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# Hydrology and Ecological flow thresholds

Chapter 3 contribution to the Northern Australia Water Futures Assessment (NAWFA); "*Assessing the likely impacts of development on aquatic ecological assets in northern Australia*"

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# CHAPTER 3 HYDROLOGY AND ECOLOGICAL FLOW THRESHOLDS

## 3.1 SUMMARY

This Chapter addresses a number of the activities in the NAWFA; '*Assessing the likely impacts of development on aquatic ecological assets in northern Australia*' project. There are five main areas of study reported here;

**1. Review of broad scale surface-groundwater interactions in northern Australia including the Dampier peninsula in Western Australia.**

This desk top review draws mainly from the extensive surface and groundwater studies carried out as part of the CSIRO Northern Australia Sustainable Yields (NASY) project, in particular those covering rainfall-runoff modelling (Petheram et al., 2009b), river modelling (Petheram et al., 2009a), groundwater modelling (Crosbie et al., 2009) and climate scenarios for northern Australia (Li et al., 2009). Additional information from the few detailed studies of surface-groundwater interactions that have been carried out in the Daly and Fitzroy catchments since the NASY project is also included. The key findings are as follows;

a. Groundwater information is very scarce across northern Australia and for most of the region it is therefore only possible to make broad scale assessments of groundwater resources and their recharge by surface drainage. Preliminary estimates of diffuse recharge rates range between <1 mm $yr^{-1}$ and >200 mm $yr^{-1}$; with the lowest rates in the most arid regions with vertisol soils and annual grasses (e.g., much of the Flinders-Leichhardt region), and the highest rates generally associated with wet tropic climates and more permeable soil types.

b. Across northern Australia, typically more than 90% of annual rainfall and runoff occurs during the wet season and during this period groundwater recharge occurs via a combination of diffuse infiltration of rainfall, floodplain inundation and leakage from losing streams and rivers. In the subsequent dry season, river flows recede rapidly and the majority of surface water features cease to flow or even dry completely before the following wet season. There are, however, several iconic perennial rivers in northern Australia that rely on significant groundwater input (up to 50%) through the dry season – notable inclusions are the Daly River and Roper River (NT), the Fitzroy River (WA) and many of the rivers on Cape York peninsula (QLD). Other regions where dry season flows are dependent on groundwater include the Kimberley, Ord-Bonaparte, Arafura, Northern Coral region and the South-West & South-East gulf regions.

c. Potential changes in annual diffuse groundwater recharge due to climate change (relative to modelled historical recharge) are predicted to vary from +39% to -5%. In terms of surface water features that are dependent (to some extent) upon groundwater discharge, the impacts of climate change will be more immediate to those which are fed by shallow, local unconfined aquifers (e.g. the Flinders-Leichhardt, Mitchell and Kimberley regions). Conversely, the impacts of climate change will be delayed for surface water features that are fed by deep, regional aquifers (e.g. the Daly and Fitzroy regions). In some areas with significant levels of current groundwater extraction (e.g. the Darwin Rural Area), despite increases in diffuse recharge under a future climate, groundwater levels are likely to continue to decline and may threaten a number of groundwater dependent ecosystems in the area.

d. Development impacts on groundwater have only been estimated in very few locations. For example, in the Daly catchment with the high degree of interconnection between the Daly River and the adjacent aquifers, the greatest impacts to groundwater resources from increased development will occur in parts of aquifers that are distal to the rivers; that is, groundwater extraction will lead to large drawdown of water levels in the aquifers that cannot be mitigated through increased leakage from the rivers.

e. From the brief review of the groundwater characteristics of the Dampier Peninsula in Western Australia, it is clear that many of the springs in this Peninsula are fed by groundwater and there are several possible mechanisms by which this occurs. Progress in identifying which mechanisms apply to which springs could be made by (i) collating and analysing the disparate groundwater information associated with a number of production and observation bores on the Peninsula and (ii) the collection of water samples from the springs for hydro-chemical identification of the source aquifers.

## KNOWLEDGE GAPS

Despite a broad general knowledge of the locations of significant groundwater discharge to rivers and streams in northern Australia, there are several fundamental knowledge gaps around the nature of interactions in complex geological environments, and how these systems will respond to potential future climate change and increased water resource development. Specific examples that warrant focussed research include:

- mound Spring ecosystems on the Dampier Peninsula;
- ‘rejected recharge’ and artesian springs from the Great Artesian Basin that sustain dry season flows in rivers on Cape York Peninsula; and
- spring-fed rivers in carbonate aquifers of the South East Gulf region.

## 2. Review of the surface water regimes in key Queensland catchments.

The analysis of the surface water regimes in four Queensland catchments (Leichardt, Flinders, Gilbert and Mitchell) is based on the rainfall-runoff modelling (Petheram et al., 2009b) and IQQM river modelling (Petheram et al., 2009a) carried out as part of the NASY project. Climate change scenarios are also from the NASY project (Li et al., 2009), as are the State prescribed water development entitlements for these catchments. The key findings are as follows;

a. The Queensland rivers (Leichardt, Flinders, Gilbert and Mitchell) are highly seasonal and dominated by rainfall and flows that occur during the wet season. These rivers are also prone to flooding in the wet season, but they also have long periods of zero flow in the dry season.

b. The (theoretical) implementation of full use of existing water allocation entitlements in these Queensland rivers will generally increase the number of zero flow days experienced along the river, especially in the Leichardt catchment. However, the impact on high flow threshold exceedence is much smaller, and again the Leichardt catchment appears to be the only one with significant reductions in high flows under development.

c. The greatest impact on river system flows under full development will be felt in the Leichardt River, where abstractions would increase the loss of flow in the river by 43%. The equivalent figures for the other Queensland rivers are; Flinders (11%), Gilbert (5%) and Mitchell (5%).

d. Any climate change in the region will bring additional perturbations to the flow in these rivers and these are summarised in the section below.

KNOWLEDGE GAPS

- Much of the gauged river flow data in northern Australia is too poor in quality or based on too short a duration of observations for accurate discharge estimation, especially at high and low flows (Petheram et al., 2009b). This is why we were unable to provide any reliable flow analysis for the Norman River. Substantial effort is required to (a) sustain and enhance current gauging stations in northern Australia and (b) carry out rigorous flow calibration, particularly at high and low flows.

- The river modelling and climate and development scenarios for Queensland are different from those used in other regions in northern Australia. It is therefore recommended that future modelling of runoff be undertaken using a consistent and robust set of methods and scenarios.
- In Queensland (and other regions in northern Australia) there is no comprehensive information on current levels of actual water use (rather than entitlements and/or permits). Further effort is therefore required to establish what current water use levels are in order to assess current and future ecological impacts.

## 3. Hydro-ecological linkages and how these may be affected by climate change and/or development.

Since the flow requirements for the ecosystems and biota across northern Australia are largely unknown, we used the high ($Q_5$) and low flow ($Q_{90}$) standard metrics method described by McJannet et. al., (2009), for a number of river nodes in a selection of catchments in Western Australia, Northern Territory and Queensland. For each location $Q_5$ and $Q_{90}$ were calculated using historical river flow data and the mean number of days above the historic $Q_{90}$ and below the historic $Q_5$ was then calculated for each of the future climate and/or development scenarios. Where rivers are ephemeral, we also calculated the number of days of zero flow under each scenario. The rates of rise and fall in stream flow are also reported for the wet season months as these could be related to fish migrations, habitat suitability and breeding events. We have also examined how climate and development may impact specific species (e.g. turtles, fish and geese) in the very few places where suitable flow thresholds exist. The key findings of this part of the study were;

a. Stream flow in northern rivers is extremely seasonal with the vast majority (> 90 percent) of total annual flow occurs during the wet season months (November to April). The aquatic ecosystems that are dependent on these river flows are adapted to the prevailing conditions, responding to both wet season high flows and the long dry season low flows.
b. There is a general lack of quantitative relationships between flow and specific ecological flora and fauna in the NAWFA reporting area. As a result the consequence

of flow changes on ecological systems is largely unknown. The few existing site-specific thresholds used here demonstrate the value of such information and resources for development of more of these thresholds and associated relationships are best targeted at areas containing high priority ecological assets that may come under significant development pressure.

c. In the absence of species specific thresholds, standard metrics, derived solely from the river flow regime, provided useful guideline information and have the advantage that they enable comparisons within and between regions. The selected metrics relate mainly to the high and low flow conditions which are important drivers of floodplain and in-stream ecosystem structure and processes in northern Australia.
d. In general, exceedence of high and low flow thresholds in most northern rivers under future climate scenarios are quite large and likely to have a significant impact on associated aquatic biota. The implementation of additional development water entitlements in Queensland can exacerbate the climate impact, but the relatively modest development water requirements reported for NT and WA developments do not usually add much further impact on high and low river flows.
e. For locations where both site specific and standard metrics were available it was found that the standard metrics adequately reflected the directions (and to some degree magnitude) of potential change derived for the site specific metrics.
f. Low flows under dry climate change scenarios are likely to be altered significantly. Some areas are likely to experience considerable increases in the duration of low and zero flows which may have major ecological impacts. Combining climate change with development pressures can exacerbate changes to low flow conditions.
g. Flooding is an important factor that sustains many environmental assets by providing connectivity across the floodplain and facilitating migration. Under dry climate change scenarios flood frequency can be reduced greatly and this may have impacts on provision of habitat and breeding grounds. Under wet climate change conditions flooding may become much more frequent and this could have both positive and negative impacts depending on flow requirements of different species.

KNOWLEDGE GAPS

- Where specific high priority aquatic biota may be at risk from climate change and/or development pressure, studies need to be carried out to quantify the relationship between the species in question and key aspects of the river flow regime that it is dependent on.

- Despite the fact that there are large areas of groundwater dependant ecosystems in northern Australia there are no known locations with quantitative groundwater related ecological metrics. Further monitoring of the interactions between groundwater level and the functioning of ecosystems is therefore recommended. The work described below on dry season pools that are sustained by groundwater is a good example of such monitoring.

- It is also worth noting that any change in river flow is likely to result in changes to water quality including sediment and nutrient loads, water temperature and dissolved oxygen levels. These changes in turn may also affect productivity and habitat quality and as such should be carefully considered in future investigations.

## 4. A remote sensing study of in-stream pools as ecological refugia.

The above species specific low flow thresholds are closely tied with the existence of in-stream pools which form critical refugia for many aquatic biota. An important key to quantifying river flow regime impacts on freshwater ecology is therefore to define the relationship between flow and the formation of in-stream pools. This part of the study therefore examined the application of remotely sensed (LiDAR, LandSat and Ikonos) data to identify stretches of the river which contain breaks and pools, in order to quantify pool size and numbers. We have also looked at whether there are relationships between river flow and pool number and total area as a step towards defining flow thresholds below which aquatic biota may be undesirably impacted. The regions of interest for this low flow and stream pool study are the central reaches of the main river channels in the Fitzroy, Mitchell and Daly catchments where pools are likely to form during the dry season. The key findings of this part of the study are;

a. In the Fitzroy River the preceding wet season affects the rate at which pools form in the early dry season, but the late dry season pool number is insensitive to wet season flow. This implies that groundwater is the primary source of base flow in this river at this time.
b. Both the Fitzroy and Mitchell Rivers show a decline in pool numbers at the end of the dry season. This may be due to the disappearance of small pools which cannot be sustained by groundwater flow at this time.
c. Many more pools form in the Fitzroy and Mitchell rivers than in the Daly River. This is because (i) flows are much lower for longer in the two former rivers and (ii) there is a greater groundwater contribution in the Daly River.

d. Most of the pools in all three rivers analysed are relatively small (~ 200 to 600 m in length) and the number of small pools generally increases as the dry season progresses.
e. There are reasonably good relationships between pool numbers or total pool area and flow, but the relationships are quite different for each river. Some of these relationships may be useful for setting ecologically acceptable low flows, however, additional information on the response of key aquatic biota to pool characteristics is needed to quantify these thresholds.

KNOWLEDGE GAPS

- The accuracy of the pool numbers and size (especially of small pools) determined using the relatively coarse LandSat data (30m) needs to be assessed. This can be done by comparing the LandSat results with those derived using higher resolution imagery (e.g. Ikonos) and/or ground survey.
- The current analysis of the LandSat data gives useful information on the total number of pools in a river reach, however, further analysis is recommended to determine the rates of production and loss of specific pools along a river reach. This will help identify the locations of specific pools that may be of local significance (both ecologically and culturally) as well as confirming whether the loss of small pools occurs throughout the dry season, or only towards the end of it.
- It may also be possible to determine pool (surface) temperatures using LandSat data and it is recommended that this is investigated as a means of assessing how the suitability of pool habitats evolves as the dry season progresses. Additional information on the response of key aquatic biota to pool characteristics (size, depth, temperature) is needed to quantify thresholds above or below which undesirable ecological impacts occur.

## 5. Prediction of flood extent and associated wetland connectivity.

Flood flows provide opportunities for the off-stream floodplain wetlands to be connected with the main channels of floodplain river systems, and these ‘flood pulses’ are thought to be the major determinant of the high biodiversity of floodplains (Junk et al., 1989). This part of the study describes the use of a hydro-dynamic model of the Fitzroy catchment to quantify the timing, frequency and duration of the connectivity of a number (30) of floodplain wetlands and the main river channel. The wetlands ranged in size from 7 to 470ha and were located at distances of 0.6 to 26km form the main Fitzroy River channel. Wetland connectivity is calculated for three floods of different sizes with annual return periods ranging from 1.5, 3 and 14 years. The key findings of this part of the study are;

a. We have demonstrated how a hydrodynamic model can be used to quantify connectivity between floodplain wetlands and the main river channel. This method can be used to derive the timing, duration and frequency of connectivity of a range of wetlands on the floodplain.
b. In the Fitzroy catchment, the duration of wetland connectivity ranges from 1 to 40 days per flood and is not only related to distance from the main river channel, but also the topography between the wetland and river. Some wetlands connect in relatively small and frequent floods and others only connect in much larger, less frequent floods. Wetlands in the lower part of the floodplain tend to have greater connectivity because of the longer duration of inundation in this area.
c. The study provides an overview of the connectivity status for the major wetlands in the Fitzroy floodplain. The information could be useful to future studies on (i) movement and recruitment patterns of fish during floods (ii) wetland habitat characteristics and (iii) biodiversity of individual wetlands.

KNOWLEDGE GAPS

- The current hydro-dynamic flood simulations tend to hold water on the floodplain for longer than is detected at stream gauges or in remotely sensed flood images. Further analysis is therefore needed to see if the fault lies entirely within the hydro-dynamic model and if so, a solution derived.

- Hydro-dynamic models are costly and time consuming to set up and so an alternative method for quantifying wetland connectivity should be investigated. Potential options include the use of remotely sensed flood area and relating this to gauged river flow. This method could be tested in catchments where hydro-dynamic models already exist, e.g. the Fitzroy in Western Australia and the Tully-Murray catchments in Queensland.

- Further information is required on the role of flood pulse connectivity on a number of important ecological responses such as fish migration and recruitment between and within individual wetlands.

## 3.2 INTRODUCTION

### 3.2.1 Aims and objectives

This Chapter reviews the hydrological characteristics of a number of selected catchments in Western Australia, Northern Territory and Queensland that have been identified by the State and Jurisdictions as having important ecological assets that are sustained by surface and/or groundwater regimes. The nominated assets in each State have been listed in section 2.1.2. The approach is to give a broad indication of the surface and ground water regimes across the entire study area and to complement this with more specific hydrological information for a number of catchments where sufficient data exist. Long term historical hydrological regimes are described first and then compared with how they may change under the latest climate change predictions for the region with and without any surface and/or groundwater abstractions associated with State and Jurisdiction prescribed development entitlements. This part of the review draws heavily on the recently published Northern Australia Sustainable Yields (NASY) project reports, in particular those covering rainfall-runoff modelling (Petheram et al., 2009b), river modelling (Petheram et al., 2009a), groundwater modelling (Crosbie et al., 2009) and climate scenarios for northern Australia (Li et al., 2009).

In order to translate changes in hydrological regimes into potential impacts on supported ecological assets the exceedence of high and low flow thresholds was examined under historical and future climate and development scenarios. The approach follows that reported by McJannet et al., (2009) for the whole of northern Australia and uses two forms of analyses. Firstly, in the very few places where flow related metrics (a more general term for thresholds and other facets of the flow regime) for the sustainability of specific aquatic species or ecosystems were known, these ‘site specific’ metrics were used. However, in the vast majority of locations where the flow requirements for ecological assets are largely unknown a set of ‘standard metrics’ that can be derived from the flow data alone were used. Both of these approaches are described in more detail in the methods section.

Many aquatic biota in the region survive the long dry season by using the refugia provided by in-stream pools. This chapter therefore also includes a description of how remote sensing techniques may be used to track the seasonal and inter-annual evolution of pools in major streams. By relating this to flow measured at a nearby river gauge it may be possible to identify flow related ecological thresholds (as in the ELOHA approach) that can be used to estimate how future climate and/or development might influence in-stream pools and the aquatic biota they support. Many of the ecosystems on the floodplain adjacent to the major streams are dependent on flooding. For example, the biological health of floodplain wetlands is highly dependent on their ‘connectivity’ with the main stream and other wetlands (e.g. see Karim et al., (2011)). We will illustrate how hydrological connectivity can be quantified in the Fitzroy catchment and how the connectivity is affected by the frequency, size and duration of flooding.

A summary of the specific Services and Activities, as specified in the Project Plan, addressed in this chapter is given below. Note that other members of the project may also address ecological aspects of these services and activities which will be reported in other Chapters.

