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Water in the Kimberley 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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Australian Government

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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

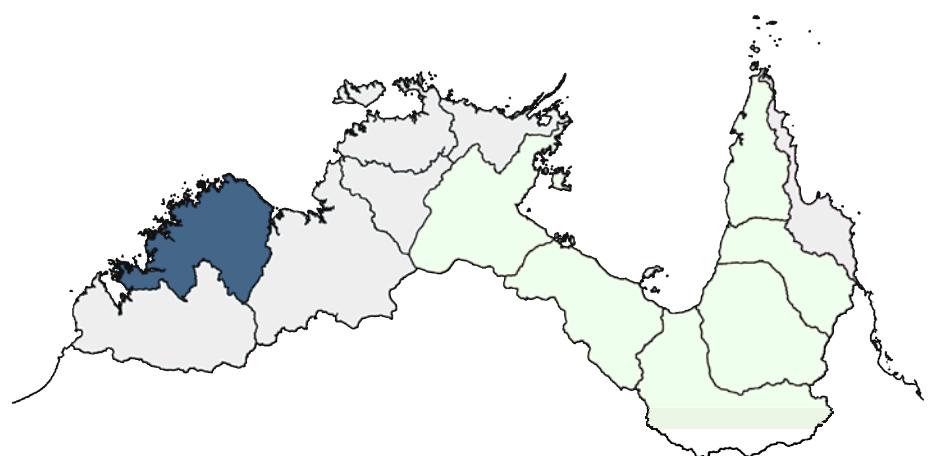
Units of measurement

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 Kimberley region



KI-1 Water availability and demand in the Kimberley region

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

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

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

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

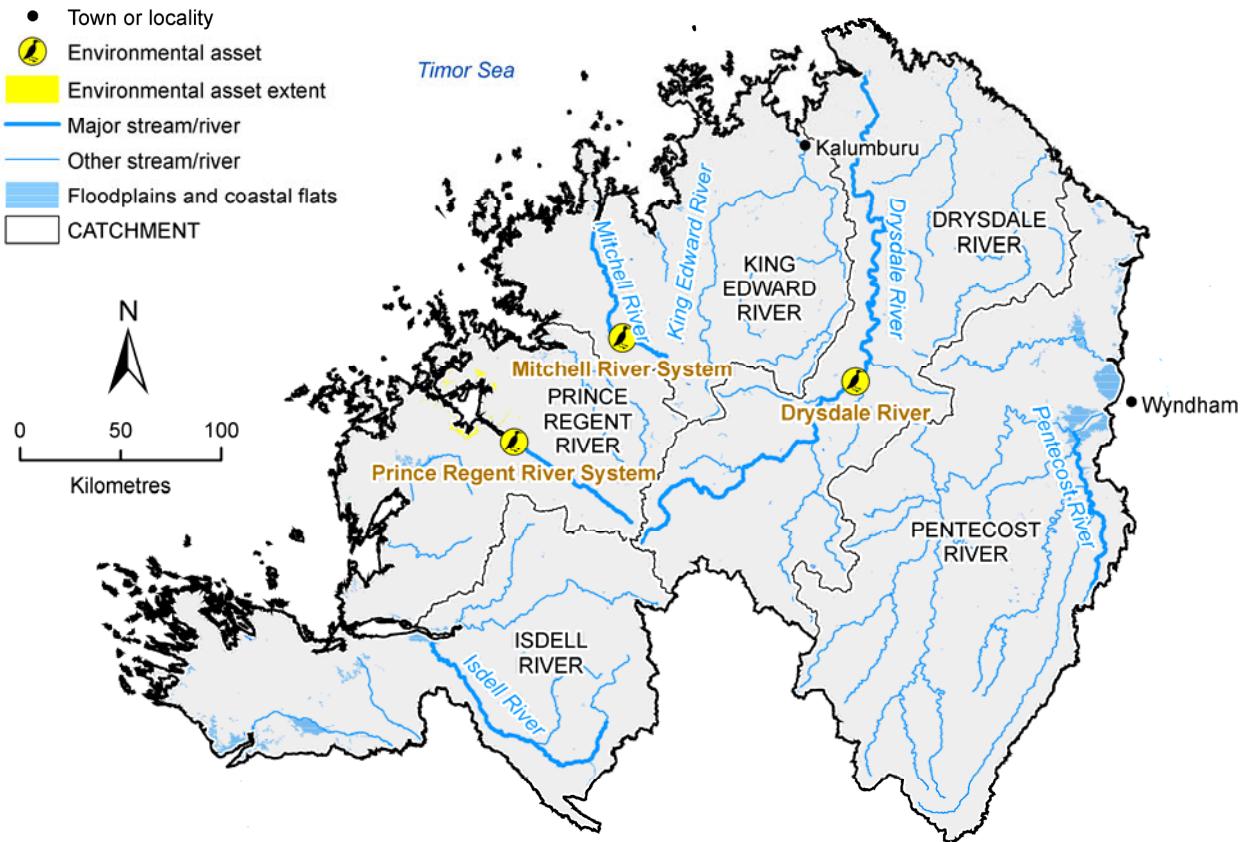


Figure KI-1. Major rivers, towns and location of assets selected for assessment of changes to hydrological regime in the Kimberley region

KI-1.1 Regional summary

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

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

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

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

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

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

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

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

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

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

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

The region is generally datapoor.

KI-1.2 Water resource assessment

Term of Reference 3a

KI-1.2.1 Under historical climate and current development

Term of Reference 3a (i)

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

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

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

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

* BFI (baseflow index) and baseflow volume derived from gauged data.

** Aggregated recharge from Zhang and Dawes (1998).

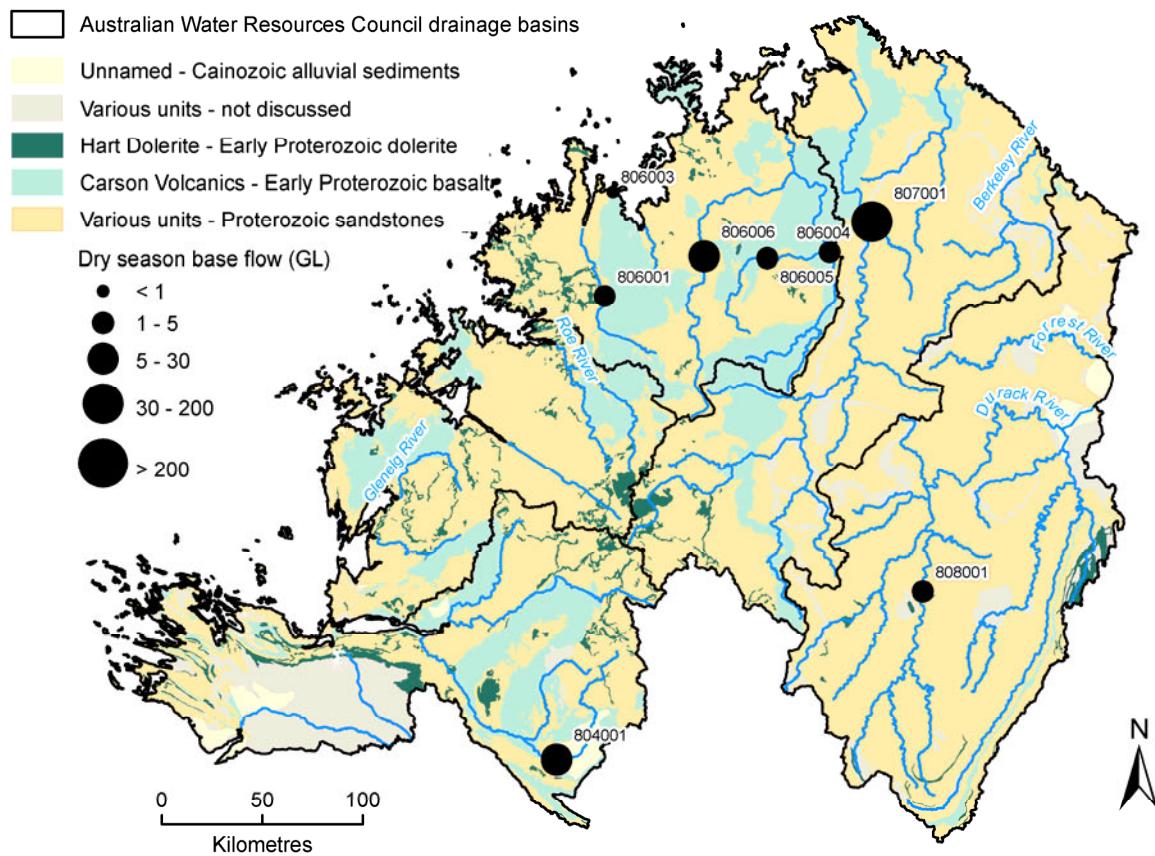


Figure KI-2. Surface geology of the Kimberley region with modelled mean dry season baseflow

KI-1.2.2 Under recent climate and current development

Term of Reference 3a (ii)

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

KI-1.2.3 Under future climate and current development

Term of Reference 3a (iii)

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

KI-1.2.4 Under future climate and future development

Term of Reference 3a (iv)

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

KI-1.3 Changes to flow regime at environmental assets

Term of Reference 3b

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

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

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

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

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

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

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

KI-1.4 Seasonality of water resources

Term of Reference 4

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

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

KI-1.5 Surface–groundwater interaction

Groundwater discharges to swamps, creeks and rivers throughout the year in the Kimberley region (Allen, 1966). The Drysdale, Isdell, King Edward and Mitchell rivers all have sustained baseflow during much of the dry season because of

groundwater discharge (Figure KI-2). During the wet season, both intense and prolonged rainfall periods result in large volumes of surface water runoff and consequent flow in the tributaries and major rivers. It is likely that during the wet season, elevated river levels would lead to recharge of the aquifers that are either incised by or underlying the rivers.

KI-1.6 Water storage options

Term of Reference 5

KI-1.6.1 Surface water storages

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

KI-1.6.2 Groundwater storages

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

KI-1.7 Data gaps

Term of Reference 1e

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

KI-1.8 Knowledge gaps

Term of Reference 1e

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

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

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

Many environmental assets depend not simply on duration above or below certain flow levels, but on triggers (e.g. for reproduction or migration) set by the rate of change of flow. In addition, some environmental assets depend on the frequency and duration of events that occur less than annually (i.e. once every 5, 10 or 20 years or more). Further

analysis is therefore required to look at how the timing, duration and rate of rise and fall in flow rates at critical times of the season will vary under the various scenarios.

KI-1.9 References

- Allen AD (1966) The Hydrogeology of the Kimberley Plateau. Geological Survey of Western Australia. Record No. 1966/16.
- McJannet DL, Wallace JW, Henderson A and McMahon J (2009) High and low flow regime changes at environmental assets across northern Australia under future climate and development scenarios. A report to the Australian Government from the CSIRO Northern Australian Sustainable Yields Project. CSIRO Water for a Healthy Country National Research Flagship, Division of Land and Water, Canberra. *In prep.*
- Zhang L and Dawes W (1998) WAVES - An integrated energy and water balance model. Technical Report No. 31/98, CSIRO Land and Water.

KI-2 Contextual information for the Kimberley region

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

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

KI-2.1 Overview of the region

KI-2.1.1 Geography and geology

The Kimberley region comprises the Australian Water Resources council river basins of the Isdell, Prince Regent, King Edward, Drysdale and Pentecost Rivers. The region covers 110,000 km² and is bounded to the south by the King Leopold Ranges and to the east by the Durack Range or the Halls Creek Orogenic Belt and the edge of the Kimberley plateau. A combination of high rainfall and a fractured dissected landscape results in thin, largely infertile, soils. The high rainfall and intense streamflow produce steep-sided valleys despite relatively low relief (906 m).

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

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

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

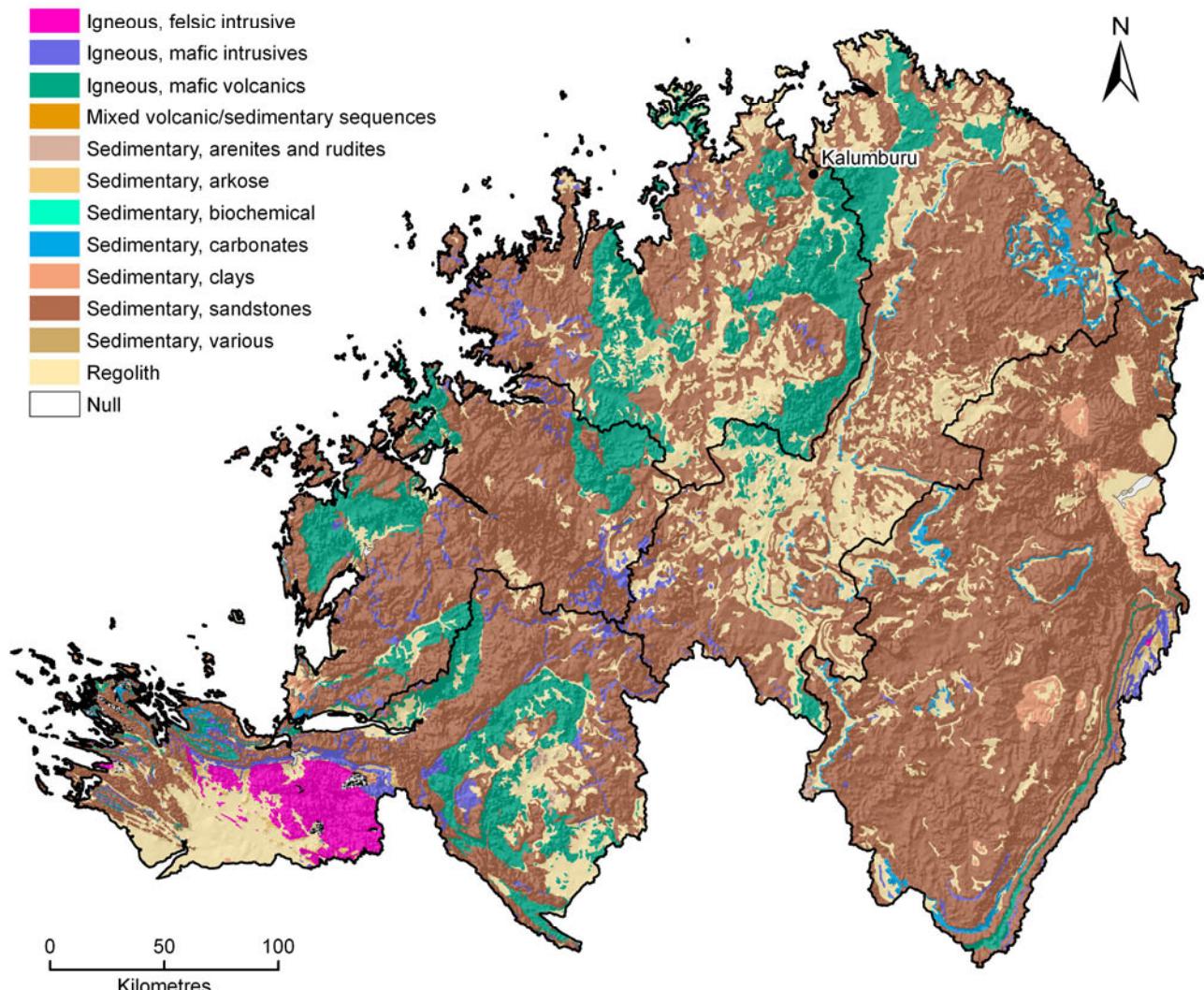


Figure KI-3. Surface geology of the Kimberley region overlaid on a relative relief surface

KI-2.1.2 Climate, vegetation and land use

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

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

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

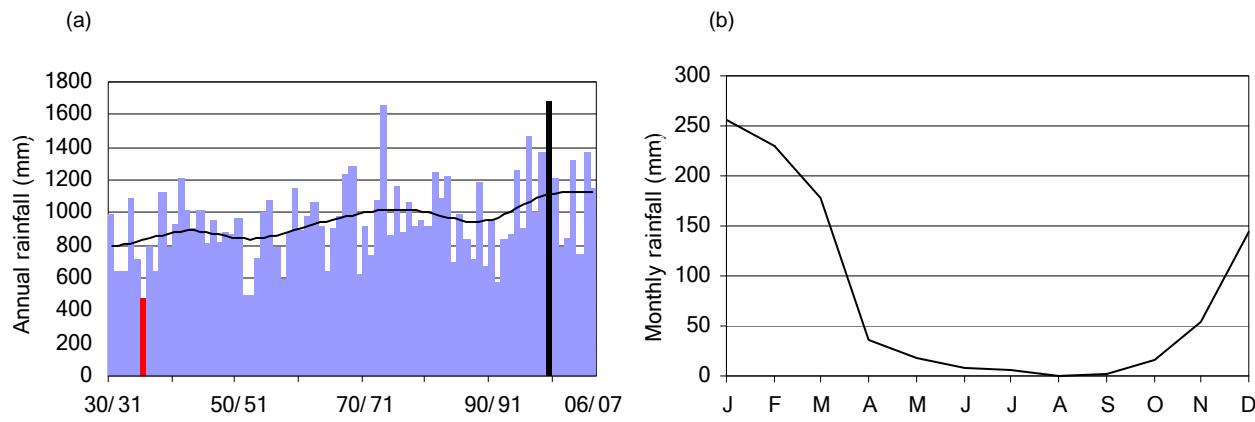


Figure KI-4. Historical (a) annual and (b) mean monthly rainfall averaged over the Kimberley region. The low-frequency smoothed line in (a) indicates longer term variability

