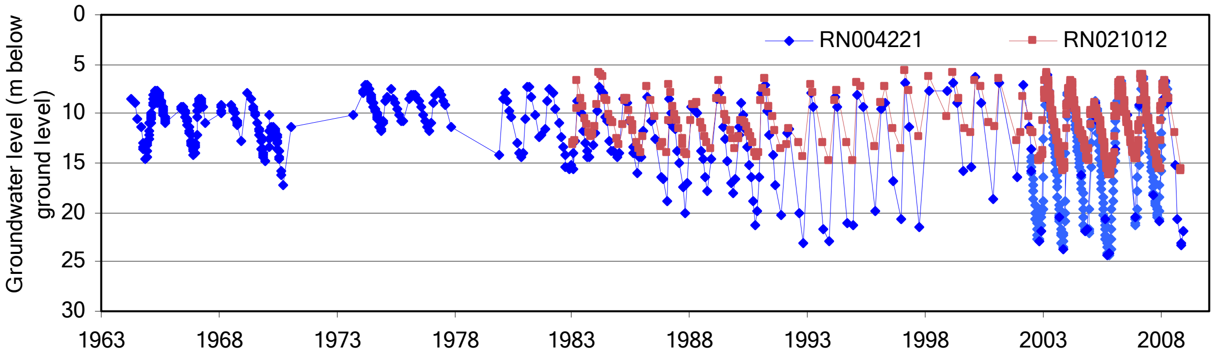

Figure VD-21. Observed groundwater levels in monitoring bores RN004221 and RN021012 in the Proterozoic carbonates in the Van Diemen region

Cretaceous sediments

Regional groundwater discharges from the aquifer provide the dry season flow for the upper reaches of the Mary and South Alligator Rivers and for a number of creeks on Melville Island.

Changes in dry season flow rates occur in response to changes in the amount of rainfall that recharges the aquifer in each preceding wet season. The changing recharge rate is reflected in the variation in water level measured in monitoring bores intersecting the aquifer. Figure VD-22 contains a plot of time series groundwater level data for four bores in the aquifer; two on the mainland (RN022966 and RN033738) and two on the Tiwi Islands (RN023946 and RN023986). The data indicates that annual groundwater rises due to recharge during the wet season vary from about 1 m to approximately 6 m.

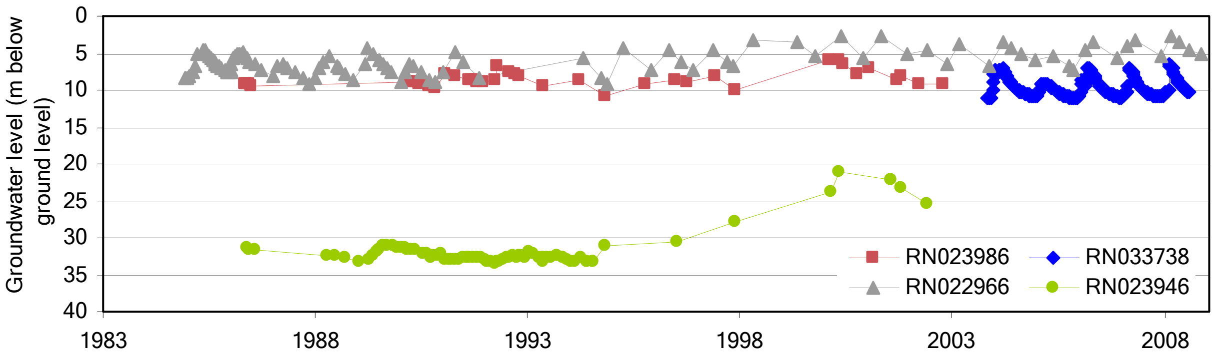

Figure VD-22. Observed groundwater levels in monitoring bores in the Cretaceous Sandstone aquifer in the Van Diemen region

Darwin Rural Area – McMinn's – Howard East Section

Groundwater recharge occurs to the Darwin Rural Area – McMinn's – Howard East Section groundwater system via:

- direct percolation of incident rainfall through soils into the laterite aquifer developed within the Cretaceous age sediments during the wet season
- vertical percolation of groundwater from the laterite aquifer through the underlying Cretaceous age sediments to the Koolpinyah Dolomite in areas where the upper units of lower permeability Bathurst Island Formation have been removed by erosion.

Groundwater flow in the Koolpinyah Dolomite (Figure VD-23) is generally from areas of higher topography to areas of lower topography (e.g. creeks, swamps and soaks in the southern end of Black Jungle Swamp, lagoons in the proximity of the rural developed area and the floodplain surrounding the area of now horticultural development). In general the directions of groundwater flow can be described as:

- westerly towards the Howard River and the coast at Hope Inlet
- diverging either westwards or eastwards from a broad central mound trending approximately north-south.

Groundwater discharge occurs from the Darwin Rural Area – McMinn's – Howard East Section groundwater system via springs, discharge to local streams and groundwater pumping. Discharge to local streams and springs occur from both the laterite aquifer and the deeper Koolpinyah Dolomite aquifer.

Major springs which represent 'windows' in the dolomite aquifer include Howard Springs, and springs in Melacca Creek and the Adelaide River 'Narrows' area. Some streams in the area, such as Holland's Creek, Baker's Creek and the upper reaches of the Howard River exhibit seasonal changes in water quality, with the quality of dry season baseflow representing a mixture of waters from the laterite and dolomite aquifers.

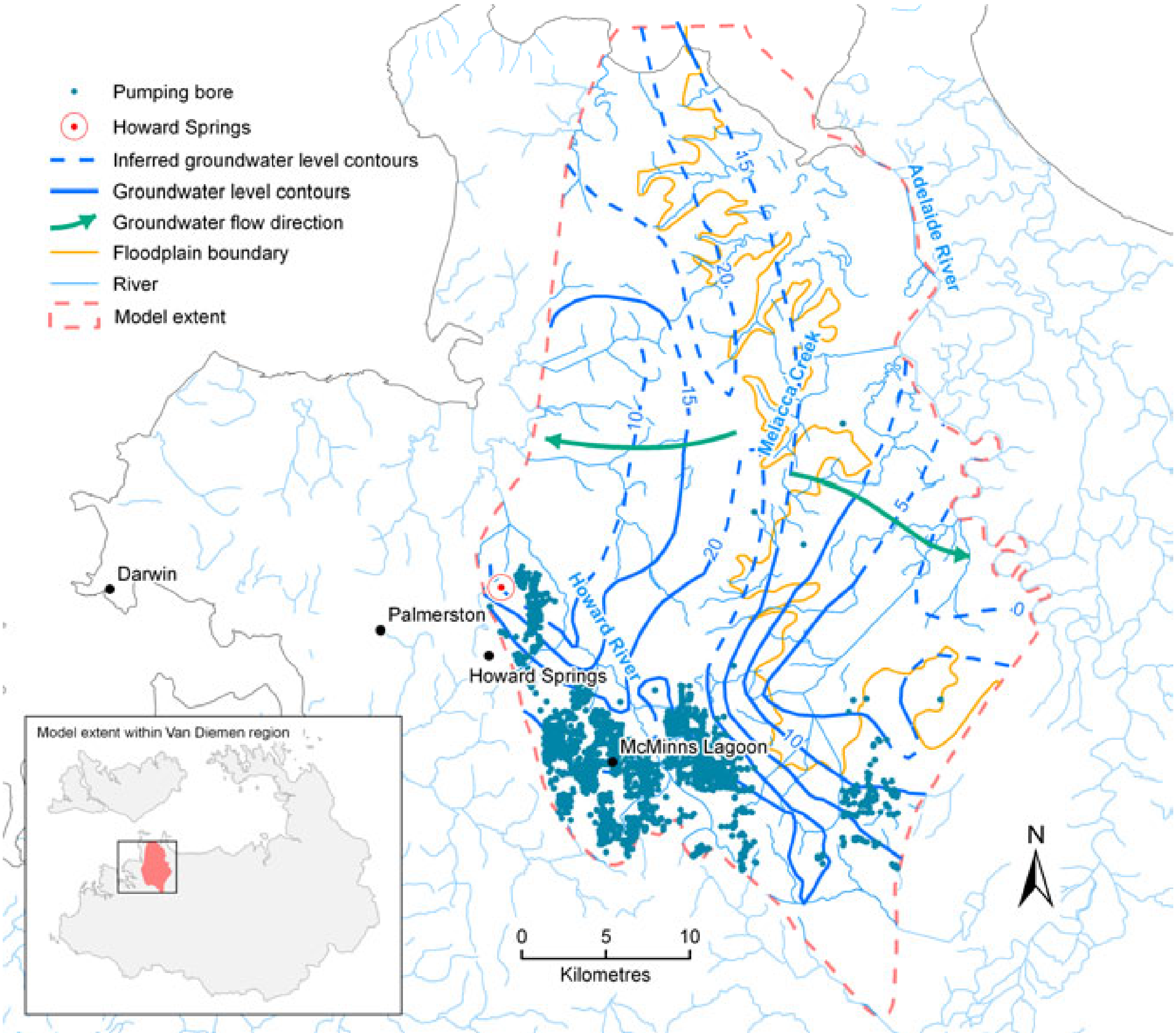

Figure VD-23. Groundwater elevation contours for Koolpinyah Dolomite - February 1997 (after EHA, 2007)

Groundwater pumping is for rural residential use, horticultural use (predominantly tropical fruit tree crops) and town water supply by Power and Water Corporation. At the time of preparation of the Darwin Rural Area – McMinn's – Howard East Section groundwater system model in 2007 there were approximately 1850 production bores operating and most of them were concentrated in the McMinn's area (Figure VD-23).

Groundwater extraction for town water supply purposes commenced in the 1960s and since 1974 only four town water supply bores have operated, providing 3,495 ML/year in 2005. At 2005 there were 1,541 rural residential bores drawing approximately 5,395 ML/year and 293 horticultural bores drawing approximately 11,220 ML/year.

The overall storage behaviour in the Darwin Rural Area – McMinn's – Howard East Section groundwater system can be summarised as very dynamic with regular annual cycles of wet season recharge and accompanying rapid, large magnitude groundwater level rises, followed by dry season recession due to natural discharge and groundwater pumping.

A comparison of many of the groundwater levels in the monitoring bores of the area (i.e. bores separately tapping the dolomite and the Cretaceous age sediments) in areas where there is appreciable groundwater pumping, with the trace of the cumulative deviation from long-term mean monthly rainfall (Figure VD-24) possibly suggests that the increase in overall groundwater pumping associated with the expansion of horticultural enterprise in 1998/1999 has resulted in a long-term groundwater overdraft in the area. Further to this point, groundwater levels in a significant number of bores, particularly in the eastern section of the Lambell's Lagoon area display groundwater elevations that decline periodically below mean sea level. This presents serious risks of sea-water intrusion in to the aquifer.

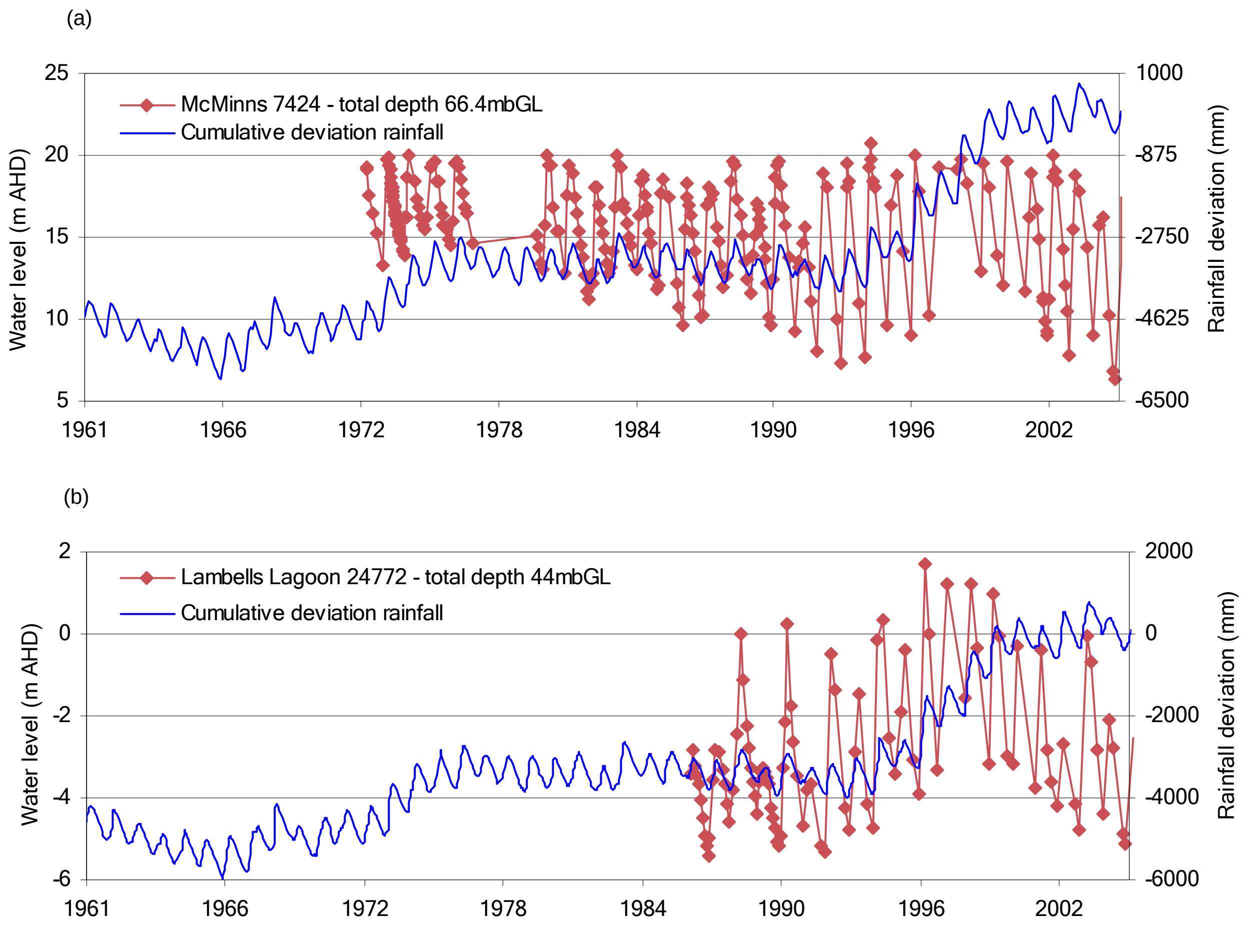

Figure VD-24. Observed groundwater level hydrographs for bores (a) MM7424 and (b) LL24772 in the Koolpinyah Dolomite, plotted with cumulative deviation from mean monthly rainfall

VD-2.3.5 Groundwater quality

The quality of most groundwater in the Van Diemen region falls within acceptable drinking water guidelines (ADWG, 2004). The only exception is groundwater beneath the floodplains that overlie the Proterozoic carbonate and Cretaceous sediments. Beneath these floodplains the groundwater is usually too saline for any agricultural purpose, including stock water supply.

Groundwaters in the Proterozoic carbonates are slightly alkaline on average but pH can range from 6.4 to 8. Calcium, magnesium and bicarbonate are the dominant ions, while salinity (as Electrical Conductivity) mostly ranges between 300 and 1000 µS/cm (Figure VD-25). Calcium, magnesium and bicarbonate concentrations in groundwater show negligible spatial variability. These ions dissolve relatively easily from the limestone and dolomite matrix and once saturation with respect to these minerals is reached the concentrations remain relatively stable. Hardness is normally high and will cause scale build-up in water delivery infrastructure.

Groundwaters in the Cretaceous Sediments are acidic with pH values of ranging from 4.5 to 5.5. The Electrical Conductivity mostly ranges between 50 and 100 µS/cm.

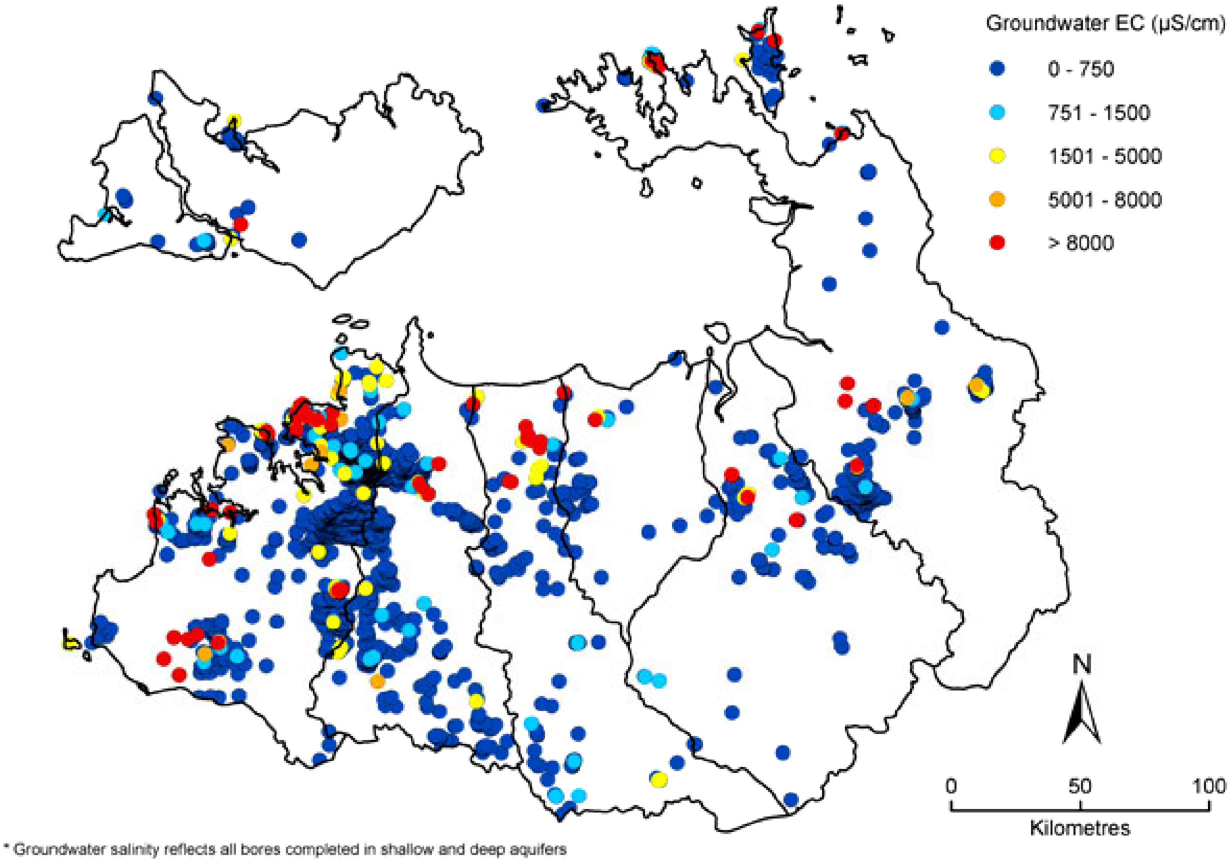

Figure VD-25. Groundwater salinity distribution for all bores drilled in the Van Diemen region

VD-2.4 Legislation, water plans and other arrangements

VD-2.4.1 Legislated water use, entitlements and purpose

Current

The Northern Territory manages its water resources through a regulatory framework that includes the *Water Act 1992*, the Water Regulations and a series of water allocation plans in preparation. Water is allocated to consumptive uses which are licensed (for industry such as horticulture and public water supplies) and non-consumptive use that includes the environment and other public benefits that are not licensed. The Northern Territory's water policy framework is not well developed with only one plan completed. Legislation applying to water allocation and management is in the process of review and revision.

The Darwin water supply area covers 8,482 km^2 and is located in and around the major towns of the Van Diemen region: Darwin, Palmerston, Batchelor, Belyuen and Adelaide River. Other major settlements in the region include Nguiu, Pirlangimpi and Milikapiti on the Tiwi Islands, and Jabiru in the east of the region. Groundwater use is metered for all towns. Water is supplied by the Power and Water Corporation from a combination of surface and groundwater supplies. Surface water supplies provide approximately 90 percent of Darwin's demand. Licensed surface water diversions from the Darwin River Dam total 46,420 ML/yr.

Groundwater is sourced from the McMinn's–Howard East borefield. Yin Foo et al. (2007) estimated use from the Proterozoic carbonates in the Howard River area between 1971 and 2005 (Figure VD-26). Annual groundwater use in 2005 was estimated to be approximately 20,500 ML.

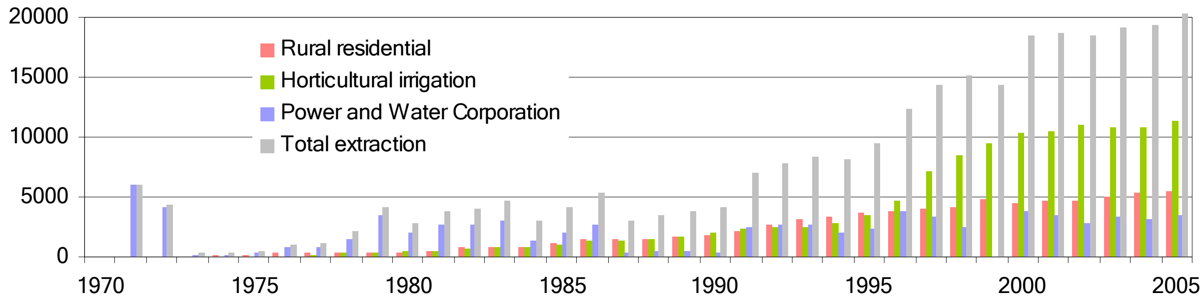

Figure VD-26. Water use from the Proterozoic Carbonate aquifer in the Howard River area (adapted from Yin Foo et al., 2007)

As of December 2008, 22 groundwater extraction licences had been issued in the Van Diemen region for a total of 24,340 ML/year <http://www.nt.gov.au/nreta/water/manage/register/pdf/GWRegister_Dec08.pdf>.

In the area that Yin Foo et al.(2007) estimated annual groundwater use to be approximately 20,500 ML, groundwater extraction licences have been issued for 12,879 ML. Of this total the Power and Water Corporation's licence is for 8,420 ML. Therefore licences for private use total 4,459 ML. Yin Foo et al. (2007) estimated the private use to be 16,800 ML.

Future

To increase current supply to Darwin, the Darwin River Dam is having its dam wall raised by 1.3 m. This will increase available yield by 20% to 49,100 ML/year. Darwin's current demand for water is about 40,000 ML/year, and current total licensed extraction totals 46,420 ML/year. Whilst the nearby Manton Dam has an additional 7,000 ML/year potential supply, recreational activities preclude its use except in emergencies.

A moratorium has been placed on future groundwater licenses in the Darwin and Rural area.

VD-2.4.2 Rivers and storages

All rivers and storages within the region have been identified. A range of new dam options were identified 20 years ago for consideration for long term water supplies. Three sites have potential:

1. Land for a potential future Marrakai Dam (next to Marrakai Crossing on the Adelaide River) has been bought and sub-leased for low level grazing. The extensive and generally low-lying catchment area upstream, however, would necessitate extensive engineering works and water treatment before use. The tidal limit for the Adelaide River can also extend this far upstream.
2. The catchment of the potential future Warrai Dam (about 18 km upstream of the Adelaide River township on the Adelaide River) is more compact than the other sites and good quality water might be collected without the need for chemical pre-treatment. About one third of the catchment is already protected within the Litchfield National Park. This site would also provide flood protection for the Adelaide River townsite and possibly could be configured to provide hydro-electric supply.
3. The potential future site of the Mt Bennet Dam on the Finniss River to the west of the Darwin River Dam is the site of high Indigenous values and there are environmental concerns related to the Rum Jungle mining operations.

In-stream storages on other rivers will not be considered.

VD-2.4.3 Unallocated water

Future water plans will not have “unallocated water” in the Northern Territory (NWC, 2008).

VD-2.4.4 Social and cultural considerations

The social and cultural values associated with the Howard River region of Darwin’s rural hinterland are documented by Woodward and others (Woodward et al., 2008). This Natural Heritage Trust (NHT) project had two primary aims:

1. To document the social use and importance of Howard River water resources and aquatic environments to Indigenous and non-Indigenous groups (e.g. hunters, plant enthusiasts, recreational fishers), including:
    - The use of surface water and groundwater resources by Indigenous traditional owners and by others with an interest in the cultural values, as defined by the beneficial use concept of the *Water Act 1992* (NT)
    - Community perceptions of change in environmental condition and use, and perceived threats to valued resources, places and traditions or beliefs.
2. To identify and assess the relative significance of resource impacts possible under different water resource use scenarios, including stakeholder perspectives on the means of protecting or enhancing social and cultural values through water resource management.

The research employed social research and socio-economic decision support tools that can help settle trade-offs between competing outcomes. To do this a combination of methods was used to build understanding of the values and issues for the Howard catchment, explore the conflicts and potential trade-offs, and evaluate several scenarios for the future. These methods included stakeholder consultations, interviews, desk-top review of literature and participatory workshops using deliberative multi-criteria analysis.

Demand for water by Darwin residents has increased significantly in this area, as has competition for groundwater to supply residential and agricultural developments. The study area is characterised by extensive wetland systems, including the Howard River and its tributaries, swamps, springs, floodplains and lagoons. Surface water features include lakes, lagoons, wetlands and streams. In the Darwin region there are generally two separate groundwater aquifers; a shallow unconfined aquifer in the laterite subsoil layer and a deep aquifer confined to weathered rocks such as dolomite.

The catchment supports a diversity of land uses including residential, horticultural, pastoral, conservation and mining. Access to groundwater plays an important part in supporting many of the area’s intensifying land uses and both groundwater and surface water flow provide a focus to public use of the ecological and cultural assets of the area, sustaining the many highly valued waterways, wetlands, rainforests, fish, plant and bird species utilised and/or appreciated by various resident and other groups. Water therefore underpins the social and cultural values associated with the area, including recreational fishing and hunting, cultural heritage, customary hunting and collecting, educational and leisure activities.

In this study area a number of recent water management issues have focussed public attention on the health of the area's waterways and on the sustainability of water resource use and, as a result, there is now a government undertaking to more closely regulate and monitor water use and to develop a water allocation plan.

Most prominent amongst recent incidents suggesting an underlying water management problem was the closure of Howard Springs, a popular freshwater spring in 2004, due to low flows and poor water quality. Elsewhere questions have been raised about the effect of groundwater extraction on the catchment's vegetation, particularly vulnerable and valuable rainforest patches.

A large part of the report assembles and consolidates relevant data currently held by various organisations pertaining to the social use and importance of the Howard River region. The report identifies the most popular locations and describes their history, current management arrangements and the environmental changes and other pressures identified by stakeholders during the course of the study. Significant Indigenous cultural sites are also identified and the utilisation of water sites in the study area is described. Qualitative data drawn from interviews with stakeholder groups is analysed in these sections.

The combined purpose of these substantive sections is to outline the specific activities that occur in the region, provide a preliminary assessment of use, including frequency and magnitude of activities, and an indication of any linkages between activities, uses and flow regime. The last section of the report provides an analysis of the stakeholder assessment of impacts of water use scenarios: reporting on the outcomes of a stakeholder consultation and evaluation that employed a Citizen's Jury combined with a Multi-Criteria Analysis.

Plans of Management for important areas such as Kakadu National Park, Litchfield Nature Park and Darwin Harbour would provide an insight into social values in this region.

VD-2.4.5 Changed diversion and extraction regimes

Within the vicinity of the Darwin area, the local Larrakia people had relied on springs and natural seepage for water supplies for many thousands of years. The first well was sunk following the arrival of Lord John Stokes in Port Darwin on the Beagle in 1839 and wells and tanks were used for Darwin's water supply through to the 1930s. As the population grew, consistent supplies through the dry season were required and construction began for the Manton Dam in 1939. During construction, an interim supply was pumped from Howard Springs for defence establishments and a small number of civilian homes and buildings. Originally intended as a short term supply, upon completion of the Manton Dam in 1942, the Howard Springs supply was kept as an alternative supply and a weir was built in the mid 1940s creating a pond for recreation and swimming. Today, Howard Springs is used solely for recreation.

As Darwin grew, the 7,000 ML/year yield from Manton Dam needed supplementing. In 1964, the McMinns borefield was developed to supplement the dam supplies and plans to construct a new dam across the Darwin River immediately to the west were put forward. The new dam on Darwin River was completed in 1972 and filled within the first wet season, providing 40,000 ML/year in yield and currently supplies roughly 90 percent of Darwin's water needs. The other 10 percent is supplied from the McMinns borefield and production bores in the adjacent Howard East Borefield. Manton Dam is retained as a reserve supply.

Currently, Darwin has six groundwater bores and two dams. Eighteen water storage tanks also hold 200 ML. One thousand two hundred km of pipelines holding 170 ML and 10 water pumping stations. The Howard East borefiled is licensed for 2,680 ML/year; the McMinns borefield for 5,740 ML/year.

Diversions from the water supplies include: 11,500 ML/year to Palmerston and rural areas; 11,500 ML/year to Berrimah and industrial areas south of Darwin; 6,000 ML/year to the Darwin city district and 9,000 ML/year to the northern suburbs. It is estimated that 10,650 ML/year is discharged to the ocean via water treatment plants (Power and Water Corporation (2006).

To increase current supply, the Darwin River Dam wall is being raised 1.3 m. This will increase available yield by 20 percent to 49,100 ML/year. A continuous release of at least 40 L/second is maintained at the dam to sustain

5 L/second downstream for consumptive use. This is estimated to equate to 3 ML/day, not including any spills when the dam is full during peak times of the wet season.

Darwin's current demand for water is about 40,000 ML/year. Current total licensed extraction totals 46,420 ML/year. Whilst the Manton Dam has an additional 7,000 ML/year, recreational activities preclude its use except in emergencies.

There is currently a moratorium on any further groundwater development in the Howard East or McMinns areas.

Long term supplies may be provided by development of one or more of the potential dam sites listed above (VD-2.4.2). All sites will require extensive engineering, environmental, cultural and heritage assessments.

VD-2.4.6 Changed land use

Darwin continues to expand as a regional centre and industry hub. Population projections estimate a doubling of the population through to 1950. In addition, there is increasing development of horticulture in the Darwin Rural area.

The large proportion of conservation area will restrict future development and land use change elsewhere in the region.

VD-2.4.7 Environmental constraints and implications of future development

The guideline for water allocation for all catchments in the Northern Territory is 80 percent for the environment and 20 percent for consumptive use from both surface water and groundwater all year, both in the wet (beginning of December to end of April) and dry (beginning of May to end of November) seasons as well as the interim months.

VD-2.5 References

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VD-3 Water balance results for the Van Diemen region

This chapter describes modelling results and the assessment of the water resources undertaken by this project for the Van Diemen region. Detailed, quantified assessments are made where possible, and relevant, and confidence is estimated. Modelling results are reported under climate and development scenarios as defined at the division level in Section 2.1 of Chapter 2. This chapter is sub-divided into:

- climate
- recharge estimation
- conceptual groundwater models
- groundwater modelling results
- rainfall-runoff modelling results
- river system water balance
- changes to flow regimes at environmental assets.

VD-3.1 Climate

VD-3.1.1 Historical climate

The Van Diemen region receives an average of 1390 mm of rainfall over a September to August water year (Figure VD-27), most of which (1327 mm) falls in the November to April wet season (Figure VD-28). Across the region there is a strong north–south gradient in annual rainfall (Figure VD-29), ranging from 1695 mm in the north to 1155 mm in the south. Over the historical (1930 to 2007) period, rainfall has been gradually increasing from an initial average of around 1100 mm to approximately 1400 mm later in the period. The highest yearly rainfall received was 1942 mm which fell in 2000, and the lowest was 765 mm in 1952.

Historical areal potential evapotranspiration (APET) is very high across the region, averaging 1936 mm over a water year (Figure VD-27), and varies moderately across the seasons (Figure VD-28). APET generally remains higher than rainfall from April until November resulting in water-limited conditions over these months. Between December and March conditions are energy-limited meaning more rain falls than can potentially be evaporated.

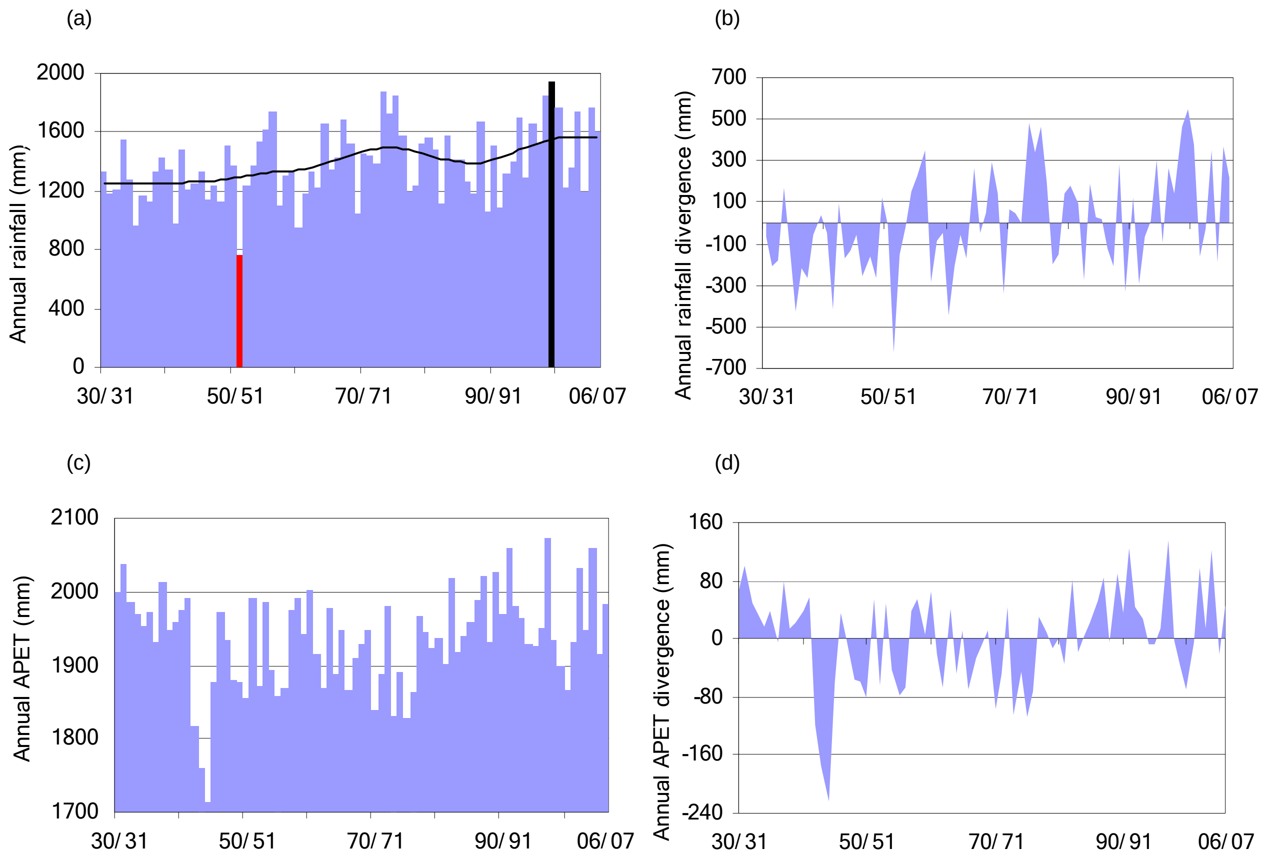


Figure VD-27. (a) Historical annual rainfall and (b) its divergence from the long-term mean; and (c) historical annual areal potential evapotranspiration and (d) its divergence from the long-term mean averaged over the Van Diemen region

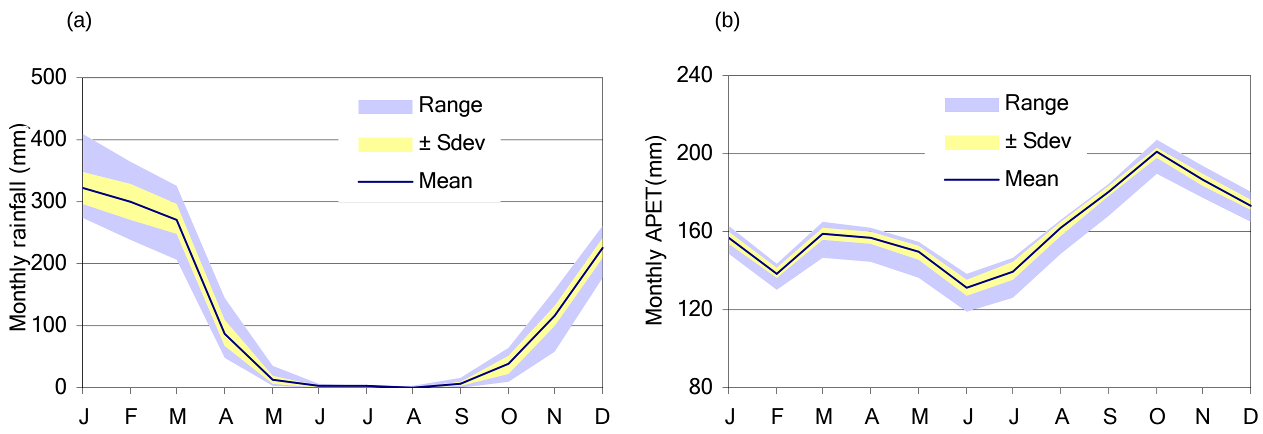


Figure VD-28. Historical mean monthly (a) rainfall and (b) areal potential evapotranspiration and their temporal variation (range and ± one standard deviation) averaged over the Van Diemen region

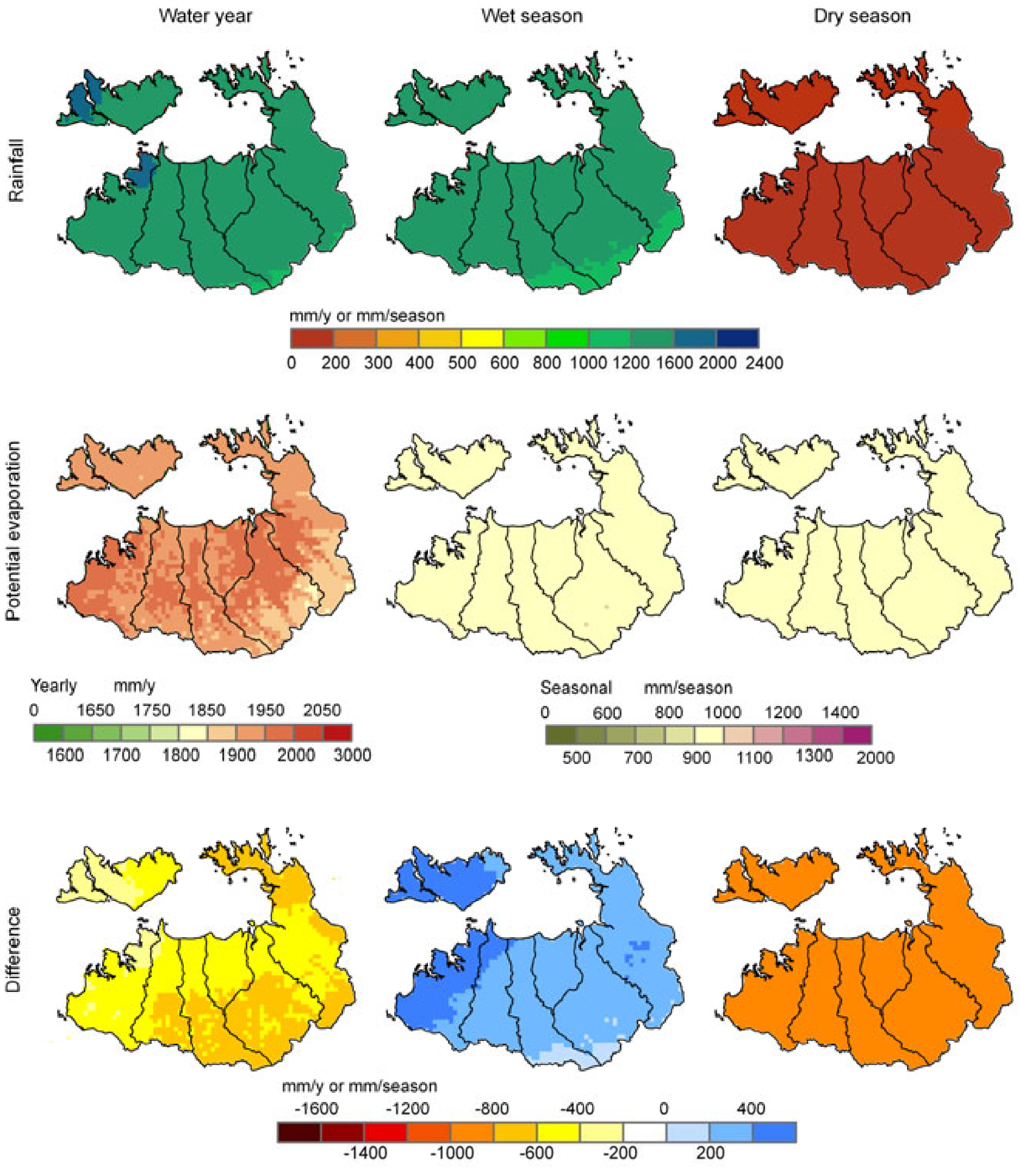


Figure VD-29. Spatial distribution of historical mean annual (water year), wet season and dry season rainfall and areal potential evapotranspiration (potential evaporation) and their difference (rainfall less areal potential evapotranspiration) across the Van Diemen region

VD-3.1.2 Recent climate

Figure VD-30 compares recent (1996 to 2007) to historical (in this case the 66-year period 1930 to 1996) mean annual rainfall for the Van Diemen region. Across the whole region, recent rainfall is between 10 and 30 percent higher than historical rainfall – a statistically significant difference for the majority of the region.

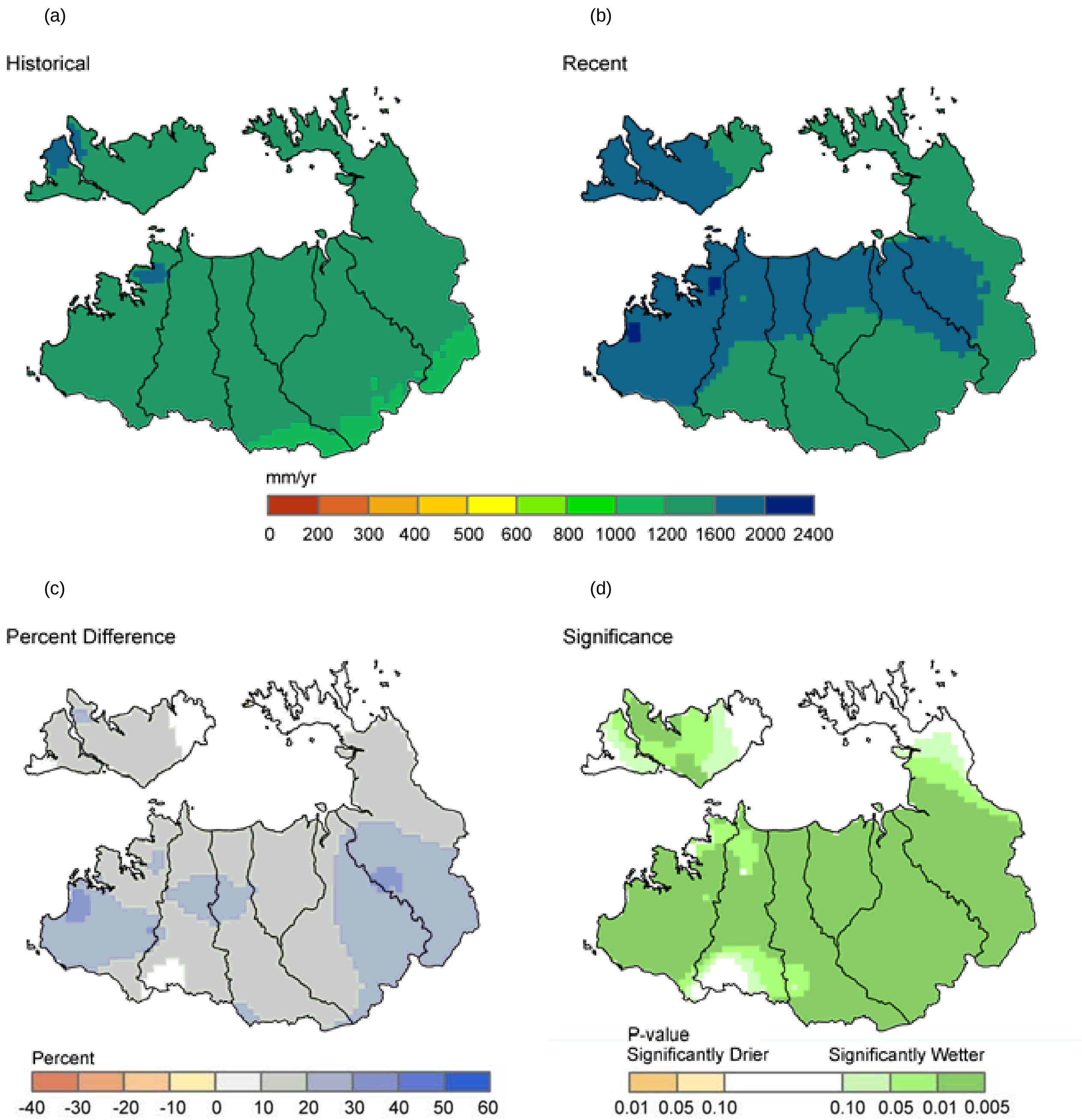


Figure VD-30. Spatial distribution of (a) historical and (b) recent mean annual rainfall; and (c) their relative percent difference and (d) the statistical significance of these differences across the Van Diemen region

VD-3.1.3 Future climate

Under Scenario C annual rainfall varies between 1226 and 1531 mm (Table VD-3) compared to the historical mean of 1390 mm. Similarly, APET ranges between 1957 and 2043 mm compared to the historical mean of 1936 mm.

A total of 45 variants of Scenario C were modelled (15 GCMs for each of the high, medium and low global warming scenarios). Subsequently, results from an extreme 'wet', median and extreme 'dry' variant are shown (referred to as scenarios Cwet, Cmid and Cdry). Under Scenario Cwet annual rainfall and APET increase by 10 percent and 1 percent, respectively. Under Scenario Cmid annual rainfall is the same as historical levels and APET increases by 2 percent. Under Scenario Cdry annual rainfall decreases by 12 percent and APET increases by 6 percent.

Under Scenario Cmid long-term monthly averages of rainfall and APET do not differ much from historical values (Figure VD-31). Under Scenario Cmid rainfall lies well within the range in values from all 45 future climate variants. The seasonality of rainfall changes slightly only in that any changes in rainfall occur in the wet season. However, there is appreciable variation in rainfall in the wet season months, varying by up to 60 mm/month. In contrast, the seasonality of

APET remains the same as any changes occur uniformly across the year. Under Scenario Cmid APET lies near the lower range in values derived from all 45 future climate variants.

The spatial distributions of rainfall and APET under Scenario C are compared to the historical distribution in Figure VD-32 and Figure VD-33. Under Scenario C the strong north–south gradient in rainfall is retained, but with a southwards shift under Scenario Cwet and a northwards shift under Scenario Cdry. Under scenarios Cmid and Cdry the rainfall gradient changes due to relatively greater decreases in rainfall occurring along the northern coastlines compared to the south of the region. The spatial distribution of APET under Scenario C is similar to the highly regionalised historical distribution.

Table VD-3. Mean annual (water year), wet season and dry season rainfall and areal potential evapotranspiration averaged over the Van Diemen region under historical climate and Scenario C

	Water year*	Wet season	Dry season
	mm/y	mm/season	
Rainfall			
Historical	1390	1327	63
Cwet	1531	1428	84
Cmid	1396	1318	62
Cdry	1226	1176	35
Areal potential evapotranspiration			
Historical	1936	972	964
Cwet	1957	973	984
Cmid	1977	991	986
Cdry	2043	1034	1008

* Note that the sum of the wet season and dry season values does not always equal the water year values because the combined wet season and dry season period (November to October) is different to the water year period (September to August).