- Review of groundwater and surface water regimes under historical conditions (Service 1) and
- Review how groundwater and surface water regimes may change with climate and/or development (Service 2) ;
- Characterise hydrological regimes in terms of a range of groundwater levels and how these levels relate to surface expressions of groundwater (Activity 25);
- Quantify how the timing and rate of rise and fall in groundwater levels (during extended drought or high recharge periods) varies under a range of climate and development scenarios (Activity 31 and 32)
- Quantify the timing and rate of rise and fall in flow rates at critical times of the season varies under a range of climate and development scenarios. (Activity 31 and 32).
- Modelling of hydrological regimes, such as extent and duration of flooding and how this relates to main channel water levels. (Activities 20-24).
- Map the spatial distribution of permanent pools in ephemeral streams and other refugia and, using climate change and potential development scenarios, make predictions about the future distribution of pools/refugia (Service 3 & Activity 11);
- Assess the current level of pool connectivity for key biota and predict, given the likelihood of increased fragmentation due to climate change or impacts from alternate development scenarios (including cumulative impacts), the potential viability of ecological systems associated with permanent pools/ refugia (Service 3);

### 3.2.2 Hydrological and geomorphological characteristics of the study area

Figure 3.1 shows a map of the 1.25 million km$^2$ study region, which includes Australia’s Timor Sea, Gulf of Carpentaria and the most northern section of the North-East Coast Drainage Divisions. The region comprises 64 surface water management areas (also referred to as river basins) as defined by the Australian Water Resources Council (AWRC). Across northern Australia there is a low density of hydrological data. For example, there is less than one operational rainfall gauge per 2000 km$^2$, less than one stream flow gauge per

7000 $km^2$ (Petheram et al., 2009b), and less than 10 percent of the region's soils have been mapped at a scale finer than 1:100,000 (Petheram and Bristow, 2008).

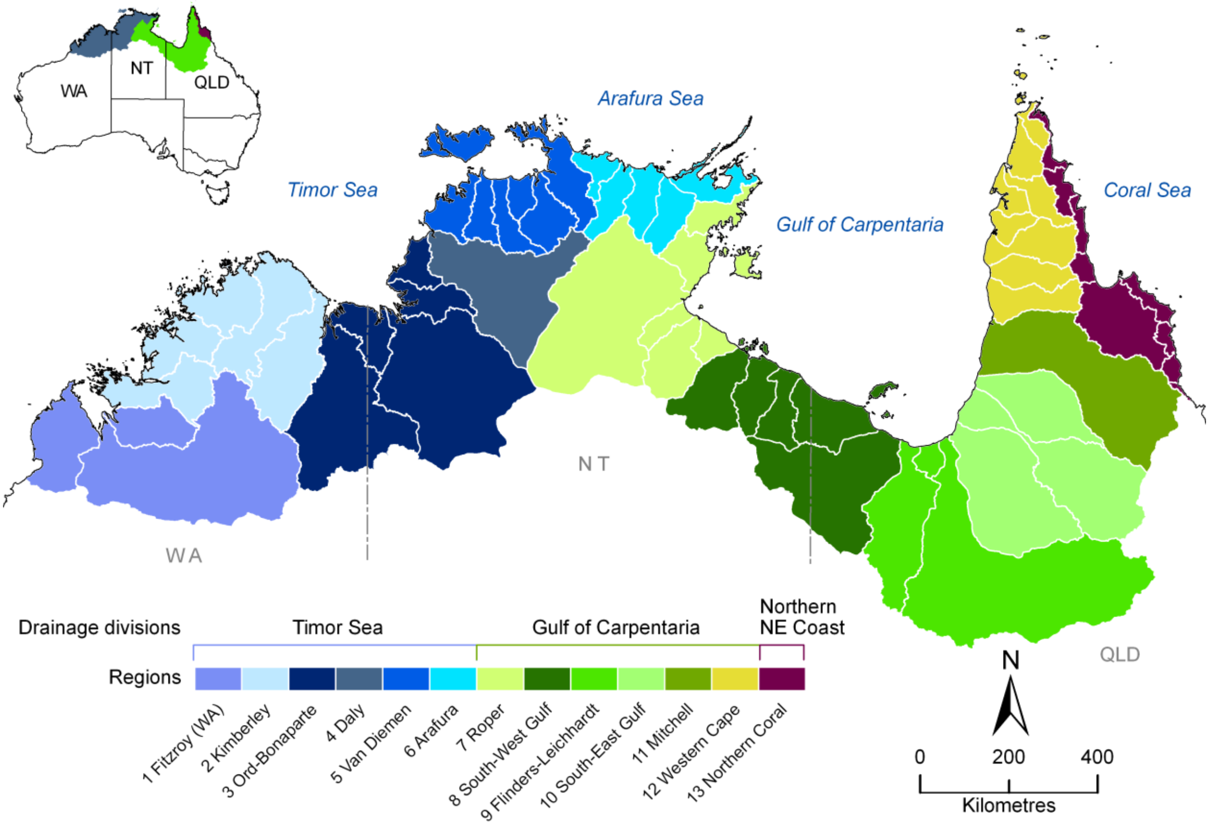



**Figure 3.1. The surface water river basins, regions and drainage divisions (inset) as used in the Northern Australia Sustainable Yields (NASY) project (reproduced from CSIRO (2009b)).**

The drainage divisions of northern Australia are underlain by a number of groundwater basins, which interact with the surface water systems, variously receiving water from and supply water to them (Figure 3.2). The NASY project also assessed those basins and their aquifers, together with those aquifers which may deliver water within the region (Crosbie et al., 2009). Further details of the relevant parts of this report are summarised in section 3.4.1.1.

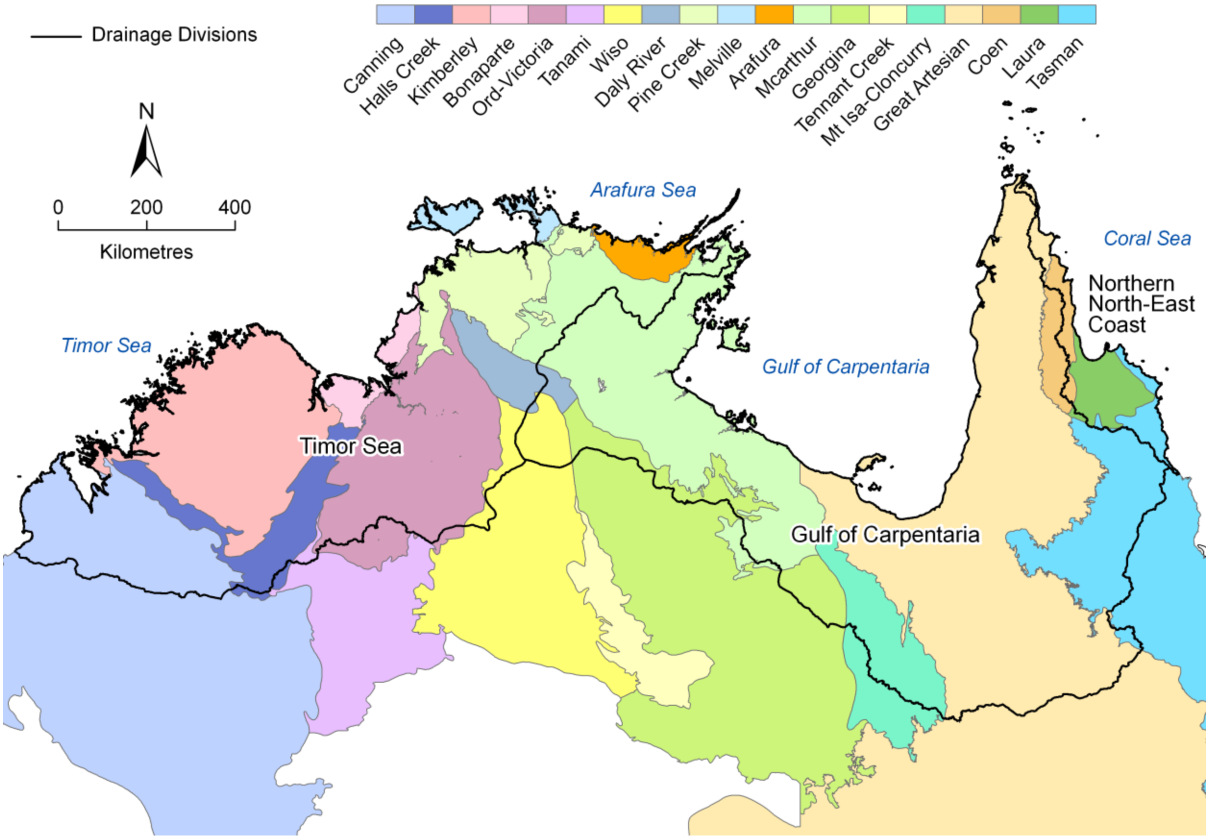



**Figure 3.2. Extents of groundwater basins that (at least in part) underlie the drainage divisions of northern Australia that were used in the Northern Australia Sustainable Yields (NASY) project (reproduced from CSIRO (2009b)). Note: Only the north-flowing region of the Great Artesian Basin was considered in the NASY project**

### 3.2.3 Geomorphology

The northern Australian landscape is generally of low relief by world standards, though outcropping bedrock ranges represent areas of regional rugged topography. These outcropping ranges include the Kimberley Ranges in the west, the Arnhem Land plateau and Barkly Tablelands in the Northern Territory and in the east, the Great Dividing Range. Rivers in the central to western regions are generally bedrock controlled in profile and flanked by discontinuous floodplains. Rivers draining to the Gulf of Carpentaria are flanked by extensive alluvial plains, generally relict floodplains of Tertiary to Quaternary age. Very low gradients of 1:50,000 often prevail for 180 km inland along some Gulf rivers. Along Cape York Peninsula these alluvial plains gradually grade to the Great Dividing Range. To the east of the Great Dividing Range (i.e. the northern North-East Coast Drainage Division) steep coastal escarpments abut a narrow coastal plain and the rivers tend to be much shorter and steeper than those found elsewhere across northern Australia.

The rocks and regolith of northern Australia can be categorised into the four broad groups outlined below, based upon their permeability and discharge characteristics, which in turn affect the pereniality of surface runoff (Petheram and Bristow, 2008).

i. Crystalline rocks and Palaeozoic and older sedimentary material, which underlie much of northern Australia and tend to have negligible primary porosity and groundwater discharge to streams from these formations is usually small and highly localised.

ii. Early to Middle Palaeozoic carbonate rocks, which generate the largest dry season baseflows (e.g. Daly, Roper, Nicolson and Gregory Rivers). These rocks are characterised by dissolution cavities near the watertable and primary porosity due to dolomitic recrystalisation.

iii. Cretaceous sandstones in the Northern Territory (e.g. Arnhem Land, Bathurst and Melville Islands), which also discharge variable quantities of groundwater to perennial streams. In the southern parts of the Gulf of Carpentaria, spring discharge occurs from the Carpentaria Basin, although these do not sustain large dry season flows (CSIRO, 2009a);

iv. Quaternary sedimentary aquifers, which tend to be local to intermediate in scale. Perhaps the primary Quaternary systems of note in northern Australia are the Quaternary sands of the Jardine River region, which in part sustain large dry season baseflows (Horn et al., 1995).

### 3.2.4 Climate and river flow

Northern Australia’s climate is characterised by highly seasonal, summer-dominated rainfall, high temperatures and high evaporation rates. A large proportion of the study area is considered to be water limited at an annual scale (Li et al., 2009). Mean annual rainfall varies across the region by more than an order of magnitude, from about 400 mm year$^{-1}$ south of the Gulf of Carpentaria, to over 4000 mm year$^{-1}$ on the steep coastal escarpments in the North-East Coast Drainage Division (Figure 3.3). Northern Australia has an orientation that is longitudinal in extent. More than 90 percent of rain falls between December and March (Li et al., 2009) as the inter-tropical convergence zone passes over the northern extent of the continent. Rainfall is primarily generated by local and organised convection, tropical cyclones or tropical depressions. The wet season has been defined by Petheram et al., (2009b) as running from November to April, and the water year from September to the August. Orographic uplift amidst the north east coast division results in high rainfall totals during the wet season and initiates some additional dry season rainfall for this region. Inter-annual variability of mean annual rainfall is approximately 30 percent higher than in other parts of the world of the same climate type (Petheram et al., 2008).

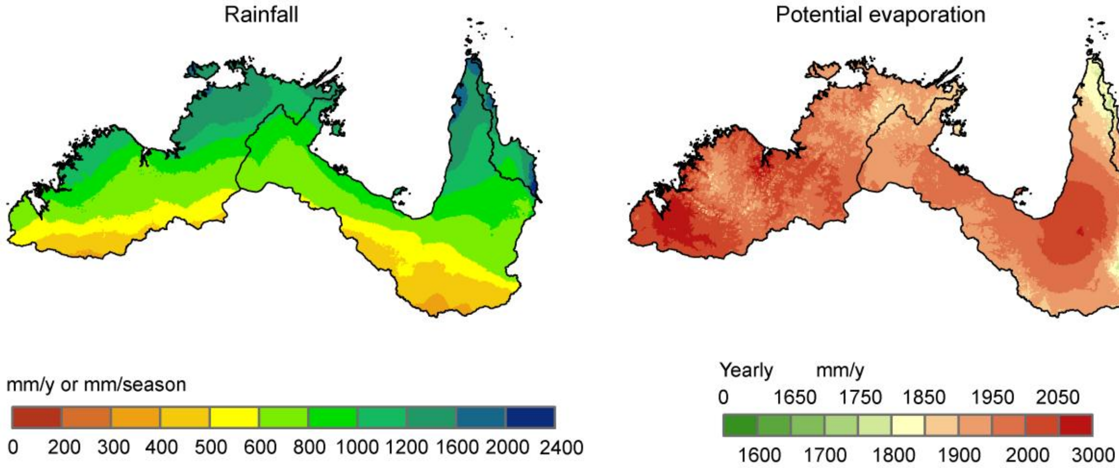



**Figure 3.3. Rainfall and potential evaporation map of northern Australia (data sourced from Li et al. (2009))**

All of the rivers considered by Petheram et al., (2009b) are externally draining and are 'gaining systems' on an annual scale, because rainfall increases coastwards. Stream flow in northern Australia is considerably more seasonal and has a higher inter-annual variability, than do other world rivers of the same climate type (Petheram et al., 2008) and many of the rivers in the region have a base flow index (BFI) < 0.3 (Petheram et al., 2008). Anthropogenic factors that confound prediction in ungauged systems elsewhere, such as river regulation, groundwater and surface water extraction and large scale land use change (e.g. clearing or forestry), are minimal in northern Australia. For example, few rivers in the region are regulated (CSIRO, 2009a; 2009b; 2009c) and northern Australia boasts the largest intact tracts of tropical savanna in the world.

### 3.2.5 Climate change scenarios

The climate change scenarios used here to assess impacts on surface and groundwater regimes are those derived by Li et al., (2009) in the NASY project. Three of the NASY scenarios were used in this project;

- historical (1930 to 2007) climate and current development (Scenario A)
- future (~2030) climate and current development (Scenario C)

- future (~2030) climate and future (~2030) development of farm dams, plantations, groundwater systems and proposed irrigation development (Scenario D).

The methods used to generate the required climate data for Scenarios A, C and D is briefly described below). For a detailed description of development of these climate scenarios see Li et al. (2009).

#### 3.2.5.1 Scenario A: historical climate

Daily climate data from 1 September 1930 to 31 August 2007 at 0.05 x 0.05 degree (~ 5 x 5 km) grid cells across the region were extracted from the SILO database (http://www.longpaddock.qld.gov.au/silo/). As rainfall in northern Australia is highly variable in space and time, due to the processes governing tropical cyclones and local thunderstorms, their interpolation was carried out using the kriging approach described by Jeffrey (2006), who also carried out the interpolation methods of other climate variables (e.g. temperature, humidity; (Jeffrey et al., 2001). In addition to daily rainfall data, the rainfall-runoff models used in the NASY project also require areal potential evapotranspiration (APET) so Morton's wet environment APET (Chiew and Leahy, 2003; Morton, 1983) was calculated for a daily time step at 0.05 x 0.05 degree resolution using SILO data (temperature; relative humidity and incoming solar radiation).

In the Queensland catchments Scenario A was derived slightly differently because of the river modelling approach that was used. To describe the current surface hydrological conditions in these catchments we report two of the scenarios analysed in the NASY project, Scenario A* and Scenario AN. In the Queensland catchments, Scenario A* represents historical climate and full use of existing entitlements, and Scenario AN uses historical climate without any development at all (i.e. no groundwater extraction or water storages). The current level of water use in these catchments is somewhere between no use of water entitlements and full use of water entitlements. The Queensland scenarios are described in more detail in Section 3.4.2.16.1.

#### 3.2.5.2 Scenario C: future climate

The future climate scenario provides estimates of possible conditions around the year 2030 under three different potential global warming scenarios based on projected high, median and low greenhouse gas emissions. These three scenarios are inferred from the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC, 2007) and the latest climate change projections for Australia (CSIRO and Bureau of Meteorology, 2007). The future climate scenarios were derived by scaling the climate data from 1 September 1930 to 31 August 2007 to represent the climate around 2030, based on analyses of 15 global climate models (GCMs) under three global warming scenarios. Thus, 45 future climate variants, each with 77 years of daily climate sequences for 0.05 x 0.05 degree grid cells across the region, were used for the rainfall-runoff modelling and associated ecological impact assessment.

In Western Australia and Northern Territory Scenario C includes future climate and current development of water resources. In the Queensland catchments Scenario C differs in that it includes future climate and no development of water resources. The Queensland scenarios are described in more detail in Section 3.4.2.16.1.

#### 3.2.5.3 Scenario D: future climate with development

This scenario uses the same climate data as in Scenario C, but adds the surface flow impacts of any proposed development of farm dams, plantations, groundwater systems and irrigation development. As in Queensland, where future development water entitlements are specified they are applied in full in this scenario.