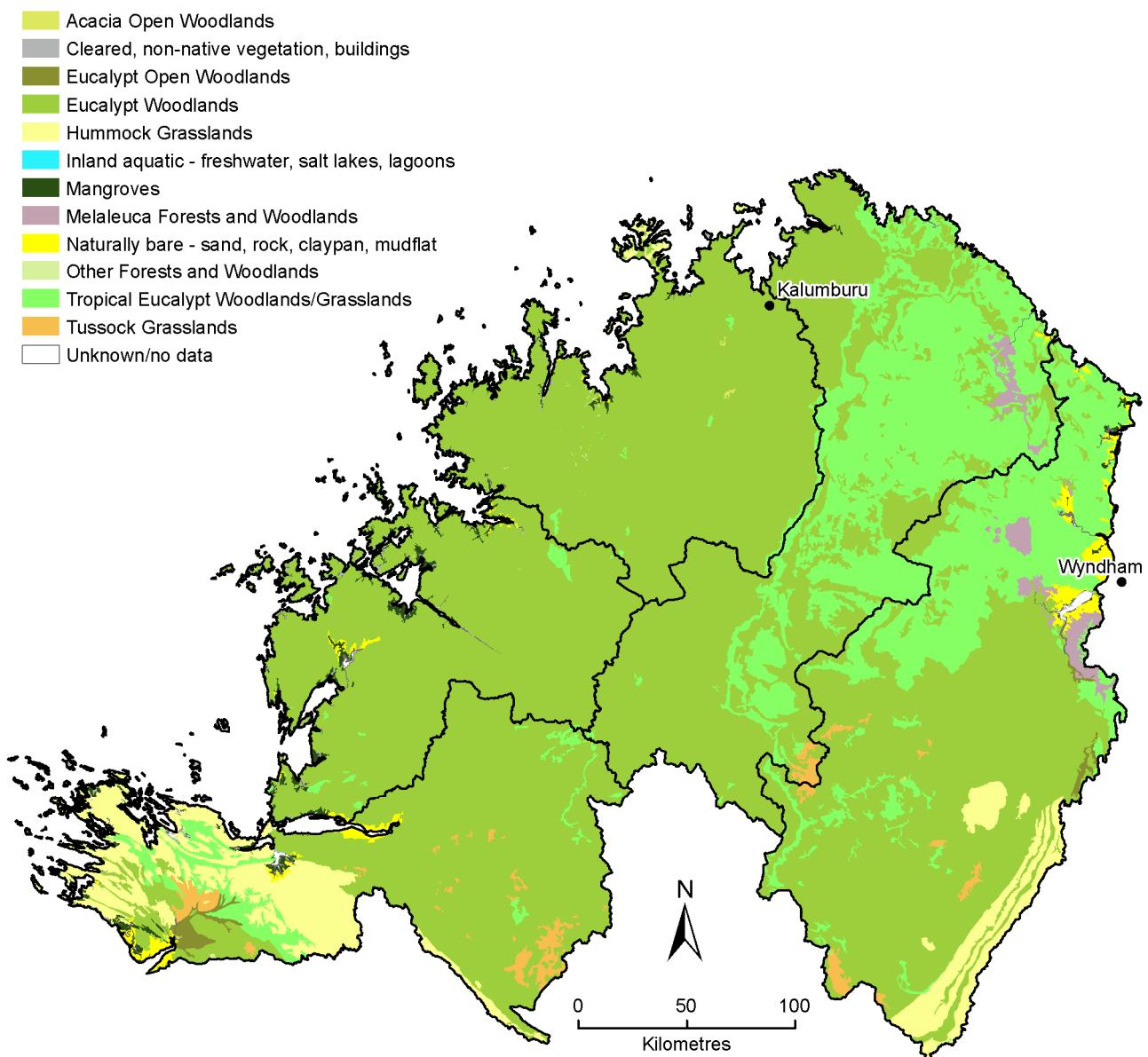


Figure KI-5. Map of current vegetation types across the Kimberley region (source DEWR, 2005)

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

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

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

The Kimberley was one of the earliest settled parts of Australia with the first arrivals landing about 40,000 years ago from the islands of what is now Indonesia. Alexander Forrest trekked across from the western coast to the Northern Territory in 1879. Forrest was the first European to discover and name the Kimberley district, as well as the Margaret and Ord rivers, the King Leopold Ranges, and the fertile area between the Fitzroy and Ord rivers. He subsequently set himself up as a land agent specialising in the region and was thus instrumental in the leasing of over 51,000,000 acres (210,000 km²) in the region during 1883.

For the past century, the main land use in the Kimberley has been for pastoral activities. Currently, over half of the region is held under pastoral lease, comprising over 90 leases and carrying about half a million head of cattle (Figure KI-6). The remaining land is either crown land, Indigenous reserve, conservation estate or freehold land in the major urban centres.

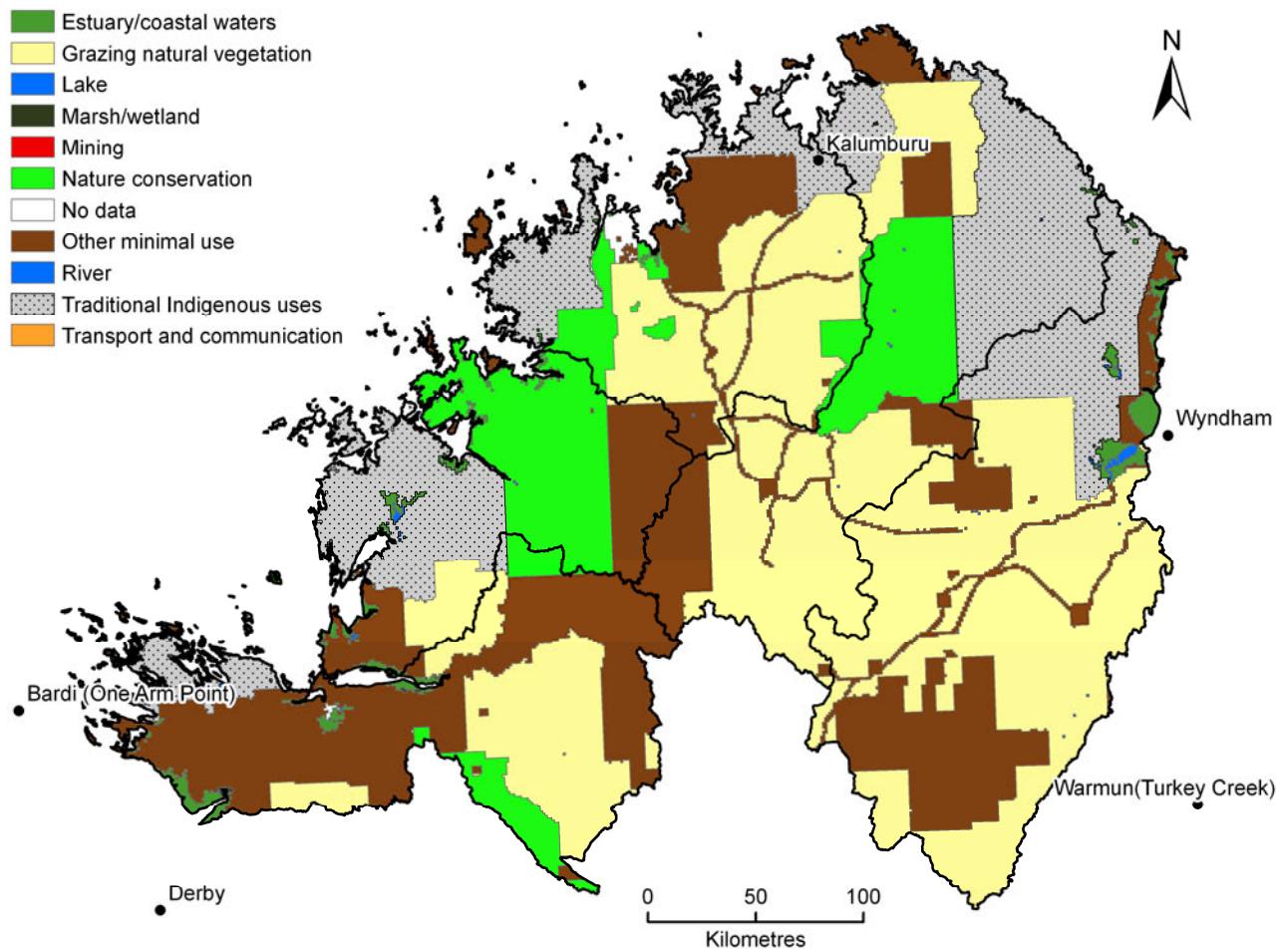


Figure KI-6. Map of dominant land uses of the Kimberley region (after BRS, 2002)

KI-2.1.3 Regional environmental asset description

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

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

The following section characterises these shortlisted wetlands and is based largely on the description of these assets as outlined by Environment Australia (2001). Chapter KI-3 presents the assessment of those shortlisted assets, and reports

hydrological regime metrics for those assets which have sufficient confidence in the modelled streamflow to enable analysis.

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

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

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

Drysdale River

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

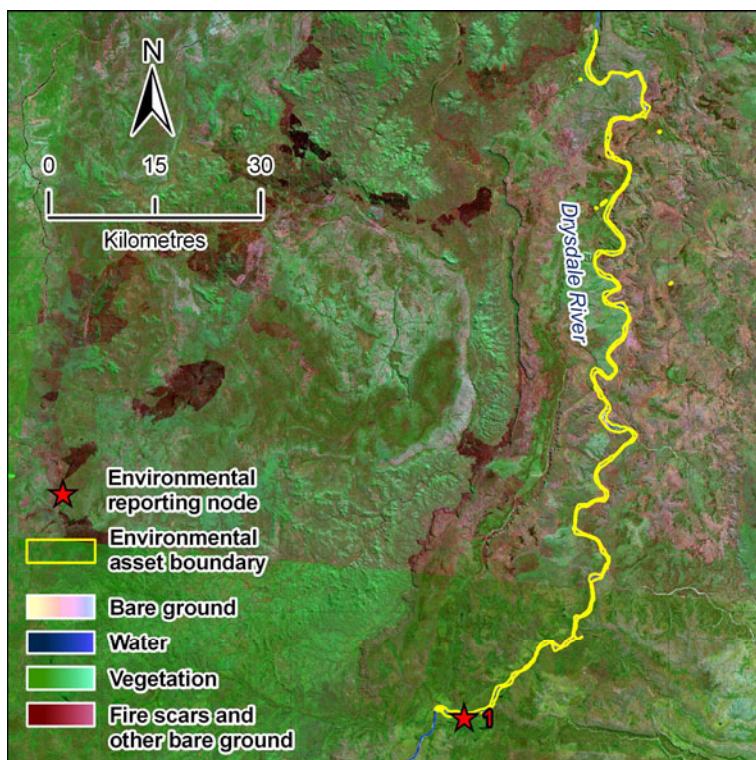


Figure KI-7. False colour satellite image of Drysdale River (derived from ACRES, 2000).
Clouds may be visible in image

Mitchell River System

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

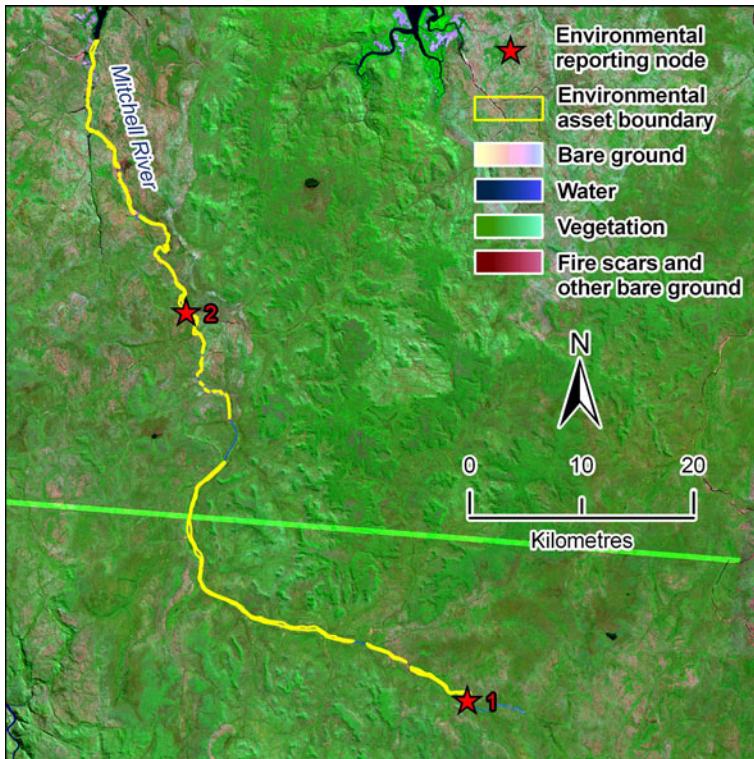


Figure KI-8. False colour satellite image of the Mitchell River System (derived from ACRES, 2000).
Clouds may be visible in image

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

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

Prince Regent River System

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

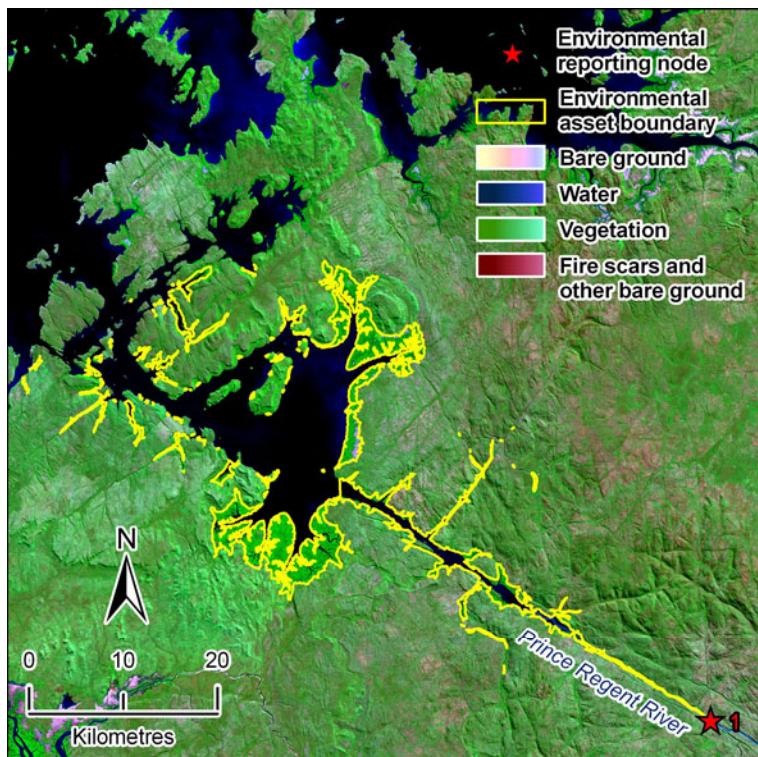


Figure KI-9. False colour satellite image of the Prince Regent River System (derived from ACRES, 2000). Clouds may be visible in image

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

KI-2.2 Data availability

KI-2.2.1 Climate

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

KI-2.2.2 Surface water

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

There are two gauging stations currently operating in the Kimberley region at a density of one station for every 54,900 km². This is the least number and lowest density of currently operating gauging stations of the 13 regions and is considerably below the Murray-Darling Basin average. For the 13 regions the median number of currently operating gauging stations per region is 12 and the median density of current gauging stations per region is one station for every 9700 km². The mean density of current stream gauging stations across the entire Murray-Darling Basin is one station for every 1300 km².

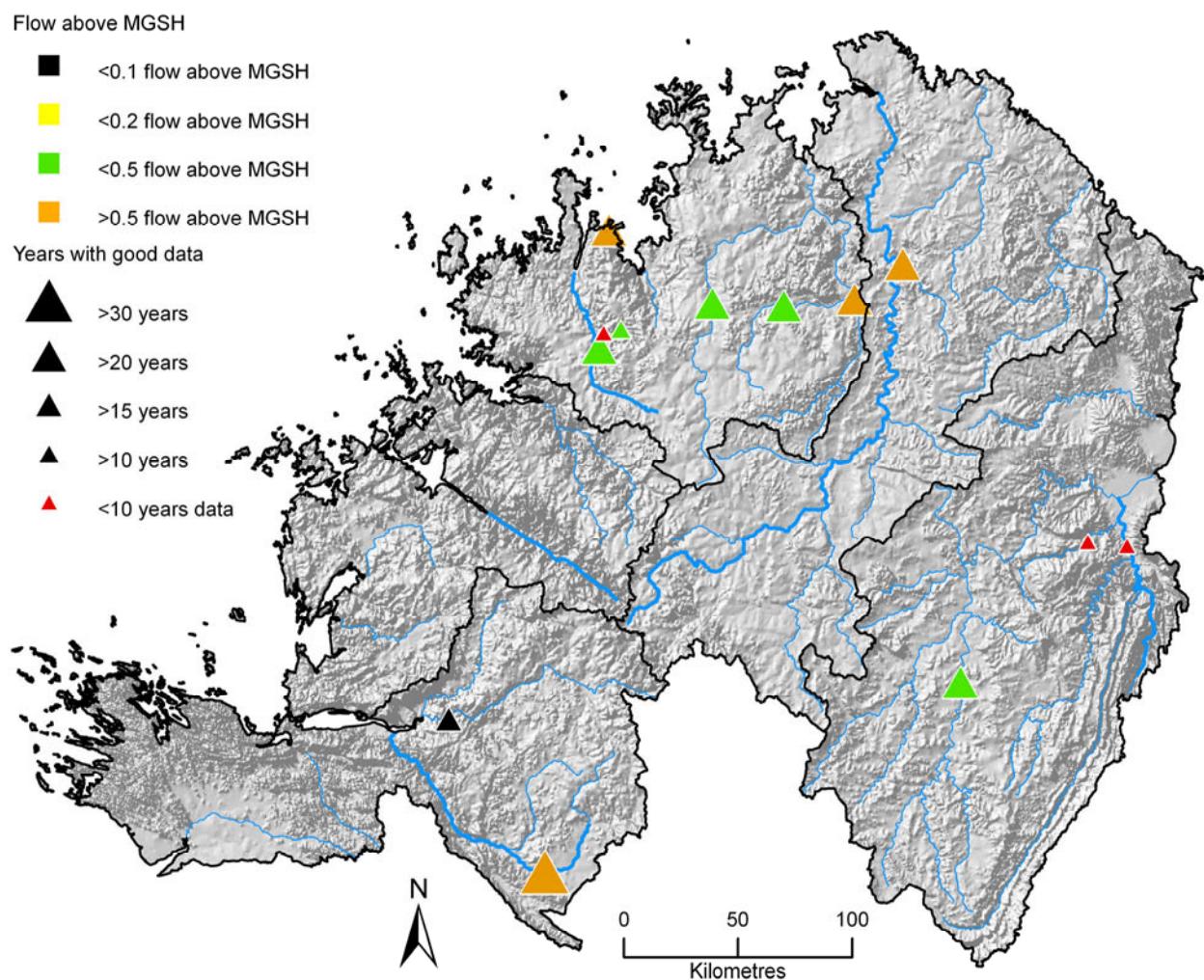


Figure KI-10. Location of streamflow gauging stations showing the proportion of flow above maximum gauged stage height across the Kimberley region, overlaid on a relative relief surface

KI-2.2.3 Groundwater

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

KI-2.2.4 Data gaps

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

KI-2.3 Hydrogeology

KI-2.3.1 Aquifer types

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

Fractured rock aquifers

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

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

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

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

Alluvial aquifers

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

KI-2.3.2 Inter-aquifer connection and leakage

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

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

KI-2.3.3 Recharge, discharge and groundwater storage

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

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

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

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

KI-2.3.4 Groundwater quality

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

KI-2.4 Legislation, water plans and other arrangements

KI-2.4.1 Legislated water use, entitlements and purpose

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

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

Current

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

Future

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

KI-2.4.2 Rivers and storages

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

KI-2.4.3 Unallocated water

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

KI-2.4.4 Social and cultural considerations

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

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

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

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

KI-2.4.5 Changed diversion and extraction regimes

There are no diversion schemes, nor extraction regimes, in the region other than for local stock and domestic supply, including provision for fishing camps and tourism activities.

KI-2.4.6 Changed land use

There has been minimal land use change to the region. There is no expected change in the near future.

KI-2.4.7 Environmental constraints and implications of future development

The region has high conservation and Indigenous values. Any future development will be managed using a precautionary approach. Environmental, water security and Indigenous needs will be recognised and will be guided by the *Kimberley Regional Water Allocation Plan*, currently under consideration.

KI-2.5 References

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KI-3 Water balance results for the Kimberley region

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

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

KI-3.1 Climate

KI-3.1.1 Historical climate

The Kimberley region receives an average of 950 mm of rainfall over a September to August water year (Figure KI-11), most of which (898 mm) falls in the November to April wet season (Figure KI-12). Across the region there is a strong north–south gradient in annual rainfall (Figure KI-13), ranging from 1223 mm in the north to 628 mm in the south. Over the first half of the historical (1930 to 2007) period, rainfall has been relatively constant at around 750 mm. The second half of the period has seen an increase in mean rainfall to approximately 1050 mm. The highest yearly rainfall received was 1679 mm which fell in 2000, and the lowest was 477 mm in 1936.

Historical areal potential evapotranspiration (APET) is very high across the region, averaging 1994 mm over a water year (Figure KI-11), and varies moderately across the seasons (Figure KI-12). APET generally remains higher than rainfall throughout the year resulting in annually water-limited conditions.

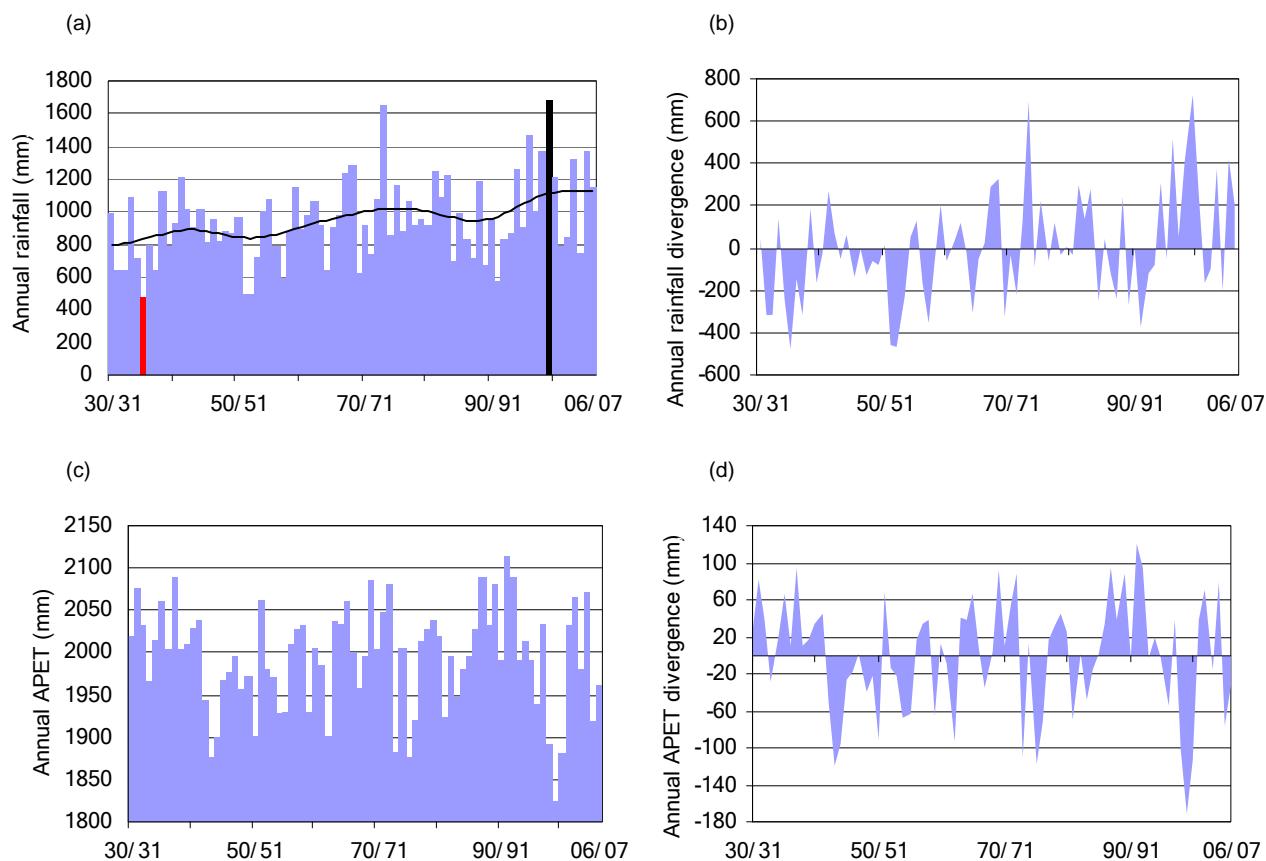


Figure KI-11. (a) Historical annual rainfall and (b) its divergence from the long-term mean; and (c) historical annual areal potential evapotranspiration and (d) its divergence from the long-term mean averaged over the Kimberley region. The low-frequency smoothed line in (a) indicates longer term variability

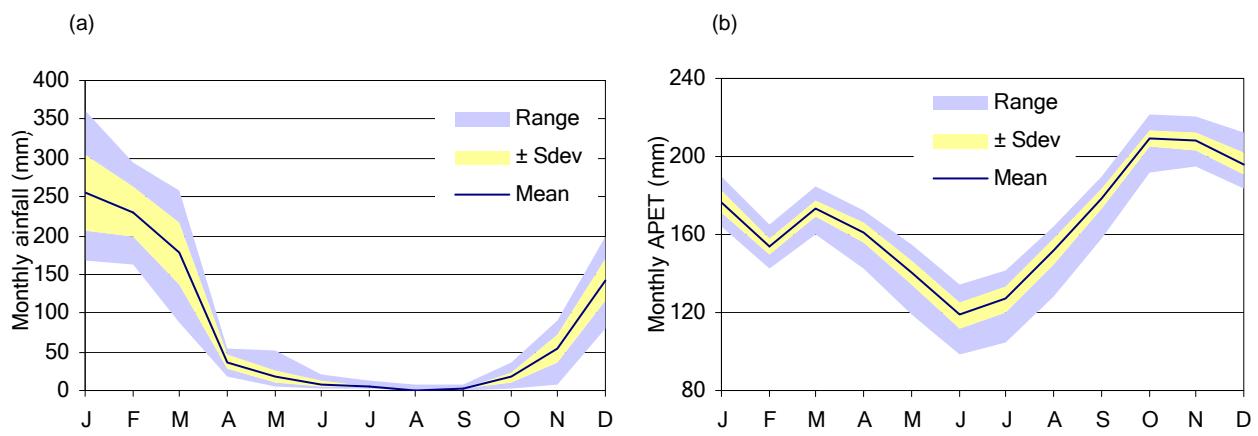


Figure KI-12. Historical mean monthly (a) rainfall and (b) areal potential evapotranspiration and their temporal variation (range and ± one standard deviation) averaged over the Kimberley region

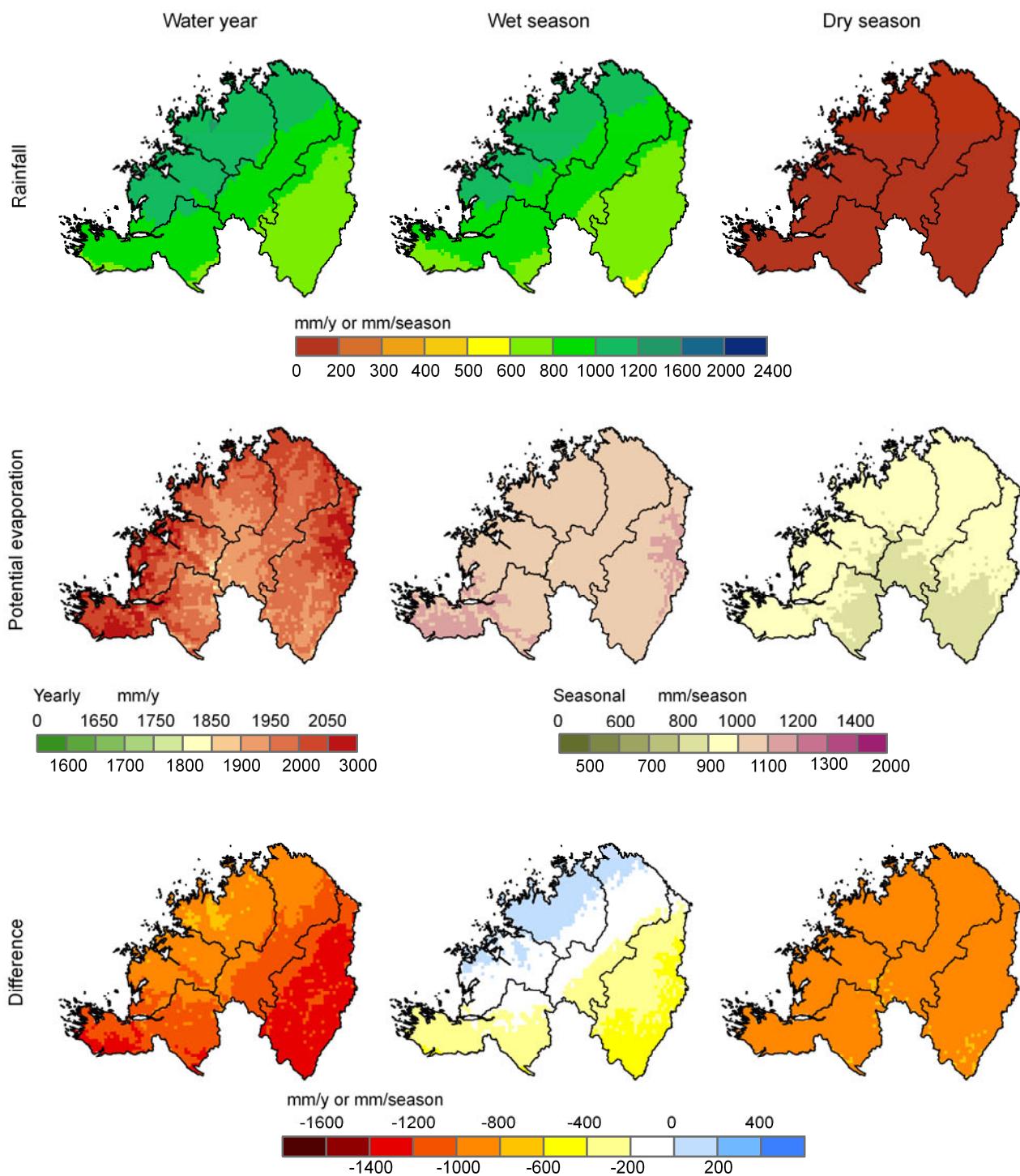


Figure KI-13. Spatial distribution of historical mean annual (water year), wet season and dry season rainfall and areal potential evapotranspiration (potential evaporation) and their difference (rainfall less areal potential evapotranspiration) across the Kimberley region

KI-3.1.2 Recent climate

Figure KI-14 compares recent (1996 to 2007) to historical (in this case the 66-year period from 1930 to 1996) mean annual rainfall for the Kimberley region. Across the whole region, recent rainfall is between 10 and 60 percent higher than historical rainfall – a statistically significant difference for the majority of the region.

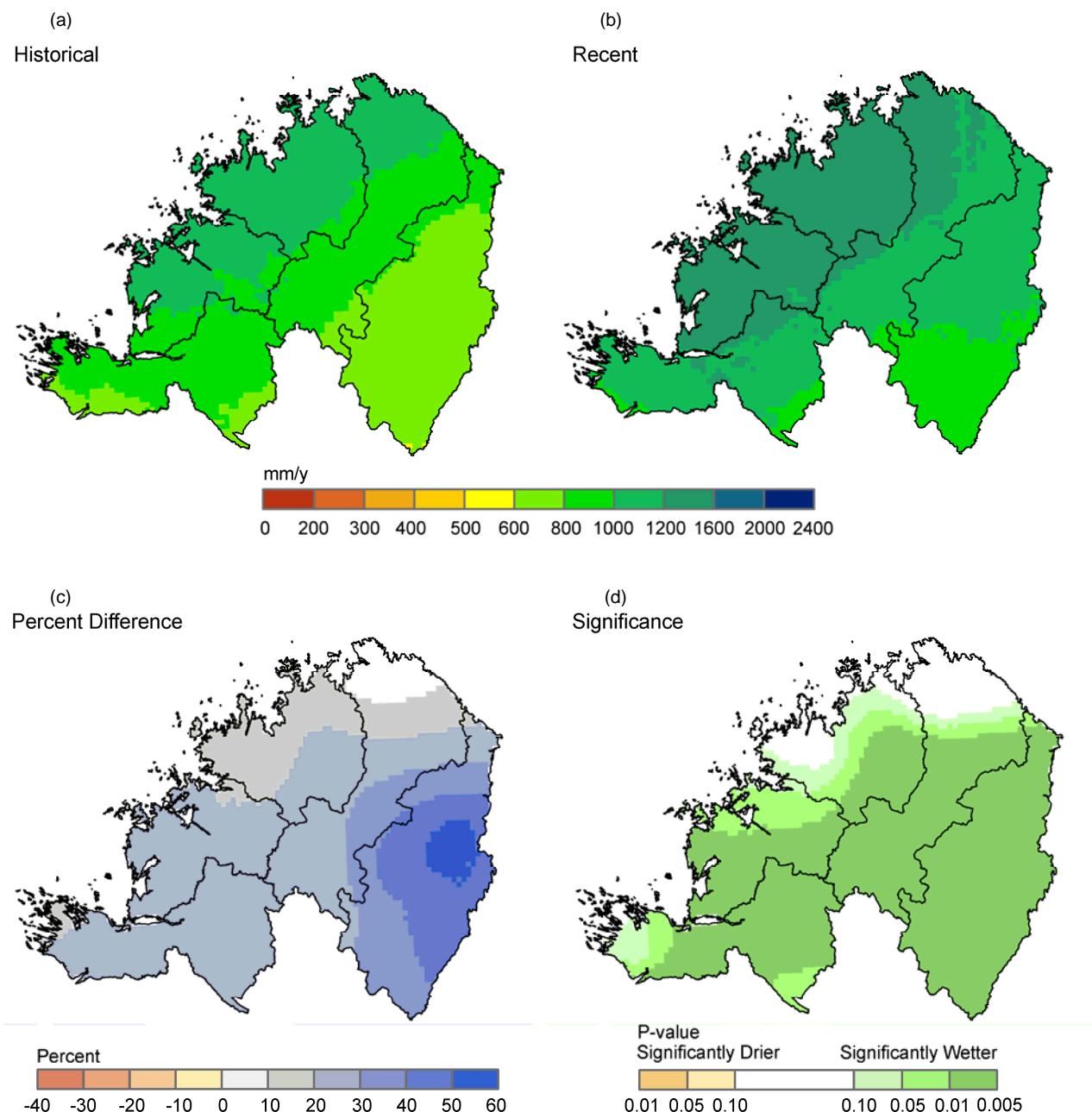


Figure KI-14. Spatial distribution of (a) historical and (b) recent mean annual rainfall; and (c) their relative percent difference and (d) the statistical significance of these differences across the Kimberley region. (Note that historical in this case is the 66-year period 1930 to 1996)

KI-3.1.3 Future climate

Under Scenario C annual rainfall varies between 819 mm and 1006 mm (Table KI-3) compared to the historical mean of 950 mm. Similarly, APET ranges between 2065 and 2076 mm compared to the historical mean of 1994 mm.

A total of 45 variants of Scenario C were modelled (15 global climate models (GCMs) for each of the high, medium and low global warming scenarios). Subsequently, results from an extreme 'wet', median and extreme 'dry' variant are shown (referred to as scenarios Cwet, Cmid and Cdry). Under Scenario Cwet annual rainfall and APET increase by 6 percent and 4 percent, respectively. Under Scenario Cmid annual rainfall increases by 1 percent and APET increases by 4 percent. Under Scenario Cdry annual rainfall decreases by 14 percent and APET increases by 4 percent.

Under Scenario Cmid long-term monthly averages of rainfall and APET do not differ much from historical values (Figure KI-15). Under Scenario Cmid rainfall lies well within the range in values from all 45 future climate variants. The

seasonality of rainfall changes slightly only in that any changes in rainfall occur in the wet season. However there is appreciable variation in rainfall in the wet season months, varying by up to 50 mm/month. In contrast, the seasonality of APET remains the same as any changes occur uniformly across the year. Under Scenario Cmid APET lies near the middle of the range in values derived from all 45 future climate variants.

The spatial distributions of rainfall and APET under Scenario C are compared to the historical distribution in Figure KI-16 and Figure KI-17. Under Scenario C the strong north–south gradient in rainfall is retained, but with a southwards shift under Scenario Cwet and a northwards shift under Scenario Cdry. Under scenarios Cmid and Cdry the rainfall gradient changes due to relatively greater decreases in rainfall occurring along the northern coastlines compared to the south of the region. The spatial distribution of APET under Scenario C is similar to the highly regionalised historical distribution. The greatest changes to APET occur in the south and east of the region.

Table KI-3. Mean annual (water year), wet season and dry season rainfall and areal potential evapotranspiration averaged over the Kimberley region under historical climate and Scenario C

	Water year mm/y	Wet season mm/season	Dry season
Rainfall			
Historical	950	898	53
Cwet	1006	938	55
Cmid	959	894	53
Cdry	819	765	44
Areal potential evapotranspiration			
Historical	1994	1069	926
Cwet	2068	1102	963
Cmid	2065	1105	957
Cdry	2076	1114	959

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

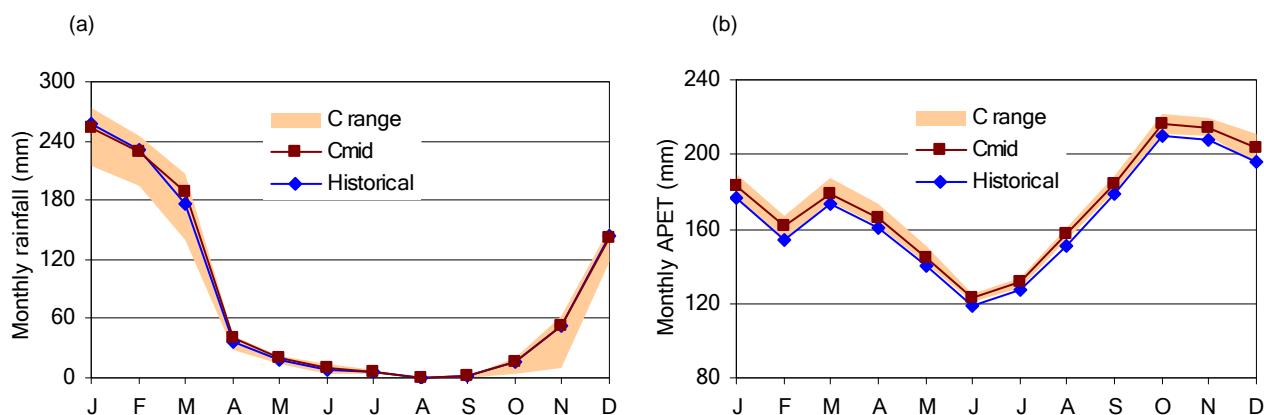


Figure KI-15. Mean monthly (a) rainfall and (b) areal potential evapotranspiration averaged over the Kimberley region under historical climate and Scenario C. (C range is the range under the 45 Scenario C simulations – the lower and upper limits in C range are therefore not the same as scenarios Cdry and Cwet)

KI-3 Water balance results for the Kimberley region

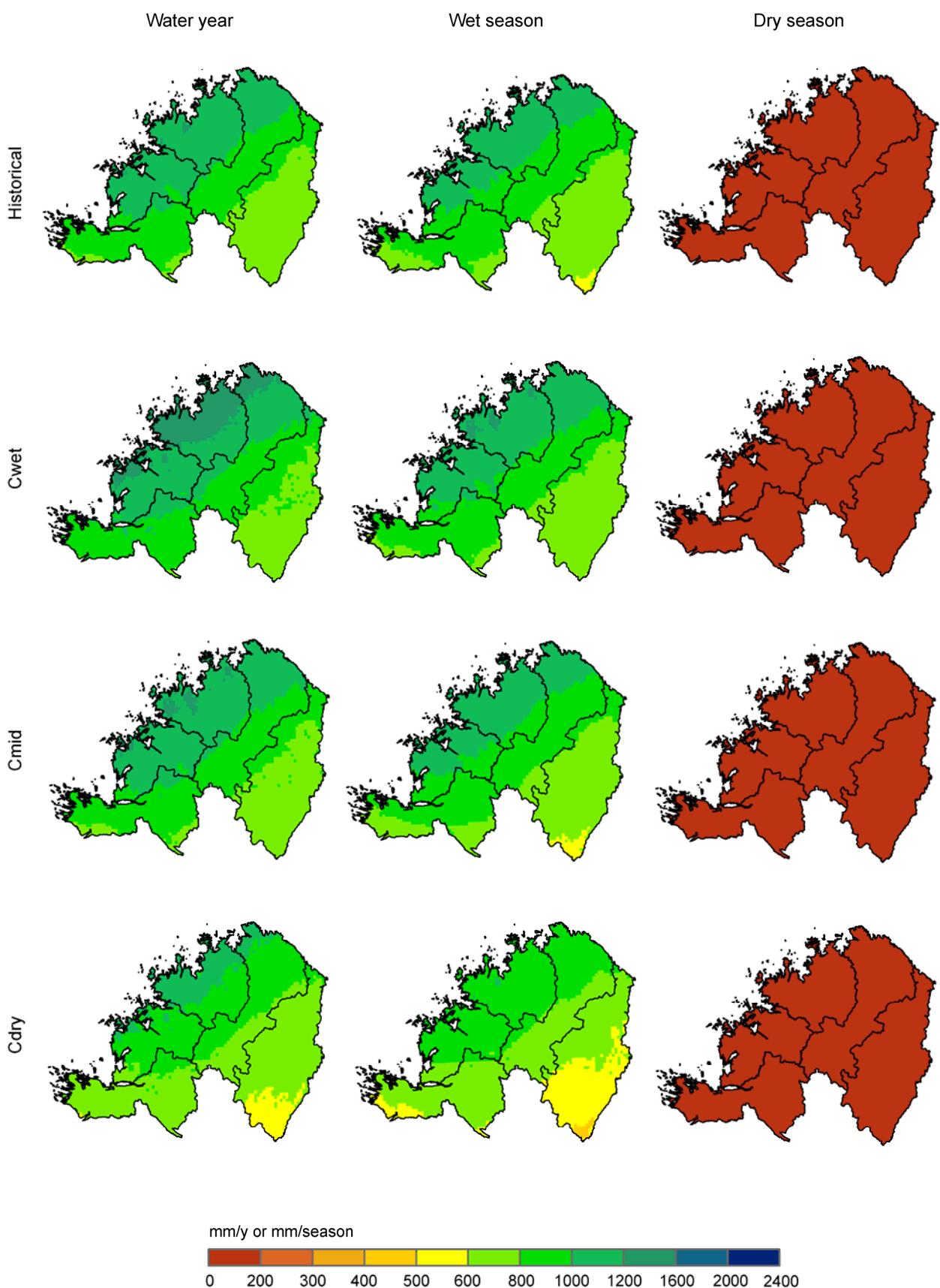


Figure KI-16. Spatial distribution of mean annual (water year), wet season and dry season rainfall across the Kimberley region under historical climate and Scenario C

KI-3 Water balance results for the Kimberley region

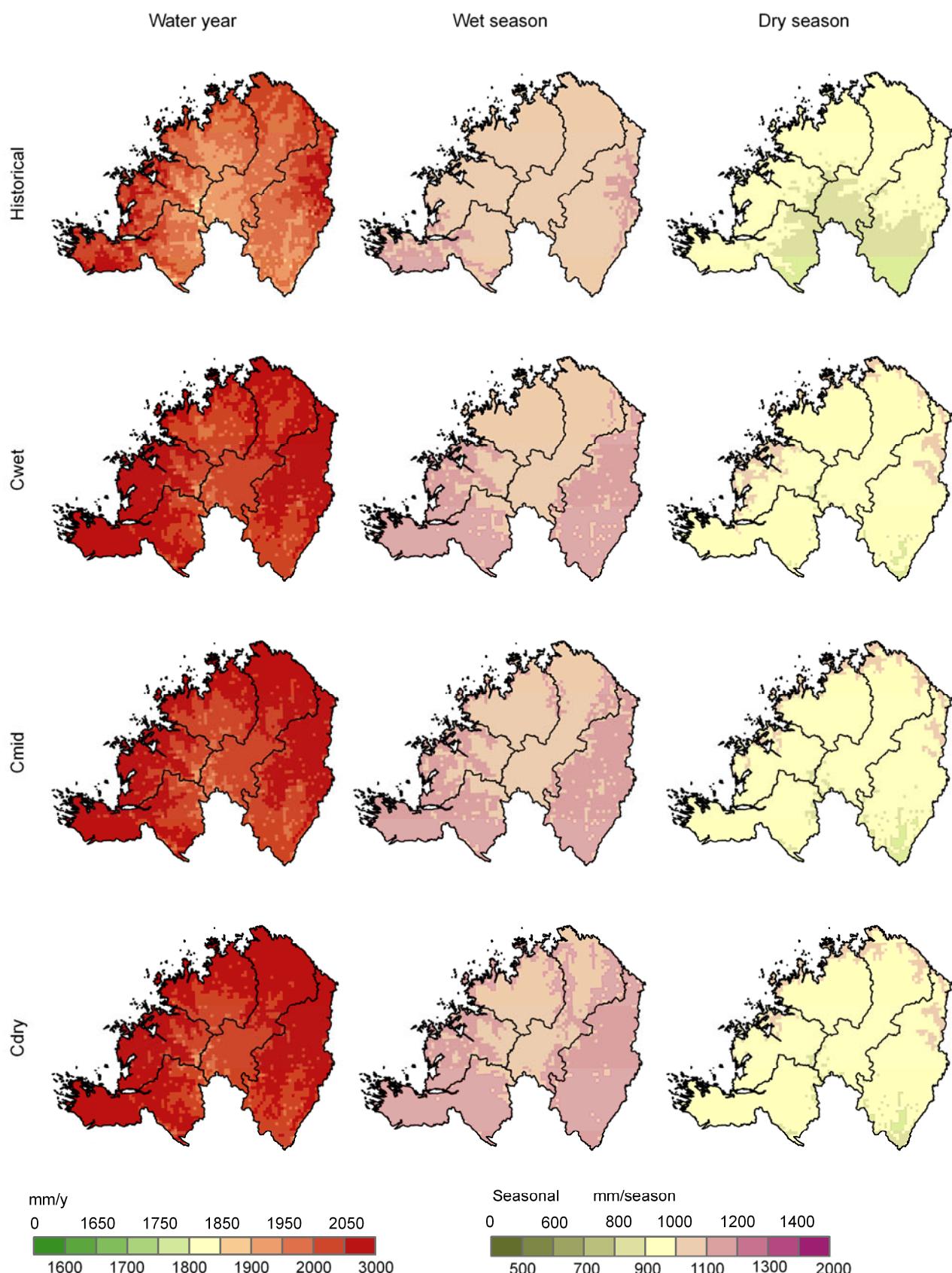


Figure KI-17. Spatial distribution of annual (water year), wet season and dry season areal potential evapotranspiration (potential evaporation) across the Kimberley region under historical climate and Scenario C

KI-3.1.4 Confidence levels

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

KI-3.2 WAVES potential diffuse recharge estimations

The WAVES model (Zhang and Dawes, 1998) was used to estimate the change in groundwater recharge across the Kimberley region under a range of different climate scenarios. WAVES is a vertical recharge flux model that can model plant physiological feedbacks in response to increased CO₂, as well as modelling the water balance of different soil, vegetation and climate regimes. It was chosen for its balance in complexity between plant physiology and soil physics. It was also used to assess recharge for the Murray-Darling Basin Sustainable Yields Project (Crosbie et al., 2008).

KI-3.2.1 Under historical climate

Figure KI-18 shows the spatial distribution of calculated historical recharge for the Kimberley region, with calculated recharge greatest in the north-east and decreasing progressively to the south-west following the rainfall gradient. The historical record was assessed to establish any difference between wet and dry periods of recharge. A 23-year period was used, which allows the projection of recharge estimates to 2030 – in other words, to estimate recharge in 2030 assuming future climate is similar to historical climate (Scenario A).

For the three variants of Scenario A the recharge does change for the 23-year period when compared to the 77-year historical value (Table KI-4). Under a wet historical climate (Awet) the Kimberley region is calculated to have, on average, a 10 percent increase in recharge (i.e., a recharge scaling factor (RSF), averaged across the region, of 1.10). Under the median estimate of historical climate (Amid) the Kimberley region is calculated to have a 2 percent decrease in recharge that is quite uniform across the region. Under a dry historical climate (Adry) the Kimberley region is calculated to have a 13 percent decrease in recharge. Where unweathered bedrock outcrops occur, confidence in the modelled results is reduced. The locations of these outcrops in the Kimberley region are shown on the historical recharge map in Figure KI-18.

Table KI-4. Recharge scaling factors in the Kimberley region for scenarios A, B and C

Region	Awet	Amid	Adry	B	Cwet	Cmid	Cdry
Kimberley	1.10	0.98	0.87	1.33	1.21	1.08	0.91

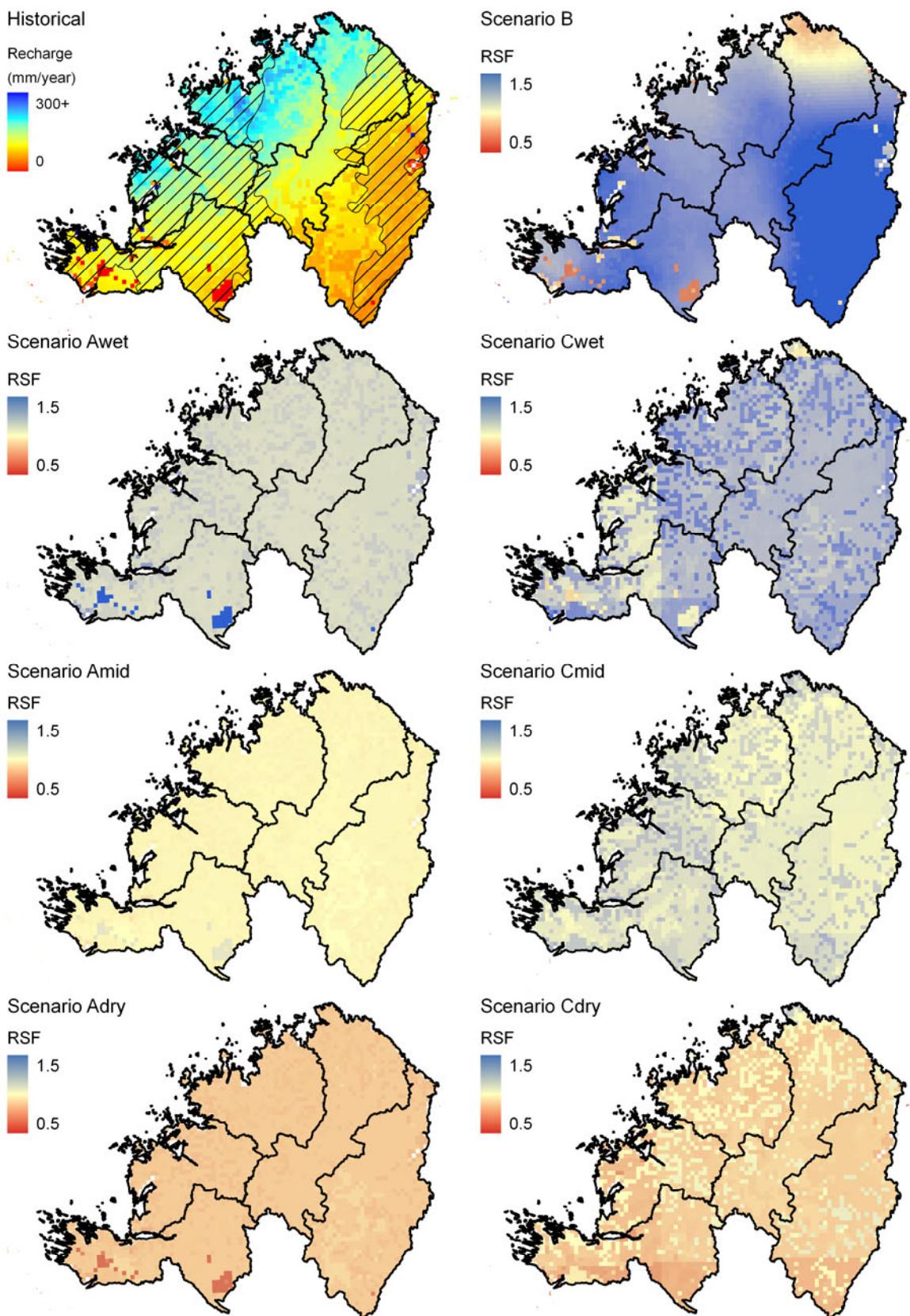


Figure KI-18. Spatial distribution of historical mean recharge rate; and recharge scaling factors in the Kimberley region for scenarios A, B and C. The hatched region on the historical recharge map identifies where unweathered bedrock outcrops occur

KI-3.2.2 Under recent climate

The recent (1996 to 2007) climate in the Kimberley region has been wetter than the historical (1930 to 2007) average and consequently the calculated recharge has seen an increase of 33 percent under Scenario B relative to Scenario A (Table KI-4). This increase has not been spatially uniform with the greatest increase in recharge in the west of the region and the north of the region shows a decrease in recharge (Figure KI-18).

KI-3.2.3 Under future climate

Figure KI-19 shows the percentage change in modelled mean annual recharge averaged over the Kimberley region under Scenario C relative to Scenario A for the 45 scenarios (15 GCMs for each of the high, medium and low global warming scenarios). The percentage change in the mean annual rainfall and recharge from the corresponding GCMs are also tabulated in Table KI-5. For the recharge projections from the GCM named 'inmcm', recharge is projected to decrease despite an increase in rainfall. This is because total rainfall is not the only climate variable that influences recharge. Daily rainfall intensity, temperature and 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.

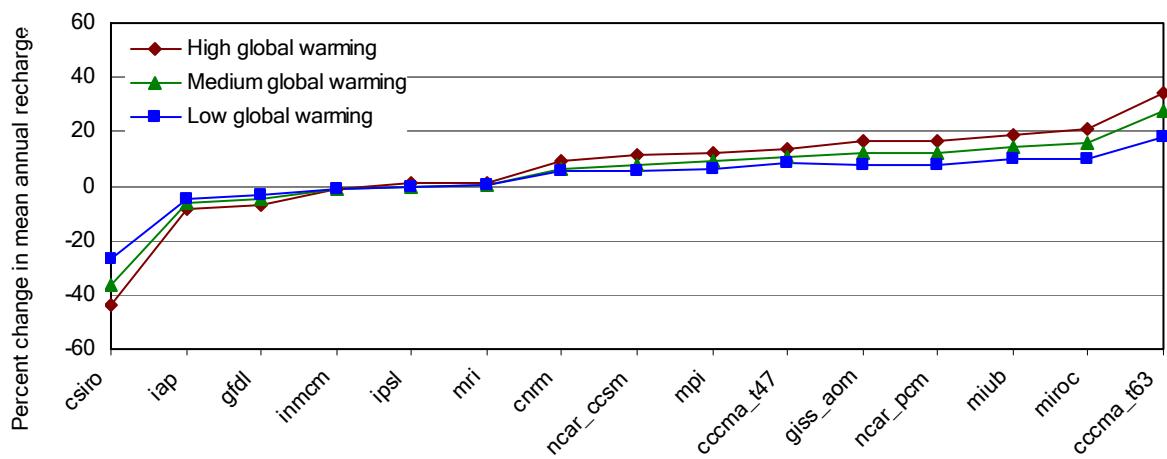


Figure KI-19. Percentage change in mean annual recharge under the 45 Scenario C simulations (15 global climate models and three global warming scenarios) relative to Scenario A recharge

Table KI-5. Summary results under the 45 Scenario C simulations (numbers show percentage change in mean annual rainfall and recharge under Scenario C relative to Scenario A)

High global warming			Medium global warming			Low global warming		
GCM	Rainfall	Recharge	GCM	Rainfall	Recharge	GCM	Rainfall	Recharge
csiro	-23%	-44%	csiro	-18%	-37%	csiro	-12%	-27%
iap	-6%	-9%	iap	-4%	-7%	iap	-3%	-5%
gfdl	-13%	-7%	gfdl	-10%	-5%	gfdl	-7%	-4%
inmcm	1%	-1%	inmcm	1%	-1%	inmcm	1%	-1%
ipsl	0%	1%	ipsl	0%	0%	ipsl	0%	0%
mri	0%	1%	mri	0%	1%	mri	0%	0%
cnrm	1%	9%	cnrm	1%	6%	cnrm	1%	5%
ncar_ccsm	4%	11%	ncar_ccsm	3%	8%	ncar_ccsm	2%	5%
mpi	1%	12%	mpi	1%	9%	mpi	1%	6%
ccma_t47	4%	14%	ccma_t47	3%	11%	ccma_t47	2%	8%
giss_aom	6%	16%	giss_aom	5%	12%	giss_aom	3%	8%
ncar_pcm	4%	16%	ncar_pcm	3%	12%	ncar_pcm	2%	8%
miub	2%	19%	miub	1%	14%	miub	1%	10%
miroc	5%	21%	miroc	4%	16%	miroc	3%	10%
ccma_t63	8%	34%	ccma_t63	6%	27%	ccma_t63	5%	18%

Under Scenario Cwet the Kimberley region is calculated to have an increase in recharge of 21 percent. Under Scenario Cmid the Kimberley region is calculated to have an increase in recharge of 8 percent. Under Scenario Cdry the Kimberley region is calculated to have a decrease in recharge of 9 percent.

KI-3.2.4 Confidence levels

The estimation of recharge from WAVES is only indicative of the actual recharge and has not been validated with field measurements. A steady state groundwater chloride mass balance has been conducted as an independent measure of recharge (Crosbie et al., 2009). The results in the Kimberley region show that the historical estimate of recharge using WAVES (120 mm/year) is less than the best estimate using the chloride mass balance (209 mm/year) but it is within the confidence limits of the chloride mass balance (51 to 424 mm/year).

KI-3.3 Conceptual groundwater models

Fractured rock aquifers across the Kimberley region, consisting of Lower Proterozoic sandstone, basalt and dolerite, are recharged directly following intense and prolonged rainfall events during the wet season as well as through river recharge when river levels are elevated. Shallow groundwater is likely to discharge locally to rivers towards the end of the wet season and early dry season, and small semi-permanent springs exist in some inland areas. Rivers do not receive prolonged groundwater discharge through the dry season in their upper reaches due to the generally low storage of the fractured rock aquifers. However river flow is maintained throughout the dry season in the lower reaches of some rivers due to regional groundwater discharge. Groundwater also discharges regionally via evapotranspiration where vegetation can access the water table and via throughflow towards the coast. Knowledge of groundwater in deeper aquifers is limited because the shallow groundwater is of good quality and has yields that meet existing demands.

KI-3.3.1 Baseflow indexing comparison with conceptual models

The annual baseflow index (BFI) values in the Kimberley region range from 0.07 to 0.32 with a median of 0.21 (n=8) (Table KI-1). All of the gauges on which analyses were performed are located towards the middle or lower reaches of the respective rivers. It is therefore likely that the rivers are receiving regional groundwater discharge in at least some of the dry season. This has a good correlation to the conceptual model developed for the region. The dry season baseflow volumes shown in Figure KI-2 are similar for all gauges except for the Drysdale River gauge which has a larger catchment area relative to the other gauges. A relatively high dry season baseflow (for location along river length) is seen in the Isdell River gauge which may be due to springs associated with the Carson Volcanics Basalt in the area. It is difficult to determine any relationship between BFI and dry season flows or any potential correlation to geology since gauges yield similar values and are located in similar fractured rock settings.

KI-3.4 Groundwater modelling results

The paucity of groundwater data and absence of an existing numerical model meant that a quantitative assessment of the water balance was not possible for the Kimberley region.

KI-3.5 Rainfall-runoff modelling results

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

KI-3.5.1 Regional synopsis

The rainfall-runoff modelling estimates runoff in 0.05 degree grid cells in 48 subcatchments (Figure KI-20). Optimised parameter values from 12 calibration catchments are used. Ten of these calibration catchments are in the Kimberley region and two are in the Ord-Bonaparte region. The majority of the calibration catchments are situated away from the coastal fringes of the region.

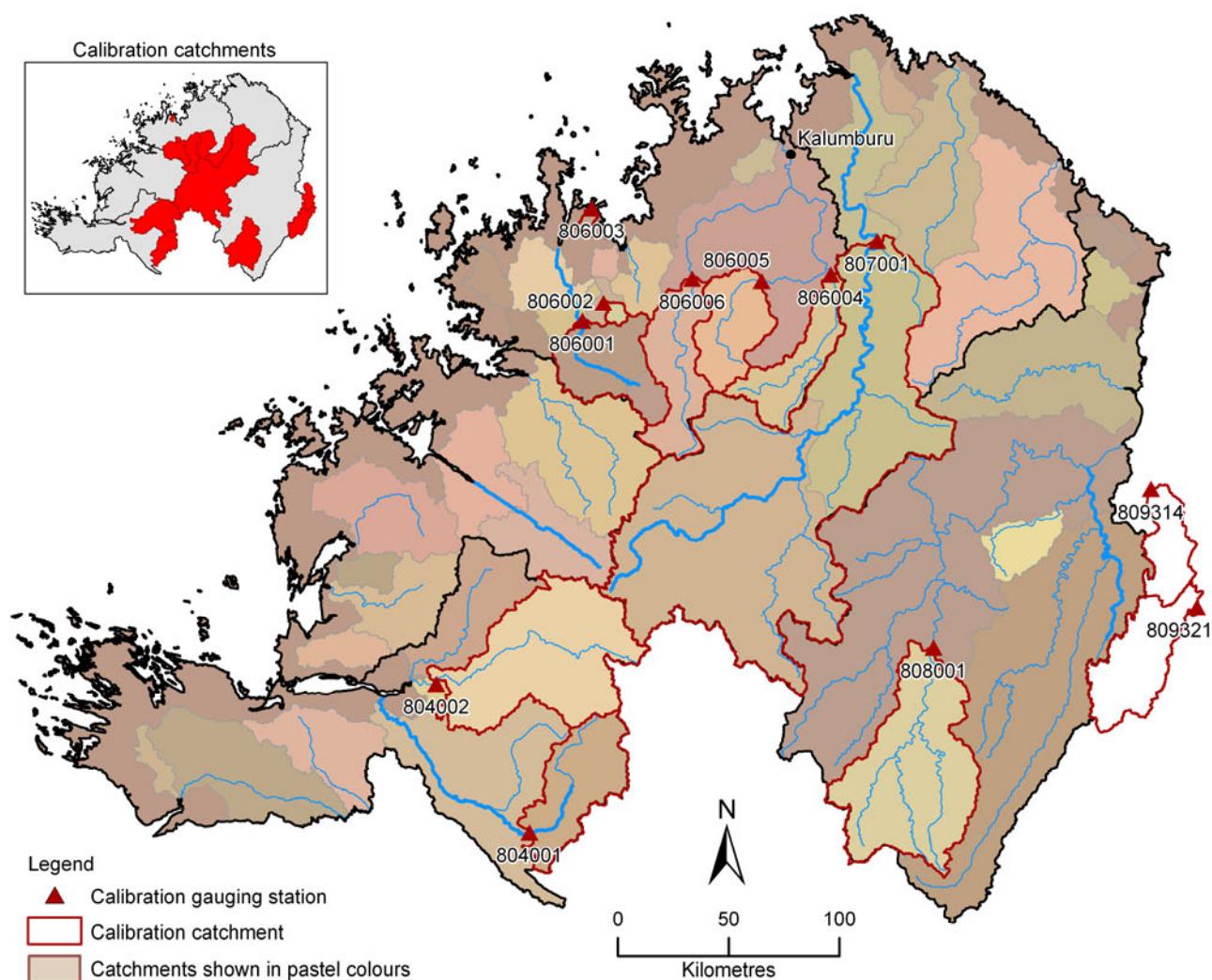


Figure KI-20. Map of the modelling subcatchments, calibration catchments and calibration gauging stations used for the Kimberley region with inset highlighting (in red) the extent of the calibration catchments

KI-3.5.2 Model calibration

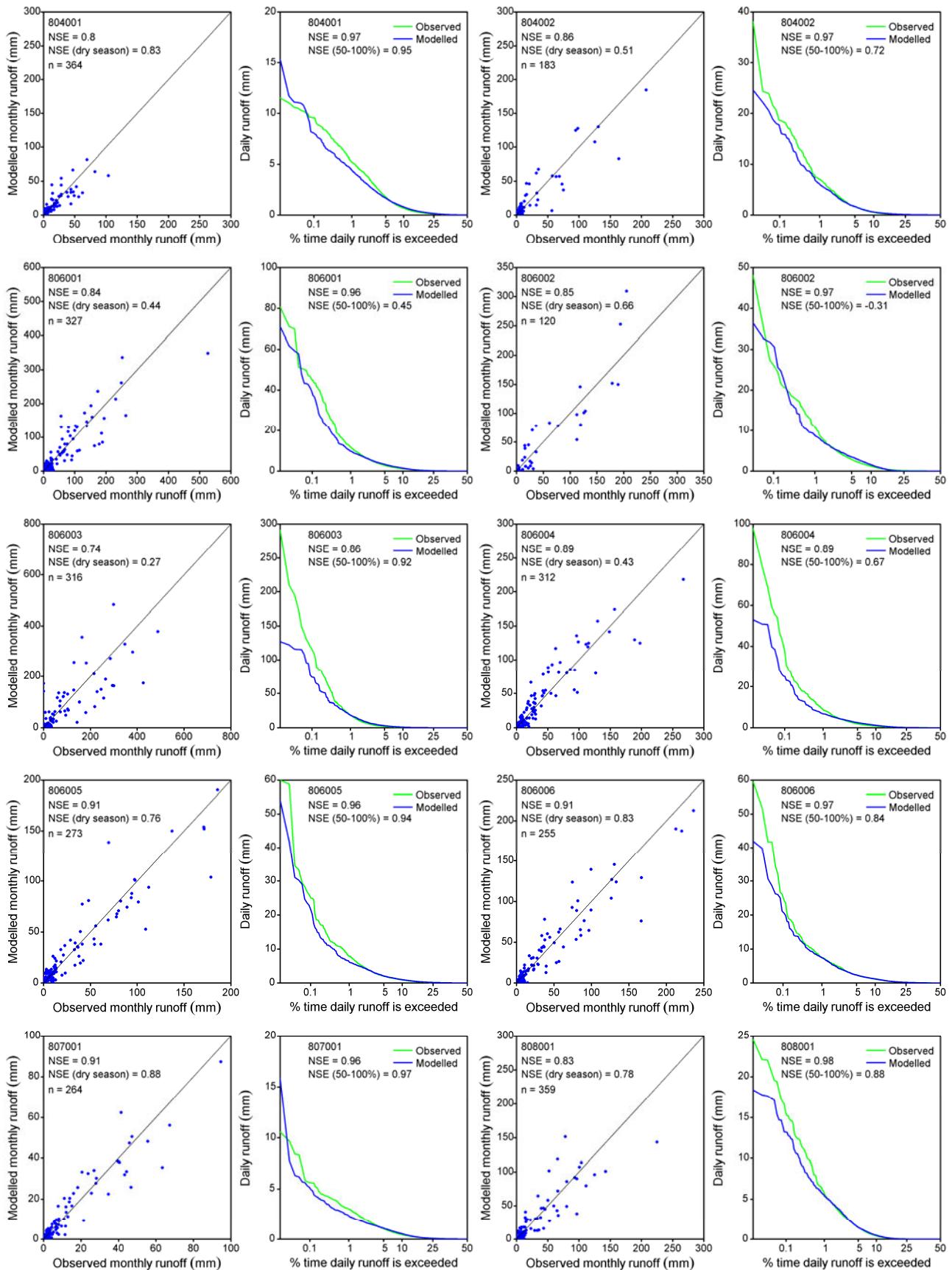
Figure KI-21 compares the modelled and observed monthly runoff and the modelled and observed daily flow exceedance curves for the 12 calibration catchments. Nash-Sutcliffe efficiency (NSE) values provide a quantitative measure of how well simulated values match observed values. NSE values are described in more detail in Section 2.2.3 of the division-level Chapter 2. On the monthly plots NSE is the monthly Nash-Sutcliffe efficiency value and NSE (dry season) is the dry season monthly Nash-Sutcliffe efficiency value. On the daily flow exceedance plots, NSE is the daily flow exceedance curve Nash-Sutcliffe efficiency value and NSE (50 to 100 percent) is the lower half of the daily flow exceedance curve Nash-Sutcliffe efficiency value.

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

The calibration method places more importance on the simulation of high runoff, and therefore rainfall-runoff modelling of the medium and high runoff is considerably better than the modelling of low runoff. It should be noted, however, that while the relative difference between the observed and simulated low flow values may be large (which is what gives rise to the low monthly dry season NSE values for example), the absolute difference between the observed and simulated low flow values is generally small because both values are small. Nevertheless, an optimisation to reduce overall error variance can result in some underestimation of high runoff and overestimation of low runoff. This is evident in some of the scatter plots comparing the modelled and observed monthly runoff and many of the daily flow exceedance curves.

For the majority of calibration catchments the disagreement between the modelled and observed daily runoff curves is discernable for runoff that is exceeded less than 0.1 percent of the time. This is accentuated in the plots because of the linear scale on the y-axis and normal probability scale on the x-axis. In any case, the volumetric constraint used in the model calibration ensures that the total modelled runoff is always within 5 percent of the total observed runoff. As indicated by the relatively low NSE values for the lower half of the daily flow exceedance curve and monthly dry season there may be considerable disagreement between observed and modelled low flow values (i.e. cease-to-flow). Overall the monthly NSE values are considered sufficient for the general purposes of estimating long-term mean annual runoff.

KI-3 Water balance results for the Kimberley region



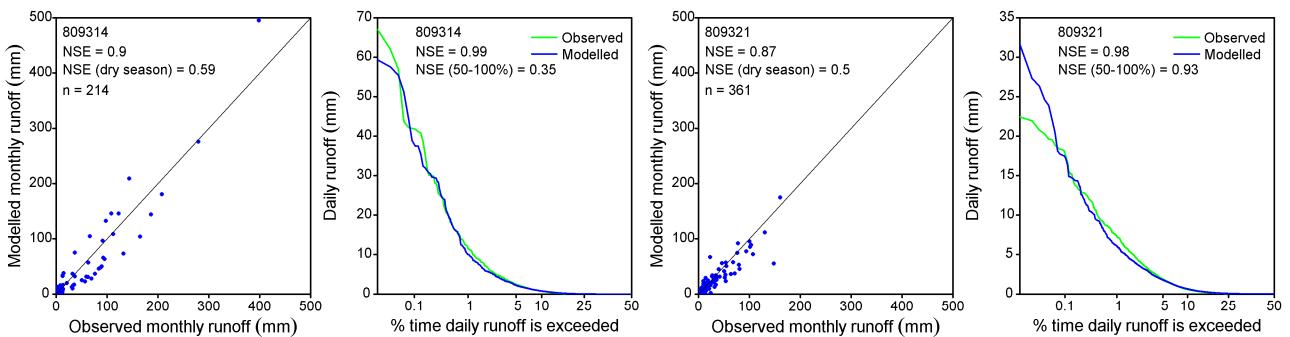


Figure KI-21. Modelled and observed monthly runoff and daily flow exceedance curve for each calibration catchment in the Kimberley region. (Red text denotes catchments that lie outside the region; blue text denotes catchments used for streamflow modelling only)

KI-3.5.3 Under historical climate

Figure KI-22 shows the spatial distribution of mean annual rainfall and runoff under Scenario A (averaged over 1930 to 2007) across the Kimberley region. Figure KI-23 shows the mean annual rainfall and runoff averaged over the region. The runoff grid extends outside of the AWRC boundary due to a discrepancy between it and the DEM-derived catchment boundary.

The mean annual rainfall and runoff averaged over the Kimberley region are 936 mm and 153 mm respectively. The mean wet season and dry season runoff averaged over the Kimberley region are 148 mm and 5 mm respectively.

In this project, all runoff grids are presented as long-term mean annual values. However the distributions of monthly and annual runoff data in northern Australia can be highly skewed; consequently the median and 10th and 90th percentile values spatially averaged over the region are also reported. The 10th percentile, median and 90th percentile annual runoff values across the Kimberley region are 311, 133 and 30 mm respectively. The median wet season and dry season runoff averaged over the Kimberley region are 129 mm and 4 mm respectively.

The mean annual rainfall varies from about 1200 mm in the north-west to 600 mm in the south-east. The mean annual runoff varies from over 400 mm in the central west to about 50 mm in the central Kimberley region i.e. the upper reaches of the Drysdale river (Figure KI-22). Runoff coefficients in the subcatchments vary from about 10 to 30 percent of rainfall. The majority of rainfall and runoff occurs during the wet season months December to April (Figure KI-24). Rainfall and runoff can vary considerably from year to year with long periods over several years or decades that are considerably wetter or drier than others (Figure KI-23). The coefficients of variation of annual rainfall and runoff averaged over the Kimberley region are 0.26 and 0.78 respectively.

The Kimberley is one of 13 regions which cover the three divisions studied in this project. Mean annual rainfall and runoff, as well as coefficients of variation, have been calculated for all of these 13 regions, and it is useful to compare the Kimberley results to results across all 13 regions. Across all 13 regions in this project 10th percentile, median and 90th percentile values are 1371, 936 and 595 mm respectively for mean annual rainfall and 374, 153 and 78 mm respectively for mean annual runoff. The mean annual rainfall (936 mm) and runoff (153 mm) averaged over the Kimberley region fall in the middle of this range. Across all 13 regions in this project the 10th percentile, median and 90th percentile values are 0.34, 0.26 and 0.19 respectively for the coefficient of variation of annual rainfall and 1.39, 0.69 and 0.48 for the coefficient of variation of runoff. The coefficients of variation of annual rainfall (0.26) and runoff (0.78) averaged over the Kimberley region fall within the middle of the values of the 13 reporting regions.

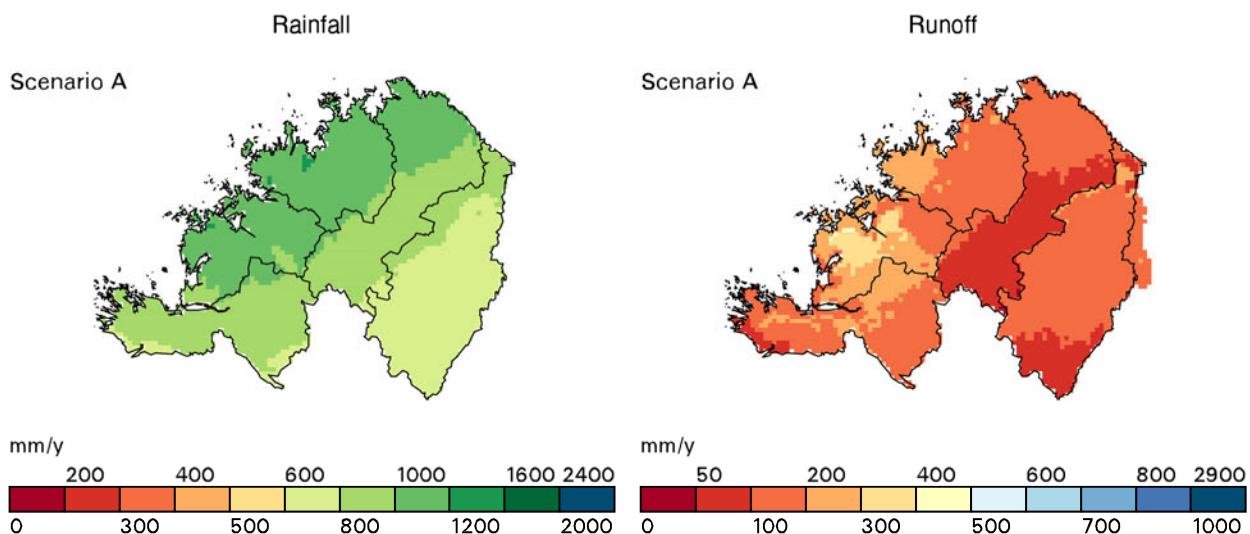


Figure KI-22. Spatial distribution of mean annual rainfall and modelled runoff across the Kimberley region under Scenario A

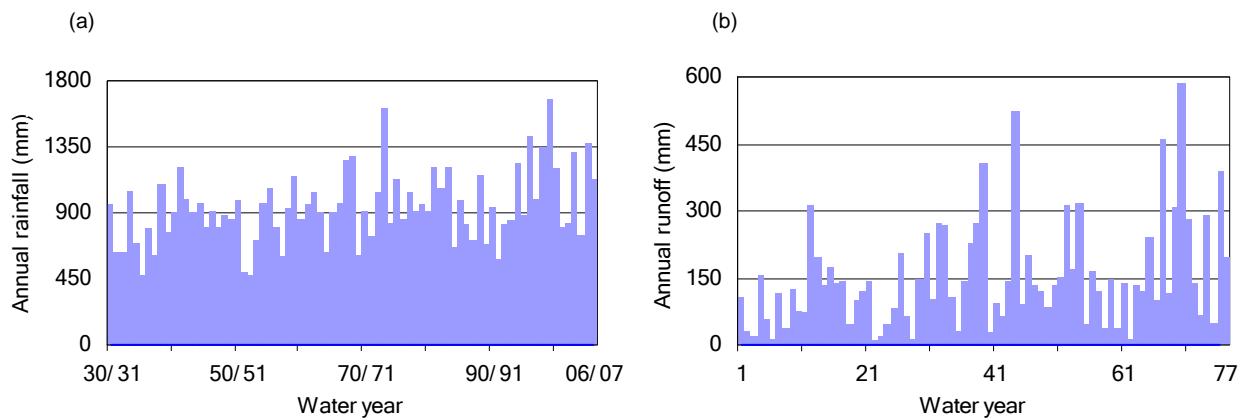


Figure KI-23. Mean annual (a) rainfall and (b) modelled runoff in the Kimberley region under Scenario A

Figure KI-24(a,b) shows the minimum and maximum monthly rainfall and runoff and the range of values between the 25th and 75th percentile monthly rainfall and runoff. Figure KI-24(c,d) shows the mean and median monthly flows and the range of values between the 25th and 75th percentile monthly rainfall and runoff. The large difference in the mean and median wet season monthly runoff values indicates that the distribution of monthly runoff in the Kimberley region is highly skewed.

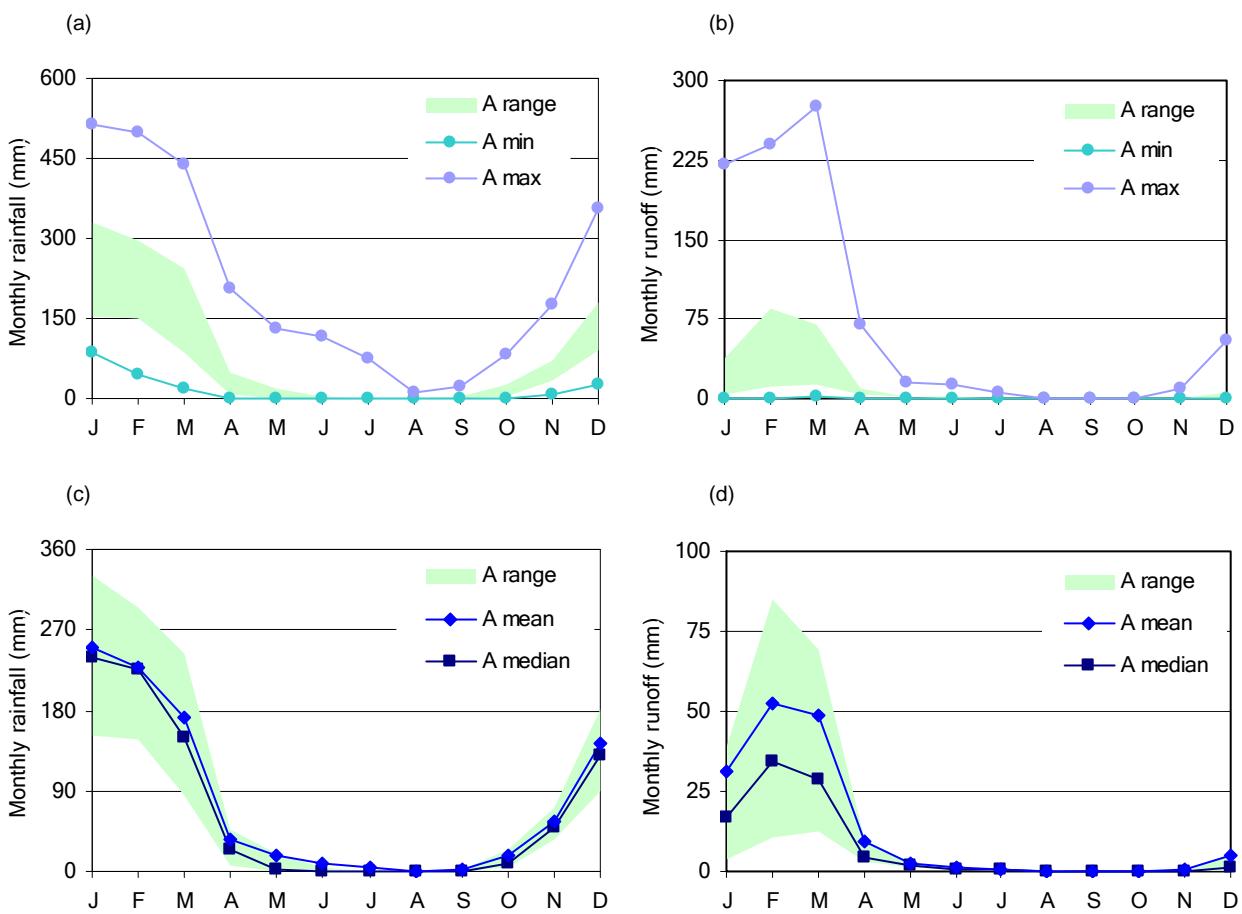


Figure KI-24. Minimum, maximum and A range monthly (a) rainfall and (b) modelled runoff; and mean, median and A range monthly (c) rainfall and (d) modelled runoff in the Kimberley region under Scenario A (A range is the 25th to 75th percentile monthly rainfall or runoff)

KI-3.5.4 Under recent climate

The mean annual rainfall and runoff under Scenario B (1996 to 2007) are 25 percent and 71 percent higher respectively than the historical (1930 to 2007) mean values. The spatial distribution of rainfall and runoff across the Kimberley region under Scenario B is shown in Figure KI-25.

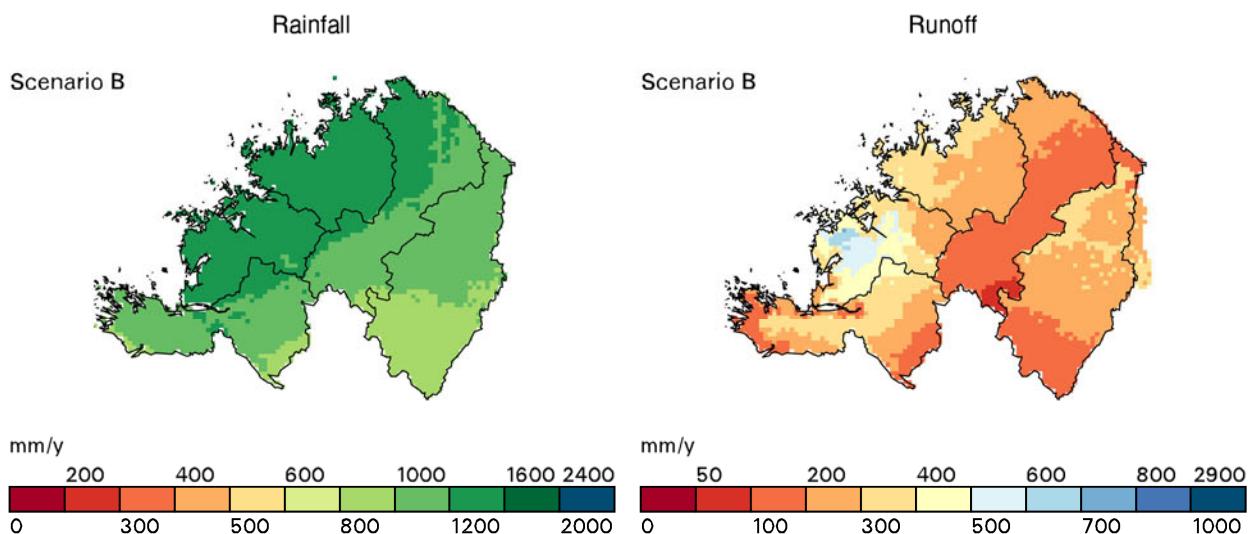


Figure KI-25. Spatial distribution of mean annual rainfall and runoff across the Kimberley region under Scenario B

KI-3.5.5 Under future climate

Figure KI-26 shows the percentage change in the mean annual runoff averaged over the Kimberley region under Scenario C relative to Scenario A for the 45 scenarios (15 global climate models (GCMs) for each of the high, medium and low global warming scenarios). The percentage change in the mean annual runoff and rainfall from the corresponding GCMs are also tabulated in Table KI-6.

The figure and table indicate that the potential impact of climate change on runoff can be very significant. Although there is considerable uncertainty in the estimates, the results indicate that runoff in ~2030 in the Kimberley region is as likely to increase as decrease. Rainfall-runoff modelling with climate change projections from eight of the GCMs shows a reduction in mean annual runoff, while rainfall-runoff modelling with climate change projections from seven of the GCMs shows an increase in mean annual runoff. The wide range of mean annual runoff values shown in Figure KI-26 and Table KI-6 is primarily due to the wide range of future projections of rainfall by the 15 GCMs.

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

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

Under scenarios Cwet, Cmid and Cdry, mean annual runoff increases by 13 percent and decreases by 1 and 27 percent relative to Scenario A. By comparison, the range based on the low global warming scenario is a 4 to -16 percent change in mean annual runoff. Figure KI-27 shows the mean annual runoff across the Kimberley region under scenarios A and C. The linear discontinuities that are evident in Figure KI-27 are due to GCM grid cell boundaries.

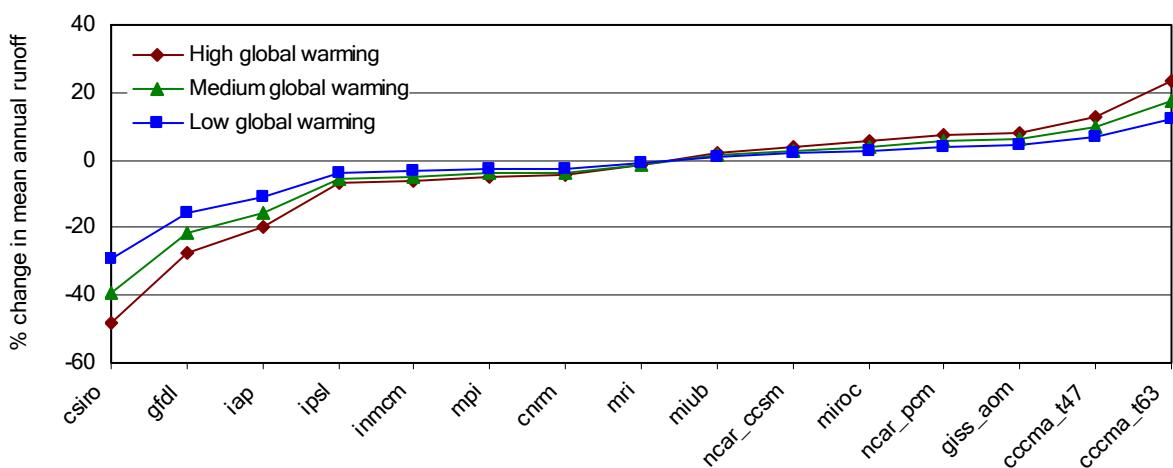


Figure KI-26. Percentage change in mean annual modelled runoff under the 45 Scenario C simulations (15 global climate models and three global warming scenarios) relative to Scenario A

Table KI-6. Summary results under the 45 Scenario C simulations for the modelled subcatchments in the Kimberley region (numbers show percentage change in mean annual rainfall and modelled runoff under Scenario C relative to Scenario A)

GCM	High global warming		Medium global warming		Low global warming			
	Rainfall	Runoff	GCM	Rainfall	Runoff	GCM	Rainfall	Runoff
csiro	-23%	-48%	csiro	-18%	-39%	csiro	-13%	-29%
gfdl	-14%	-27%	gfdl	-11%	-22%	gfdl	-7%	-16%
iap	-6%	-20%	iap	-5%	-15%	iap	-3%	-11%
ipsl	-1%	-7%	ipsl	0%	-6%	ipsl	0%	-4%
inmcm	0%	-6%	inmcm	0%	-5%	inmcm	0%	-3%
mpi	1%	-5%	mpi	0%	-4%	mpi	0%	-3%
cnrm	1%	-5%	cnrm	1%	-4%	cnrm	1%	-3%
mri	0%	-1%	mri	0%	-1%	mri	0%	-1%
miub	1%	2%	miub	1%	2%	miub	1%	1%
ncar_ccsm	3%	4%	ncar_ccsm	3%	3%	ncar_ccsm	2%	2%
miroc	5%	5%	miroc	3%	4%	miroc	2%	3%
ncar_pcm	4%	8%	ncar_pcm	3%	6%	ncar_pcm	2%	4%
giess_aom	6%	8%	giess_aom	4%	6%	giess_aom	3%	4%
cccm_t47	3%	13%	cccm_t47	3%	10%	cccm_t47	2%	7%
cccm_t63	8%	23%	cccm_t63	6%	18%	cccm_t63	4%	12%

KI-3 Water balance results for the Kimberley region

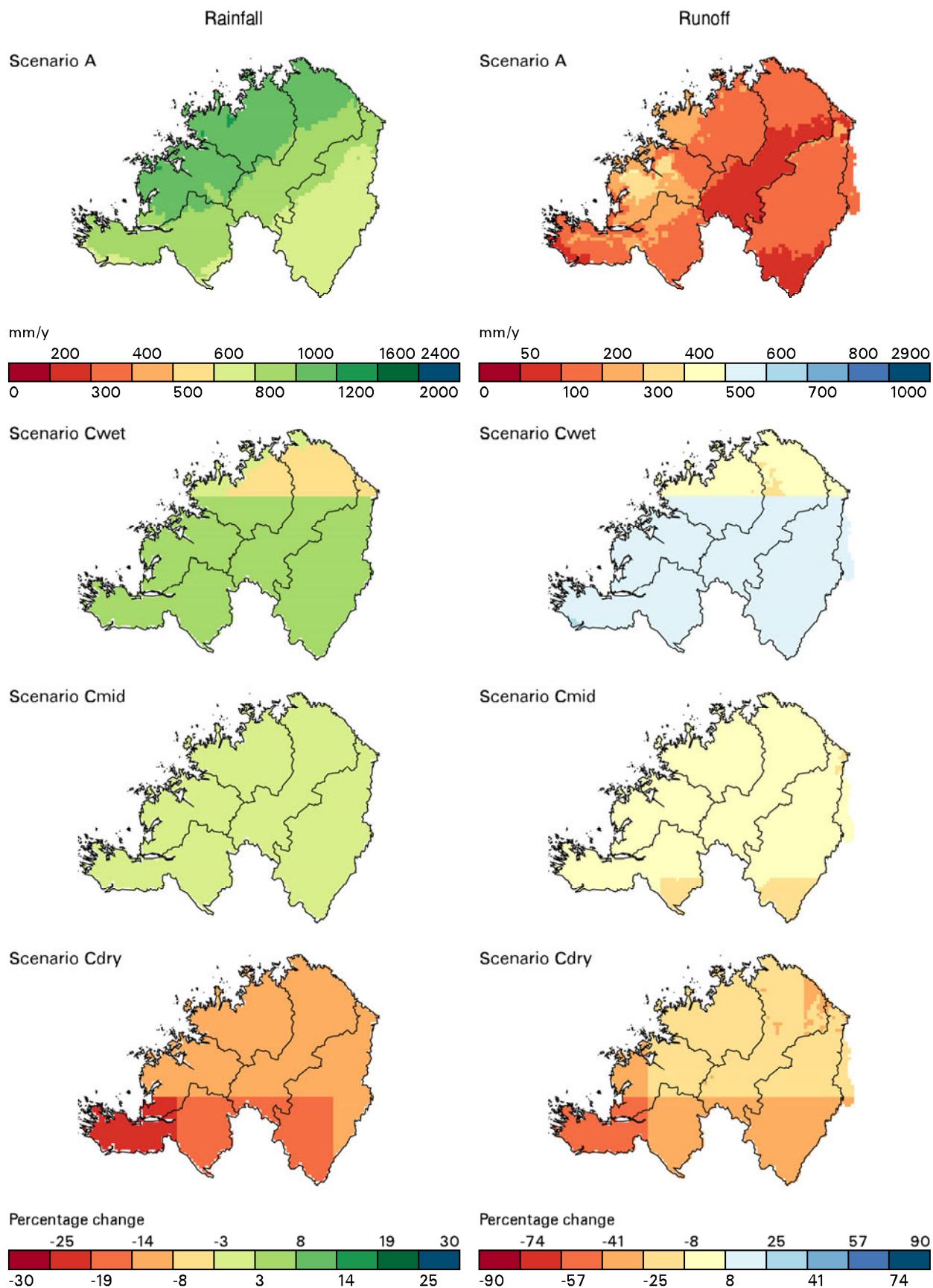


Figure KI-27. Spatial distribution of mean annual rainfall and modelled runoff across the Kimberley region under Scenario A and under Scenario C relative to Scenario A

KI-3.5.6 Summary results for all scenarios

Table KI-7 shows the mean annual rainfall, runoff and actual evapotranspiration under Scenario A averaged over the Kimberley region, and the percentage changes in the rainfall, runoff and actual evapotranspiration under scenarios B and C relative to Scenario A. The Cwet, Cmid and Cdry results are based on the mean annual runoff, and the rainfall changes shown in Table KI-7 are the changes in the mean annual value of the rainfall series used to obtain the runoff under scenarios Cwet, Cmid and Cdry. The changes in mean annual rainfall do not necessarily translate directly to the changes in mean annual runoff because of changes in seasonal and daily rainfall distributions and the relationship between rainfall and runoff is non-linear. The latter factor usually results in small changes in rainfall to be amplified in runoff (Table KI-6).

Figure KI-28 shows the mean monthly rainfall and runoff under scenarios A and C averaged over the 77 years for the region. Figure KI-29 shows the daily rainfall and flow exceedance curves under scenarios A and C averaged over the region. In Figure KI-28 Cmid is selected on a month-by-month basis, while in Figure KI-29 Cmid is selected for every day of the daily flow exceedance curve.

Table KI-7. Water balance over the entire Kimberley region under Scenario A and under scenarios B and C relative to Scenario A

Scenario	Rainfall		Runoff		Evapotranspiration	
		mm		mm		mm
A	936		153		784	
percent change from Scenario A						
B	25%		71%		16%	
Cwet	3%		13%		1%	
Cmid	0%		-1%		0%	
Cdry	-14%		-27%		-11%	

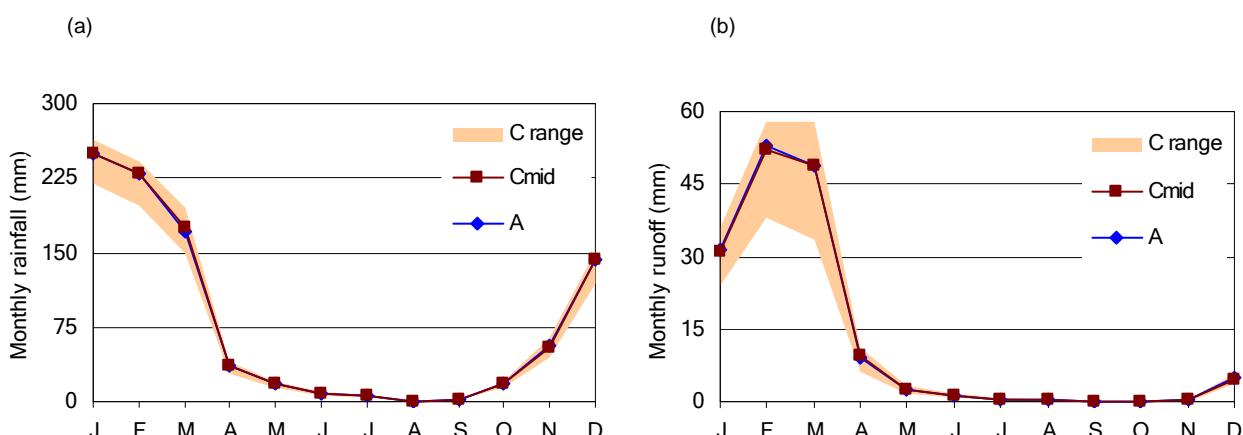


Figure KI-28. Mean monthly (a) rainfall and (b) modelled runoff in the Kimberley region under scenarios A and C. (C range is based on the consideration of each month separately – the lower and upper limits in C range are therefore not the same as scenarios Cdry and Cwet)

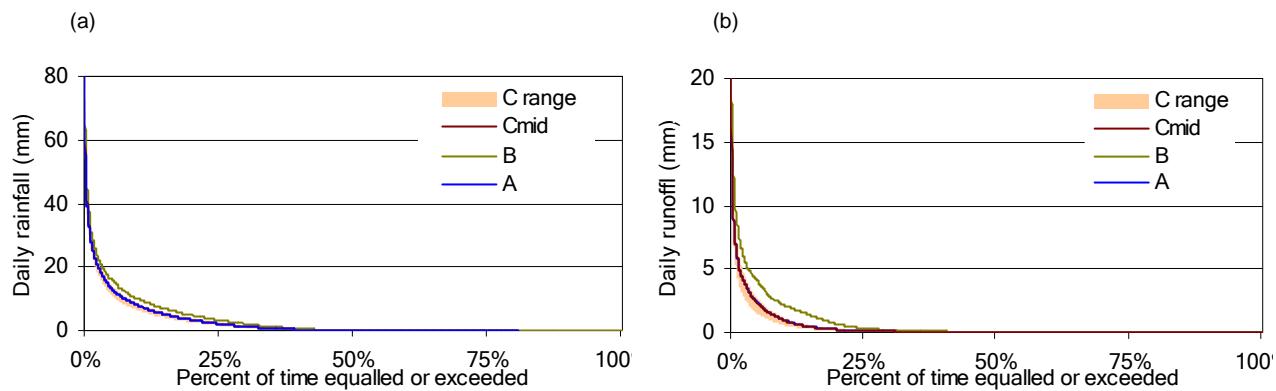


Figure KI-29. Daily flow exceedance curves for (a) rainfall and (b) runoff in the Kimberley region under scenarios A, B and C. (C range is based on the consideration of each month separately – the lower and upper limits in C range are therefore not the same as scenarios Cdry and Cwet)

KI-3.5.7 Confidence levels

The rainfall-runoff model verification analysis with data from 123 catchments from across all of northern Australia indicates that the mean annual runoff for ungauged catchments are under estimated or over estimated, when using optimised parameter values from a nearby catchment, by less than 20 percent in 40 percent of catchments and by less than 50 percent in 80 percent of the catchments. The level of confidence of the runoff estimates in the Kimberley region is varied. Along the coastal fringes of the region the level of confidence in the runoff estimates is low. Transposing parameters sets to the coastal catchments is problematic due to the lack of suitable donor catchments. Diagrams in Petheram et al. (2009) illustrate calibrated rainfall-runoff model parameter sets used to model streamflow in ungauged subcatchments in the Kimberley region. Rainfall stations are sparsely located across the Kimberley region, which contributes to the uncertainty of the rainfall-runoff modelling.

The level of confidence of the runoff estimates are highest in the central Kimberley region where there is a reasonable density of calibration catchments (Figure KI-20). The daily NSE value for Station 807001 is greater than 0.8. However the spatial distribution of runoff for this catchment appears to be different to the rest of the Kimberley region (Figure KI-22). A preliminary investigation by the Western Australia Department of Water suggests that there may be some uncertainty associated with the high end of the rating curve. However regional soil mapping also indicates there are deep sands located within the catchment. Due to the uncertainty associated with the runoff predictions from Station 807001, the high flow level of confidence was penalised two rankings (i.e. level 1 to level 3).

There is a high degree of confidence that dry season runoff in the Kimberley region is low because it is known that rainfall and baseflow are low during the dry season. The level of confidence for dry season flow map shown in Figure KI-30 provides a relative indication of how well dry season metrics, such as cease-to-flow, are simulated. Accurately predicting dry season flows in ungauged catchments in the Kimberley region is difficult as evident by Figure KI-30. There is a moderate level of confidence associated with dry season flows in the calibrated catchments in Kimberley region. A relatively large proportion of streamflow gauging stations have relatively stable low flow rating curves due to the prevalence of rock bar controls in the region.

Figure KI-30 shows the level of confidence in the modelling of the mid- to high runoff events (i.e. peak flows) and dry season runoff (respectively) for the subcatchments of the Kimberley region. It should be noted that these maps of level of confidence are not statistical confidence levels and are intended to only convey a broad reliability of prediction. The level of confidence in streamflow predictions will vary slightly from the level of confidence in runoff predictions shown below and as discussed in Section 2.2.6 of the division-level Chapter 2.

In summary the level of confidence in the long-term average monthly and annual results for the Kimberley region are low relative to other regions. As shown in Figure KI-30 however in many areas of the Kimberley region localised studies will require more detailed analysis than reported here and would most likely require the site to be visited and additional field measurements made.

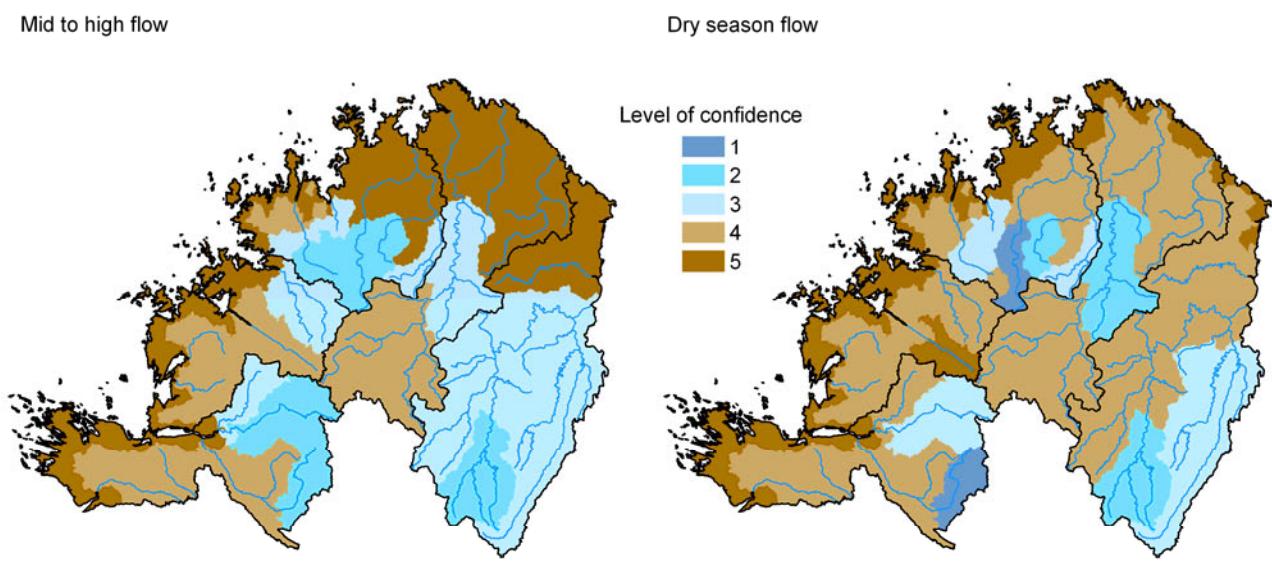


Figure KI-30. Level of confidence in the modelling of runoff for (a) mid- to high flow events and (b) monthly dry season flow events for the modelling subcatchments of the Kimberley region. 1 is the highest level of confidence, 5 is the lowest

KI-3.6 River system water balance

The Kimberley region is comprised of five AWRC river basins and has an area of 109,761 km². Under the historical climate the mean annual runoff across the region is 153 mm (Section KI-3.5.3), which equates to a mean annual streamflow across the region of 16,793 GL.

No information on infrastructure, water demand and water management and sharing rules or future development were available, and consequently there is no river modelling section to the Kimberley region report. Streamflow time series have been generated for each streamflow reporting node (SRN) based on the upstream grid cell rainfall-runoff simulations, as described in Section 2.2.5 of the division-level Chapter 2. The locations of these nodes are shown in Figure KI-31. Summary streamflow statistics for each SRN are reported in Petheram et al. (2009).

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

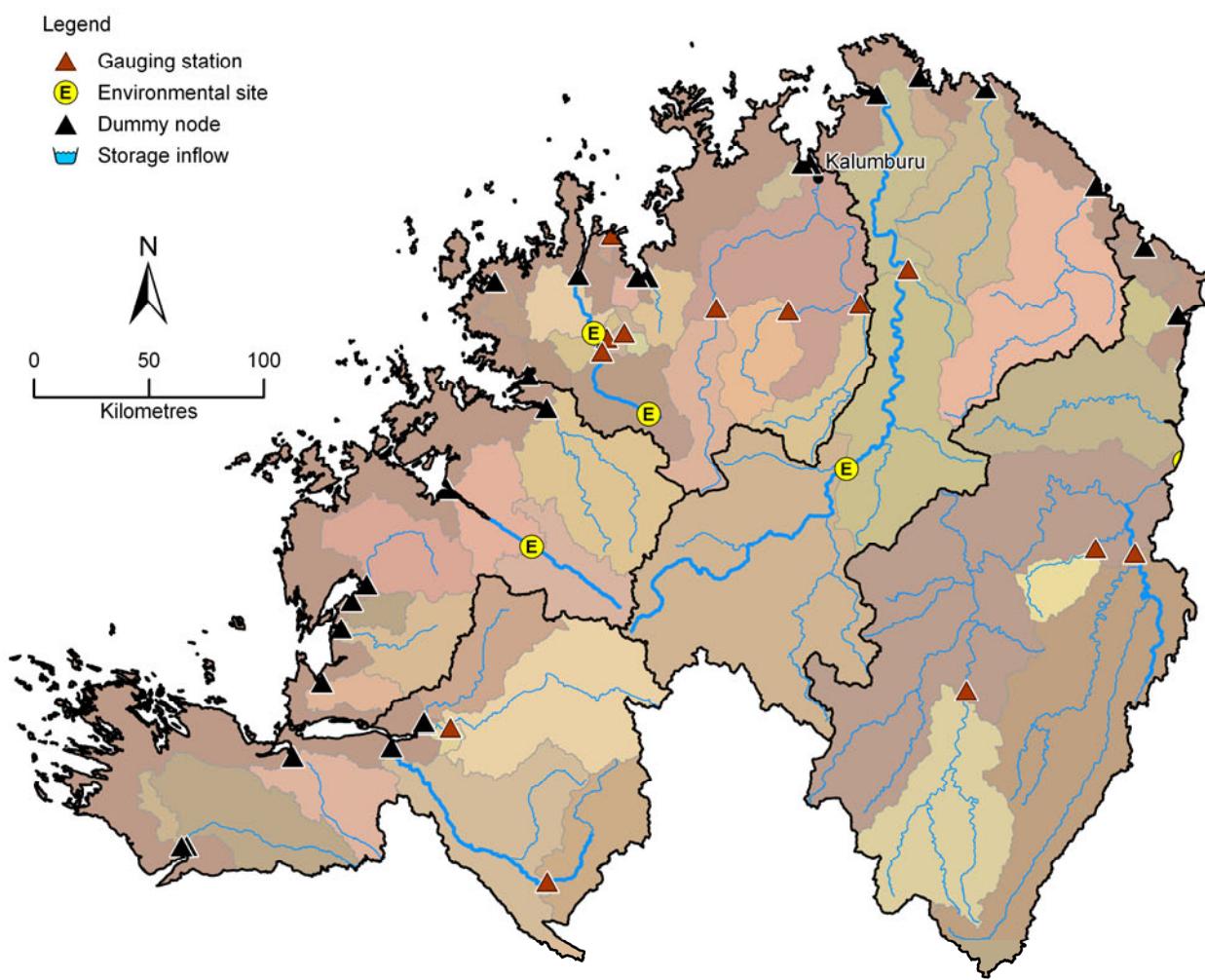


Figure KI-31. Location of streamflow reporting nodes (gauging stations, environmental sites, dummy nodes and storage inflows) in the Kimberley region. (Note there are no storage inflow streamflow reporting nodes in this region)

KI-3.7 Changes to flow regimes at environmental assets

Section 1.3 of the division-level Chapter 1 describes how environmental assets were shortlisted for assessment by this project. Three environmental assets have been shortlisted in the Kimberly region: Drysdale River, Mitchell River System and Prince Regent River System. The locations of these assets are shown in Figure KI-1 and the assets are characterised in Chapter KI-2.

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

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

In the absence of site-specific metrics for the Kimberly region a set of standard metrics related to high 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.

KI-3.7.1 Standard metrics

Table KI-8. Standard metrics for changes to surface water flow regime at environmental assets in the Kimberley region

Standard metrics	Units	A	B	Cwet	Cmid	Cdry	Dwet	Dmid	Ddry
change from Scenario A									
Drysdale River - Node 1 (confidence level: low flow = 3, high flow = 3)									
Annual flow (mean)	GL	667	+77%	+6%	-2%	-27%	nm	nm-	nm-
Wet season flow (mean)*	GL	637	+77%	+5%	-3%	-27%	nm	nm-	nm-
Dry season flow (mean)**	GL	29.8	+67%	+10%	+2%	-39%	nm	nm-	nm-
Low flow threshold (discharge exceeded 90% of the time in Scenario A)	GL/d	0.00012							
Number of days below low flow threshold (mean)	d/y	36.5	-29.8	-2.3	+3	+34.6	nm	nm-	nm-
Number of days of zero flow (mean)	d/y	32.7	-27.7	-2.1	+3	+33.8	nm	nm-	nm-
High flow threshold (discharge exceeded 5% of the time in Scenario A)	GL/d	10.7							
Number of days above high flow threshold (mean)	d/y	18.3	+20	+1.5	-0.7	-6.7	nm	nm-	nm-
Mitchell River System - Node 2 (confidence level: low flow = 3, high flow = 2)									
Annual flow (mean)	GL	382	+69%	+9%	-5%	-23%	nm	nm-	nm-
Wet season flow (mean)*	GL	370	+70%	+9%	-5%	-22%	nm	nm-	nm-
Dry season flow (mean)**	GL	11.9	+34%	+10%	-1%	-33%	nm	nm-	nm-
Low flow threshold (discharge exceeded 90% of the time in Scenario A)	GL/d	0.00774							
Number of days below low flow threshold (mean)	d/y	36.5	-35.2	-3.2	+11.2	+42	nm	nm-	nm-
Number of days of zero flow (mean)	d/y	1.17	+0.2	0	0	+0.3	nm	nm-	nm-
High flow threshold (discharge exceeded 5% of the time in Scenario A)	GL/d	5.55							
Number of days above high flow threshold (mean)	d/y	18.3	+15.2	+1.6	-1.1	-5.8	nm	nm-	nm-

* Wet season covers the six months from November to April.

** Dry season covers the six months from May to October.

NR – metrics not reported because streamflow confidence level is ranked 4 or 5.

nm – not modelled.

Drysdale River

The surface water flow confidence level for the selected reporting node for the Drysdale River (see location on Figure KI-7) is considered moderately reliable (3) for both wet season flows and dry season flows (Table KI-8). Under Scenario A annual flow into this asset is dominated by wet season flows (96 percent) which have been 77 percent higher under Scenario B. Dry season flows have also been 67 percent higher under Scenario B when compared to Scenario A. Annual and seasonal flows do not change much under scenarios Cmid and Cwet compared to Scenario A, but there are large decreases under Scenario Cdry (27 to 39 percent). There are no development scenarios for the area upstream of this asset.

Compared to under Scenario A the number of days when flow is less than the low flow threshold does not change very much under scenarios Cwet and Cmid, but there is a very large increase in low flow days under Scenario Cdry (Table KI-8). A similar pattern is seen in the number of days of zero flow. Under Scenario B the high flow threshold exceedance has been much more frequent than in Scenario A. There is little change in high flow threshold exceedance under scenarios Cmid and Cwet. Under Scenario Cdry there is a large decrease in high flow threshold exceedance from Scenario A.

Mitchell River System (WA)

The surface water flow confidence level for the selected reporting node for the Mitchell River System (WA) (see location on Figure KI-8) is considered fairly reliable (2) for wet season flows and moderately reliable (3) for dry season flows (Table KI-8). Under Scenario A annual flow into this asset is dominated by wet season flows (97 percent) which have been 70 percent higher under Scenario B. Dry season flows have also been 34 percent higher under Scenario B when

compared to Scenario A. Annual and seasonal flows do not change much under scenarios Cmid and Cwet compared to Scenario A, but there are large decreases under Scenario Cdry (22 to 33 percent). There are no development scenarios for the area upstream of this asset.

Compared to under Scenario A the number of days when flow is less than the low flow threshold does not change very much under Scenario Cwet, but there is a large and very large increase in low flow days under scenarios Cmid and Cdry respectively (Table KI-8). A small number of zero flow days were recorded at this asset and this did not change much under any of the scenarios. Under Scenario B the high flow threshold exceedance has been much more frequent than under Scenario A. There is little change in high flow threshold exceedance under scenarios Cmid and Cwet. Under Scenario Cdry there is a large decrease in high flow threshold exceedance from Scenario A.

Prince Regent River System

The surface water flow confidence level for this asset is 4 or 5 for both high flows and lows which is too unreliable to allow environmental flow metrics to be calculated for this asset.

KI-3.8 References

- Crosbie RS, McCallum JL, Walker GR and Chiew FHS (2008) Diffuse groundwater recharge modelling across the Murray-Darling basin. A report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project. CSIRO, Australia. 108pp.
- Crosbie RS, McCallum JL and Harrington GA (2009) Diffuse groundwater recharge modelling across Northern Australia. A report to the Australian Government from the CSIRO Northern Australia Sustainable Yields project, Water for a Healthy Country National Research Flagship. CSIRO, Canberra. *In prep.*
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- SKM (2009) Regionalisation of hydrologic indices. Northern Australia sustainable yields. A report prepared by Sinclair Knight Merz for the CSIRO Northern Australia Sustainable Yields project. SKM, Melbourne. 183pp.
- Zhang L and Dawes W (1998) WAVES - An integrated energy and water balance model. Technical Report No. 31/98, CSIRO Land and Water.

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.