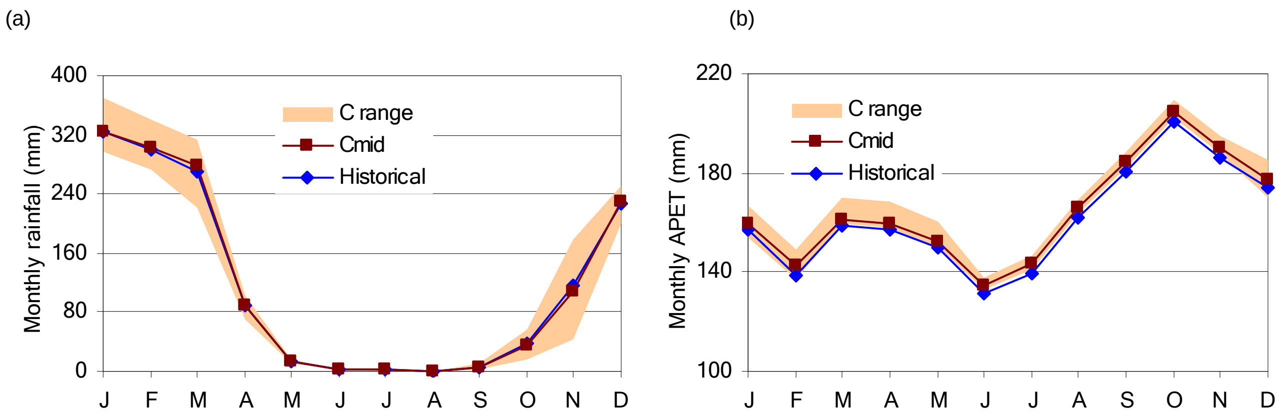


Figure VD-31. Mean monthly (a) rainfall and (b) areal potential evapotranspiration averaged over the Van Diemen region under historical climate and Scenario C. (C range is pooled from the 45 Scenario C simulations (15 global climate models and three global warming scenarios) – the lower and upper limits in C range are therefore not the same as scenarios Cdry and Cwet)

VD-3.1.4 Confidence levels

Analysis of confidence of the climate data is reported in Section 2.1.4 of the division-level Chapter 2.

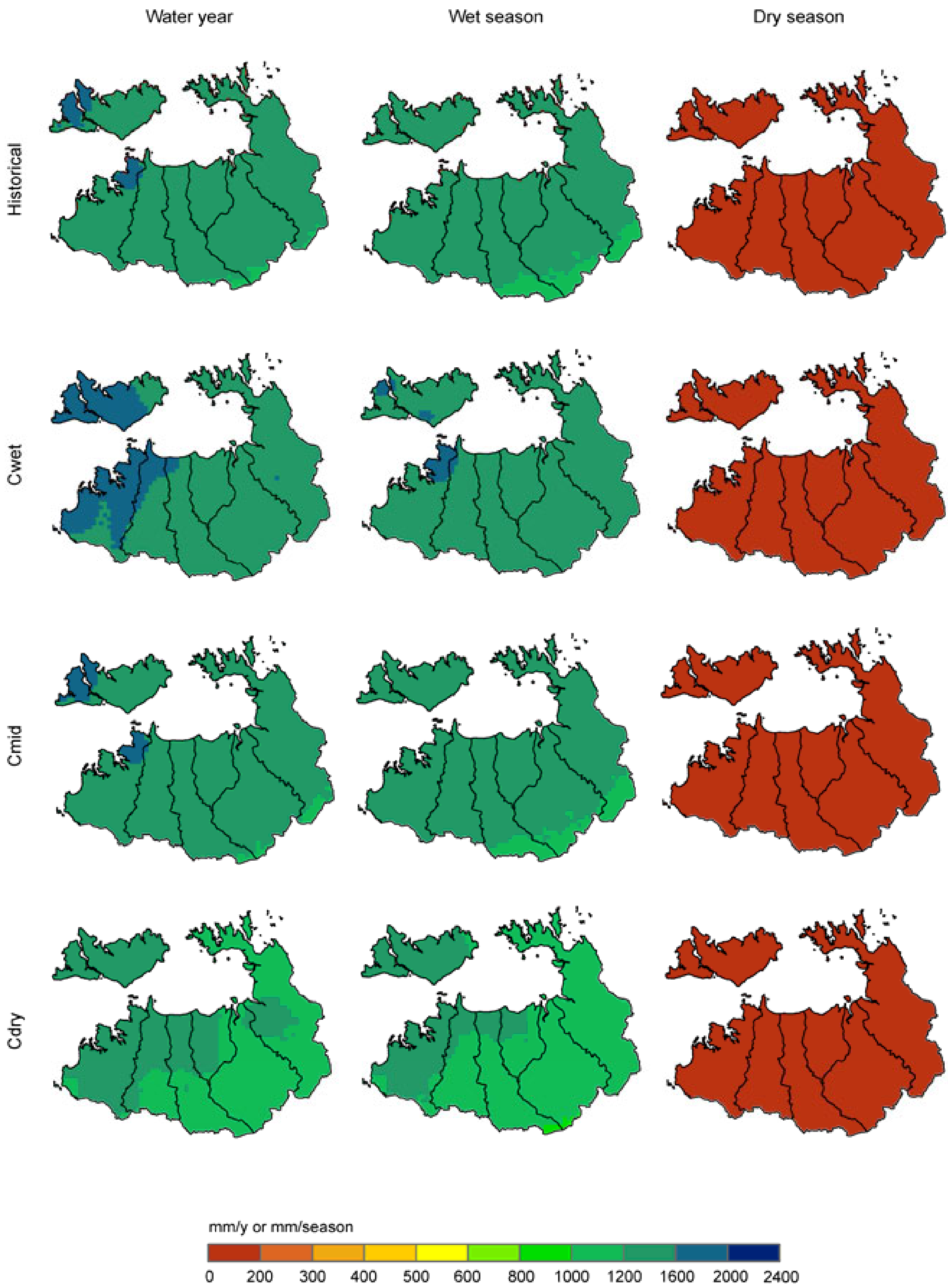


Figure VD-32. Spatial distribution of mean annual (water year), wet season and dry season rainfall across the Van Diemen region under historical climate and Scenario C

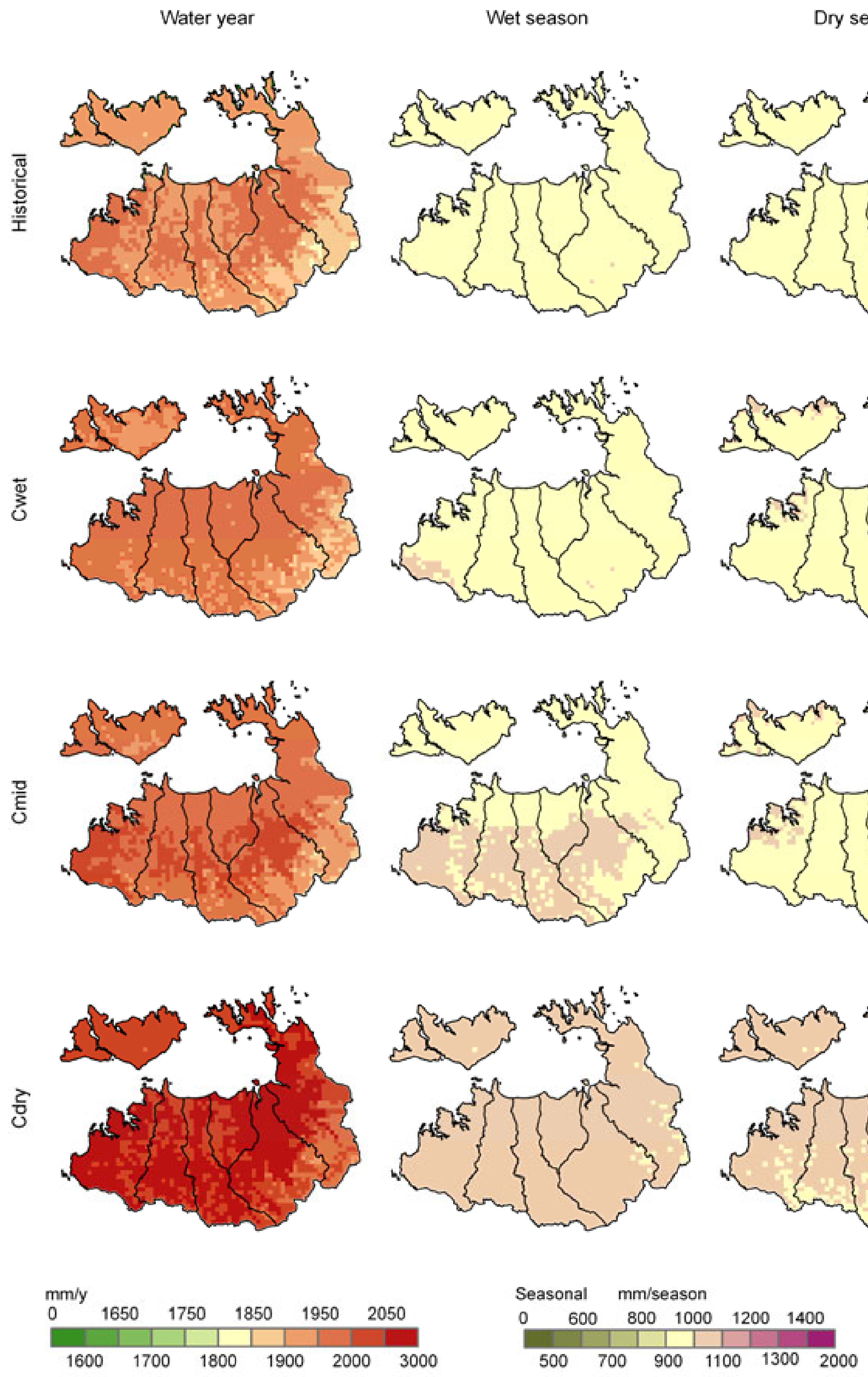


Figure VD-33. Spatial distribution of mean annual (water year), wet season and dry season areal potential evapotranspiration across the Van Diemen region under historical climate and Scenario C

VD-3.2 WAVES potential diffuse recharge estimations

The WAVES model (Zhang and Dawes, 1998) was used to estimate the change in groundwater recharge across the Van Diemen region under a range of different climate scenarios. WAVES is a vertical recharge flux model that can model plant physiological feedbacks in response to increased CO_2, as well as modelling the water balance of different soil, vegetation and climate regimes. It was chosen for its balance in complexity between plant physiology and soil physics. It was also used to assess recharge for the Murray-Darling Basin Sustainable Yields Project (Crosbie et al., 2008).

VD-3.2.1 Under historical climate

The calculated historical recharge for the Van Diemen region shows that recharge is greatest in the north-west and decreases progressively to the south-east following the rainfall gradient. The vertosol soils are particularly prominent due to the very low recharge when compared to the surrounding soil types. The historical record was assessed to establish any difference between wet and dry periods of recharge. A 23-year period was used, which allows the projection of recharge estimates to 2030 – in other words, to estimate recharge in 2030 assuming future climate is similar to historical climate (Scenario A). Under a wet historical climate (Scenario Awet) recharge increases 12 percent. Under the median estimate of historical climate (Scenario Amid) recharge decreases 3 percent, uniformly across the region. Under a dry historical climate (Scenario Adry) recharge decreases 14 percent.

Where unweathered bedrock outcrops occur, confidence in the modelled results is reduced. The locations of these outcrops in the Van Diemen region are shown on the historical recharge map in Figure VD-34.

Table VD-4. Recharge scaling factors in the Van Diemen region for scenarios A, B and C

Region	Awet	Amid	Adry	B	Cwet	Cmid	Cdry
Van Diemen	1.12	0.97	0.86	1.18	1.37	1.11	0.93

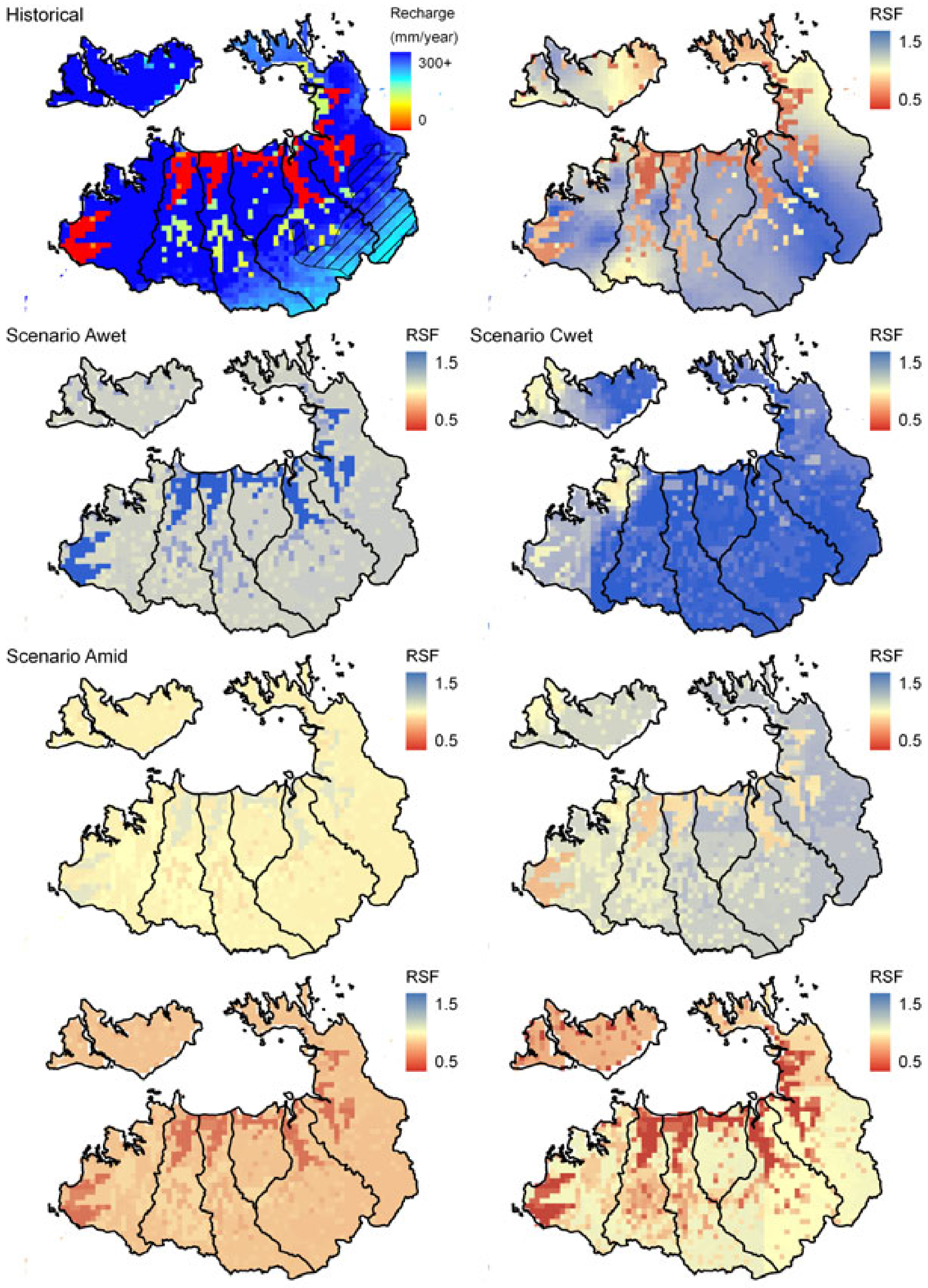


Figure VD-34. Spatial distribution of historical mean recharge rate; and recharge scaling factors across the Van Diemen region for scenarios A, B and C. The hatched region on the historical recharge map identifies where unweathered bedrock outcrops occur

VD-3.2.2 Under recent climate

The recent (1996 to 2007) climate in the Van Diemen region has been wetter than the historical (1930 to 2007) average and consequently the calculated recharge increases 18 percent under Scenario B relative to Scenario A (Table VD-4). This increase has not been spatially uniform with some areas showing an increase in recharge while others show a decrease in recharge (Figure VD-34).

VD-3.2.3 Under future climate

Figure VD-35 shows the percentage change in modelled mean annual recharge averaged over the Van Diemen region under Scenario C relative to Scenario A for the 45 scenarios (15 GCMs for each of the high, medium and low global warming scenarios). The percentage change in the mean annual rainfall and recharge from the corresponding GCMs are also tabulated in Table VD-5. Under some scenarios the recharge is projected to increase despite a decrease in rainfall. This is because total rainfall is not the only climate variable that has an influence over recharge. Daily rainfall intensity, temperature and CO_2 concentration are also important drivers (see Section 2.3.3 in the division-level Chapter 2), and specific situations can result in this counter-intuitive result. In particular, rainfall intensity is seen as a significant factor in this relationship.

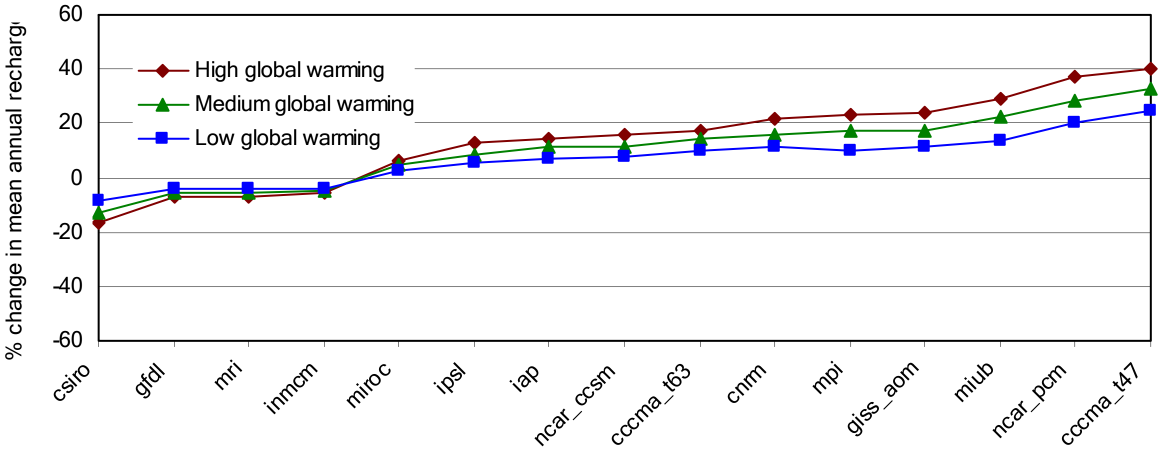


Figure VD-35. Percentage change in mean annual recharge under the 45 Scenario C simulations (15 global climate models and three global warming scenarios) relative to Scenario A recharge

Table VD-5. Summary results under 45 Scenario C simulations (numbers show percentage change in mean annual rainfall and recharge under Scenario C relative to Scenario A)

High global warming			Medium global warming			Low global warming		
GCM	Rainfall	Recharge	GCM	Rainfall	Recharge	GCM	Rainfall	Recharge
csiro	-12%	-16%	csiro	-9%	-13%	csiro	-6%	-9%
gfdl	**-15%**	**-7%**	gfdl	-11%	-5%	gfdl	-8%	-4%
mri	-6%	-7%	mri	-5%	-5%	mri	-3%	-4%
inmcm	-4%	-5%	inmcm	-3%	-5%	inmcm	-2%	-4%
miroc	-1%	6%	miroc	-1%	5%	miroc	-1%	3%
ipsl	1%	13%	ipsl	1%	9%	ipsl	0%	6%
iap	0%	14%	iap	0%	11%	iap	0%	7%
ncar_ccsm	4%	16%	**ncar_ccsm**	**3%**	**11%**	ncar_ccsm	2%	8%
cccma_t63	5%	18%	cccma_t63	4%	14%	cccma_t63	3%	10%
cnrm	3%	22%	cnrm	3%	16%	cnrm	2%	12%
mpi	-1%	23%	mpi	0%	17%	mpi	0%	10%
giss_aom	3%	24%	giss_aom	2%	17%	giss_aom	2%	11%
miub	3%	29%	miub	2%	22%	miub	2%	14%
ncar_pcm	**10%**	**37%**	ncar_pcm	8%	29%	ncar_pcm	6%	21%
cccma_t47	12%	40%	cccma_t47	9%	33%	cccma_t47	6%	25%

Under Scenario Cwet recharge increases 37 percent. Under Scenario Cmid recharge increases 11 percent. Under Scenario Cdry recharge decreases 7 percent.

VD-3.2.4 Confidence levels

The estimation of recharge from WAVES is only indicative of the actual recharge and has not been validated with field measurements. A steady state groundwater chloride mass balance (CMB) has been conducted as an independent measure of recharge (Crosbie et al., 2009). The results in the Van Diemen region show that the historical estimate of recharge using WAVES (307 mm/year) is less than the best estimate using the CMB (480 mm/year) but it is within the confidence limits of the CMB (177 to 799 mm/year).

VD-3.3 Conceptual groundwater models

VD-3.3.1 Fractured rocks

Relatively low annual rainfall and high potential evaporation means that recharge to the fractured rock aquifers is likely to only occur after prolonged periods of intense rainfall in the wet season. Recharge is more effective through sandy soils than black clay soils; the latter only permitting significant recharge early in the wet season through cracks and preferential pathways before the clays swell. Aquifers are also locally recharged through either small alluvial aquifers or directly from the river when high flows or flooding occurs. The main groundwater discharge process is through evapotranspiration. For rivers draining fractured rock aquifers in the region, flows are reduced to disconnected semi-permanent pools and then dry river beds as the dry season progresses.

VD-3.3.2 Karstic carbonate rocks

Processes in karstic carbonate rocks are similar to those for the fractured rocks, except that groundwater flow is predominantly through dissolution features rather than fractures. The main groundwater discharge processes are through evapotranspiration and spring discharge to rivers. River flows are maintained to varying degrees by the spring discharge.

Groundwater discharging from the Proterozoic carbonate aquifer in the catchment of Berry Creek maintains perennial flows in the lower reaches of the creek (Figure VD-2). A conceptual model for the interconnection between the Proterozoic carbonate aquifer and Berry Creek is given in Figure VD-36 whereby localised groundwater discharge is fed into the creek via a fault or extensively fractured part of the aquifer.

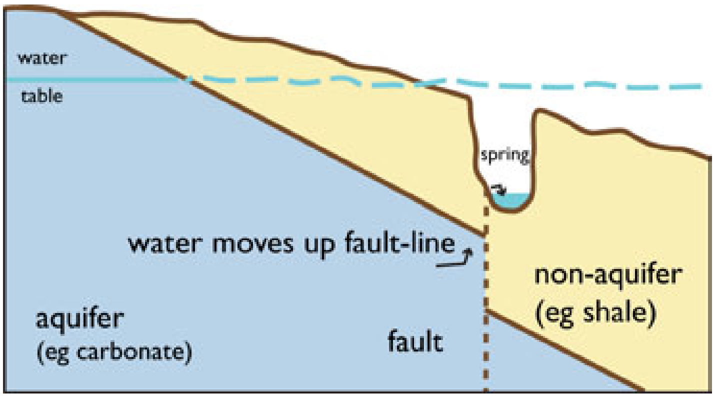


Figure VD-36. Schematic of hydrogeological cross-section of conceptual model for groundwater discharge to Berry Creek in the Van Diemen region

VD-3.3.3 Cretaceous sediments

Processes occurring in the Cretaceous sediments are similar to those for the fractured rocks. The main groundwater discharge is through evapotranspiration and spring discharge to rivers. River flows are maintained to varying degrees by the spring discharge.

Spring discharge from the Cretaceous sediments is most common in the south of the region. It occurs where a layer of porous and permeable sandstone overlies a low permeability rock such as shale or granite (Figure VD-37). Water stored in the upper layer seeps out at the contact between the two rock types, generally in the form of a seepage zone or swampy area. Key examples of this mechanism occur in the Mary and South Alligator Rivers (Figure VD-2).

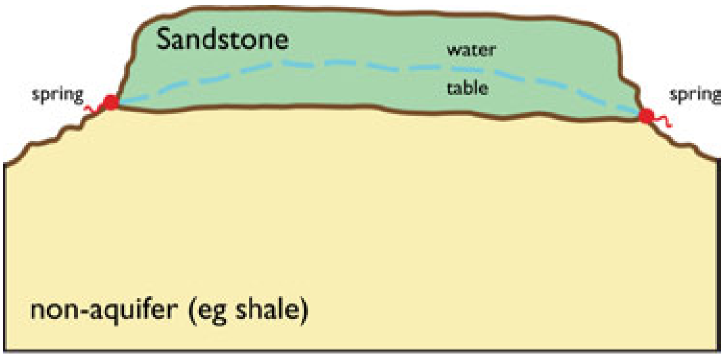


Figure VD-37. Schematic of hydrogeological cross-section of conceptual model for groundwater discharge to the Mary and South Alligator rivers in the Van Diemen region

VD-3.4 Groundwater modelling results

VD-3.4.1 Historical groundwater balance

No attempt has been made to develop a detailed groundwater balance for the region due to the lack of data. However, the following general comments can be made.

- The main hydrological characteristic of the region is the great variability in rainfall from year to year, within a single year and over periods of years. This variability results in a similar great variability in both surface water runoff and groundwater recharge.
- The period of record for the few river gauging stations and groundwater monitoring points within the region is biased towards a period of above average rainfall (based on the existing rainfall data). This must be taken into consideration when analysing flow and recharge data.
- Jolly et al (2000) and Tien (2002) derived a value of 5mm/day for evapotranspiration by correlating gauged and predicted groundwater fed river flows at Berry Creek and Howard Springs, respectively. Similar values of ET are expected to apply to most of the Van Diemen region.
- Tien (2002) developed a water balance for the catchment area of Howard Springs. Mean annual groundwater recharge, runoff and ET were calculated to be 200 mm/year, 350mm/year and 1050 mm/year respectively.
- Cook et al. (1998), using unsaturated zone soil water content, matric potential data, stable isotopes, ^{14}C, CFC-11 and CFC-12, estimated that the net groundwater recharge rate was approximately 200 mm/year beneath a eucalypt savannah site near the Howard River. That study also found that the native vegetation was not dependent on groundwater during the dry season.

VD-3.4.2 Groundwater model development

The Darwin Rural Area – McMinn's – Howard East Section groundwater system model (EHA, 2007) is based on a three dimensional finite element framework developed in the FEFLOW® simulation code (Diersch, 2007). The model was originally designed to examine the impact of alternative scenarios of groundwater extraction from the Koolpinyah Dolomite.

The finite element mesh and boundaries for the model were constructed by taking into account the following key hydrological features:

- Howard River
- Litchfield Creek
- Holland's Creek
- other creeks feeding into Black Jungle Swamp
- the Adelaide River flood plain boundary

- a sub-cropping, weathered clayey dolerite dyke located adjacent to Lambell's Lagoon
- aggregated bore location points.

For simplicity the model was constructed assuming a three-layered groundwater system as follows:

- Upper layer – laterite aquifer
- Middle layer – combined Cretaceous age sediments underlying the laterite zone combined with the transitional zone of weathered dolomite at the uppermost section of the Koolpinyah Dolomite
- The fractured zone of the Koolpinyah Dolomite.

The model area was first divided into two recharge zones, primarily based on previous modelling studies (Yin Foo, 2004). The southern zone was then refined into two areas (i.e. the Howard River area and flood plain area) to yield three discrete recharge zones (Figure VD-38). Further details about how recharge and other model parameters were estimated and implemented in the model, as well as the calibration procedure and performance are provided in EHA (2007, 2009).

The calibrated FEFLOW model simulated a mean annual groundwater discharge rate of 6047 ML/year for the section of the model covering the Howard River upstream of gauging station G8150179, which is consistent with a stream baseflow analysis that suggested the rate should be > 4700 ML/year.

For the purposes of examining recharge variability under different future climate scenarios, the WAVES model was used to provide simulated values of mean daily surface rainfall recharge for each month and for the three recharge zones over the model domain. This data was then input to a FEFLOW model recharge power function (i.e. a file providing temporal changes to recharge) for the upper model layer (i.e. the laterite aquifer).

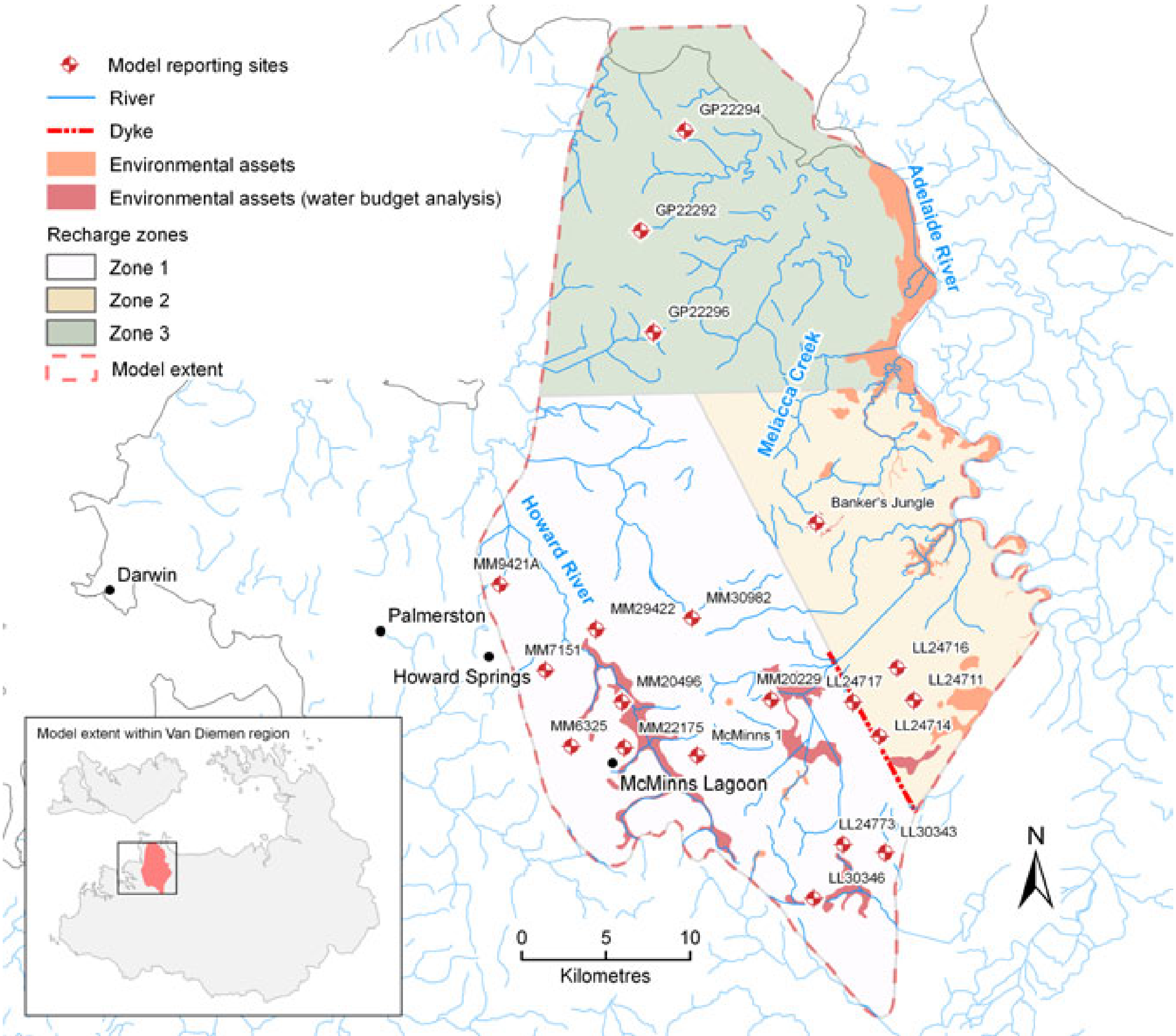


Figure VD-38. Locations of groundwater and surface water model reporting sites in the Van Diemen region (after EHA, 2007)

VD-3.4.3 Under historical climate

The Darwin Rural Area – McMinn's – Howard East Section groundwater system model was run for a 23-year predictive simulation (1/9/2007 to 31/8/2030) using monthly time-step recharge rates calculated using the WAVES model with historical rainfall for the area. Groundwater extraction rates were maintained at current levels and land use at current configuration.

Three variants of scenario A were examined, specifically:

- Scenario Awet – using WAVES model generated recharge based on the 90th percentile of 23-year recharge from the 77-year record (1 September 1930 to 31 August 2007)
- Scenario Amid – using WAVES model generated recharge based on the 50th percentile of 23-year recharge from the 77-year record (1 September 1930 to 31 August 2007)
- Scenario Adry – using WAVES model generated recharge based on the 10th percentile of 23-year recharge from the 77-year record (1 September 1930 to 31 August 2007).

Groundwater level hydrographs for the laterite (model layer 1) and the dolomite (model layer 2) aquifers were derived from the FEFLOW model output at a series of sites across the model domain (Figure GW26) some of which corresponded to the locations of existing monitoring points and two additional locations chosen to represent sites of interest as follows:

- Banker's Jungle – a site that hosts spring-related rainforest approximately 2.8 km south–south-east of the main Melacca Creek spring aggregation
- McMinn's 1 – a location in McMinn's East bore field (latitude -12.550357°; longitude 131.158257°) that corresponds to an area of high concentration of rural residential water bores.

Table VD-6 provides a summary of median simulated groundwater levels under the historical climate Scenario A at four selected sites for the laterite and dolomite aquifers respectively.

Table VD-6. Median simulated groundwater levels in the laterite and dolomite aquifers under scenarios A, B and C

Site	Model development data period (1964–2005)	Awet	Amid	Adry	B	Cwet	Cmid	Cdry
	m AHD							
Laterite aquifers								
24714	2.01	2.09	1.93	1.73	2.27	2.11	2.00	1.82
20496	17.39	17.79	17.52	16.71	17.99	17.7	17.65	17.09
Bankers Jungle	5.22	5.29	5.21	4.99	5.49	5.37	5.29	5.12
McMinn's 1	18.28	19.9	18.53	15.93	20.51	19.58	19.39	16.97
Dolomite aquifers								
24714	1.99	1.97	1.84	1.67	2.14	1.98	1.91	1.73
20496	17.73	18.14	17.75	16.73	18.4	18.05	17.95	17.16
Bankers Jungle	5.55	5.59	5.48	5.29	5.79	5.66	5.62	5.42
McMinn's 1	17.61	18.95	17.86	15.49	19.56	18.84	18.52	16.02

In addition to the groundwater elevation data, mean annual water balance data was also extracted from the model. Table VD-7 Summarises this water balance data for the entire model domain by presenting mean annual data for the key water balance items. It should be noted that there is significant temporal variation in these water balance items.

Table VD-7. Mean annual groundwater balance for entire Darwin Rural Area – McMinn's – Howard East Section groundwater system under scenarios A, B and C

	Model development data period (1964–2005)	Awet	Amid	Adry	B	Cwet	Cmid	Cdry
	GL/y							
Recharge (gains)								
Rainfall	103.30	125.39	110.19	99.10	126.63	118.53	114.59	103.18
Sub-total	**103.30**	**125.39**	**110.19**	**99.10**	**126.63**	**118.53**	**114.59**	**103.18**
Discharge (losses)								
Extraction from dolomite	20.23	20.11	20.11	20.11	20.15	20.11	20.11	20.11
Evapotranspiration	46.35	59.98	55.65	51.35	62.52	58.89	57.43	53.36
Seepage	33.62	57.83	36.38	29.84	44.79	44.27	37.82	32.19
Sub-total	**100.20**	**137.92**	**112.14**	**101.30**	**127.46**	**123.27**	**115.37**	**105.66**

The main characteristic of the observed hydrographs for bores in the Darwin Rural Area – McMinn's – Howard East Section groundwater system is a repeated annual pattern of sharp groundwater level rises in response to wet season rains, followed by a dry season recession of groundwater levels in response to aquifer through flow, groundwater discharge and groundwater pumping. This pattern is very evident in the simulated hydrographs for the historical climate (Scenario A) in both the laterite and underlying dolomite aquifers (Figure VD-39).

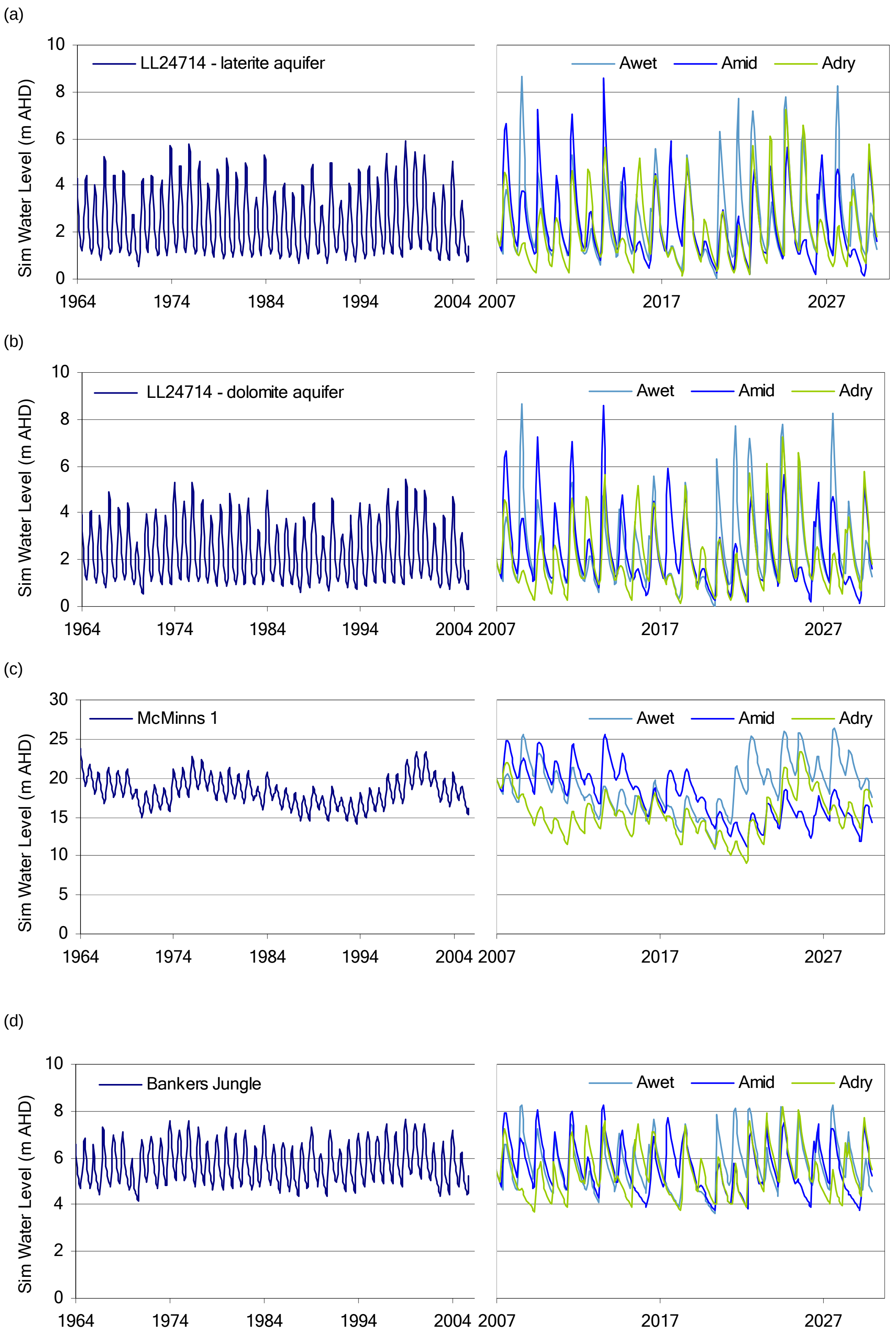


Figure VD-39. Groundwater levels under Scenario A at selected sites in the (a) laterite aquifer and (b-d) dolomite aquifer during the model development period and under historical climate

The overall temporal pattern of groundwater level response in the laterite and dolomite are broadly similar, however the amplitude of the water level response to recharge can vary at individual sites and in some locations the groundwater levels in the dolomite are above those of the laterite, reflecting semi-confined conditions.

The simulated changes in groundwater levels between 2007 and 2030 have at least three implications for groundwater management:

- The aquifer has limited storage, so groundwater pumping relies on the annual wet season recharge. Were recharge to reduce for several consecutive years, pumping would have to reduce.
- In areas close to the Adelaide River, there is a theoretical risk of seawater intrusion into the Koolpinyah Dolomite if there is a direct or appreciable indirect hydraulic connection between the river and the dolomite during times when the elevation of the groundwater surface in the dolomite aquifer falls below mean sea level.
- Where the groundwater levels typically reach ground surface (or reasonably close to ground surface) in response to wet season rainfall, longer-term changes to the peak wet season groundwater elevations can adversely impact on surface discharge to streams and other groundwater dependent ecosystems.

Under the historical climate scenario (Scenario A) it is clear that the application of the recharge rates derived from the WAVES model does replicate the very strong annual cycle of wet season recharge / dry season recession as well as the longer period cycles in groundwater storage fluctuation (Figure VD-39).

Further to this, the water level hydrographs generated from the groundwater model using the WAVES model output for the dry variant (Adry) not surprisingly indicate declines in dry season groundwater levels below those predicted during the model development period (1964 to 2005) (Figure VD-39).

The implications of the declines in groundwater levels and increased frequency of substantially lower wet season recharge at the Banker's Jungle site (Figure VD-39(d)), would be periodically reduced spring discharge and evapotranspiration. At bore LL24714 in the Lambell's Lagoon area the implication would be groundwater levels regularly approaching mean sea level at the end of the dry season (Figure VD-39(b)).

In addition to these impacts, under the dry variant (Adry), median groundwater levels would decline in the McMinn's area and this would impact on bore yields, particularly in heavily utilised areas (Figure VD-39(c)).

VD-3.4.4 Under recent climate

The Darwin Rural Area – McMinn's – Howard East Section groundwater system model was run for a 23-year predictive simulation (1/9/2007 to 31/8/2030) using monthly time-step recharge rates calculated using the WAVES model with consecutive periods of historical rainfall for the area over recent years (1 September 1996 to 31 August 2007). Groundwater extraction rates were maintained at current levels and land use at current configuration.

Groundwater level hydrographs were obtained from FEFLOW model output for the laterite (model layer 1) and dolomite (model layer 2) aquifer at selected sites across the model area, including historical monitoring bores as well as at Banker's Jungle and the McMinn's East bore field area. Key examples of hydrographs for the most utilised (i.e., the dolomite) aquifer are provided in Figure VD-40, while results for both aquifers at all 20 reporting sites are provided in EHA (2009).

A summary of median simulated groundwater levels under the recent climate scenario (Scenario B) is provided for the laterite and dolomite aquifers in Table VD-6. The mean annual water balance for the entire model under recent climate is provided in Table VD-7.

Under the recent climate scenario (Scenario B) it is clear that the application of the recharge rates derived from the WAVES model replicates the very strong annual cycle of wet season recharge / dry season recession and the longer period cycles in groundwater storage fluctuation are broadly replicated (Figure VD-40).

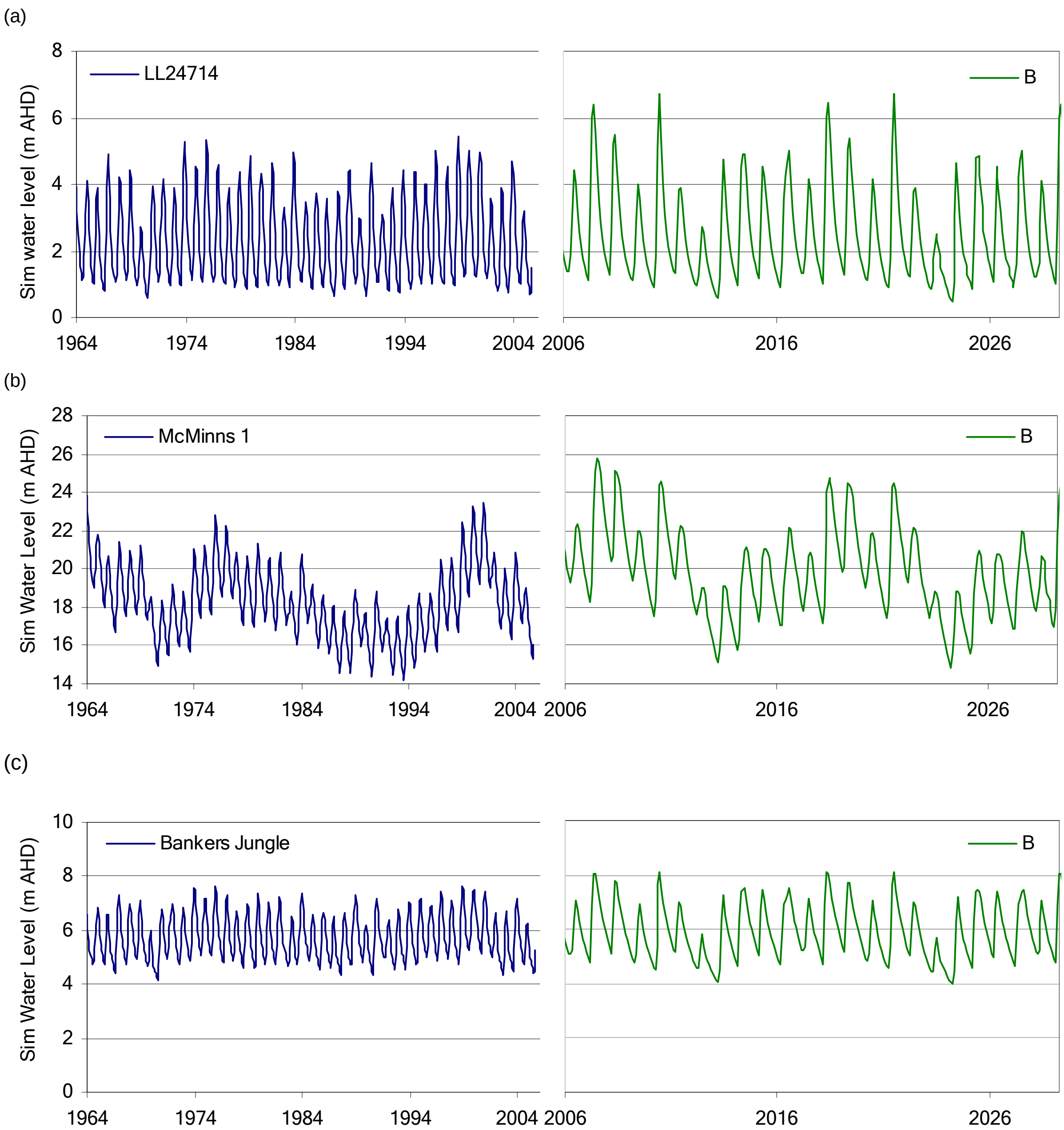


Figure VD-40. Simulated groundwater levels for representative bores in the dolomite aquifer during the model development period and under Scenario B

In accordance with the generally higher rainfall under recent climate, the groundwater model runs also indicate higher wet season groundwater level peaks (Figure VD-40) Furthermore the water level hydrographs generated from the groundwater model using the WAVES model output under recent climate not surprisingly indicate slightly higher peak wet season groundwater levels beyond those from the model development period (1964 - 2005).

In the Lambell's Lagoon area, under the recent climate scenario, peak wet season groundwater levels are higher in some years (Figure VD-40(a)) however the minimum dry season water levels remain similar to those for the model development period (1964 to 2005).

For the Banker's Jungle area, under the recent climate scenario, the predicted median groundwater levels slightly increase over those for the model development period (1964 - 2005), however the model predicts some years with substantially lower wet season recharge. This would result in periodic reduced spring discharge and evapotranspiration.

VD-3.4.5 Under future climate

The Darwin Rural Area – McMinn's – Howard East Section groundwater system model was run for a 23-year predictive simulation (1/9/2007 to 31/8/2030) using monthly time-step recharge rates calculated using WAVES with climate data generated from 15 different GCMs and three global warming scenarios. Groundwater extraction rates were maintained at current levels and land use at current configuration.

Three variants of scenario C were examined, specifically:

- Scenario Cwet – using WAVES model generated recharge based on the second wettest GCM simulation under the high global warming scenario
- Scenario Cmid – using WAVES model generated recharge based on the median GCM simulation under the middle global warming scenario; and
- Scenario Cdry – using WAVES model generated recharge using the second driest GCM simulation under the high global warming scenario.

Groundwater level hydrographs were obtained from FEFLOW model output for the laterite (model layer 1) and dolomite (model layer 2) aquifers at selected sites across the model area, including historical monitoring bores as well as at Banker's Jungle and McMinn's East bore field. Key examples of hydrographs for the most utilised (i.e., the dolomite) aquifer are provided in Figure VD-41, while results for both aquifers at all 20 reporting sites are provided in EHA (2009).

A summary of median simulated groundwater levels under the future climate scenario (Scenario C) is provided for the laterite and dolomite aquifers in Table VD-6. The mean annual water balance for the entire model under future climate is provided in Table VD-7.

Under the future climate scenario (Scenario C) it is clear that the application of the recharge rates derived from the WAVES model again produces hydrographs that reflect a strong annual cycle of wet season recharge / dry season recession as well as the longer period cycles in groundwater storage fluctuation. However the groundwater level hydrographs generated from the groundwater model using the WAVES model output suggest that under the future climate scenario there will be more frequent occasions when wet season recharge is substantially lower than the long-term average.

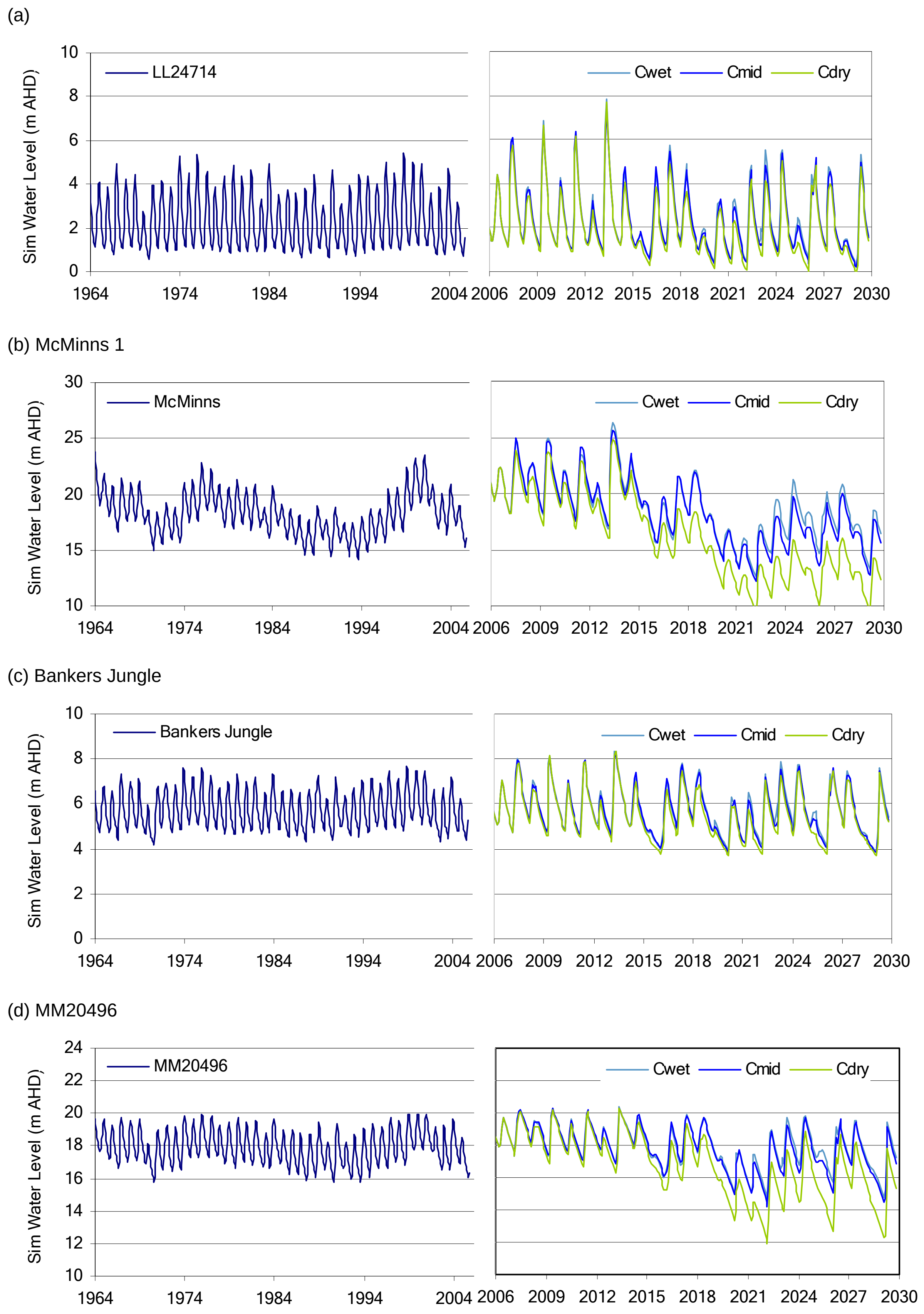


Figure VD-41. Simulated groundwater levels at selected sites in the dolomite aquifer during the model development period and under future climate Scenario C

Further to this the water level hydrographs generated from the groundwater model using the WAVES model output under future climate for the dry variant (Cdry) not surprisingly indicate declines in dry season groundwater levels below those simulated during the model development period (1964 to 2005) (Figure VD-41).

One of the implications of the declines in groundwater levels and increased frequency of missed substantial wet season recharge at the McMinn's site (located within an area of high concentration of bores) (Figure VD-25), would be in an overall reduction in bore yields over the dry season and during periods where wet season recharge was substantially missed, hence causing appreciable stress to existing groundwater supplies. In the heavily used section of the McMinn's area, under the future climate scenarios the model predicts declines in median water levels for the dry scenario (Figure VD-41(b)), whilst over the simulation period the mid and wet scenarios reflect potential increases in median groundwater levels.

In the Lambell's Lagoon area, under the future climate scenarios, although peak wet season groundwater levels would be higher (Figure VD-41 (a)) in some years, minimum dry season groundwater levels would be drawn closer to mean sea level.

For the Banker's Jungle area, under the future climate scenario (Figure VD-41(c)) the predicted median groundwater levels remain very similar to the model development period (1964 to 2005), however the model predicts some years with substantially missed wet season recharge. This would result in periodic reduced spring discharge and evapotranspiration.

VD-3.4.6 Under future climate and future development

No simulations of the model were performed for the future climate / future development scenario as it is considered that the Darwin Rural Area – McMinn's – Howard East Section groundwater system is already in overdraft and any further development would only exacerbate declines in the condition of this resource.

VD-3.4.7 Confidence levels

Key limitations of the current Darwin Rural Area – McMinn's – Howard East Section groundwater system model are:

- Although it is possible to characterise the hydrogeology of the modelled area into at least a four-layer system, a fine finite element mesh a FEFLOW model becomes unwieldy due to long computational times. Accordingly the model developed and used for the simulations discussed herein was a three-layer model prepared with:
  - upper layer – laterite aquifer
  - middle layer – combined Cretaceous age sediments underlying the laterite zone combined with the transitional zone of weathered dolomite at the uppermost section of the Koolpinyah Dolomite
  - the fractured zone of the Koolpinyah Dolomite.
- The current 3-layer model configuration may predispose the model to some degree of numerical instability. Representatives of the developers of the FEFLOW code have recommended that a 5-layer model configuration could overcome some of these. Currently NRETAS is attempting to redevelop the model with a 5-layer configuration, however significant issues have been encountered with respect to lengthy model run times;
- The groundwater monitoring network is spatially biased to the historical areas of development and the monitoring of the dolomite system. Bores at different depths (in different aquifers) show similar water level changes, so appear to be in communication: presumably, the bore seals have failed.
- Groundwater discharge to streams and springs characterises the system, however whilst there is an existing stream gauging network it could be improved to provide additional information against which the model predictions could be compared and to provide information to support additional redevelopment / refinement of the model. Such improved hydrographic coverage could include the development of a continuous stream gauge on Baker's Creek, as well as the introduction of a program of systematic and "end-of-wet-season" and "end-of-dry season" spot-gauging at strategic locations.
- At the time of preparation of the model the available digital elevation model data for the area included two coverages and this data set was used to derive natural surface elevation values for some bores for which not specific surveyed elevation value was available. The key implication of the use of that DEM is that the reference levels of a series of monitoring bores, particularly in the Lambell's Lagoon area, were altered and lowered suggesting increased risk of seawater intrusion. At the time of preparation of this report NRETAS had

undertaken re-surveying of these monitoring bores and were incorporating the revised data into the aforementioned revised groundwater flow model.

- As with the modelling of most groundwater systems, improved spatial coverage of groundwater monitoring bores across the model domain would allow the model predictions to be better scrutinised and would provide additional data to support redevelopment / recalibration to improve the model over time.
- It has been suggested that the spring at Howard Springs has been formed by the collapse of younger Cretaceous age strata into a solution cavity developed in the underlying Koolpinyah Dolomite (i.e. formation of a doline) with subsequent stream erosion only leaving the southern wall of the doline at the surface. Such a geological model implies a direct connection between the Koolpinyah Dolomite and the surface at the site of Howard Springs. The groundwater model described herein does not explicitly incorporate such a direct connection.
- Available stream gauging for the main spring group at Melacca Creek has indicated mean discharges in the order of 340 L/sec. In contrast the model projects mean discharges for this feature at only 6 L/sec. These reason for this difference may well lie in the adequacy of the digital elevation model used to define the surface of the upper model layer as surface discharge phenomena are inherently influenced by the assumed elevation of the land surface. In the case of the main spring group in Melacca Creek, a discharge of 340 L/sec would probably lead to stream incision, which in-turn would promote further groundwater discharge. Accordingly, the uncertainty of the DEM is a major limitation of the model.
- It is noted that the non-inclusion of Howard Springs, and the discrepancy between observed spring flow at Melacca Creek and model simulated discharge in that area suggests that the model may over estimate the specific yield value of the overlying sediments. As a result, any long-term predictions using the model potentially under estimate the magnitude of groundwater level impacts from pumping.
- However while there are differences between the magnitude of the observed discharges from Howard Springs and Melacca Creek and the model projected discharges from these features, it is reasonable to use the model for the purposes of the assessment of relative changes to discharges from these features.
- The model incorporates assumptions for a seasonable pattern of groundwater pumping for horticultural enterprises and rural residential users for which there is a relative paucity of metered use data and the model could be further refined if suitable sample metered use data was gathered.

VD-3.5 Rainfall-runoff modelling results

In this section the term runoff is the sum of overland flow, interflow and baseflow. It is equivalent to streamflow expressed as a mm depth equivalent. All plots show data averaged over the modelled subcatchments of the Van Diemen region. For this reason rainfall reported in this section may vary slightly from that reported elsewhere due to differences between the catchment boundaries (shown in Figure VD-1) and the DEM-derived catchment boundaries used here. In this section, where annual data are reported years are represented by numbers 1 through 77. Consistently throughout this report, annual data are based on the water year (1 September to 31 August) and the dry season is defined as 1 May to 31 October. Unless stated otherwise scenarios Cwet, Cmid and Cdry are selected on the basis of the ranked mean annual runoff. For more details on methods refer to Section 2.2 of the division-level Chapter 2.

VD-3.5.1 Regional synopsis

The rainfall-runoff modelling estimates runoff in 0.05 degree grid cells in 103 subcatchments (Figure VD-42). Optimised parameter values from 20 calibration catchments are used. All of these calibration catchments are in the Van Diemen region. One calibration catchment is located on Melville Island. Calibration catchments are predominantly located in the mid to upper reaches of catchments.

VD-3.5.2 Model calibration

Figure VD-43 compares the modelled and observed monthly runoff and the modelled and observed daily flow exceedance curves for the 20 calibration catchments. Nash-Sutcliffe efficiency (NSE) values provide a quantitative measure of how well simulated values match observed values. NSE values are described in more detail in Section 2.2.3 of the division-level Chapter 2. On the monthly plots NSE is the monthly Nash-Sutcliffe efficiency value and NSE (dry season) is the dry season monthly Nash-Sutcliffe efficiency value. On the daily flow exceedance plots, NSE is the daily flow exceedance curve Nash-Sutcliffe efficiency value and NSE (50 to 100 percent) is the lower half of the daily flow exeedance curve Nash-Sutcliffe efficiency value.

The results indicate that the ensemble calibration of the rainfall-runoff models Sacramento and IhacresClassic can reasonably reproduce the observed monthly runoff series (NSE values generally greater than 0.6) and the daily flow exceedance characteristic (NSE values generally greater than 0.8). The volumetric constraint used in the model calibration also ensures that the total modelled runoff is within 5 percent of the total observed runoff.

The calibration method places more importance on the simulation of high runoff, and therefore rainfall-runoff modelling of the medium and high runoff is considerably better than the modelling of low runoff. It should be noted, however, that while the relative difference between the observed and simulated low flow values may be large (which is what gives rise to the low monthly dry season NSE values for example), the absolute difference between the observed and simulated low flow values is generally small because both values are small. Nevertheless, an optimisation to reduce overall error variance can result in some underestimation of high runoff and overestimation of low runoff. This is evident in some of the scatter plots comparing the modelled and observed monthly runoff and many of the daily flow exceedance curves. For the majority of calibration catchments the disagreement between the modelled and observed daily runoff curves is discernable for runoff that is exceeded less than 1 percent of the time. This is accentuated in the plots because of the linear scale on the y-axis and normal probability scale on the x-axis. In any case, the volumetric constraint used in the model calibration ensures that the total modelled runoff is always within 5 percent of the total observed runoff. As indicated by the relatively low NSE values for the lower half of the daily flow exceedance curve and monthly dry season there may be considerable disagreement between observed and modelled low flow values (i.e. cease-to-flow). Overall the monthly NSE values are considered suitable for the general purposes of estimating long-term mean annual runoff.

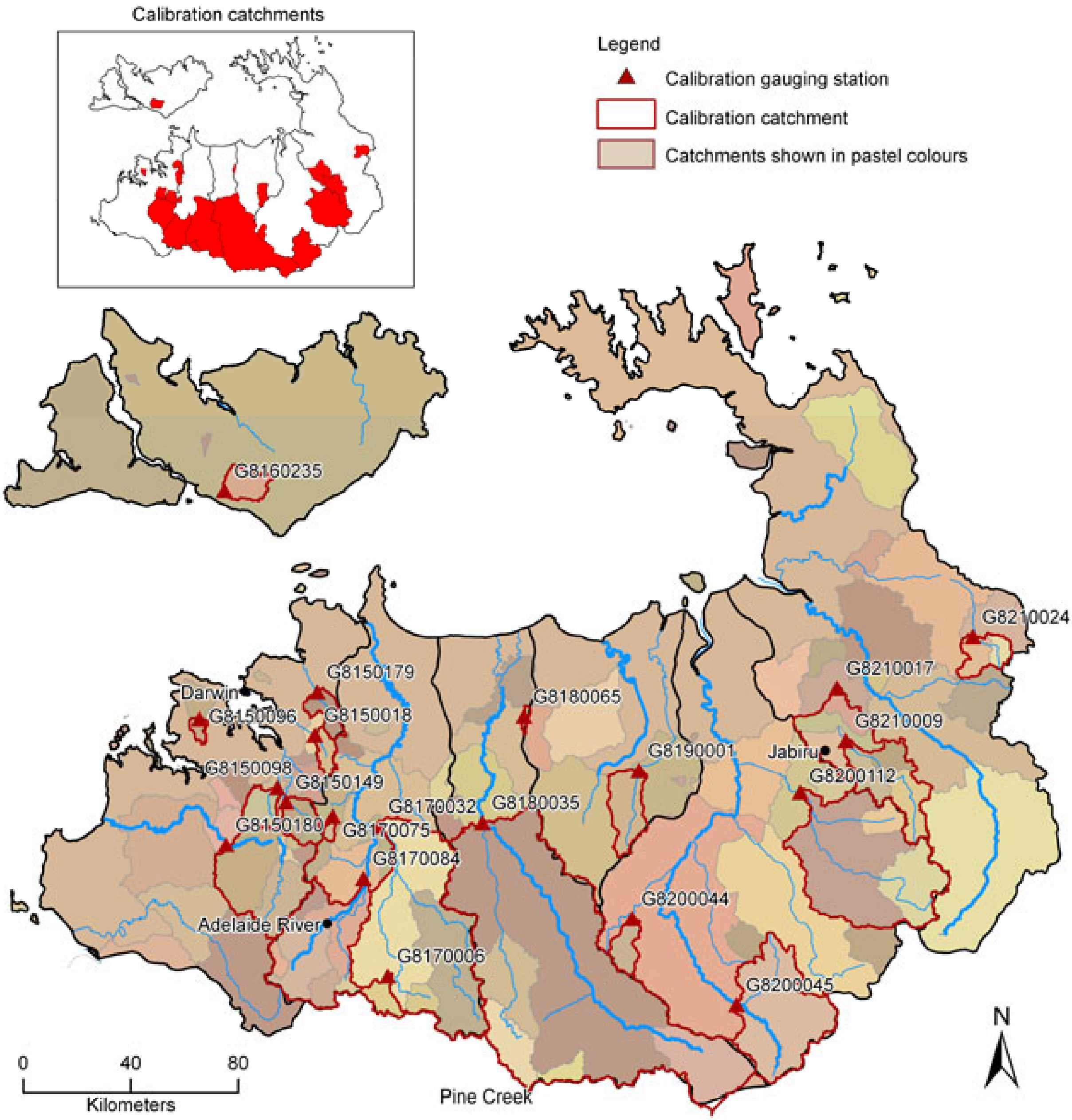
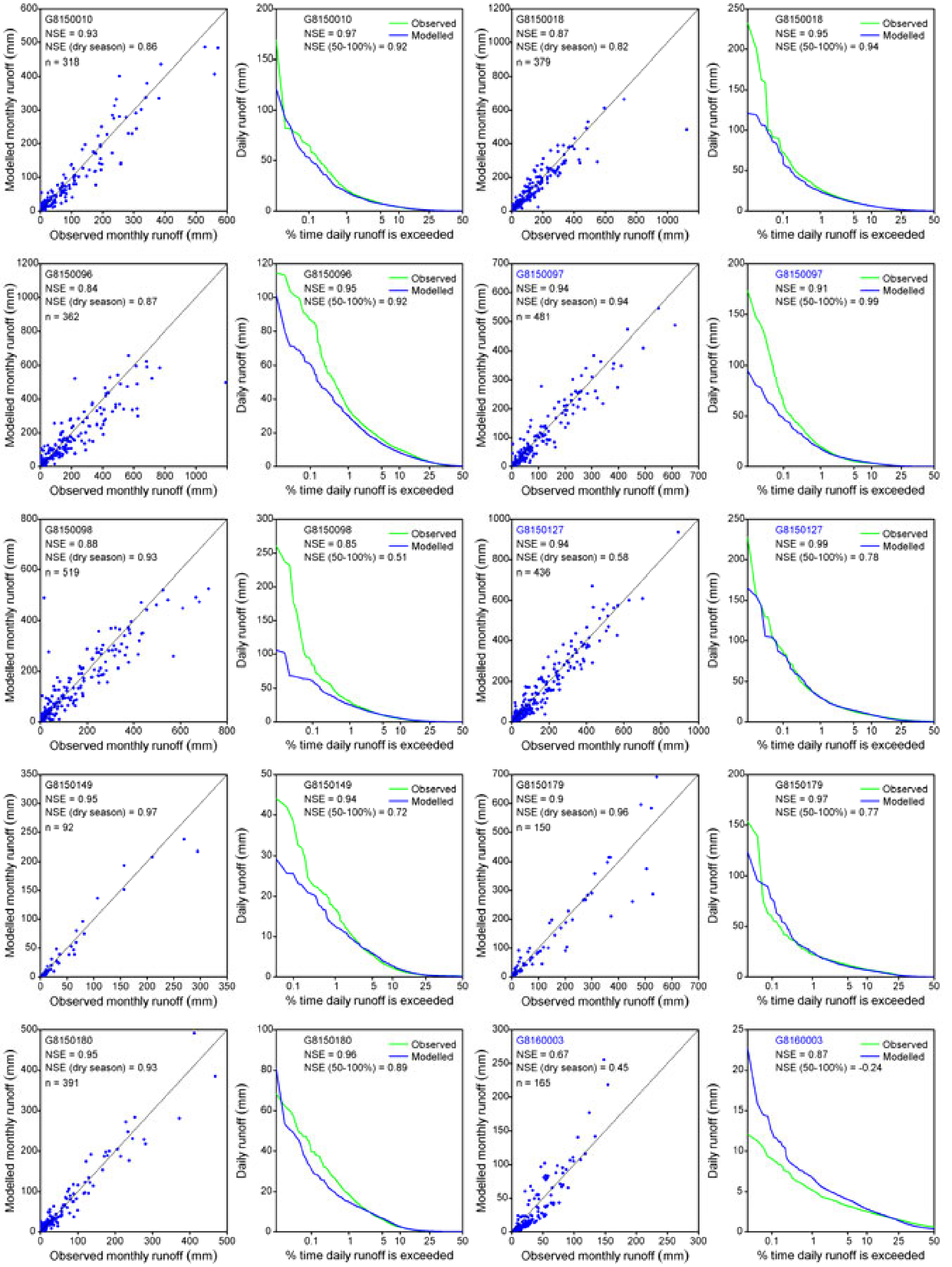
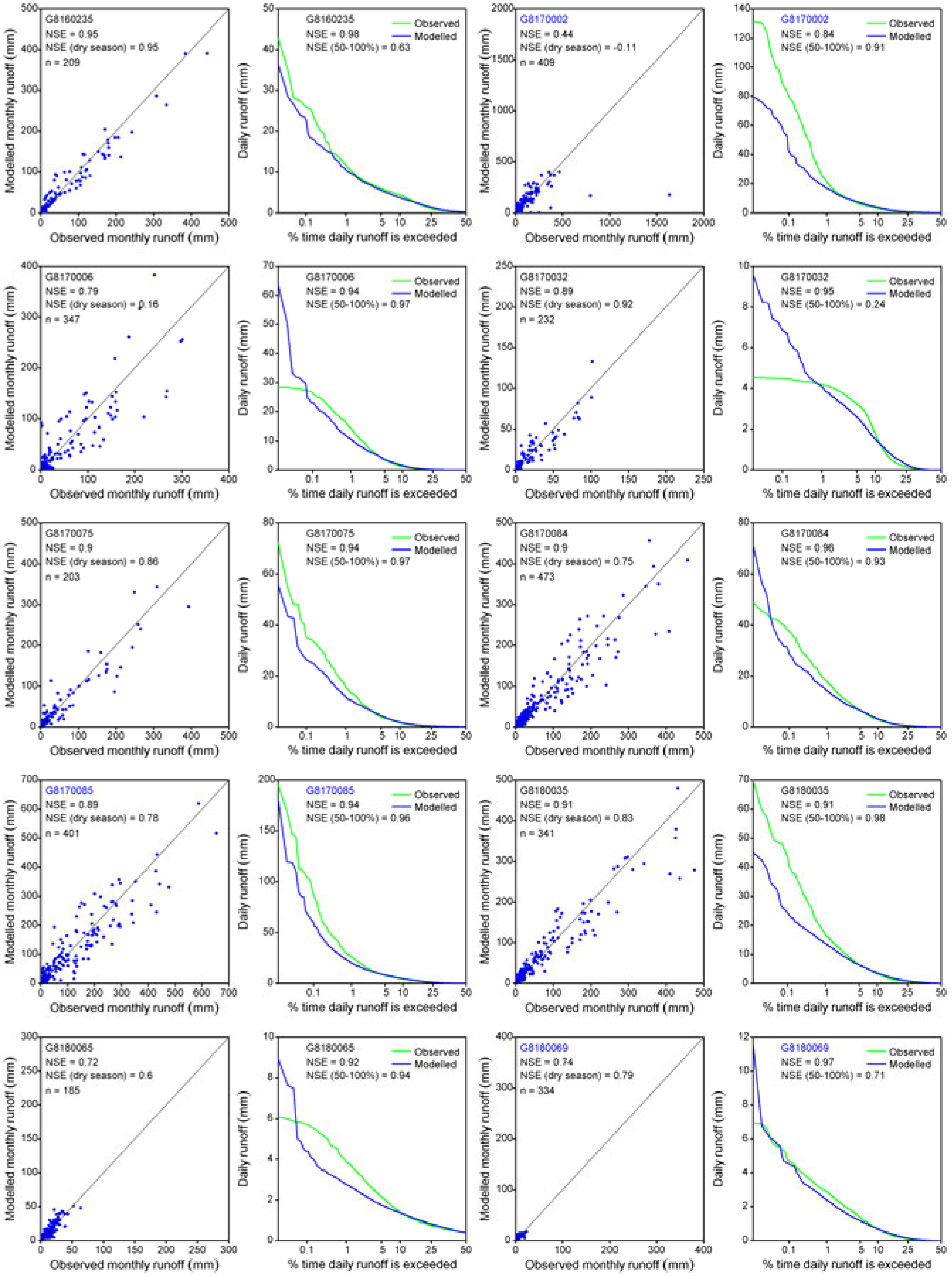


Figure VD-42. Map of the modelling subcatchments, calibration catchments and calibration gauging stations used for the Van Diemen region with inset highlighting (in red) the extent of the calibration catchments



G8150010
NSE = 0.93
NSE (dry season) = 0.86
n = 318
G8150010
NSE = 0.97
NSE (50-100%) = 0.92
G8150018
NSE = 0.87
NSE (dry season) = 0.82
n = 379
G8150018
NSE = 0.95
NSE (50-100%) = 0.94
G8150096
NSE = 0.84
NSE (dry season) = 0.87
n = 362
G8150096
NSE = 0.95
NSE (50-100%) = 0.92
G8150097
NSE = 0.94
NSE (dry season) = 0.94
n = 481
G8150097
NSE = 0.91
NSE (50-100%) = 0.99
G8150098
NSE = 0.88
NSE (dry season) = 0.93
n = 519
G8150098
NSE = 0.85
NSE (50-100%) = 0.51
G8150127
NSE = 0.94
NSE (dry season) = 0.58
n = 436
G8150127
NSE = 0.99
NSE (50-100%) = 0.78
G8150149
NSE = 0.95
NSE (dry season) = 0.97
n = 92
G8150149
NSE = 0.94
NSE (50-100%) = 0.72
G8150179
NSE = 0.9
NSE (dry season) = 0.96
n = 150
G8150179
NSE = 0.97
NSE (50-100%) = 0.77
G8150180
NSE = 0.95
NSE (dry season) = 0.93
n = 391
G8150180
NSE = 0.96
NSE (50-100%) = 0.89
G8160003
NSE = 0.67
NSE (dry season) = 0.45
n = 165
G8160003
NSE = 0.87
NSE (50-100%) = -0.24
Observed
Modelled
Modelled monthly runoff (mm)
Observed monthly runoff (mm)
Daily runoff (mm)
% time daily runoff is exceeded


G8160235
NSE = 0.95
NSE (dry season) = 0.95
n = 209
G8160235
NSE = 0.98
NSE (50-100%) = 0.63
G8170002
NSE = 0.44
NSE (dry season) = -0.11
n = 409
G8170002
NSE = 0.84
NSE (50-100%) = 0.91
G8170006
NSE = 0.79
NSE (dry season) = 0.16
n = 347
G8170006
NSE = 0.94
NSE (50-100%) = 0.97
G8170032
NSE = 0.89
NSE (dry season) = 0.92
n = 232
G8170032
NSE = 0.95
NSE (50-100%) = 0.24
G8170075
NSE = 0.9
NSE (dry season) = 0.86
n = 203
G8170075
NSE = 0.94
NSE (50-100%) = 0.97
G8170084
NSE = 0.9
NSE (dry season) = 0.75
n = 473
G8170084
NSE = 0.96
NSE (50-100%) = 0.93
G8170085
NSE = 0.89
NSE (dry season) = 0.78
n = 401
G8170085
NSE = 0.94
NSE (50-100%) = 0.96
G8180035
NSE = 0.91
NSE (dry season) = 0.83
n = 341
G8180035
NSE = 0.91
NSE (50-100%) = 0.98
G8180065
NSE = 0.72
NSE (dry season) = 0.6
n = 185
G8180065
NSE = 0.92
NSE (50-100%) = 0.94
G8180069
NSE = 0.74
NSE (dry season) = 0.79
n = 334
G8180069
NSE = 0.97
NSE (50-100%) = 0.71
Observed
Modelled
Modelled monthly runoff (mm)
Observed monthly runoff (mm)
Daily runoff (mm)
% time daily runoff is exceeded

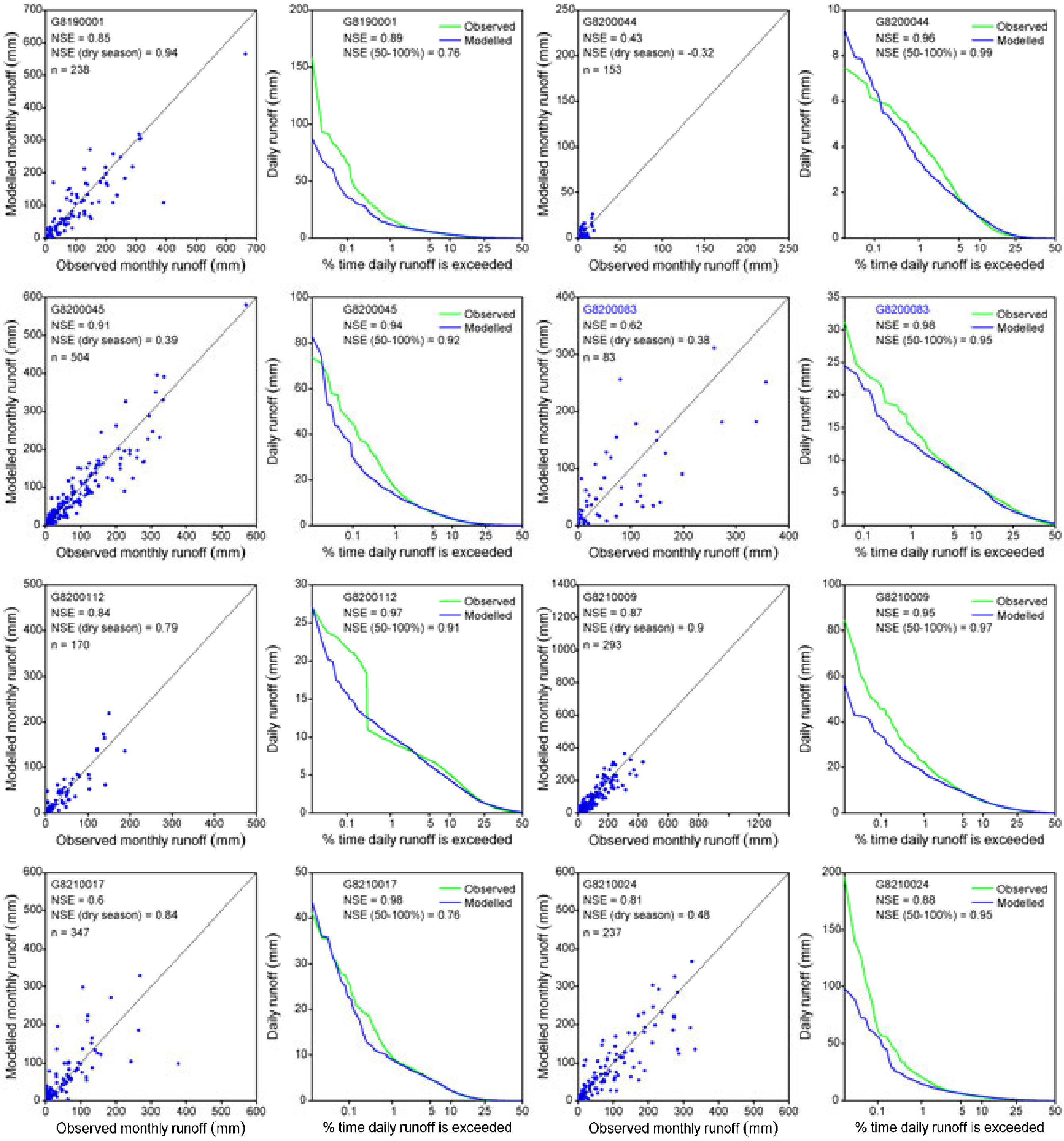


Figure VD-43. Modelled and observed monthly runoff and daily flow exceedance curve for each calibration catchment in the Van Diemen region. (Red text denotes catchments located outside the region; blue text denotes catchments used for surface water modelling only)

VD-3.5.3 Under historical climate

Figure VD-44 shows the spatial distribution of mean annual rainfall and runoff under Scenario A (averaged over 1930 to 2007) across the Van Diemen region. Figure VD-45 shows the mean annual rainfall and runoff averaged over the region.

The mean annual rainfall and runoff averaged over the Van Diemen region are 1386 mm and 375 mm respectively. The mean wet season and dry season runoff averaged over the Van Diemen region are 361 mm and 13 mm respectively.

In this project, all runoff grids are presented as long-term mean annual values. However, the distribution of monthly and annual runoff data in northern Australia can be highly skewed; consequently the median and additional percentile values spatially averaged over the region are also reported. The 10th percentile, median and 90th percentile annual runoff values across the Van Diemen region are 640, 345 and 158 mm respectively. The median wet season and dry season runoff averaged over the Van Diemen region are 336 mm and 11 mm respectively.

The mean annual rainfall varies from over 1600 mm in the north-west to about 1000 mm in the south-east. The mean annual runoff varies from over 600 mm in the north-east to about 200 mm in the south (Figure VD-44). Runoff coefficients vary from about 15 to 40 percent of rainfall. The majority of rainfall and runoff occurs during the wet season months December to April (Figure VD-46). Rainfall and runoff can vary considerably from year to year with long periods over several years or decades that are considerably wetter or drier than others (Figure VD-45). The coefficients of variation of annual rainfall and runoff averaged over the Van Diemen region are 0.18 and 0.49 respectively.

The Van Diemen is one of 13 regions which cover the three divisions studied in this project. Mean annual rainfall and runoff, as well as coefficients of variation, have been calculated for all of these 13 regions, and it is useful to compare the Van Diemen results to results across all 13 regions. Across all 13 regions in this project 10th percentile, median and 90th percentile values are 1371, 936 and 595 mm respectively for mean annual rainfall and 374, 153 and 78 mm respectively for mean annual runoff. The mean annual rainfall (1386 mm) and runoff (375 mm) averaged over the Van Diemen region fall at the upper end of this range. Across all 13 regions in this project the 10th, median and 90th percentile values are 0.34, 0.26 and 0.19 respectively for the coefficient of variation of annual rainfall and 1.39, 0.69 and 0.48 for the coefficient of variation of runoff. The coefficient of variation of annual rainfall (0.18) and runoff (0.49) averaged over the Van Diemen region are among the lowest of the 13 reporting regions.

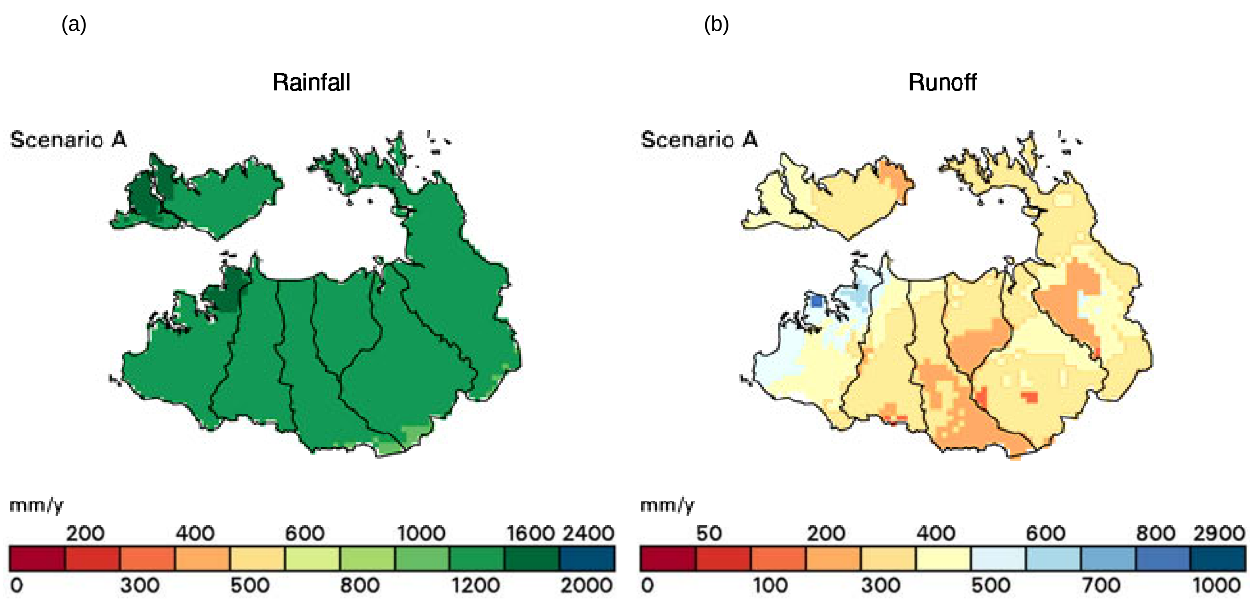


Figure VD-44. Spatial distribution of mean annual (a) rainfall and (b) modelled runoff across the Van Diemen region under Scenario A

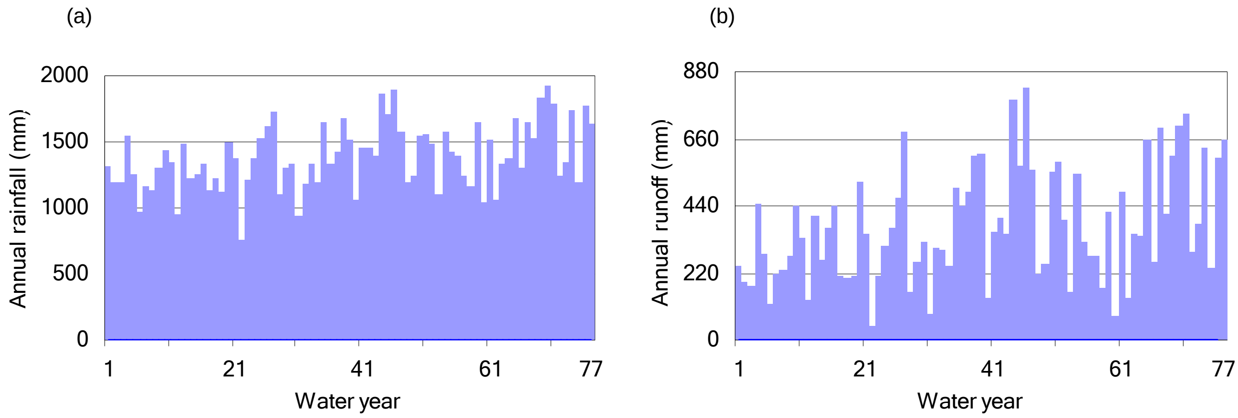


Figure VD-45. Annual (a) rainfall and (b) modelled runoff in the Van Diemen region under Scenario A

Figure VD-46 (a and b) shows the minimum and maximum monthly rainfall and runoff and the range of values between the 25th and 75th percentile monthly rainfall and runoff. Figure VD-46 (c and d) shows the mean and median monthly flows and the range of values between the 25th and 75th percentile monthly rainfall and runoff.

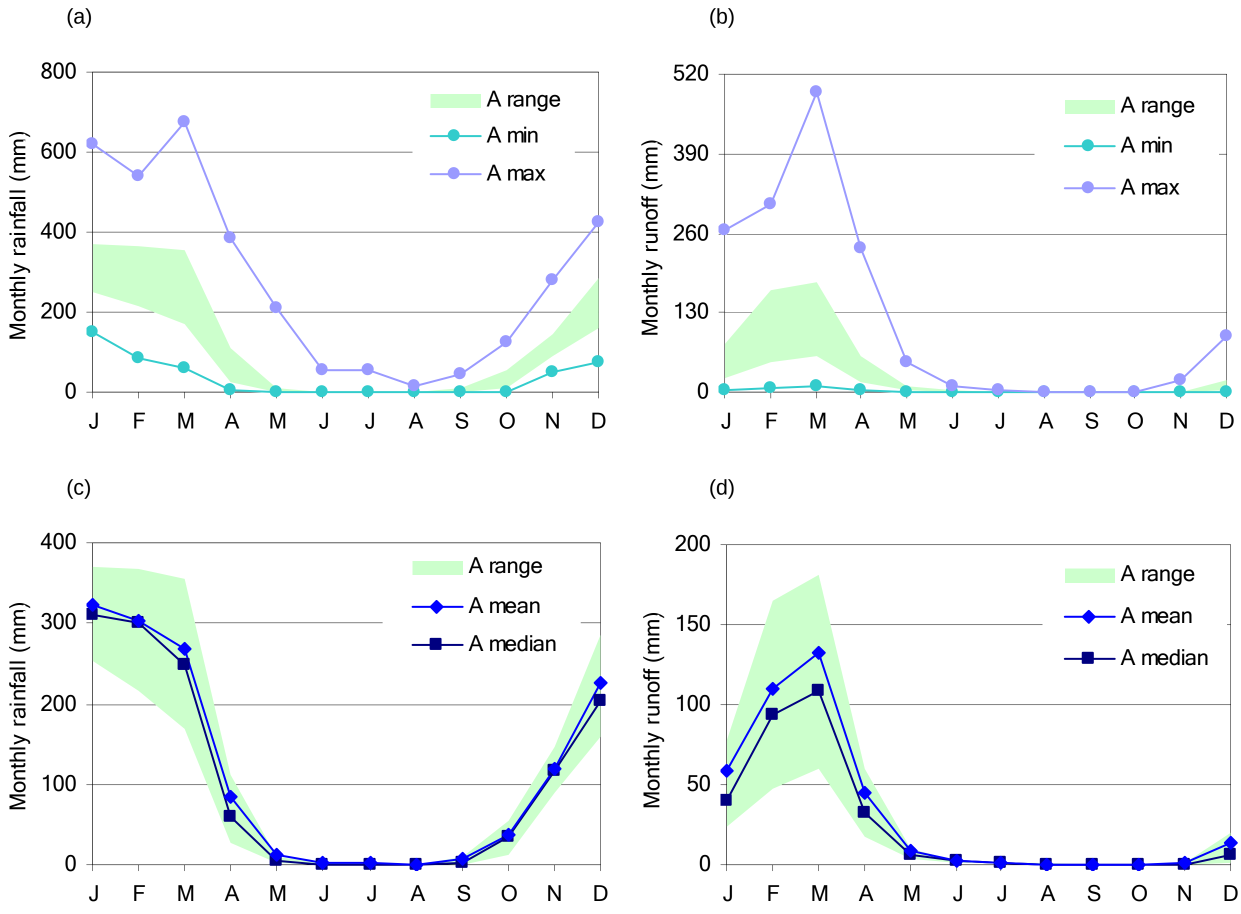


Figure VD-46. Minimum, maximum and A range monthly (a) rainfall and (b) modelled runoff; and mean, median and A range monthly (c) rainfall and (d) modelled runoff in the Van Diemen region under Scenario A (A range is the 25th to 75th percentile monthly rainfall or runoff)

VD-3.5.4 Under recent climate

The mean annual rainfall and runoff under Scenario B (1996 to 2007) are 16 percent and 44 percent higher respectively than the historical (1930 to 2007) mean values. The spatial distribution of rainfall and runoff across the Van Diemen region under Scenario B is shown in Figure VD-47.

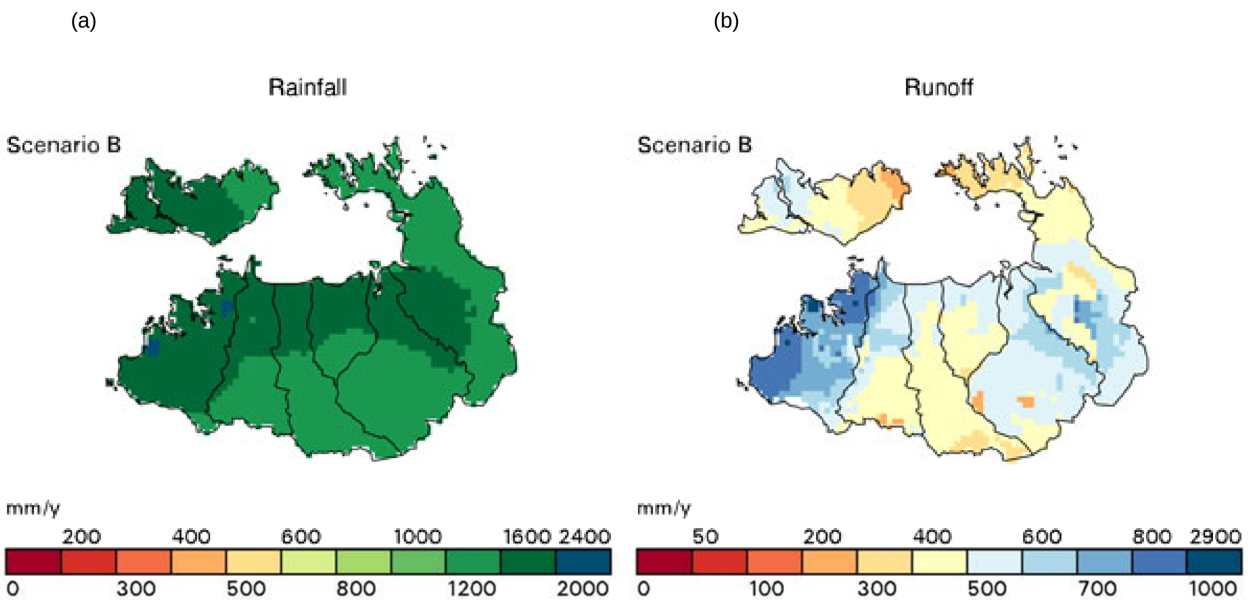


Figure VD-47. Spatial distribution of mean annual (a) rainfall and (b) modelled runoff across the Van Diemen region under Scenario B

VD-3.5.5 Under future climate

Figure VD-48 shows the percentage change in the mean annual runoff averaged over the Van Diemen region under Scenario C relative to Scenario A for the 45 scenarios (15 global climate models (GCMs) for each of the high, medium and low global warming scenarios). The percentage change in the mean annual runoff and rainfall from the corresponding GCMs are also tabulated in Table VD-8.

The figure and table indicate that the potential impact of climate change on runoff can be very significant. Although there is considerable uncertainty in the estimates, the results indicate that runoff in ~2030 in the Van Diemen region is as likely to increase as decrease. Rainfall-runoff modelling with climate change projections from seven of the GCMs shows a reduction in mean annual runoff, while rainfall-runoff modelling with climate change projections from eight of the GCMs shows an increase in mean annual runoff. The wide range of mean annual runoff values shown in Figure VD-48 and Table VD-8 is primarily due to the wide range of future projections of rainfall by the 15 GCMs.

Because of the large variation between GCM simulations and the method used to obtain the climate change scenarios, the biggest increase and biggest decrease in runoff come from the high global warming scenario. For the high global warming scenario, rainfall-runoff modelling with climate change projections from four of the GCMs indicates a decrease in mean annual runoff greater than 10 percent while rainfall-runoff modelling with climate change projections from three of the GCMs indicates an increase in mean annual runoff greater than 10 percent.

In subsequent reporting here and in other sections, only results from an extreme 'wet', 'mid' and extreme 'dry' variant are shown (referred to as scenarios Cwet, Cmid and Cdry). Under Scenario Cwet, results from the second highest increase in mean annual runoff from the high global warming scenario are used. Under Scenario Cdry, results from the second highest reduction in mean annual runoff from the high global warming scenario are used. Under Scenario Cmid, the median mean annual runoff results from the medium global warming scenario are used. These are shown in bold in Table VD-8.

Under scenarios Cwet, Cmid and Cdry, mean annual runoff increases by 24 and 1 percent and decreases by 25 percent percent relative to Scenario A. By comparison, the range based on the low global warming scenario is a 12 to -15 percent change in mean annual runoff. Figure VD-49 shows the mean annual runoff across the Van Diemen region under scenarios A and C. The linear discontinuities that are evident in Figure VD-49 are due to GCM grid cell boundaries.

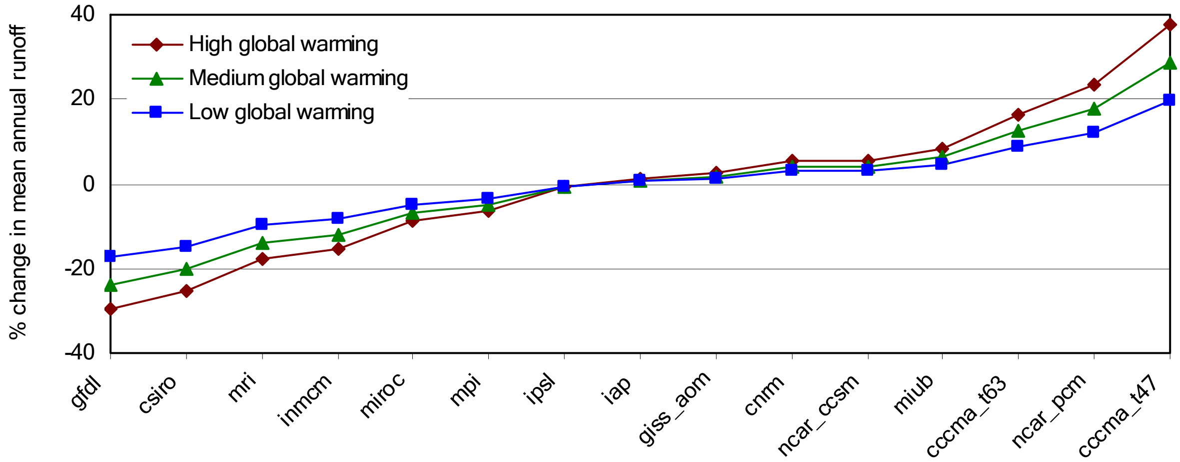


Figure VD-48. Percentage change in mean annual modelled runoff under the 45 Scenario C simulations (15 global climate models and three global warming scenarios) relative to Scenario A

Table VD-8. Summary results under the 45 Scenario C simulations for the modelled subcatchments in the Van Diemen region (numbers show percentage change in mean annual rainfall and modelled runoff under Scenario C relative to Scenario A)

High global warming			Medium global warming			Low global warming		
GCM	Rainfall	Runoff	GCM	Rainfall	Runoff	GCM	Rainfall	Runoff
gfdl	-15%	-30%	gfdl	-12%	-24%	gfdl	-8%	-17%
csiro	**-12%**	**-25%**	csiro	-9%	-20%	csiro	-6%	-15%
mri	-7%	-18%	mri	-5%	-14%	mri	-4%	-10%
inmcm	-4%	-15%	inmcm	-3%	-12%	inmcm	-2%	-8%
miroc	-2%	-9%	miroc	-1%	-7%	miroc	-1%	-5%
mpi	-1%	-6%	mpi	-1%	-5%	mpi	0%	-3%
ipsl	0%	-1%	ipsl	0%	-1%	ipsl	0%	-1%
iap	0%	1%	**iap**	**0%**	**1%**	iap	0%	1%
giss_aom	3%	2%	giss_aom	2%	2%	giss_aom	2%	1%
cnrm	3%	5%	cnrm	3%	4%	cnrm	2%	3%
ncar_ccsm	4%	5%	ncar_ccsm	3%	4%	ncar_ccsm	2%	3%
miub	3%	8%	miub	2%	6%	miub	2%	5%
cccma_t63	5%	16%	cccma_t63	4%	12%	cccma_t63	3%	9%
ncar_pcm	**10%**	**24%**	ncar_pcm	8%	18%	ncar_pcm	6%	12%
cccma_t47	11%	38%	cccma_t47	9%	29%	cccma_t47	6%	20%

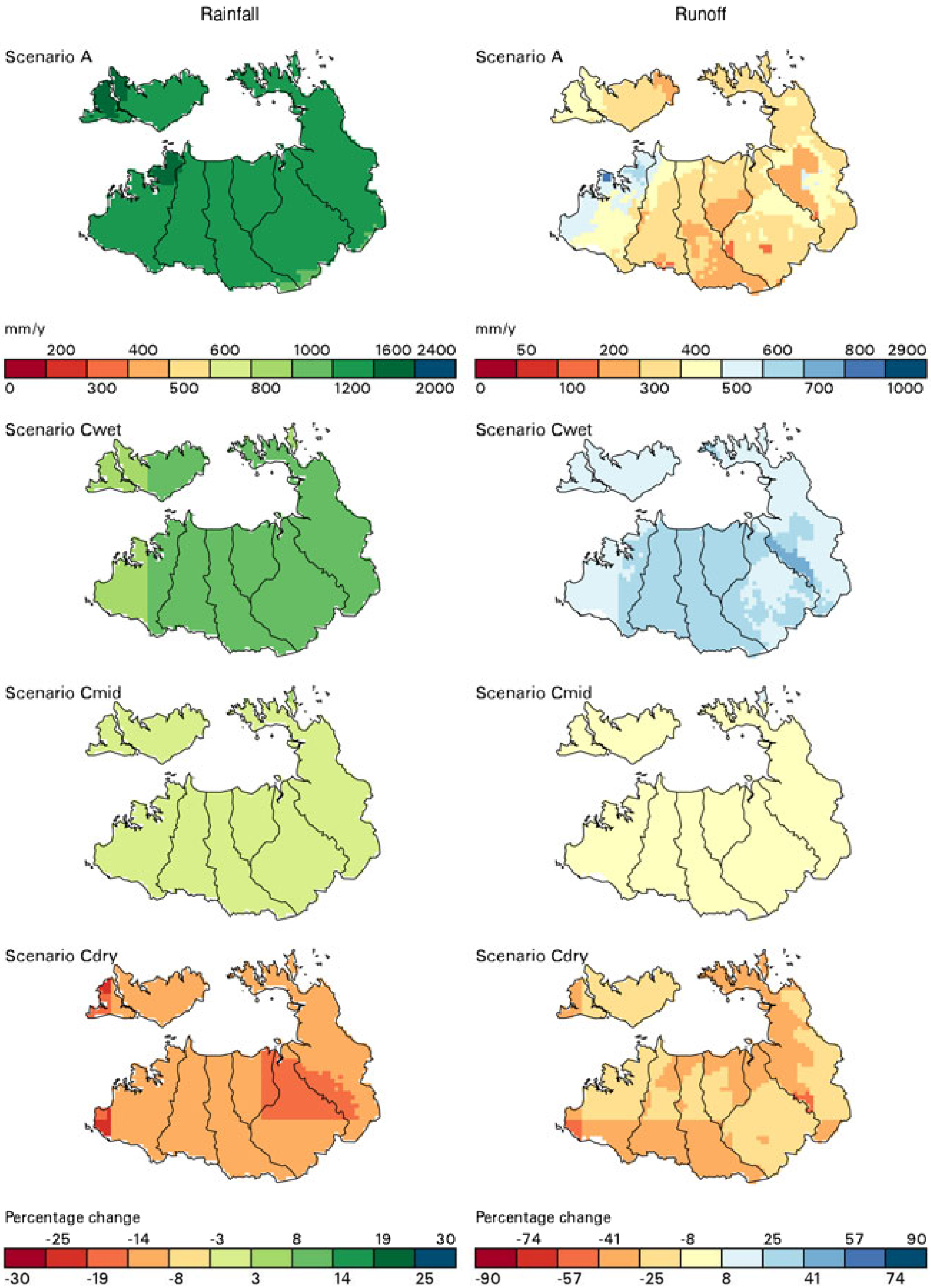


Figure VD-49. Spatial distribution of mean annual rainfall and modelled runoff across the Van Diemen region under Scenario A and under Scenario C relative to Scenario A

VD-3.5.6 Summary results for all scenarios

Table VD-9 shows the mean annual rainfall, runoff and actual evapotranspiration under Scenario A averaged over the Van Diemen region, and the percentage changes in the rainfall, runoff and actual evapotranspiration under scenarios B and C relative to Scenario A. The Cwet, Cmid and Cdry results are based on the mean annual runoff, and the rainfall changes shown in Table VD-9 are the changes in the mean annual value of the rainfall series used to obtain the runoff under scenarios Cwet, Cmid and Cdry. The changes in mean annual rainfall do not necessarily translate directly to the changes in mean annual runoff because of changes in seasonal and daily rainfall distributions and the relationship between rainfall and runoff is non-linear. The latter factor usually results in small changes in rainfall to be amplified in runoff (Table VD-8).

Figure VD-50 shows the mean monthly rainfall and runoff under scenarios A and C averaged over 1930 to 2007 years for the region. Figure VD-51 shows the daily rainfall and flow exceedance curves under scenarios A and C averaged over the region. In Figure VD-50 and Figure VD-51 Cwet, Cmid and Cdry are selected on a month-by-month basis, while in Figure VD-51 Cwet, Cmid and Cdry are selected for every day of the daily flow exceedance curve.

Table VD-9. Water balance over the modelled subcatchments of the Van Diemen region under Scenario A and under scenarios B and C relative to Scenario A

Scenario	Rainfall	Runoff	Evapotranspiration
	mm		
A	1386	375	1012
	percent change from Scenario A		
B	16%	44%	5%
Cdry	-12%	-25%	-7%
Cmid	0%	1%	0%
Cwet	10%	24%	5%

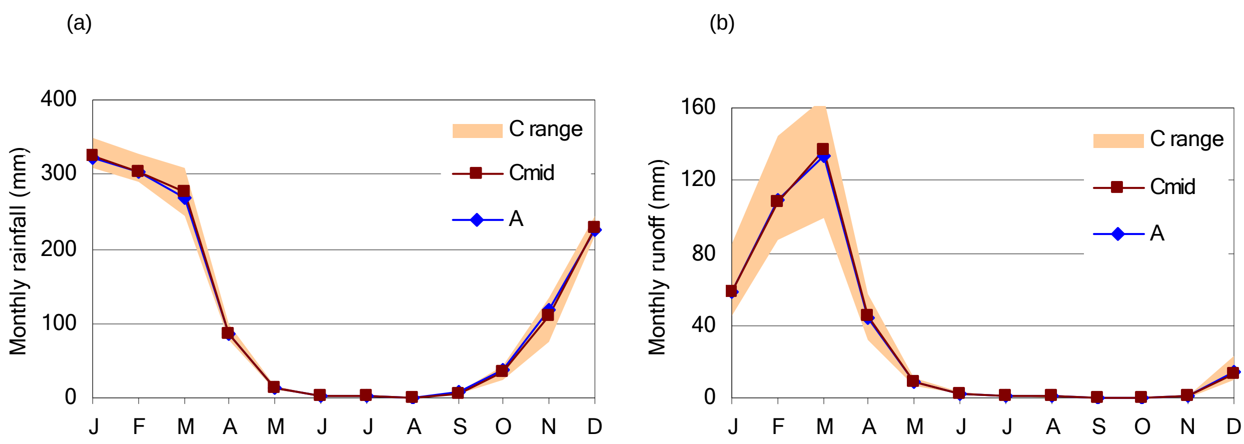


Figure VD-50. Mean monthly (a) rainfall and (b) modelled runoff in the Van Diemen region under scenarios A and C

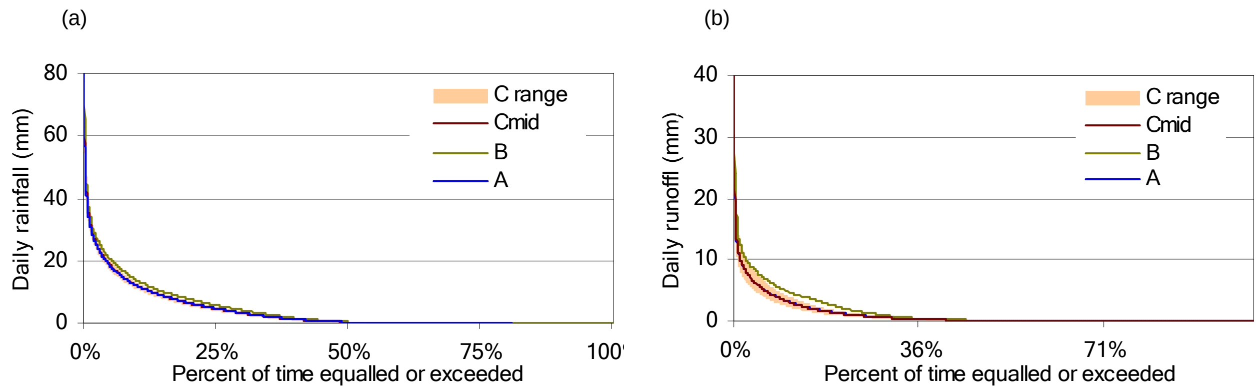


Figure VD-51. Daily flow exceedance curves for (a) rainfall and (b) modelled runoff in the Van Diemen region under scenarios A, B and C

VD-3.5.7 Confidence levels

The rainfall-runoff model verification analysis with data from 123 catchments from across all of northern Australia indicates that the mean annual runoff for ungauged catchments are under estimated or over estimated, when using optimised parameter values from a nearby catchment, by less than 20 percent in 40 percent of catchments and by less than 50 percent in 80 percent of the catchments.

In the Van Diemen region the level of confidence of the wet season or mid to high runoff estimates is relatively high due to the relatively large number of suitable streamflow gauging stations. The estimates in the mid to upper reaches of many of the catchments in the Van Diemen region are better than the lower coastal reaches where there are fewer gauging stations (Figure VD-52). Runoff estimates are also better closer to Darwin where there are more suitable gauging stations than in the eastern part of the region. In those areas with a greater density of gauging stations there also appears to be better predictions of streamflow in neighbouring ungauged catchments. Diagrams in Petheram et al. (2009) illustrate which calibrated rainfall-runoff model parameter sets are used to model streamflow in the ungauged subcatchments in the Van Diemen region.

However, variable geology can confound rainfall-runoff modelling simulations, particularly low or dry season flows. In the Van Diemen region dolomitic limestone and Cretaceous sandstone aquifers can be problematic for rainfall-runoff modelling, due to variable connections between the surface and groundwater systems and water bypassing gauging stations, thus violating model assumptions (unless the modifications to the model structure have been made). There was little information to suggest at which stations this may occur.

Figure VD-52 shows the level of confidence in the modelling of the mid to high runoff events (i.e. peak flows) and dry season runoff (respectively) for the subcatchments of the Van Diemen region. It should be noted that these maps of level of confidence are not statistical confidence levels and are intended to only convey a broad reliability of prediction. The level of confidence in streamflow predictions will vary slightly from the level of confidence in runoff predictions shown below and as discussed in Section 2.2.6 of the division-level Chapter 2.

There is a high degree of confidence that dry season runoff in the Van Diemen region is low because it is known that rainfall and baseflow are low during the dry season. The map of level of confidence for dry season flow shown in Figure VD-52 provides a relative indication of how well dry season metrics, such as cease-to-flow, are simulated.

In summary the long-term average monthly and annual results for the Van Diemen region are considered reasonable. As shown in Figure VD-52, in many areas of the Van Diemen region localised studies will require more detailed analysis than undertaken and reported here and would most likely require the site to be visited and additional field measurements made.

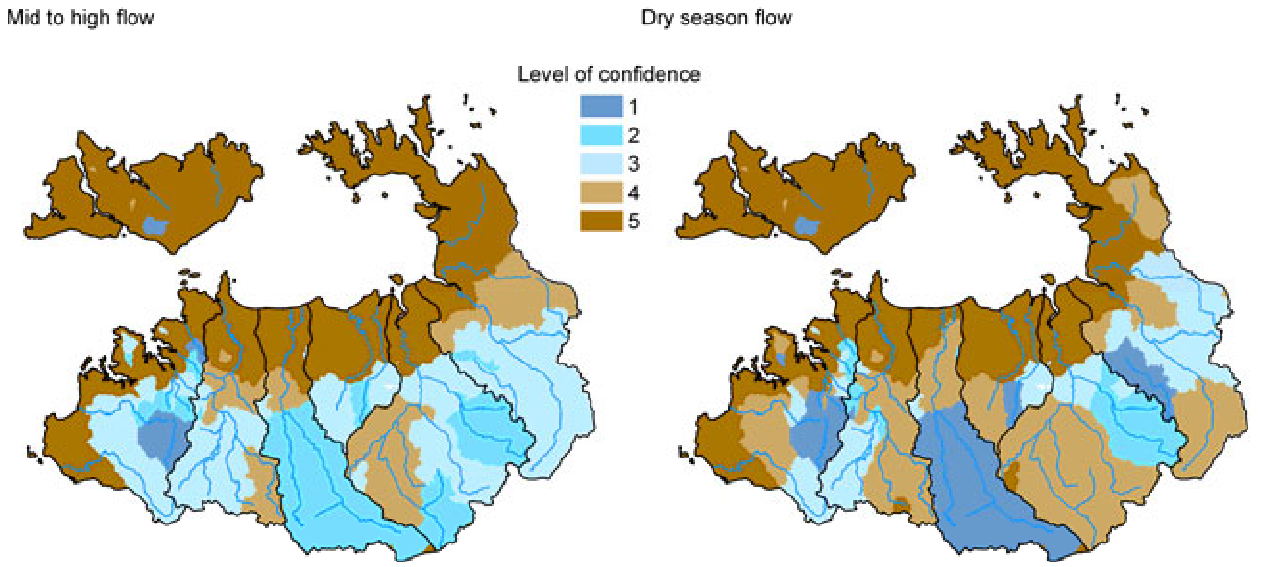


Figure VD-52. Level of confidence of the modelling of runoff for (a) mid- to high events and (b) monthly dry season flow events for the modelling subcatchments of the Van Diemen region. 1 is the highest level of confidence, 5 is the lowest

VD-3.6 River system water balance

The Van Diemen region is comprised of seven AWRC river basins and has an area of 67,586 km^2. Under the historical climate the mean annual runoff across the region is 375 mm (Section VD-3.5.3), which equates to a mean annual streamflow across the region of 25,345 GL.

No information on infrastructure, water demand and water management and sharing rules or future development were available for most of the Van Diemen region. The exception is Darwin River Dam, which is described in this section by a simple one node model.

For the rest of the region streamflow time series have been generated for each streamflow reporting node (SRN) based on the upstream grid cell rainfall-runoff simulations, as described in Section 2.2.5 of the division-level Chapter 2. The locations of these nodes are shown Figure VD-53. Summary streamflow statistics for each SRN are reported in Petheram et al. (2009). In addition to the streamflow time series generated by the rainfall-runoff model ensemble, a range of hydrological metrics computed using regression analysis are also available for each SRN (as described in Section 2.2.7 of the division-level Chapter 2). The complete set of results for the multiple regression analysis are reported in SKM (2009). The merit of each approach is discussed in Section 2.2.7 of the division-level Chapter 2.

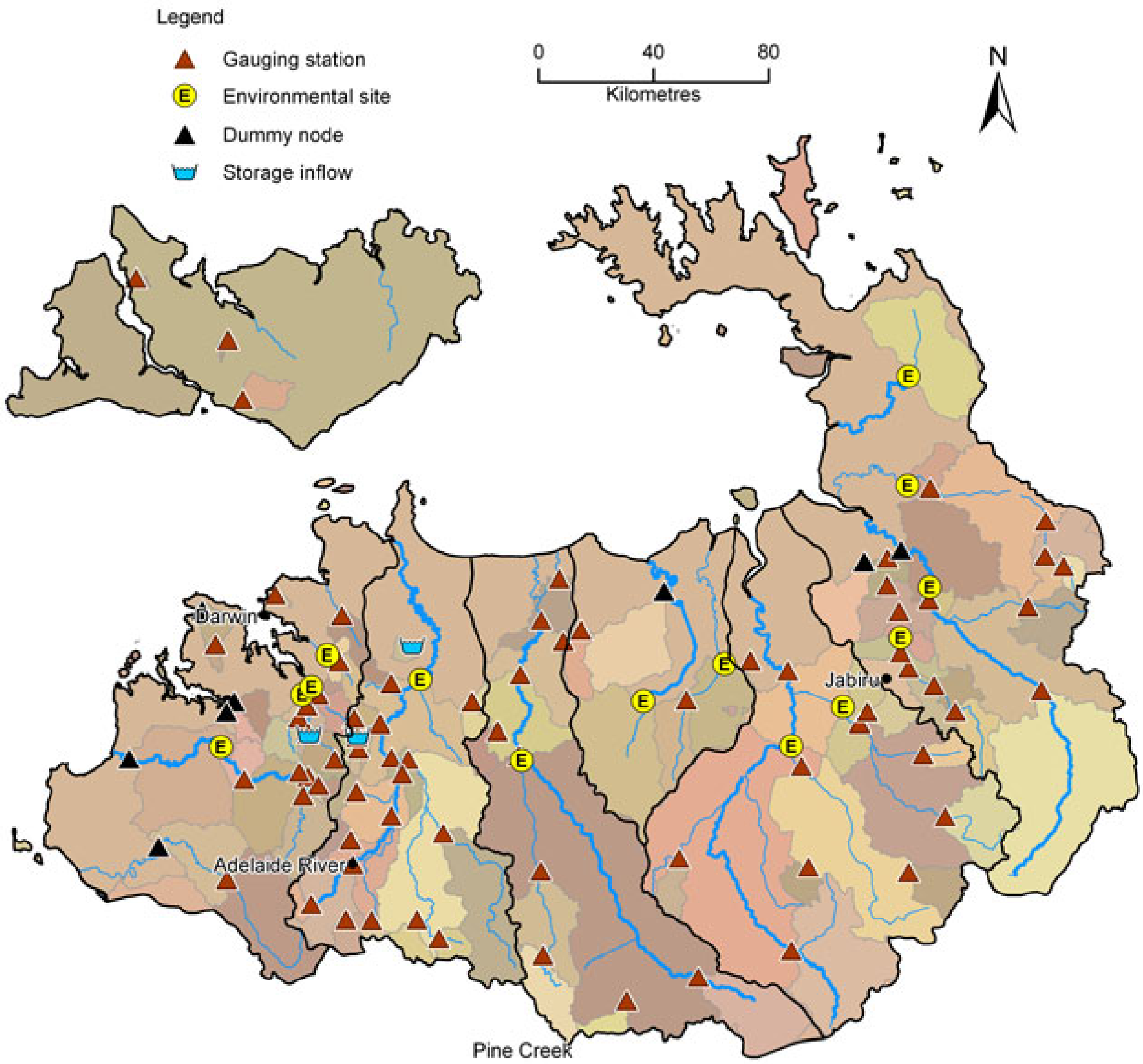


Figure VD-53. Location of streamflow reporting nodes (gauging stations, environmental sites, dummy nodes and storage inflows) in the Van Diemen region

Darwin River Dam catchment

General information about river modelling methods is presented at the division-level in Chapter 2. In that chapter, scenarios are defined in Section 2.1 and river modelling methods which apply to all regions are described in Section 2.2. The following section summarises this generic river modelling approach as applied to the Van Diemen region. The river modelling results for the Van Diemen river model are reported using a range of metrics, which were consistently applied across all regions. The use of a common set of metrics across the entire project area enables comparisons between regions.

In this section where annual data are reported, years are represented by numbers 1 through 77. Consistently throughout the report, annual data are based on the water year (1 September to 31 August) and the dry season is defined as 1 May to 31 October. Scenarios Cwet, Cmid and Cdry are selected on the basis of the ranked mean annual rainfall for the modelled subcatchments in VD-3.5.5.

A model of the Darwin River Dam was set up as a daily water balance in Microsoft Excel (SKM 2005). The model was developed in 2005 and calibrated to historical climate, storage levels, release and extraction information. The model was originally developed for a simulation period from 1 July 1900 to 28 February 2003. The model period was extended as part of the Northern Australia Sustainable Yields Project to include data up to 31 August 2007. The model simulation period was 1 September 2007 to 31 August 2084 for all scenarios.

The Darwin River Dam model has been used in the Northern Australia Sustainable Yields Project to assess thirteen scenarios:

- Scenario A – historical climate sequence and current development
  This scenario incorporates the effects of current land use and uses a constant demand where the daily pattern is based on historical extractions. There are no restriction rules for the Darwin River Dam. Modelling commences on the 1 September 2007 and streamflow metrics are produced by modelling the 77-year historical climate sequence between 1 September 1930 and 31 August 2007. This scenario is used as a baseline for comparison with all other scenarios.
- Scenario AN – historical climate sequence and without-development
  Current levels of development such as public storages and demands are not considered when determining without-development conditions. Inflows were not modified for groundwater extraction, major land use change or farm dam development because the impact of these factors on catchment yields in this region is considered to be negligible. Hence this scenario used the same inflow sequence as Scenario A.
- Scenario BN – recent climate and without-development
  This scenario assumes without-development conditions (as per Scenario AN) and uses seven consecutive 11-year climate sequences between 1 September 1996 and 31 August 2007 to generate 77-year time series for runoff and climate. See Section 2.1.2 of the division-level Chapter 2 for more detail on Scenario B.
- Scenario CN – future climate and without-development
  Scenarios CNwet, CNmid and CNdry represent a range of future climate conditions assuming without-development conditions (as per Scenario AN).
- Scenario B – recent climate and current development
  This scenario incorporates the effects of current land use and constant demand pattern as per Scenario A and uses seven consecutive 11-year climate sequences between 1 September 1996 and 31 August 2007 to generate 77-year time series for runoff and climate. See Section 2.1.2 of the division-level Chapter 2 for more detail on Scenario B.
- Scenario C – future climate and current development
  Scenarios Cwet, Cmid and Cdry represent a range of future climate conditions assuming current levels of development (i.e. as per Scenario A). Rainfall-runoff results from Section VD-3.5 were used to scale the inflows to the Darwin River Dam using the approach outlined in Section 2.2.4 of the division-level Chapter 2.
- Scenario D – future climate and 2030 development
  Scenarios Dwet, Dmid and Ddry represent a range of future climate conditions for a 2030 development scenario. Under Scenario D the daily demand pattern used under Scenario A was increased proportionally so that the

total annual demand is equal to 50,000 ML. Projections of commercial forestry and farm dams for 2030 are negligible and hence no adjustments were made to the Scenario C runoff time series.

The Northern Australia Sustainable Yields Project scenario simulations use comparable but different initial conditions and a different simulation period than what was used by SKM (2005). Results from these scenarios are not intended to be directly comparable with the SKM (2005) simulations.

The changes in inflows between scenarios reported in this chapter differ from the changes in runoff reported in Section VD-3.5. These differences are due to differences in the methods by which the GCMs were ranked and differences in areas that are considered to contribute runoff to the surface water model. In Section VD-3.5 the entire region is considered while a subset of this area is considered here. The scenarios presented in this project may not eventuate but they encompass consequences that might arise if no management changes are made. Consequently results from this assessment are designed to highlight pressure points in the system, both now and in the future. This assessment does not elaborate on what management actions might be taken to address any of these pressure points. Where management changes to mitigate the effects of climate change have recently been implemented, the impacts of the changes predicted in this section may be an overestimate.

VD-3.6.1 River model configuration

The Darwin River Dam was commissioned in 1972 and supplies approximately 90 percent of Darwin's water supply. The Darwin River Dam model consists of a single node to represent the dam (Table VD-10) and has one diversion (Table VD-11). It is shown by the left-most storage inflow symbol in Figure VD-53. Table VD-10 presents a summary of average annual values for the Darwin River Dam under Scenario A. Average annual releases are the sum of the controlled releases and extractions from the dam. The degree of regulation metric is defined in this project to be the sum of the net evaporation and controlled releases from the dam divided by the total inflows. Controlled releases include water for irrigation demands, for hydropower generation and for environmental water provisions, but exclude spills. The degree of regulation for the Darwin River Dam is 0.64, which is high.

Table VD-10. Storages in the Darwin River Dam system model

	Active storage	Average annual Inflow	Average annual release	Average annual diversion	Average annual net evaporation	Degree of regulation
	GL	GL/y				
Major storages						
Darwin River Dam	204.8	136.0	49.1	49.0	37.8	0.64
Region total	**204.8**	**136.0**	**49.1**	**49.0**	**37.8**	**0.64**

Table VD-11. Modelled water use configuration in the Darwin River Dam system model

Water users	Number of nodes	Licence or long term diversions	Model notes
		GL/y	
Town Water Supply	1	49.1	Daily demand pattern
Sub-total	**1**	**49.1**	

Model setup

A summary of the model details are provided in Table VD-12. The Darwin River Dam spillway is currently being upgraded and raised by 1.3 m, which increases the dam full supply from to 265 GL to 324.8 GL. All scenarios have been considered with this dam configuration.

Table VD-12. Darwin River Dam system model setup information

Model setup information		Start date	End date
Darwin River Dam	Excel Spreadsheet	1/09/1930	31/08/2007
Connection			
Baseline models			
Warm up period		1/08/2007	31/08/2084
Connection			
Modifications			
Data	Data extension from 2003 to 2007		
Inflows	No adjustment		
Initial storage volume	281.8 GL Modelled level from the 1 August 2007		
Storage	Dam volume increased from 274.4 to 324.8 GL		

VD-3.6.2 River system water balance

The mass balance table (Table VD-13) shows the net fluxes for the Darwin River Dam system. The fluxes under Scenario A are displayed in GL/year and all of the other scenarios are presented as a percentage change from Scenario A.

Diversions are for the town water supply of Darwin and are discussed further in Section VD-3.6.5. The end-of-system flows represent the releases and spills made from the dam.

The large increase in inflows under Scenario B is due to the statistically significant increase in rainfall under Scenario B relative to Scenario A. This is shown in Figure VD-30.

Net evaporation from the Darwin River Dam is a large proportion of the average annual inflow to the lake (approximately 28 percent) and controlled releases (approximately 77 percent).

Table VD-13. River system model mean annual water balance under Scenario A and under scenarios B, C and D relative to Scenario A

	A	B	Cwet	Cmid	Cdry	Dwet	Dmid	Ddry
	GL/y							
Storage volume								
Change over period	0.02	0.02	0.00	0.04	-0.04	-0.01	0.03	-0.04
	GL/y	percent change from Scenario A						
Inflows								
Subcatchments								
Gauged	136.0	62%	32%	1%	-21%	32%	1%	-21%
Sub-total	**136.0**	**62%**	**32%**	**1%**	**-21%**	**32%**	**1%**	**-21%**
Diversions								
Town Water Supply								
High Security	49.0	0%	0%	0%	-5%	2%	2%	-4%
Sub-total	**49.0**	**0%**	**0%**	**0%**	**-5%**	**2%**	**2%**	**-4%**
Outflows								
End of system flow	49.1	192%	100%	0%	-64%	98%	-1%	-65%
Sub-total	**49.1**	**192%**	**100%**	**0%**	**-64%**	**98%**	**-1%**	**-65%**
Net evaporation								
Darwin River Dam	37.8	-26%	-16%	5%	14%	-16%	4%	14%
Sub-total	**37.8**	**-26%**	**-16%**	**5%**	**14%**	**-16%**	**4%**	**14%**

VD-3.6.3 Inflows and water availability

In this section water availability is simply taken to be the inflows to the Darwin River Dam. When computing water availability for this project ecological, social, cultural and economic values are not considered.

Inflows to the model have been calculated from calibration to historical climate, storage levels, release and extraction information. The average annual inflow and mean annual water availability for the Darwin River Dam is 136 GL/year. Table VD-14 shows the annual water availability under Scenario AN in GL/year and the relative change in the water availability under each of the other scenarios.

Table VD-14. Annual water availability at the Darwin River Dam under Scenario AN and under scenarios BN and CN relative to Scenario AN

Catchment	AN	BN	CNwet	CNmid	CNdry
	GL/y	percent change from Scenario A			
Darwin River Dam	136.0	62%	32%	1%	-21%

A time series of the total annual water availability for Darwin River Dam is presented in Figure VD-54(a). The lowest water availability was 44 GL in Year 22 (red bar) and the highest annual water availability was 322 GL in Year 67 (black bar). Figure VD-54(b) shows the difference in the annual surface water availability under scenarios AN and CN.

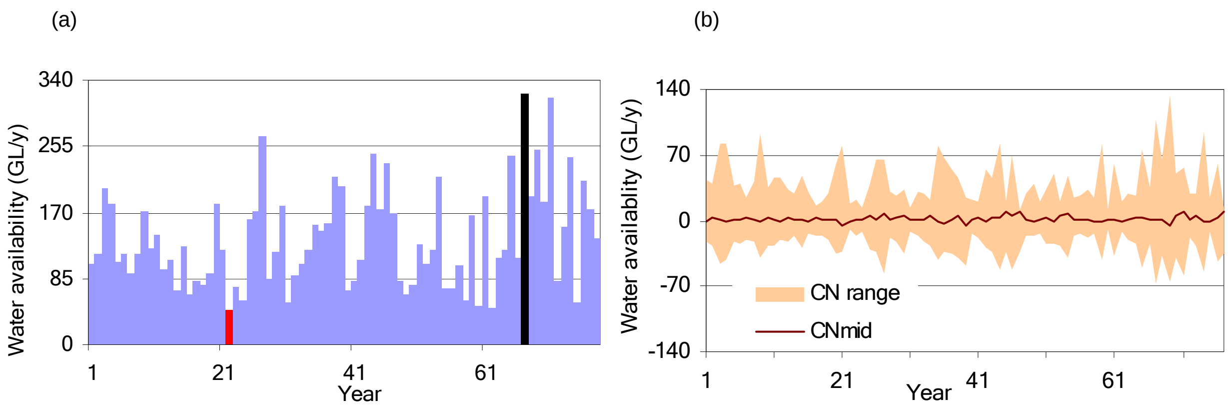


Figure VD-54. Surface water availability in the Darwin River Dam system under (a) Scenario AN; and (b) change in availability under Scenario CN relative to Scenario AN

VD-3.6.4 Storage behaviour

The modelled behaviour of major public storages gives an indication of the level of regulation of a system and how reliable the storage is during extended periods of low or no inflows. Table VD-15 presents metrics for the lowest predicted storage level for each of the scenarios. The average and maximum number of years between spills is also presented. A spill commences when the storage exceeds the full supply volume and ends when the storage falls below 90 percent of the full supply volume. The end condition is applied to remove the periods when the dam is close to full and oscillates between spilling and just below full which distorts the analysis. The period between spills is the length of time from when one spill ends (i.e. the storage falls below 90 percent of the fully supply volume) until the next spill commences (i.e. when the storage exceeds the full supply volume).

Table VD-15. Details of dam behaviour

	A	B	Cwet	Cmid	Cdry	Dwet	Dmid	Ddry
Darwin River Dam								
Minimum storage volume (GL)	122	200	173	120	100	171	119	99
Number of times storages at minimum	1	1	1	1	1	1	1	1
Minimum storage date	27 Nov Year 24	26 Nov Year 22	20 Oct Year 24	22 Nov Year 24	27 Nov Year 24	20 Oct Year 24	11 Nov Year 24	27 Nov Year 24
Average years between spills	1.4	1.1	0.9	1.4	3.5	0.9	1.5	3.9
Maximum years between spills	6.6	3.7	3.7	6.6	22.7	3.7	6.7	22.7

The time series of the storage behaviour for the Darwin River Dam for the period including the minimum storage date are presented in Figure VD-55.

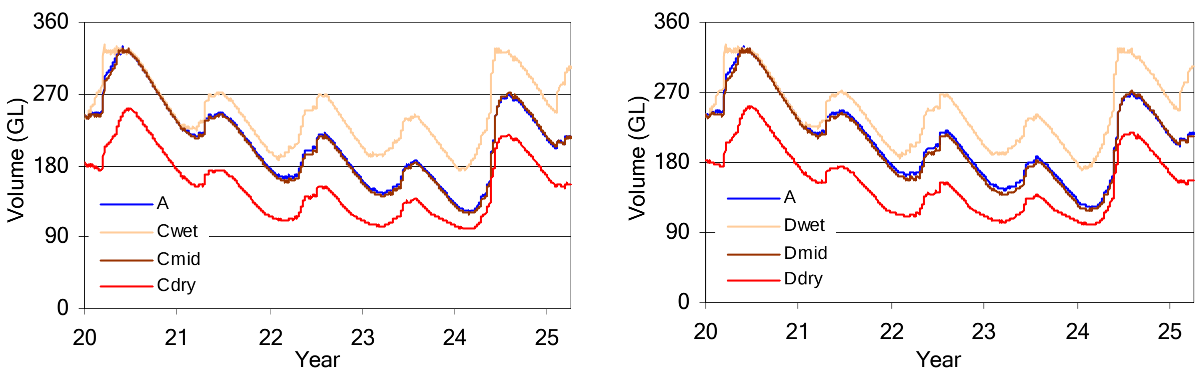


Figure VD-55. Storage behaviour over the maximum days between spills for the Darwin River Dam under scenarios A, C and D

VD-3.6.5 Consumptive water use

Diversions

Table VD-16 presents the total average annual diversion for the Darwin River Dam under Scenario A and under each of the other scenarios relative to Scenario A. Because there are no restrictions in place for the Darwin River Dam, diversions are met unless there is no water accessible (i.e. dam volume is below active storage volume). This situation only occurs under scenarios Cdry and Ddry. Mean annual diversions drop less under Scenario Ddry than Scenario Cdry because the demand is 2 percent higher under Scenario D. This means that when water is not accessible under the extreme dry climate, the percentage change from Scenario A is less under Scenario D because of the larger demand when water is accessible.

Table VD-16. Total mean annual diversions in the Darwin River Dam system under Scenario A and under scenarios B, C and D relative to Scenario A

	A	B	Cwet	Cmid	Cdry	Dwet	Dmid	Ddry
Reach	GL/y	percent change from Scenario A						
Darwin River Dam	49.0	0%	0%	0%	-5%	2%	2%	-4%
Total	**49.0**	**0%**	**0%**	**0%**	**-5%**	**2%**	**2%**	**-4%**

Level of use

The level of use for the region is indicated by the ratio of total use to total surface water availability. Net evaporation is not included in the computation. Table VD-17 shows the level of use of indicators for each of these scenarios. The level of use for water diverted from the Darwin River Dam is high for current irrigation allocations at 36 percent under Scenario A. Net evaporation accounts for the difference between the degree of regulation of the Darwin River Dam and the level of use.

Table VD-17. Relative level of surface water use under scenarios A, B and C

	A	B	Cwet	Cmid	Cdry	Dwet	Dmid	Ddry
	GL/y							
Total surface water availability	136	220	179	138	107	179	138	107
Streamflow use	49	49	49	49	46	50	50	47
Sub-total	**49**	**49**	**49**	**49**	**46**	**50**	**50**	**47**
	percent							
Relative level of use	36%	22%	27%	36%	43%	28%	36%	44%

Use during dry periods

Table VD-18 shows the average annual diversions as well as the annual diversions for the lowest 1-, 3- and 5-year periods under Scenario A and the percentage change from Scenario A under each of the other scenarios. These figures indicate the impact on water use during dry periods. Because a constant demand pattern is used by the model and there are no restrictions rules in place for the Darwin River Dam, diversions do not change unless water is not accessible. The results in Table VD-18 indicate the relative impact on surface water use during dry periods is greatest for a 1-year period.

Table VD-18. Indicators of surface water diversions in the Darwin River Dam during dry periods under Scenario A and under scenarios B, C and D relative to Scenario A

Annual diversion	A	B	Cwet	Cmid	Cdry	Dwet	Dmid	Ddry
	GL/y	percent change from Scenario A						
Lowest 1-year period	49.0	0%	0%	-3%	-69%	2%	-6%	-69%
Lowest 3-year period	49.0	0%	0%	-1%	-51%	2%	-1%	-52%
Lowest 5-year period	49.0	0%	0%	-1%	-31%	2%	0%	-31%
Average	49.0	0%	0%	0%	-5%	2%	2%	-4%

Reliability

The average reliability of the water products is indicated by the ratio of the total net diversions to the total long-term average diversion limit or equivalent benchmark. Table VD-19 is the average reliability percentage under Scenario A and the relative change for each of the other scenarios.

Table VD-19. Average reliability of water products in the Darwin River Dam system under Scenario A and under scenarios B,C and D relative to Scenario A

		A	B	Cwet	Cmid	Cdry	Dwet	Dmid	Ddry
	Licence volume or long-term diversion limit	Average annual diversions	percent change from Scenario A						
	GL/y								
Licensed private usage									
Town water supply									
High security	49.1	49.0	0%	0%	0%	-5%	0%	0%	-6%

VD-3.6.6 River flow behaviour

The Darwin River Dam model is a single node. Consequently releases and spills from the dam are not routed downstream.

VD-3.6.7 Share of water resource

Non-diverted water shares

There are several ways of considering the relative level of the impact on non-diverted water and diversions. Table VD-20 presents two indicators of the relative impact on non-diverted water.

- the average annual non-diverted water as a proportion of the maximum mainstream average annual flow
- the average annual non-diverted water as a proportion of Scenario A non-diverted water.

Non-diverted water is defined as the total available water minus the sum of the diverted water and the net evaporation.

Table VD-20. Relative level of non-diverted water in the Darwin River Dam System under scenarios A, B, C and D

	A	B	Cwet	Cmid	Cdry	Dwet	Dmid	Ddry
Non-diverted water as a percentage of total available water	36%	65%	55%	36%	16%	54%	35%	16%
Non-diverted share relative to Scenario A non-diverted share	100%	292%	200%	100%	36%	198%	99%	35%

Combined water shares

Figure VD-56 combines the results from the water availability, use and non-diverted water and the average annual water balance into a bar chart. The size of the bars indicates the total water availability and the sub-division of the bars indicates the net evaporation, diverted, and non-diverted water fractions.

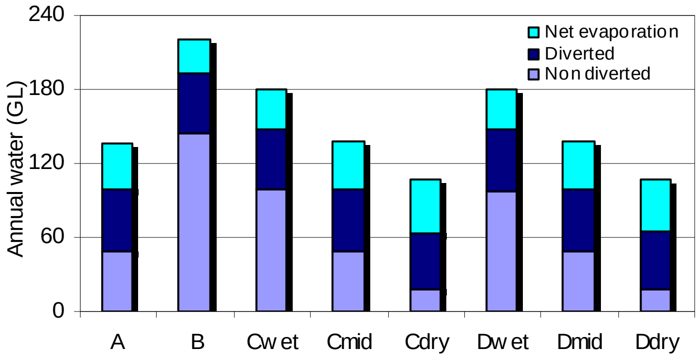


Figure VD-56. Comparison of diverted and non-diverted shares of water in the Darwin River Dam system under scenarios A, B, C and D

VD-3.7 Changes to flow regimes at environmental assets

Section 1.3 of the division-level Chapter 1 describes how environmental assets were shortlisted for assessment by this project. Six environmental assets have been shortlisted in the Van Diemen region: Murgnella-Cooper Floodplain System, Kakadu National Park, Adelaide River Floodplain System, Finniss Floodplain and Fog Bay Systems, Mary Floodplain System, and Port Darwin. The locations of these assets are shown in Figure VD-1 and the assets are characterised in Chapter VD-2.

This section presents the assessment of these shortlisted assets and reports metrics for those assets which have sufficient confidence in the modelled streamflow to enable analysis. Confidence in results for low flows and high flows was calculated separately on a scale of 1 to 5, with 1 indicating results with the highest confidence (as described in Section 2.2.6 of the division-level Chapter 2). Hydrological regime metrics (as defined in Section 2.5 of the division-level Chapter 2) for either low flows or high flows are reported only where confidence levels are 1, 2 or 3. If confidence levels in the low flows or high flows are ranked 4 or 5, results are not reported and are labelled NR (not reported).

Some of the assets in this region have multiple nodes at which streamflow modelling results are available. When reporting hydrological regime metrics for such assets a single node was selected. The selected node was that with the highest streamflow confidence level and the largest proportion of streamflow to the asset. Results for all nodes are presented in McJannet et al. (2009).

In the absence of site-specific metrics for the Van Diemen region a set of standard metrics related to high and low flows have been utilised. However the conversion of these metrics into environmental impacts still requires development of quantitative relationships between flow and ecology.

VD-3.7.1 Standard metrics

Table VD-21. Standard metrics for changes to surface water flow regime at environmental assets in the Van Diemen region

Standard metrics	Units	A	B	Cwet	Cmid	Cdry	Dwet	Dmid	Ddry
			change from Scenario A						
Murgnella-Cooper Floodplain System - Node 2 (confidence level: low flow = 3, high flow = 3)									
Annual flow (mean)	GL	679	+32%	+21%	-1%	-22%	nm	nm	nm
Wet season flow (mean)*	GL	660	+32%	+22%	-1%	-22%	nm	nm	nm
Dry season flow (mean)**	GL	19.1	+34%	+2%	0%	-24%	nm	nm	nm
Low flow threshold (discharge exceeded 90% of the time in Scenario A)	GL/d	0.00307							
Number of days below low flow threshold (mean)	d/y	36.5	-13.8	-12.5	+2.1	+26.1	nm	nm	nm
Number of days of zero flow (mean)	d/y	1.19	+0.1	0	+0	+0.4	nm	nm	nm
High flow threshold (discharge exceeded 5% of the time in Scenario A)	GL/d	9.63							
Number of days above high flow threshold (mean)	d/y	18.3	+8.3	+5.6	-0.8	-5.6	nm	nm	nm
Kakadu National Park - Node 6 (confidence level: low flow = 3, high flow = 3)									
Annual flow (mean)	GL	1700	+53%	+24%	-3%	-23%	nm	nm	nm
Wet season flow (mean)*	GL	1670	+53%	+24%	-3%	-23%	nm	nm	nm
Dry season flow (mean)**	GL	27.8	+49%	-2%	-1%	-25%	nm	nm	nm
Low flow threshold (discharge exceeded 90% of the time in Scenario A)	GL/d	0.000672							
Number of days below low flow threshold (mean)	d/y	36.5	-18.4	-14.1	+2.6	+27.8	nm	nm	nm
Number of days of zero flow (mean)	d/y	2.21	-0.9	-0.9	+0.2	+3	nm	nm	nm
High flow threshold (discharge exceeded 5% of the time in Scenario A)	GL/d	26.3							
Number of days above high flow threshold (mean)	d/y	18.3	+13.6	+6.2	-1	-5.7	nm	nm	nm
Adelaide River Floodplain System - Node 1 (confidence level: low flow = 4, high flow = 2)									
Annual flow (mean)	GL	1490	+48%	+29%	0%	-26%	nm	nm	nm
Wet season flow (mean)*	GL	1450	+47%	+29%	0%	-26%	nm	nm	nm
Dry season flow (mean)**	GL	NR	NR	NR	NR	NR	nm	nm	nm
Low flow threshold (discharge exceeded 90% of the time in Scenario A)	GL/d	NR							
Number of days below low flow threshold (mean)	d/y	NR	NR	NR	NR	NR	nm	nm	nm
Number of days of zero flow (mean)	d/y	NR	NR	NR	NR	NR	nm	nm	nm
High flow threshold (discharge exceeded 5% of the time in Scenario A)	GL/d	23.8							
Number of days above high flow threshold (mean)	d/y	18.3	+13.2	+6	-0.2	-7.1	nm	nm	nm

*Wet season covers the six months from November to April.

**Dry season covers the six months from May to October.

NR – metrics not reported because streamflow confidence level is ranked 4 or 5
nm – not modelled.

Table VD-21 (continued). Standard metrics for changes to surface water flow regime at environmental assets in the Van Diemen region

Standard metrics	Units	A	B	Cwet	Cmid	Cdry	Dwet	Dmid	Ddry
			change from Scenario A						
Finniss Floodplain and Fog Bay Systems - Node 1 (confidence level: low flow = 1, high flow = 1)									
Annual flow (mean)	GL	504	+65%	+26%	+0%	-24%	nm	nm	nm
Wet season flow (mean)*	GL	489	+65%	+27%	+0%	-24%	nm	nm	nm
Dry season flow (mean)**	GL	15	+56%	+17%	0%	-28%	nm	nm	nm
Low flow threshold (discharge exceeded 90% of the time in Scenario A)	GL/d	0.0175							
Number of days below low flow threshold (mean)	d/y	36.5	-33.7	-22.2	+2.3	+39.5	nm	nm	nm
Number of days of zero flow (mean)	d/y	0.792	-0.2	0	0	+0	nm	nm	nm
High flow threshold (discharge exceeded 5% of the time in Scenario A)	GL/d	8.26							
Number of days above high flow threshold (mean)	d/y	18.3	+17.1	+5.3	+0.1	-5.5	nm	nm	nm
Mary Floodplain System - Node 1 (confidence level: low flow = 1, high flow = 2)									
Annual flow (mean)	GL	1550	+50%	+28%	-1%	-29%	nm	nm	nm
Wet season flow (mean)*	GL	1540	+49%	+28%	-1%	-29%	nm	nm	nm
Dry season flow (mean)**	GL	16.9	+125%	+8%	+1%	-37%	nm	nm	nm
Low flow threshold (discharge exceeded 90% of the time in Scenario A)	GL/d	0.00118							
Number of days below low flow threshold (mean)	d/y	36.5	-15	-15.5	+4.7	+29.9	nm	nm	nm
Number of days of zero flow (mean)	d/y	1.42	-0.5	-0.5	+0.4	+6.3	nm	nm	nm
High flow threshold (discharge exceeded 5% of the time in Scenario A)	GL/d	25							
Number of days above high flow threshold (mean)	d/y	18.3	+11.2	+6.2	-0.3	-7	nm	nm	nm
Port Darwin - Node 3 (confidence level: low flow = 2, high flow = 1)									
Annual flow (mean)	GL	87	+50%	+26%	0%	-21%	nm	nm	nm
Wet season flow (mean)*	GL	84.3	+50%	+26%	0%	-20%	nm	nm	nm
Dry season flow (mean)**	GL	2.75	+50%	+9%	+1%	-27%	nm	nm	nm
Low flow threshold (discharge exceeded 90% of the time in Scenario A)	GL/d	0.00051							
Number of days below low flow threshold (mean)	d/y	36.5	-19.8	-20.1	+3.8	+27.1	nm	nm	nm
Number of days of zero flow (mean)	d/y	10.6	-4.8	-8	+2	+15.2	nm	nm	nm
High flow threshold (discharge exceeded 5% of the time in Scenario A)	GL/d	1.32							
Number of days above high flow threshold (mean)	d/y	18.3	+8.4	+4.5	-0.6	-4.8	nm	nm	nm

*Wet season covers the six months from November to April.

**Dry season covers the six months from May to October.

NR – metrics not reported because streamflow confidence level is ranked 4 or 5
nm – not modelled.

Murgnella-Cooper Floodplain System

The surface water flow confidence level for the selected reporting node for the Murgnella-Cooper Floodplain System (see location on Figure VD-9) is considered moderately reliable (3) for both wet season and dry season flows (Table VD-21). Under Scenario A annual flow into this asset is dominated by wet season flows (97 percent) which have been 32 percent higher under Scenario B. Dry season flows have also been 34 percent higher under Scenario B when compared to Scenario A. Annual and seasonal flows do not change much under Scenario Cmid compared to Scenario A, but there is a moderate increase under Scenario Cwet (2 to 22 percent) and a moderate decrease under Scenario Cdry (22 to 24 percent). There are no development Scenarios for the area upstream of this asset.

Compared to Scenario A the number of days when flow is less than the low flow threshold does not change very much under Scenario Cmid, but there is a large decrease under Scenario Cwet and a very large increase under Scenario Cdry (Table VD-21).There are very few zero flow days at this asset and this does not change under any of the Scenarios. Under Scenario B the high flow threshold exceedance has been much more frequent than under Scenario A. There is little change in high flow threshold exceedance under Scenario Cmid. Under Scenario Cwet there is a large increase in high flow exceedance from Scenario A; conversely there is a large decrease in high flow days under Scenario Cdry.

Kakadu National Park

The surface water flow confidence level for the selected reporting node for the Kakadu National Park (see location on Figure VD-10) is considered moderately reliable (3) for both wet season flows and dry season flows (Table VD-21). Under Scenario A annual flow into this asset is dominated by wet season flows (98 percent) which have been 53 percent higher in Scenario B. Dry season flows have also been (49 percent) higher in Scenario B when compared to Scenario A. Annual and seasonal flows do not change much under Scenario Cmid compared to Scenario A, but there are moderate increases under Scenario Cwet (24 percent) and moderate decreases under Scenario Cdry (23 to 25 percent). There are no development scenarios for the area upstream of this asset.

Compared to Scenario C the number of days when flow is less than the low flow threshold does not change very much under Scenarios Cmid, but there is a large decrease in low flow days under Scenario Cwet, and a very large increase in low flow days under Scenario Cdry (Table VD-21). Zero flow days are rare at this node and this does not change much under any scenario. However, there are three other nodes that enter the Kakadu National Park where zero flow occurs for between 27 and 36 percent of the year (on average) and there are moderate increases and decreases in the number of zero flow days when compared to Scenario A under Scenarios Cdry and Cwet respectively. In Scenario B the high flow threshold exceedance has been much more frequent than in Scenario A. Under Scenarios Cmid high flow threshold exceedance does not change much from Scenario A. Conversely, there is a large increase in high flow days under Scenario Cwet and a large decrease in high flow days under the Scenario Cdry.

Adelaide River Floodplain System

The surface water flow confidence level for the selected reporting node for the Adelaide River Floodplain System (see location on Figure VD-11) is considered fairly reliable (2) for wet season flows and unreliable (4) for dry season flows (Table VD-21). Under Scenario A annual flow into this asset is dominated by wet season flows (97 percent) which have been 47 percent higher under Scenario B. Annual and seasonal flows do not change under Scenarios Cmid when compared to Scenario A, but there is a moderate increase under Scenario Cwet (29 percent) and a moderate decrease under Scenario Cdry (26 percent). There are no development Scenarios for the area upstream of this asset.

Under Scenario B the high flow threshold exceedance has been much more frequent than in Scenario A (Table VD-21). There is little change in high flow threshold exceedance under Scenario Cmid. Under Scenario Cwet there is a large increase in high flow exceedance from Scenario A; conversely, there is a large decrease in high flow days under the Scenario Cdry. There are no low flow metrics reported for this asset.

Finniss Floodplain and Fog Bay Systems

The surface water flow confidence level for the selected reporting node for the Finniss Floodplain and Fog Bay Systems (see location on Figure VD-12) is considered reliable (1) for both wet season and dry season flows (Table VD-21). Under Sceanrio A annual flow into this asset is dominated by wet season flows (97 percent) which have been 65 percent higher under Scenario B. Dry season flows have also been 56 percent higher under Scenario B when compared to Scenario A. Annual and seasonal flows do not change under Scenarios Cmid when compared to Scenario A, but there is a moderate increase under Scenario Cwet (17- 27 percent) and a moderate decrease under Scenario Cdry (24 to 28 percent). There are no development Scenarios for the area upstream of this asset.

Comapred to Scenario A the number of days when flow is less than the low flow threshold does not change very much under Scenario Cmid, but there is a considerable decrease under Scenario Cwet and a very large increase under Scenario Cdry (Table VD-21).There are very few zero flow days at this asset and this does not change under any of the scenarios. Under Scenario B the high flow threshold exceedance has been much more frequent than in Scenario A. There is little change in high flow threshold exceedance under Scenario Cmid. Under Scenario Cwet there is a moderate increase in high flow exceedance from Scenario A; conversely there is a moderate decrease in high flow days under Scenario Cdry.

Mary Floodplain System

The surface water flow confidence level for the selected reporting node for the Mary Floodplain System (see location on Figure VD-13) is considered fairly reliable (2) for wet season flows and reliable (1) for dry season flows (Table VD-21). Under Scenario A annual flow into this asset is dominated by wet season flows (99 percent) which have been 49 percent higher under Scenario B. Dry season flows have also been 125 percent higher under Scenario B when compared to Scenario A. Annual and seasonal flows do not change much under Scenarios Cmid when compared to Scenario A, but there is a moderate increase under Scenario Cwet (8 to 28 percent) and a large decrease under Scenario Cdry (29 to 37 percent). There are no development Scenarios for the area upstream of this asset.

Compared to Scenario A the number of days when flow is less than the low flow threshold increases moderately under Scenario Cmid, decreases considerably under Scenario Cwet and increases greatly under Scenario Cdry (Table VD-21). A similar pattern occurs with the number of zero flow days. Under Scenario B the high flow threshold exceedance has been much more frequent than in Scenario A. There is little change in high flow threshold exceedance under Scenario Cmid. Under Scenario Cwet there is a large increase in high flow exceedance from Scenario A; conversely there is a large decrease in high flow days under Scenario Cdry.

Port Darwin

The surface water flow confidence level for the selected reporting node for Port Darwin (see location on Figure VD-14) is considered reliable (1) for wet season flows and fairly reliable (2) for dry season flows (Table VD-21). Under Scenario A annual flow into this asset is dominated by wet season flows (97 percent) which have been 26 percent higher under Scenario B. Dry season flows have also been 9 percent higher under Scenario B when compared to Scenario A. Annual and seasonal flows do not change much under Scenarios Cmid when compared to Scenario A, but there is a moderate increase under Scenario Cwet (9 to 26 percent) and a moderate decrease under Scenario Cdry (21 to 27 percent). There are no development Scenarios for the area upstream of this node at this asset.

Compared to Scenario A the number of days when flow is less than the low flow threshold does not change much under Scenario Cmid, but there is a very large decrease under Scenario Cwet and a very large increase under Scenario Cdry (Table VD-21). Comapred to Scenario A the number of days of zero flow days at this asset decreased by almost 50 percent under Scenario B and 75 percent under Scenario Cwet. There was little change in the number of zero flow days under Scenario Cmid compared to Scenario A but a large increase (240 percent) under Scenario Cdry. Under Scenario B the high flow threshold exceedance has been much more frequent than in Scenario A. There is little change in high flow threshold exceedance under Scenario Cmid. Under Scenario Cwet there is a moderate increase in high flow exceedance from Scenario A; conversely there is a moderate decrease in high flow days under Scenario Cdry.

VD-3.8 References

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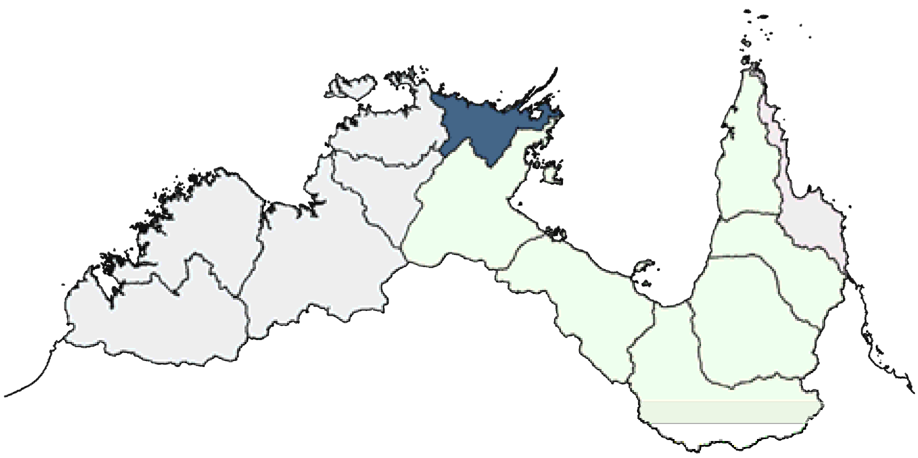
Water in the Arafura region



AR-1 Water availability and demand in the Arafura region

The first part of this report (the Preamble, Chapter 1 and Chapter 2) reports at the division level, including division-wide descriptions of climate and geology and methods which apply to all regions. Subsequent chapters report at the region level. In particular, Chapters AR-1, AR-2 and AR-3 focus on the Arafura region (Figure AR-1).

This chapter summarises the water resources of the Arafura region, using information from Chapter AR-2 and Chapter AR-3, and directly addresses the Terms of Reference, specifically terms 3, 4 and 5 as listed in the Preamble. Essentially, this chapter provides a synoptic view of the region and covers:

- regional observations
- water resource assessment
- seasonality of water resources
- surface–groundwater interaction
- changes to flow regime at environmental assets
- water storage options
- data and knowledge gaps.

For further details on the context of the region (physical and climate descriptions, hydrogeology and legislation) see Chapter AR-2. Region-specific methods and results are provided in Chapter AR-3. Modelling results are reported under climate and development scenarios as defined at the division level in Section 2.1 of Chapter 2.

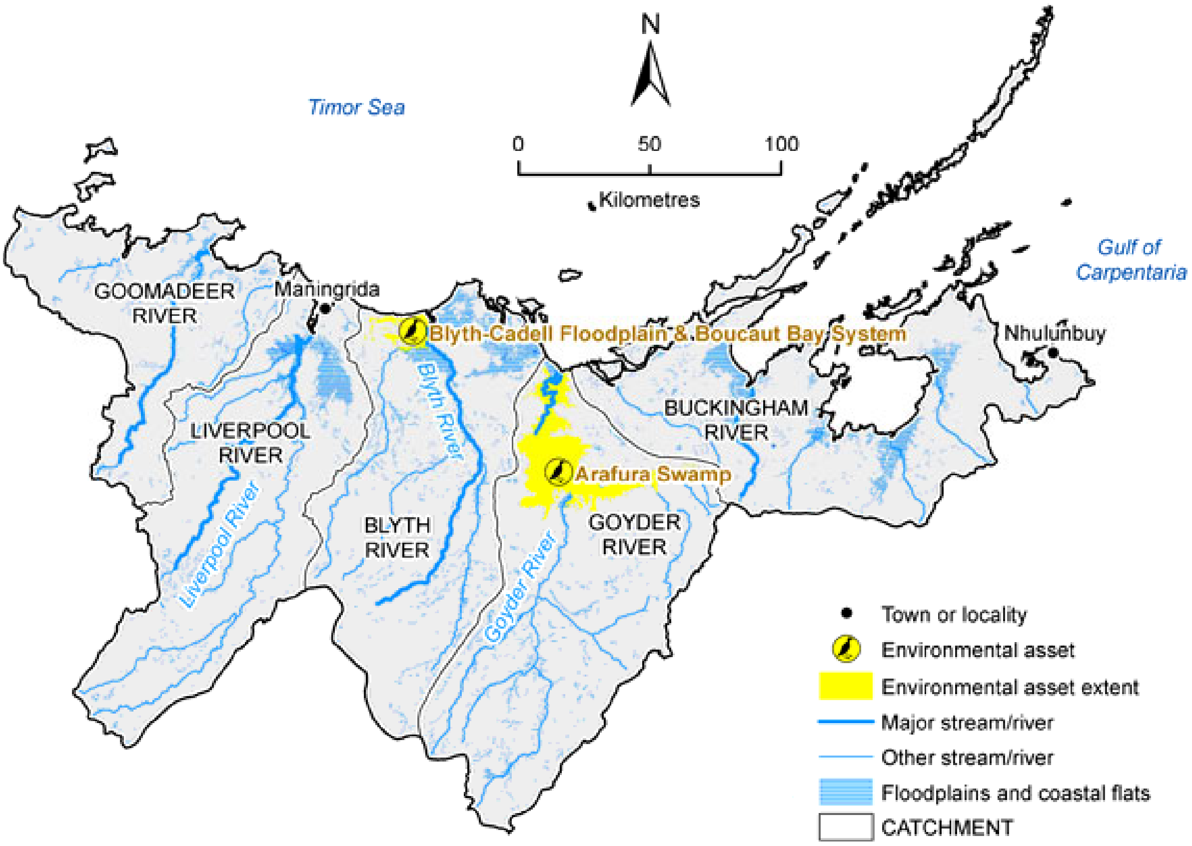


Figure AR-1. Major rivers, towns and location of environmental assets selected for assessment of changes to hydrological regime in the Arafura region

AR-1.1 Regional summary

These regional observations summarise key modelling results and other relevant water resource information about the Arafura region.

The Arafura region has a high inter-annual variability in rainfall and hence runoff and recharge. Coefficients of variation are among the lowest of the regions across northern Australia and the region may experience long periods of many years that are considerably wetter or drier than others.

The mean annual rainfall for the region is 1186 mm. Mean annual areal potential evapotranspiration (APET) is 1898 mm. The mean annual runoff averaged over the modelled area of the Arafura region is 240 mm, 20 percent of rainfall. These values are amongst the highest across northern Australia. Under the historical climate the mean annual streamflow over the Arafura region is estimated to be 10,920 GL.

There is a very strong seasonality in rainfall patterns, with 96 percent of rainfall falling between November and May, and a very high dry season (May to October) APET. The region has a relatively high rainfall intensity, and hence rapid runoff and short lag between rainfall and runoff with a slightly increasing amount and intensity of rainfall over the historical (1930 to 2007) period.

There is a strong north–south rainfall gradient and between 12 and 38 percent of precipitation flows as runoff.

Annually, APET is greater than rainfall, and the region is thus water-limited – in other words there is more energy available to remove water than there is water available to be removed. The region is one of only a few, however, that is not water-limited throughout the entire year, with wet season (November to April) rain exceeding APET, particularly towards the coast.

The Arafura region has a recent (1996 to 2007) climate record that is statistically significantly wetter than the historical (1930 to 2007) record. Rainfall was 15 percent higher; runoff was 38 percent higher. It is likely that future (~2030) conditions will be similar to historical conditions; hence, future runoff and recharge will also be similar to historical levels, and lower than the recent past.

There are a number of short perennial rivers in the region, mostly near the coast. These are fed during the dry season by discharge from (i) the shallow Cretaceous sandstone aquifers and (ii) outcrops of the Dook Creek Formation, a Proterozoic karstic carbonate sequence. Groundwater extracted for the bauxite mine operated by Rio Tinto may be having a significant impact on the perennial Yirrkala Creek and Latram River.

The major aquifers in the region have been developed in the Proterozoic carbonates and Cretaceous sediments. The presence or absence of the Cretaceous sediments has a large impact on recharge to the Proterozoic carbonates. More work is required to understand this impact. Recharge via sinkholes to aquifers in the Proterozoic carbonates is important but has not yet been quantified.

A large proportion of the groundwater use is metered across the region. A significant exception is Rio Tinto's Ranger uranium mine.

None of the environmental assets in this region have any site-specific ecology related flow metrics by which to gauge the potential impacts of future climate change and development scenarios.

Flows are highly dominated by wet season flows with dry season flows only a small fraction of total annual flow. However, environmental assets are adapted to this strong seasonality and any significant changes in the frequency and duration of wet season high flows and dry season low flows are likely to have an environmental impact. In the recent past there has been significantly more flow, with fewer low flow days and more high flow days than the historical record. Annual and seasonal flows do not change much under the median future climate; hence there is little expected change in the high and low flow threshold exceedance. In contrast, there would be large changes to the high flow threshold exceedance under the dry and wet extreme future climates which could have negative environmental impacts.

The region is generally datapoor.

AR-1.2 Water resource assessment

Term of Reference 3a

AR-1.2.1 Under historical climate and current development

Term of Reference 3a (i)

The mean annual rainfall and runoff averaged over the Arafura region are 1173 mm and 240 mm respectively. These values fall within the upper end of the range of values from the 13 regions. The coefficients of variation of annual rainfall and runoff averaged over the Arafura region are 0.21 and 0.48 respectively. The coefficient of variation of annual rainfall and runoff averaged over the Arafura region are among the lowest of the 13 reporting regions. The 10th percentile, median and 90th percentile annual runoff values across the Arafura region are 406, 219 and 110 mm respectively.

Under a continuation of the historical climate, mean annual potential diffuse recharge to groundwater in unconfined aquifers of the Arafura region is likely to be similar to the historical (1930 to 2007) average rate across the majority of the region. Groundwater extraction is currently high in this region, particularly for Rio Tinto's bauxite mine which has an average metered usage of 9.3 GL/year out of the total 15.3 GL/year estimated for the region (Table AR-1). Groundwater extraction for the Ranger uranium mine is not included in this estimate, but is likely to be significant. Future extraction at current rates under a historical climate is likely to have greatest impacts on the local watertable around the bore fields for these mines, and nearby perennial rivers.

Table AR-1. Estimated groundwater contribution (baseflow) to streamflow, modelled diffuse recharge and groundwater extraction for the Arafura region under historical climate

Station	River	Station name	Annual BFI *	Dry season BFI *	Dry season baseflow *
					GL
G8230237	Liverpool	D/S Cuthbertson Falls	0.3	0.7	18.2
G8260052	Upper Latram	U/S Eldo Rd Crossing	0.4	0.6	0.6
G8260053	Lower Latram	above Tidal Reach	0.5	0.7	3.7
		Historical recharge **	Estimated groundwater extraction		
			GL/y		
Entire Arafura region		8,590			15.3 + Ranger Mine

* BFI (baseflow index) and baseflow volume derived from gauged data.
** Aggregated potential diffuse recharge from Zhang and Dawes (1998).

AR-1.2.2 Under recent climate and current development

Term of Reference 3a (ii)

The mean annual rainfall and runoff under the recent (1996 to 2007) climate are 15 percent and 38 percent higher respectively than the historical mean values.

Under a recent climate, mean annual diffuse groundwater recharge is likely to be significantly higher than the historical average rate across most of the region. The only exception to this is in the far north-west of the region where recharge is likely to be lower, and similarly in pockets in the centre of the region where vertosol soils are dominant. This higher recharge would help to partially mitigate the impacts of intensive groundwater extraction around mine sites, and could provide a buffer between wells and nearby perennial rivers.

AR-1.2.3 Under future climate and current development

Term of Reference 3a (iii)

Rainfall-runoff modelling with climate change projections from seven of the GCMs shows a reduction in mean annual runoff, while rainfall-runoff modelling with climate change projections from eight of the GCMs shows an increase in mean annual runoff. For the high global warming scenario, rainfall-runoff modelling with climate change projections from five of the GCMs indicates a decrease in mean annual runoff greater than 10 percent while rainfall-runoff modelling with climate change projections from five of the GCMs indicates an increase in mean annual runoff greater than 10 percent. Under scenarios Cwet, Cmid and Cdry, mean annual runoff increases by 16 and 1 percent and decreases by 22 percent relative to Scenario A. By comparison, the range based on the low global warming scenario is an 8 to -12 percent change in mean annual runoff.

Under the future climate, mean annual diffuse groundwater recharge is likely to be significantly higher than the historical average rate across most of the region. Again, this may help to mitigate the impacts of intensive groundwater extraction around mine sites, and could provide a buffer between wells and nearby perennial rivers.

AR-1.2.4 Under future climate and future development

Term of Reference 3b

This scenario was not modelled for this region. Minimal future development is expected.

AR-1.3 Changes to flow regime at environmental assets

Term of Reference 4

Section 1.3 of the division-level Chapter 1 describes how environmental assets were shortlisted for assessment by this project. Two environmental assets were shortlisted for the Arafura region: Arafura Swamp and the Blyth-Cadell Floodplain & Boucaut Bay System. These assets are characterised in Chapter AR-2.

In deciding whether it is feasible to report hydrological regime metrics for these shortlisted assets, it is important to consider the confidence levels in modelled streamflow (as described in Section 2.2.6 of the division-level Chapter 2). Confidence in results for low flows and high flows was calculated separately. Hydrological regime metrics (as defined in Section 2.5 of the division-level Chapter 2) for either low flows or high flows are reported only where confidence levels are sufficiently high. If confidence in the low flow or high flow is too low, metrics are not reported, and hence an important gap in our knowledge is identified.

Some of the assets in this region have multiple nodes at which streamflow modelling results are available. When reporting hydrological regime metrics for such assets a single node was selected. The selected node was that with the highest streamflow confidence level and the largest proportion of streamflow to the asset. The locations of nodes for each asset are shown on satellite images in Section AR-2.1.3. Results for all nodes are presented in McJannet et al. (2009).

In this region, the confidence levels in modelled streamflow are sufficiently high to report hydrological regime metrics at only the Blyth-Cadell Floodplain & Boucaut Bay System. The surface water flow confidence level for the Arafura Swamp is considered unreliable for low flows so metrics relating to such flows will not be reported. In contrast, the confidence level for high flows at this asset is considered moderately reliable and thus high flow metrics are reported.

Annual flow into all assets is dominated by wet season flow, which has been much higher (>50 percent) under the recent climate. Dry season flows at the Blyth-Cadell Floodplain & Boucaut Bay System have also been significantly (>50 percent) higher under the recent climate.

Under the future climate, flows are expected to be similar to the historical record, though the wet extreme future climate may see moderate increases, while the extreme dry future climate may see moderate decreases.

The number of days when flow is below the low flow threshold is projected to be much greater under the future dry extreme climates. Zero flow days are generally rare, and this is unlikely to change.

AR-1.4 Seasonality of water resources

Term of Reference 3a (iv)

Under the historical, recent and future climates, 96 percent of rainfall and 91 percent of runoff occur during the wet season. Runoff is highest in February and March.

AR-1.5 Surface–groundwater interaction

Term of Reference 4

Reaches of rivers in the Arafura region where significant groundwater discharge is known to occur towards the end of the dry season are shown in Figure AR-2. The data used to compile this map represents flows after a series of below average and above average wet seasons. These flows are sustained by significant regional groundwater discharge from aquifers developed in karstic carbonate rocks and Cretaceous sediments. Rivers with perennial reaches, where dry season flow is sourced from karstic rocks, include the Goyder, Blyth and Habgood. Perennial rivers where dry season flow is sourced from Cretaceous sediments include the Cato and Latram, as well as Yirrkala and Jungle creeks.

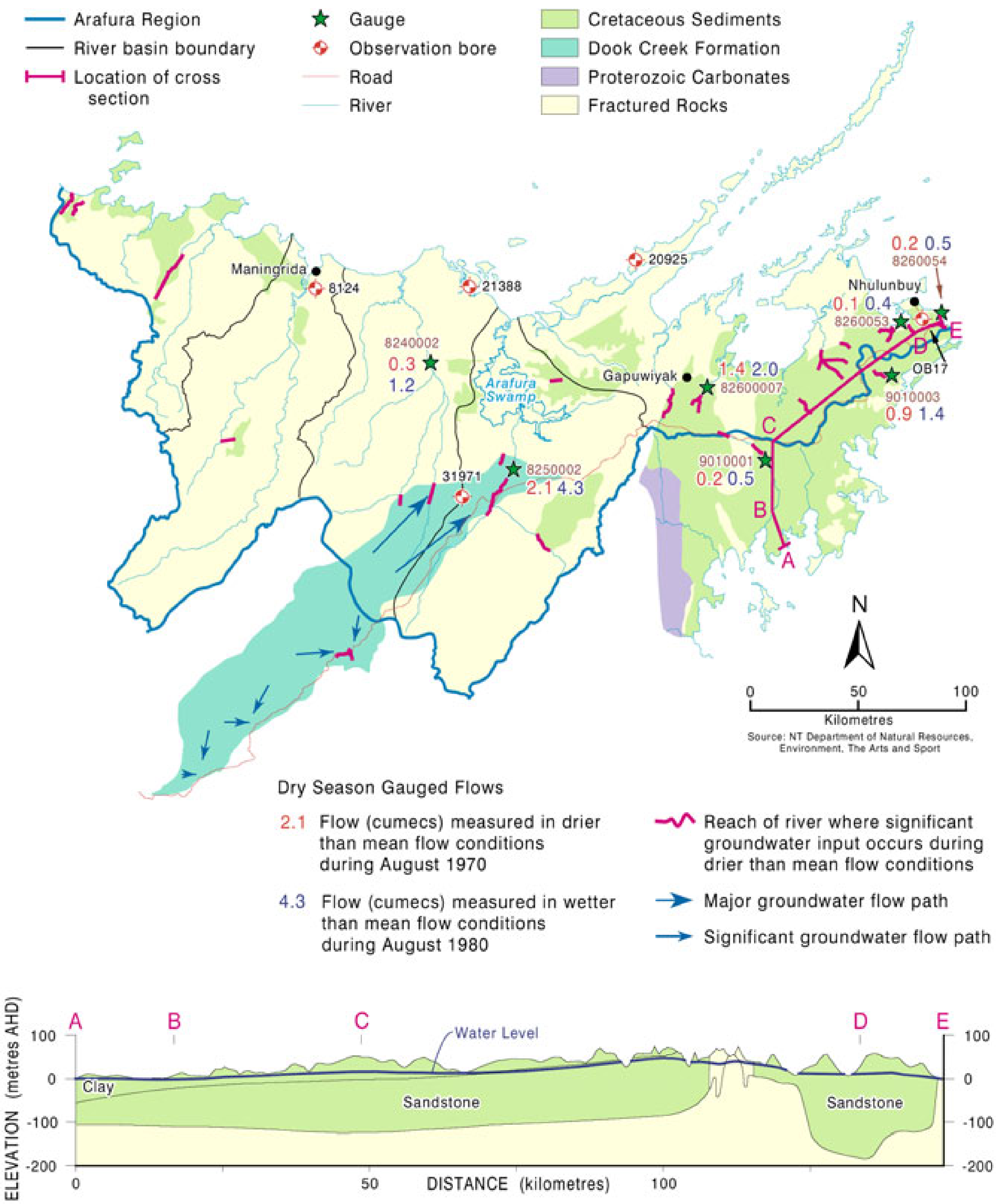


Figure AR-2. Hydrogeology of the Arafura region with dry season gauged flows (map provided by NRETAS, 2009)

The amount of recharge to an aquifer system can be estimated from data on dry season streamflow. Williams et al. (2003) presented a detailed analysis of gauged dry season instantaneous flow data at gauging station G8250002.

Streamflow and rainfall data were used in the Williams study to predict regional groundwater discharge fluxes at the gauge for the full period of rainfall record. The predicted groundwater discharge fluxes and gauged dry season flows are plotted in Figure AR-3. The predicted discharge fluxes were equated to a mean annual recharge rate of 90 mm/year for the period.

The technique of Williams et al. (2003) provided a good match between predicted and gauged data. The existing flow records, while biased towards above average rainfall years, have captured groundwater discharge data over a large range of conditions that are likely to occur in the Arafura region (Figure AR-3).

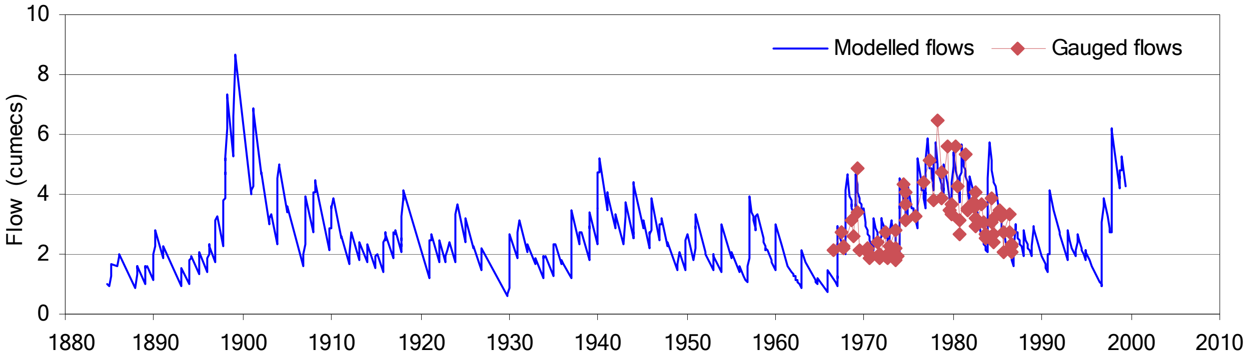


Figure AR-3. Dry season flows in the Goyder River of the Arafura region at gauge G8250002

The Goyder River is entirely fed by groundwater during the dry season and accordingly provides the major water source for the Arafura Swamp at this time. Williams et al. (2003) stated that the Arafura Swamp and surrounding area are significant for a variety of cultural, environmental and economic reasons. The uniqueness of the area has been recognised and the Arafura Swamp and catchment have been included on the Register of the National Estate. The land on which the Arafura Swamp occurs is owned by the Yolgnu, the Indigenous people of north-east Arnhem Land. The Arafura Swamp is vital to their livelihoods. The swamp's flora and fauna are basic food sources. The wetland flora is also used for medicinal purposes. The Arafura Swamp forms an important ecological habitat. It contains the largest paperbark swamp in Australia and it is home to a diverse number of wetland species.

Evapotranspiration requirements for the swamp were determined by Williams et al. (2003) to be approximately 5 mm/day. Using this value they calculated the area of swamp inundated for different flow rates at gauge G8250002. The area ranged from 17 km^2 for a flow rate of 1 m^3/second up to 104 km^2 for a flow rate of 6 m^3/second.

AR-1.6 Water storage options

Term of Reference 5

AR-1.6.1 Surface water storages

There are no large surface water storages in the region.

AR-1.6.2 Groundwater storages

Groundwater development in the Arafura region is very low and groundwater recharge rates are high. Under current development managed aquifer recharge (MAR) would have limited applicability as storages in the local carbonate aquifers (i.e. Dook Creek Formation) are likely to be at full capacity towards the end of the wet season when surface water is available for injection. Potential evapotranspiration exceeds rainfall for most of the year resulting in near year-round water-limited conditions. When water is not limited aquifers are expected to be at full capacity. Therefore the only opportunity for MAR in this region is if future development leads to groundwater levels not fully recovering each wet season.

AR-1.7 Data gaps

Term of Reference 1e

Streamflow gauging stations are or have been located at 17 locations within the Arafura region. The greatest concentration of streamflow gauging stations is to the east in the vicinity of the town of Nhulunbuy. The rest of the Arafura region is sparsely gauged, and where streamflow gauging stations do exist the streamflow records are short and intermittent. There are two gauging stations currently operating in the Arafura region at density of one gauge for every 22,800 km^2. For the 13 regions the median number of currently operating gauging stations per region is 12 and the median density of gauging stations per region is one gauge for every 9700 km^2.

Groundwater extraction for the Ranger uranium mine is significant, but not metered.

The region contains major perennial rivers with dry season flows maintained by discharge from aquifers developed in both the Cretaceous sediments and the Proterozoic carbonates. However, since 1987 the only gauging stations that have been in operation on these perennial rivers have been used to determine the impact of bauxite operations near Nhulunbuy. Given the mineral potential of this region, it is important that a representative network of gauging stations and groundwater monitoring sites are operated so that the impact of future mining developments will be able to be adequately assessed.

AR-1.8 Knowledge gaps

Term of Reference 1e

In the north-eastern part of the region extensive bauxite deposits occur in areas that are underlain by Cretaceous sandstones. The only mining development that has occurred to date in this area has been the bauxite mine located near Nhulunbuy. The operator of the mine extracts approximately 10 GL/year. The bore production, groundwater level and river flow data collected since the borefield commenced operation should allow an aquifer simulation model to be developed to quantify the impact the mine has had, and will have in the future, on recharge and discharges to the nearby river and wetlands. It would also enable the impacts of future mining developments to the many perennial rivers in the region to be quantified. None of the environmental assets in this region have any site-specific metrics by which to gauge the potential impacts of future climate change and development. In the absence of site-specific metrics a set of standard metrics related to high and low flows have been utilised; however, the conversion of these metrics into environmental impacts still requires development of quantitative relationships between flow and specific ecological entities (for example, macrophyte populations, fish passage, faunal and floral habitats, etc.).

Flooding is an important factor that sustains many environmental assets and this occurs when the stream breaks out of its banks (a level known as bankfull stage or discharge). However, bankfull discharge is not known for many streams, nor is the dependence of area flooded on increasing stream depth, so it is difficult to predict when assets are inundated. Further information about bankfull stage and discharge are needed for most environmental assets.

Dry season flows are poorly understood in this region therefore the ability to predict the potential impacts of the various scenarios on low or zero flows at environmental assets is very limited. Improved monitoring of low streamflow conditions is needed along with the development of hydrological models that combine surface and groundwater regimes. Further monitoring of groundwater levels is also required so that the potential impacts of climate change and development scenarios on groundwater-dependent ecosystems can be better understood.

Many environmental assets depend not simply on duration above or below certain flow levels, but on triggers (e.g. for reproduction or migration) set by the rate of change of flow. In addition, some environmental assets depend on the frequency and duration of events that occur less than annually (i.e. once every 5, 10 or 20 years or more). Further analysis is therefore required to look at how the timing, duration and rate of rise and fall in flow rates at critical times of the season will vary under the various scenarios.

AR-1.9 References

Williams D, Chudleigh I and Jolly P (2003) Arafura Swamp Water Study Water Resources Study Water Resources Technical Report, Department of Infrastructure, Planning and Environment.

Zhang L and Dawes W (1998) WAVES - An integrated energy and water balance model. Technical Report No. 31/98, CSIRO Land and Water.

AR-2 Contextual information for the Arafura region

This chapter summarises the background information for the region, outlining existing knowledge of water resources and prior and current investigations relevant to the water resources of the region. This chapter also outlines the current and potential future legislation, water plans and other water resource management arrangements. This chapter is arranged into four sections:

- physical and climate descriptions
- data availability
- hydrogeology
- legislation, water plans and other arrangements.

AR-2.1 Overview of the region

AR-2.1.1 Geography and geology

The Arnhem Inlier forms basement to sedimentary and minor volcanic rocks of the McArthur Basin in north-eastern Arnhem Land. It comprises granites, migmatite and metasedimentary rocks.

The Pine Creek Orogen underlies the west of the region. It consists of multiple sequences of deformed and metamorphosed Palaeoproterozoic successions, which are unconformably overlain by the Palaeo- to Mesoproterozoic McArthur Basin in the east. Archaean granite-gneiss, granite and minor metasedimentary rocks are exposed as small inliers and form the basement to Palaeoproterozoic strata. The Pine Creek Orogen hosts over a thousand mineral occurrences and is the most prospective province of the Northern Territory. The region contains approximately 20 percent of the world's low-cost uranium resource and has a significant potential for gold.

The McArthur Basin underlies the centre and east of the region. The McArthur Basin succession comprises sandstone, shale, carbonate, and interbedded volcanic and intrusive igneous rocks.

The Arafura Basin underlies the central northern part of the region. It consists of Neoproterozoic sediments. Onshore Arafura Basin sediments unconformably overlie Proterozoic strata of the McArthur Basin and Pine Creek Orogen. Neoproterozoic sedimentary strata of the Arafura Basin consist of shallow marine sandstone, mudstone, and minor carbonates, which were deposited on a stable platform.

The on-shore Money Shoal Basin is relatively undeformed and is composed primarily of Cretaceous aged sediments. The basin contains mildly deformed, largely flat-lying sediments; these consist of Cretaceous successions of marine and continental clastics, predominantly sandstones with minor coals, shales, claystones and marls. Money Shoal Basin strata overlie Proterozoic strata of the Pine Creek Orogen.

The current drainage system probably came into existence in the Cretaceous when uplift in the north of the Northern Territory resulted in a drainage divide between inland draining streams to the south and streams draining to the sea in the north.

The alluvial plains that cover an extensive area along the coastal northern edge of the region are underlain by primarily marine sediments that have been deposited in the last 10,000 years since the end of the ice age. Figure AR-4 shows the surface geology of the region.

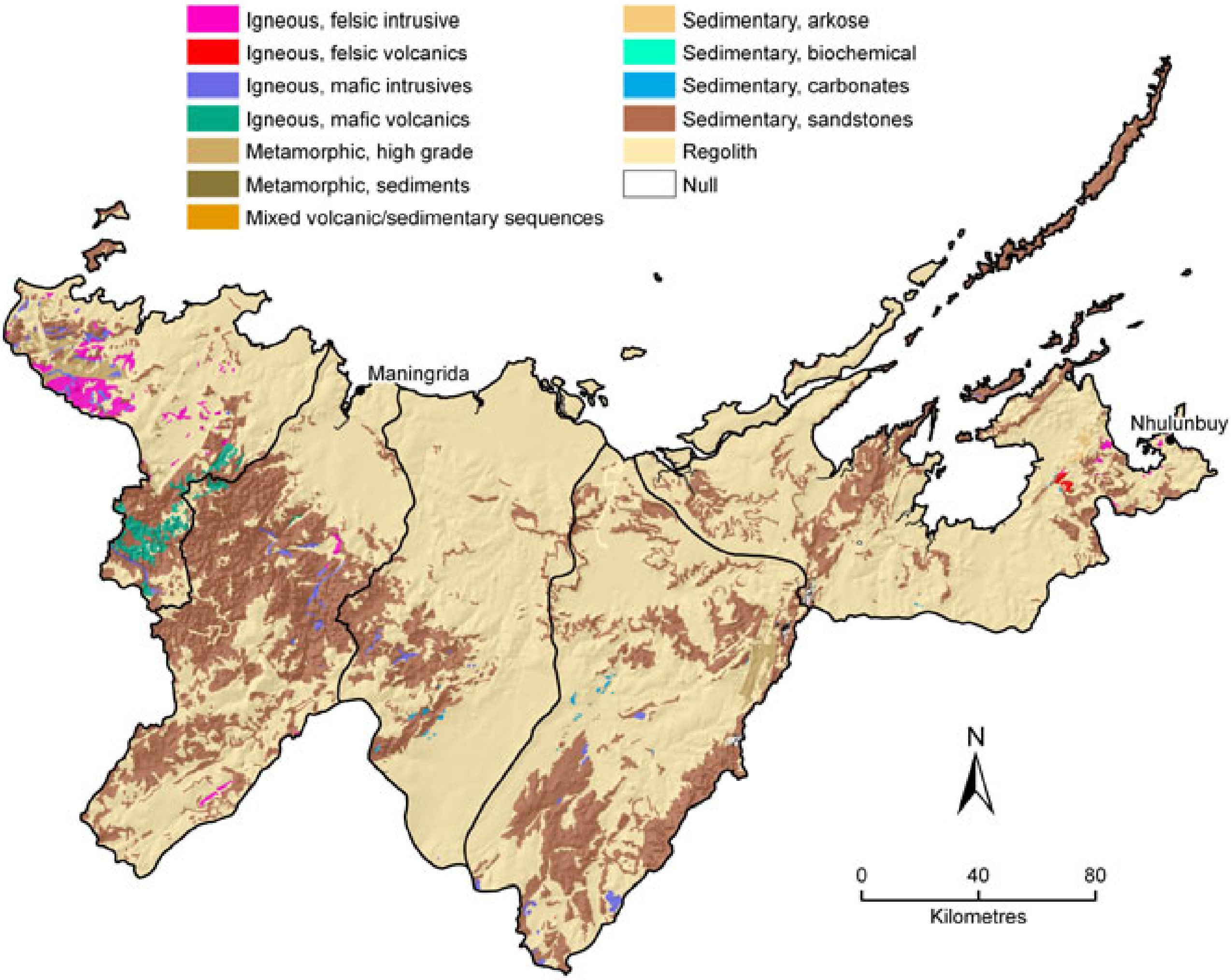


Figure AR-4. Surface geology of the Arafura region overlaid on a relative relief surface

AR-2.1.2 Climate, vegetation and land use

The Arafura region receives an average of 1186 mm of rainfall over the September to August water year, most of which (1140 mm) falls in the November to April wet season (Figure AR-5). Across the region there is a strong north–south gradient in annual rainfall, ranging from 1383 mm in the north to 920 mm in the south. Over the first half of the historical (1930 to 2007) period, rainfall has been relatively constant at around 1050 mm. The second half of the period has seen an increase in mean annual rainfall to approximately 1350 mm. The highest yearly rainfall received was 1821 mm which fell in 2001, and the lowest was 595 mm in 1952. Potential evapotranspiration (APET) is very high across the region, averaging 1898 mm over a water year, and varies moderately across the seasons. APET generally remains higher than rainfall throughout the year resulting in year-round water-limited conditions, which the vegetation has adapted to.

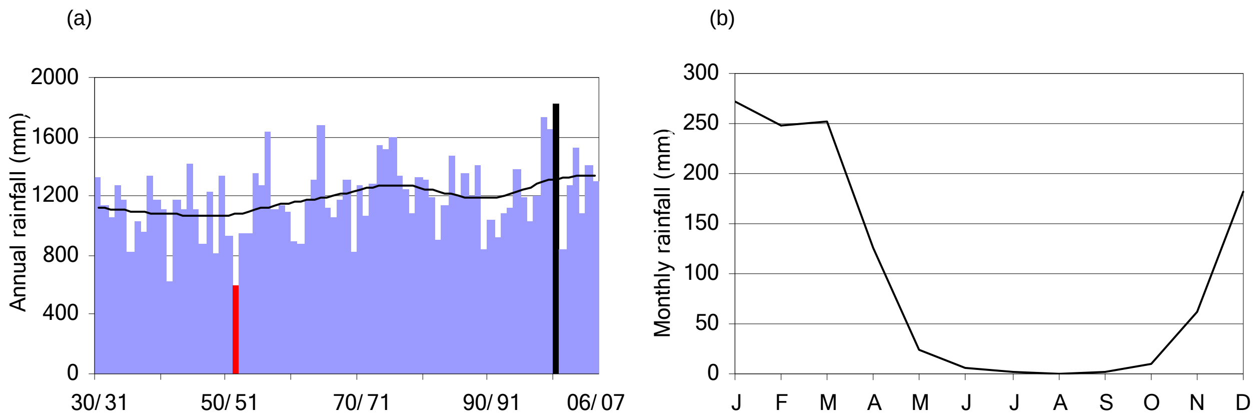


Figure AR-5. Historical (a) annual and (b) mean monthly rainfall averaged over the Arafura region. The low-frequency smoothed line in (a) indicates longer-term variability

Eucalypt forests and woodlands dominated by darwin woollybutt (*Eucalyptus miniata*) and darwin stringybark (*Eucalyptus tetrodonta*) with tussock and hummock grass understorey are the most extensive vegetation away from the immediate coast (Connor et. al., 1996). However there is a diversity of vegetation communities in the bioregion, varying with topography and drainage (Kerle, 1996). Monsoon vine forest thicket consists of small rainforest patches that are widespread in the region and contain relatively high plant species richness. They occur mainly on relict dune systems, along rivers, around springs and in other areas offering topographic protection from fire. They are currently being threatened by increased abundance of feral animals (principally pigs and water buffalo), weeds, and changes in fire regimes.

Undulating low plateaux, and gravel rises are vegetated with darwin stringybark (*E. tetrodonta*) and darwin woolly butt (*E. miniata*), in association with ironwood (*Erythrophleum chorostachys*). In most places tall grasses such as speargrass (*Sorghum* spp.) dominate the ground flora, with a mid layer of shrubs including Acacias, fan palm (*Livistona humilis*), zamia palm (*Cycas armstrongii*) and screw palm (*Pandanus spiralis*). Cypress pine (*Callitris intratropica*) and smooth-stemmed bloodwood (*Corymbiableeseri*), northern box (*E. tectifica*) and round-leaved bloodwood (*C. latifolia*) also occur as co-dominants in parts of the region.

Paper bark swamps occur on some river systems, on riverine and poorly drained soils. Species include *Melaleuca leucadendra , M. cajuputi* and *M. viridiflora*. Grasslands and sedgelands occur on the seasonal floodplains including wild rice (*Oryza rufopogon*) and spikerush (*Eleocharis* spp.).

Coastal communities vary from beach dunes to salt flats, swamps, shrublands and mangrove closed forest. There are a number of species of mangrove, the most common being the white mangrove (*Avicennia marina*). Dunes may include coastal sheoak (*Casuarina equisetifolia)*. Coastal heathlands also occur in this bioregion.

There have been a number of records of incursions of the weed *Mimosa pigra* in wetlands in this bioregion, this weed has the potential for major impacts. Occasional records of mission grass (*Pennisetum polystachion*), gamba grass (*Andropogon gayanus*) and para grass (*Urochloa mutica*) are also cause for concern. A number of commonly occurring weed species such as annual mission grass (*Pennisetum pedicillatum*), Sida spp, and Hyptis are found in areas of disturbance such as outstations and roadsides.

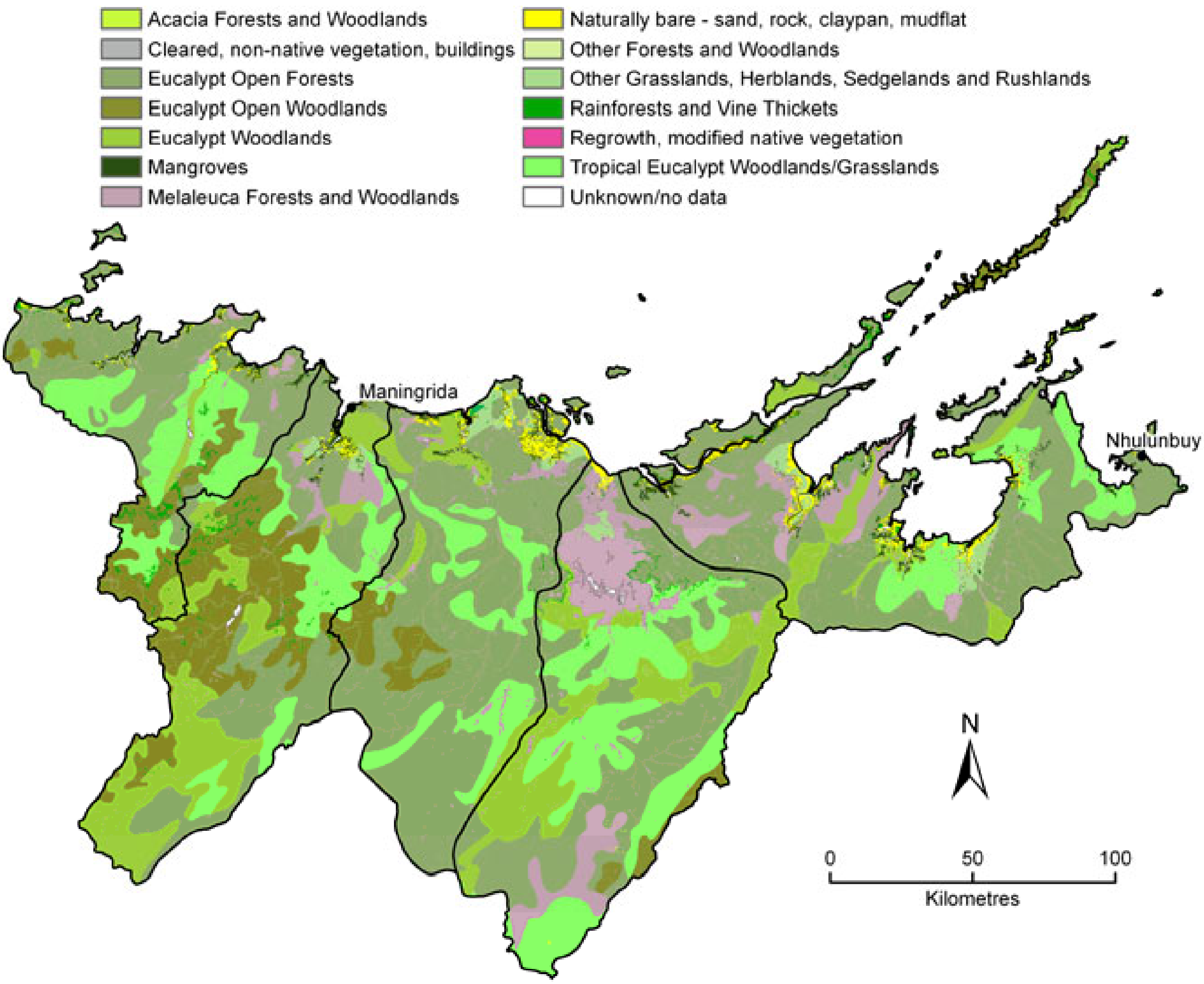


Figure AR-6. Map of current vegetation types across the Arafura region (source DEWR, 2005)

All of the region lies within Arnhem Land under the management of the Arnhem Land Aboriginal Land Trust. There are no national parks or reserves declared within the region, although Cape Arnhem Peninsula (Nanydjaka) is managed by the Dhimurru Land Management Aboriginal Corporation as a conservation area.

Bauxite (aluminium) mining occurs on Gove Peninsula and manganese is mined on Groote Eylandt. Aboriginal land is leased to companies to undertake the mining operations. Bauxite mining at Gove is causing localised land degredation.

Tourism is a growing industry within the bioregion, and there is localised impact from 4WD vehicles.

The bioregion is generally notable for the relative lack of degradation and modification.

The sub-coastal floodplain environments (most notably Arafura Swamp) are likely to be affected by rising sea levels, and have suffered some impacts due to feral animals, particularly Asian water buffalo (*bubalus bubalis*).

Pigs and buffalo are causing widespread damage to monsoon rainforest patches. Changes in fire regime have also led to degradation of monsoon forests, and are likely to have impacted on the floristic and structure of Eucalypt forests.

Traditional land management practices, particularly fire management, continue across most of the region. However, Aboriginal landowners often lack the resources and training to combat new threats such as weeds and feral animals. In areas where Aboriginal people are not currently able to maintain traditional management practices, late season wildfires are a particular concern. This is an issue in plateau country, extending into the neighbouring Arnhem Plateau bioregion, which contains important and vulnerable sandstone heaths.

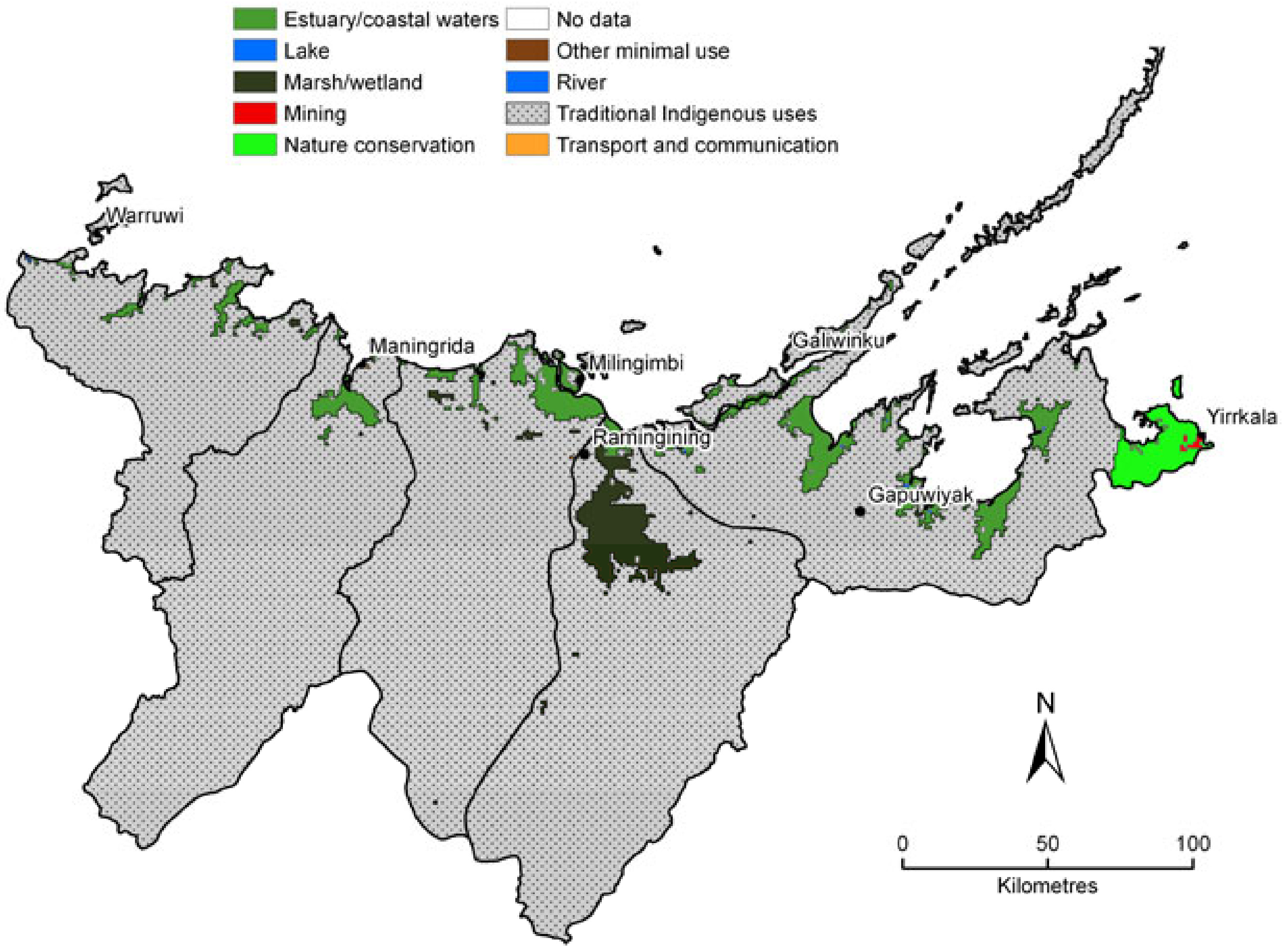


Figure AR-7. Map of dominant land uses of the Arafura region (after BRS, 2002)

AR-2.1.3 Regional environmental asset description

Environmental assets were chosen from wetlands which are listed in the Directory of Important Wetlands in Australia (Environment Australia, 2001). From this directory, environmental assets were shortlisted for assessing changes to the hydrological regime under the climate and development scenarios. The selection of this shortlist was undertaken in consultation with state governments and the Australian Government through direct discussions and through internal reviews (see Section 1.3 in the division-level Chapter 1 for further detail).

All nationally, or internationally, important wetlands listed for the Arafura region in the Directory of Important Wetlands in Australia (Environment Australia, 2001) are detailed in Table AR-2, with asterisks identifying the two shortlisted assets: Arafura Swamp and Blyth-Cadell Floodplain & Boucaut Bay System. The location of these shortlisted wetlands is shown in Figure AR-1. There are no wetlands classified as Ramsar sites in this region. Wetlands may be nationally or regionally significant depending on more locally specific criteria. All wetlands are important for a variety of ecological reasons or because they bear historical significance or have high cultural value, particularly to Indigenous people.

The following section characterises these shortlisted wetlands and is based largely on the description of these assets as outlined by Environment Australia (2001). Chapter AR-3 presents the assessment of those shortlisted assets, and reports hydrological regime metrics for those assets which have sufficient confidence in the modelled streamflow to enable analysis.

Table AR-2. List of Wetlands of National Significance located within the Arafura region

Site code	Name	Area	Ramsar site
		ha	
NT021 *	Arafura Swamp	71,400	No
NT022 *	Blyth-Cadell Floodplain & Boucaut Bay System	35,500	No

* Asterisk against the site code identifies those shortlisted for assessment of changes to hydrological regime.

Arafura Swamp

The Arafura Swamp (Figure AR-8) is a good example of a wooded swamp, the largest in the Northern Territory and possibly one of the largest in Australia. The site has an area of 71,400 ha and an elevation ranging between zero and 20 m above sea level (Environment Australia, 2001).

Figure AR-8. False colour satellite image of the Arafura Swamp (derived from ACRES, 2000). Clouds may be visible in image

Billabongs and river channels support floating mat communities and monsoon vine-forest occurs in patches along the river. The site is known to be a significant breeding area for Magpie Goose. The site is a major breeding area for both crocodile species. Saltwater crocodiles occur in high densities, especially in billabongs near the northern end. Large numbers of fruit bats roost and feed in the site's large melaleuca forests.

The site has great cultural significance to Indigenous people, both in the past (mainly Djinba tribe) and present (Ramingining community and others) (Environment Australia, 2001). Campsites and large middens occur around the swamp. Hunting, gathering and fishing using traditional methods continue today. The margins of the swamp are used for pastoral grazing and were formerly a major area for saltwater crocodile hunting. Minor commercial harvesting of crocodile eggs from floating mats occurs within the site.

Blyth-Cadell Floodplain and Boucaut Bay System

The Blyth-Cadell Floodplain and Boucaut Bay System (Figure AR-9) is a good example of a floodplain-tidal wetland system typical of the Top End Region and is the largest, contiguous, non-forested freshwater floodplain in Arnhem Land (excluding sites on Van Diemen Gulf). The site has an area of 35,500 ha and an elevation ranging between zero and 7 m above sea level (Environment Australia, 2001).

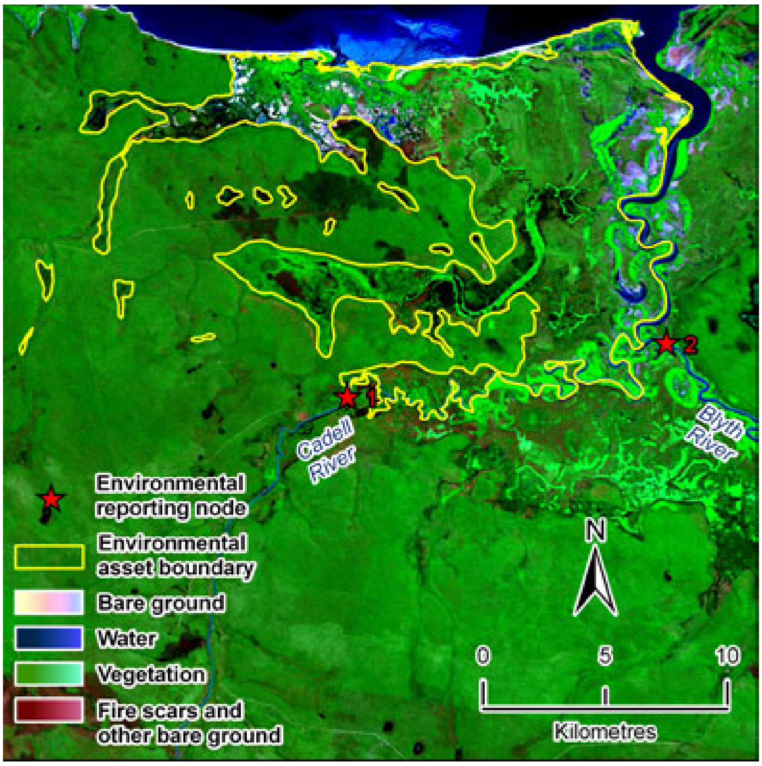


Figure AR-9. False colour satellite image of the Blyth-Cadell Floodplain and Boucaut Bay System (derived from ACRES, 2000). Clouds may be visible in image

The site is an important migration stop-over site for shorebirds in Arnhem Land with more than 15,000 waders regularly recorded in the area 10 km either side of the mouth of the Blyth River (Environment Australia, 2001). The floodplain swamps and grasslands remain a significant breeding area for Saltwater Crocodiles. Two Aboriginal communities are located within 25 km of the site and traditional use of the wetlands is still practised. (Environment Australia, 2001).

AR-2.2 Data availability

AR-2.2.1 Climate

The rainfall-runoff modelling uses historical daily climate data (Scenario A) from the SILO database for the period 1 September 1930 to 31 August 2007 at 0.05 x 0.05 degree (~ 5 x 5 km) grid cells. Full details and characterisation of the SILO database are provided at the division level in Section 2.1 of Chapter 2. Scenario B and Scenario C climate data are rescaled versions of the Scenario A data; this is also discussed in Section 2.1 of Chapter 2.

AR-2.2.2 Surface water

Streamflow gauging stations are or have been located at 17 locations within the Arafura region. Four of these gauging stations are either flood warning stations and measure stage height only, or have less than ten years of measured data. Of the remaining 13 stations, four recorded more than half of their total volume of flow during events that exceed the maximum gauged stage height. Figure AR-10 shows the spatial distribution of good quality data (duration) and the percentage of flow above maximum gauged stage height (MGSH) (this assessment was only undertaken on stations with ten years or more of data). The greatest concentration of streamflow gauging stations is to the east in the vicinity of the town of Nhulunbuy. The rest of the Arafura region is sparsely gauged, and where streamflow gauging stations do exist the streamflow records are short and intermittent.

There are two gauging stations currently operating in the Arafura region at density of one gauge for every 22,800 km^2. For the 13 regions the median number of currently operating gauging stations per region is 12 and the median density of current gauging stations per region is one gauge for every 9,700 km^2. The Arafura region has a low density of gauging stations relative to other regions in northern Australia and the density is considerably lower than the MDB average. The mean density of current stream gauging stations across the entire MDB is one gauge for every 1,300 km^2.

In Figure AR-10 the productive aquifer layer includes key dolostone and limestone formations and Cretaceous sandstone formations. Consequently these productive aquifers exhibit a wide range of bore yields. Many gauging stations, particularly those in the eastern half of the region, are located within or downstream of productive aquifers (Figure AR-10). Hence the extrapolation of streamflow values recorded at these gauges to the broader region can be misleading.

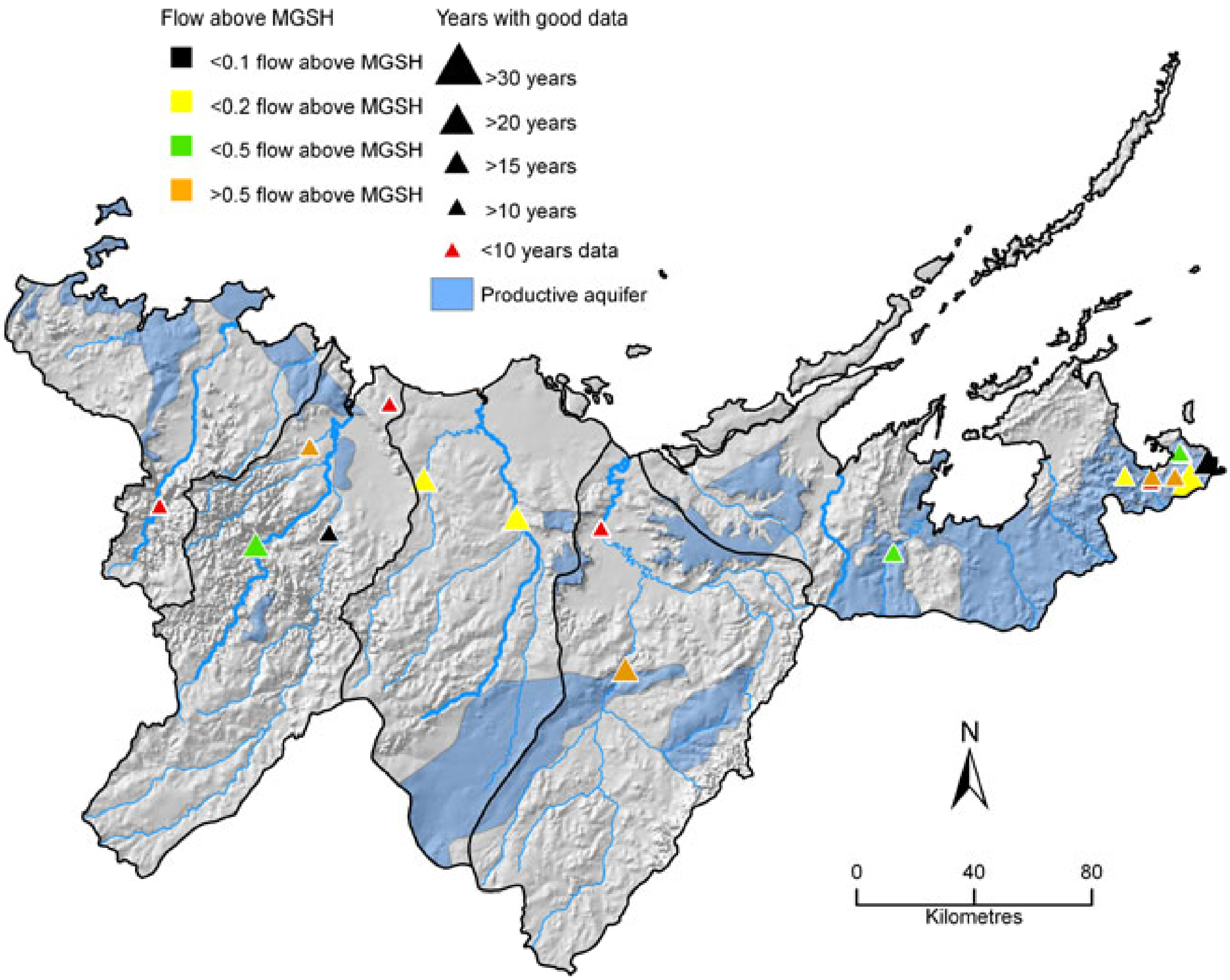


Figure AR-10. Location of streamflow gauging stations overlaid on a relative relief surface showing the proportion of gauges with flow above maximum gauged stage height across the Arafura region. Productive aquifer layer includes key dolostone, limestone and Cretaceous sandstone formations

AR-2.2.3 Groundwater

The Arafura region contains a total 875 registered groundwater bores. Eighty-nine of these bores have surveyed elevations that could enable watertable surfaces to be constructed for the main aquifers. However these bores are not necessarily monitored on a regular basis. There are 95 water level monitoring bores in the region; 92 are historical and three are current (Figure AR-11).

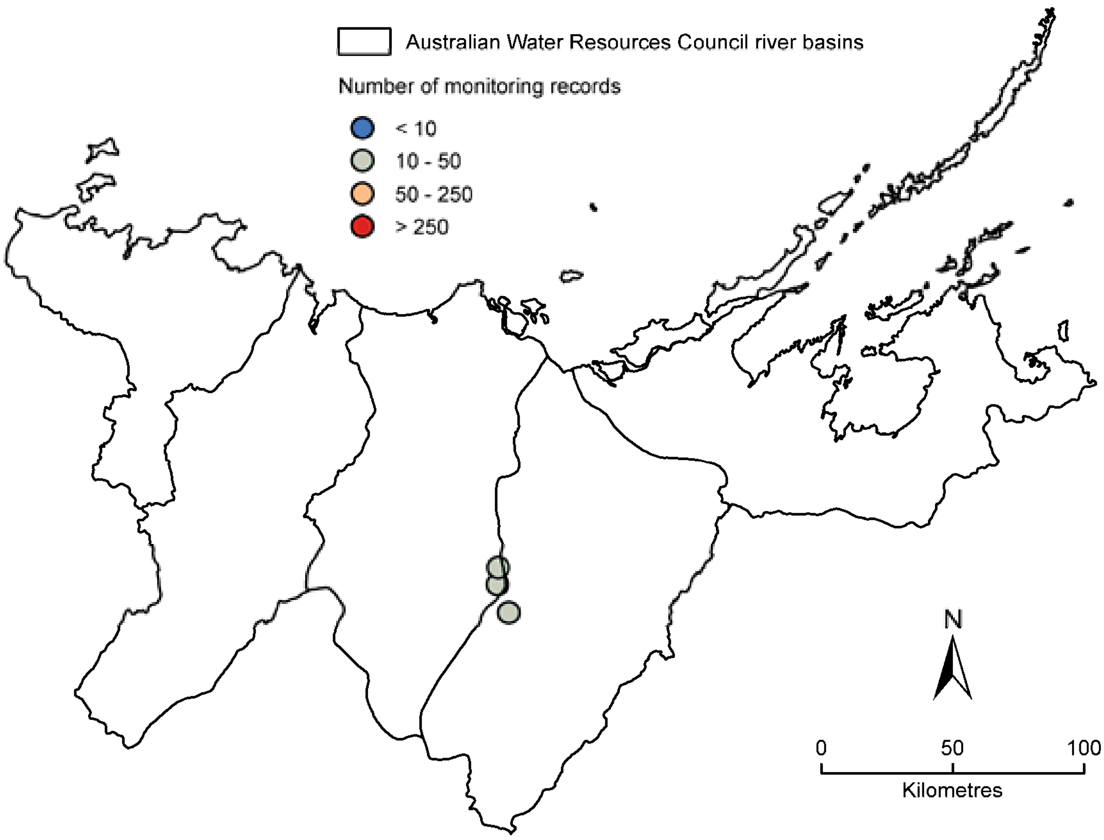


Figure AR-11. Current groundwater monitoring bores in the Arafura region

AR-2.2.4 Data gaps

Groundwater extraction for the Ranger uranium mine is significant, but not metered.

The region contains major perennial rivers with dry season flows maintained by discharge from aquifers developed in both the Cretaceous sediments and the Proterozoic carbonates. However since 1987 the only gauging stations that have been in operation on these perennial rivers have been used to determine the impact of bauxite operations near Nhulunbuy. Given the mineral potential of this region, it is important that a representative network of gauging stations and groundwater monitoring sites are operated so that the impact of future mining developments will be able to be adequately assessed.

AR-2.3 Hydrogeology

This section describes the key sources of groundwater in the Arafura region. The description is primarily based on reports and water bore data held by the Northern Territory Government Department of Natural Resources, Environment, Arts and Sports (NRETAS). The distribution of water bores in the region in 2008 is shown on Figure AR-12.

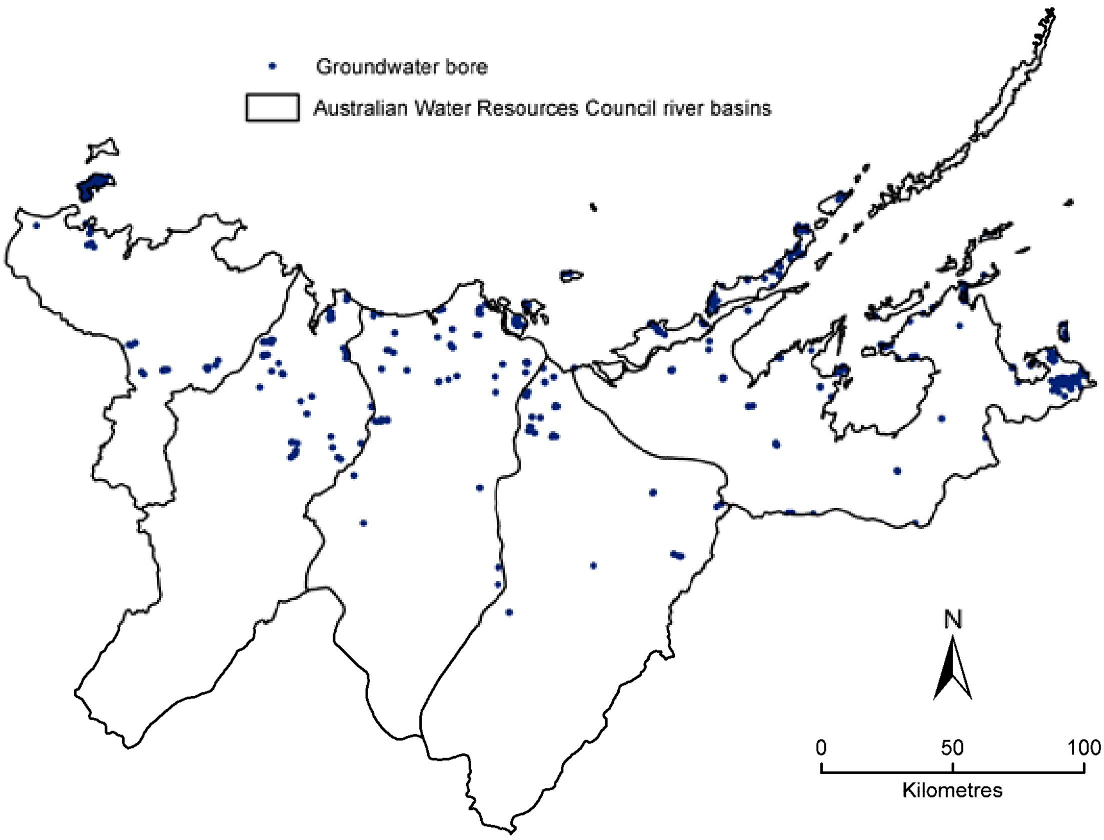


Figure AR-12. Location of groundwater bores in the Arafura region

AR-2.3.1 Aquifer types

There are three major aquifer types in the Arafura region. These types are fractured rocks, karstic carbonate rocks and Cretaceous sediments, all of which are briefly described below and their areal extent is shown on Figure AR-2.

Fractured rocks

A variety of Precambrian (older than 500 million years) rocks form the bedrock of the area. These are mainly sedimentary but also include granite and volcanic rocks. Sandstone, siltstone and greywacke are the main sedimentary rock types. In some areas they are flat-lying while in other areas they have been folded, faulted and show low grade metamorphism.

Water is usually intersected in weathered fractured zones within the fractured rocks. Groundwater yields are controlled by the degree of fracturing of these units and are likely to be greater in areas located along large scale joints and fault zones.

Karstic carbonate rock – Proterozoic carbonates (includes the Dook Creek Formation)

The major karstic aquifer in the region occurs within the Proterozoic carbonate rocks of the Dook Creek Formation. The Dook Creek Formation contributes very significant dry season flow to the Goyder and Blyth rivers. The Goyder River is the main source of water during the dry season for the Arafura Swamp. The detailed hydrogeology of the Proterozoic carbonates is not known as little investigation work has been undertaken.

Cretaceous sediments

The Cretaceous sediments form a mantle of lateritised claystone and sandstone covering much of the area. On Figure AR-2 sediments have only been mapped where it is expected that they form the major aquifer at that locality. However they overlie the karstic rock aquifers over much of the region. The beds are sub-horizontal and may be divided into an upper claystone and siltstone unit and a basal sandstone unit.Outcrop is generally sparse due to the soft nature of the rock but in places silicification has altered them to porcellanite and quartzite.

In the north east the formation may be over 100 m thick with most of that thickness being permeable sandstone (cross-section in Figure AR-2). The Cretaceous sandstone aquifer contributes significant dry season flows to many rivers across the region, particularly in the north east. The sandstone provides the source of water for most communities in north east Arnhem Land and for the bauxite mine near Nhulunbuy.

AR-2.3.2 Inter-aquifer connection and leakage

In the region there is likely to be some degree of connection between the fractured rock aquifers, karstic carbonate aquifers and the basal sandstone of the Cretaceous sediments. However, there is no data to demonstrate or quantify these processes.

AR-2.3.3 Recharge, discharge and groundwater storage

Recharge occurs only in the wet season when rainfall intensity and duration is sufficient, and leads to a rise in groundwater levels. In the dry season the levels naturally fall as groundwater is either transpired or discharged to wetlands and rivers, where it evaporates or is discharged to the sea. The amount and rate at which the groundwater levels rise and fall depend on the type, size and other physical properties of the aquifer as well as the amount of recharge. The recharge/discharge cycle that applies in the Arafura region is summarised in Figure AR-13.

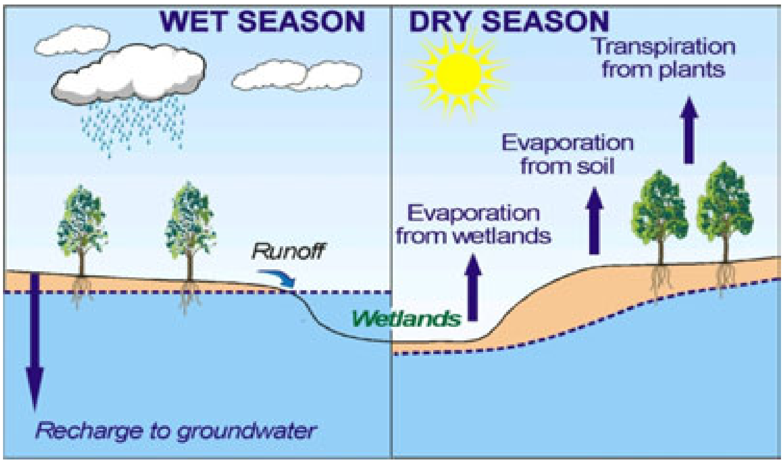


Figure AR-13. Schematic of the recharge and discharge cycle that applies in the Arafura region

Recharge beneath native vegetation is dominated by bypass flow and not diffuse movement through soil horizons. The most likely mechanism for this is via macro-pores such as cracks and root holes in the soil. Sinkholes and stream sinks have been located over the Proterozoic carbonates.

Groundwater discharge occurs across the region mostly as evaporation and transpiration (ET). Groundwater discharge is also important for maintaining perennial reaches of many rivers within the region. The most visible of these discharges take the form of springs on or adjacent to the banks of rivers such as the Blyth, Goyder, Habgood, Cato and Latram, as well as Yirrkala and Jungle Creeks. However the majority of discharge occurs as diffuse discharge through the beds of rivers. The Northern Territory Government currently maintains one river gauging station for all of the above perennial rivers in Arnhem Land.

Specific comments relating to recharge and discharge for each of the three major aquifer types follow. The locations of monitoring bores and river gauging stations in the Arafura region that are referenced in the following sections are shown on Figure AR-2.

Fractured rocks

A number of the towns in the region obtain their water supply from aquifers developed in sandstone of Proterozoic age. The sandstone has been fractured and extensively weathered to depths of up to 100 metres. Time series groundwater level data for representative fractured rock aquifer bores located at Maningrida (RN008124), Millingimbi (RN021388) and Galiwinku (RN020925) is shown in Figure AR-14.

The variability of recharge rate to the fractured rock aquifers is reflected in the variability in water levels measured in monitoring bores intersecting the aquifer. The variation in water level in bore RN008124 over the 15-year period for which records exist ranged from a low of 1 m in 1989/90 to a high of 9 m in 1994/95; the mean annual variation was approximately 4 m.

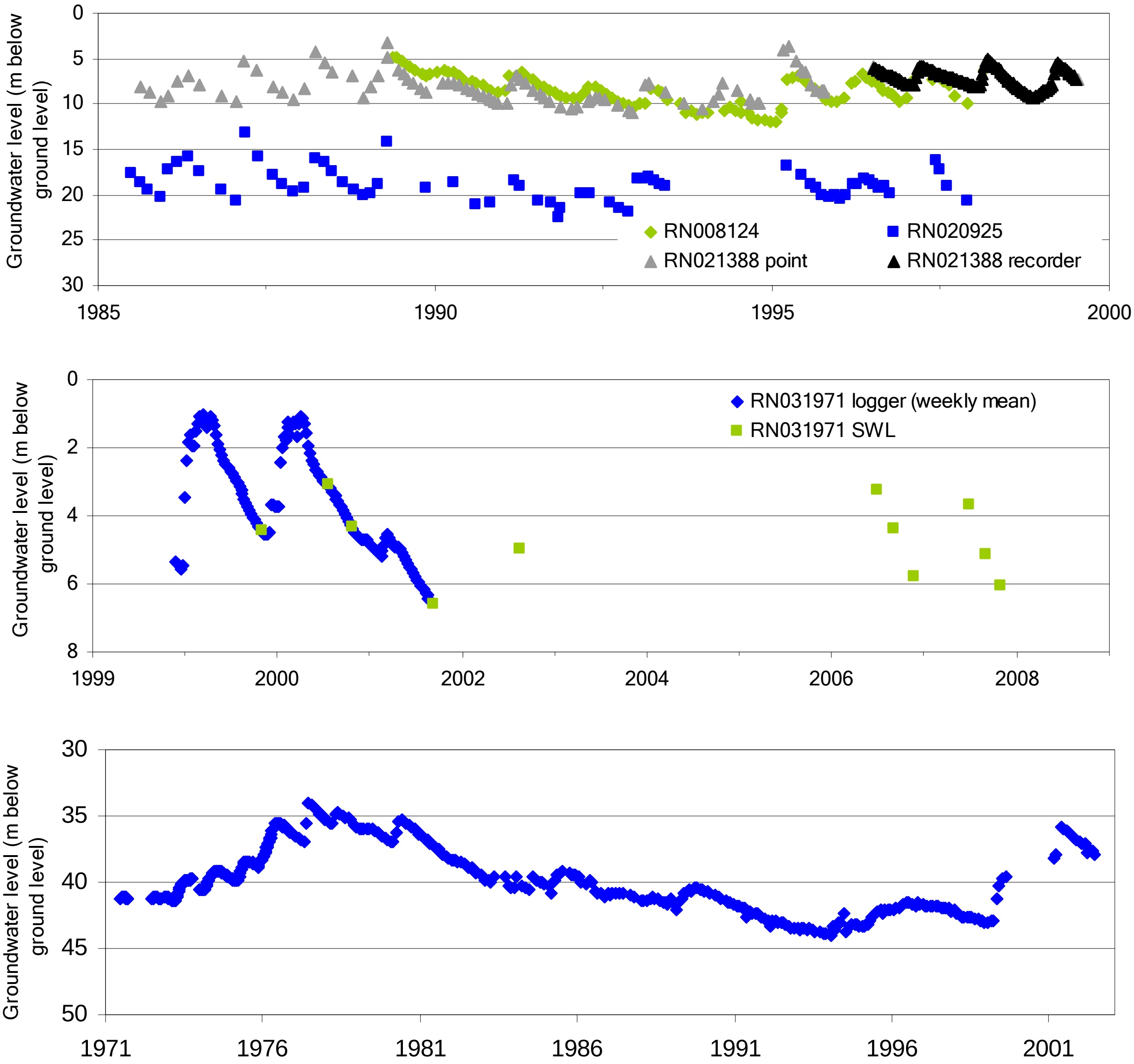


Figure AR-14. Observed groundwater levels in monitoring bores in the fractured rock aquifer (RN008124, RN020925 and RN021388), Proterozoic carbonates (RN031970) and Cretaceous sediments (OB17)

Proterozoic carbonates

There are only limited data available for groundwater levels in the Proterozoic carbonates. Time series groundwater level data are shown in Figure AR-14 for bore RN031970 located in the Dook Creek Formation near the Goyder River.

Within the region groundwater discharge from the aquifer developed in the Proterozoic carbonates provides the dry season flow for the Goyder, Blyth and Habgood rivers. The Goyder River flows into the Arafura Swamp (refer Figure AR-14. Williams et al (2003) estimated recharge to the area of the Dook Creek Formation that provides the source of dry season flows for the Goyder River. Based on predicted groundwater discharge fluxes to the river, mean annual recharge was estimated at 90 mm/year for the period 1884 to 1999.

Cretaceous sediments

Regional groundwater discharge from the Cretaceous sediments provides the dry season flow for the perennial Yirrkala and Jungle Creek and Cato and Latram rivers.

Changes in dry season streamflow rates occur in response to changes in the amount of rainfall that recharges the aquifer during the preceding wet season. The variability in recharge rate is reflected in the variability in groundwater levels measured in monitoring bores intersecting the aquifer. Time series groundwater level data for bore OB17 located near

Yirrkala (URS 2003) is plotted in Figure AR-14. The data indicates that annual groundwater level rises due to recharge during the wet season vary from minimal to over 3 metres. Prowse et al. (1999) demonstrated that periods of the monitoring record when groundwater levels are relatively low correspond to periods when streamflows in the perennial rivers of north east Arnhem Land are lower. Likewise, periods of high groundwater levels correspond to periods of higher streamflow. The mean annual wet season rise in groundwater level during the monitoring period was approximately 1 m/year.

URS (2003) determined that no recharge will occur in the area in which bore OB17 is located until approximately 800 mm of rainfall has occurred during the wet season. The same study developed a numerical groundwater model for the sandstone aquifer and determined that the steady state recharge rate (ie average recharge rate) to the area that OB17 is located in was 100 mm per wet season. The rest of the model domain was assigned a recharge rate of 384 mm/year; however no reason was given for the reduction in recharge rate beneath the area containing the bauxite.

AR-2.3.4 Groundwater quality

The quality of most groundwater from the fractured rock aquifers across the Arafura region falls within acceptable drinking water guidelines (ADWG, 2004) except beneath floodplains such as the Arafura Swamp where the water is too saline for most purposes.

Groundwaters in the Proterozoic carbonates are slightly alkaline on average but pH can range from 6.4 to 8. Calcium, magnesium and bicarbonate are the dominant ions, while the salinity (as electrical conductivity) is mostly in the range 300 to 1000 µS/cm (Figure AR-15). Calcium, magnesium and bicarbonate concentrations are similar throughout the carbonate aquifer as they dissolve relatively easily from the limestone and dolomite matrix and, once saturation with respect to the latter minerals is reached, the concentrations stabilise. Hardness is normally high and will cause scale build-up in water delivery infrastructure.

Groundwaters in the Cretaceous sediments are acidic with pH values of ranging from 4.5 to 5.5. The salinity as electrical conductivity mostly ranges between 50 and 100 µS/cm.

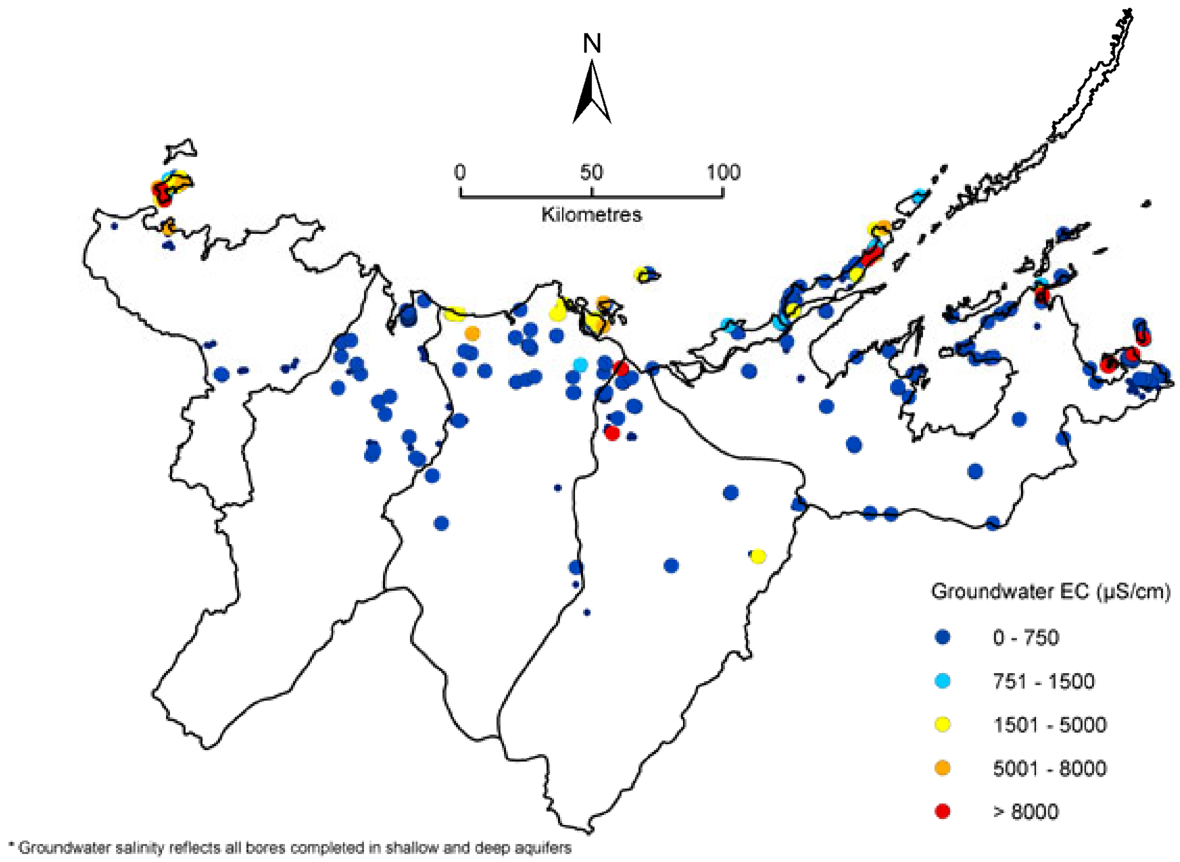


Figure AR-15. Groundwater salinity distribution for all bores drilled in the Arafura region

AR-2.4 Legislation, water plans and other arrangements

AR-2.4.1 Legislated water use, entitlements and purpose

Current

Currently there are no groundwater extraction licences in the Arafura region (NRETA, 2009). URS (2003) reported that a groundwater extraction licence existed to extract 12,000 ML from the borefield that supplies Rio Tinto's bauxite mine near Yirrkala and the town of Nhulunbuy.

The towns in the Arafura region are Yirrkala, Nhulunbuy, Gapuwyak, Galiwinku, Millingimbi, Ramingining, Maningrida, Warruwi, Minjilang, Gunbalanya and Jabiru. The total population living within the region is probably less than 30,000. The main activity occurring in the region is mining. Other activities include tourism and grazing.

Groundwater use is metered for all towns and Rio Tinto's bauxite mining operation near Yirrkala. Metered data is not available for the water extracted at the Rio Tinto's Ranger uranium mine.

The largest user of groundwater in the region for which data is available is Rio Tinto's bauxite mine. URS (2003) documented extraction from the borefield that supplies both the mine and the town of Nhulunbuy; the data yielded a mean annual extraction of 9300 ML/year.

Water use by the towns of Arnhem Land (excluding Nhulunbuy) was documented by the Northern Territory Civil and Drafting Services (2005). Borefield extraction data for a typical town, Milingimbi, indicates that borefield production is approximately the same throughout the year. This community had an estimated population of 920 and an average water use of 500 to 600 L/person/day throughout the year. This is consistent with data the Northern Territory Civil and Drafting Services (2005) compiled for other towns in the Arnhem Land, equating to a regional town water supply extraction of approximately 6000 ML/year.

Future

Currently there are no applications for groundwater extraction licences in the area.

AR-2.4.2 Rivers and storages

There are no significant storages on any river in the region. The Arafura Swamp, within the estuarine system of the Goyder River is an extensive region of billabongs and river channels covering over 700 km^2.

AR-2.4.3 Unallocated water

The entire region is under Indigenous Native Title. Hence, under the Northern Territory's water administration regime it is an unallocated system where no licences for commercial use of surface or groundwater have been granted.

AR-2.4.4 Social and cultural considerations

Water governance on the Indigenous estates surrounding the Maningrida area were studied by Altman (2008) in a series of case studies prepared for the North Australian Indigenous Land and Sea Management Alliance's Indigenous Water Policy Group. Maningrida is a large Indigenous township located within the Arnhem Land Aboriginal Land Trust region encompassing a number of entire river catchments, including the Mann-Liverpool and Cadell-Blyth River catchments. The Land Trust manages land held under inalienable Aboriginal title following passage of *the Aboriginal Land Rights (Northern Territory) Act 1976*. Prior to that, it was Crown land reserved for exclusive Indigenous use since the early 20th century. Arnhem Land represents a 'frontier' in water management: under the Northern Territory's water administration regime it is an unallocated system where no licences for commercial use of surface or groundwater have been granted.

The region is characterised by a pattern of monsoonal rainfall that generates an abundance of water during the wet season (December to April). Although it is commonplace to talk of distinct wet and dry seasons in this region, indigenous seasonality is classified into at least six seasons with each highly dependent on actual weather conditions rather than time of year (Altman, 1987). Another notable difference in hydrological concepts relates to groundwater/surface water interactions. The distinction between ground and surface water that is now dominating discussions about water governance in managerial circles is not so prominent in Indigenous classifications, although the inter-connections between the two are strongly recognised in Indigenous religious beliefs.

Jackson and Altman (*in press*) observe that the high awareness and deep understanding that Aboriginal people have of the connectivity between groundwater and surface water is evident in the most sacred Creation stories which depict the route taken by the mythical Being, the Rainbow Serpent, who is said to have travelled underground between various water places. Local knowledge of the network of groundwater flows and discharge sites contributed to recent hydrological studies and helped establish the records of the historical behaviour of water places (Zaar, 2003). The frequent occurrence of water themes throughout local mythology is testimony to the detailed understanding local Aboriginal people have of the hydro-ecology, as well as their economic and spiritual significance.

The Maningrida case focuses on just three linked broad perspectives on water: a historical analysis of the political economy of water; a sectoral analysis of water in the regional ‘hybrid’ economy; a spatial analysis of water governance in Maningrida and the hinterland. A series of dichotomies is evident, both between western and Aboriginal views about water, but also in recent times within the Aboriginal domain. The summary provided in Jackson and Altman (*in press*) highlights the cross-cultural contestation over water values and property rights and the need for a new water governance paradigm for this region that lies ‘beyond the state’s water allocation system’.

Zaar’s water resource assessments of West and East Arnhem Land included a component on Indigenous knowledge of water occurrence and significance. A separate report containing Aboriginal knowledge collected during field trips was produced for both east and west Arnhem Land (Zaar and Prowse, 1999; Zaar, 2003). The data consists largely of placenames and their location. Some of these placenames, where appropriate, have been recorded on the Water Resource Map and are also included in the GIS version of the map. Stories relating to water were also recorded e.g. the rainbow serpent which is associated with billabongs and freshwater springs is responsible for the production of most water plants such as water lilies, algae and palms, found growing near water (Zaar, 2003). The roar of waterfalls in the escarpment country is said to be the sound of the serpent’s voice. The East Arnhem Land Study includes transcribed narratives describing the formation of cultural water sites.

AR-2.4.5 Changed diversion and extraction regimes

There are no significant diversions or extraction regimes in the region.

AR-2.4.6 Changed land use

The region retains a near-pristine condition, with minimal changed land use.

AR-2.4.7 Environmental constraints and implications of future development

The entire region is under Indigenous Native Title. There is no formal environmental water reserve established, and no future development is envisaged beyond localised stock and domestic supplies.

AR-2.5 References

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AR-3 Water balance results for the Arafura region

This chapter describes modelling results and the assessment of the water resources undertaken by this project for the Arafura region. Detailed, quantified assessments are made where possible, and relevant, and confidence is estimated. Modelling results are reported under climate and development scenarios as defined at the division level in Section 2.1 of Chapter 2. This chapter is sub-divided into:

- climate
- recharge estimation
- conceptual groundwater models
- groundwater modelling results
- rainfall-runoff modelling results
- river system water balance
- changes to flow regimes at environmental assets.

AR-3.1 Climate

AR-3.1.1 Historical climate

The Arafura region receives an average of 1186 mm of rainfall over the September to August water year (Figure AR-16), most of which (1140 mm) falls in the November to April wet season (Figure AR-17). Across the region there is a strong north–south gradient in annual rainfall (Figure AR-18), ranging from 1383 mm in the north to 920 mm in the south. Over the first half of the historical (1930 to 2007) period, annual rainfall has been relatively constant at around 1050 mm. The second half of the historical period has seen an increase in mean annual rainfall to approximately 1350 mm. The highest yearly rainfall received was 1821 mm which fell in 2001, and the lowest was 595 mm in 1952.

Historical areal potential evapotranspiration (APET) is very high across the region, averaging 1898 mm over a water year (Figure AR-16), and varies moderately across the seasons (Figure AR-17). APET generally remains higher than rainfall throughout the year resulting in year-round water-limited conditions.

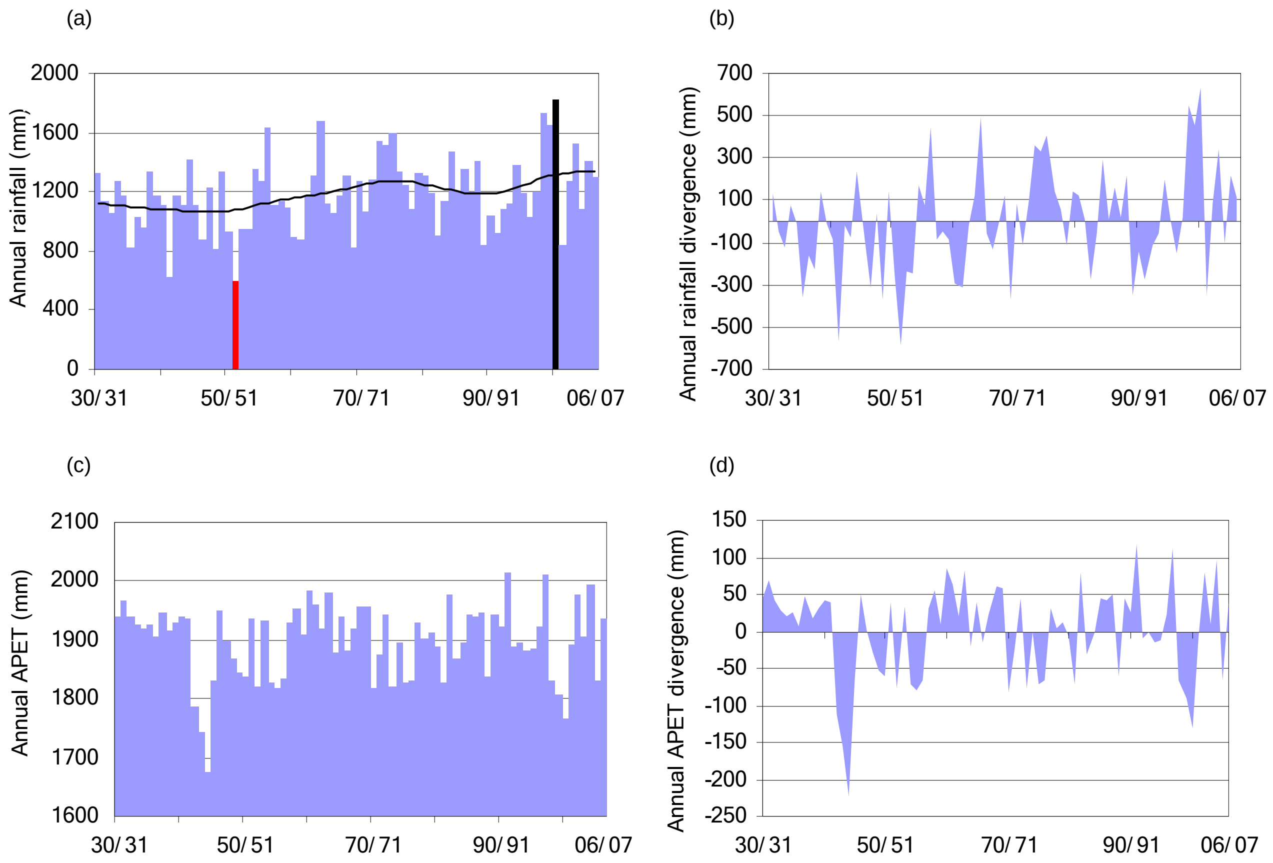

Figure AR-16. (a) Historical annual rainfall and (b) its divergence from the long-term mean; and (c) historical annual areal potential evapotranspiration and (d) its divergence from the long-term mean averaged over the Arafura region. The low-frequency smoothed line in (a) indicates longer term variability

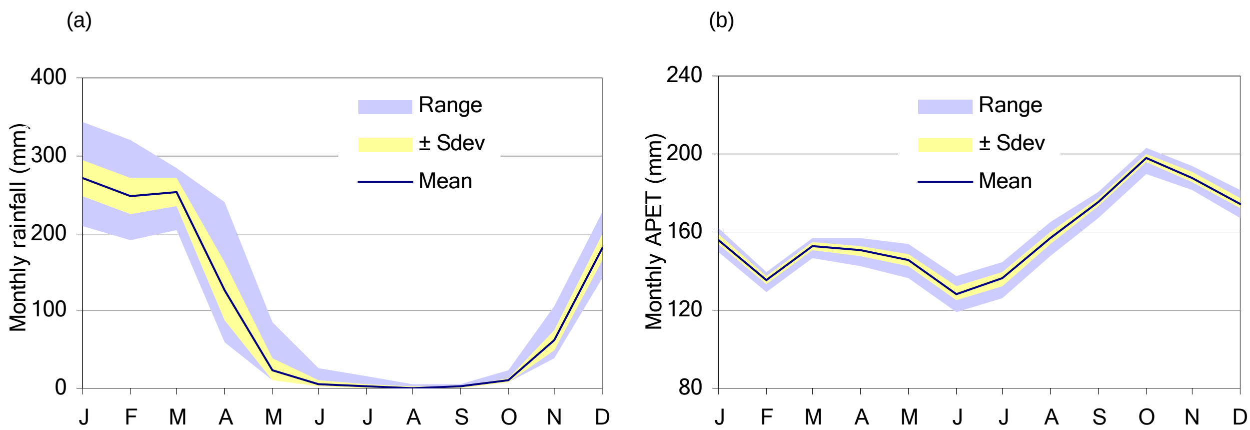

Figure AR-17. Historical mean monthly (a) rainfall and (b) areal potential evapotranspiration and their temporal variation (range and ± one standard deviation) averaged over the Arafura region

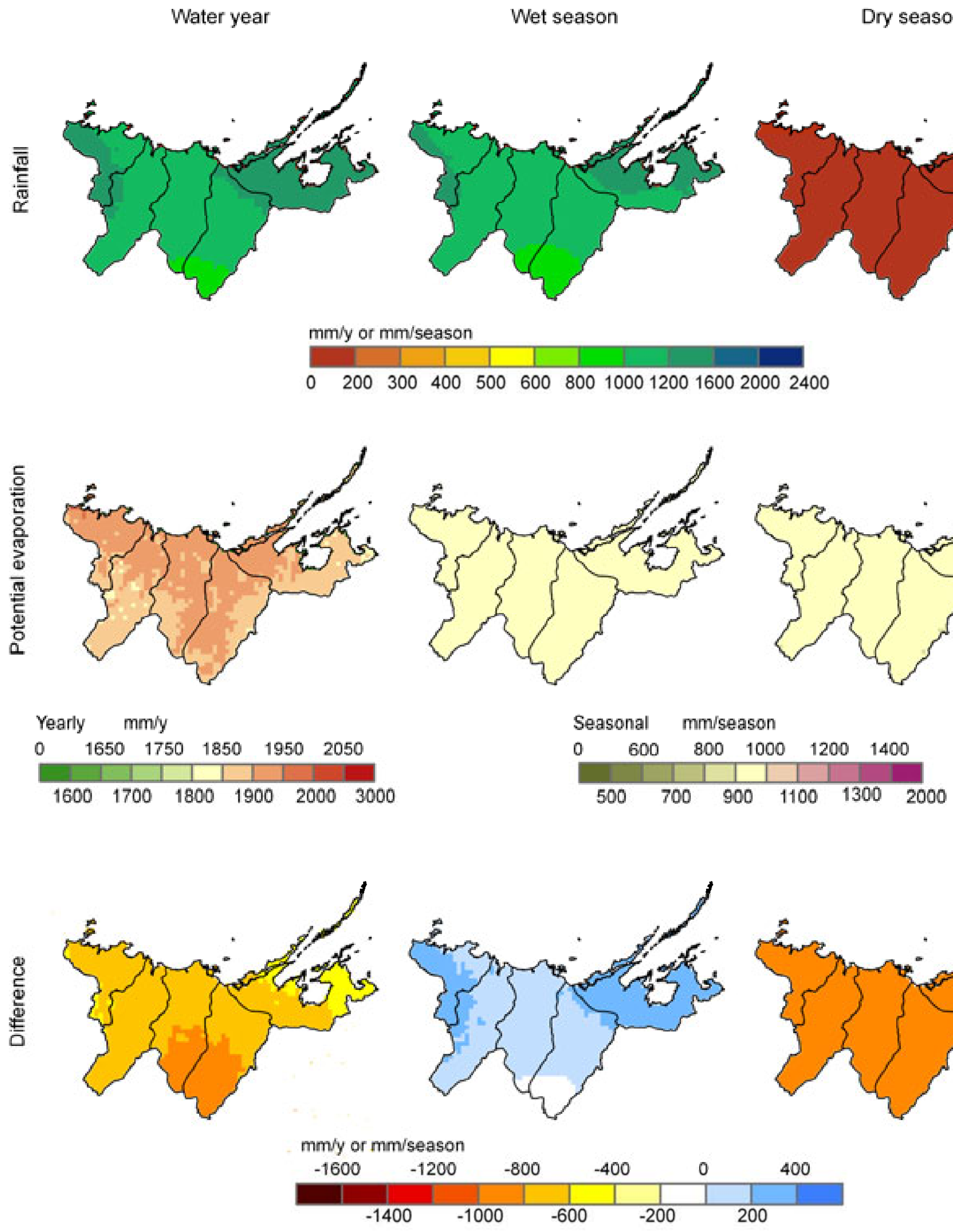

Figure AR-18. Spatial distribution of historical mean annual (water year), wet season and dry season rainfall and areal potential evapotranspiration (potential evaporation) and their difference (rainfall less areal potential evapotranspiration) across the Arafura region

AR-3.1.2 Recent climate

Figure AR-19 compares recent (1996 to 2007) to historical (in this case the 66-year period from 1930 to 1996) mean annual rainfall for the Arafura region. Across the whole region, recent rainfall is between 10 and 20 percent higher than historical rainfall – a statistically significant difference for the majority of the region.

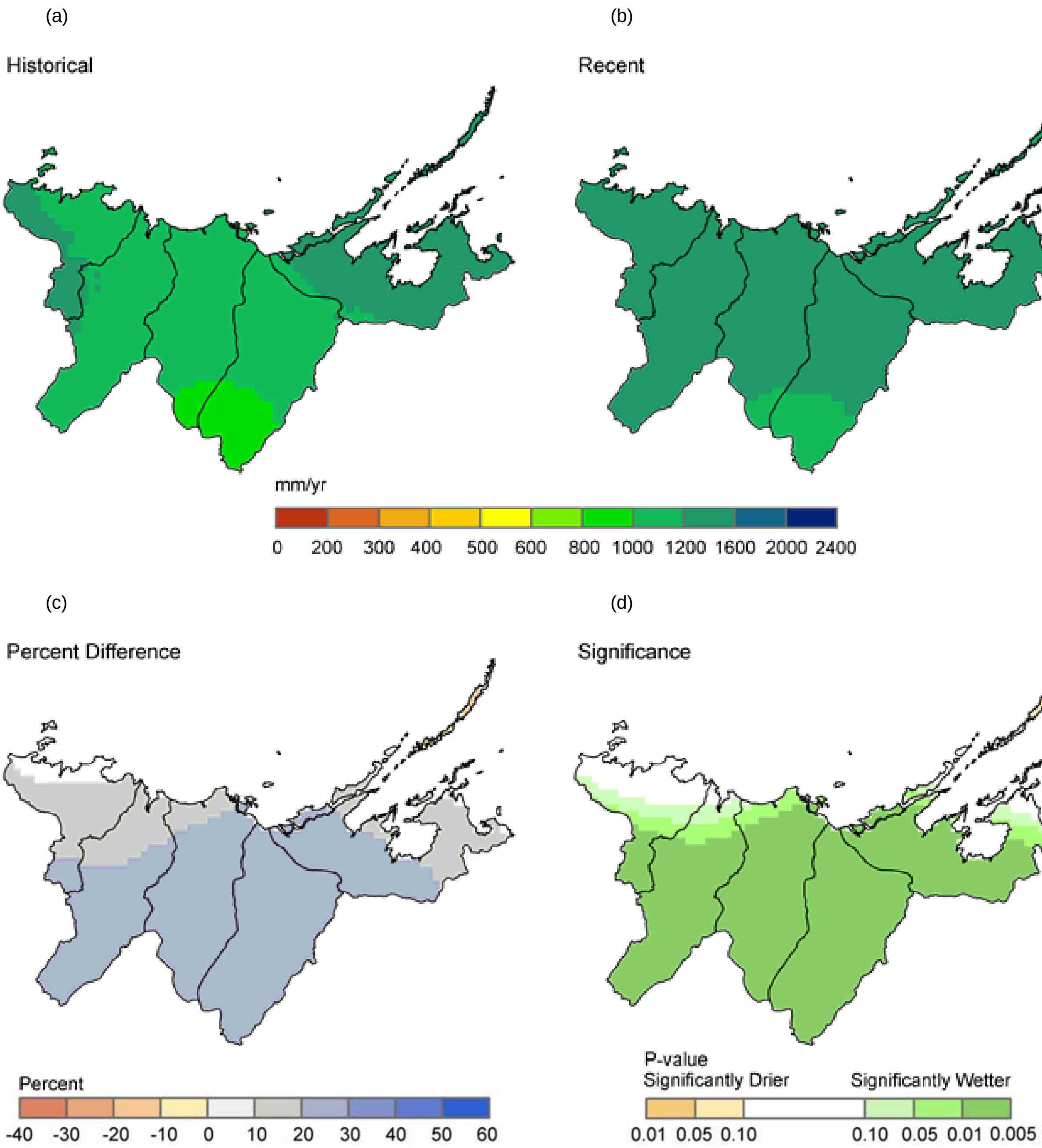

Figure AR-19. Spatial distribution of (a) historical and (b) recent mean annual rainfall; and (c) their relative percent difference and (d) the statistical significance of these differences across the Arafura region

AR-3.1.3 Future climate

Under Scenario C annual rainfall varies between 1060 and 1266 mm (Table AR-3) compared to the historical mean of 1186 mm. Similarly, APET ranges between 1918 and 1995 mm compared to the historical mean of 1898 mm.

A total of 45 variants of Scenario C were modelled (15 global climate models (GCMs) for each of the high, medium and low global warming scenarios). Subsequently, results from an extreme ‘wet’, median and extreme ‘dry’ variant are shown (referred to as scenarios Cwet, Cmid and Cdry). Under Scenario Cwet annual rainfall and APET increase by 7 percent and 1 percent, respectively. Under Scenario Cmid annual rainfall increases by 1 percent and APET increases by 2 percent. Under Scenario Cdry annual rainfall decreases by 11 percent and APET increases by 5 percent.

Under Scenario Cmid long-term monthly averages of rainfall and APET do not differ much from historical values (Figure AR-20). Under Scenario Cmid rainfall lies well within the range in values from all 45 future climate variants. The seasonality of rainfall changes slightly only in that any changes in rainfall occur in the wet season. However there is appreciable variation in rainfall in the wet season months, varying by up to 100 mm/month. In contrast, the seasonality of APET remains the same as any changes occur uniformly across the year. Under Scenario C APET is greater than historical values for all months of the year, with historical values approximately equal to the lower bound of the range in values derived from all 45 future climate variants.

The spatial distributions of rainfall and APET under Scenario C are compared to the historical distribution in Figure AR-21 and Figure AR-22. Under Scenario C the strong north–south gradient in rainfall is retained, but with a southwards shift under Scenario Cwet and a northwards shift under Scenario Cdry. The spatial distribution of APET under Scenario C is similar to the highly regionalised historical distribution.

Table AR-3. Mean annual (water year), wet season and dry season rainfall and areal potential evapotranspiration averaged over the Arafura region under historical climate and Scenario C

Scenario	Water year*	Wet season	Dry season
	mm/y	mm/season	
Rainfall			
Historical	1186	1140	46
Cwet	1266	1201	51
Cmid	1202	1143	45
Cdry	1060	1017	30
Areal potential evapotranspiration			
Historical	1898	958	941
Cwet	1918	959	958
Cmid	1931	973	957
Cdry	1995	1013	981

* Note that the sum of the wet season and dry season values does not always equal the water year values because the combined wet season and dry season period (November to October) is different to the water year period (September to August).

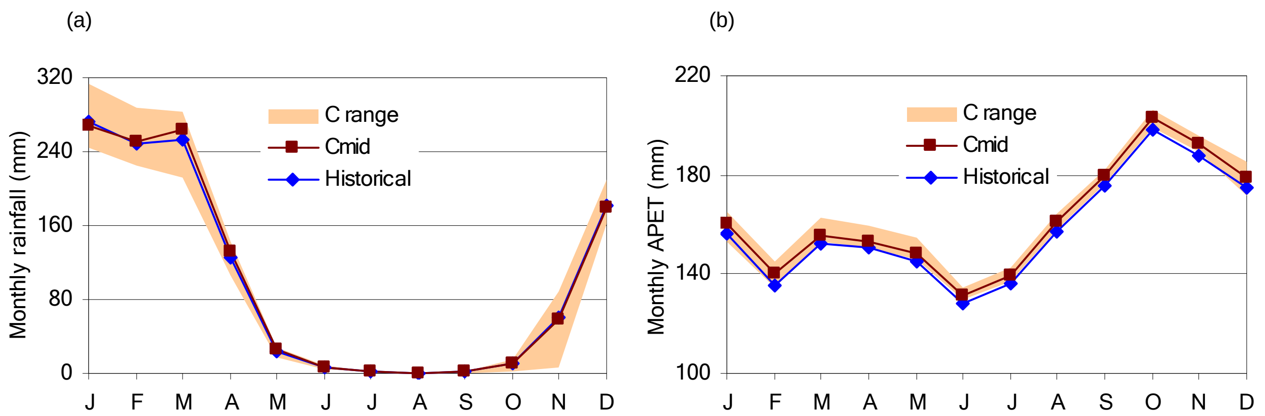

Figure AR-20. Mean monthly (a) rainfall and (b) areal potential evapotranspiration averaged over the Arafura region under historical climate and Scenario C. (C range is pooled from all 45 Scenario C simulations (15 global climate models and three global warming scenarios) – the lower and upper limits in C range are therefore not the same as scenarios Cdry and Cwet)

AR-3.1.4 Confidence levels

Analysis of confidence of the climate data is reported in Section 2.1.4 of the division-level Chapter 2.

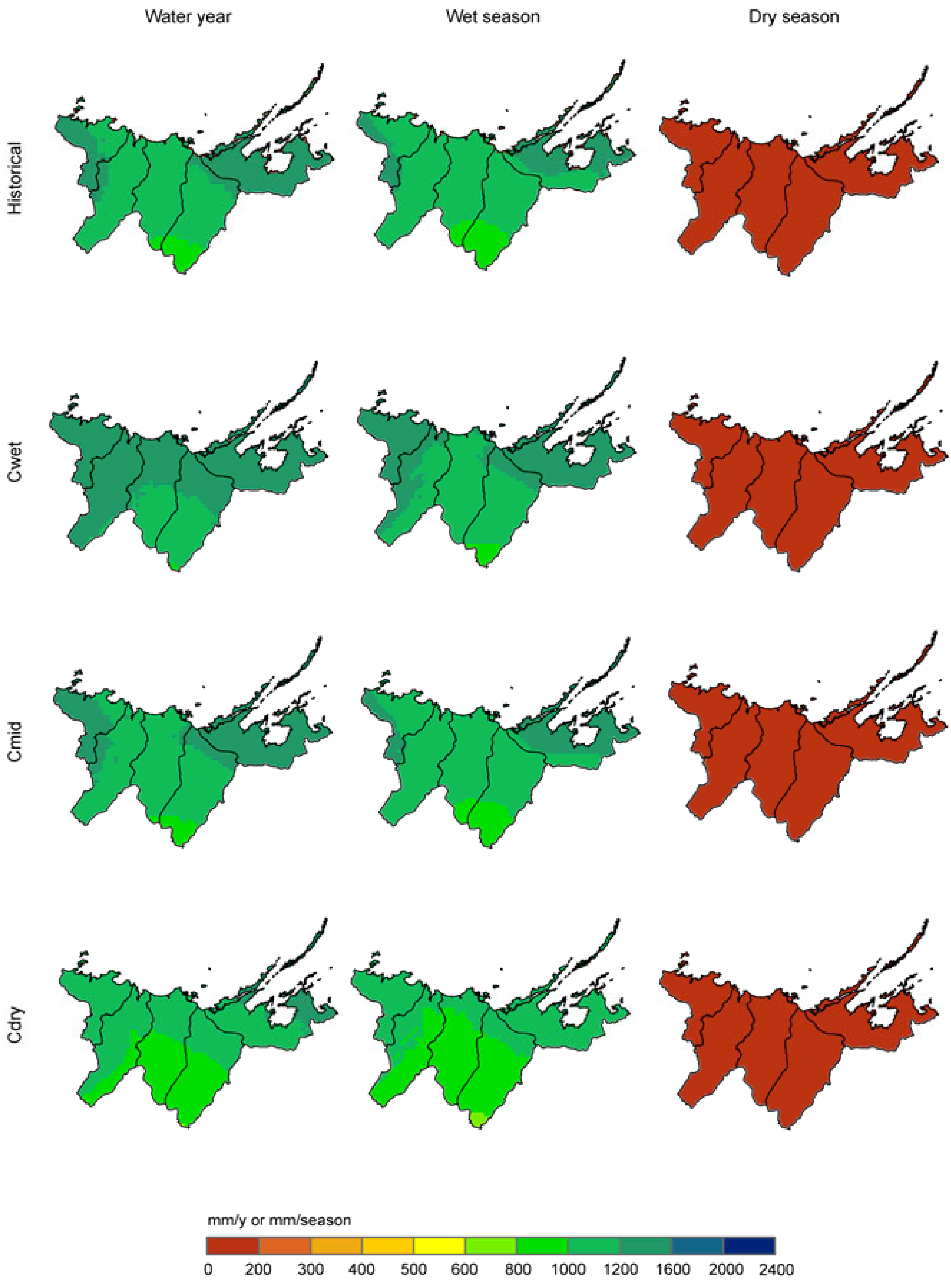

Figure AR-21. Spatial distribution of mean annual (water year), wet season and dry season rainfall across the Arafura region under historical climate and Scenario C

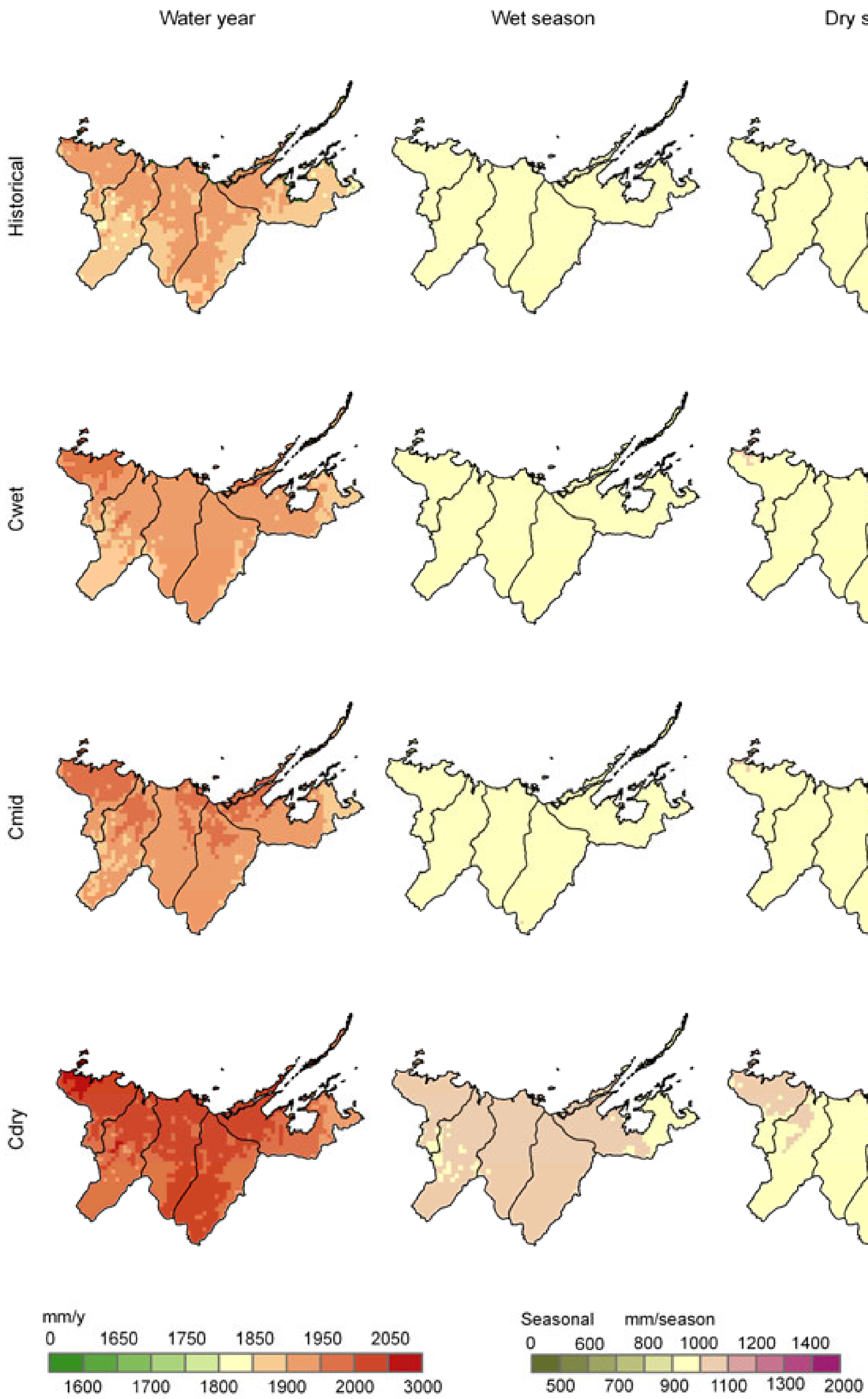

Figure AR-22. Spatial distribution of mean annual (water year), wet season and dry season areal potential evapotranspiration across the Arafura region under historical climate and Scenario C

AR-3.2 WAVES potential diffuse recharge estimations

The WAVES model (Zhang and Dawes, 1998) was used to estimate the change in groundwater recharge across the Arafura region under a range of different climate scenarios. WAVES is a vertical recharge flux model that can model plant physiological feedbacks in response to increased CO_2, as well as modelling the water balance of different soil, vegetation and climate regimes. It was chosen for its balance in complexity between plant physiology and soil physics. It was also used to assess recharge for the Murray-Darling Basin Sustainable Yields Project (Crosbie et al., 2008).

Where unweathered bedrock outcrops occur, confidence in the modelled results is reduced. The locations of these outcrops in the Arafura region are shown on the historical recharge map in Figure AR-23.

Table AR-4. Recharge scaling factors in the Arafura region for scenarios A, B and C

Region	Awet	Amid	Adry	B	Cwet	Cmid	Cdry
Arafura	1.13	0.97	0.85	1.27	1.34	1.15	0.91

AR-3.2.1 Under historical climate

The calculated historical recharge for the Arafura region shows that recharge is greatest in the north-east and decreases progressively to the south following the rainfall gradient (Figure AR-28). The historical record was assessed to establish any difference between wet and dry periods of recharge. A 23-year period was used, which allows the projection of recharge estimates to 2030 – in other words, to estimate recharge in 2030 assuming future climate is similar to historical climate (Scenario A). Under a wet historical climate (Scenario Awet) recharge increases 13 percent. Under the median estimate of historical climate (Scenario Amid) recharge decreases 3 percent, quite uniformly across the region. Under a dry historical climate (Scenario Adry) recharge decreases 15 percent.

AR-3.2.2 Under recent climate

The recent (1996 to 2007) climate in the Arafura region has been wetter than the historical (1930 to 2007) average and consequently the calculated recharge increases 27 percent under Scenario B relative to Scenario A (Table AR-4). This increase has not been spatially uniform with the west of the catchment showing recharge close to the historical average and some areas on vertosol soils showing a decrease in recharge (Figure AR-23).

AR-3.2.3 Under future climate

Figure AR-24 shows the percentage change in modelled mean annual recharge averaged over the Arafura region under Scenario C relative to Scenario A for the 45 scenarios (15 global climate models (GCMs) for each of the high, medium and low global warming scenarios). The percentage change in the mean annual rainfall and recharge from the corresponding GCMs are also tabulated in Table AR-5. Under some scenarios the recharge is projected to increase despite a decrease in rainfall. This is because total rainfall is not the only climate variable that influences recharge. Daily rainfall intensity, temperature and CO_2 concentration are also important drivers (see Section 2.3.3 in the division-level Chapter 2), and specific situations can result in this counter-intuitive result. In particular, rainfall intensity is seen as a significant factor in this relationship.

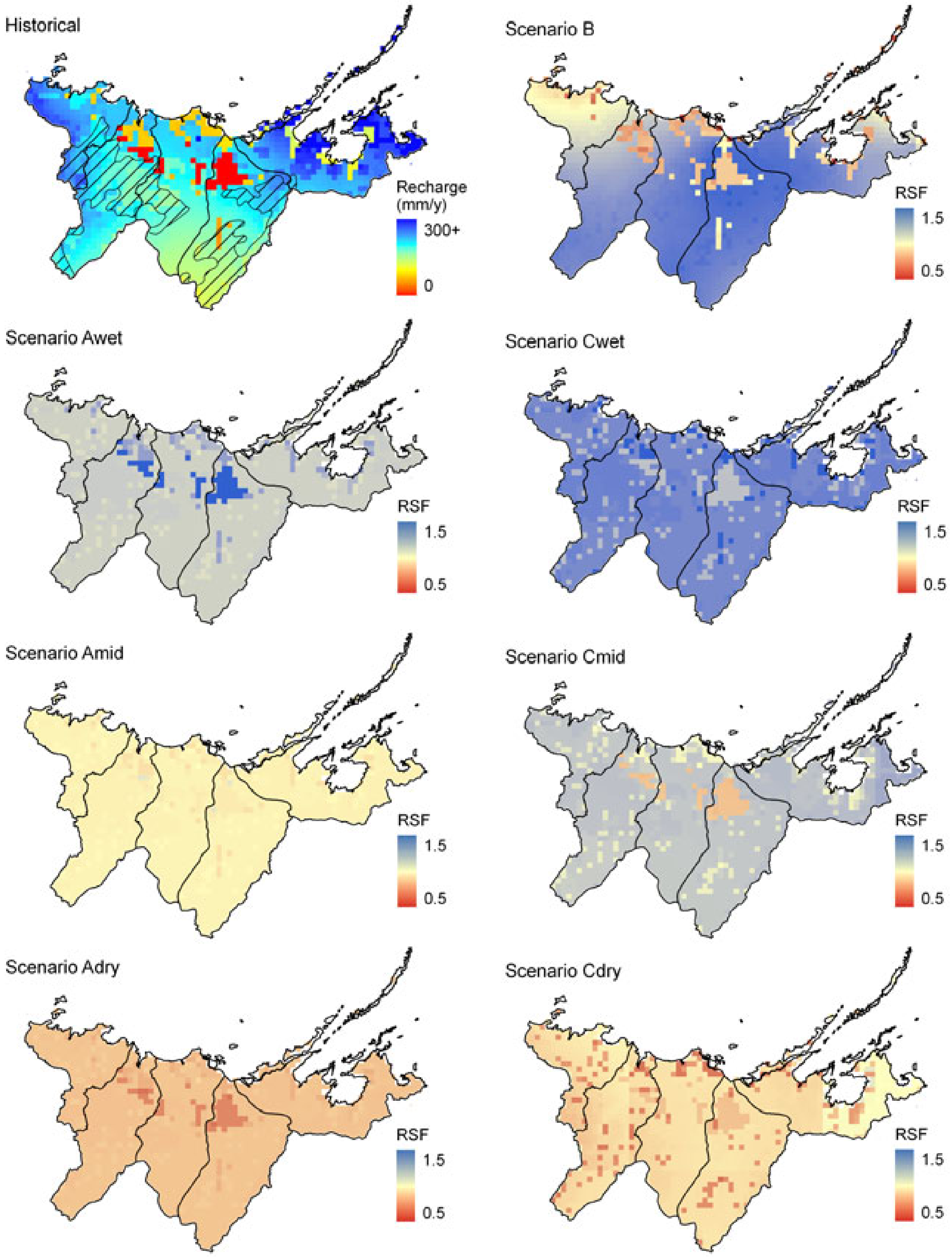

Figure AR-23. Spatial distribution of historical mean recharge rate; and recharge scaling factors across the Arafura region. The hatched region on the historical recharge map identifies where unweathered bedrock outcrops occur

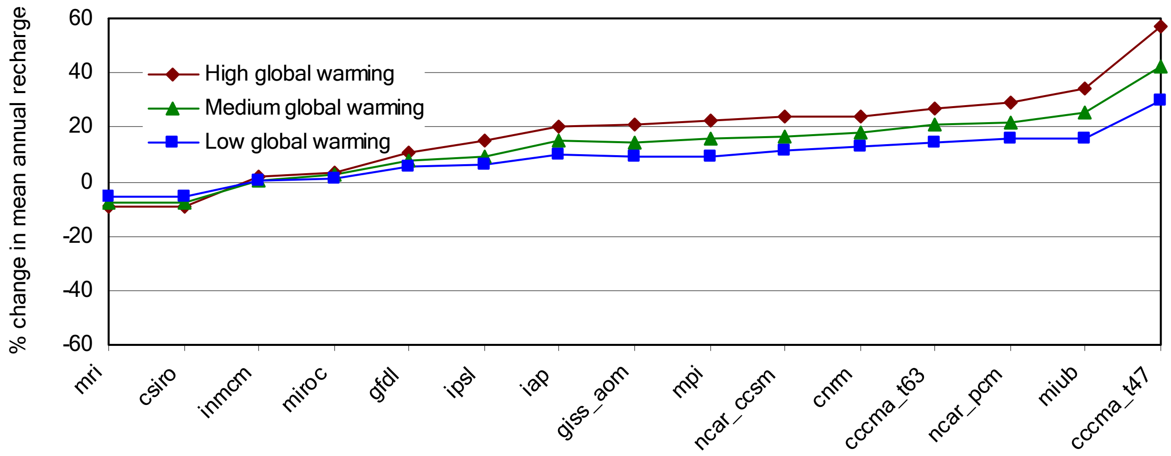

Figure AR-24. Percentage change in mean annual recharge under the 45 Scenario C simulations (15 global climate models and three global warming scenarios) relative to Scenario A recharge

Table AR-5. Summary results under the 45 Scenario C simulations (numbers show percentage change in mean annual rainfall and recharge under Scenario C relative to Scenario A)

High global warming			Medium global warming			Low global warming		
GCM	Rainfall	Recharge	GCM	Rainfall	Recharge	GCM	Rainfall	Recharge
mri	-8%	-10%	mri	-6%	-8%	mri	-4%	-6%
csiro	**-11%**	**-9%**	csiro	-8%	-8%	csiro	-6%	-5%
inmcm	-2%	2%	inmcm	-2%	1%	inmcm	-1%	0%
miroc	-4%	3%	miroc	-3%	3%	miroc	-2%	1%
gfdl	-11%	10%	gfdl	-8%	8%	gfdl	-6%	5%
ipsl	0%	15%	ipsl	0%	9%	ipsl	0%	6%
iap	2%	20%	**iap**	**2%**	**15%**	iap	1%	10%
giss_aom	2%	21%	giss_aom	1%	14%	giss_aom	1%	9%
mpi	-1%	22%	mpi	-1%	16%	mpi	0%	9%
ncar_ccsm	6%	24%	ncar_ccsm	5%	17%	ncar_ccsm	3%	11%
cnrm	3%	24%	cnrm	3%	18%	cnrm	2%	13%
cccma_t63	5%	27%	cccma_t63	4%	21%	cccma_t63	3%	14%
ncar_pcm	7%	29%	ncar_pcm	6%	22%	ncar_pcm	4%	16%
miub	**4%**	**34%**	miub	3%	25%	miub	2%	16%
cccma_t47	13%	57%	cccma_t47	10%	43%	cccma_t47	7%	30%

Under Scenario Cwet recharge increases 34 percent. Under Scenario Cmid recharge increases 15 percent. Under Scenario Cdry recharge decreases 9 percent.

AR-3.2.4 Confidence levels

The estimation of recharge from WAVES is only indicative of the actual recharge and has not been validated with field measurements. A steady state groundwater chloride mass balance has been conducted as an independent measure of recharge (Crosbie et al., 2009). The results in the Arafura region show that the historical estimate of recharge using WAVES (196 mm/year) is greater than the best estimate using the chloride mass balance (101 mm/year) and is outside of the confidence limits of the chloride mass balance (30 to 188 mm/year).

AR-3.3 Conceptual groundwater models

AR-3.3.1 Fractured rocks

Relatively low annual rainfall and high potential evaporation means that recharge to the fractured rock aquifers is likely to only occur after prolonged periods of intense rainfall in the wet season. Recharge is more effective through sandy soils than black clay soils; the latter only permitting significant infiltration early in the wet season through cracks and preferential pathways before the clays swell. Aquifers are also locally recharged through either small alluvial aquifers or directly from the river when high flows or flooding occurs. The main groundwater discharge process is evapotranspiration. For rivers draining fractured rock aquifers in the region flows are reduced to disconnected, semi-permanent pools and then dry river beds as the dry season progresses.

AR-3.3.2 Karstic carbonate rocks

Processes occurring in karstic carbonate rocks are similar to those for the fractured rocks, except that groundwater flow is primarily along dissolution features rather than fractures. The main groundwater discharge processes are through evapotranspiration and spring discharge to rivers. River flows are maintained to varying degrees by the spring discharge.

Groundwater discharging from Proterozoic carbonates maintains perennial flows in the lower reaches of the the Habgood River (Figure AR-2.). A conceptual model for the interconnection between the Proterozoic carbonate aquifer and the Habgood River is given in Figure AR-25 whereby discharge to the river is focussed along a fault or highly fractured zone in the aquifer.

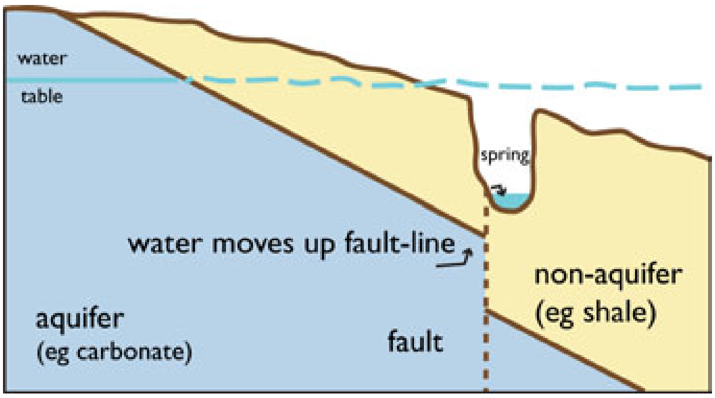

Figure AR-25. Schematic of Hydrogeological cross-section showing groundwater discharge to the Habgood River in the Arafura region

Groundwater discharge from the Dook Creek Formation maintains permanent flows in the Goyder and Blyth Rivers. The conceptual model for these interactions is that springs occur where solution cavities terminate in the rivers (cf. faults in the previous model) as diagrammatically shown in Figure AR-26.

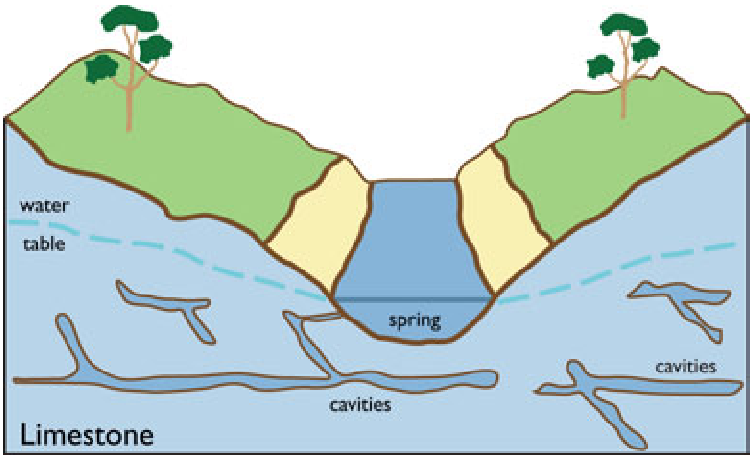

Figure AR-26. Schematic of hydrogeological cross-section showing groundwater discharge to the Goyder and Blyth Rivers in the Arafura region

AR-3.3.3 Cretaceous sediments

Processes occurring in the Cretaceous sediments are similar to those for the fractured rocks. The main groundwater discharge processes are through evapotranspiration and spring discharge to rivers. River flows are maintained to varying degrees by the spring discharge.

Spring discharge from the Cretaceous sediments primarily occurs in the centre and east of the region. It occurs where a layer of porous and permeable sandstone overlies a low permeability rock such as shale or granite (Figure AR-27). Water stored in the upper layer seeps out at the contact between the two rock types, generally in the form of a seepage zone or swampy area. Key examples of this are in the Cato and Latram Rivers and Yirrkala and Jungle Creeks (Figure AR-2).

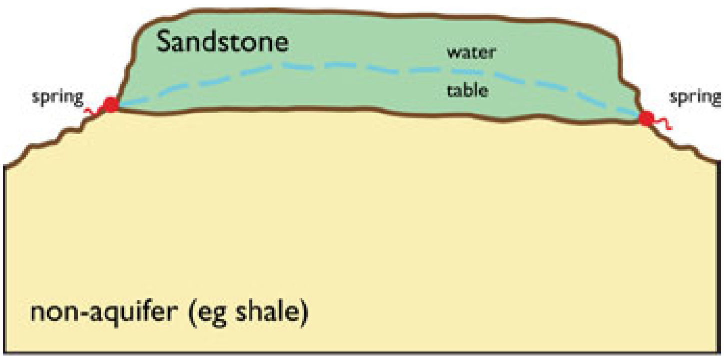

Figure AR-27. Schematic of hydrogeological cross-section for groundwater discharge that provides the dry season flow for Jungle Creek in the Arafura region

AR-3.4 Groundwater modelling results

AR-3.4.1 Historical groundwater balance

No attempt has been made to develop a detailed groundwater balance for the region due to the lack of data. However the following general comments can be made.

- The main hydrological characteristic of the region is the great variability in rainfall from year to year, within a single year and over periods of years. This variability results in a similar great variability in both surface water runoff and groundwater recharge.
- The period of record for the few river gauging stations and groundwater monitoring points within the catchment is biased towards a period of above average rainfall (based on the existing rainfall data). This needs to be taken into consideration when analysing flow and recharge data.
- Data and modelling results reported by Williams et al (2003) suggests evapotranspiration during the dry season from the Arafura Swamp averages 5 mm per day.

AR-3.5 Rainfall-runoff modelling results

In this section the term runoff is the sum of overland flow, interflow and baseflow. It is equivalent to streamflow expressed as a mm depth equivalent. All plots show data averaged over the modelled subcatchments of the Arafura region. For this reason rainfall reported in this section may vary slightly from that reported elsewhere due to differences between the catchment boundaries (shown in Figure AR-1) and the DEM-derived catchment boundaries used here. In this section, where annual data are reported years are represented by numbers 1 through 77. Consistently throughout this report, annual data are based on the water year (1 September to 31 August) and the dry season is defined as 1 May to 31 October. Unless stated otherwise scenarios Cwet, Cmid and Cdry are selected on the basis of the ranked mean annual runoff. For more details on methods refer to Section 2.2 of the division-level Chapter 2.

AR-3.5.1 Regional synopsis

The rainfall-runoff modelling estimates runoff in 0.05 degree grid cells in 37 subcatchments (Figure AR-28). Optimised parameter values from eight calibration catchments are used. Six of these calibration catchments are in the Arafura region, one is in the Van Diemen Gulf region and one is in the Roper region.

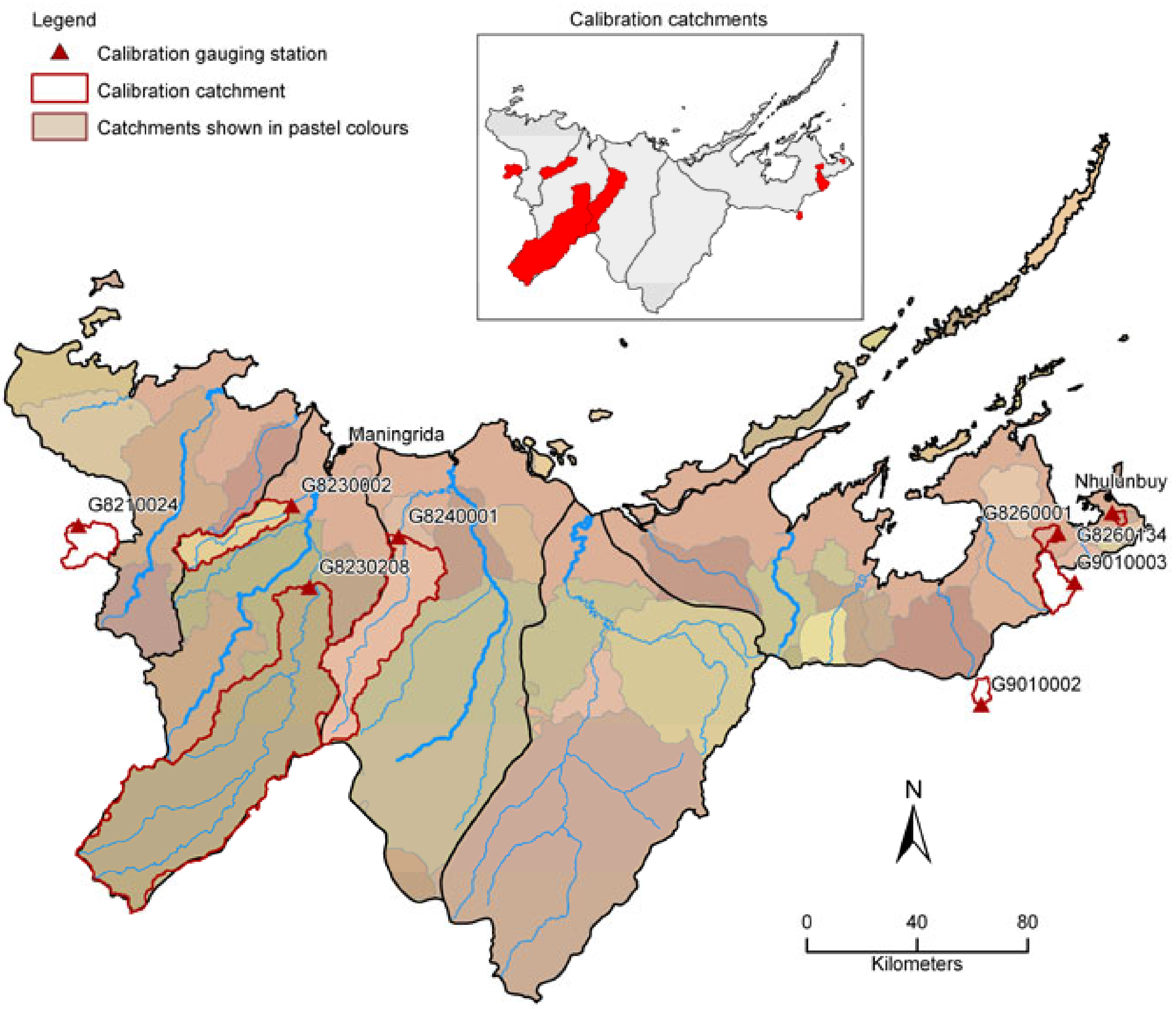

Figure AR-28. Map of the modelling subcatchments, calibration catchments and calibration gauging stations used for the Arafura region with inset highlighting (in red) the extent of the calibration catchments

AR-3.5.2 Model calibration

Figure AR-29 compares the modelled and observed monthly runoff and the modelled and observed daily flow exceedance curves for the eight calibration catchments. Nash-Sutcliffe efficiency (NSE) values provide a quantitative measure of how well simulated values match observed values. NSE values are described in more detail in Section 2.2.3 of the division-level Chapter 2. On the monthly plots NSE is the monthly Nash-Sutcliffe efficiency value and NSE (dry season) is the dry season monthly Nash-Sutcliffe efficiency value. On the daily flow exceedance plots, NSE is the daily flow exceedance curve Nash-Sutcliffe efficiency value and NSE (50 to 100 percent) is the lower half of the daily flow exeedance curve Nash-Sutcliffe efficiency value.

The results indicate that the ensemble calibration of the rainfall-runoff models Sacramento and IhacresClassic can reasonably reproduce the observed monthly runoff series (NSE values generally greater than 0.7) and the daily flow exceedance curve (NSE values generally greater than 0.9). The volumetric constraint used in the model calibration also ensures that the total modelled runoff is within 5 percent of the total observed runoff.

The calibration method places more importance on the simulation of high runoff, and therefore rainfall-runoff modelling of the medium and high runoff is considerably better than the modelling of low runoff. It should be noted, however, that while the relative difference between the observed and simulated low flow values may be large (which is what gives rise to the low monthy dry season NSE values for example), the absolute difference between the observed and simulated low flow values is generally small because both values are small. Nevertheless, an optimisation to reduce overall error variance can result in some underestimation of high runoff and overestimation of low runoff. This is evident in some of the scatter plots comparing the modelled and observed monthly runoff and many of the daily flow exceedance curves. In most calibration catchments the disagreement between the modelled and observed daily runoff characteristics is discernable for runoff that is exceeded less than 1 percent of the time,. This is accentuated in the plots because of the linear scale on the y-axis and normal probability scale on the x-axis. In any case, the volumetric constraint used in the model calibration ensures that the total modelled runoff is always within 5 percent of the total observed runoff. As indicated by the relatively low NSE values for the lower half of the daily flow exceedance curve and monthly dry season there may be considerable disagreement between observed and modelled low flow values (i.e. cease-to-flow). Overall the monthly NSE values are considered sufficient for the general purposes of estimating long-term mean annual runoff.

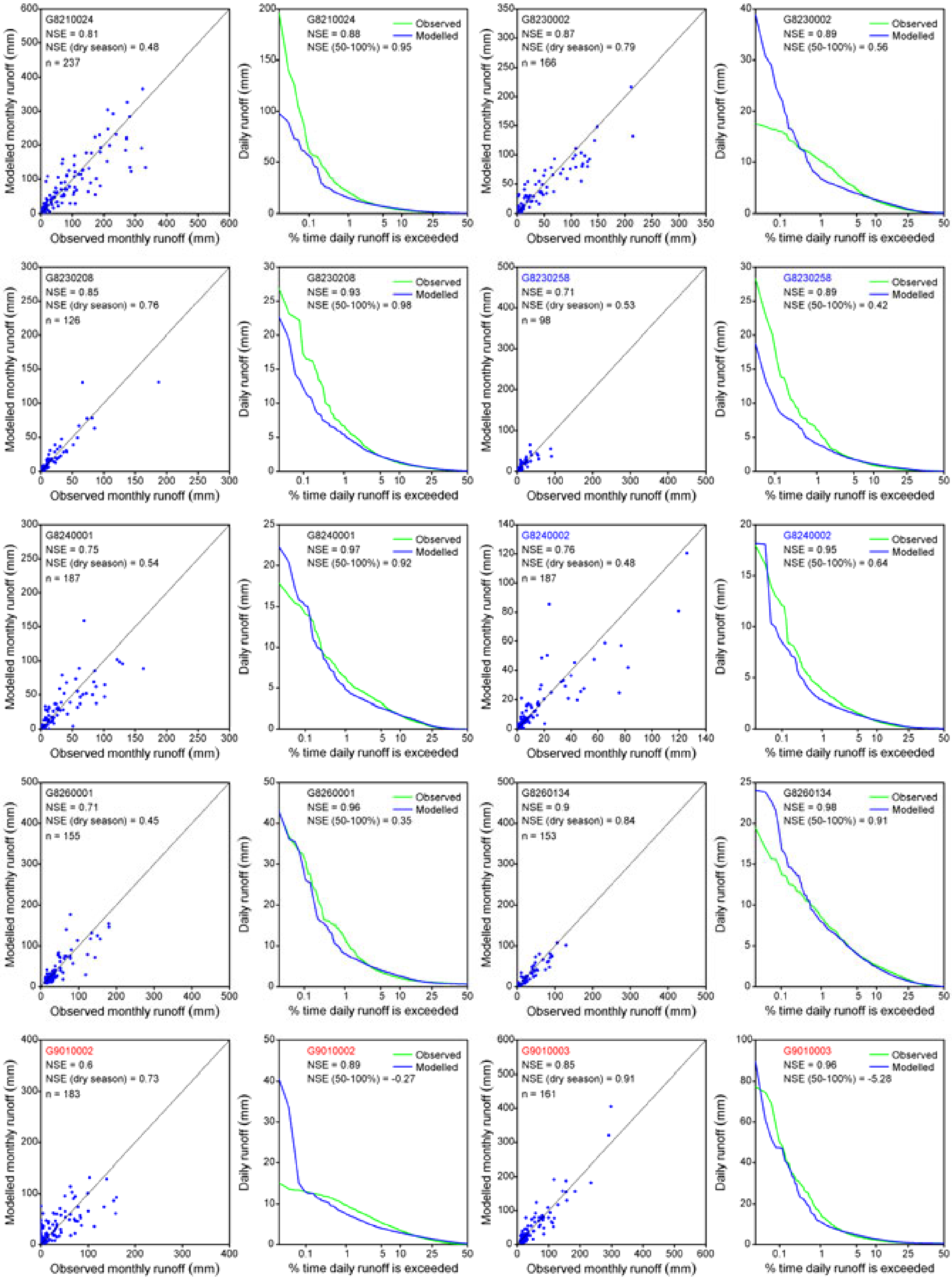

Figure AR-29. Modelled and observed monthly runoff and daily flow exceedance curve for each calibration catchment in the Arafura region. (Red text denotes catchments located outside the region; blue text denotes catchments used for streamflow modelling only)

AR-3.5.3 Under historical climate

Figure AR-30 shows the spatial distribution of mean annual rainfall and runoff under Scenario A (averaged over 1930 to 2007) across the Arafura region. Figure AR-31 shows the mean annual rainfall and runoff averaged over the region. The blank space along the southern boundary of the runoff grid is due to a discrepancy between the Australian Water Resources council boundaries and the DEM catchment boundaries.

The mean annual rainfall and runoff averaged over the Arafura region are 1173 mm and 240 mm respectively. The mean wet season and dry season runoff averaged over the Arafura region are 217 mm and 23 mm respectively.

In this project, all runoff grids are presented as long-term mean annual values. However the distributions of monthly and annual runoff data in northern Australia can be highly skewed; consequently the median and additional percentile values spatially averaged over the region are also reported. The 10th percentile, median and 90th percentile annual runoff values across the Arafura region are 406, 219 and 110 mm respectively. The median wet season and dry season runoff averaged over the Arafura region are 195 mm and 19 mm respectively.

The mean annual rainfall varies from over 1200 mm in the west and east of the region to less than 800 mm in the south. The mean annual runoff varies from over 500 mm in the north-east to less than 100 mm in the central southern part of the region (Figure AR-30) and runoff coefficients vary from 12 to 38 percent of rainfall. The majority of runoff occurs during the wet season months December to April (Figure AR-32). Rainfall and runoff can vary considerably from year to year with long periods over several years or decades that are considerably wetter or drier than others (Figure AR-31). The coefficients of variation of annual rainfall and runoff averaged over the Arafura region are 0.21 and 0.48 respectively.

The Arafura is one of 13 regions which cover the three divisions studied in this project. Mean annual rainfall and runoff, as well as coefficients of variation, have been calculated for all of these 13 regions, and it is useful to compare the Arafura results to results across all 13 regions. Across all 13 regions in this project 10th percentile, median and 90th percentile values are 1371, 936 and 595 mm respectively for mean annual rainfall and 374, 153 and 78 mm respectively for mean annual runoff. The mean annual rainfall (1173 mm) and runoff (240 mm) averaged over the Arafura region fall in the upper end of this range. Across all 13 regions in this project the 10th percentile, median and 90th percentile values are 0.34, 0.26 and 0.19 respectively for the coefficient of variation of annual rainfall and 1.39, 0.69 and 0.48 for the coefficient of variation of runoff. The coefficients of variation of annual rainfall (0.21) and runoff (0.48) averaged over the Arafura region are among the lowest of the 13 reporting regions.

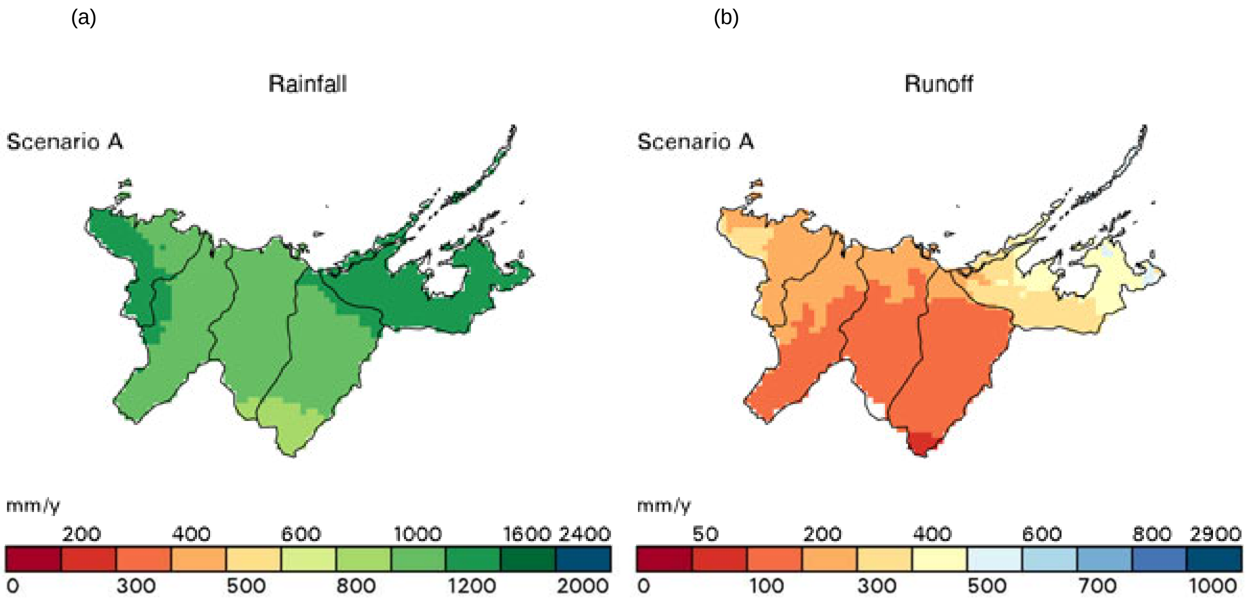

Figure AR-30. Spatial distribution of mean annual (a) rainfall and (b) modelled runoff across the Arafura region under Scenario A

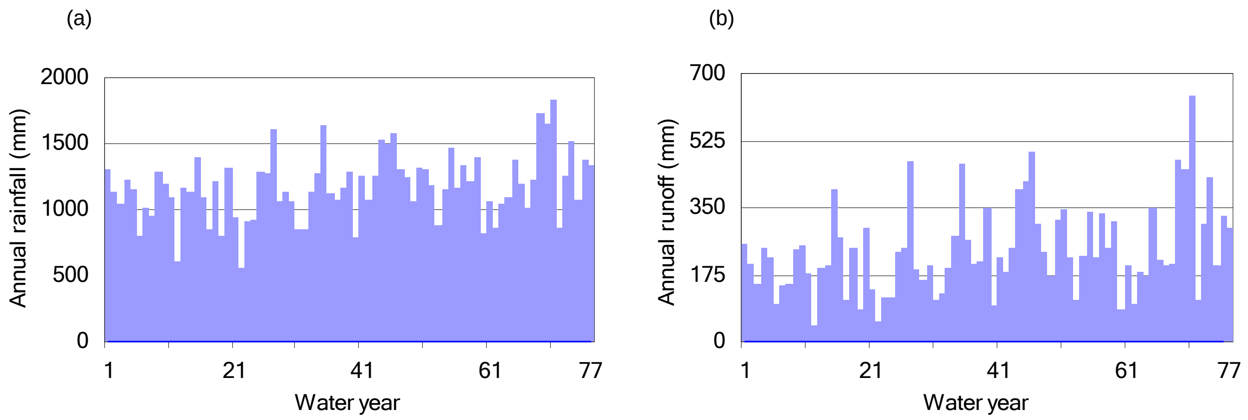

Figure AR-31. Annual (a) rainfall and (b) modelled runoff in the Arafura region under Scenario A

Figure AR-32(a, b) shows the minimum and maximum monthly rainfall and runoff and the range of values between the 25th and 75th percentile monthly rainfall and runoff. Figure AR-32(c, d) shows the mean and median monthly flows and the range of values between the 25th and 75th percentile monthly rainfall and runoff.

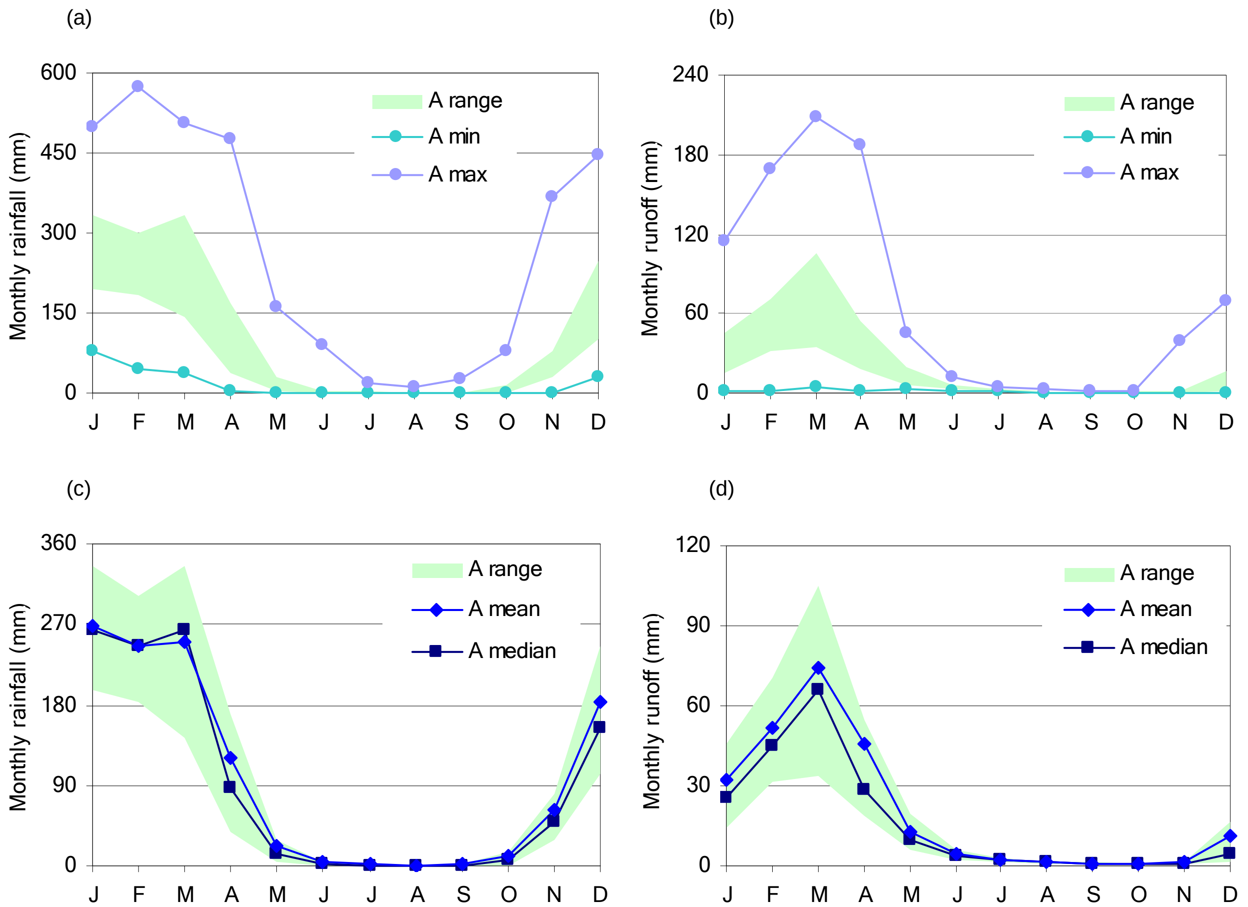

Figure AR-32. Minimum, maximum and A range monthly (a) rainfall and (b) modelled runoff; and mean, median and A range monthly (c) rainfall and (d) modelled runoff in the Arafura region under Scenario A (A range is the 25th to 75th percentile monthly rainfall or runoff)

AR-3.5.4 Under recent climate

The mean annual rainfall and runoff under Scenario B (1996 to 2007) are 15 percent and 38 percent higher respectively than the historical (1930 to 2007) mean values. The spatial distribution of rainfall and runoff across the Arafura region under Scenario B is shown in Figure AR-33.

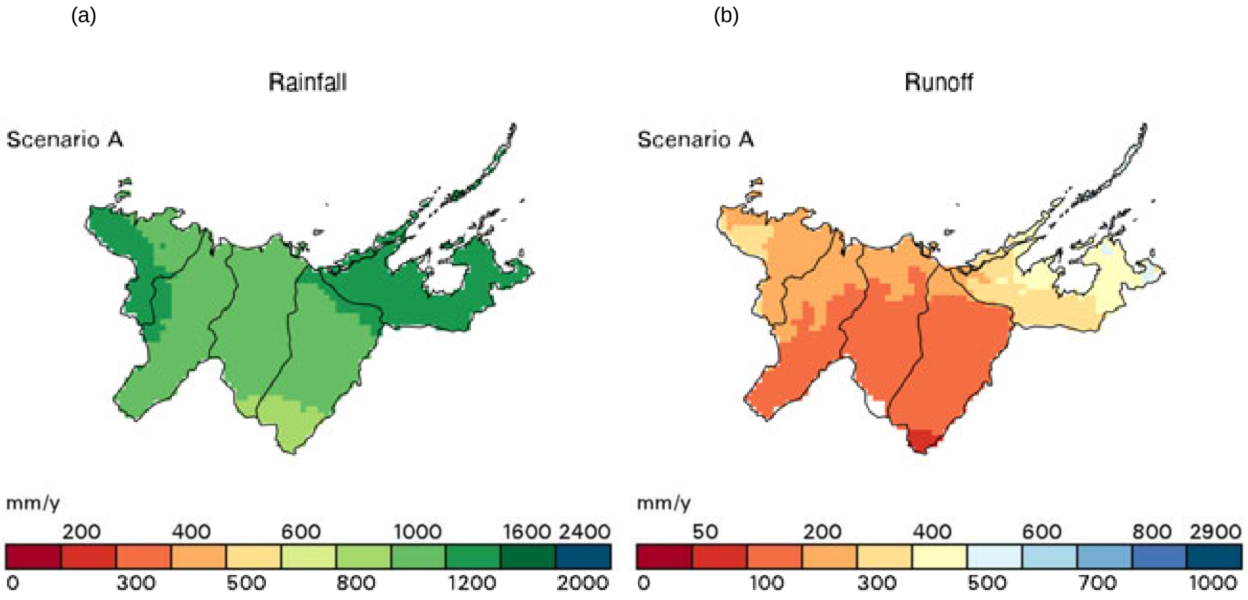

Figure AR-33. Spatial distribution of mean annual (a) rainfall and (b) modelled runoff across the Arafura region under Scenario B

AR-3.5.5 Under future climate

Figure AR-34 shows the percentage change in the mean annual runoff averaged over the Arafura region under Scenario C relative to Scenario A for the 45 scenarios (15 global climate models (GCMs) for each of the high, medium and low global warming scenarios). The percentage change in the mean annual runoff and rainfall from the corresponding GCMs are also tabulated in Table AR-6.

The figure and table indicate that the potential impact of climate change on runoff can be very significant. Although there is considerable uncertainty in the estimates, the results indicate that runoff in ~2030 in the Arafura region is as likely to increase as it is to decrease. Rainfall-runoff modelling with climate change projections from seven of the GCMs shows a reduction in mean annual runoff, while rainfall-runoff modelling with climate change projections from eigth of the GCMs shows an increase in mean annual runoff. The wide range of mean annual runoff values shown in Figure AR-34 and Table AR-6 is primarily due to the wide range of future projections of rainfall by the 15 GCMs.

Because of the large variation between GCM simulations and the method used to obtain the climate change scenarios, the biggest increase and biggest decrease in runoff come from the high global warming scenario. For the high global warming scenario, rainfall-runoff modelling with climate change projections from five of the GCMs indicates a decrease in mean annual runoff greater than 10 percent while rainfall-runoff modelling with climate change projections from five of the GCMs indicates an increase in mean annual runoff greater than 10 percent.

In subsequent reporting here and in other sections, only results from an extreme ‘wet’, ‘mid’ and extreme ‘dry’ variant are shown (referred to as scenarios Cwet, Cmid and Cdry). Under Scenario Cwet, results from the second highest increase in mean annual runoff from the high global warming scenario are used. Under Scenario Cdry, results from the second highest reduction in mean annual runoff from the high global warming scenario are used. Under Scenario Cmid, the median mean annual runoff results from the medium global warming scenario are used. These are shown in bold in Table AR-6.

Under scenarios Cwet, Cmid and Cdry, mean annual runoff increases by 16 and 1 percent and decreases by 22 percent relative to Scenario A. By comparison, the range based on the low global warming scenario is an 8 to -12 percent change in mean annual runoff. Figure AR-35 shows the mean annual runoff across the Arafura region under scenarios A and C. The linear discontinuities that are evident in Figure AR-35 are due to GCM grid cell boundaries.

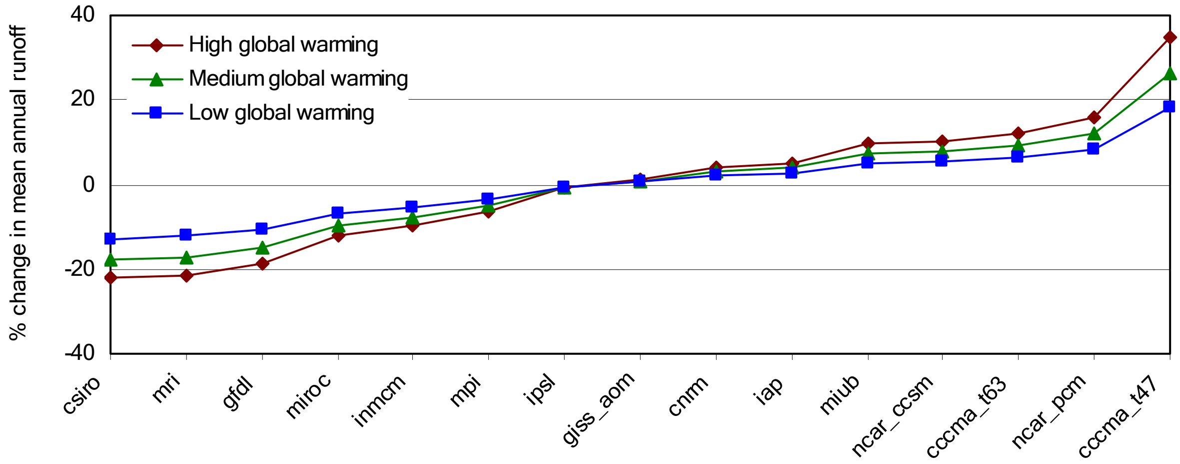

Figure AR-34. Percentage change in mean annual modelled runoff under the 45 Scenario C simulations (15 global climate models and three global warming scenarios) relative to Scenario A

Table AR-6. Summary results under the 45 Scenario C simulations for the modelled subcatchments in the Arafura region (numbers show percentage change in mean annual rainfall and modelled runoff under Scenario C relative to Scenario A)

High global warming			Medium global warming			Low global warming		
GCM	Rainfall	Runoff	GCM	Rainfall	Runoff	GCM	Rainfall	Runoff
csiro	-11%	-22%	csiro	-9%	-18%	csiro	-6%	-13%
mri	**-9%**	**-22%**	mri	-7%	-17%	mri	-5%	-12%
gfdl	-11%	-19%	gfdl	-9%	-15%	gfdl	-6%	-11%
miroc	-4%	-12%	miroc	-3%	-10%	miroc	-2%	-7%
inmcm	-3%	-10%	inmcm	-2%	-8%	inmcm	-1%	-5%
mpi	-2%	-6%	mpi	-1%	-5%	mpi	-1%	-4%
ipsl	0%	-1%	ipsl	0%	-1%	ipsl	0%	-1%
giss_aom	1%	1%	**giss_aom**	**1%**	**1%**	giss_aom	1%	1%
cnrm	3%	4%	cnrm	2%	3%	cnrm	2%	2%
iap	2%	5%	iap	1%	4%	iap	1%	3%
miub	3%	10%	miub	3%	7%	miub	2%	5%
ncar_ccsm	5%	10%	ncar_ccsm	4%	8%	ncar_ccsm	3%	5%
cccma_t63	4%	12%	cccma_t63	3%	9%	cccma_t63	2%	6%
ncar_pcm	**7%**	**16%**	ncar_pcm	5%	12%	ncar_pcm	4%	8%
cccma_t47	13%	35%	cccma_t47	10%	26%	cccma_t47	7%	18%

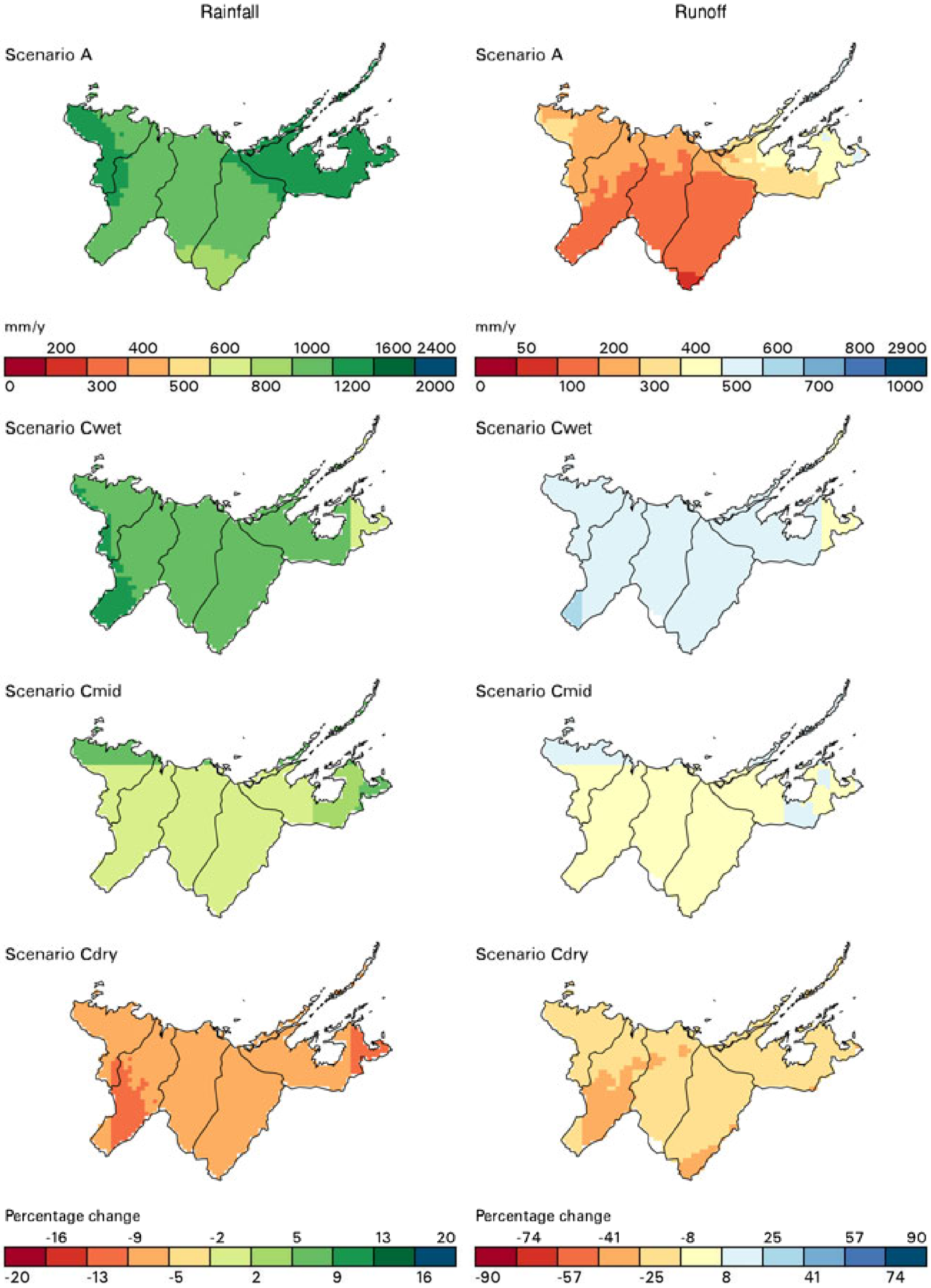

Figure AR-35. Spatial distribution of mean annual rainfall and modelled runoff across the Arafura region under Scenario A and under Scenario C relative to Scenario A

AR-3.5.6 Summary results for all scenarios

Table AR-7 shows the mean annual rainfall, runoff and actual evapotranspiration under Scenario A averaged over the Arafura region, and the percentage changes in the rainfall, runoff and actual evapotranspiration under scenarios B and C relative to Scenario A. The Cwet, Cmid and Cdry results are based on the mean annual runoff, and the rainfall changes shown in Table AR-7 are the changes in the mean annual value of the rainfall series used to obtain the runoff under scenarios Cwet, Cmid and Cdry. The changes in mean annual rainfall do not necessarily translate directly to the changes in mean annual runoff because of changes in seasonal and daily rainfall distributions and the relationship between rainfall and runoff is non-linear. The latter factor usually results in small changes in rainfall to be amplified in runoff (Table AR-6).

Figure AR-36 shows the mean monthly rainfall and runoff under scenarios A and C averaged over the 1930 to 2007 for the region. Figure AR-37 shows the daily rainfall and flow exceedance curves under scenarios A and C averaged over the region. In Figure AR-36 Cwet, Cmid and Cdry are selected on a month-by-month basis, while in Figure AR-37 Cwet, Cmid and Cdry are selected for every day of the daily flow exceedance curve.

Table AR-7. Water balance over the entire Arafura region under Scenario A and under scenarios B and C relative to Scenario A

Scenario	Rainfall	Runoff	Evapotranspiration
	mm		
A	1173	240	933
	percent change from Scenario A		
B	15	38	9
Cwet	7	16	5
Cmid	1	1	1
Cdry	-9	-22	-5

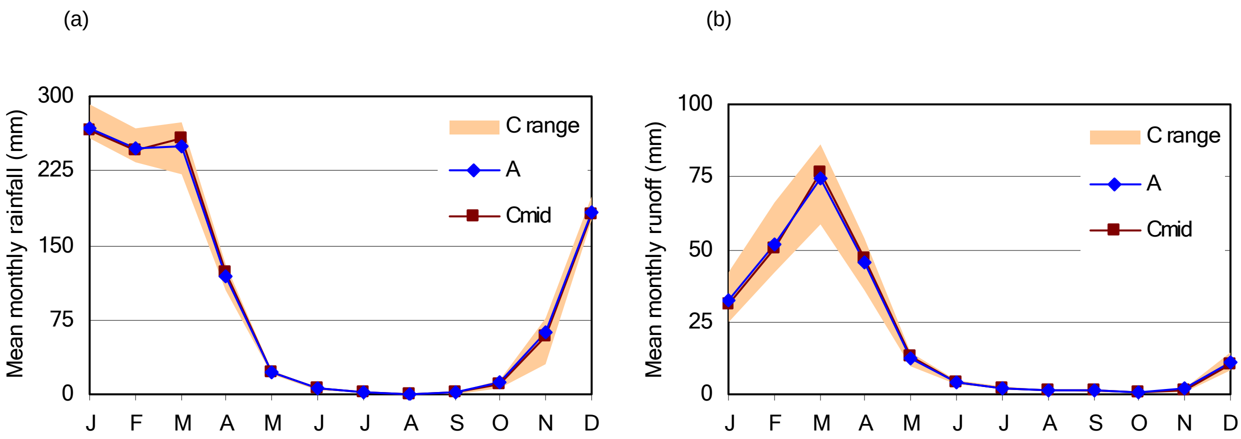

Figure AR-36. Mean monthly (a) rainfall and (b) modelled runoff in the Arafura region under scenarios A and C

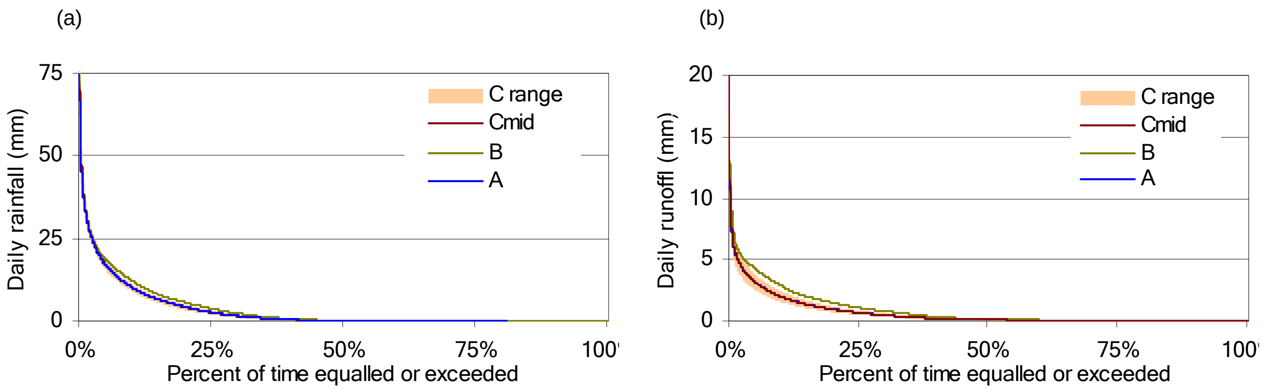

Figure AR-37. Daily flow exceedance curves for (a) rainfall and (b) modelled runoff in the Arafura region under scenarios A, B and C

AR-3.5.7 Confidence levels

The rainfall-runoff model verification analysis with data from 123 catchments from across all of northern Australia indicates that the mean annual runoff for ungauged catchments are under estimated or over estimated, when using optimised parameter values from a nearby catchment, by less than 20 percent in 40 percent of catchments and by less than 50 percent in 80 percent of the catchments. For the Arafura region the level of confidence of the runoff estimates is low because there are few calibration catchments with high quality gauging station data. NSE values for monthly runoff and daily flow exceedance curve characteristic are also low relative to other regions. This may be due to a combination of factors, including: poor rainfall records in the region, gauging stations may be sited in ‘open systems’ (i.e. flow may bypass the gauge) and variable quality streamflow records due to the difficulty of operating and maintaining stations in remote areas. The majority of streamflow gauging stations with acceptable quality data are located in the eastern and western parts of the region, with few suitable stations in between. Consequently transposing parameters sets in the Arafura region is problematic because of the distances between donor and target subcatchments. Further some areas of the Arafura have complex surface–groundwater interactions due to dolomitic limestone and Cretaceous sandstone aquifer systems. Diagrams in Petheram et al. (2009) illustrate which calibrated rainfall-runoff model parameter sets are used to model streamflow in the ungauged subcatchments in the Arafura region.

No gauging stations are sited on the coastal area of the Arafura and parameter sets for these regions were donated from far away calibration catchments. Figure AR-38 illustrates the level of confidence in modelling the mid to high runoff events (i.e. peak flows) and dry season runoff (respectively) for the subcatchments of the Arafura region. It should be noted that these maps of level of confidence are not statistical confidence levels and are intended to only convey a broad reliability of prediction. The level of confidence in streamflow predictions will vary slightly from the level of confidence in runoff predictions shown below and as discussed in Section 2.2.6 of the division-level Chapter 2.

There is a high degree of confidence that dry season runoff in the Arafura region is low because it is known that rainfall and baseflow are low during the dry season. The map of level of confidence for dry season flow shown in Figure AR-38 provides a relative indication of how well dry season metrics, such as cease-to-flow, are simulated.

In summary the level of confidence in the long-term average monthly and annual results for the Arafura region are low relative to other regions. As shown in Figure AR-38, in many areas of the Arafura region localised studies will require more detailed analysis than undertaken and reported here and would most likely require the site to be visited and additional field measurements made.

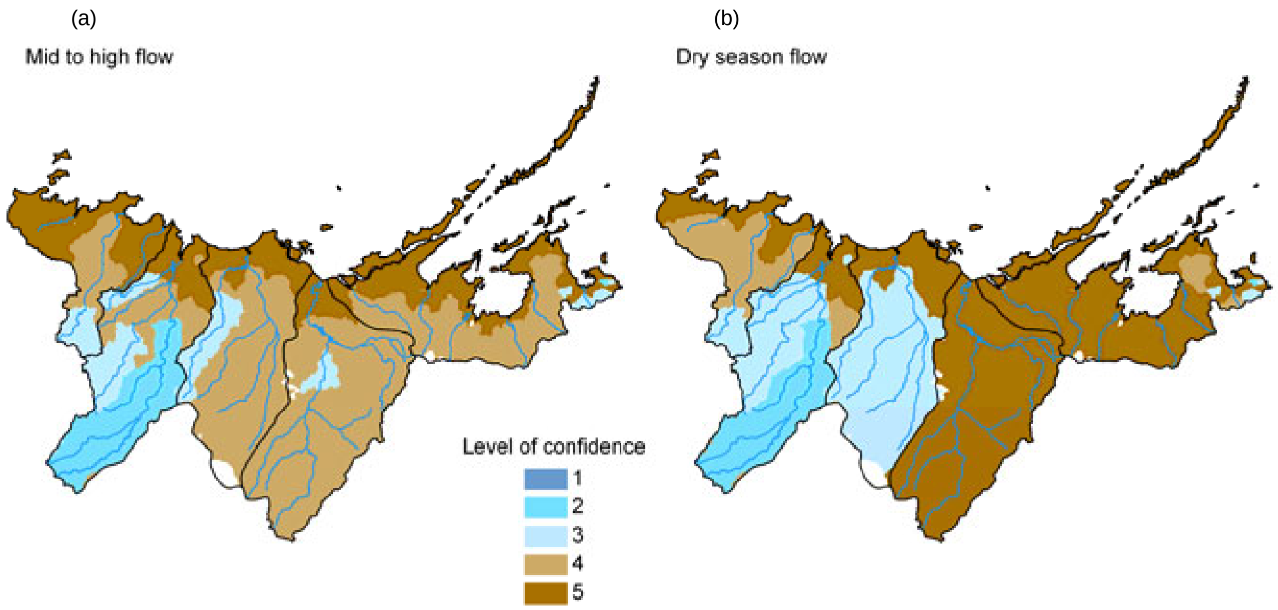

Figure AR-38. Level of confidence in the modelling of runoff for (a) mid- to high flow events and (b) monthly dry season flow events for the modelling subcatchments of the Arafura region. 1 is the highest level of confidence, 5 is the lowest

AR-3.6 River system water balance

AR-3.6.1 River model configuration

The Arafura region is comprised of five AWRC river basins and has an area of 45,499 km^2. Under the historical climate the mean annual runoff across the region is 240 mm (Section AR-3.5.3), which equates to a mean annual streamflow across the region of 10,920 GL.

No information on infrastructure, water demand, water management, sharing rules or future development were available, and consequently there is no river modelling section to the Arafura region report. Streamflow time series have been generated for each streamflow reporting node (SRN) based on the upstream grid cell rainfall-runoff simulations, as described in Section 2.2.5 of the division-level Chapter 2. The locations of these nodes are shown in Figure AR-39. Summary streamflow statistics for each SRN are reported in Petheram et al. (2009). In addition to the streamflow time series generated by the rainfall-runoff model ensemble, a range of hydrological metrics computed using regression analysis are also available for each SRN (as described in Section 2.2.7 of the division-level Chapter 2). The complete set of results for the multiple regression analysis is reported in SKM (2009). The merit of each approach is discussed in Section 2.2.7 of the division-level Chapter 2.

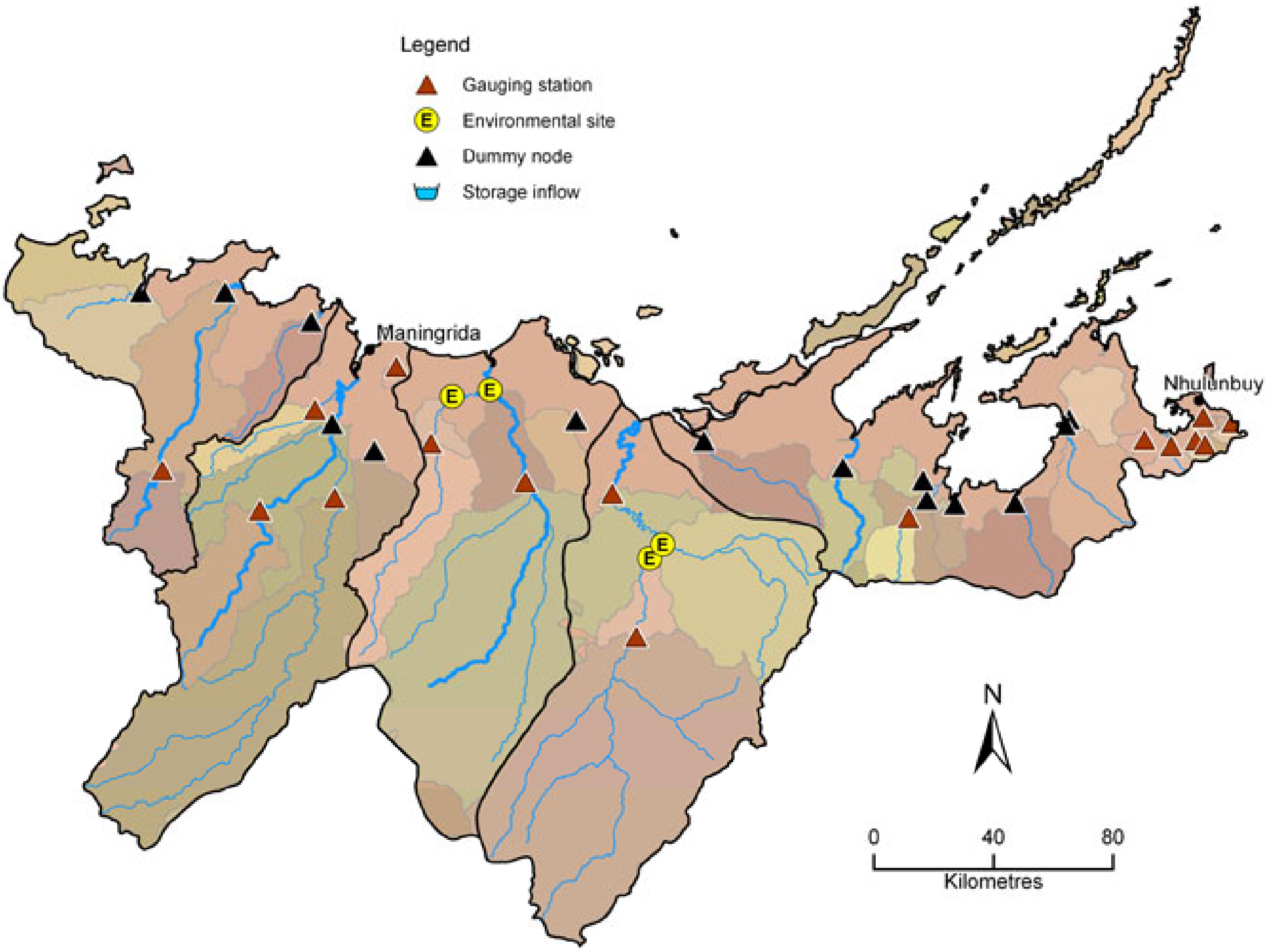

Figure AR-39. Location of streamflow reporting nodes (gauging stations, environmental sites, dummy nodes and storage inflows) in the Arafura region. Note there are no storage inflow streamflow reporting nodes in this region

AR-3.7 Changes to flow regimes at environmental assets

Section 1.3 of the division-level Chapter 1 describes how environmental assets were shortlisted for assessment by this project. Two environmental assets have been shortlisted in the Arafura region: Arafura Swamp and Blyth-Cadell Floodplain and Boucaut Bay System. The locations of these assets are shown in Figure AR-1 and the assets are characterised in Chapter AR-2.

This section presents the assessment of these shortlisted assets and reports metrics for those assets which have sufficient confidence in the modelled streamflow to enable analysis. Confidence in results for low flows and high flows was calculated separately on a scale of 1 to 5, with 1 indicating results with the highest confidence (as described in Section 2.2.6 of the division-level Chapter 2). Hydrological regime metrics (as defined in Section 2.5 of the division-level Chapter 2) for either low flows or high flows are reported only where confidence levels are 1, 2 or 3. If confidence levels in the low flows or high flows are ranked 4 or 5, results are not reported and are labelled NR (not reported).

In the absence of site-specific metrics for the Arafura region a set of standard metrics related to high and low flows have been utilised. However the conversion of these metrics into environmental impacts still requires development of quantitative relationships between flow and ecology.

AR-3.7.1 Standard metrics

Table AR-8. Standard metrics for changes to surface water flow regime at environmental assets in the Arafura region

Standard metrics	Units	A	B	Cwet	Cmid	Cdry	Dwet	Dmid	Ddry
			change from Scenario A						
Arafura Swamp - Node 1 (confidence level: low flow = 4, high flow = 3)									
Annual flow (mean)	GL	741	+50%	+18%	-3%	-28%	nm	nm	nm
Wet season flow (mean)*	GL	714	+48%	+19%	-3%	-28%	nm	nm	nm
Dry season flow (mean)**	GL	NR	NR	NR	NR	NR	nm	nm	nm
Low flow threshold (discharge exceeded 90% of the time in Scenario A)	GL/d	NR							
Number of days below low flow threshold (mean)	d/y	NR	NR	NR	NR	NR	nm	nm	nm
Number of days of zero flow (mean)	d/y	NR	NR	NR	NR	NR	nm	nm	nm
High flow threshold (discharge exceeded 5% of the time in Scenario A)	GL/d	12.4							
Number of days above high flow threshold (mean)	d/y	18.3	+11.6	+4.7	-1	-6.6	nm	nm	nm
Blyth-Cadell Floodplain & Boucaut Bay System - Node 2 (confidence level: low flow = 3, high flow = 3)									
Annual flow (mean)	GL	663	+55%	+20%	-4%	-27%	nm	nm	nm
Wet season flow (mean)*	GL	610	+55%	+21%	-4%	-27%	nm	nm	nm
Dry season flow (mean)**	GL	53.1	+51%	+6%	0%	-25%	nm	nm	nm
Low flow threshold (discharge exceeded 90% of the time in Scenario A)	GL/d	0.0584							
Number of days below low flow threshold (mean)	d/y	36.5	-32.6	-13.5	+4.3	+34.2	nm	nm	nm
Number of days of zero flow (mean)	d/y	1.27	+0.2	0	0	0	nm	nm	nm
High flow threshold (discharge exceeded 5% of the time in Scenario A)	GL/d	9							
Number of days above high flow threshold (mean)	d/y	18.3	+11.6	+5.6	-1.2	-6.1	nm	nm	nm

*Wet season covers the six months from November to April.

**Dry season covers the six months from May to October.

NR – metrics not reported because streamflow confidence level is ranked 4 or 5
nm – not modelled.

Arafura Swamp

The surface water flow confidence level for the selected reporting node for the Arafura Swamp (see location on Figure AR-8) is considered moderately reliable (3) for wet season flows and unreliable (4) for dry season flows (Table AR-8). Under Scenario A annual flow into this asset is dominated by wet season flows (96 percent) which have been 48 percent higher under Scenario B. Annual and seasonal flows do not change much under Scenario Cmid when compared to Scenario A, but there are moderate increases under Scenario Cwet (18 to 19 percent) and moderate decreases under Scenario Cdry (28 percent). There are no development Scenarios for the area upstream of this asset.

Under Scenario B the high flow threshold exceedance has been much more frequent than under Scenario A (Table AR-8). Compared to Scenario A there is little change in high flow threshold exceedance under Scenario Cmid. Under Scenario Cwet high flow exceedance increases moderately from Scenario A; conversely, there is a large decrease in high flow days under the Scenario Cdry. There are no low flow metrics reported for this asset.

Blyth-Cadell Floodplain & Boucaut Bay System

The surface water flow confidence level for the selected reporting node for Blyth-Cadell Floodplain & Boucaut Bay System (see location on Figure AR-9) is considered moderately reliable (3) for both wet season flows and dry season flows (Table AR-8). Under Scenario A annual flow into this asset is dominated by wet season flows (92 percent) which have been 55 percent higher under Scenario B. Annual and seasonal flows do not change much under Scenario Cmid when compared to Scenario A, but there are moderate increases under Scenario Cwet (6 to 21 percent) and moderate decreases under Scenario Cdry (25 to 27 percent). There are no development Scenarios for the area upstream of this asset.

Compared to Scenario A the number of days when flow is less than the low flow threshold changes somewhat under Scenario Cmid, but there is a large increase in low flow days under Scenario Cdry and also a large decrease in low flow days under Scenario Cwet (Table AR-8). There was no change to the number of zero flow days at this asset compared to Scenario A, except under Scenario B which had a small increase. Under Scenario B the high flow threshold exceedance has been much more frequent than under Scenario A. There is only a small change in high flow threshold exceedance under Scenario Cmid when compared to Scenario A. Under Scenario Cwet there is a large increase in high flow exceedance from Scenario A; conversely, there is a large decrease in high flow days under Scenario Cdry.

AR-3.8 References

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About the project

The Northern Australia Sustainable Yields (NASY) Project has assessed the water resources of northern Australia. The project modelled and quantified, within the limits of available data, the changes to water resources under four scenarios: historical climate; recent climate; future climate considering current water use and future climate with potential future water demand. The project identified regions that may come under increased, or decreased, stress due to climate change and increased water use.

The assessments made in this project provide key information for further investigations carried out through the Australian Government's Northern Australia Water Futures Assessment. This initiative aims to develop a knowledge base so that any development proceeds in an ecologically, culturally and economically sustainable way.

The NASY project was commissioned by the National Water Commission in consultation with the Australian Government Department of the Environment, Water, Heritage and the Arts. This followed a March 2008 agreement by the Council of Australian Governments to undertake comprehensive scientific assessments of water yield in all major water systems across the country and provide a consistent analytical framework for water policy decisions across the nation. CSIRO is also undertaking assessments in south-west Western Australia and Tasmania.

The NASY project was reviewed by a Steering Committee and a Technical Reference Panel. Both include representation from federal and state governments, as well as independent experts.

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CSIRO and the Flagships program

Australia is founding its future on science and innovation. Its national science agency, CSIRO, is a powerhouse of ideas, technologies and skills. CSIRO initiated the National Research Flagships to address Australia's major research challenges and opportunities. They apply large scale, long term, multidisciplinary science and aim for widespread adoption of solutions.