### 3.2.6 Development scenarios

Future water abstractions and use for hydropower, agriculture, mining and town water supplies were specified by the jurisdictions and are summarised in the NASY river modelling report by Petheram et al., (2009a). In Queensland the IQQM river system models were setup assuming a full use of existing entitlements. Full use of existing entitlements refers to the total entitlements within a plan area including existing water authorisations and unallocated reserves. This refers to the water accounted for in the draft Gulf Resource Operations Plan, but the licences are interim or not allocated as yet. Current levels of usage (i.e. 2009) in the IQQM catchments are unknown. Hence for the IQQM river system modelling catchments Scenario A* refers to the full use of existing entitlements under the historical climate. Scenario D refers to the full use of existing entitlements under a future climate for Queensland and all other catchments.

## 3.3 METHODS

### 3.3.1 General methodological approach

Hydrological analysis in the NAWFA project has used the same approach as that used in the NASY project which is the most comprehensive assessment of surface water and groundwater resources of northern Australia that has been undertaken to date. The methodology is well suited to the NAWFA project and is described below.

Given the vast size of the northern Australian region and the general paucity of reliable rainfall, river flow and groundwater data a two tier approach was taken in the NASY project to the assessment of the key hydrological variables that are most closely associated with important ecological assets. Across the entire region broad scale assessments were made using simple conceptual models where the results obtained are relative or semi-quantitative at best. At this scale it is not possible to make accurate predictions for specific river reaches, local aquifers or the biota that they support. However, in a few places where more detailed hydrological and ecological information exist, we have performed analyses at a more specific and detailed scale. These results are much more useful for managing river flows in order to sustain important biota. These few examples also serve to illustrate the level of information that is required for this purpose.

#### 3.3.1.1 Groundwater regimes (Service 1)

The groundwater assessment and modelling component of the NASY project (Crosbie et al., 2009; CSIRO, 2009a; 2009b; 2009c) has collated existing data to report on the occurrence, status and possible future condition of groundwater resources across the three Drainage Divisions of the Northern Australia. Across all regions there has been a broad scale assessment of current and future levels of groundwater allocations and use, the derivation of a conceptual groundwater recharge-flow-discharge model, and a detailed analysis of groundwater recharge rates under historical, recent and future climates (Crosbie et al., 2009).

Quantitative groundwater modelling in the NASY project was only possible in the Daly region, the Fitzroy (WA) region and a very small part of the Van Diemen region, due to limited data and lack of groundwater models for the remaining regions and Drainage Divisions in northern Australia. The only region in the NASY reporting area where a detailed groundwater model was available in proximity to environmental assets was the Daly region.

The Daly region is represented with an existing, calibrated, regional-scale, FEFLOW numerical groundwater flow model coupled to a calibrated MIKE11 surface water model (Knapton, 2006). The input to the MIKE11 model is via the NAM rainfall-runoff module which generates runoff discharges based on climatic data. The recharge input to the FEFLOW was generated using the WAVES model. Surface–groundwater interaction along the rivers occurs where the MIKE11 model is joined to the FEFLOW model. Input climatic data are consistent for both the NAM and WAVES models. The coupled model has enabled quantitative assessment of the impacts of climate change and current and future development through implementation of the three scenarios (scenarios A, C and D) as well as an addition scenario B, which represents the surface and groundwater regimes under the recent climate between 1996 and 2007. Modelling of the interaction between surface and groundwater is discussed in more detail in Crosbie et al., 2009 and CSIRO (2009a; 2009b; 2009c).

#### 3.3.1.2 Surface water regimes (Service 1)

The surface water assessments made in the NASY project involved a number of separate tasks, including:

- rainfall-runoff modelling at the regional scale under scenarios A, B and C
- river system modelling
- assessment of regions without river models
- evaluation of levels of confidence

Petheram et al., (2009b) tested five different rainfall-runoff models and found that an ensemble of Sacramento (Burnash et al., 1973) and IhacresClassic (Croke et al., 2006) was the optimal combination of models for runoff estimation in northern Australian catchments. This combination balanced model performance with the practicalities of running multiple rainfall-runoff models at a 5 x 5 km grid cell scale across an area of 1.25 million km$^2$ in a short space of time. The Sacramento and IhacresClassic models were used to extend stream flow records at existing gauging station locations and to simulate runoff at each 0.05 degree grid cell over the entire region under each scenario.

For rainfall-runoff modelling, the Nash-Sutcliffe (Nash and Sutcliffe, 1970) metrics provide a direct measure of the level of confidence in runoff prediction. These metrics were computed for every catchment that contained a river gauge and transposed to the many ungauged catchments multiple cross-verification simulations (Petheram et al., 2009b). Since rainfall-runoff models are biased in their calibration to a particular range of flows, usually the mid-to high flows (i.e. peak flow events), the level of confidence for the high and low flow predictions were estimated separately. Levels of confidence in high and low flow prediction were expressed on a scale of 1 through 5; with 1 representing results with the highest confidence and 5 representing the most unreliable results. Details are provided in Petheram et al. (2009b).

Wherever jurisdictions have developed river system models, these were used within the NASY project (Petheram et al., 2009a). These models encapsulate descriptions of current infrastructure, water demands and water management and sharing rules and can be used to assess the implications of the changes in inflows given by the rainfall-runoff simulations on the reliability of water supply to users. They may also be used to support water management planning by assessing the trade-offs between supplies to various competing categories of users.

#### 3.3.1.3 High and low flow metrics

In a study of the potential impact of climate and development changes on stream flow at selected environmental assets across northern Australia, McJannet et al., (2009) reported that the flow requirements for the ecosystems and biota in this region are largely unknown. They also identified a few locations, such as the Daly River (see Erskine et al., 2003) the Fitzroy River (see Morgan et al., 2005) and the Ord River (Braimbridge and Malseed, 2007; Trayler et al., 2006) where sufficient environmental flow information has been collected to allow site specific flow metrics to be derived and used to assess the potential impacts of climate change and development. For environmental assets where there is little or no quantitative information, McJannet et al., (2009) derived a set of standard metrics for high and low flow regime change which were used to assess the potential impacts of future climate and development scenarios. The use of standard metrics for all environmental assets provides a consistent means for cross regional comparison.

A number of metrics have been reported in the literature that are associated with ecologically significant low flows in a river (Kennard et al., 2010; Nathan and McMahon, 1992; Olden and Poff, 2003). One of the most commonly used metrics is the flow that is exceeded for 90 percent of the time, $Q_{90}$ (Gordon et al., 1992). A schematic diagram of the flow duration curve from which $Q_{90}$ is derived is shown in Figure 3.4.

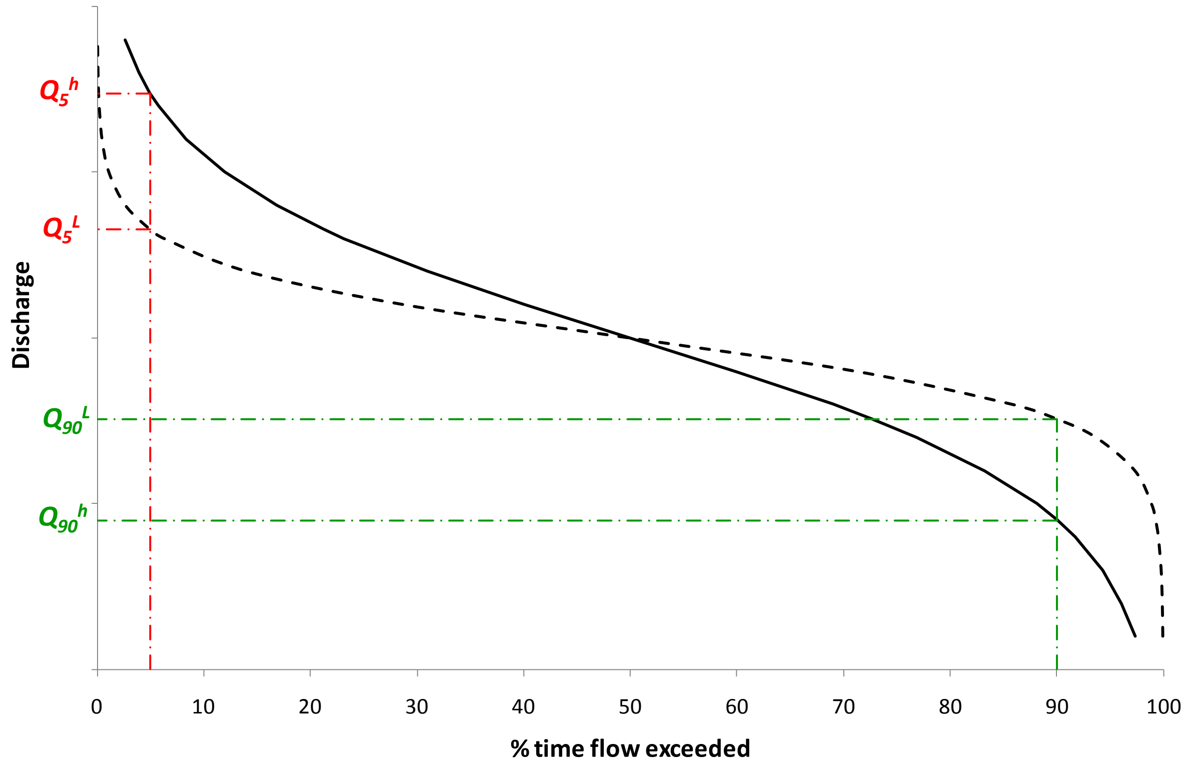



**Figure 3.4. Idealised examples of the flow duration curves for a high (solid line) and low (dotted line) variability rivers. The low flow threshold $Q_{90}$ and high flow threshold $Q_5$ are shown for both river types.**

Since many of the floodplain wetlands of northern Australia require flood or high level flows to facilitate connectivity with other water bodies, it is necessary to have another metric to assess the change to the high flow regime at important environmental assets locations. Since the flow above which floodplains commence inundation is not known for most of the asset locations, it is therefore necessary to use some other metric of high flow as a surrogate. Other studies have used high flow metrics based on flows exceeded between 10 and 1 percent of the time (Kennard et al., 2010; Olden and Poff, 2003) and McJannet et. al., (2009) opted for the flow exceeded 5 percent of the time ($Q_5$) in their analyses of a range of environmental assets across northern Australia. The derivation of $Q_5$ is also shown diagrammatically in Figure 3.4.

In this study we have used the high ($Q_5$) and low flow ($Q_{90}$) standard metrics method described by McJannet et. al., (2009) and these were calculated using historical (Scenario A or AN for Queensland) river flow data for a number of river nodes in a selection of catchments in Western Australia, Northern Territory and Queensland. The mean number of days above the historic $Q_{90}$ and below the historic $Q_5$ was then calculated for each of the other scenarios. It has been noted by Petheram et al. (2008) that for many of the streams of northern Australia the value of the low flow metric ($Q_{90}$) is zero, therefore it is best suited to rivers where flow is perennial. In streams that cease to flow a more suitable metric is the mean number of days per year with zero flow. The number and mean duration of events above the high flow threshold and below the low flow threshold are also reported. The duration of high and low flow events is reported to be an important driver of ecosystem structure and processes in northern Australia (Warfe et al., 2011). The rates of rise and fall in stream flow are also reported for the wet season months as these could be related to fish migrations, habitat suitability and breeding events (Mallen-Cooper and Stuart, 2003).

The final and most general metrics used are changes to the mean annual flow, wet season (November to April) flow and dry season (May to October) flow. These metrics along with those described above give a good indication of the direction of changes to the hydrological regime under the given scenarios.

The above low and high flow metrics are summarised as:

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

All of the time series analysis for the standard flow metrics was undertaken using the River Analysis Package (RAP) which is described by Marsh (2004). This software is available free of charge from the eWater CRC.

#### 3.3.1.4 In-steam pools as ecological refugia (Service 3)

##### 3.3.1.4.1 Introduction

There is a broad concern and a wide literature on the subject of how river flow regimes support important aquatic biota. The flow-biota interaction occurs at all flows, but is arguably the most sensitive at the high and low flow ends of the flow regime. The relationship between high (flood) flows and floodplain connectivity is described in sections 3.3.1.5 (methods) and 3.4.2.18 (results) and this section concentrates on the way that low flows interact with aquatic biota. Several approaches have been used, e.g. 'ecologically acceptable low flows' (Acreman, 2005), where low flow levels are identified below which there are thought to be unacceptable ecological impacts. In the USA and Australia, the ELOHA (Ecological Limits of Hydrologic Alteration) approach has been favoured because of its scientific basis (Arthington et al., 2006) and the existence of practical application guidelines (Poff et al., 2010). ELOHA has several components including the establishment of '*baseline*' hydrological conditions and "*determining the flow-ecology relationships that quantify biological responses to different degrees of hydrological alteration*..." The former is relatively straight forward using well established hydrological analyses techniques provided suitable river flow data exist. The latter is much more challenging and there are very few combined ecological-hydrological studies that have established reliable flow-ecology relationships that quantify specific low flow thresholds or other such metrics. Some examples of these relationships and associate thresholds for the Daly River in Northern Territory are described in the following section.

##### 3.3.1.4.2 Flow-ecology relationships from the Daly River

Two major reports summarise the identification of water dependent ecosystems in the Daly River catchment and the future risks to them (Begg et al., 2001; Erskine et al., 2004). The first report (Begg et al., 2001) provides a detailed classification and inventory of water dependent ecosystems (i.e. wetlands) along with estimates of future water demands associated with the local Land Use Concept Plan. These two data sets are combined in a spatially explicit GIS to derive future potential impacts on wetlands. Of more relevance to environmental assets supported by dry season flows, the report by Erskine et al. (2003) and its update Erskine et al. (2004) summarise the results from five projects within the National River Health Environmental Flow Initiative. Four of these projects provide quantitative data on the relationship between important aquatic biota and flow that can be used in the ELOHA approach:

- Modelling Dry-season flows and predicting the impact of water extraction on a flagship species - the pig-nosed turtle (*Carettochelys insculpta*);
- Environmental water requirements of *Vallisneria nana* in the Daly River, Northern Territory;
- Tree water use and sources of transpired water in riparian vegetation along the Daly River, Northern Territory
- Periphyton and phytoplankton response to reduced dry season flows in the Daly River.

The aim of these projects was to provide recommendations on environmental flows consistent with maintaining the biota and wider ecosystem values of the Daly River. The ecology-flow relationships and associated thresholds for each of these four studies are briefly described below.

**a) Modelling dry-season flows and predicting the impact of water extraction on a flagship species — the pig-nosed turtle (*Carettochelys insculpta*).**

The work by Georges et al. (2002) reported in Erskine et al. (2003) gives data for the success of turtle nesting and their main food source, the aquatic macrophyte *Vallisneria nana.* Turtle nesting success and *V. nana* bed occurrence are related to the Daly river flow at the Dorisvale gauge ($Q_D$) and the graphs below were constructed from values reported in Erskine et al. (2003). Figure 3.5 shows that turtle nesting success declines below 100% when $Q_D$ falls below 7.6 m$^3$ s$^{-1}$.

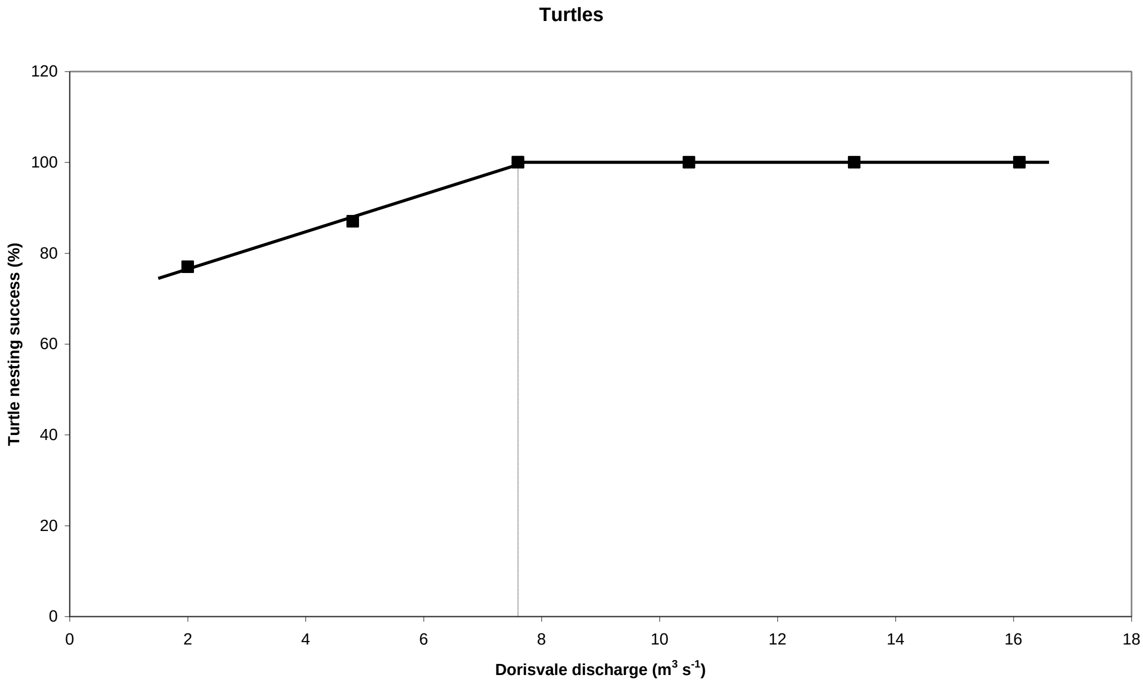



**Figure 3.5 The relationship between pig-nosed turtle (*Carettochelys insculpta*) breeding success and flow at the Dorisvale gauge on the Daly middle reaches.**

### b) Environmental water requirements of *Vallisneria nana* in the Daly River, Northern Territory

*Vallisneria nana* is an aquatic macrophyte that forms a key habitat and food source for many turtle and fish species. It is the dominant macrophyte in the Daly River and its growth is dependent on flow; too low and its exposure to air is fatal, too high and it can be washed away. Rea et al. (2002) have used a hydrodynamic model to predict the optimum flow conditions for *Vallisneria nana* and report that below 10 $m^3 s^{-1}$ there is a sudden decrease in the habitat availability for this plant. A flow of ~ 12 $m^3 s^{-1}$ (at the Oolloo crossing river gauge) is reported as 'the inflection point on the response curve for % exposure and depth preference of *Vallisneria nana*'.

It is also possible to construct a flow-macrophyte abundance relationship form the data reported by Erskine et al. (2003). Their observations of the decline in pool numbers as flow decreased during the dry season are shown in Figure 3.6.

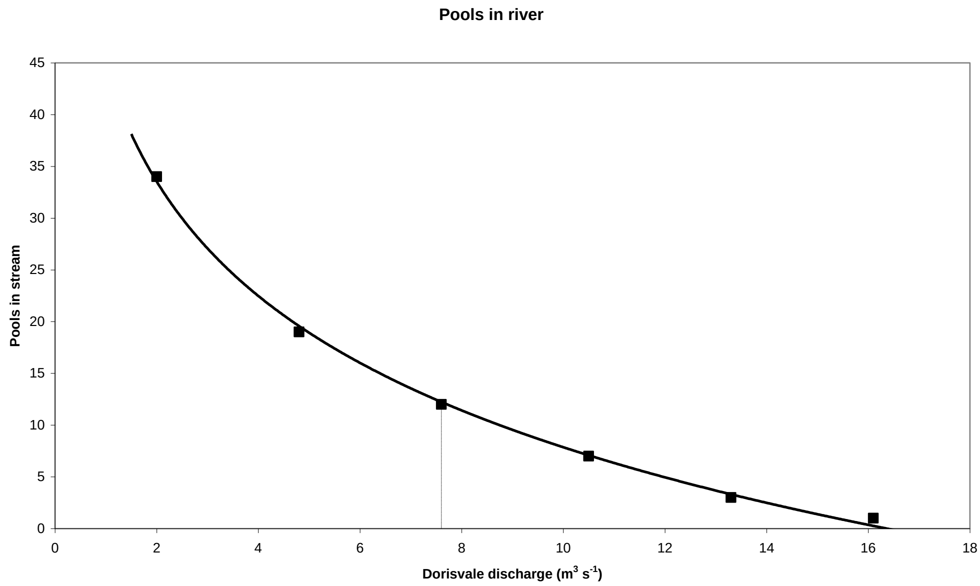



**Figure 3.6 The increase in the number of pools in the Daly middle reaches as flow at the Dorisvale gauge decreases.**

This relationship does not show any clear threshold, but Erskine et al. (2003) also reported the number of *V. nana* beds per pool, which is plotted in Figure 3.7. This shows a clear threshold around 11 $m^3\ s^{-1}$, below which the number of macrophyte beds per pool sharply declines.

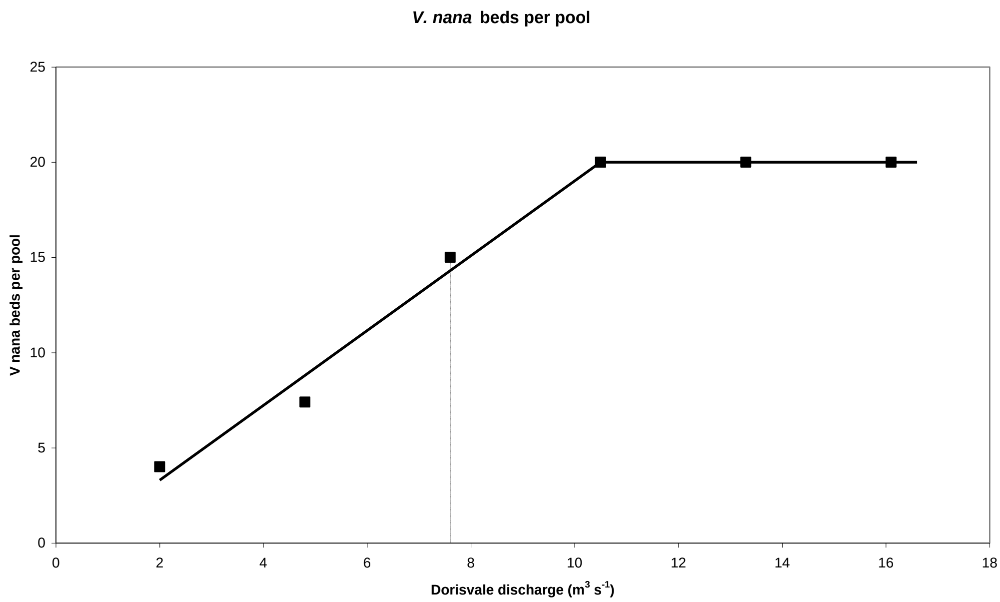



**Figure 3.7 The number of *Vallisneria nana* beds per pool in the Daly middle reaches as a function of flow at the Dorisvale gauge.**

By taking the product of *V. nana* beds per pool and pool numbers we can construct the relationship between the total number of *V. nana* beds and flow, and this is shown in Figure 3.8. This shows that there is an optimum flow around 7.6 $m^3$ $s^{-1}$, so both turtle nesting success and availability of their main food source (*V. nana*) therefore appear to be optimal at the same river flow (7.6 $m^3$ $s^{-1}$). The impacts of climate and/or development on turtles and macrophytes can now be quantified using this threshold and this is described in section 3.4.2.16.3.

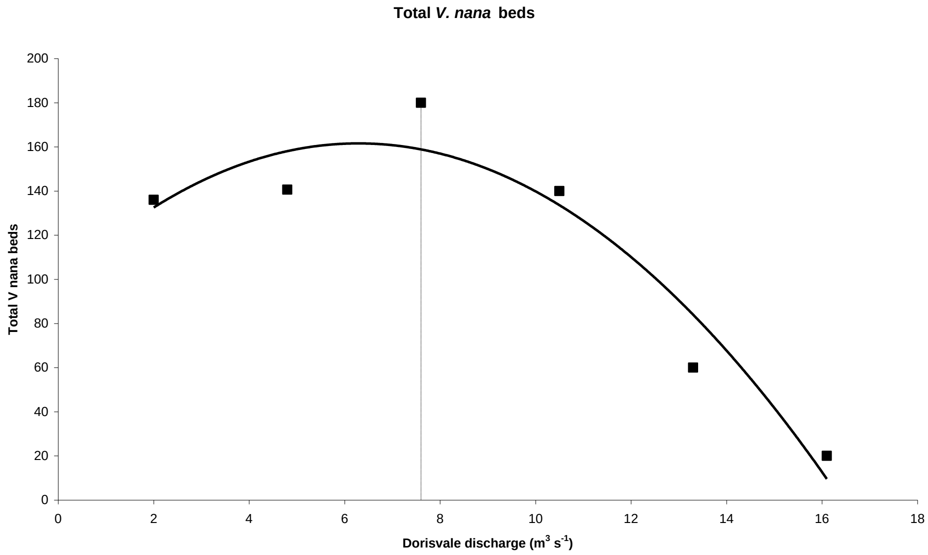



**Figure 3.8 Total number of *Vallisneria nana* macrophyte beds as a function of flow at the Dorisvale gauge on the Daly middle reaches.**

### c) Tree water use and sources of transpired water in riparian vegetation along the Daly River, Northern Territory

This study by O'Grady et al. (2006) reports riparian tree water use and found no difference between tree water use between the different study sites, however, water use tended to be higher in the wet season, reflecting the contribution of deciduous species. Different species water use was similar (at 2.3 to 2.7 $m^3$ $m^2$ $day^{-1}$; Erskine et al. (2003)), and stand water use ranged between 1.8 and 4.1 mm $day^{-1}$ (O'Grady et al., 2006). The amount of ground water used by the trees was found to be a function of landscape position, e.g. trees at lower elevations, closer to the river used more ground water than trees higher on the levees. Extrapolation of the sample tree data along the ~ 80km Daly River reach gave an average water use of 3.2 mm $day^{-1}$, with 60 to 75 % of this estimated to have come from groundwater. The summary table in Erskine et al. (2003) says that all of the riparian vegetation water use can be met by maintaining dry season river flow of not less than 2 $m^3$ $s^{-1}$. Although we don't have sufficient data to construct a flow-ecological health relationship, we can use this threshold to explore how often these riparian trees are subjected to undesirable levels of low flow. Again this is summarised in section 3.4.2.16.3.

**d) Periphyton and phytoplankton response to reduced dry season flows in the Daly River.**

This study by Townsend et al. (2002) evaluates the responses of phytoplankton, benthic diatoms and microalgae to dry season flows in the Daly River. They found the relationship shown in Figure 3.9 for the dependence of the macroalgae *spirogyra* to flow.

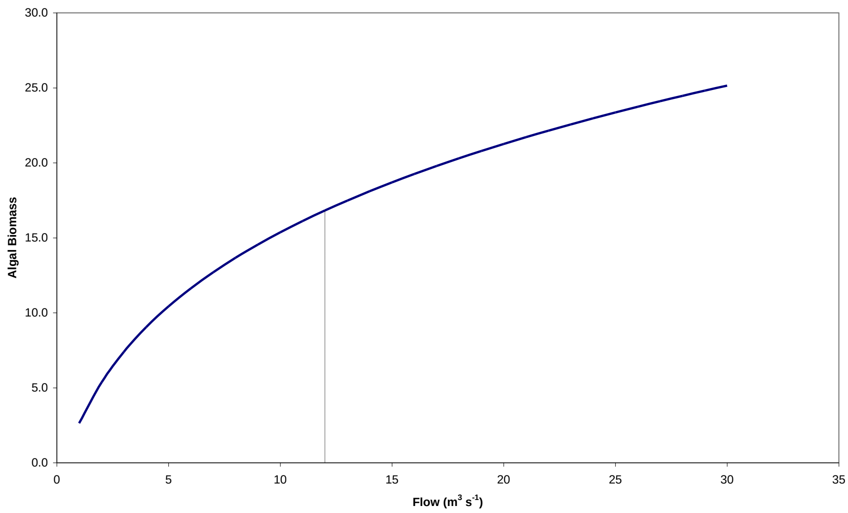



**Figure 3.9 The increase in algal biomass in the Daly River middle reaches with flow.**

Although no threshold is evident in the above figure, the authors refer to a threshold of 12 $m^3 s^{-1}$, below which loss of habitat becomes important. They also refer to simulations which show that flow proportional extraction is better than a fixed regime and that when this proportion exceed 8% the natural flow variability, spirogyra biomass would be adversely affected.

The above species specific low flow metrics are closely tied with the existence of in-stream pools which form critical refugia for many aquatic biota. An important key to quantifying river flow regime impacts on freshwater ecology is therefore to define the relationship between flow and the formation of in-stream pools. This is explored in the following section where LandSat remote sensing data are used to quantify the development of pools in three northern rivers, the Daly in NT, the Mitchell in QLD and the Fitzroy in WA.

#### 3.3.1.4.3 Objectives of the low flow and stream pool study

Section 3.3.1.4.2 clearly demonstrates that quantitative flow-ecology relationships are vital if the consequences of flow changes (due to climate or development) are to be estimated. Many aquatic biota use river pools towards the end of the dry season as habitat or refugia, as demonstrated by the work of Georges et al. (2002) and Erskine et al. (2003) on the success of turtle nesting and their main food source based on a ground survey of pools within the stream bed towards the end of the dry season. However, the process of developing relationships between discharge and pool characteristics through manual observation is a costly and time consuming activity, so this part of the study explores the relationship between stream pools and flow for a central reach of the Fitzroy River, WA; the Mitchell River, QLD and the Daly River, NT using remote sensing techniques of varying resolution (e.g. LiDAR, LandSat and Ikonos). We have examined how well these different remote sensing data can be used to identify stretches of the river which contain breaks and pools, including pool size and numbers. We have also looked at whether there are relationships between river flow and pool number and total area as a means of defining flow thresholds below which aquatic biota may be undesirably impacted.

#### 3.3.1.4.4 Study Regions

The regions of interest for this low flow and stream pool study is the in the Fitzroy, Mitchell and Daly catchments in northern Western Australia. Central reaches of the main river channels in each of these catchments where pools are likely to form during the dry season are shown in Figure 3.10. The reach analysed in the Fitzroy catchment is 275 km long and runs between Fitzroy Crossing (upstream) to Looma (downstream). The reach includes 221 km of the Fitzroy River and 54 km of the Cunningham River anabranch (see Figure 3.10). The gauge used to examine how the pools vary with flow is Fitzroy Barrage (No. 802003). In the Mitchell we analysed 243 km reach in the middle of the catchment and the reference flow gauge is Gamboola (No. 9190011A). For the Day River we analysed a 171 km section of the middle reaches and used the flow gauge at Beeboom (No 8140042) as the reference gauge.

#### 3.3.1.4.5 Methods of pool identification

**LiDAR**

Laser altimetry (LiDAR) data were sourced for high resolution flood hydrodynamic modelling (see section 3.3.1.5) at five locations on the Fitzroy River. The largest of the five scenes, the Fitzroy Crossing coverage, was provided by Main Roads Western Australia and had a resolution of 2 m x 2 m. These data were provided to the department in a pre-processed form that contained a number of no-data “holes”, many of which coincided with the river channel. It was considered that, as standing water typically results in a non-returned LIDAR signal that these no-data “holes” may represent pools. If this is the case then the LiDAR data could be used as a high resolution snap shot of pool location which could provide an ideal dataset for testing other lower resolution approaches.

**LandSat**

LandSat 5 Thematic Mapper data for identifying pools were sourced from the USGS archive; these datasets have a resolution of 30 m and have been terrain corrected (Table 3.1). Only images which were cloud free along the rivers reaches were chosen and the number of these varied from 6 (Daly in 2000 and Fitzroy in 2008) to 16 (Fitzroy in 2006).

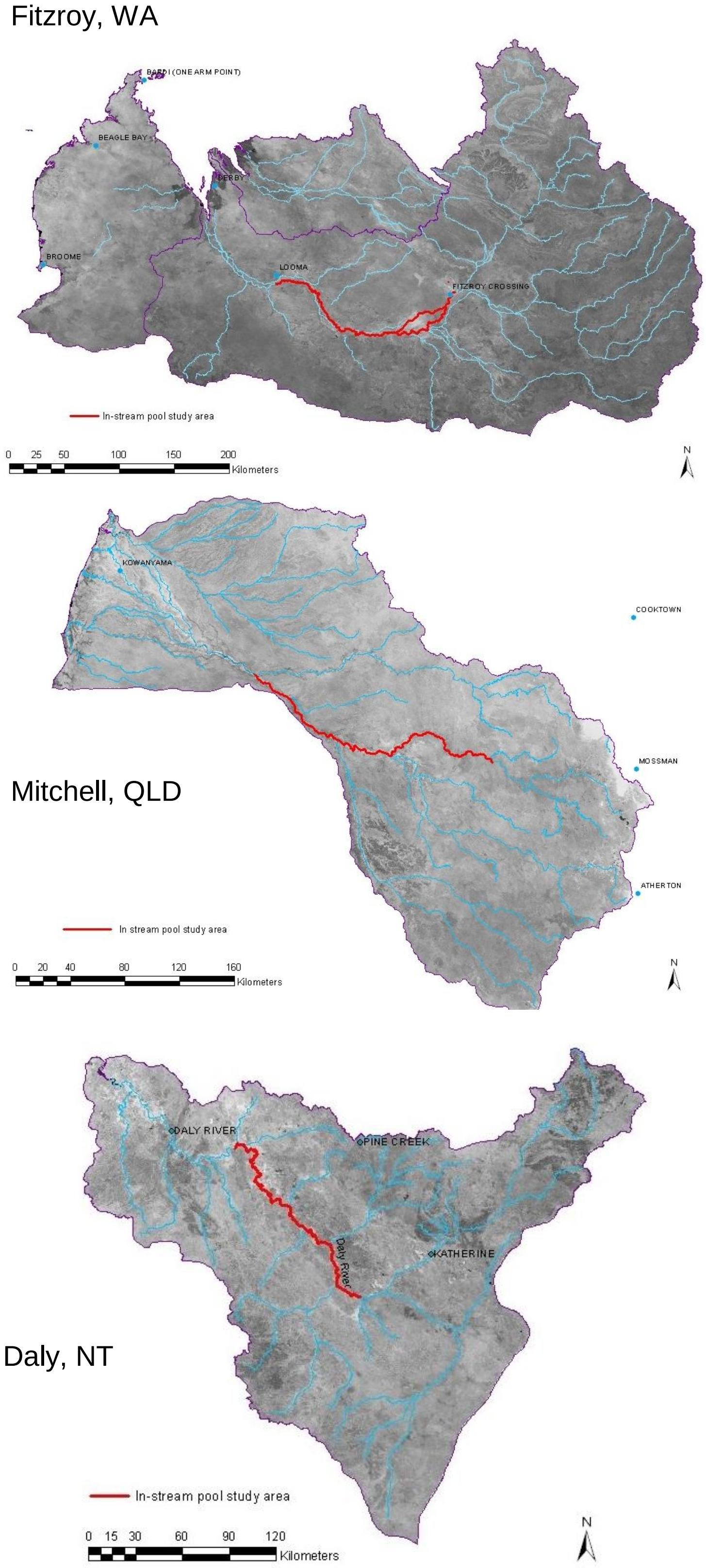



**Figure 3.10 Diagrams of the Fitzroy (top), Mitchell (middle) and Daly catchments showing the river reaches (red) which have been analysed for in-stream pools.**

**Table 3.1 Availability of mostly cloud free LandSat imagery for the Fitzroy, Mitchell and Daly Rivers the years chosen for pool analysis.**

| Daly | Mitchell | Fitzroy | Fitzroy | Fitzroy |
|---|---|---|---|---|
| | | | | |
| 2000 | 2005 | 2005 | 2006 | 2008 |
| | | | | |
| - | 25-Feb | 13-Feb | 16-Feb | - |
| 31-Mar | 29-Mar | 17-Mar | 4-Mar | 9-Mar |
| - | - | - | 20-Mar | - |
| - | - | 2-Apr | 5-Apr | 10-Apr |
| - | - | 18-Apr | 21-Apr | - |
| 2-May | - | 20-May | 7-May | 12-May |
| 5-Jun | - | 5-Jun | 8-Jun | - |
| - | - | 21-Jun | 24-Jun | - |
| - | - | 27-Jul | 10-Jul | - |
| - | - | - | 26-Jul | - |
| - | 4-Aug | 8-Aug | 11-Aug | - |
| - | 20-Aug | - | 27-Aug | - |
| 7-Sep | 5-Sep | 9-Sep | 12-Sep | 1-Sep |
| - | 21-Sep | 25-Sep | 28-Sep | - |
| 25-Oct | 23-Oct | 11-Oct | 14-Oct | - |
| - | 8-Nov | 12-Nov | - | 11-Nov |
| 28-Dec | - | - | 1-Dec | 6-Dec |

3.3.1.4.6 Suitability of techniques

**LiDAR**

To investigate whether the LiDAR data could be used to identify pool in the river channel, the “holes” in the LiDAR were analysed using ArcGIS software. The resultant polygons were then compared with Google Earth imagery of the Fitzroy and Margaret Rivers, (see Figure 3.11) and later with the LandSat TM5 image for the same time period (Figure 3.12).

Comparing the LiDAR with Google Earth imagery (Figure 3.11) showed that “holes” that occurred within the river channels did indeed coincide with the presence of water in the river, though the shape and extent of the observed water was generally much smaller than could be seen in the Google Earth image. This could possibly be explained by the different timing of data collection and is explored further below through comparison with LandSat TM5 data.

It is worth noting the presence of off-river “holes” in the LiDAR data (Figure 3.11) that were unlikely to be non-returns from water as they occurred on rocky elevated areas. The presence of these ‘holes’ could not be explained, but could be related to problems with data collection in a highly dissected landscape.

The LiDAR data was captured in May 2008 and this coincided with a cloud free LTM5 overpass providing a further means by which to assess the performance of LiDAR data. The two data sets are compared in Figure 3.12 which shows that the spatial extent of the pools is not well matched. This suggests that the LiDAR holes may be artefacts related to the interpolation settings used when processing the raw LiDAR data. This is supported by the fact that none of the other four LIDAR scenes along the Fitzroy contained these “holes”, which used a different raw data processing routine.


**Figure 3.11 Coincidence of in river ‘holes’ (outlined in yellow) from LiDAR data with observed standing water from Google Earth imagery.**

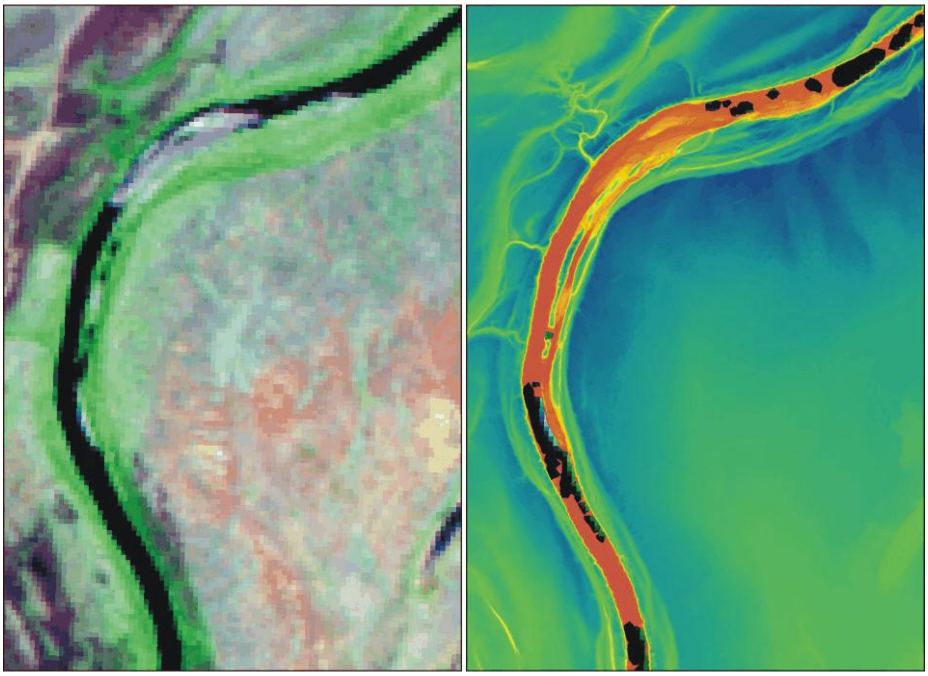


**Figure 3.12 LandSat TM image (left) with pools shown in black and LiDAR data (right) also with pools shown in black.**

As LiDAR has much finer spatial resolution to other remote sensing products (e.g. < 1m compared with 30m for LandSat) it has the potential to provide a better dataset for identifying pools, however, our preliminary analysis suggests that obtaining a reliable relationship between LiDAR returns and the presence of water in streams will require further analyses using unprocessed 'raw' LiDAR data. As this was not possible within the scope of the current project we opted to use LandSat data for all subsequent pool identification work.

**LandSat**

Utilising the reflectance properties of water it is possible to use LandSat imagery to identify water as is illustrated in Figure 3.13. From this figure it is possible to clearly identify standing water within (and outside) the river channel.

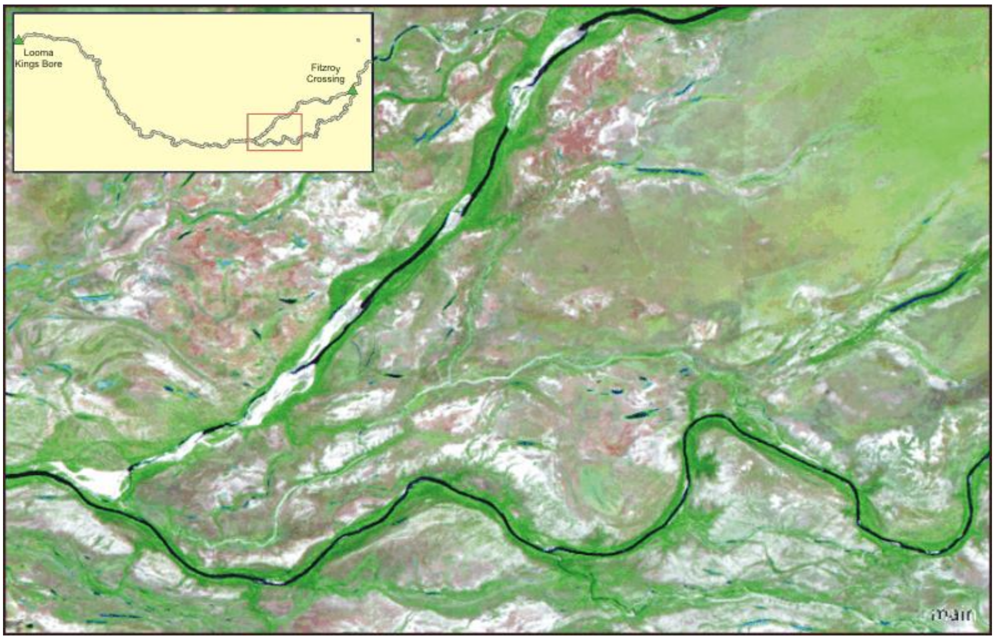



**Figure 3.13 Example LandSat TM image of the Fitzroy River with pools shown in black.**

An object based image analysis (OBIA) has been used in this study. OBIA allows pixels to be clustered into objects that better reflect the scale of the features and processes being studied (Benz et al., 2004). A NIR band (LTM 5) threshold and two band ratios (NDVI and NDWI) sensitive to the presence of water and plant canopy liquid water have also been used. The imagery is segmented into a population of objects based on proximity to the river channel. A binary classification model is then applied that separates the land covers into target and non target groups. Some degree of manual editing of the data is then required due to residual 'false positives' in the water class. Once completed a range of spatial and geometric pool metrics have been extracted. These include pool; number, area, length, width and a number of other object shape indices. Some of these are illustrated in Figure 3.14 for the central reach of the Fitzroy River.

To test the reliability of LandSat images for identifying pools within the river channel we started our analysis in the Fitzroy River for the 2008 calendar year. Table 3.1 shows the availability of LandSat data through 2008. For this year we had seven overpasses which provide reliable data for our analysis.

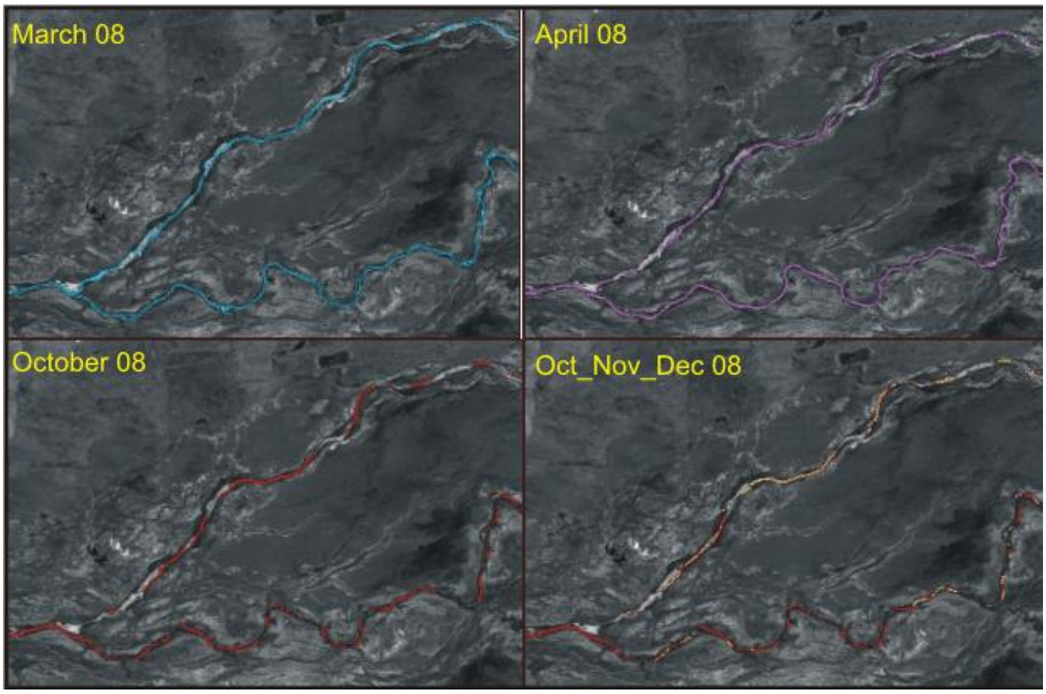



**Figure 3.14 Fitzroy River channel and pool classifications showing the change in pool distribution through the seasons.**

**Verification of results**

In the absence of any high resolution coincident data in 2008, we have used an October 2005 Ikonos image from the Google archive. The October 2005 LTM5 image has been processed and results shown in Figure 3.15. Gauge records at Fitzroy Crossing for this date show a flow 1.82 $m^3/s$. Fairly good agreement exists though spatial error due to the resolution of the 30m LandSat resolution are evident, as are some false positives due to riparian vegetation sometimes being mapped using the NIR threshold.

Further verification of LandSat pools using more temporally coincident high resolution images is required to ascertain the accuracy with which LandSat data can identify in-stream pools. As LandSat imagery is most likely to be in error when identifying smaller objects, for the remainder of this study we have only counted pools that contained more than 4 pixels. This means that pools less than 0.36 ha (or up to 120 m in length) are not counted. This cut off is consistent with the pool survey and modelling analysis by Georges et al., (2002) who ignored pools less than 300 m in length.

**Figure 3.15 October 2005 Ikonos image clearly showing pools (left) and the same image with the identified pools from LandSat analysis overlain (right).**

### 3.3.1.5 Flood extent and duration (Service 4)

#### 3.3.1.5.1 Introduction

Flood flows provide opportunities for the off-stream floodplain wetlands to be connected with the main channels of floodplain river systems, and these ‘flood pulses’ are thought to be the major determinant of the high biodiversity of floodplains (Junk et al., 1989). The Fitzroy River is one of the Australia’s few unregulated river systems and it supports a large number of off-stream wetlands of distinct ecology and environmental value (Kennard, 2011).

An important issue for the management of these wetlands under present and future climate is to know the extent, timing and duration of their connectivity to support ways to maintain or even enhance an optimal level of connection and biophysical exchanges between off-stream wetlands and a main river channel. This information is scarce for the majority of Australian floodplains, including the Fitzroy, since field based monitoring of connectivity for numerous individual wetlands is both difficult and time consuming. A number of studies have used a combination of remotely sensed inundated area and concurrent river flow to predict how flooded area changes with river flow (e.g. Frazier and Page, 2006; Overton, 2005). The same approach has also been used to quantify how the number of inundated wetlands changes with river flow (Shaikh et al., 2001). However, this approach is not dynamic and only gives information on potential wetland inundation when flow is not changing rapidly (due to the time difference between when the remote sensing images can be obtained and the peak of inundation) and it is not yet possible to define the duration of wetland connectivity, which can have an important influence on wetland ecology.

In this study we have used a two-dimensional hydrodynamic model to simulate the time history of inundation across the Fitzroy floodplain. The algorithm developed by Karim et al. (2011) was used to combine the hydrodynamic model output with floodplain topography to quantify overbank flood pulse connectivity between wetlands and the main stream channel.

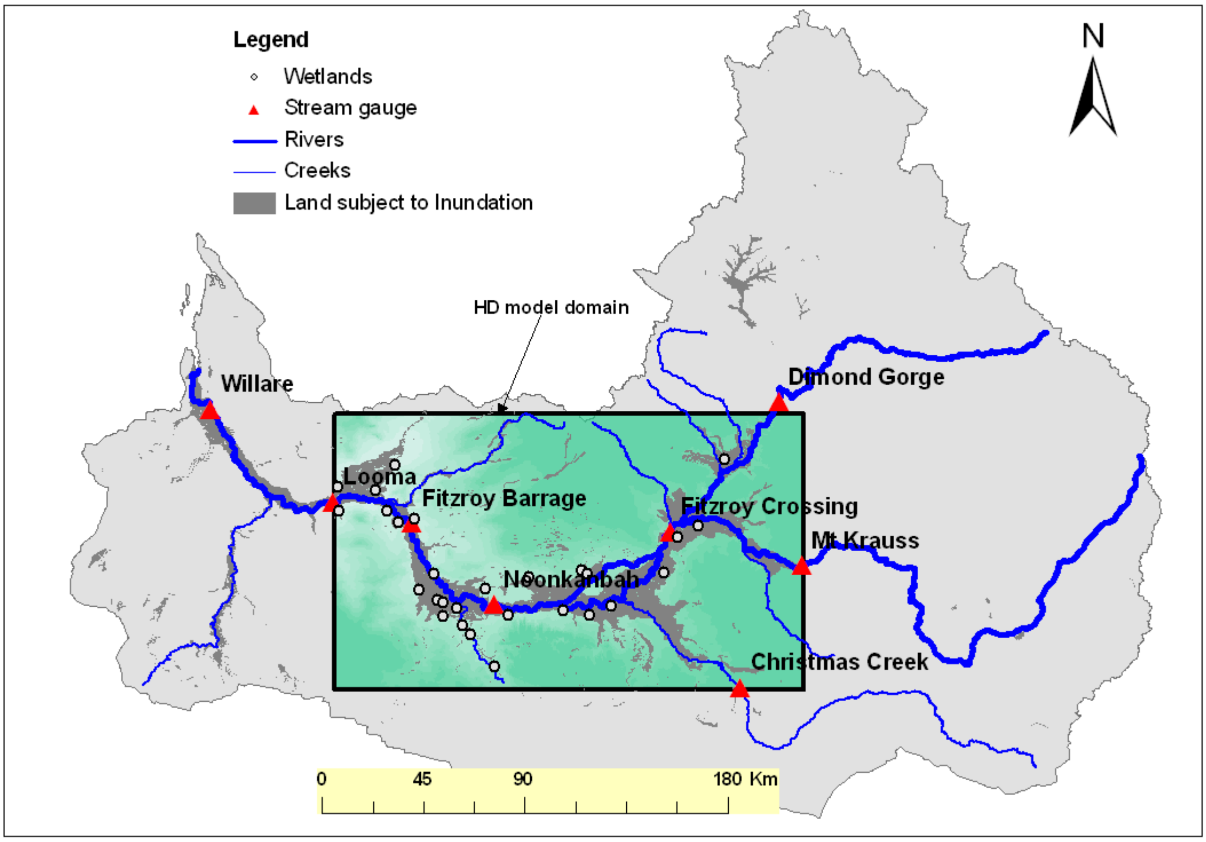



**Figure 3.16 Fitzroy catchment and hydrodynamic model domain showing rivers and major creeks (blue) and stream gauges (red). The model has a water level boundary at Looma and a discharge boundary at Dimond Gorge, Mt. Krauss and Christmas Creek.**

#### 3.3.1.5.2 Data collection and analysis

*Stream flow data*

The gauging stations in the Fitzroy catchment that were used in this study include three in the upper catchment (e.g. Dimond Gorge, Mt. Krauss, Christmas Creek) and four gauges in the floodplain (e.g. Fitzroy Crossing, Noonkanbah, Fitzroy Barrage and Looma) as shown in Figure 3.16. Mean daily discharge and stage height data for the period of 1955 to 2010 were obtained from the Department of Water, GoWA (Government of Western Australia). Data were checked for quality and based on continuity and quality, data from 1980 to 2010 were used in our modelling. Gauge flow data for the upper catchments were used to calibrate a rainfall-runoff model and stage height records from floodplain gauges were used to calibrate the floodplain hydrodynamic model.

The Fitzroy catchment has a semi-arid monsoonal climate with an average rainfall of 560 mm most of which (500 mm) falls in the December to April wet season. Stream flow analysis shows there are strong inter-annual and seasonal variability in stream flow (Figure 3.17). The floodplain from Fitzroy Crossing to Looma is often extensively inundated by monsoon rain and there has been 27 floods (ranging from minor to large) in the last 30 years. Figure 3.18 shows a summary of flood frequency based on 30 years [1980-2009] of gauge flow data at Fitzroy Crossing. The annual recurrence interval (ARI) of selected flood events is shown on this figure. To assess how connectivity changes with flood magnitude we studied one large flood (e.g. 2002, ARI: 14 years) and one small flood (e.g. 2001, ARI: 1.5 year), see Figure 3.19. We also examined a medium size flood (e.g. 2001, ARI: 3 years) that has a secondary peak to evaluate effects of this on wetland connectivity.

**Topography**

We used a Shuttle Radar Topography Mission (SRTM) derived 30 m digital elevation model (DEM) to reproduce floodplain topography in the hydrodynamic (HD) model. The DEM was hydrologically corrected by ensuring stream networks were continuous. Laser altimetry (LiDAR) derived fine resolution (2 m grid) elevation data (±0.3 m horizontal and ±0.1 m vertical accuracy) were used at a number of locations to improve the resolution of key features within the topographic model. Using this DEM, computational grids in the HD model domain were generated by re-sampling the DEM into 90 m grids to keep computational time within a reasonable limit.

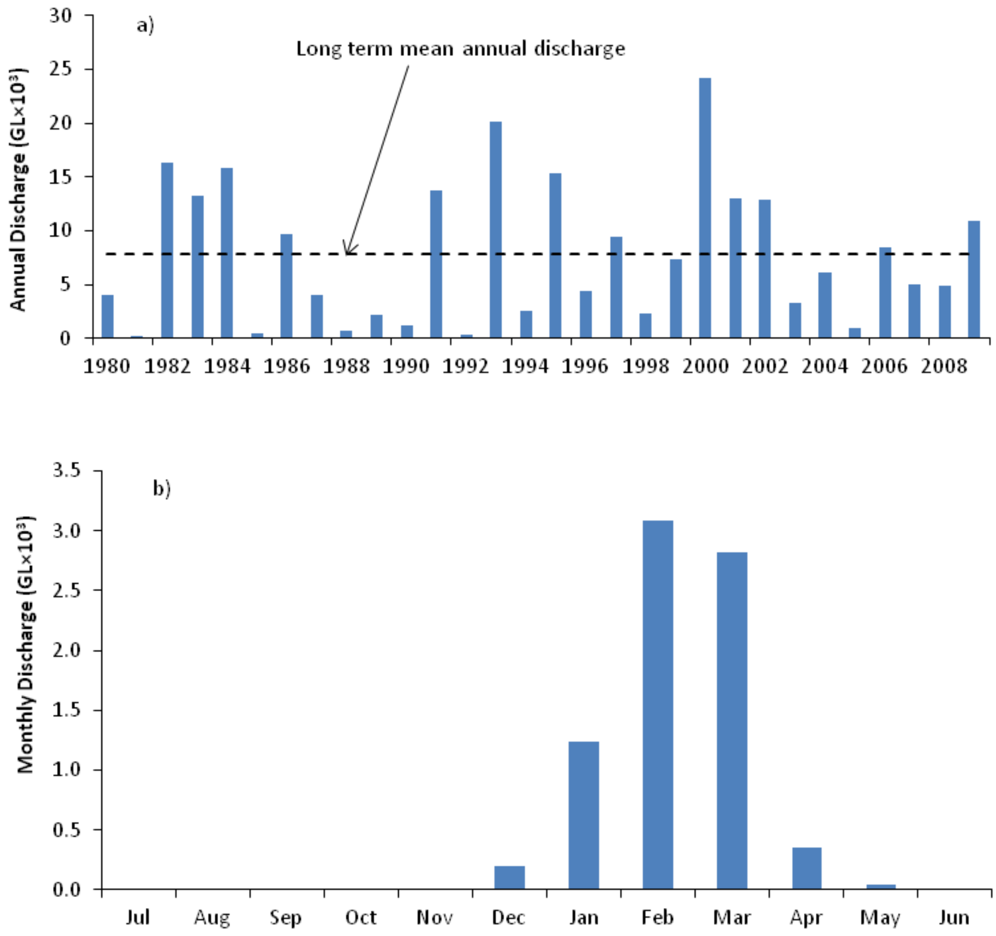



**Figure 3.17 Long term (1980-2009) mean of a) annual and b) seasonal flow based on gauge data at Fitzroy Crossing (see Figure 3.16 for gauge location)**

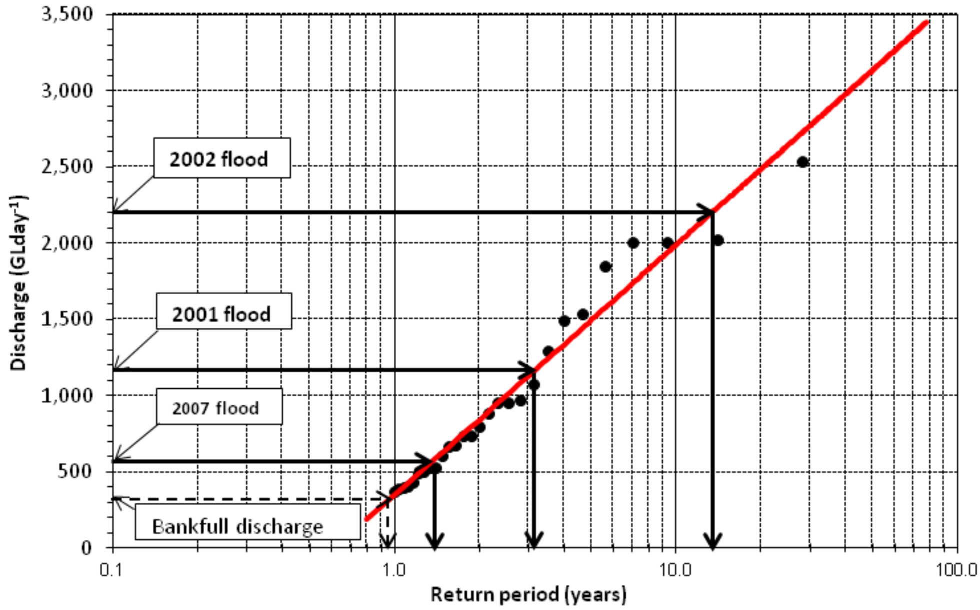



**Figure 3.18 Flood frequency based on gauge flow data at Fitzroy Crossing using peak over threshold (POT) method (Robson and Reed, 1999). [Data period: 1980-2009]**

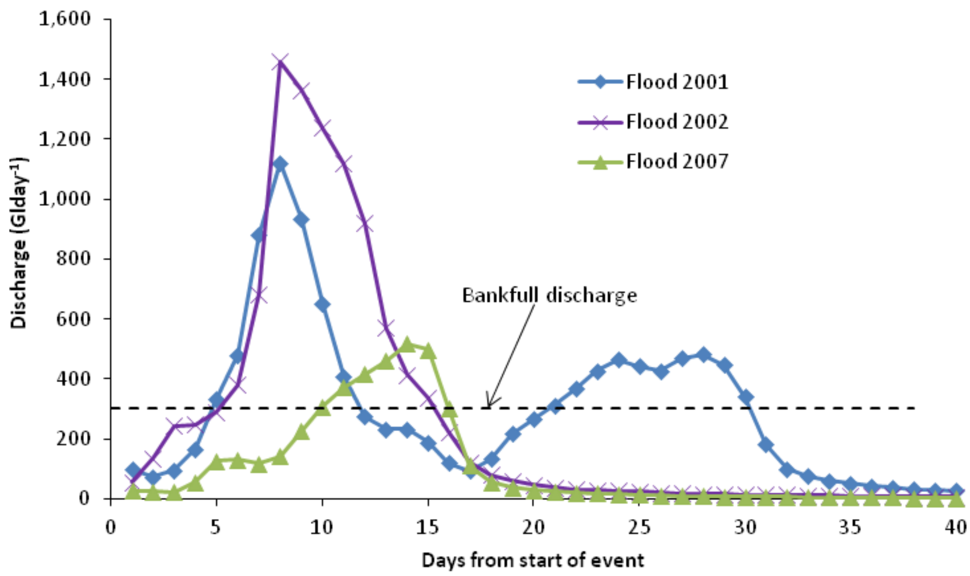



**Figure 3.19 Stream gauge records at Noonkanbah for the flood events in 2001, 2002 and 2007**

### Surface roughness

We used Manning's roughness coefficient (*n*) to represent the hydraulic roughness of the land surface to the propagating flood wave. At first, a land use map was developed based on Geoscience Australia dynamic land cover map, which is based on the MODIS 250 EVI time series data, with the same size grid as the HD model and then converted this to a roughness map by an appropriate substitution of land use code with roughness coefficient. The land uses were classified as major streams (e.g. rivers and large creeks), small streams (e.g. creeks), swamp/wetlands, riparian vegetation, agriculture, bare soil and Savanna. Riparian vegetation and Swamp/Wetland land use classes were identified based on Geo-Australia 1:250,000 topographic maps. Stream networks were generated using the 30 m SRTM DEM. The methodology of deriving the stream network is briefly described here. The watercourses lines in the topographic mapping Hydrography feature dataset were used to inform the DEM derived stream network so that flow accumulations were forced to follow the river channels as depicted in the topographic mapping. Once the stream network was derived from the DEM, the represented rivers were deemed as either "Major" or "Small". Initial roughness coefficients were estimated based on published literature (Arcement and Schneider, 1989 ; Land and Water Australia, 2009) and then refined as a part of calibration process.

### Wetlands

We have explored a number of data sources to identify floodplain wetlands in the Fitzroy catchment. These include 1:250,000 topographic map, the directory of important wetlands of

Australia (Environment Australia, 2001) and Geoscience Australia's dynamic land cover map (Geoscience Australia, 2011). Wetland area and location data from these three sources were combined and compared with Google Earth imagery. Given the very large number of wetlands on the Fitzroy floodplain we finally selected named wetlands with an area of 6 ha or more. A brief summary of physical properties of individual wetland is given in Table 3.2.

**Table 3.2 Physical properties of wetlands in the Fitzroy floodplain studied for hydrological connectivity.**

| | | | | | Distance from the Fitzroy River | |
|---|---|---|---|---|---|---|
| ID* | Wetland Name | Type | Perimeter (km) | Area (ha) | Lateral (km) | Longitudinal (km) |
| 1 | Duck Hole | Perennial | 1.9 | 7 | 4.3 | 260.8 |
| 2 | Lilyhole Billabong | Perennial | 2.5 | 15.2 | 7 | 229.5 |
| 3 | Coorie Billabong | Perennial | 3.3 | 21.2 | 3.9 | 218.1 |
| 4 | Jillyardie Waterhole | Perennial | 3.9 | 26.2 | 3.8 | 198.5 |
| 5 | Pelican Billabong | Perennial | 2.8 | 21.5 | 2.4 | 168.3 |
| 6 | Sevenmile Billagong | Non-perennial | 1.7 | 9 | 3.6 | 154.6 |
| 7 | Patersons Dam | Perennial | 1.1 | 7.8 | 13.7 | 156.3 |
| 8 | Quanbun Billabong | Perennial | 3.3 | 9 | 11.3 | 158.2 |
| 9 | Red Billabong | Non-perennial | 1.8 | 6.7 | 1.4 | 143.9 |
| 10 | Mallallah Swamp I | †DIWA wetland | 2.7 | 38.9 | 13.1 | 131.9 |
| 11 | Mallallah Swamp II | †DIWA wetland | 15 | 378.5 | 10.8 | 132 |
| 12 | Sandy Billabong | Non-perennial | 14.2 | 108 | 4.3 | 99.2 |
| 13 | Balwynah Pool | Perennial | 2 | 9.1 | 2.7 | 116.3 |
| 14 | Gumhole Billabong | Perennial | 1.7 | 6.6 | 25.8 | 107.6 |
| 15 | Peaceful Lagoon | Non-perennial | 2.6 | 16.4 | 12.6 | 100.8 |
| 16 | Duckhole Billabong | Perennial | 4 | 22.9 | 10.3 | 95.8 |
| 17 | Goosehole Billagong | Perennial | 5.1 | 31.7 | 3.6 | 88.5 |
| 18 | SandHill Swamp | †DIWA wetland | 8.6 | 211.8 | 7.7 | 86.7 |
| 19 | Backhouse Waterhole | Perennial | 3.5 | 20.4 | 3.7 | 85.1 |
| 20 | Slaughter Hole | Perennial | 3.2 | 17.4 | 5.3 | 80 |
| 21 | Quonga Waterhole | Perennial | 2 | 9.7 | 8.4 | 73.1 |
| 22 | Broken Wagon Pool | Perennial | 1.8 | 8.4 | 0.6 | 68.6 |
| 23 | Troys Lagoon | Perennial | 1.6 | 10.4 | 1.5 | 42.9 |
| 24 | Ligligin Waterhole | Perennial | 1.8 | 8.9 | 1.6 | 35.7 |
| 25 | Ninemile Pool | Perennial | 1.1 | 7.3 | 2.6 | 32.8 |
| 26 | Yallamungie Pool | Perennial | 2.1 | 11 | 3.2 | 21.2 |
| 27 | Camballin Floodplain | †DIWA wetland | 35.8 | 469.6 | 1.1 | 18.9 |
| 28 | Le Lievre Swamp | Non-perennial | 8.2 | 250.5 | 14.7 | 19.3 |
| 29 | Lake Daley | Perennial | 6.3 | 189.9 | 3.9 | 1.5 |
| 30 | Upper Liveringa Pool | Perennial | 4.2 | 24.1 | 3.9 | 1.3 |

*Small ID number denotes the wetland is located in the upstream river reaches

†DIWA: Directory of Important Wetlands in Australia (2001)

Selected wetlands include both perennial and non-perennial and are located across the floodplain ranging from less than a kilometre to 25 km from the Fitzroy River. Some wetlands are located outside the boundary of overbank inundation. These wetlands however could be connected to the river through floodplain creeks (tributaries of the Fitzroy River).

#### 3.3.1.5.3 Hydro-dynamic modelling

**Model configuration**

The hydrodynamic (HD) model was configured for the floodplain area which provides a significant contribution to groundwater recharge to the Fitzroy River Valley (FRV) alluvial aquifer. The upstream boundary of the HD model was set at Dimond Gorge, well above the floodplain boundary to capture and define the upper catchment flows to the floodplain and the downstream boundary was set at Looma to avoid any tidal influence on flood discharge. The model covers an area of 25,000 $km^2$ (Figure 3.16) and consists of a water level boundary at Looma and three inflow boundaries at Dimond Gorge, Mt Krauss and Christmas Creek.

We used the MIKE 21 HD model (DHI, 2009) to simulate flood wave propagation and floodplain inundation. The MIKE 21 model is a fully dynamic two-dimensional HD model based on the depth-averaged Saint-Venant equations describing the time evolution of water levels and two Cartesian velocity components. Governing flow equations are solved by an implicit finite difference scheme with the variables defined on a space-staggered rectangular grid. The model has been widely used all over the world including Australia to describe floodplain inundation and flood discharge estimation.

**Flow condition**

Water sources on the floodplain include locally generated runoff and stream flows from the upper catchment. Runoff within the model domain was simulated using the Simhyd rainfall-runoff model (Chiew et al., 2002). Because no small gauged catchments exist in the Fitzroy catchment, the Simhyd rainfall-runoff model was calibrated (by minimising the sum of least squares between observed and simulated daily runoff) to a small catchment neighbouring the Fitzroy catchment (809310) and was then tested on three stream flow gauging stations in the Fitzroy catchment; Dimond Gorge, Mt. Krauss and Christmas Creek. Model predictions were found satisfactory in terms of flow magnitude and matching between the peak flows. There were 169 sub-catchments in the HD domain and runoff in each sub-catchment was simulated using the calibrated rainfall-runoff model. Simulated runoff were added to the HD model as source points at the outlet of each sub-catchment, derived using 30 m grid SRTM data and are typically located at the stream junctions/inflow to main rivers. Water sources from the upper catchments were obtained from stream gauge records and added as inflow boundary conditions to the HD model at Dimond Gorge, Mt. Krauss and Christmas Creek.

**Flood simulation**

The HD model consists of approx. 3 millions grids (2308 × 1344) of which approximately 20% are dry cells (i.e. not subject to inundation and excluded from computation). The computational time step (8 sec) was selected after satisfying numerical stability criteria for floods of different magnitudes. Starting from the first day of flooding, simulation was continued for 40 days irrespective of flood receding time. For each run, it takes about 7 days of computer time to simulate a flood event. At the HD model boundaries, daily time step stage heights and discharges were specified. The model uses an inbuilt interpolation technique to derive flow variables at each computational time step. An initial water level map was generated by running the model on dry land for a constant inflow. Initial discharges at all computational grids were specified as zero. Model outputs include water surface elevation, depth, velocity and flow flux for each computational grids and the data can be saved at any desired time step as a multiple of computational time step (we used a 6 hour interval).

**Model calibration**

The availability of remotely sensed flood inundation data (e.g. area and depth of flooding) for the Fitzroy floodplain has made it possible to evaluate the HD model performance in predicting temporal and spatial inundation dynamics. These remote sensing data along with stream gauge data were used to calibrate the hydrodynamic model. The model was calibrated against the large flood event in 2002. We used a number of MODIS images at different stages of flooding to compare spatial metrics of inundation area and depth across the floodplain. In addition, gauged water heights at key locations (e.g. Fitzroy Crossing, Noonkanbah, Fitzroy Barrage and Looma) were used to compare simulated stage heights and time of peak arrival at different locations. Model grids that represent streams were carefully checked and manually edited to ensure stream channels were continuous. Final calibration was made by changing the Manning's roughness coefficient. Surface roughness coefficients were varied iteratively for the major land uses (e.g. Savanna, riparian vegetation) within the recommended range to attain a close agreement between observed and simulated water depths. The calibration also optimized the match between observed and simulated time of peak arrival at different locations in the floodplain.

#### 3.3.1.5.4 Connectivity analysis

In this study we considered connectivity of wetlands with the main Fitzroy River channel through floodplain flows (i.e. overbank flooding). Connection and disconnection during overbank flooding were identified using a threshold water depth of 30 cm following that used in similar study by Karim et al. (2011). Based on HD model outputs we first identified time series information on wet or dry cells at each wetland and along the intervening floodplain pathways, from which the timing and duration of connection with surrounding water bodies and/or with the main stream were estimated. A wetland was considered connected to other water bodies when it started receiving water from overbank flow and was considered disconnected when water receded below its bank level as shown in Figure 3.20. In this figure, $t_1$ represents the start and $t_2$ the end of hydrologic connection, while the difference between $t_2$ and $t_1$ is the duration of connection. Connection time and duration of connection are different for floods of different magnitudes. In general, large flood events produce early and longer duration of connection. The estimation of connection time of a particular wetland to the river system was based on time series water depths derived from the hydrodynamic model at six-hourly time steps. To do this, an algorithm was developed to uniquely identify areas of contiguous water during each time step, by tagging all water bodies and river sections which were contiguous in that time step. The same procedures were repeated for all time steps and the results were accumulated to obtain the temporal sequence of connection and disconnection. Further details of this analysis technique are available in Karim et al. (2011).

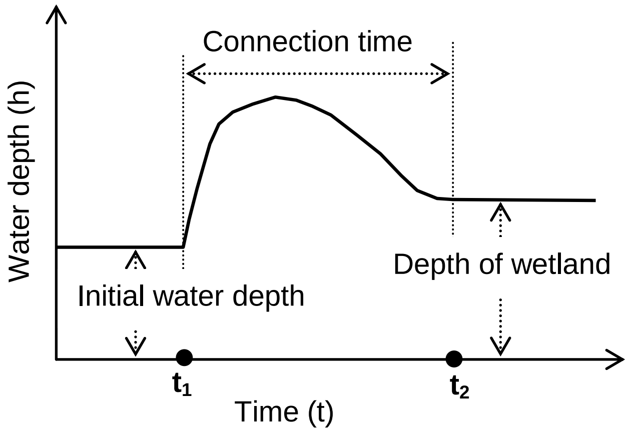



**Figure 3.20 A schematic view of connectivity analysis based on water depths in wetland ($t_1$ represents time of receiving flood water and $t_2$ represents ending of flow connection with surrounding water bodies). [reproduced from Karim et al. (2011)]**

# 3.4 RESULTS AND DISCUSSION

## 3.4.1 Groundwater regimes (Service 1)

### 3.4.1.1 Review of groundwater-surface water interactions in Northern Australia

#### 3.4.1.1.1 Introduction

The purpose of this review is to summarise the existing knowledge regarding groundwater-surface water (GW-SW) interactions in Northern Australia. Specifically, the intention is to

> *Review limited available data on groundwater levels and their relationship to surface expressions and integrate into a complimentary review of the broader-scale NASY study including surface-groundwater modelling in the Daly River, and ongoing work in the Fitzroy River.*

This review will rely heavily upon results of the Northern Australia Sustainable Yields (NASY) project (CSIRO, 2009a; 2009b; 2009c) to provide an overview of GW-SW interactions across northern Australia. As part of the NASY project, quantitative groundwater models were developed for parts of the Daly (Knapton et al., 2010) and Van Diemen (EHA, 2007) reporting regions; the main findings of these assessments will be summarised. Finally, the review will try to capture the results of recent field/modelling-based research into GW-SW interactions in the Daly River, NT (Smerdon et al., 2011) and Fitzroy River, WA (Gardner et al., 2011; Harrington et al., 2011). All of the available information for northern Australia will be summarised according to the reporting regions used for the NASY project (Figure 3.1).

#### 3.4.1.1.2 Background

Across northern Australia, typically more than 90% of annual rainfall and runoff occurs during the wet season between November and April (CSIRO, 2009a; 2009b; 2009c). During this period groundwater recharge occurs via a combination of diffuse infiltration of rainfall, floodplain inundation and leakage – either laterally or vertically – from losing streams and rivers. In the subsequent dry season, river flows recede rapidly and the majority of surface water features cease to flow or even dry completely before the following wet season. There are however several iconic perennial rivers in northern Australia that rely on significant groundwater input through the dry season – notable inclusions are the Daly River and Roper River (NT), and many of the rivers on Cape York Peninsula (QLD). A schematic representation of the main GW-SW interactions that occur during the wet and dry seasons is provided, by way of an example from the Fitzroy River, in Figure 3.21.

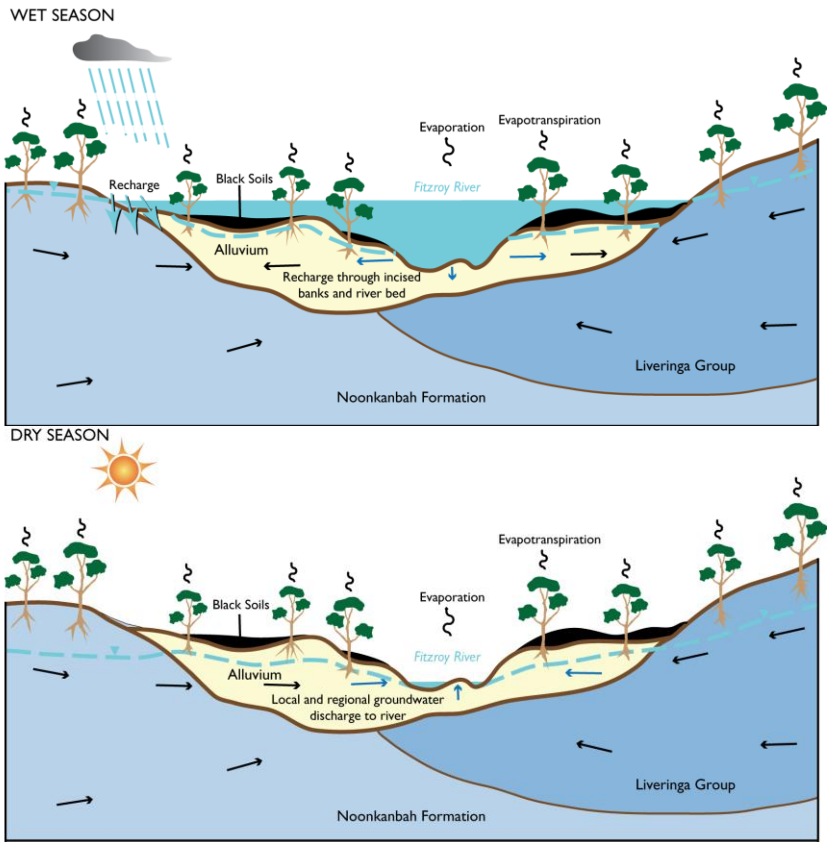



**Figure 3.21. Schematic representation of GW-SW interactions in the Fitzroy River, WA (CSIRO, 2009c).**

#### 3.4.1.1.3 Fitzroy Region

GW-SW interactions in the Fitzroy region have been observed in the Fitzroy, Meda, Lennard and Alexander rivers. In a recent study, Harrington et al. (2011) characterised GW-SW interactions between the Fitzroy River and local aquifers through the use of hydrochemical and environmental isotope sampling and numerical modelling. The study focused on a reach of the river between Jubilee Downs and Liveringa stations and the authors identified two locations of active groundwater discharge along this reach: the first near the confluence of the Fitzroy River and the Cunningham Anabranch, and the second between a well-known waterfall and Yungngora Community on Noonkanbah Station. Two conceptual models of GW-SW interactions were proposed to explain observed chemical/isotopic trends in the river (Figure 3.22). At the first site, regional groundwater flow in a sandstone aquifer is thought to be driven upwards into the river as it meets a low permeability shale formation, while at the second location a series of north-south trending faults are believed to provide preferential pathways for deep, very old regional groundwater to discharge to the river via shallow local aquifers. Modelling of river chemistry profiles indicated that the total rate of groundwater discharge over the 100 kilometre study reach is ~102 000 m$^3$/day, including ~3 700 m$^3$/day from deep regional aquifers, with the remaining discharge sourced from shallow local aquifers.

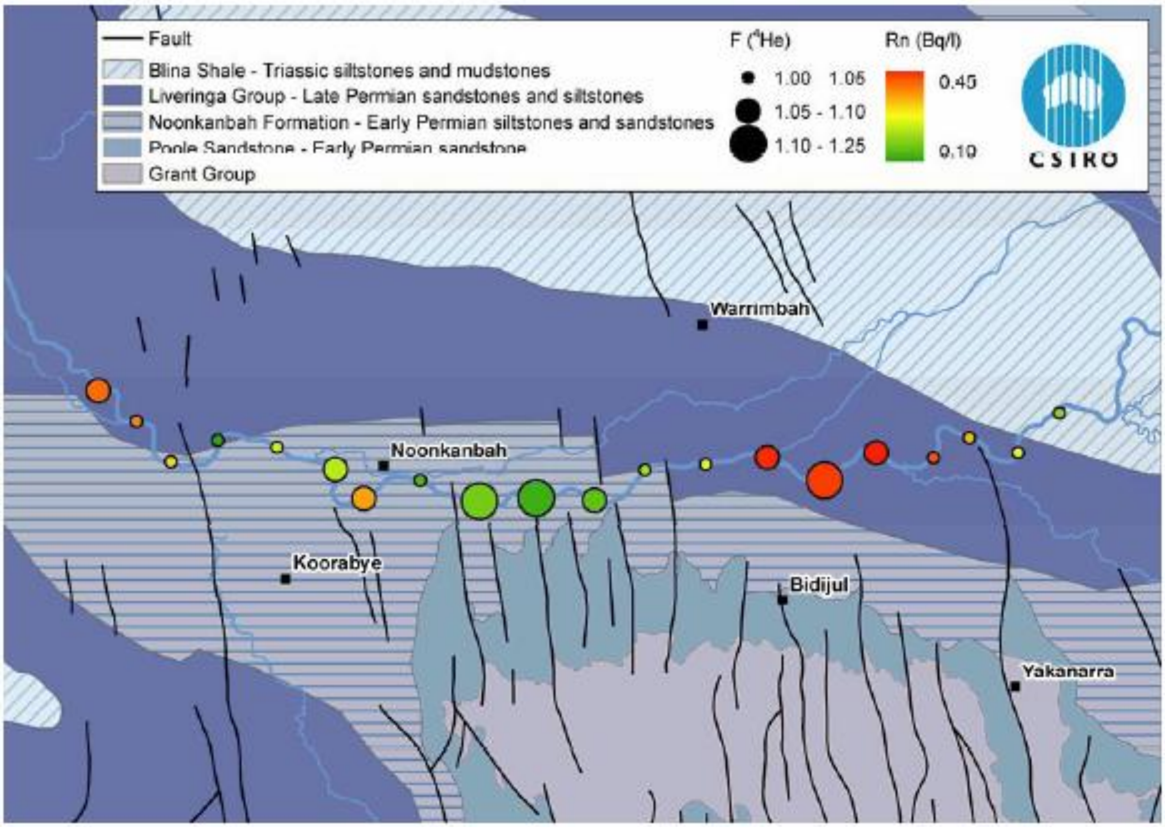



**Figure 3.22. Helium-4 and radon-222 concentrations along a reach of the Fitzroy River (Harrington et al., 2011). Observations of high radon-222 activities are indicative of groundwater discharge into the river, while high helium-4 concentrations are indicative of very old groundwater in the river.**

#### 3.4.1.1.4 Daly Region

In the Daly region, groundwater discharge has been observed in reaches of the Daly, Douglas, Katherine and Flora rivers, mostly as diffuse discharge through the beds of the rivers. At some locations groundwater discharges in the form of discrete springs associated with karst aquifers developed in the Tindall Limestone and Oolloo Dolostone (Figure 3.23).

Knapton et al. (2010) developed an integrated GW-SW numerical model of the Tindall Limestone and Daly River in order to estimate potential impacts of climate change and groundwater development. They demonstrated the high degree of interconnection between the Daly River and the adjacent aquifers, and found that the greatest impacts to groundwater resources – particularly from increased development – will occur in parts of aquifers that are distal to the rivers; that is, groundwater extraction will lead to large drawdown of water levels in the aquifers that cannot be mitigated through increased leakage from the rivers (Figure 3.24).

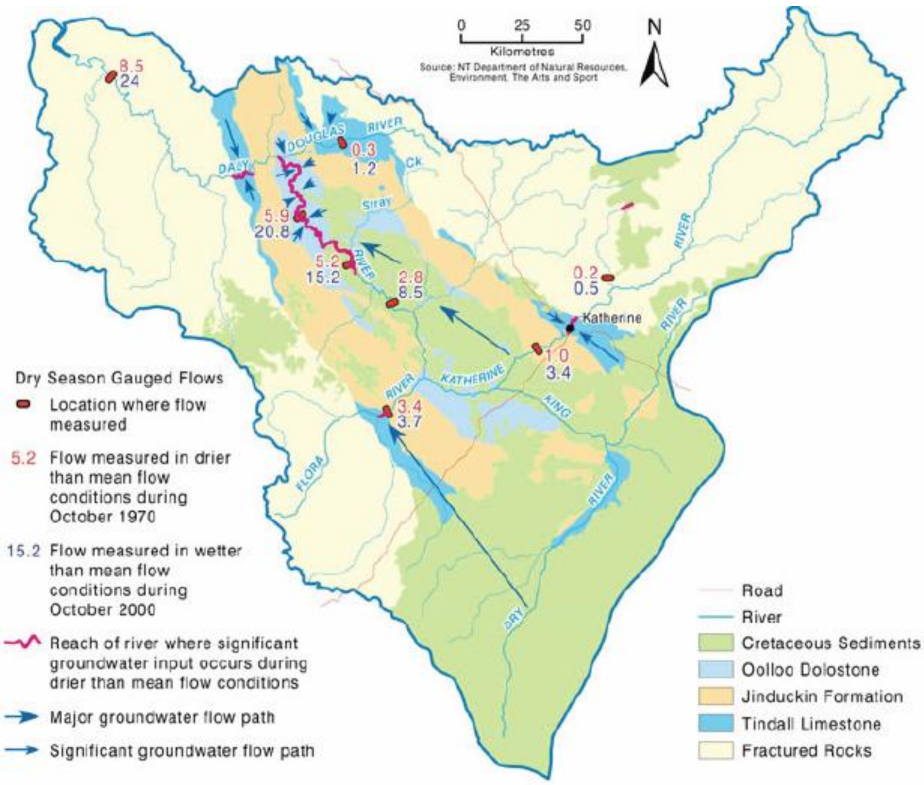



**Figure 3.23. Groundwater-surface water interactions in the Daly region (CSIRO, 2009c).**

Knapton et al. (2010) also summarise the published knowledge of GW-SW interactions along the Daly River, including the following information. Jolly et al. (2000) state that aquifers in the Daly Basin supply more than 10 $m^3$/s of baseflow to the Daly River and Jolly (2001) have estimated the average late dry season groundwater discharge to the river to be between 10-20 $m^3$/s. According to Tickell (2002a), the groundwater contribution upstream of Stray Creek to the total river flow between Dorisvale and Mount Nancar is approximately 40%. A study by Tickell et al. (2002b) estimated a discharge flux of ~34 $m^3$/s from the Daly Basin aquifers, of which ~47% was derived from the Tindall Limestone and ~53% derived from the Oolloo Dolostone. Knapton et al. (2010) also cite other reports published by the Northern Territory Department of Natural Resources, Environment, The Arts and Sport (Tickell, 2005; Tickell, 2007; Tickell, 2008a; Tickell, 2008b; Tickell et al., 2002) as sources documenting GW-SW interactions in the Daly Basin.

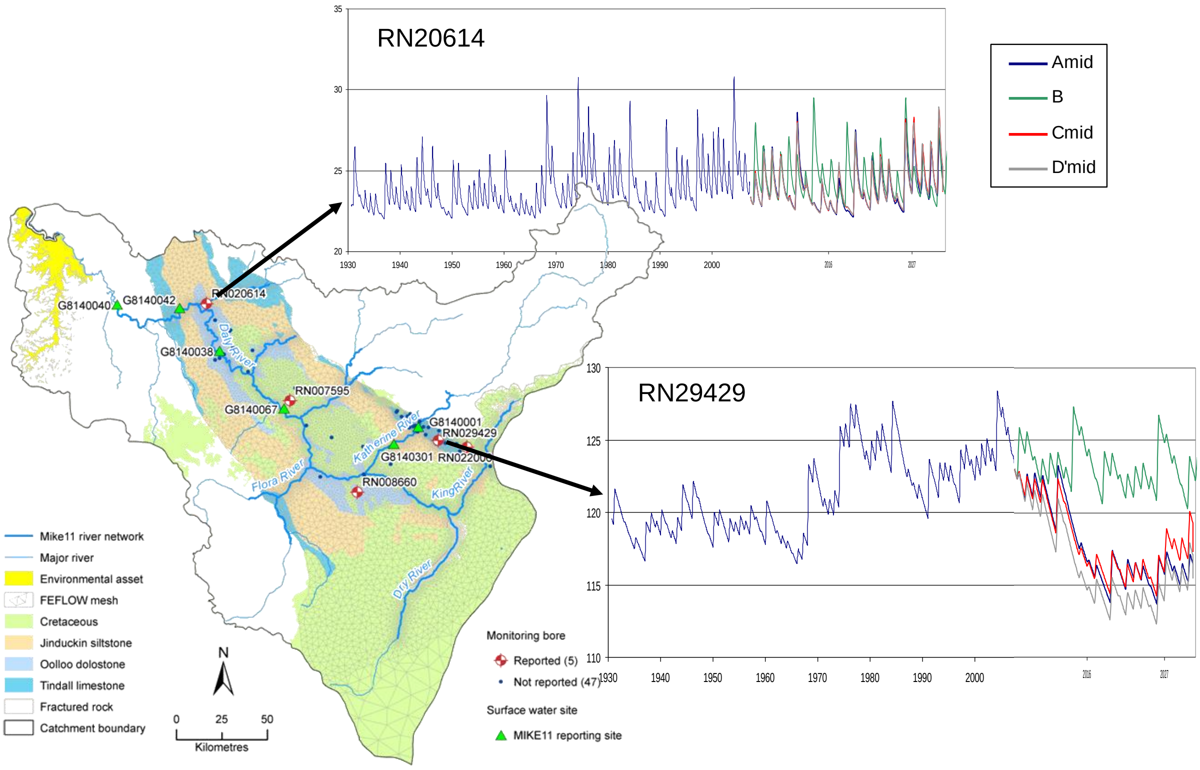



**Figure 3.24. Projected groundwater levels under future climate scenarios for the Daly region (after CSIRO (2009c)). Aquifer drawdown by pumping is mitigated in bores situated close to rivers.**

More recently, Smerdon et al. (2011) characterised GW-SW interactions between the Daly River and the Oolloo Dolostone aquifer through the use of hydrochemical and environmental isotope sampling and numerical modelling. The authors estimated that the average diffuse groundwater discharge to the Daly River at the end of dry season periods is ~5$m^3$/d/m. Over the extent of the studied area, older regional-scale groundwater was found to contribute ~40% of baseflow to the Daly River. In the vicinity of large springs, the contribution of groundwater discharge to baseflow was estimated at ~90%, at a rate of ~200$m^3$/d/m.

#### 3.4.1.1.5 Van Diemen Region

In the Van Diemen region, significant groundwater discharge occurs toward the end of the dry season in the Howard, Mary, and South Alligator rivers, and in the Berry, Bluewater, Taracumbi and Takamprimili creeks (Figure 3.25). Discharge is believed to derive from karstic rocks (Berry Creek and Howard River) and from Cretaceous sediments (Mary, South Alligator and Howard rivers and Bluewater, Taracumbi and Takamprimili creeks). In the Darwin rural area, groundwater discharge from the McMinn's-Howard East groundwater system occurs via springs and via diffuse discharge to local streams. The latter occurs from both the shallow laterite aquifer and the deeper Koolpinyah Dolomite aquifer. Major springs which represent “windows” into the dolomite aquifer include Howard Springs, and springs in Melacca Creek and the Adelaide River `Narrows' area. Some streams in the area, such as Holland's Creek, Baker's Creek and the upper reaches of the Howard River exhibit seasonal changes in water quality, with the quality of dry season baseflow representing a mixture of waters from the laterite and dolomite aquifers (CSIRO, 2009c; EHA, 2007).

EHA (2009) undertook a numerical groundwater modelling exercise as part of the NASY project to determine the impacts of future climate change on already-stressed groundwater resources in the Darwin Rural Area – McMinn’s – Howard East Section. They found that despite projected increases in diffuse recharge under a future climate, groundwater levels are likely to continue to decline under current levels of extraction. Such trends will continue to threaten a number of groundwater dependent ecosystems in the area, including Lambell’s Lagoon.

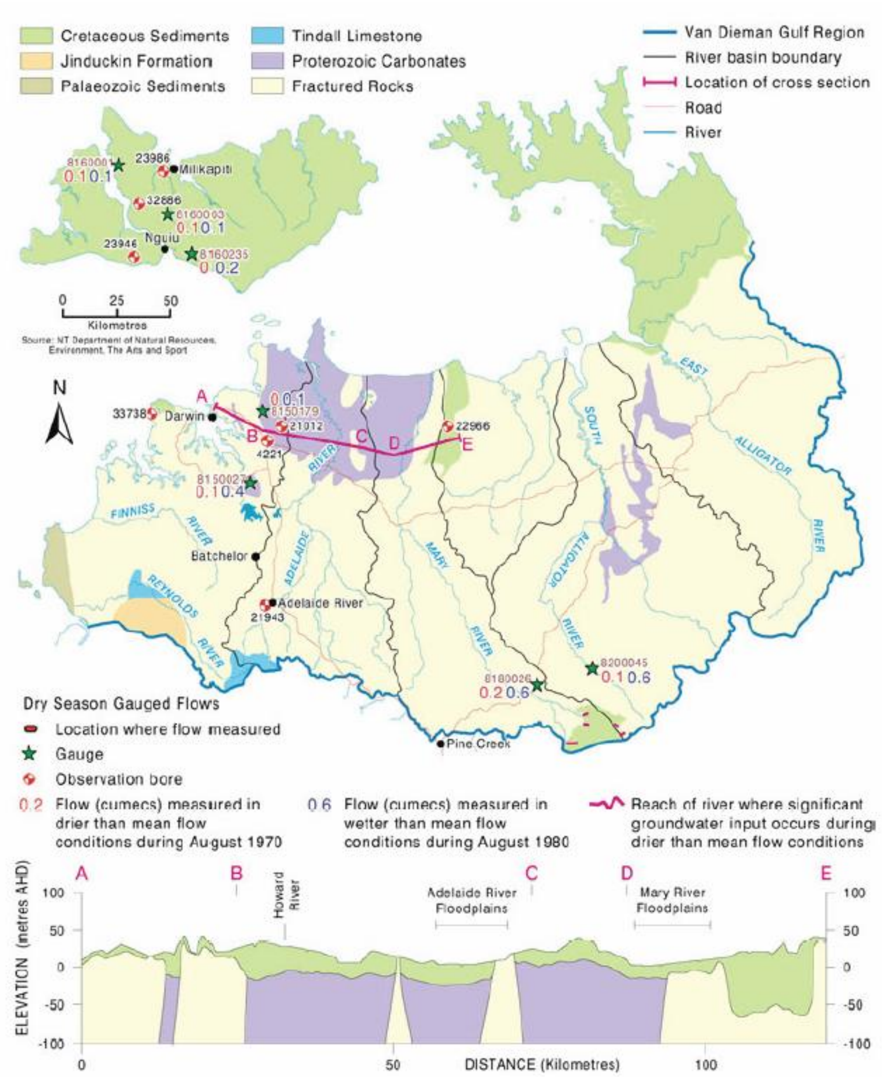



**Figure 3.25. Groundwater-surface water interactions in the Van Diemen region (CSIRO, 2009c).**

3.4.1.1.6 Other NASY Project Regions

### Western Australia

- In the Kimberley region, groundwater discharge is believed to sustain a number of swamps, creeks and rivers. More specifically, certain reaches of the Drysdale, Isdell, King Edward and Mitchell rivers are all sustained through the dry season by groundwater baseflow (CSIRO, 2009c).

### Northern Territory

- In the Ord-Bonaparte region, baseflow surveys of the Fitzmaurice and Victoria rivers have indicated that both are sustained by groundwater, while groundwater discharge to the Wickham and Moyle rivers is also believed to occur (CSIRO, 2009c). Springs in the Victoria River Basin have flows ranging from seeps to 170 $m^3$/d. Spring flows depend on short-term rainfall patterns and are known to gradually decrease as the dry season progresses, often not being able to maintain permanent flows (Tickell and Rajaratnam, 1998).

- In the Arafura region, significant groundwater discharge occurs toward the end of the dry season period in the Goyder, Blyth, Habgood, Cato and Latram rivers and in the Yirrkala and Jungle Creeks (CSIRO, 2009c).
- In the Roper region, groundwater discharge from karst aquifers provides significant baseflow to the Roper, Mainoru, Wilton, Koolatong, Walker and Rosie rivers and Flying Fox Creek. Groundwater discharge from Cretaceous sediments provides significant baseflow to the Durabudboi River and Wonga Creek on the mainland and to the Angurugu, Emerald and Amagula rivers on Groote Eylandt (CSIRO, 2009a).

**Queensland**

- In the Flinders-Leichhardt region, groundwater discharge from local alluvial aquifers maintains baseflow in the Flinders and Leichhardt rivers until groundwater levels fall below those of the river bed (CSIRO, 2009a). Permanent or near-permanent waterholes along most of the larger watercourses are believed to be derived from surface flows from the previous wet season, rather than as the result of groundwater contribution (Petheram and Bristow, 2008). Groundwater discharge is also believed to occur in tributaries of the Flinders River, such the Woolgar River, Hampstead Creek and Porcupine Creek (AGE, 2005).
- In the Northern Coral region, groundwater is critical for maintaining river flow into the dry season in many catchments (CSIRO, 2009b). Rivers identified as potentially receiving groundwater discharge from the Gilbert River Formation and Dalrymple sandstone aquifers include the Normanby, Laura, Little Laura, Hann, Olive, Pascoe, Kennedy and Marrett rivers (DNRM, 2005). Of these rivers, however, only the Hann River maintains flow through the entire dry season. In the Bathurst Heads - Cape Melville National Park area, spring discharges also support wetlands and swamps (CSIRO, 2009b).
- In the Mitchell region, the Mitchell River (Qld.) is partly sustained by year-round groundwater discharge from both local and regional aquifers (CSIRO, 2009a). Significant (i.e. ~50 million $m^3$/year) groundwater discharge from the Gilbert River Formation occurs to the Mitchell River, with highest contributions to baseflow occurring around November (Cox and Barron, 1998). Permanent waterholes maintained by groundwater discharge are common in the Palmer and Walsh rivers and major creeks (CSIRO, 2009a). Numerous permanent and semi-permanent springs rise from the base of the Gilbert River Formation (Bultitude et al., 1996). There is no reported evidence of groundwater discharge to major watercourses in the east of the region (DNRW, 2006).

- In the South-West Gulf region, groundwater discharge from aquifer developed in karstic rocks provides significant baseflow to a number of rivers and streams. The Robinson and Calvert rivers source their dry season flow from Proterozoic carbonates, while the Gregory River and Lawn Hill Creek source their dry season flow from the Camooweal Dolostone and Thorntonia Limestone. Small springs occur in some parts of the region after average-to-above average rainfall years, though most cease to flow by early in the dry season. These springs often drain a very small area (less than 10 $km^2$) and some feature low (i.e. < 10 L/second) flows throughout the year (CSIRO, 2009a).
- In the South-East Gulf region, groundwater discharge from the Gilbert River Formation provides significant baseflow to a number of streams, including the Gilbert, Norman, Yappar and Clara rivers (CSIRO, 2009a). Spring discharge occurs in outcrop areas of the Gilbert River Formation and Eulo Queen Group and supports significant surface water features such as Cobbold and Porcupine Gorge National Parks (DNRM, 2005). Throughflow from these aquifers to the west and south-west supports mound springs and associated environments of the Flinders Spring Group (CSIRO, 2009a).
- In the Western Cape region, a number of rivers receive groundwater discharge from the Gilbert River Formation aquifer (and its equivalents) including the Jardine, Wenlock, Archer, Coen, Holroyd and Delhunty rivers (CSIRO, 2009a; DNRM, 2005).

###### 3.4.1.1.7 Potential Impacts of Climate Change

Using the NASY climate scenarios as a guide (Li et al., 2009), future climate in northern Australia is expected to be similar to that experienced during the period 1930-2007. Rainfall is predicted to remain within ±5% of 1990 levels, with future potential evapotranspiration being 1-4% higher throughout the year (CSIRO, 2009a; 2009b; 2009c). Potential changes in diffuse groundwater recharge (relative to modelled historical recharge) were estimated for each NASY region; these results are summarised in Table 3.3 below. By averaging these results, the predicted annual diffuse recharge across all of northern Australia is seen to vary from +39% to -5% of historical (i.e. 1930-2007) recharge.

**Table 3.3. Predicted changes in mean annual diffuse groundwater recharge (from historical recharge) as modelled for the NASY project (CSIRO, 2009a; 2009b; 2009c).**

| NASY Region | % change under the wettest modelled scenario (Cwet) | % change under the driest modelled scenario (Cdry) |
|---|---|---|
| Arafura | + 34 | - 9 |
| Daly | + 38 | - 2 |
| Fitzroy | + 26 | - 13 |
| Flinders-Leichhardt | + 32 | - 12 |
| Kimberley | + 21 | - 9 |
| Mitchell | + 54 | - 8 |
| Northern Coral | + 37 | + 2 |
| Ord-Bonaparte | + 39 | - 3 |
| Roper | + 48 | - 2 |
| South East Gulf | + 49 | - 2 |
| South West Gulf | + 39 | - 1 |
| Van Diemen | + 37 | - 7 |
| Western Cape | + 49 | + 1 |
| **Average % change** | **+ 39** | **- 5** |

In terms of surface water features that are dependent (to some extent) upon groundwater discharge, the impacts of climate change will be more immediate to those which are fed by shallow, local unconfined aquifers. These aquifers are inherently more dynamic and respond quickly to changes in rainfall regimes. This category is pertinent for GW-SW interactions in, for example, the Flinders-Leichhardt, Mitchell and Kimberley regions. Conversely, the impacts of climate change will be delayed for surface water features that are fed by deep, regional aquifers. This category is pertinent for GW-SW interactions in, for example, the Daly and Fitzroy regions.

#### 3.4.1.1.8 Knowledge Gaps

Despite a broad general knowledge of the locations of significant groundwater discharge to rivers and streams in northern Australia, there are several fundamental knowledge gaps around the nature of interactions in complex geological environments, and how these systems will respond to potential future climate change and increased water resource development. Specific examples that warrant focussed research include:

- mound Spring ecosystems on Dampier Peninsula;
- ‘rejected recharge’ and artesian springs from the Great Artesian Basin that sustain dry season flows in rivers on Cape York Peninsula; and
- spring-fed rivers in carbonate aquifers of the South East Gulf region.

### 3.4.2 Groundwater characterisation across northern Australia

The hydrogeology across northern Australia is extremely variable, reflecting complex interactions between climate, soil type, vegetation cover and underlying geology. Most of the region can be broadly categorised into one of four main aquifer types; these are fractured hard rocks of either igneous or metamorphic origin, sedimentary carbonates, consolidated sandstones and shallow alluvial aquifers. Fractured hard rocks, such as those which dominate the Kimberley Plateau of Western Australia and the higher elevations of the Great Dividing Range in Queensland, are generally considered to be poor aquifers, with local recharge and flow systems that fill and spill each wet season (Figure 3.26). The main sedimentary carbonate aquifers are associated with the Daly, Wiso and Georgina Basins in the Northern Territory and western Queensland. These large, regional aquifers have high recharge rates and contain groundwater of very long residence time. Sedimentary rock aquifers include both near-surface sandstone aquifers (e.g., Cretaceous sandstones in the Northern Territory) and deeper, confined aquifers such as the Gilbert River Formation of the Great Artesian Basin. Alluvial aquifers account for the most significant shallow groundwater resources across the north, with aquifers of varying widths and horizontal extents bordering every major surface water drainage feature.

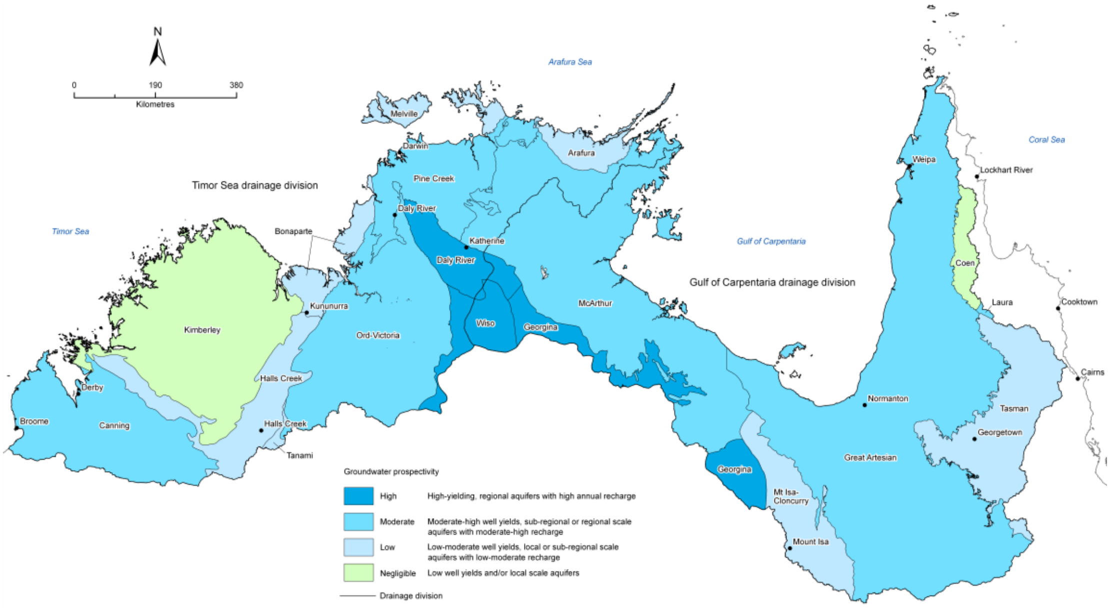



**Figure 3.26. Map showing generalised hydrogeology of northern Australia in terms of groundwater prospectivity (NALWTF, 2009).**

Groundwater quality is as variable as the aquifer type across northern Australia, although most groundwater is very fresh (<1,000 mg/L total dissolved solids) and generally exhibits no evidence of anthropogenic contamination. Some exceptions occur locally where commercial, industrial or agricultural activities have lead to point source pollution.

Groundwater recharge to surficial aquifers can either occur by diffuse rainfall recharge, river leakage or localised infiltration beneath floodplains following overbank flows. