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Water in the Daly region of the Timor Sea Drainage Division

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

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Raising National Water Standards Program

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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

CSIRO

Contributors* to the Northern Australia Sustainable Yields Project

Project director	Tom Hatton
Sustainable Yields coordination	Mac Kirby
Project Leader	Richard Cresswell
Project Support	Andrea Davis, Malcolm Hodgen, Sue Jackson, Helen Beringen, Justin Story, Siobhan Duffy, Therese McGillion, Jeff Camkin
Data Management	<u>Mick Hartcher</u>
Climate	<u>Tim McVicar</u> , Randall Donohue, Janice Bathols, Francis Chiew, Dewi Kirono, Lingtao Li, Steve Marvanek, David Post, Nick Potter, Ian Smith, Tom Van Neil, Wenju Cai <i>New South Wales Department of Water and Energy</i> : Jin Teng
Catchment Yield	<u>Cuan Petheram</u> , Paul Rustomji, Jamie Vleeshouwer, Donna Hughes, Jean-Michel Perraud, Ang Yang, Lu Zhang <i>Sinclair Knight Merz</i> : Brad Neal, Amanda Bell, Werner Hennecke, Damon Grace, Derek Goodin, Rory Nathan, David Stephens, Nicola Logan, Sarah Gosling, Zuzanna Graszkiewicz <i>Queensland Department of Environment and Resource Management</i> : Alex Loy, Greg Hausler, Sarah Giles, David Li, Amanda Casey
Groundwater	<u>Glenn Harrington</u> , Russell Crosbie, Phil Davies, James McCallum, Warrick Dawes, Matthew Lenahan, David Rassam <i>Sinclair Knight Merz</i> : Rick Evans, Roger Cranswick, Eliza Wiltshire <i>Jolly Consulting</i> : Peter Jolly <i>Environmental Hydrology Associates</i> : Peter Evans, Jerome Arunakumaren, Wesley Burrows, Judith Raue <i>Northern Territory Department of Natural Resources, Environment, The Arts and Sport</i> : Anthony Knapton, Lynton Fritz, Steven Tickell <i>Queensland Department of Environment and Resource Management</i> : Linda Foster, Ralph DeVoil
Environment	<u>Dave McLennan</u> , Anne Henderson, Joe McMahon, Jim Wallace
Reporting	<u>Susan Cuddy</u> , Becky Schmidt, Heinz Buettikofer, Elissa Churchward, Alex Dyce, Simon Gallant, Chris Maguire, Frances Marston, Linda Merrin, Ben Wurker <i>dmwcreative</i> : Maureen Wicks, David Wicks

* CSIRO unless otherwise indicated; Team Leaders underlined

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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 ($\mu\text{S}/\text{cm}$) \approx 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 $-\infty$ 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 \approx 1.7 EC)
TRaCK	Tropical Rivers and Coastal Knowledge Research Hub
WRON	Water Resources Observation Network

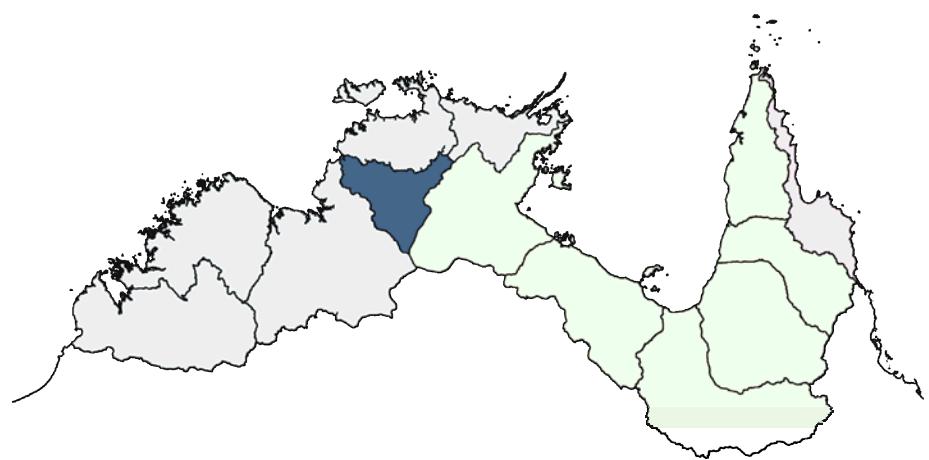
Units of measurement

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 90 th , 50 th and 10 th 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: 1 st September, 1930 to 31 st August, 2007 – except for recurrence interval calculation, when Historical refers to the period 1 st September, 1930 to 31 st August, 1996 (i.e. prior to Recent)
Recent	Scenario B: 1 st September, 1996 to 31 st 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

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.

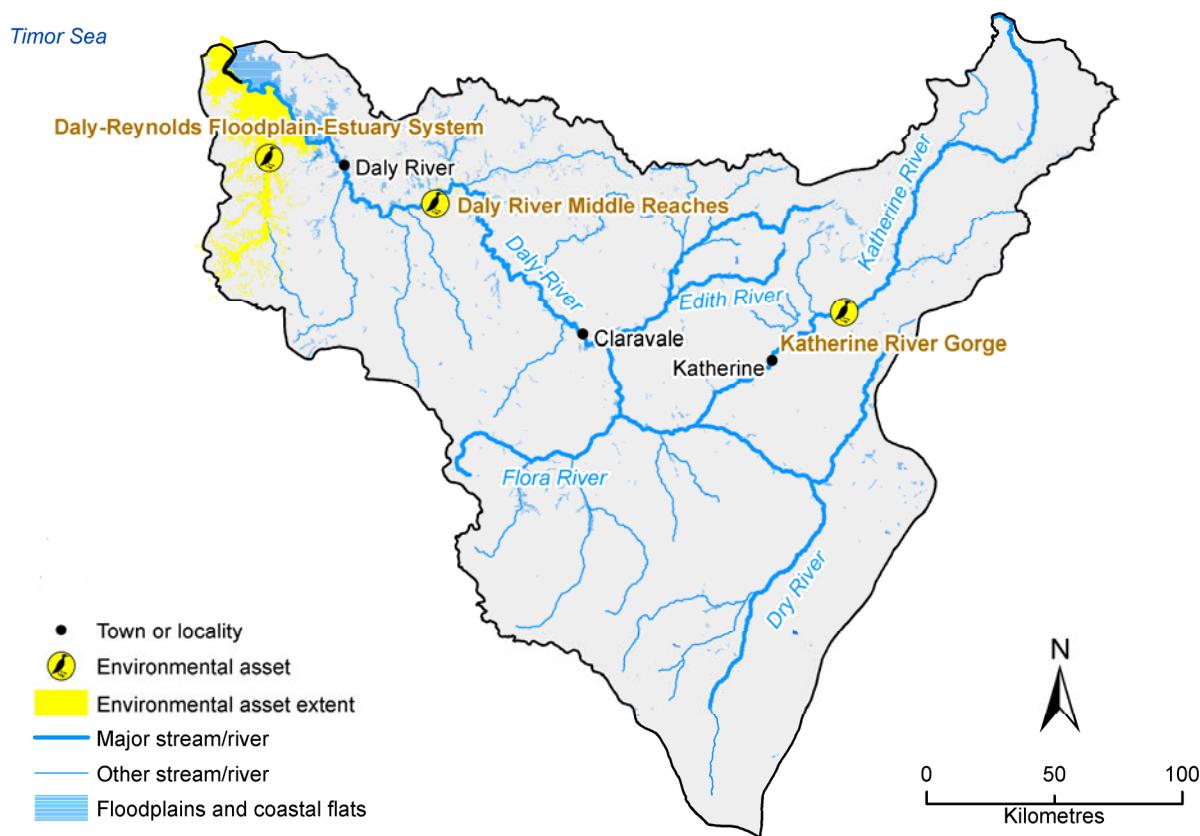


Figure DA-1. Major rivers, towns and location of assets selected for assessment of changes to hydrological regime in the Daly region

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 10th percentile, median and 90th 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 Ooloo 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-Estuaries 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 km²) 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).

DA-1 Water availability and demand in the Daly region

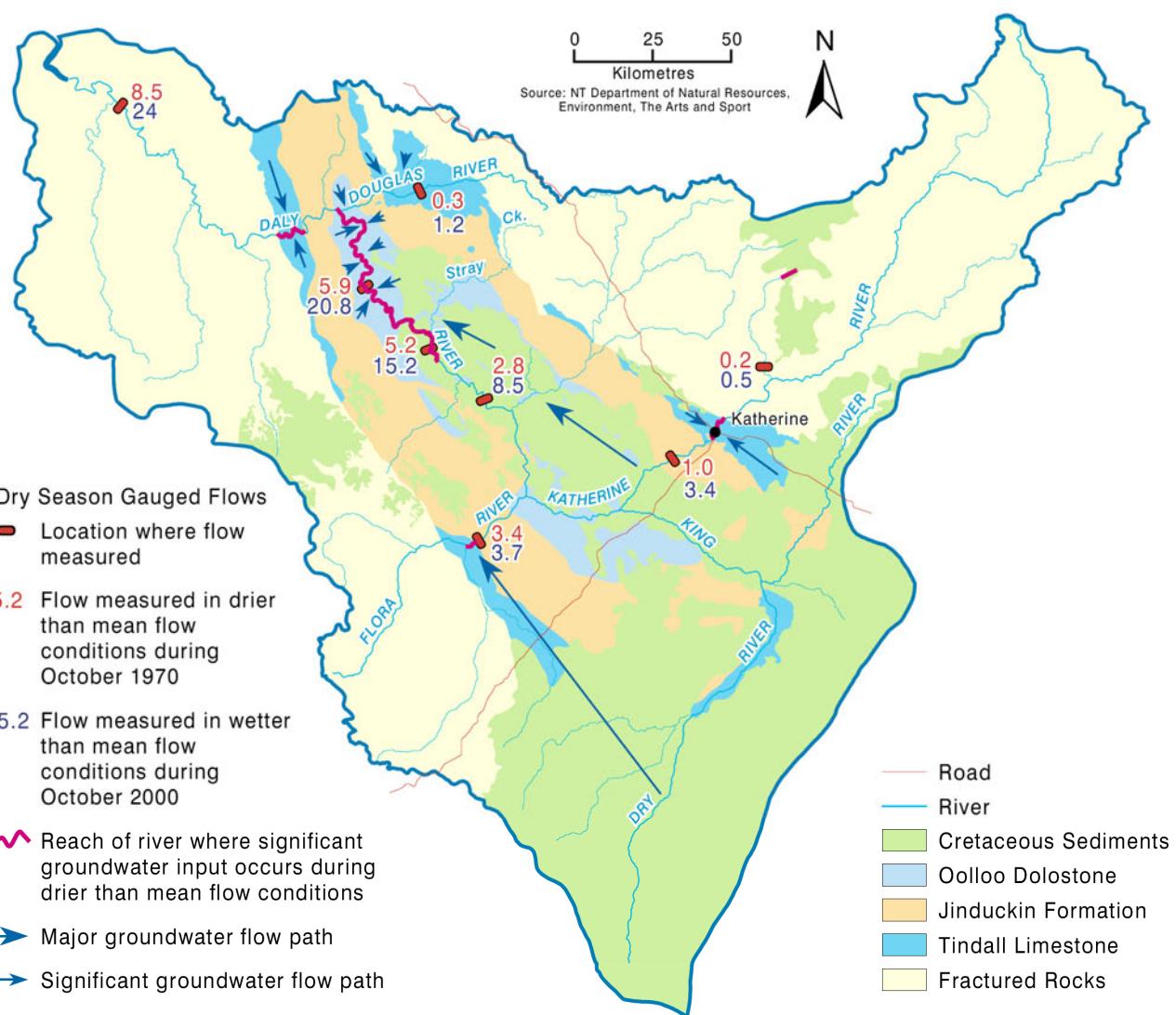


Figure DA-2. Hydrogeology of the Daly region showing reaches of rivers where significant groundwater input occurs (derived from map provided by NRETAS, 2009)

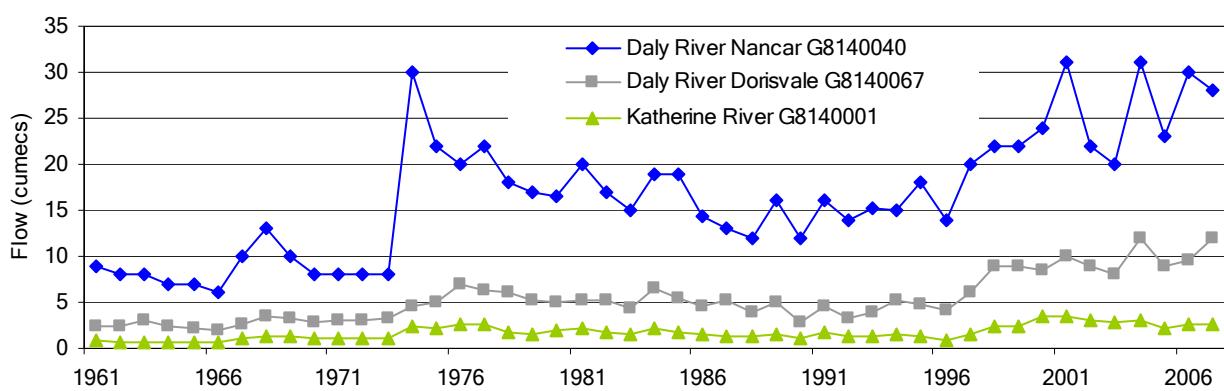


Figure DA-3. Discharge at gauging stations G8140001, G8140067 and G8140040 in the Daly Region for each year of record

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 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 km². 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.

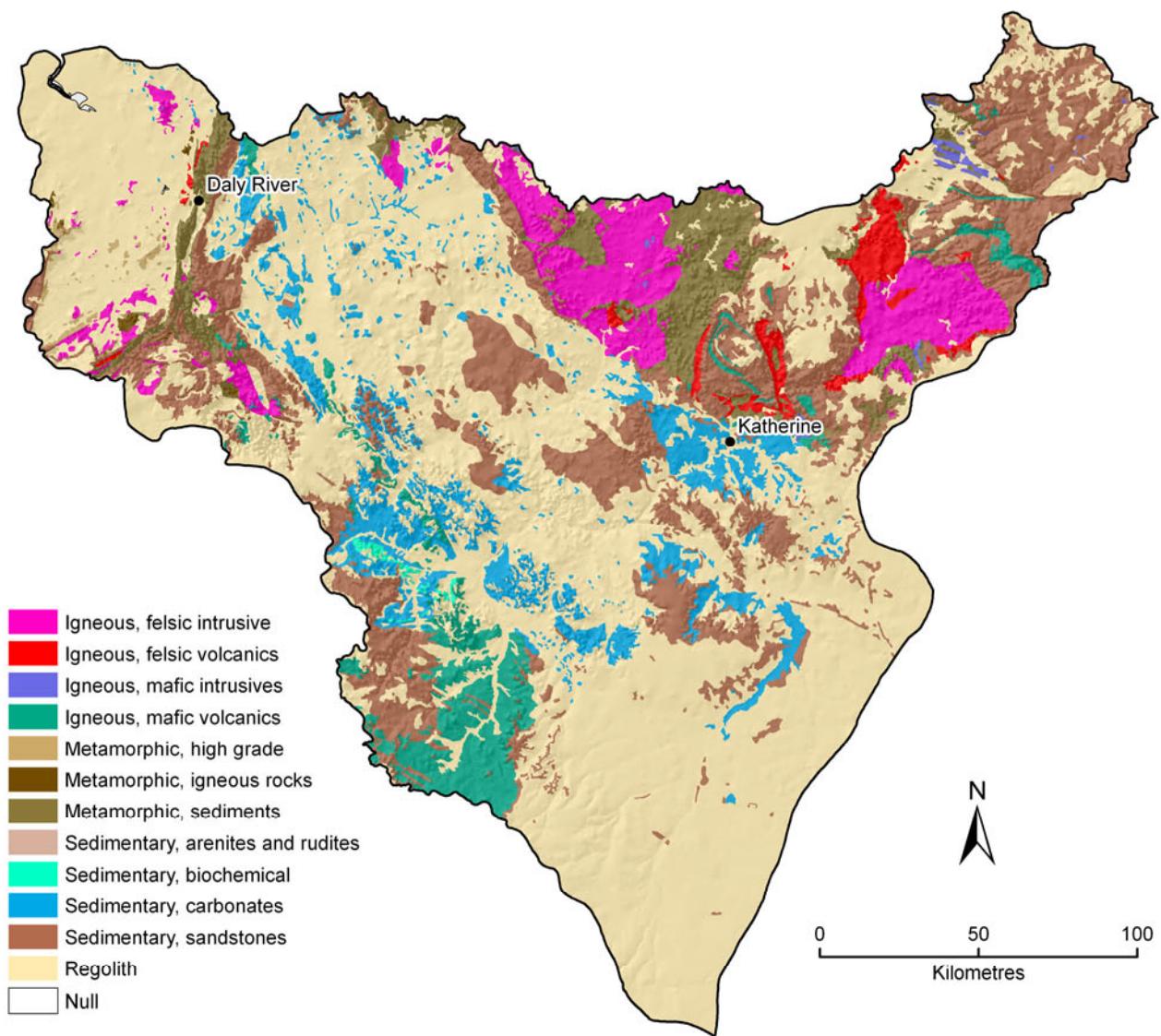


Figure DA-4. Surface geology of the Daly region overlaid on a relative relief surface

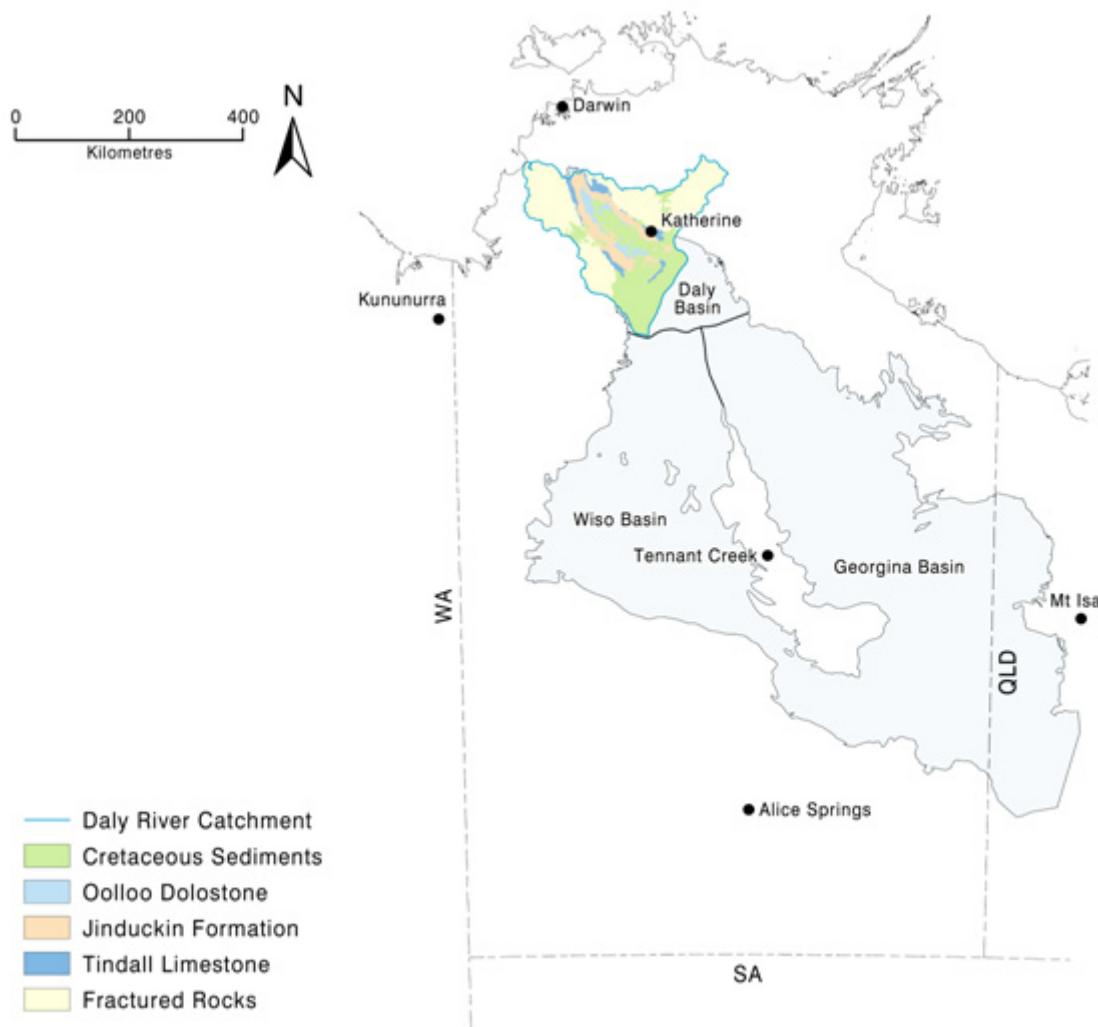


Figure DA-5. Location of Daly, Wiso and Georgina basins (modified from map supplied by the Northern Territory Department of Natural Resources, Environment, The Arts and Sport)

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.

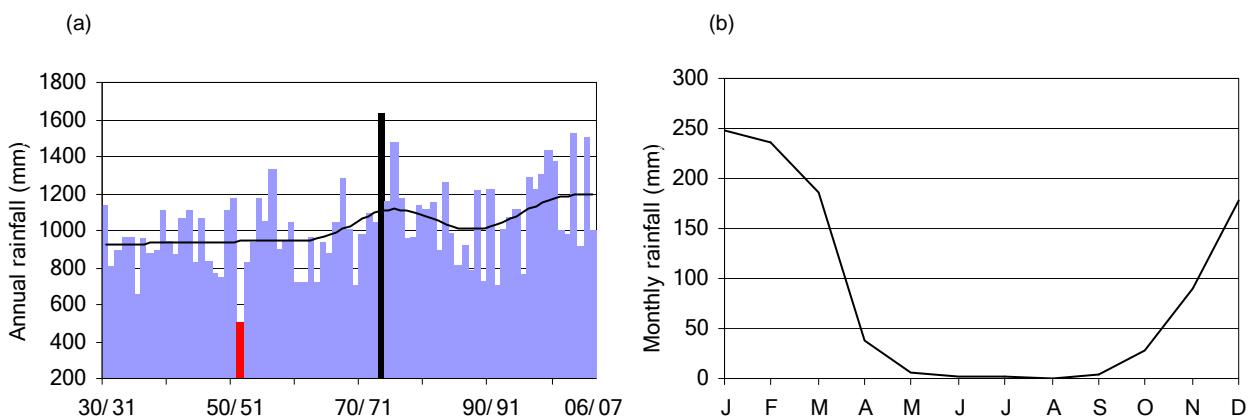


Figure DA-6. Historical (a) annual and (b) mean monthly rainfall averaged over the Daly region. The low-frequency smoothed line in (a) indicates the longer term variability

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.

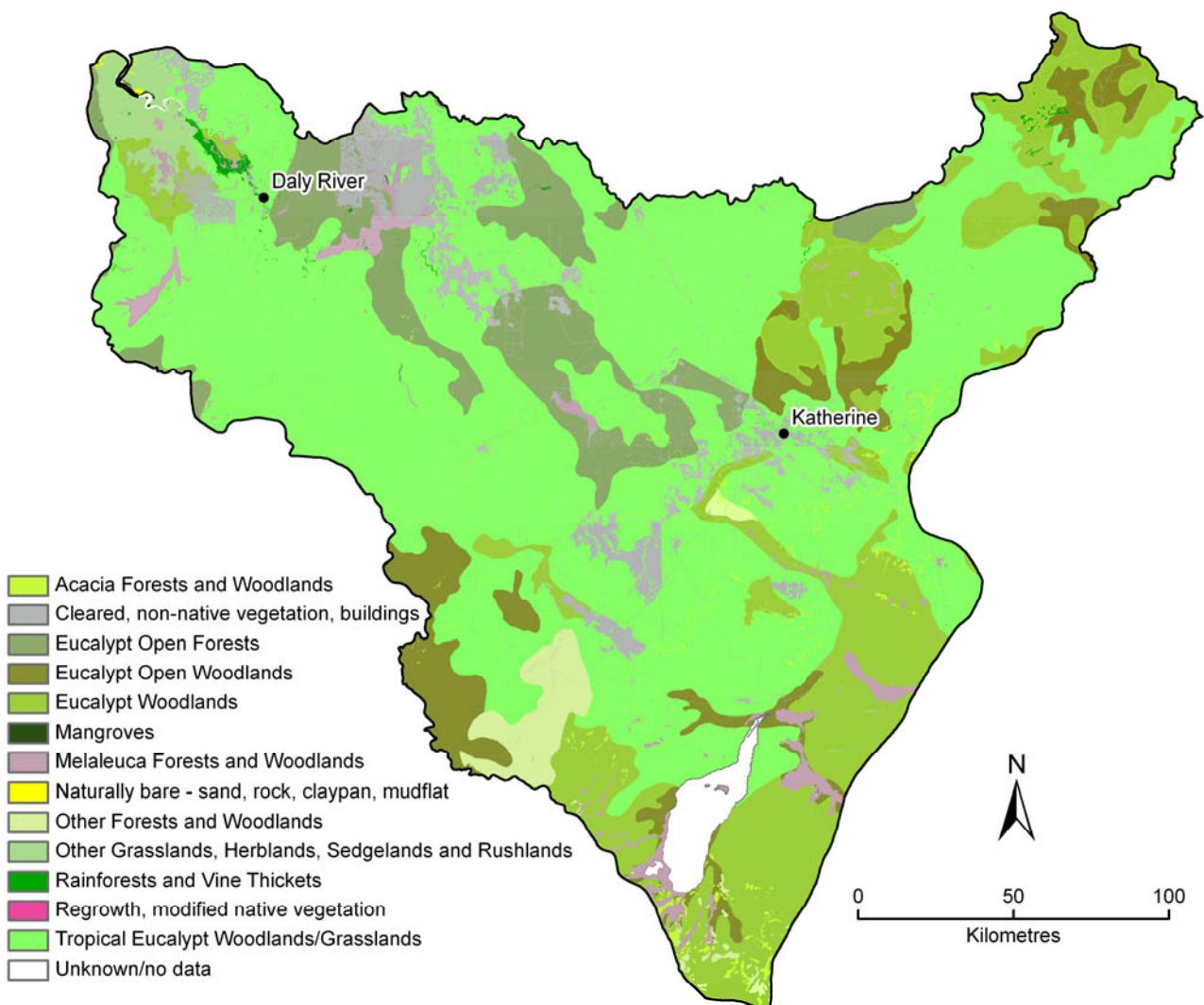


Figure DA-7. Map of current vegetation types across the Daly region (source DEWR, 2005)

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.

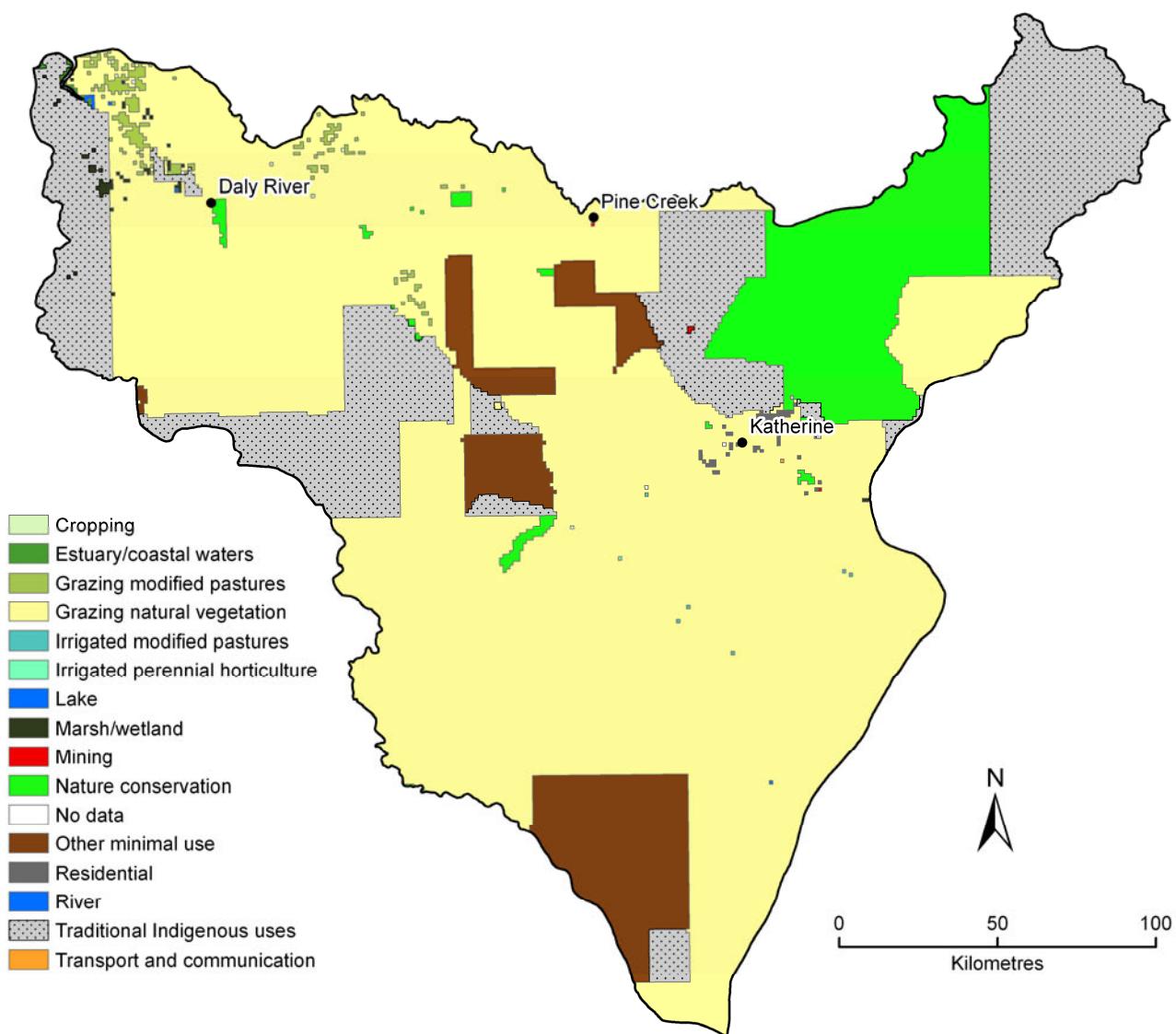


Figure DA-8. Map of dominant land uses of the Daly region (after BRS, 2002)

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 ha	Ramsar site
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 Ooloo 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*)

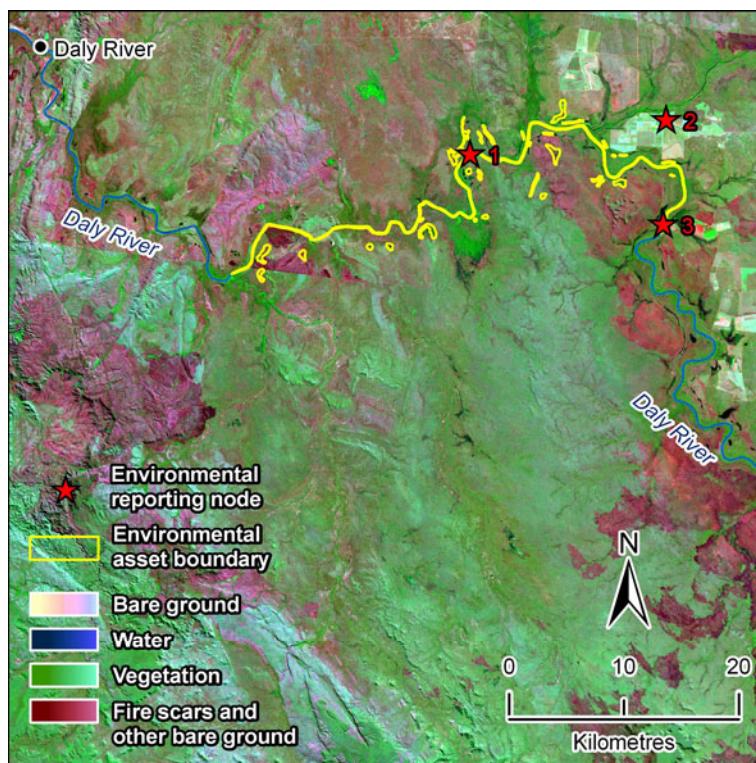


Figure DA-10. False colour satellite image of Daly River Middle Reaches (source ACRES, 2000). Clouds may be visible in image

Daly-Reynolds Floodplain-Estuary System

The Daly-Reynolds Floodplain-Estuary system covers an area of 1590 km² 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.

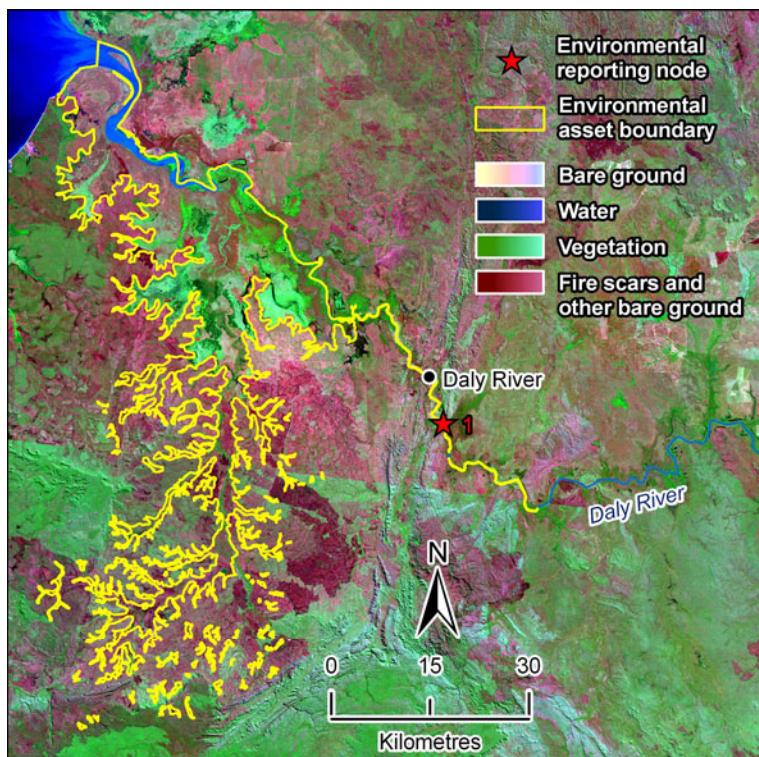


Figure DA-11. False colour satellite image of the Daly-Reynolds Floodplain-Estuary System
(source: ACRES, 2000). Clouds may be visible in image

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.

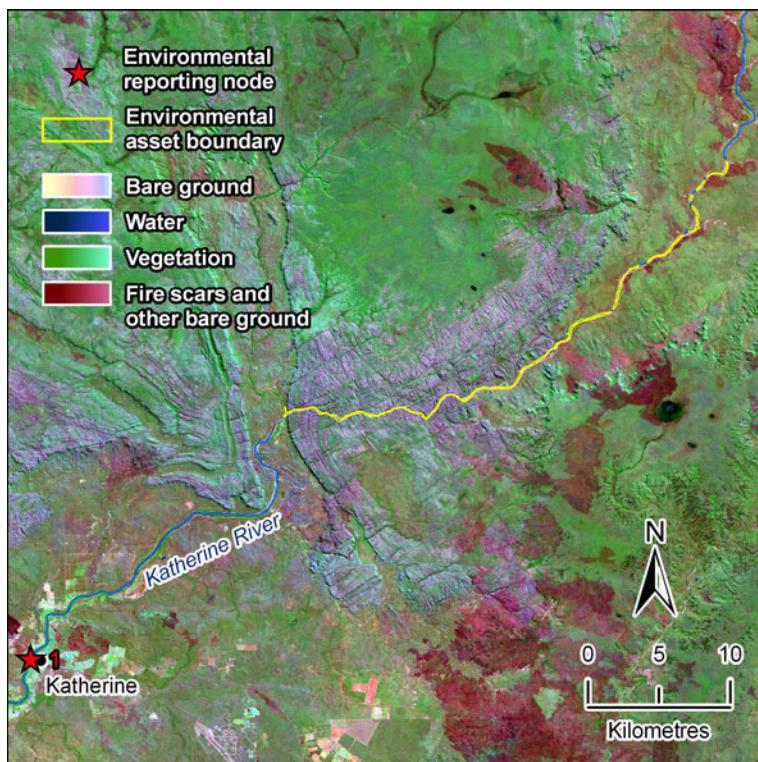


Figure DA-12. False colour satellite image of the Katherine River Gorge (source ACRES, 2000).

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 km². 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 km². 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 km². 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 km².

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.

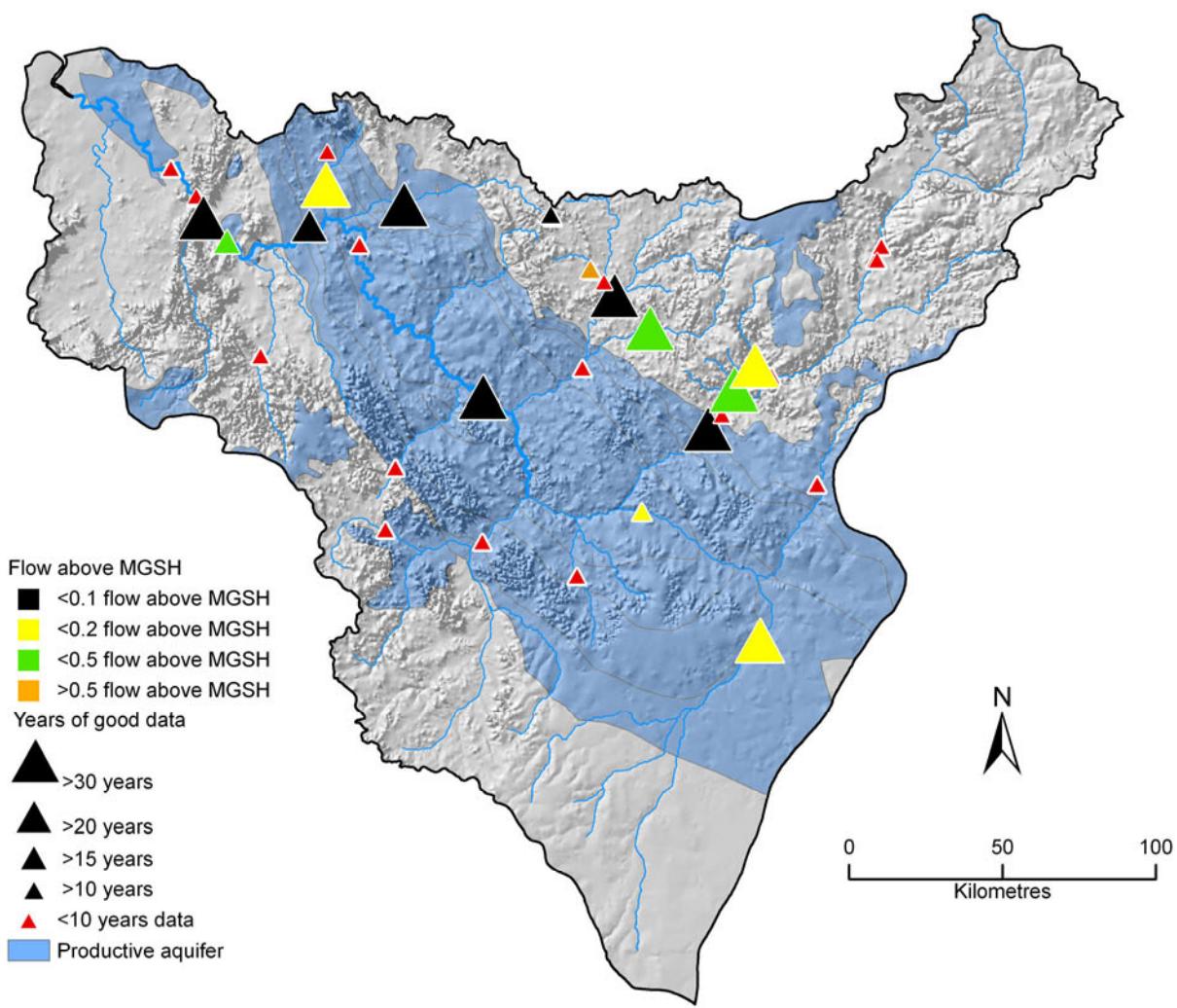


Figure DA-13. Location of streamflow gauging stations overlaid on a relative relief surface showing the proportion of gauges with flow above maximum gauged stage height across the Daly region. Productive aquifer layer includes key dolostone, limestone and Cretaceous sandstone formations

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).

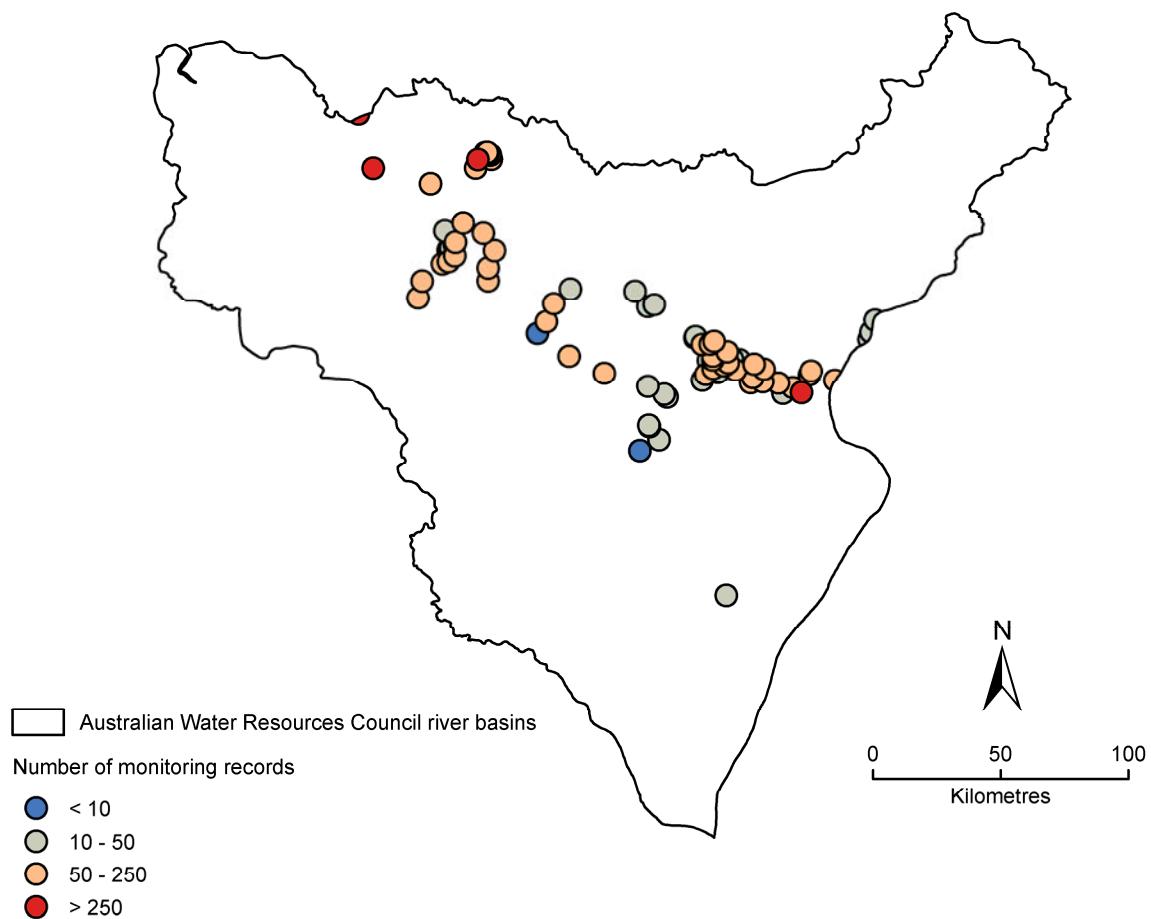


Figure DA-14. Current groundwater monitoring bores in the Daly region

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.

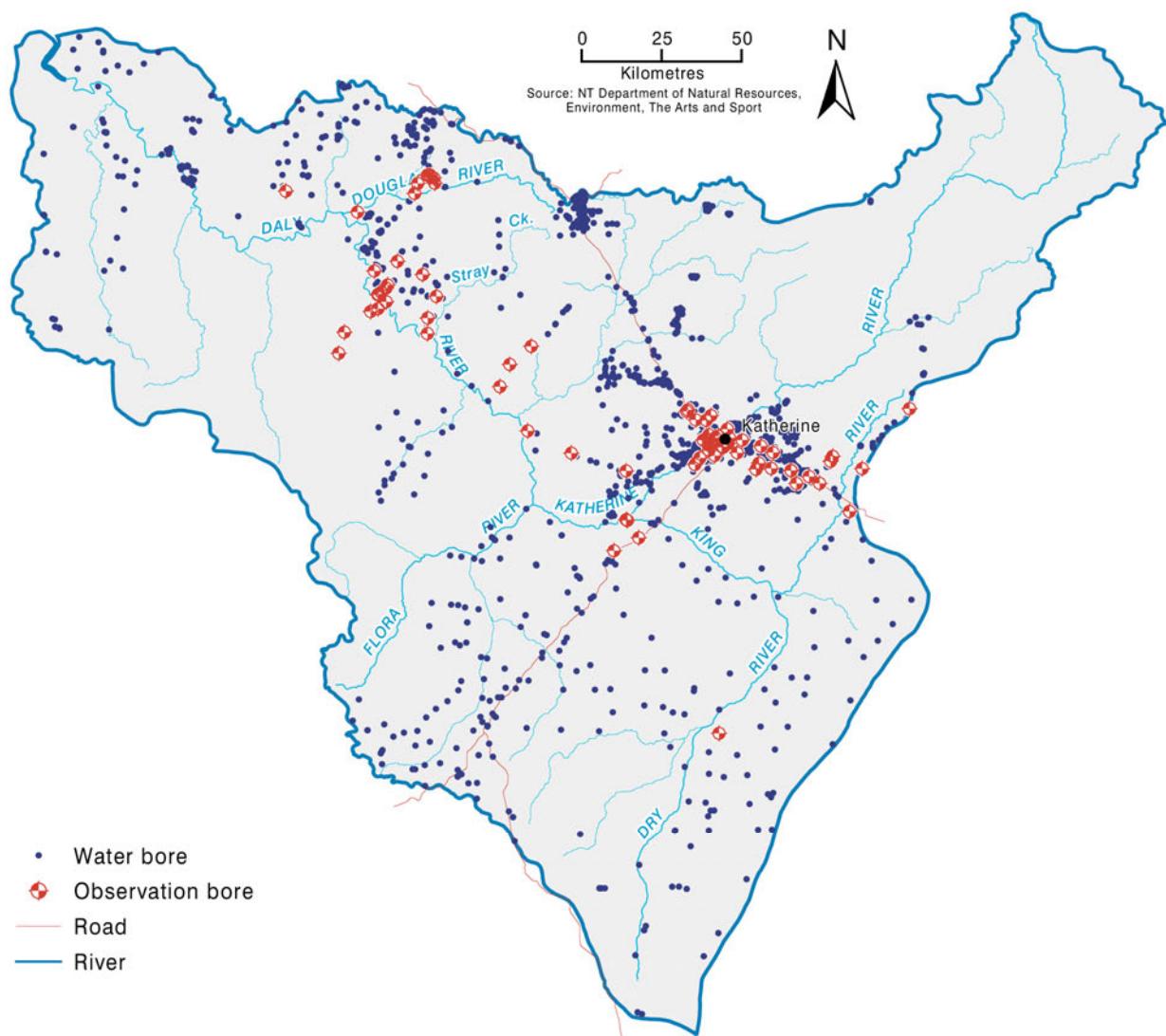


Figure DA-15. Location of groundwater bores in the Daly region (map provided by NRETAS, 2009)

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.

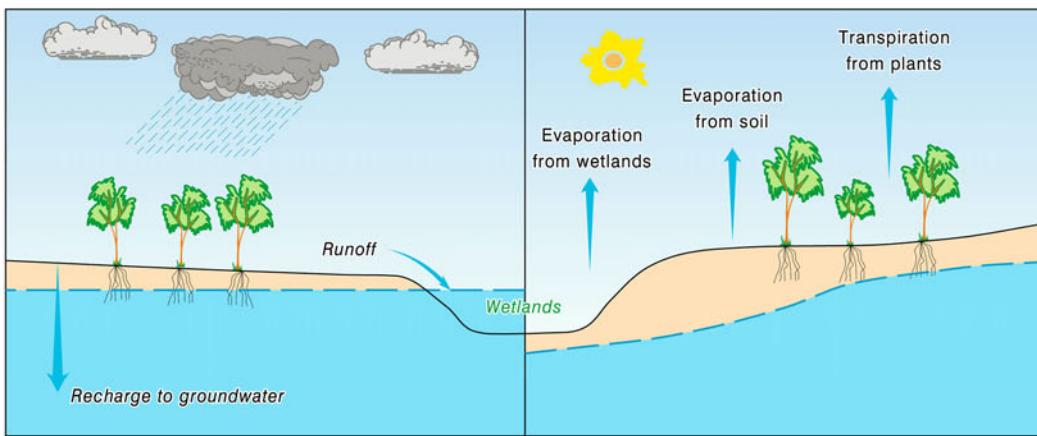


Figure DA-16. Schematic of the recharge and discharge cycle that applies in the Daly region. Note that where rivers are perennial, the groundwater level is maintained above the base of the river during the dry season (right image).

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 Ooloo Dolostone. Water chemistry was used to estimate that recharge over uncleared land over the Ooloo 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.

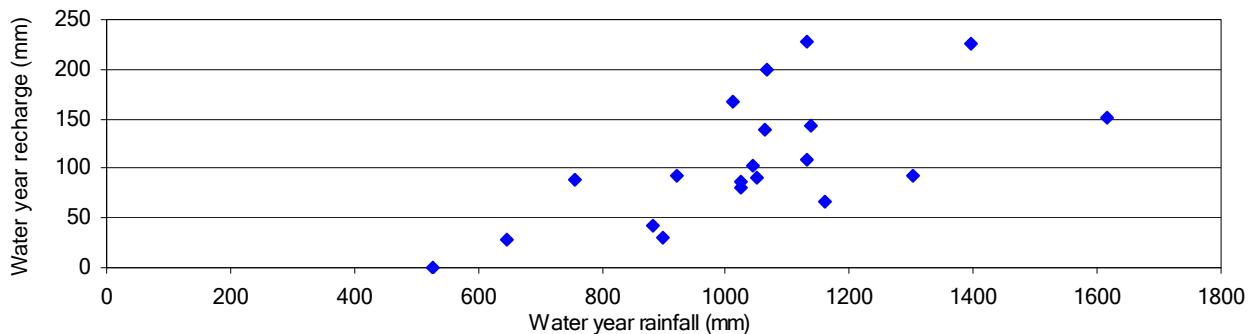


Figure DA-17. Recharge in the Katherine area of the Daly region

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.

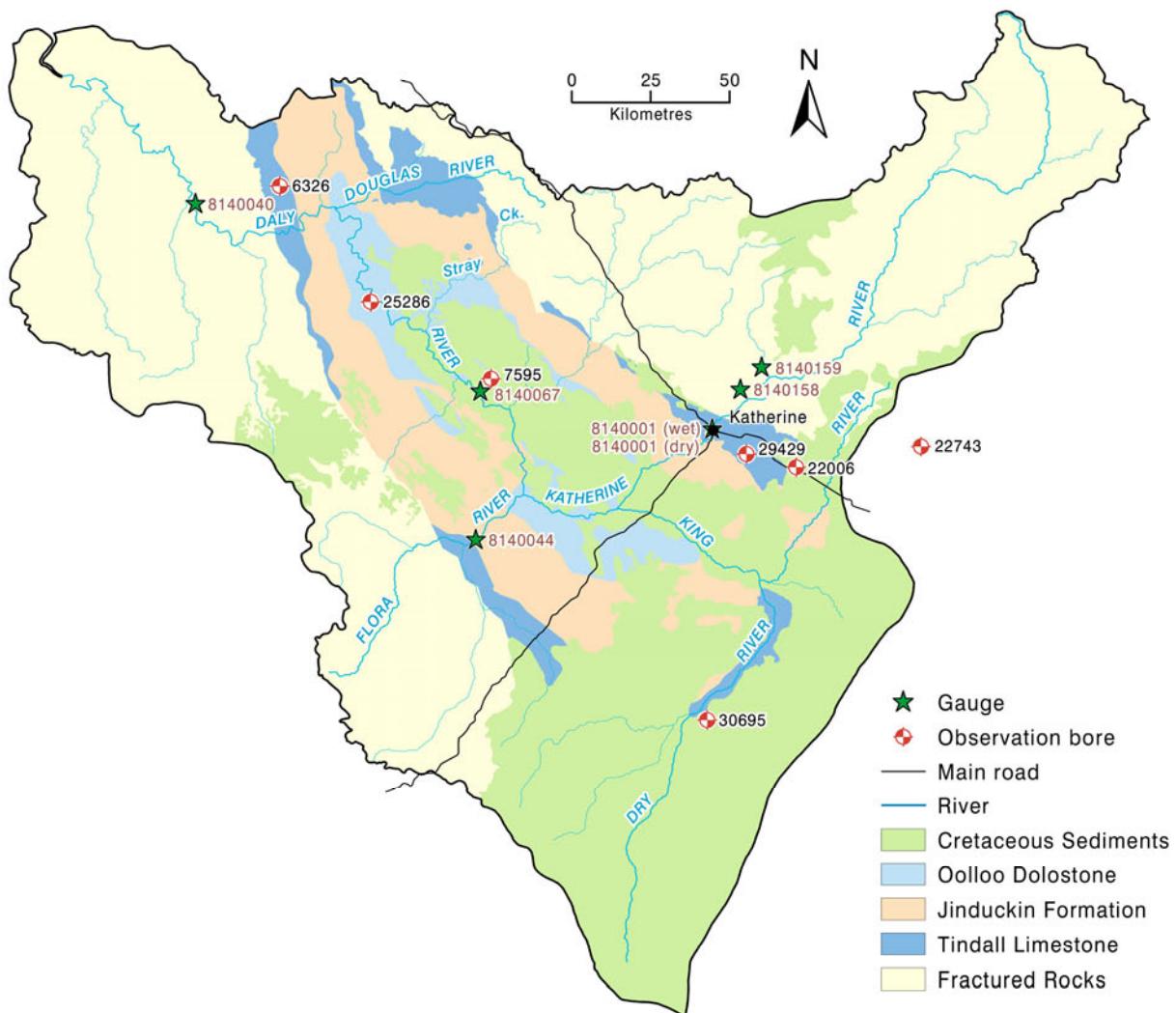


Figure DA-18. Location of monitoring bores and gauging stations referred to in this report (map provided by NRETAS, 2009)

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.

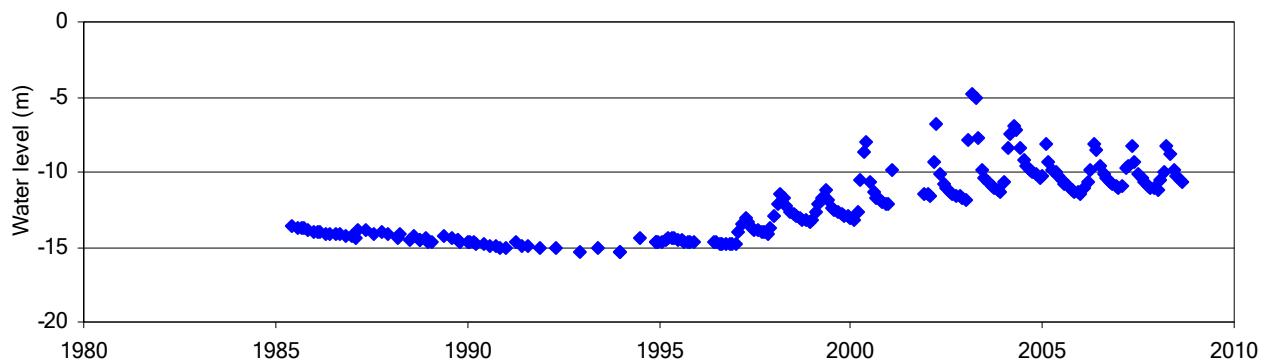


Figure DA-19. Observed groundwater level in bore RN022743 in the Daly region

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 perenniarity 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.

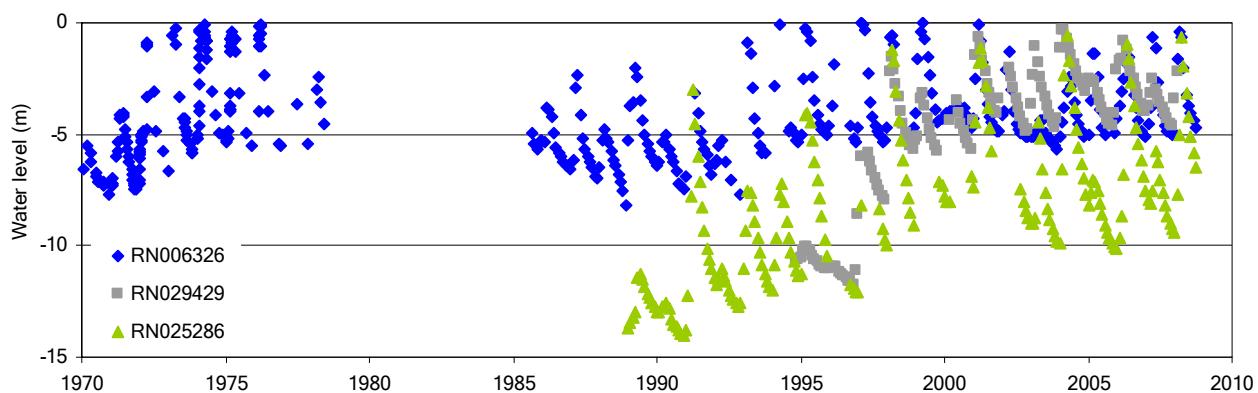


Figure DA-20. Observed groundwater levels in bores RN006326, RN025286 and RN029429 in the Daly region

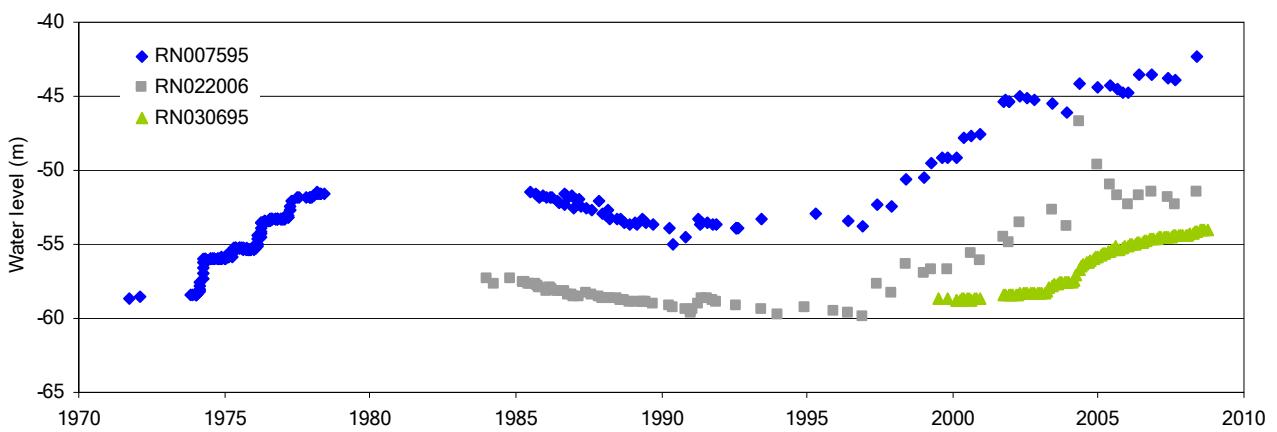


Figure DA-21. Observed groundwater levels in bores RN007595, RN022006 and RN030695 in the Daly region

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

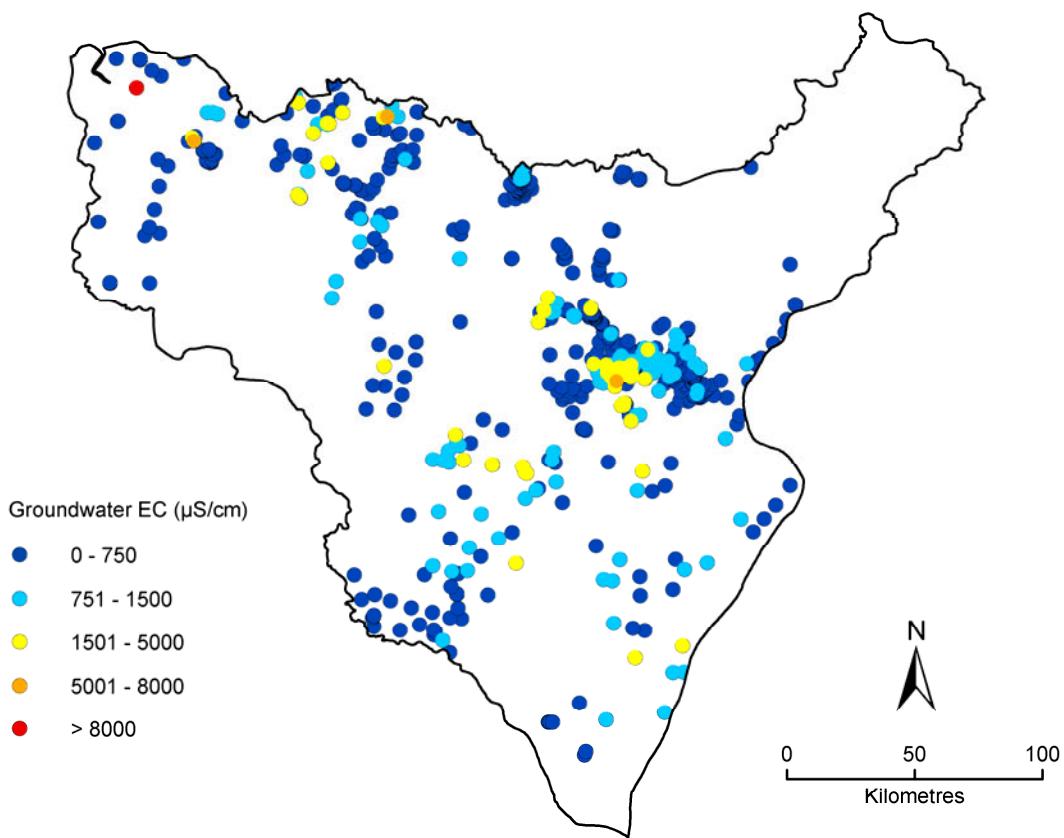
Most water from the fractured rock aquifers across the Daly River catchment fall within acceptable drinking water guidelines (ADWG, 2004). Occasionally elevated levels of arsenic are an issue.

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 $\mu\text{S}/\text{cm}$ (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 $\mu\text{S}/\text{cm}$ (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 $\mu\text{S}/\text{cm}$.



* Groundwater salinity reflects all bores completed in shallow and deep aquifers

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.

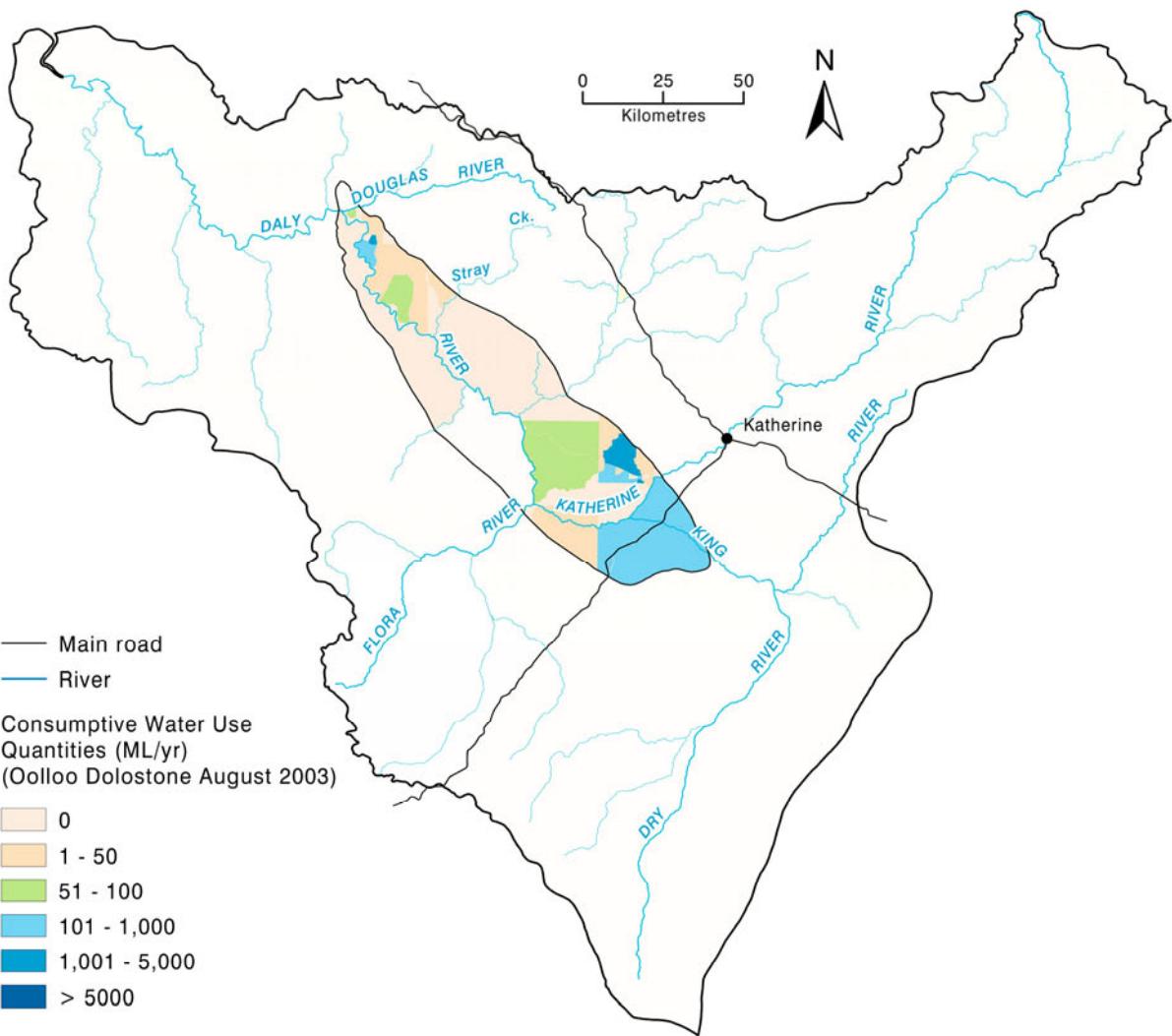


Figure DA-23. Water use from the Oolloo Dolostone aquifer (Source: Northern Territory Government, August 2003)

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.

DA-2.5 References

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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 a 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.

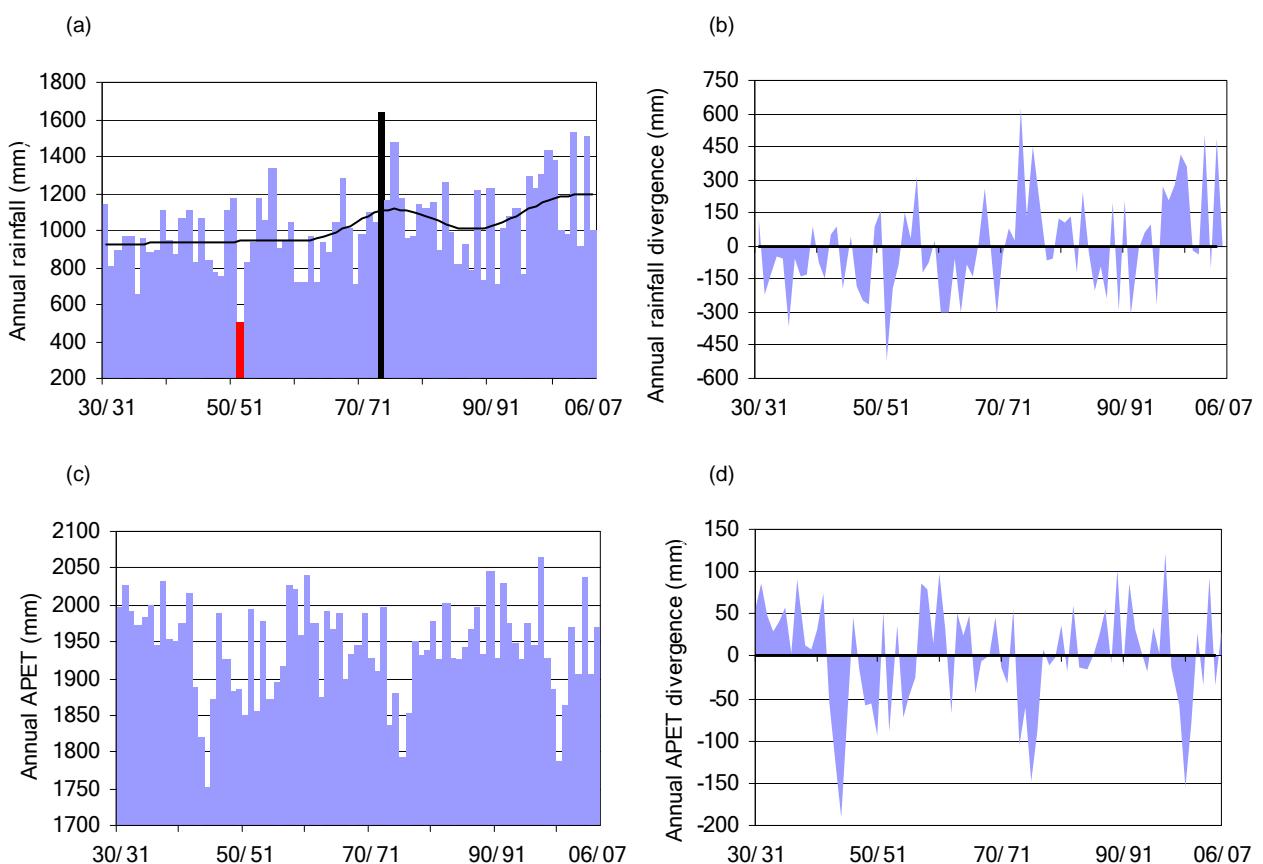


Figure DA-24. (a) Historical annual rainfall and (b) its divergence from the long-term mean; and (c) historical annual areal potential evapotranspiration and (d) its divergence from the long-term mean averaged over the Daly region. The low-frequency smoothed line in (a) indicates longer term variability

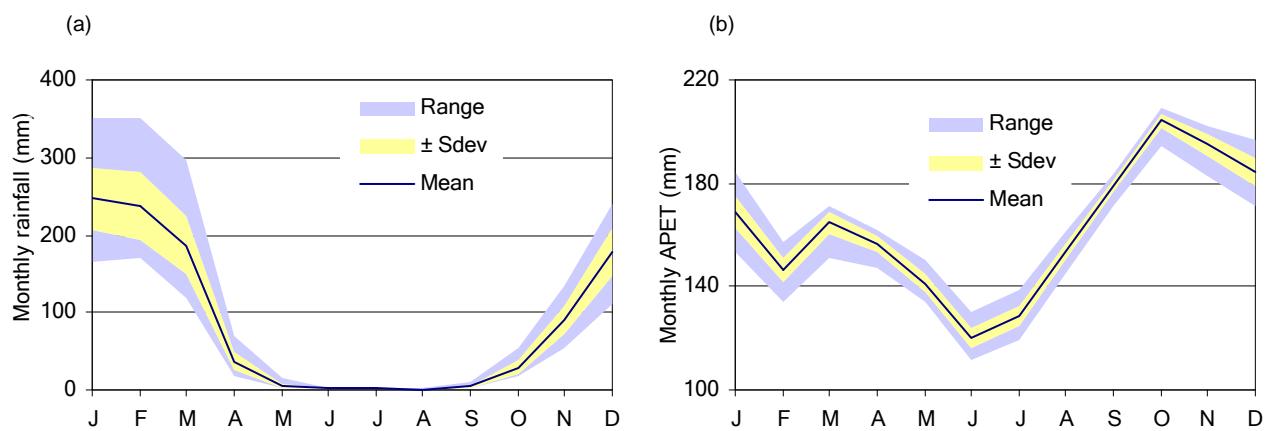


Figure DA-25. Historical mean monthly (a) rainfall and (b) areal potential evapotranspiration and their temporal variation (range and \pm one standard deviation) averaged over the Daly region

DA-3 Water balance results for the Daly region

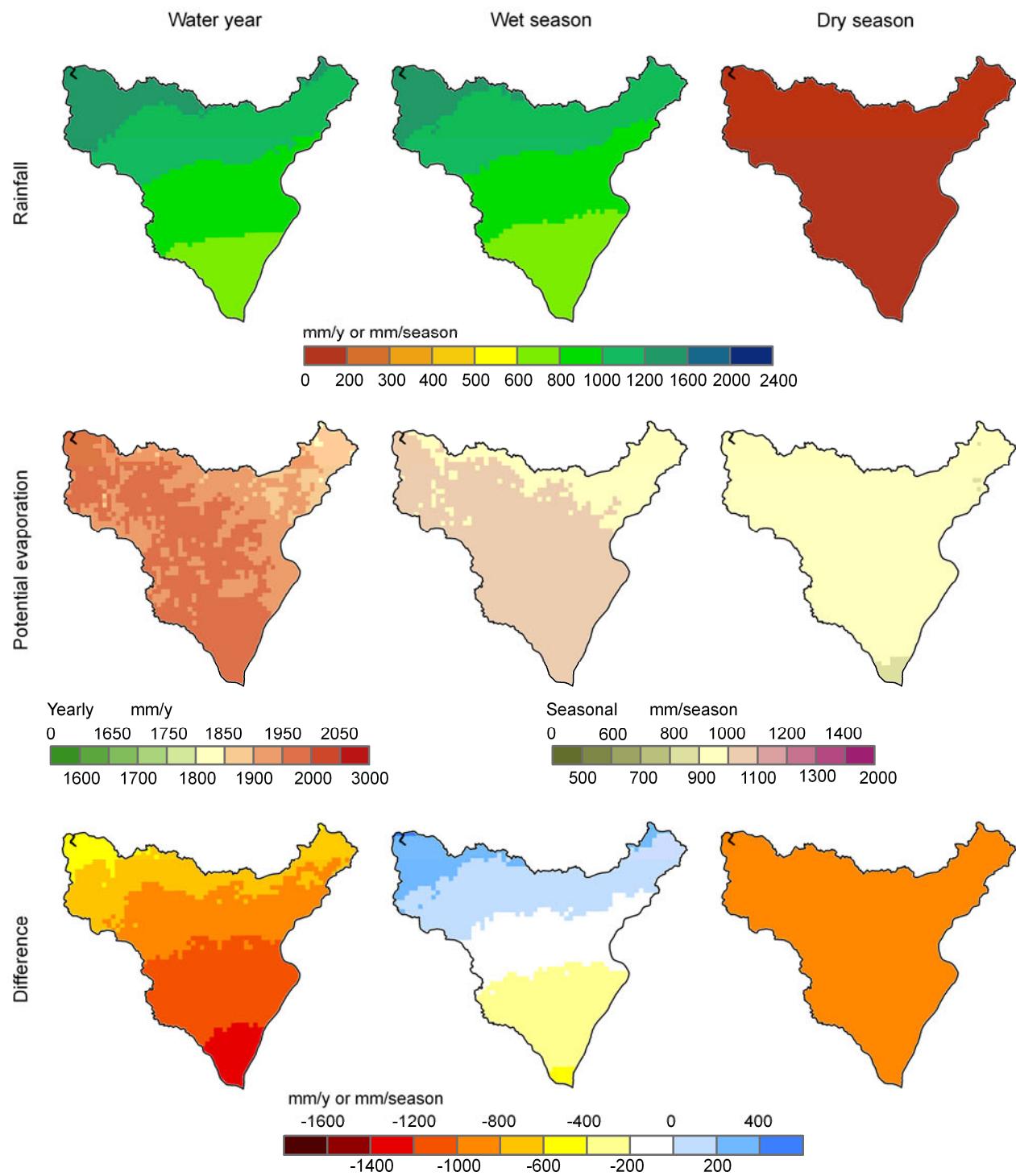


Figure DA-26. Spatial distribution of historical mean annual (water year), wet season and dry season rainfall and areal potential evapotranspiration (potential evaporation) and their difference (rainfall less areal potential evapotranspiration) across the Daly region

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.

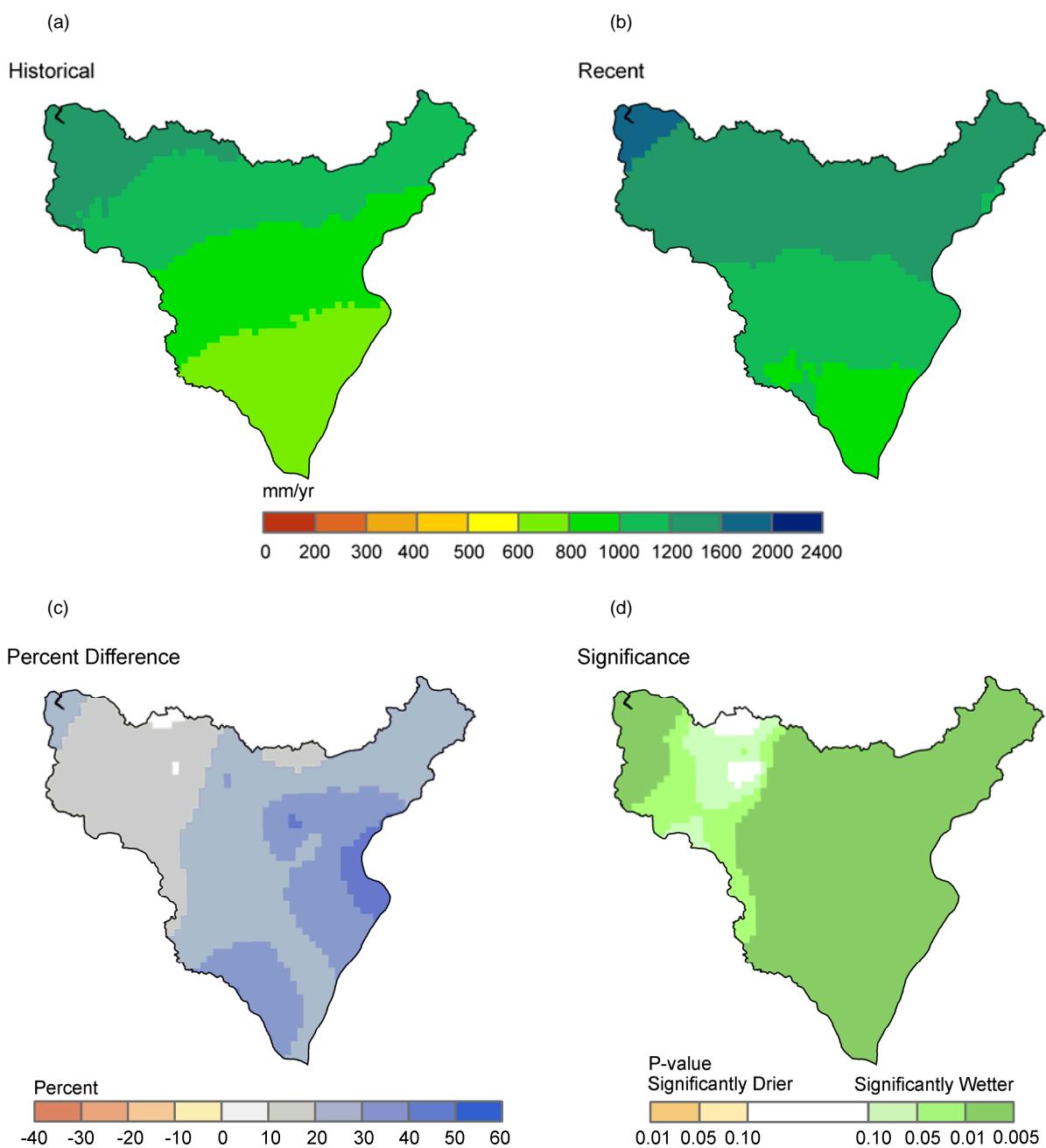


Figure DA-27. Spatial distribution of (a) historical and (b) recent mean annual rainfall; and (c) their relative percent difference and (d) the statistical significance of these differences across the Daly region. (Note that historical in this case is the 66-year period 1930 to 1996)

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).

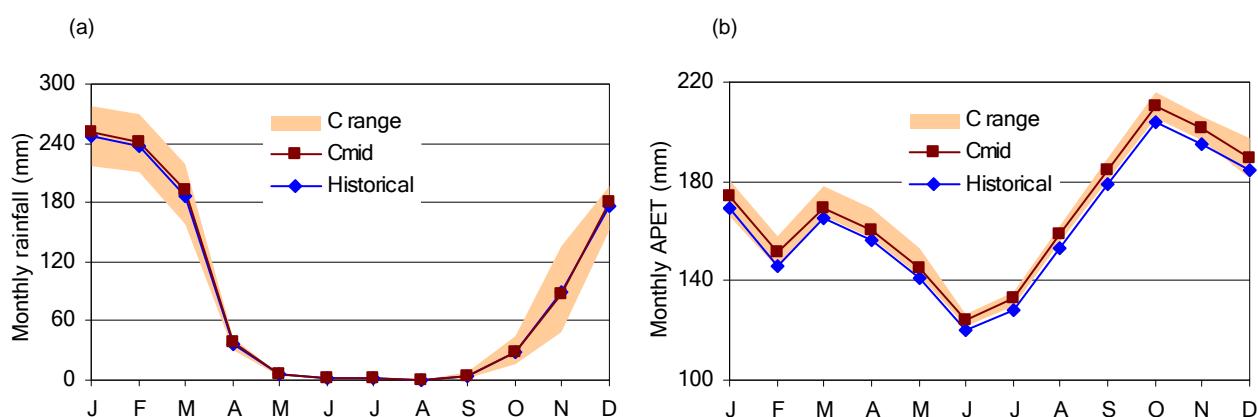


Figure DA-28. Mean monthly (a) rainfall and (b) areal potential evapotranspiration averaged over the Daly region under historical climate and Scenario C. (C range is the range under the 45 Scenario C simulations – the lower and upper limits in C range are therefore not the same as scenarios Cdry and 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.

DA-3 Water balance results for the Daly region

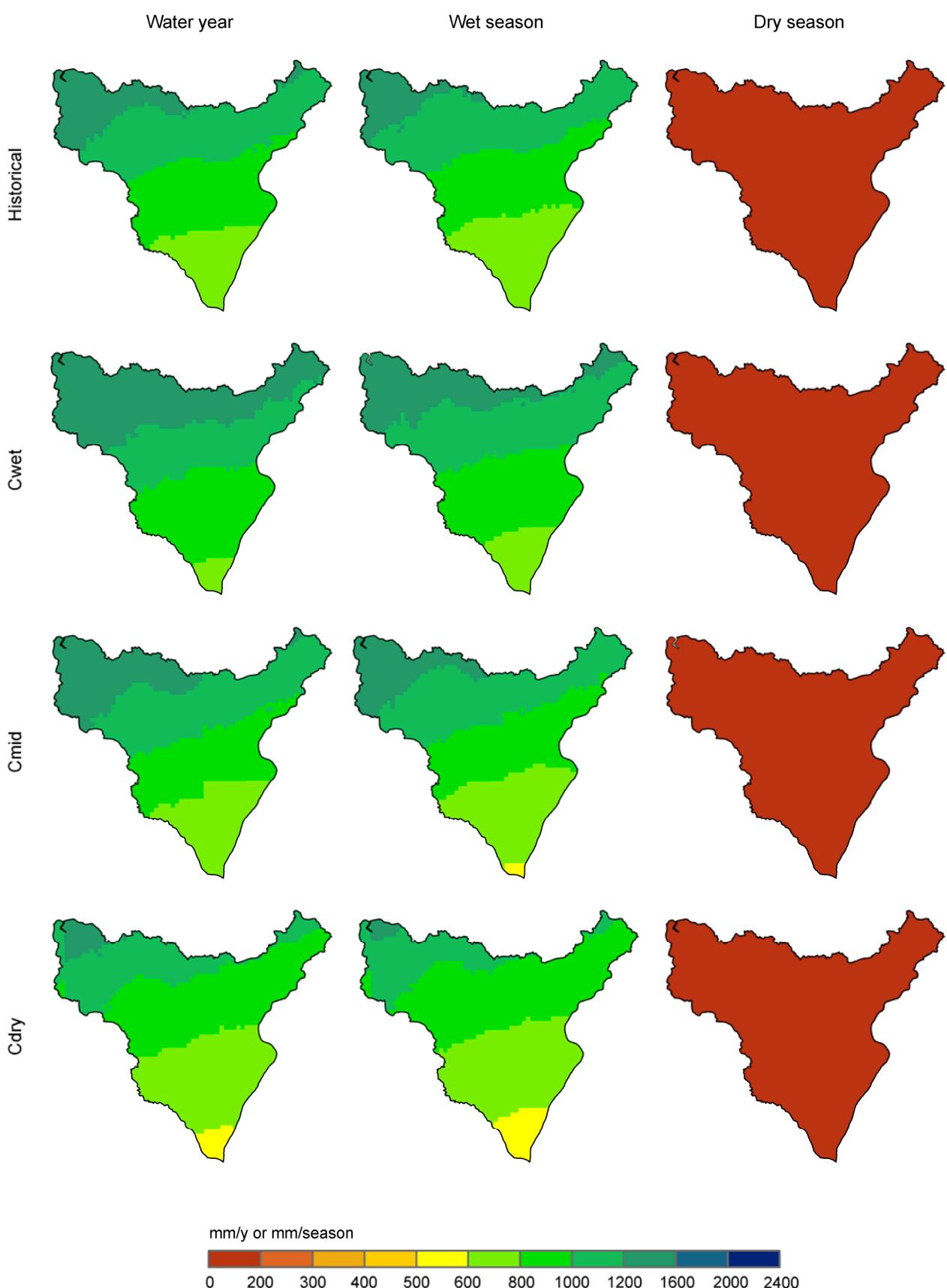


Figure DA-29. Spatial distribution of mean annual (water year), wet season and dry season rainfall across the Daly region under historical climate and Scenario C

DA-3 Water balance results for the Daly region

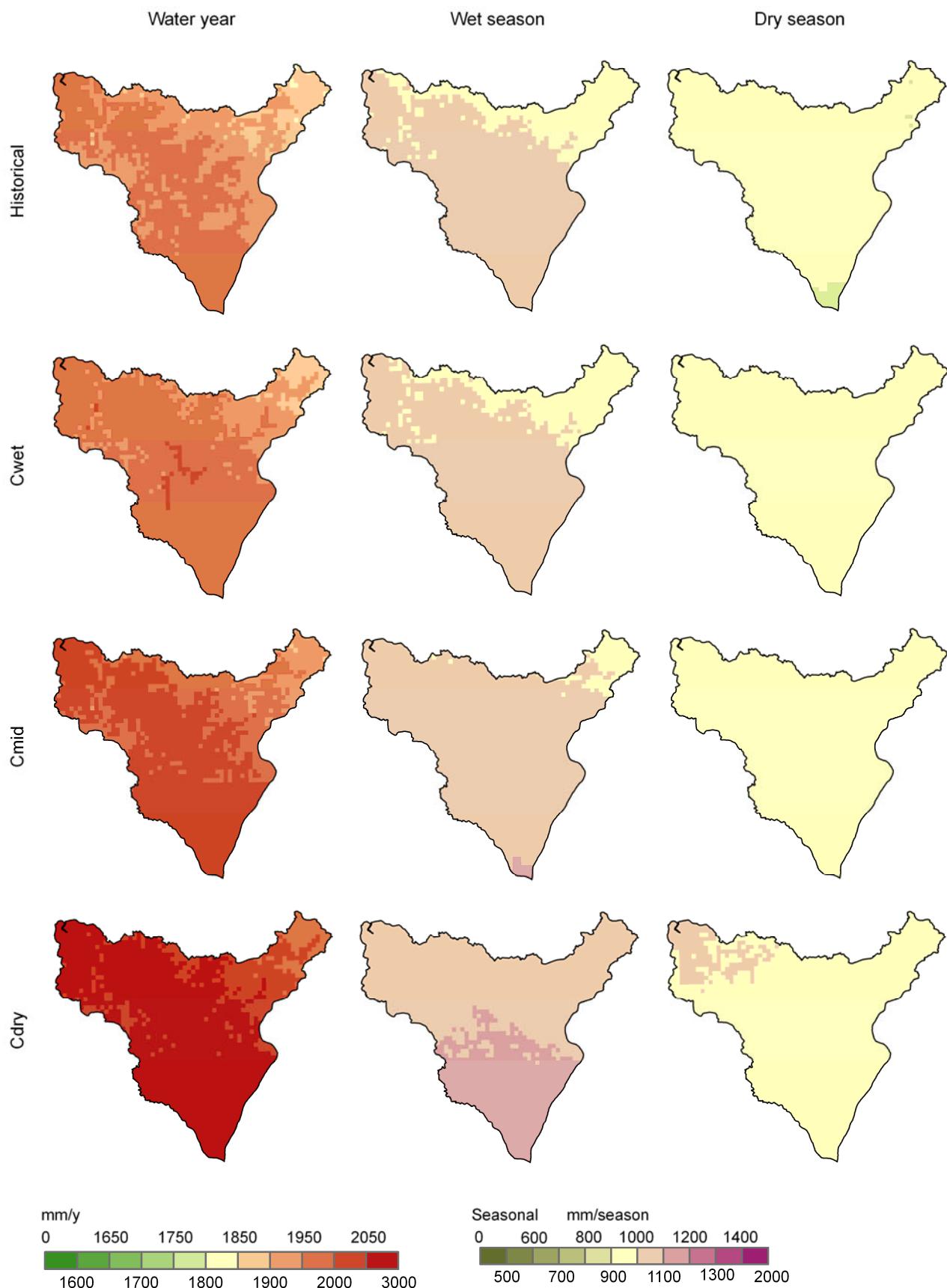


Figure DA-30. Spatial distribution of mean annual (water year), wet season and dry season areal potential evapotranspiration across the Daly region under historical climate and Scenario C

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 CO₂, 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 than 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

DA-3 Water balance results for the Daly region

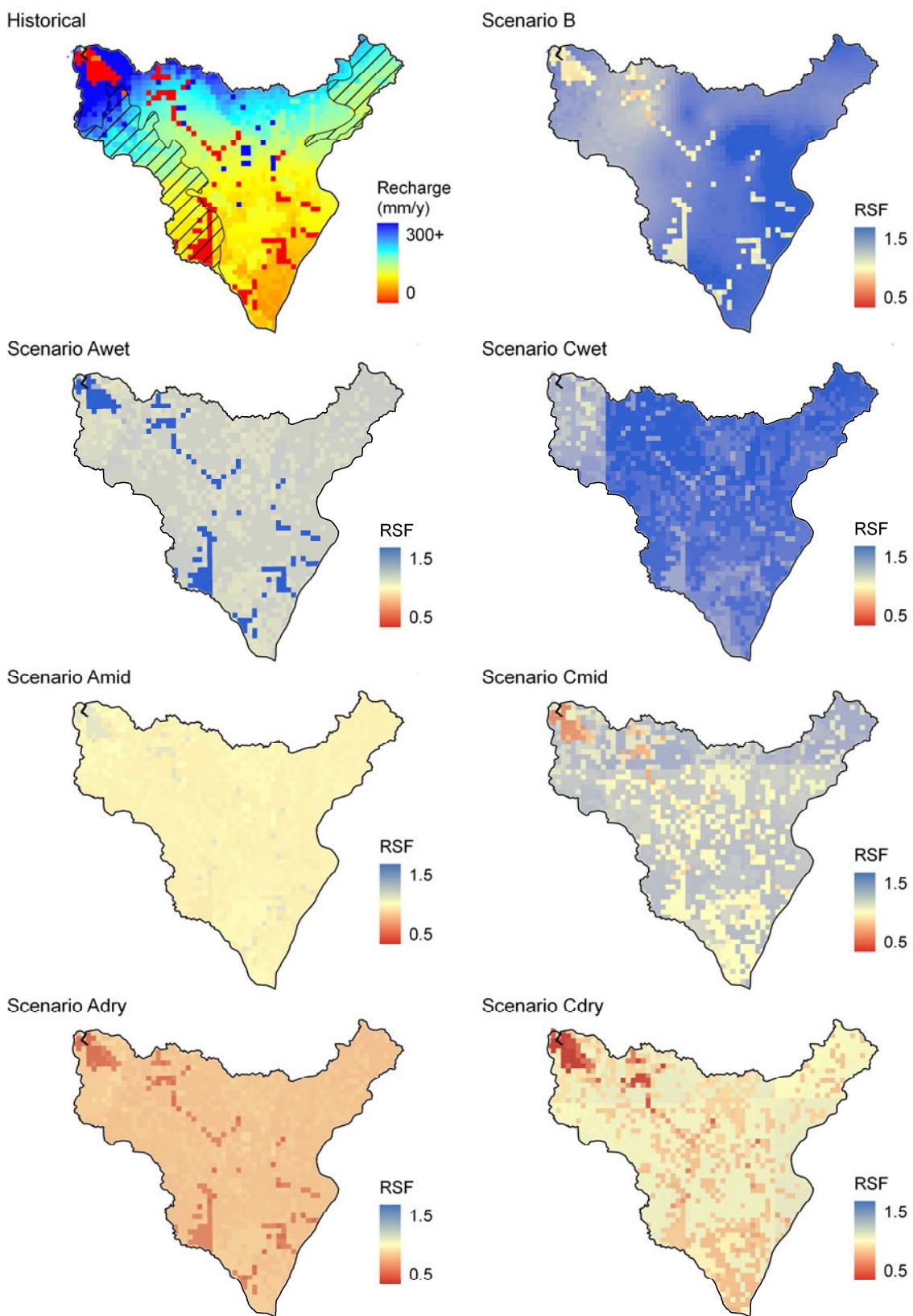


Figure DA-31. Spatial distribution of historical mean recharge rate; and recharge scaling factors in the Daly region for scenarios A, B and C. The hatched region on the historical recharge map identifies where unweathered bedrock outcrops occur

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 CO₂ 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.

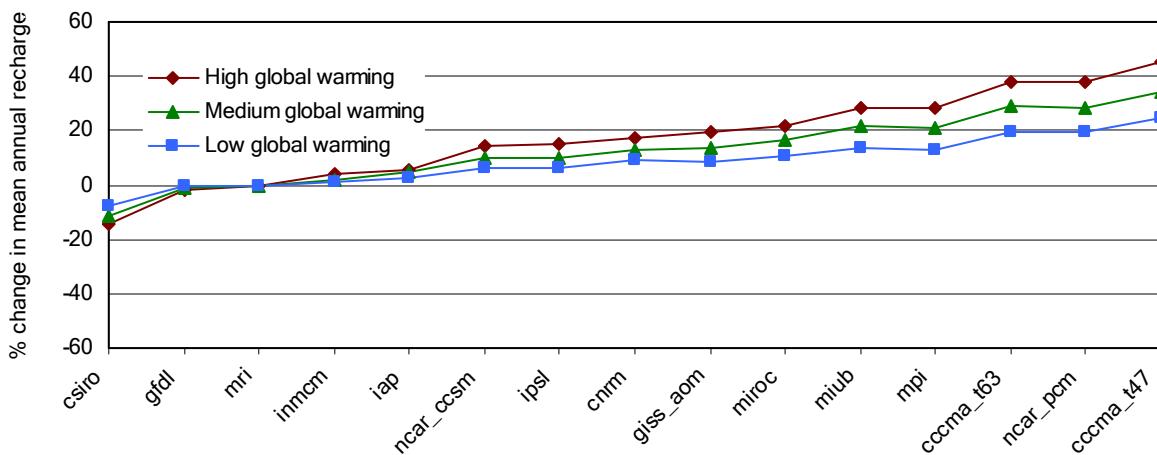


Figure DA-32. Percentage change in mean annual recharge under the 45 Scenario C simulations (15 global climate models and three global warming scenarios) relative to Scenario A recharge

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%
ccma_t63	9%	38%	ccma_t63	7%	29%	ccma_t63	5%	20%
ncar_pcm	11%	38%	ncar_pcm	8%	28%	ncar_pcm	6%	20%
ccma_t47	12%	45%	ccma_t47	9%	34%	ccma_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 Ooloo Dolostone. Early Cretaceous rocks overlie much of the Ooloo Dolostone and large areas of the Tindall Limestone to the south-east (Figure DA-2).

The aquifers of the Ooloo 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 m²/day for the Tindall and 10,000 m²/day for the Ooloo) and relatively low storage with estimates ranging from 0.01 to 0.07.

The Jinduckin Formation overlies the Tindall Limestone and underlies the Ooloo 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 Ooloo 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 Ooloo 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 Ooloo 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 Ooloo 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 Ooloo 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.

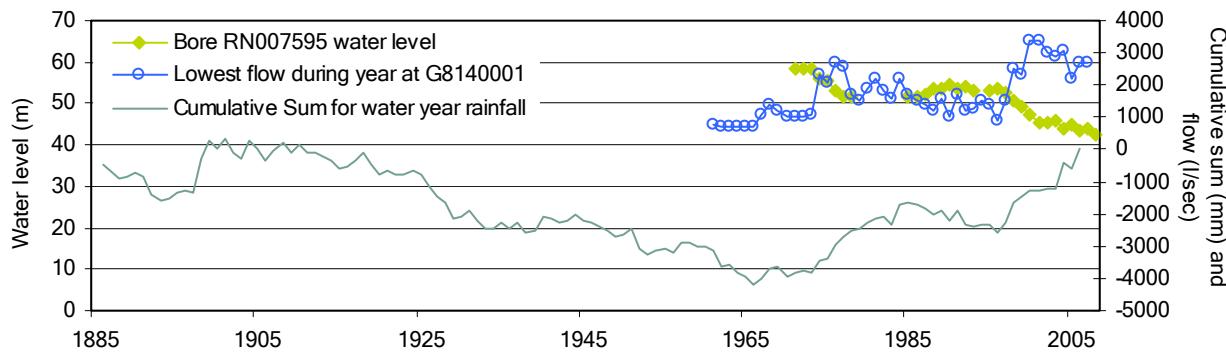


Figure DA-33. Discharge at gauging station G8140001 in the Daly region, with cumulative deviation from mean rainfall and water levels in nearby bore for each year of record

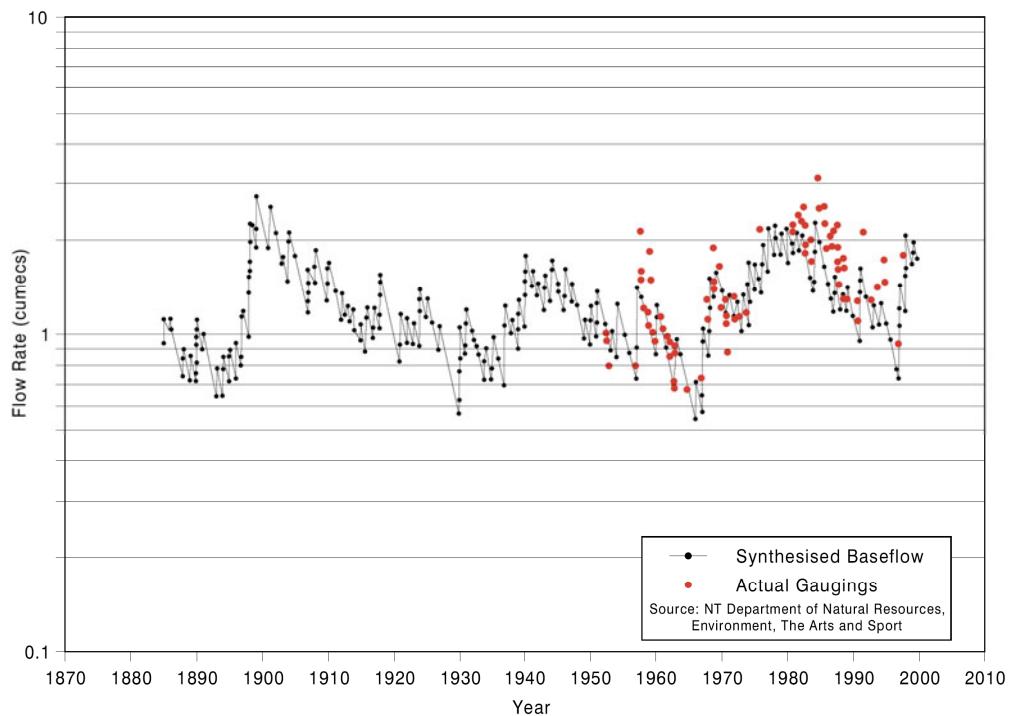


Figure DA-34. Flows from groundwater to river at gauging station G8140001 in the Daly region (after Jolly et al., 2000)

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 km² 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 km² 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.

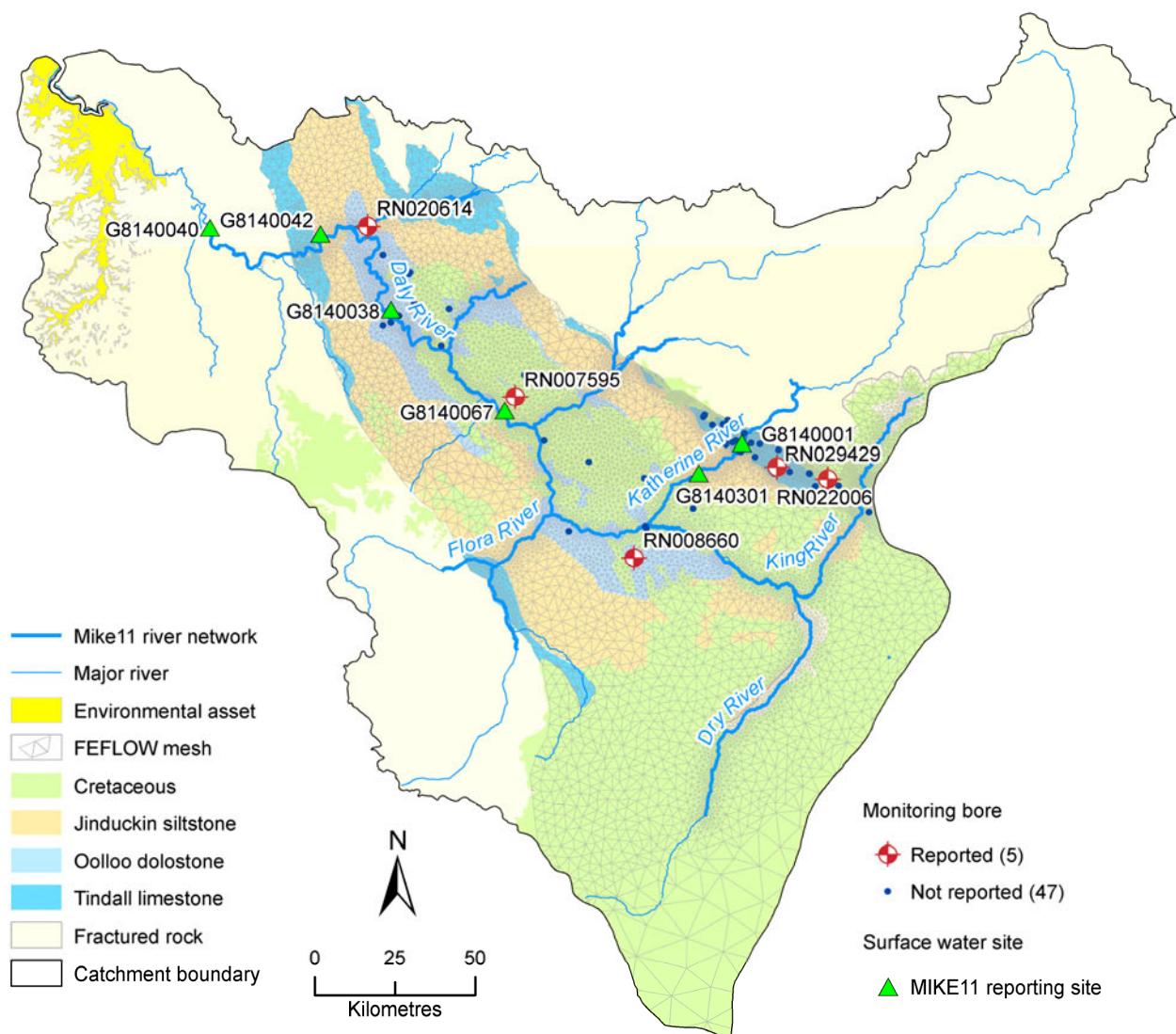


Figure DA-35. Groundwater and surface water model reporting sites for the Daly region

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.

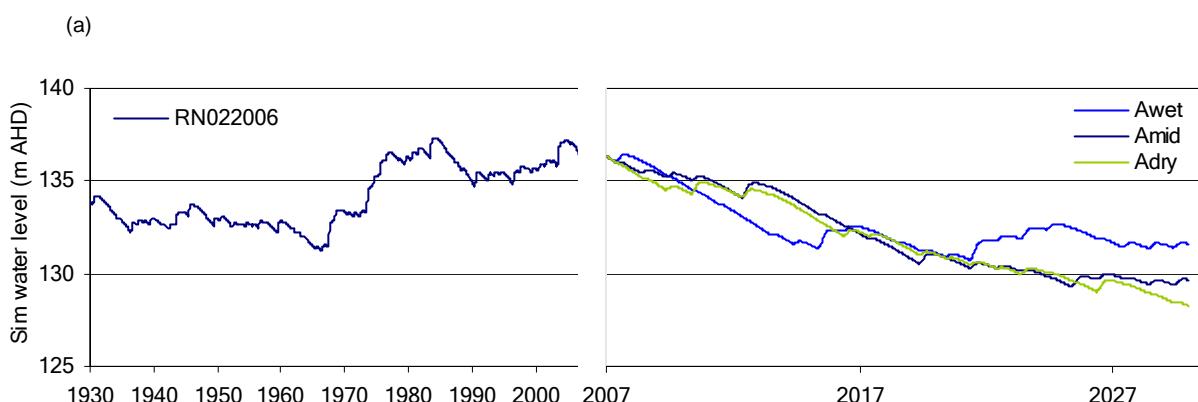
DA-3.4.3 Under historical climate

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, RN008660 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.



DA-3 Water balance results for the Daly region

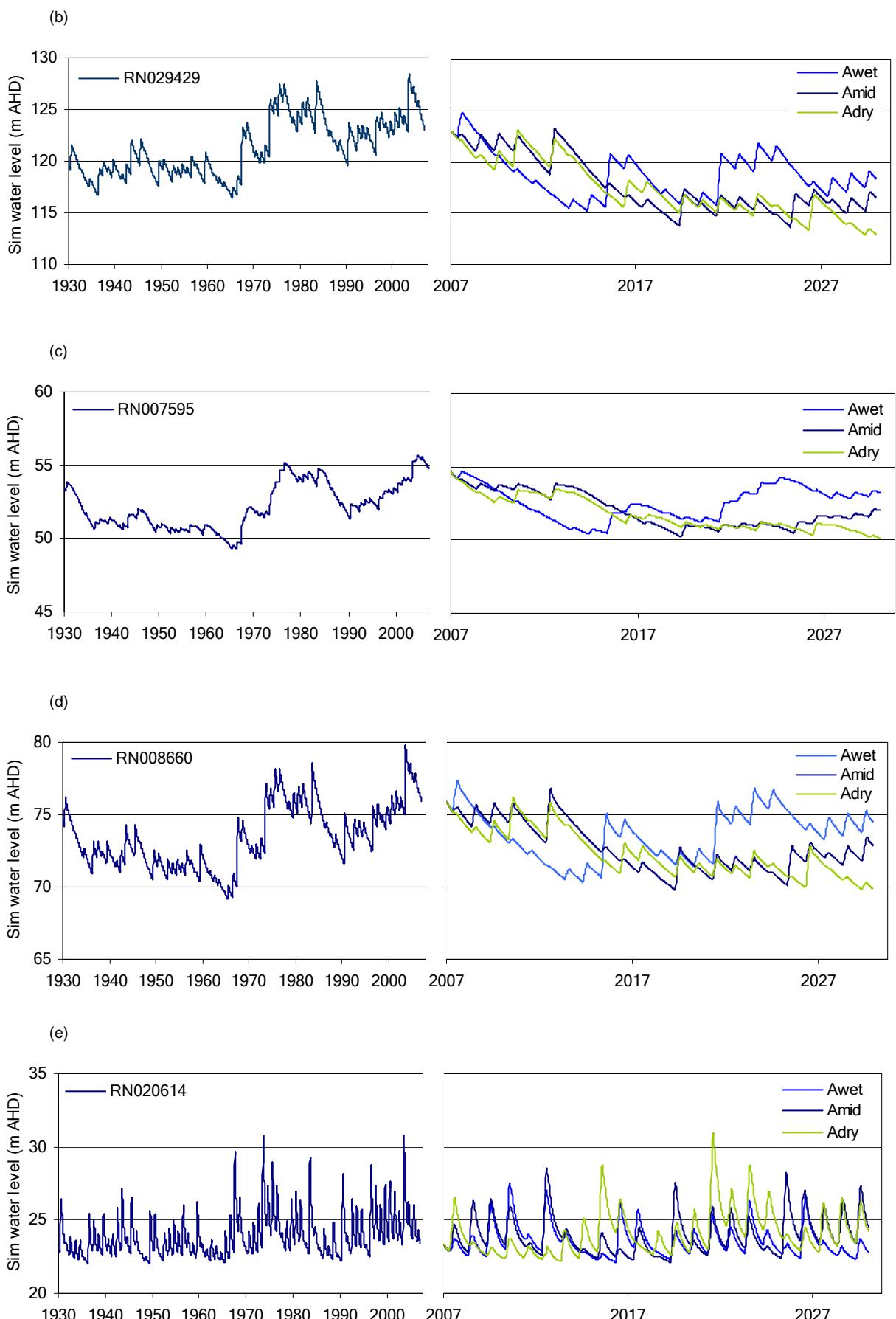


Figure DA-36. Simulated groundwater levels for selected observation bores in the Daly region for the warm-up period and Scenario A forecast

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).

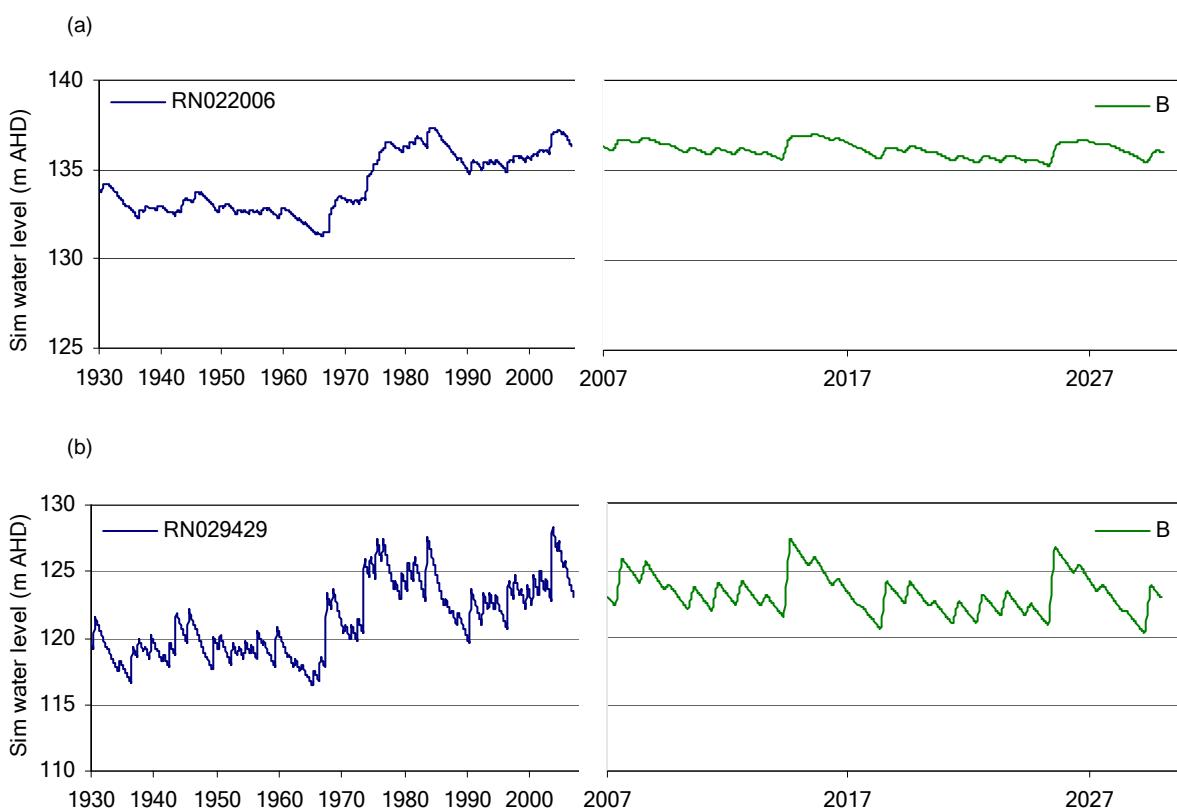
Under Awet average annual recharge increases 9 percent (after scaling) compared to the historical period. The elevated groundwater levels at the end of the historical period can not be sustained under this variant of Scenario A and a new equilibrium level is reached after approximately 5 to 10 years (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.



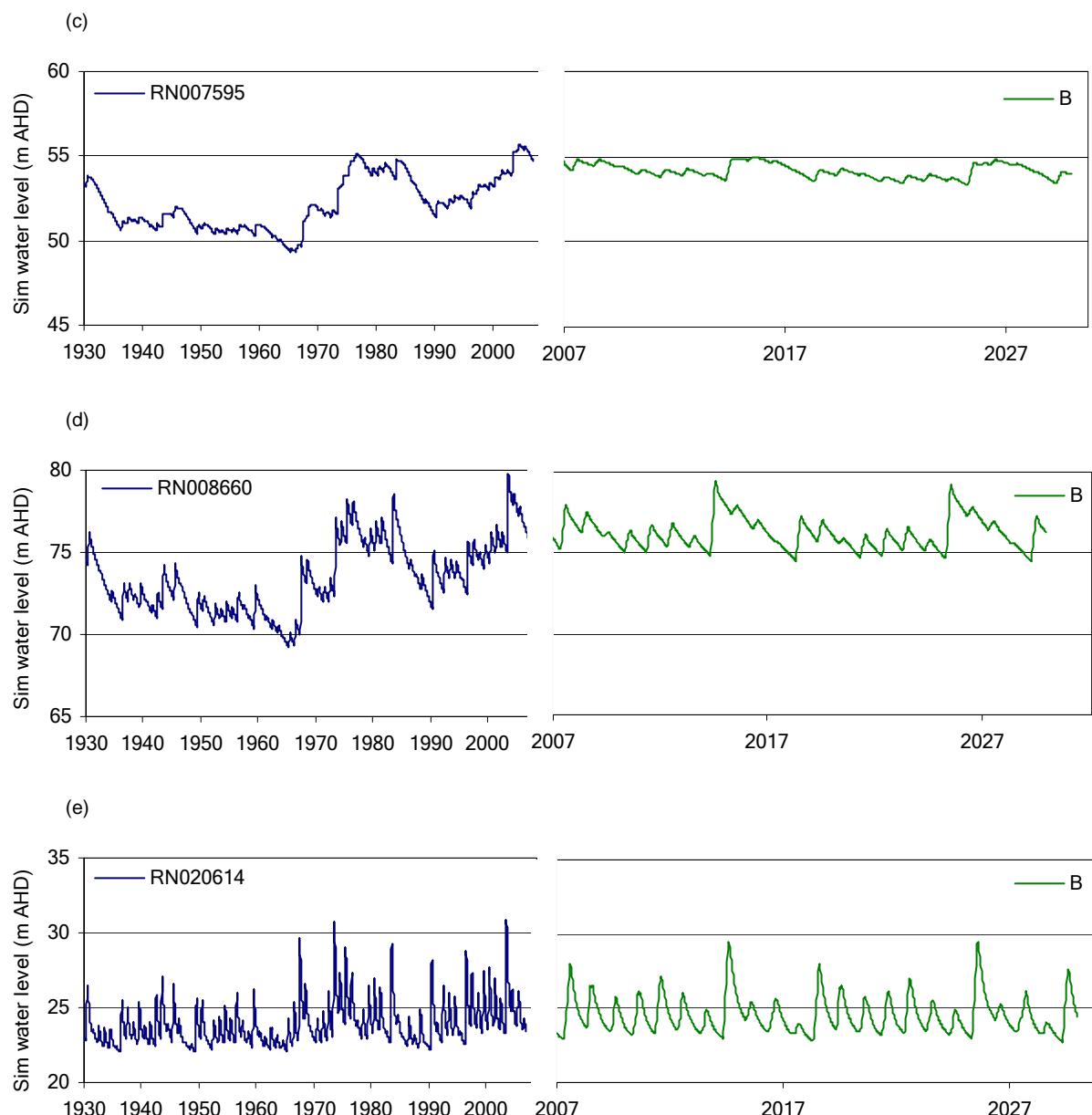


Figure DA-37. Simulated groundwater levels for selected observation bores in the Daly region for the warm-up period and Scenario B forecast

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.

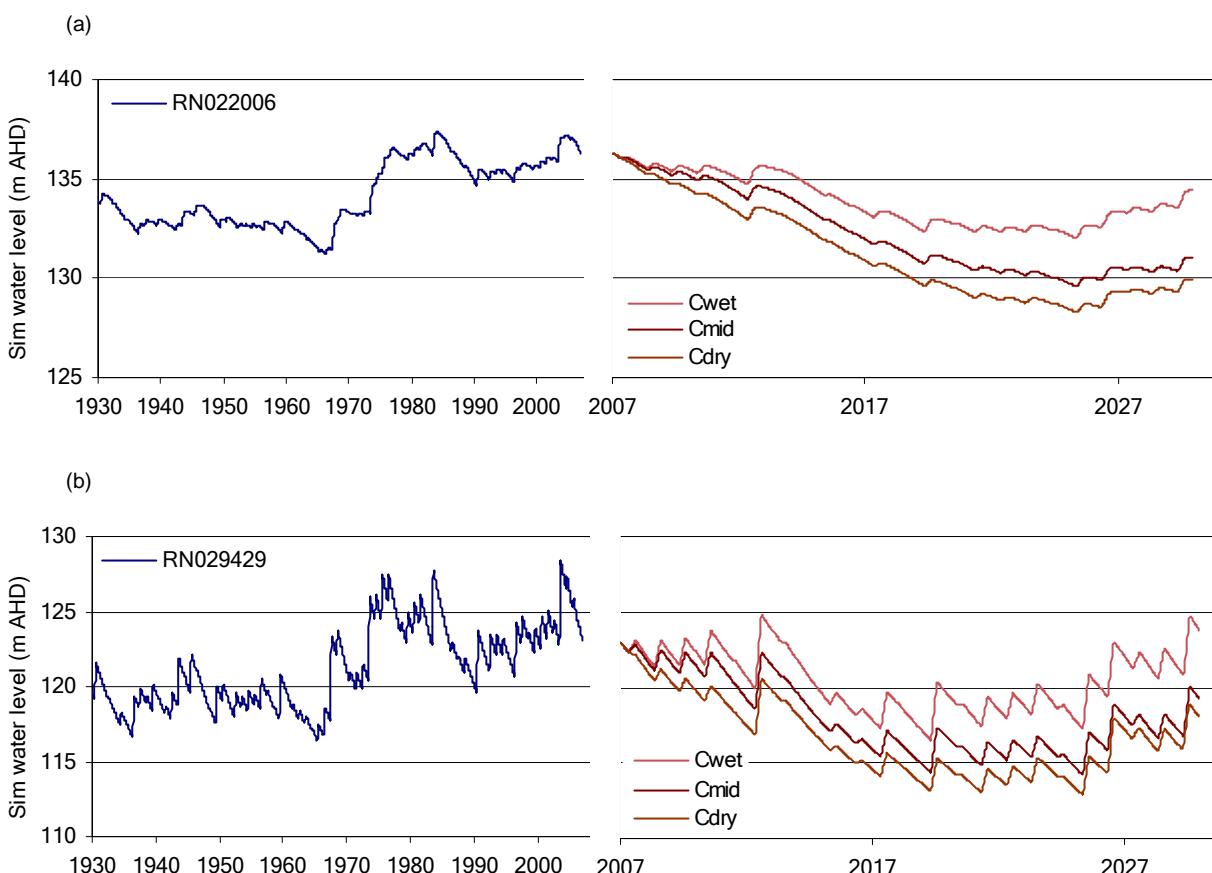
Scenario C' uses the scaled recharge and runoff and the current entitlements. Scenario D' uses the same recharge and runoff time series as Scenario C' but the future entitlements for groundwater extraction. A comparison of the total extraction for the Katherine and Oolloo areas implemented in the model 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.



DA-3 Water balance results for the Daly region

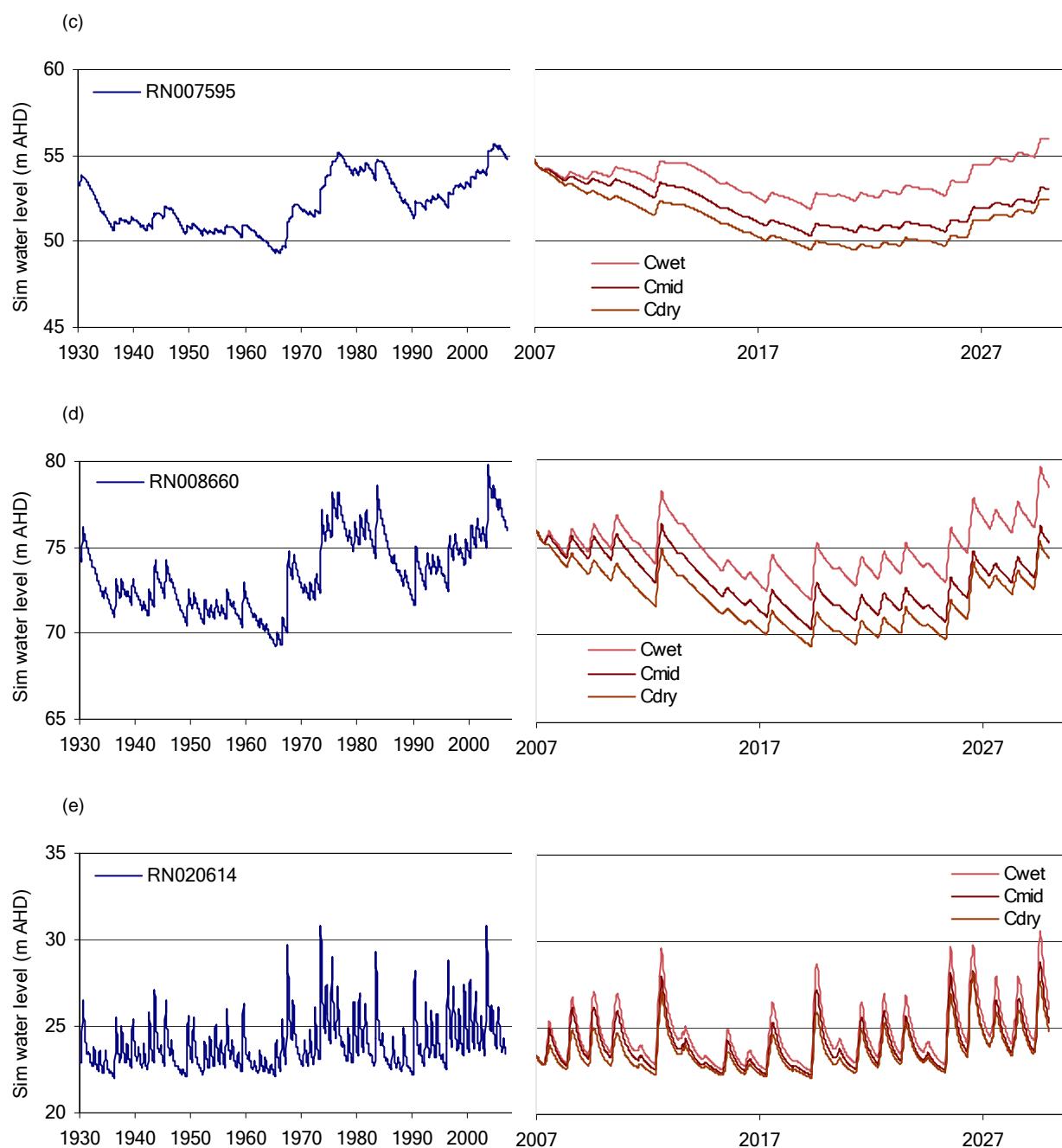
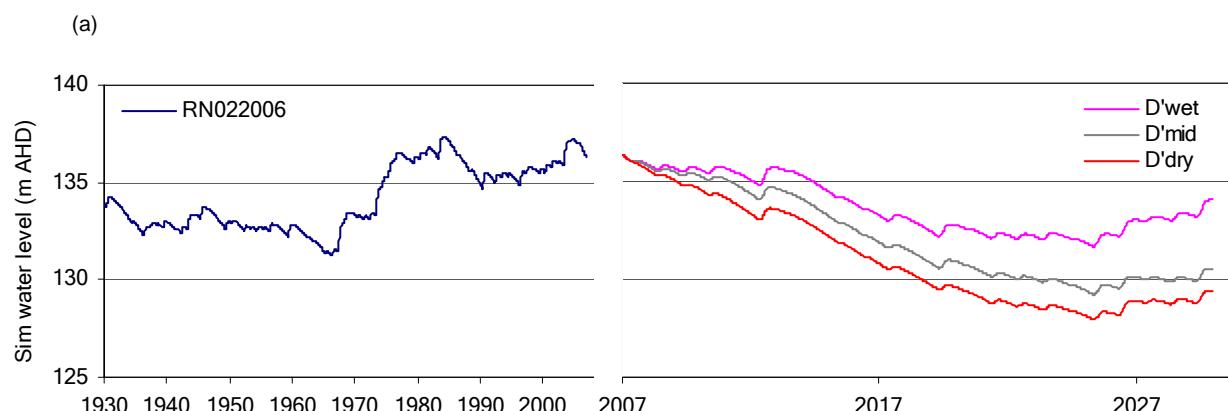


Figure DA-38. Simulated groundwater levels for five bores in the Daly region for the warm-up period and Scenario C forecast



DA-3 Water balance results for the Daly region

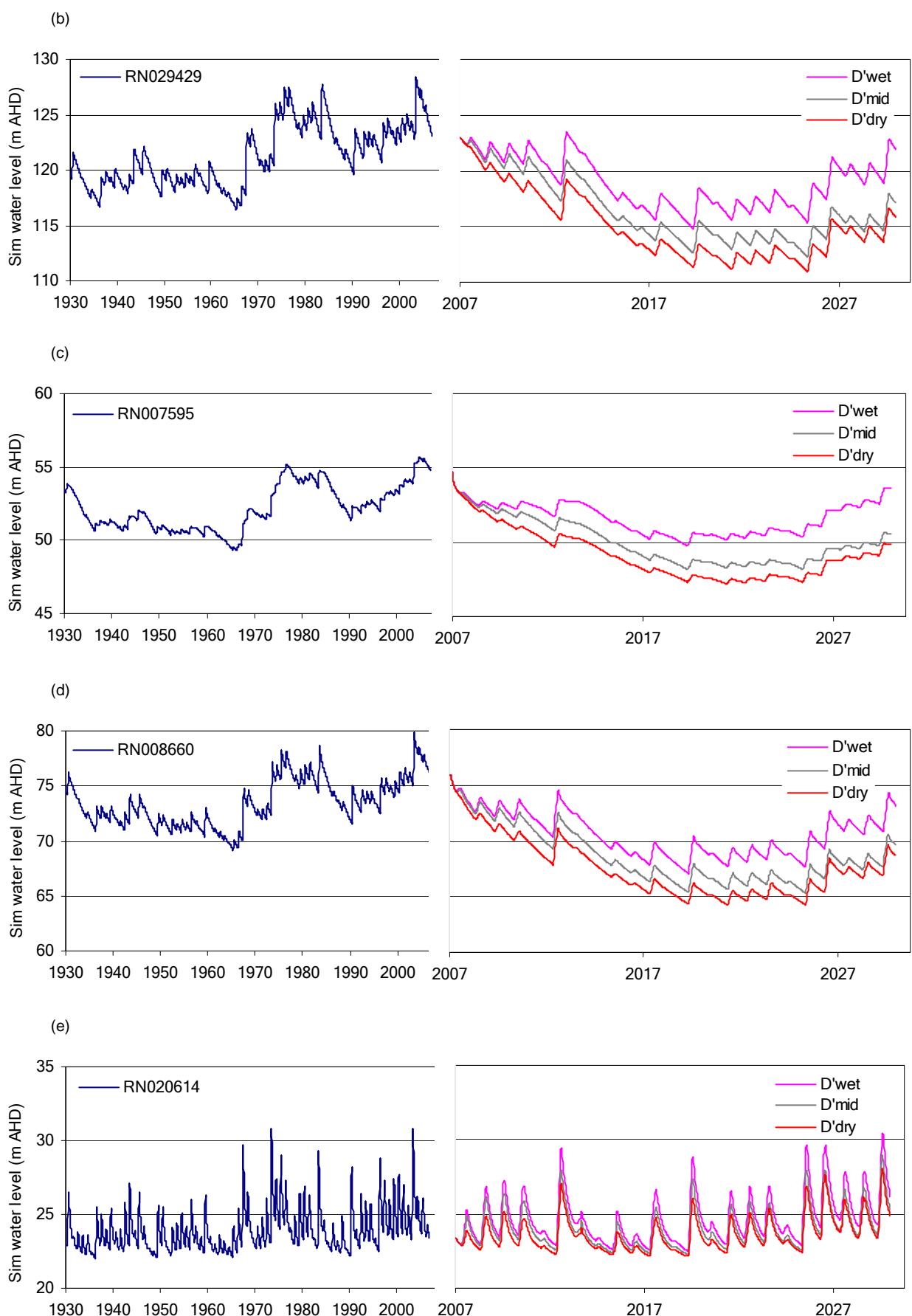


Figure DA-39. Simulated groundwater levels for five bores in the Daly region for the warm-up period and Scenario D forecast

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 $\mu\text{S}/\text{cm}$. 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 $\text{Ca}/\text{SO}_4^{2-}$ 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 matter. 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 or 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).

DA-3 Water balance results for the Daly region

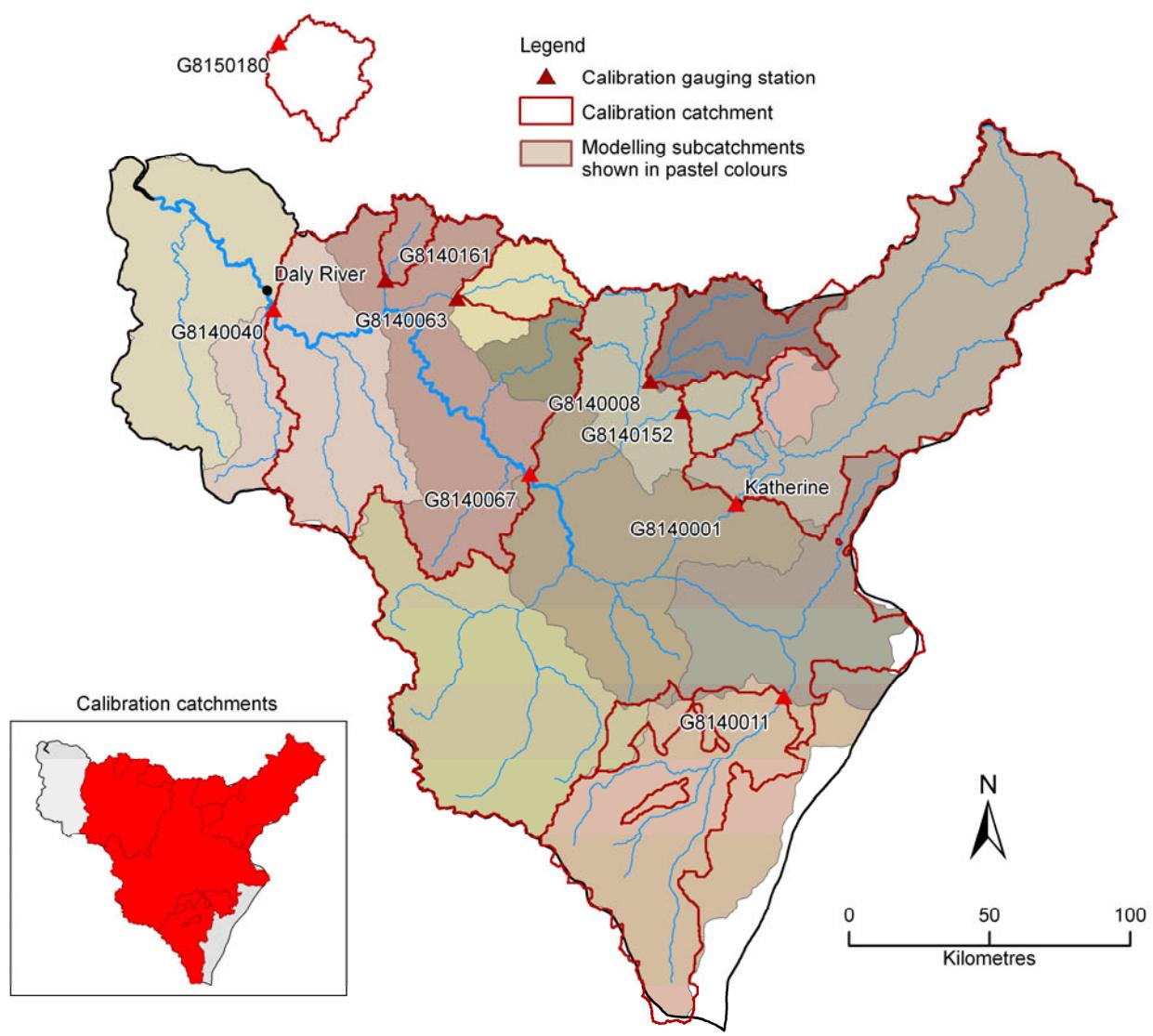


Figure DA-40. Map of the modelling subcatchments, calibration catchments and calibration gauging stations fused or the Daly region with inset highlighting (in red) the extent of the calibration catchments

DA-3 Water balance results for the Daly region

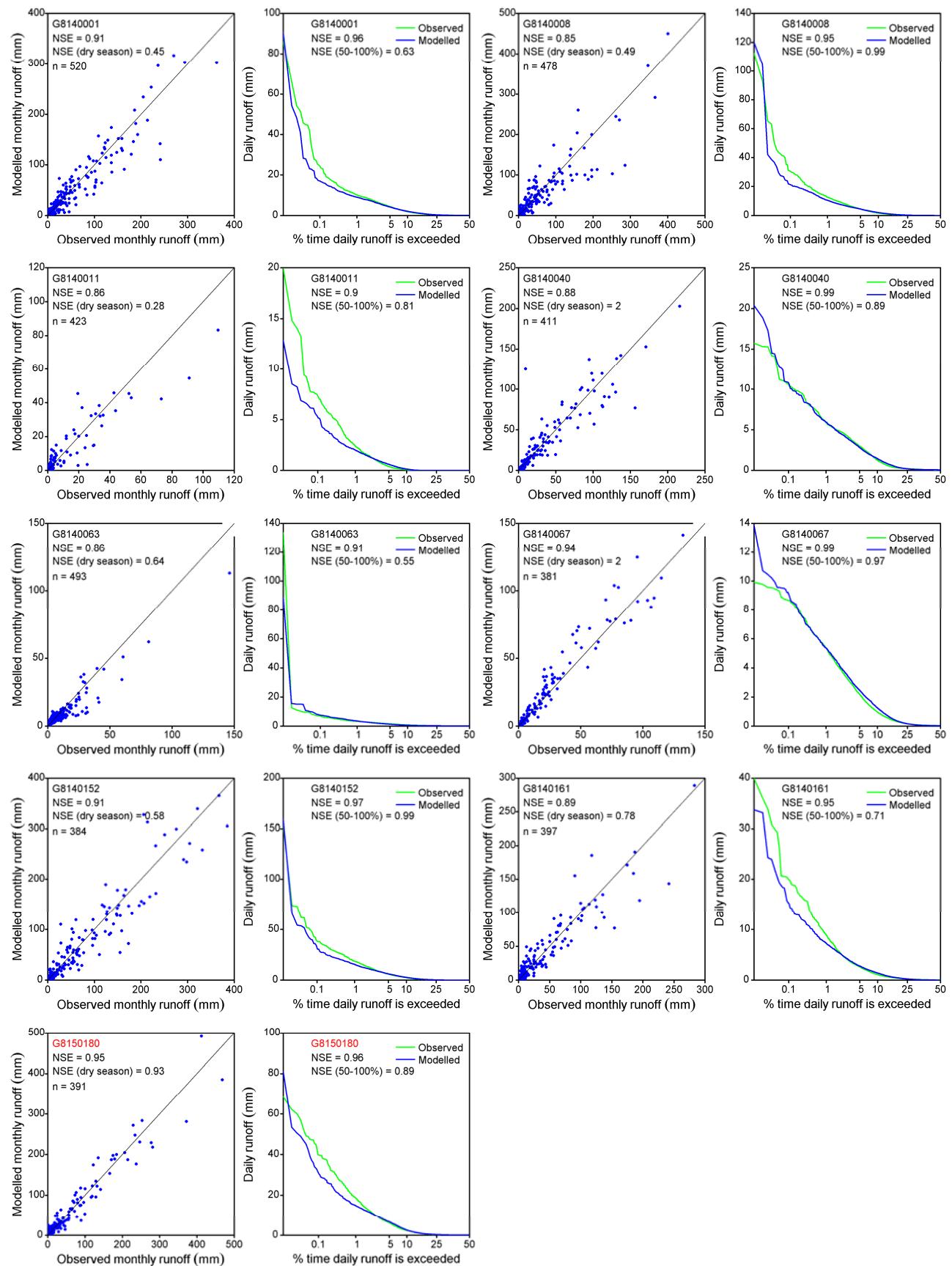


Figure DA-41. Modelled and observed monthly runoff and daily flow exceedance curve for each calibration catchment in the Daly region.
 (Red text denotes catchments located outside the region; blue text denotes catchments used for surface water modelling only)

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 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.

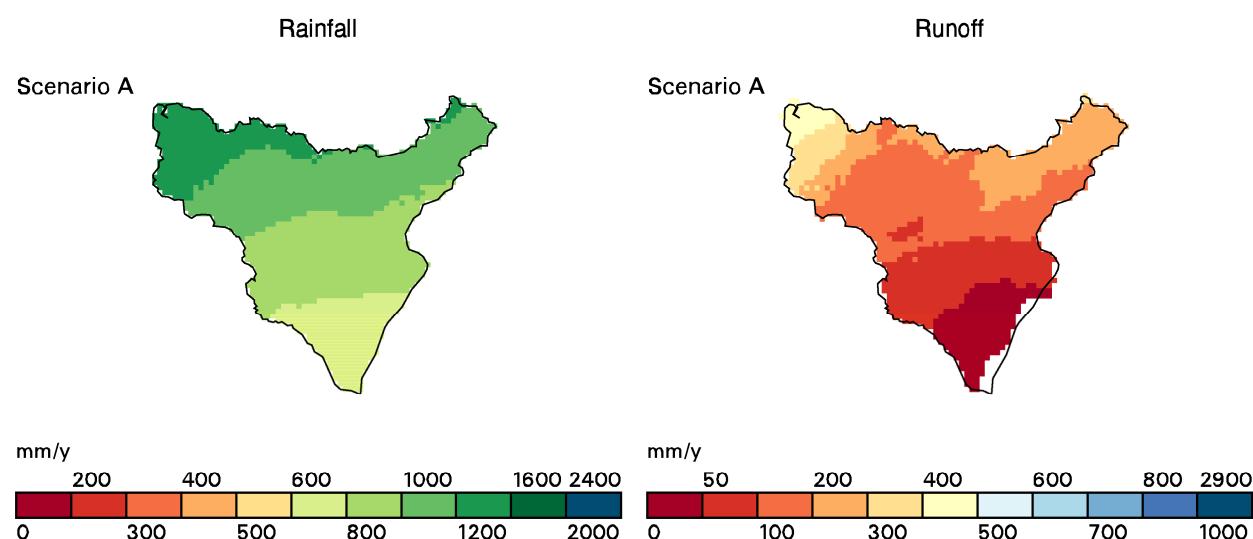


Figure DA-42. Spatial distribution of mean annual rainfall and modelled runoff across the Daly region under Scenario A

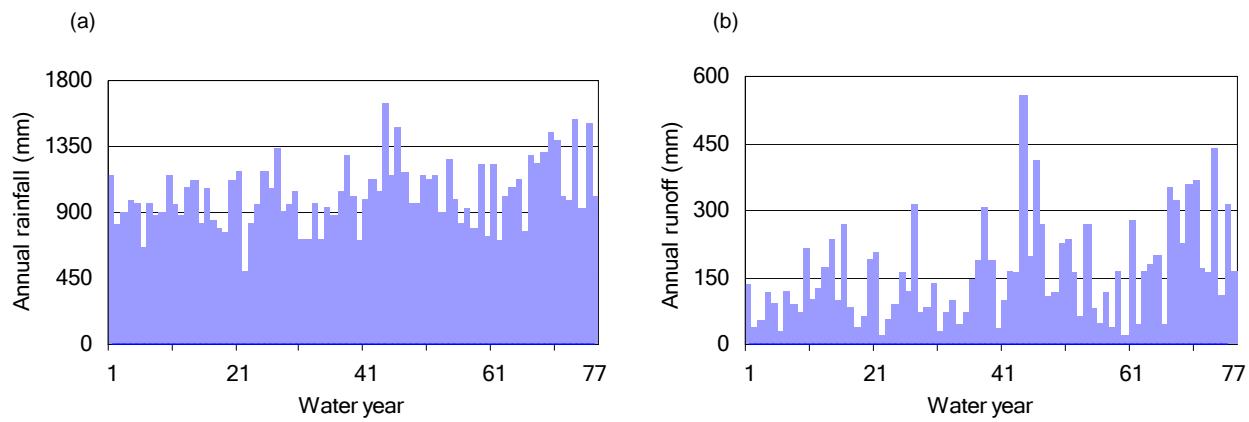


Figure DA-43. Mean annual (a) rainfall and (b) modelled runoff in the Daly region under Scenario A

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.

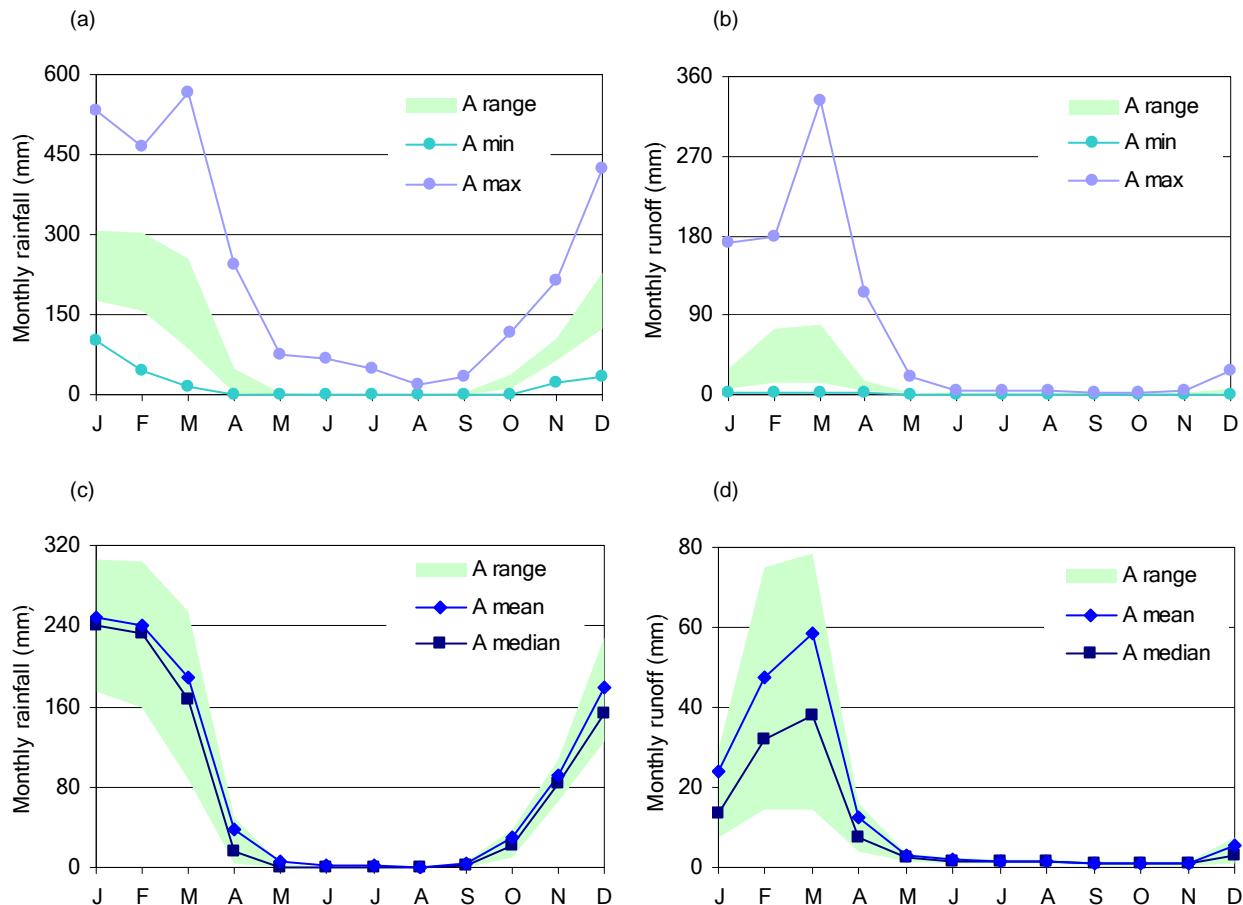


Figure DA-44. Minimum, maximum and A range monthly (a) rainfall and (b) modelled runoff; and mean, median and A range monthly (c) rainfall and (d) modelled runoff in the Daly region under Scenario A (A range is the 25th to 75th percentile monthly rainfall or runoff)

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.

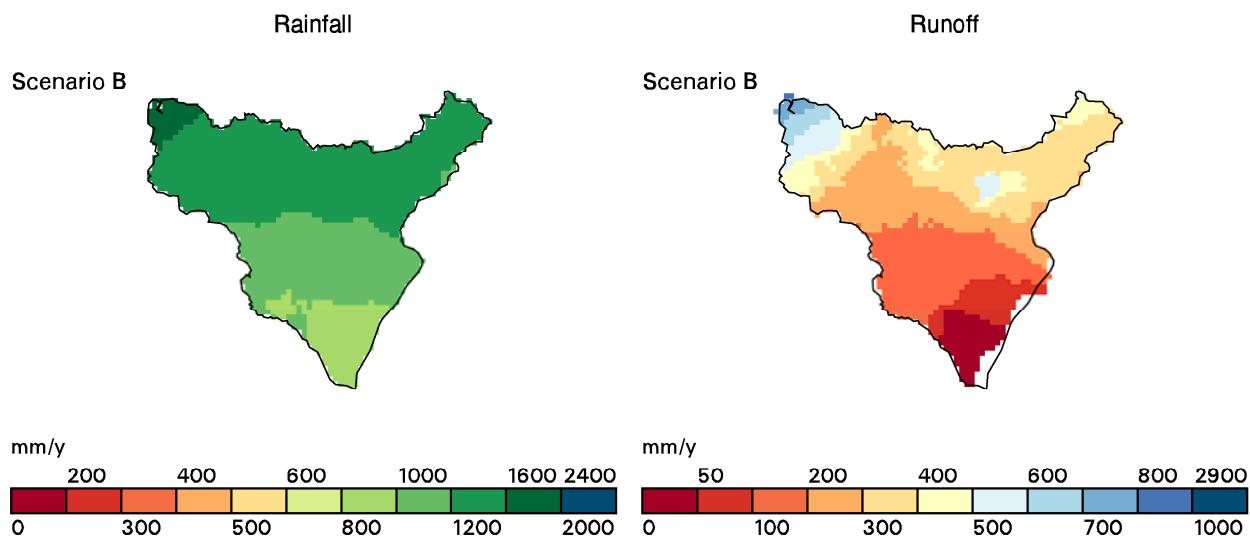


Figure DA-45. Spatial distribution of mean annual rainfall and modelled runoff across the Daly region under Scenario B

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.

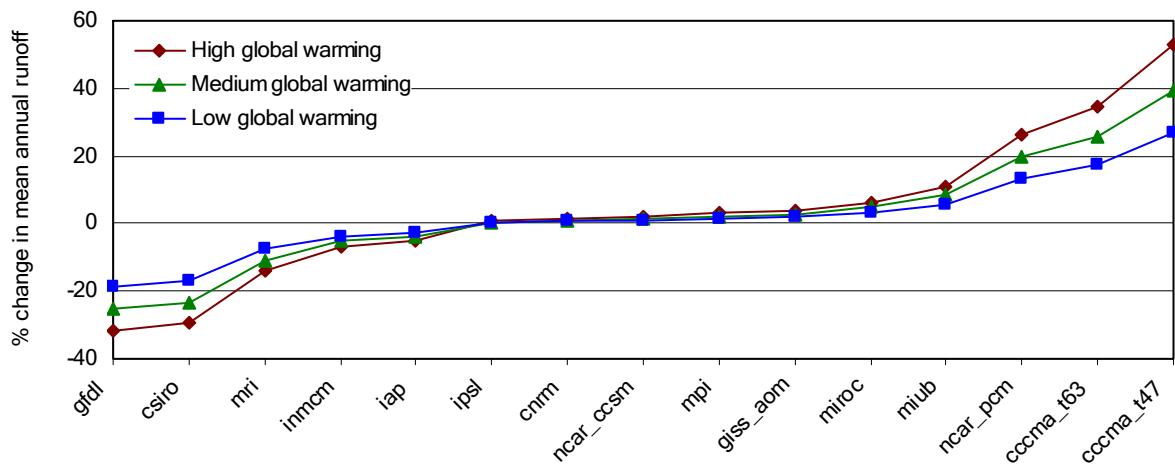


Figure DA-46. Percentage change in mean annual modelled runoff under the 45 Scenario C simulations (15 global climate models and three global warming scenarios) relative to Scenario A

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)

GCM	High global warming		Medium global warming		Low global warming			
	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%
cccm_t63	9%	34%	cccm_t63	7%	26%	cccm_t63	5%	18%
cccm_t47	11%	53%	cccm_t47	9%	40%	cccm_t47	6%	27%

DA-3 Water balance results for the Daly region

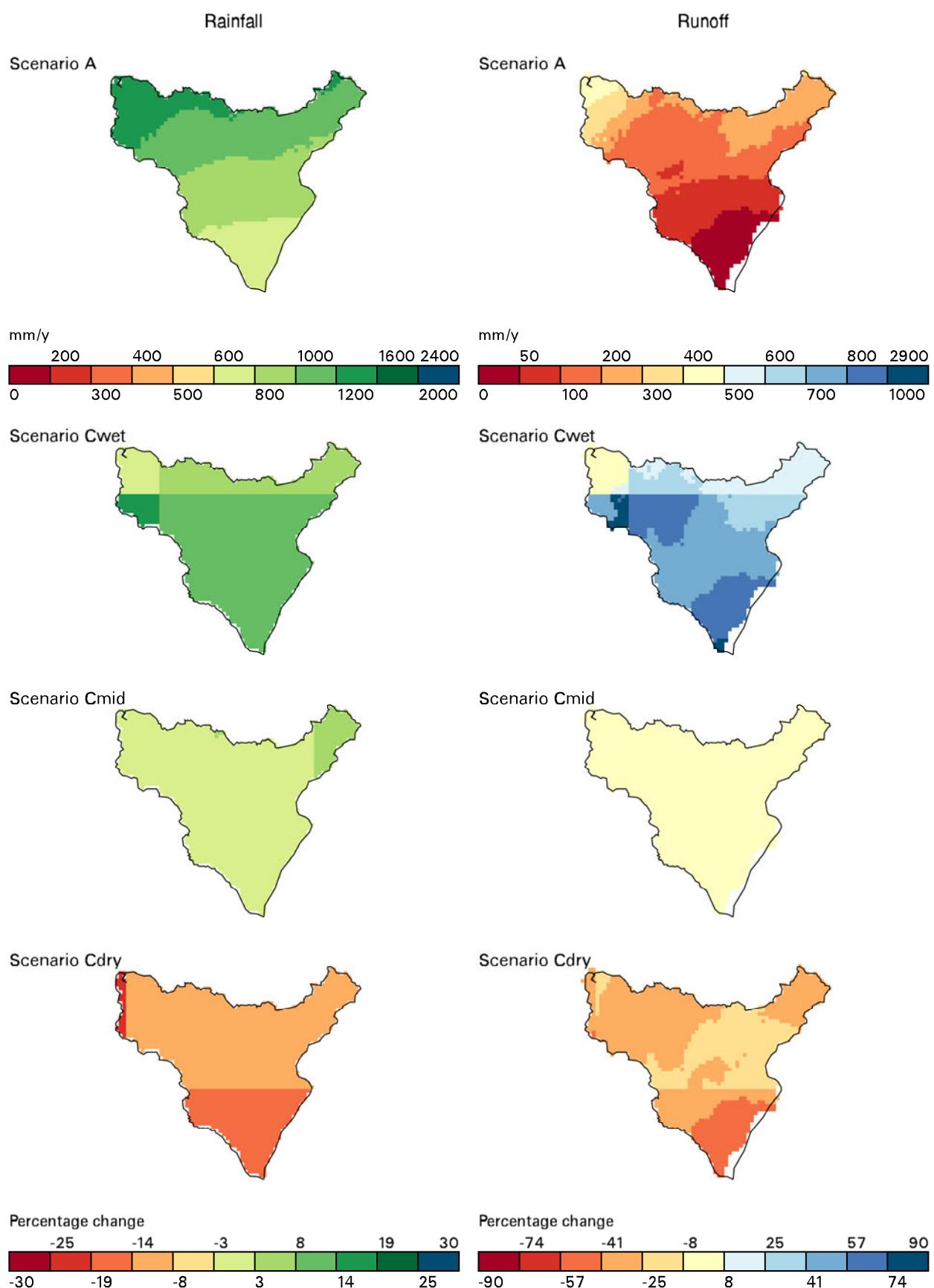


Figure DA-47. Spatial distribution of mean annual rainfall and runoff across the Daly region under scenarios A and C

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	mm	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%

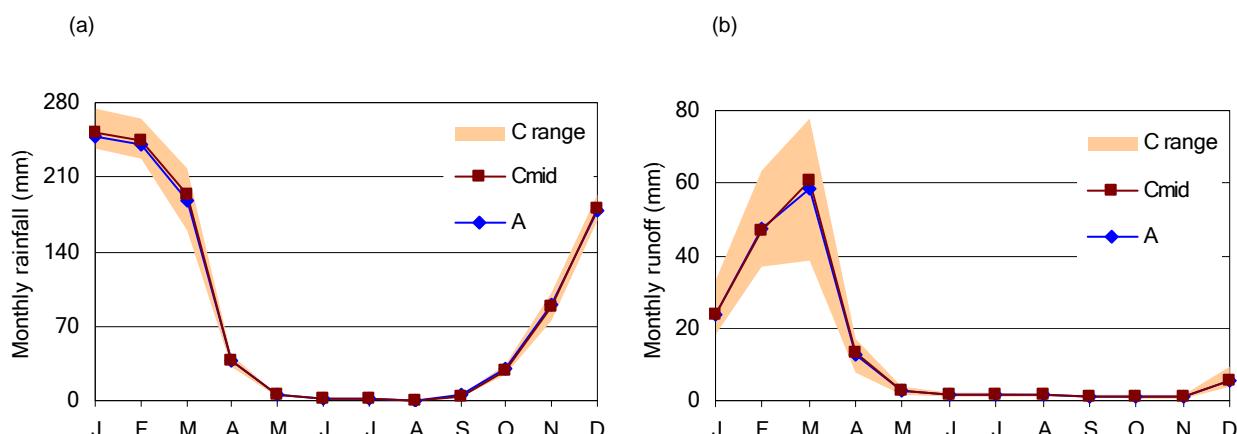


Figure DA-48. Mean monthly (a) rainfall and (b) modelled runoff in the Daly region under scenarios A and C

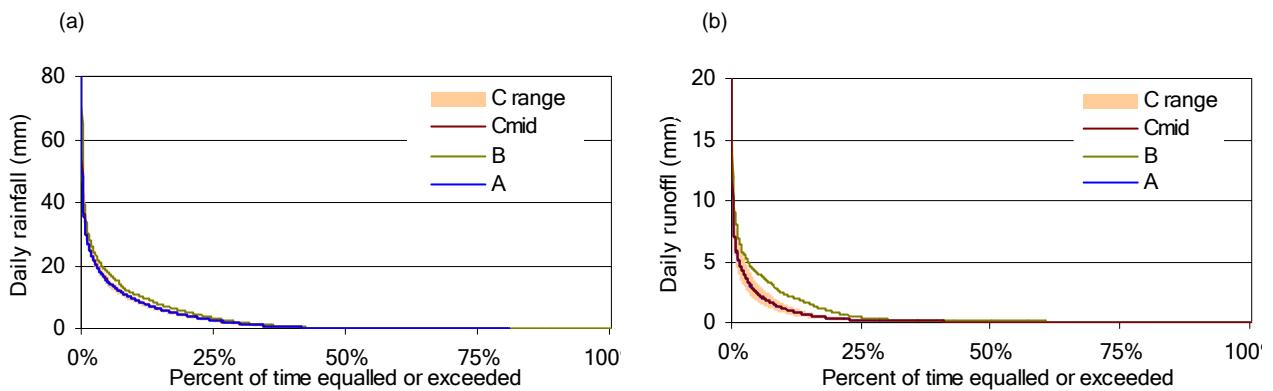


Figure DA-49. Daily flow exceedance curves for (a) rainfall and (b) runoff in the Daly region under scenarios A and C

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 (G8140040) 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.

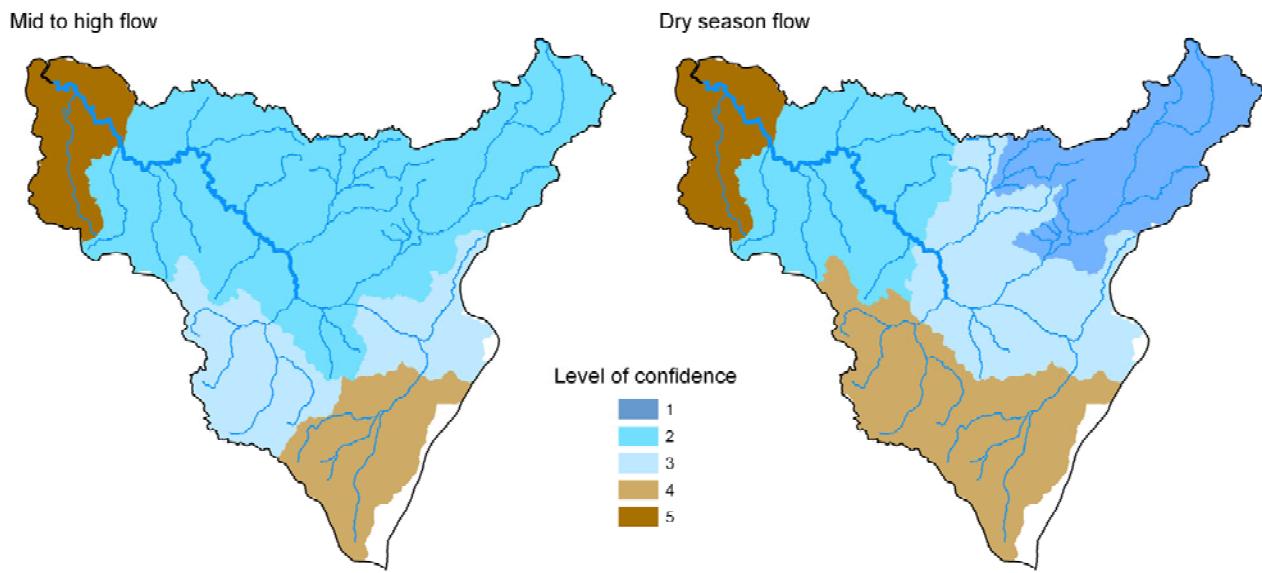


Figure DA-50. Level of confidence of the modelling of runoff for (a) mid- to high flow events and (b) monthly dry season flow events for the modelling subcatchments of the Daly region. 1 is the highest level of confidence, 5 is the lowest

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			

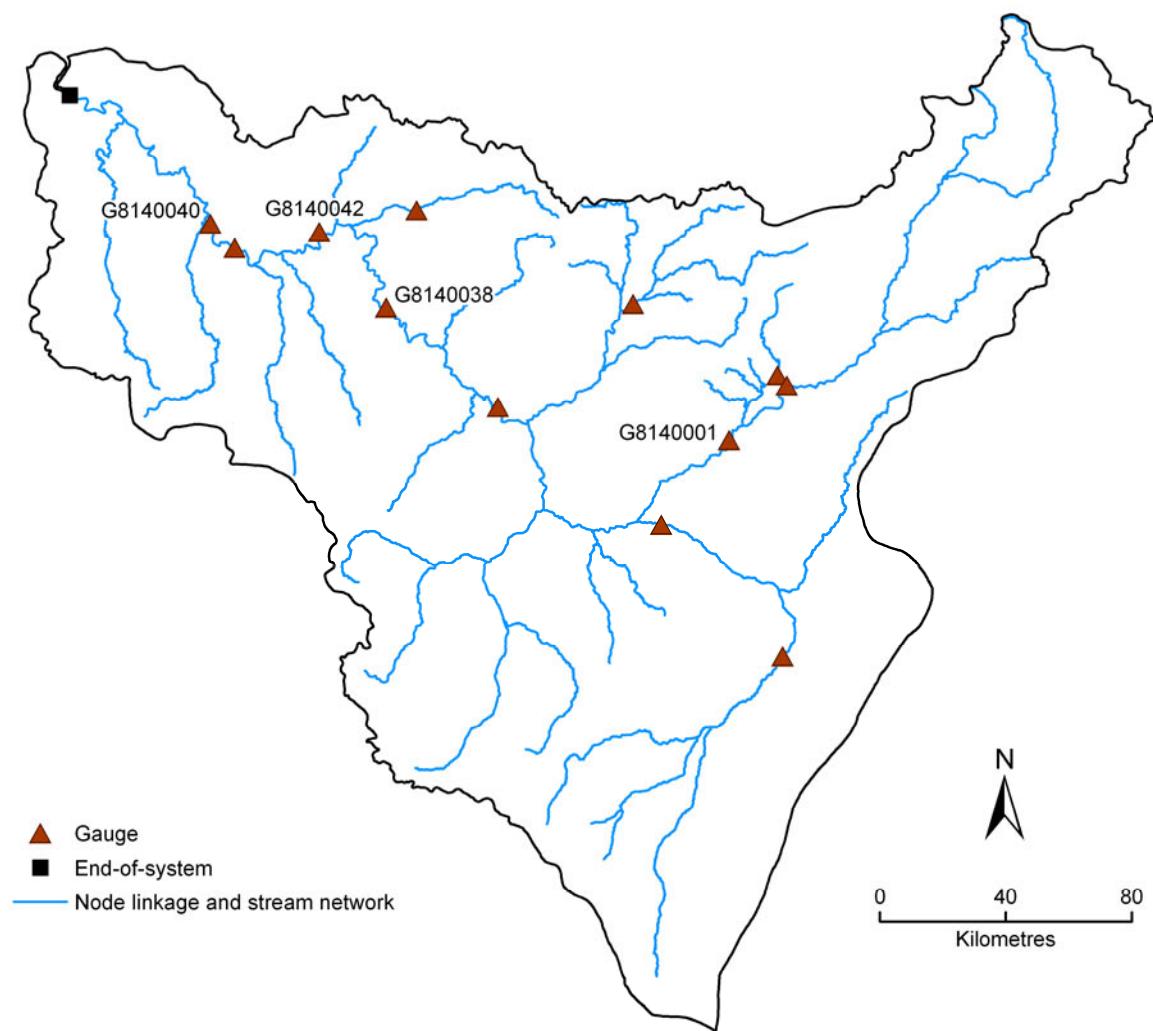


Figure DA-51. Location of key gauging stations used to calibrate the MIKE11 model

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.

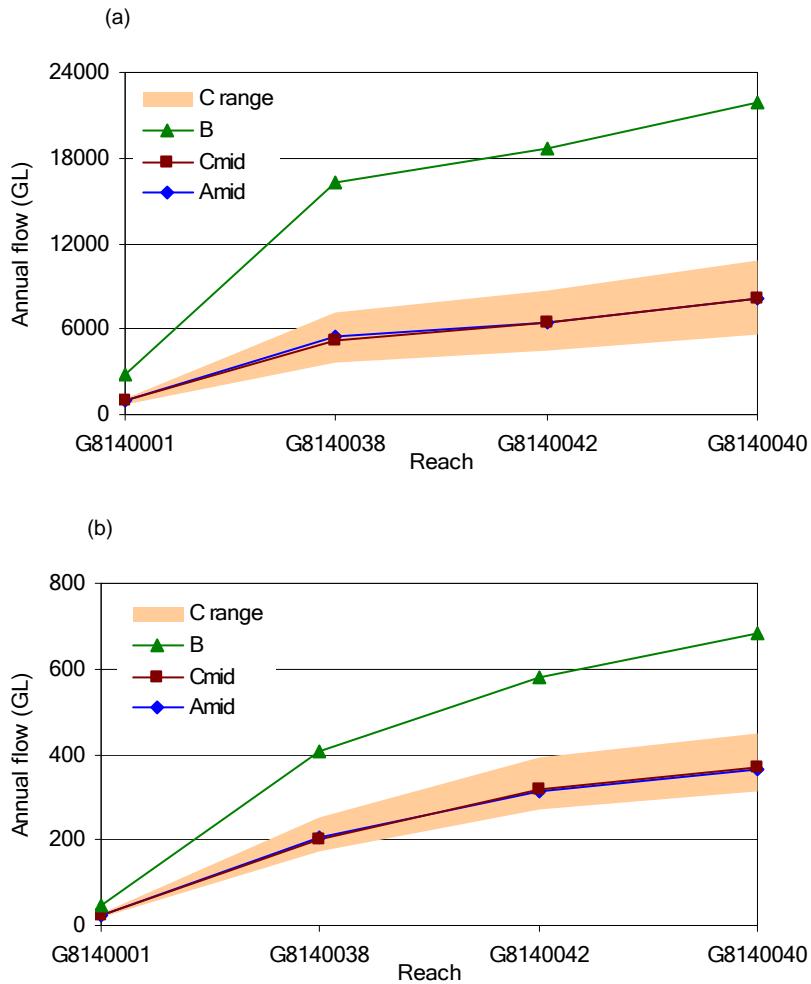


Figure DA-52. Transect of (a) total river flow and (b) total river flow during the dry season under scenarios Amid, B and C

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.

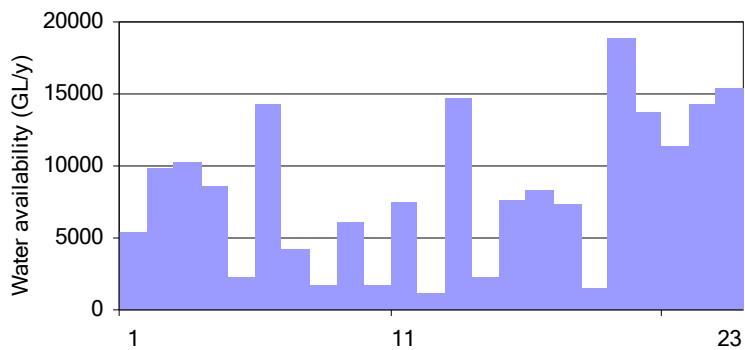


Figure DA-53. Water availability under Scenario Amid

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.

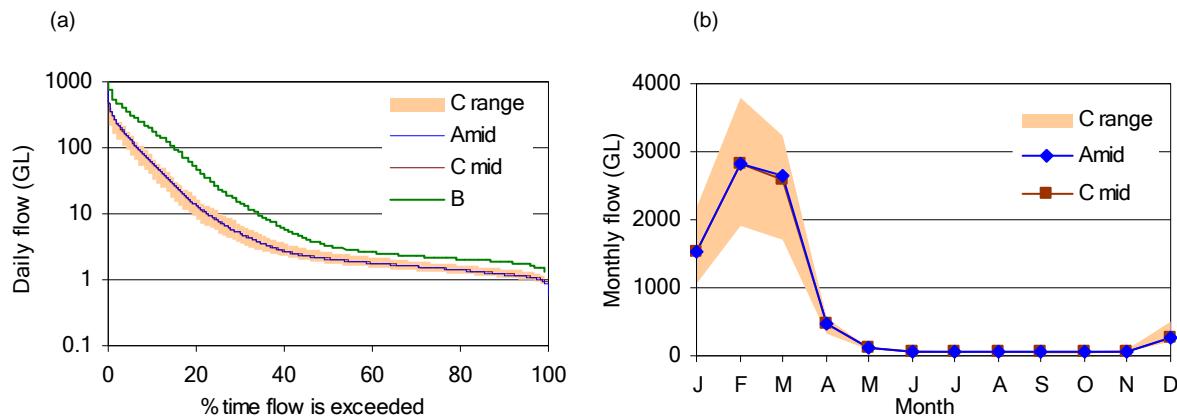


Figure DA-54 (a) Daily flow exceedance curves and (b) monthly flow for the Daly region at G8140040 under scenarios Amid, B and C.
Scenario B is not shown in (b)

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-Estuuary 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)***	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-Estuuary 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 <i>V. nana</i> 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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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.

For further information:

Water for a Healthy Country Flagship

Project Leader
Dr Richard Cresswell
Phone: 07 3214 2767
Email: Richard.Cresswell@csiro.au
Web: www.csiro.au/partnerships/NASY

Northern Australia Water Futures Assessment

Department of the Environment, Water, Heritage and the Arts
Phone: 02 6274 1111
Email: northern.assessment@environment.gov.au
Web: <http://www.environment.gov.au/nawfa>

Contact Us

Phone: 1300 363 400
+61 3 9545 2176

Email: enquiries@csiro.au
Web: www.csiro.au/flagships

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.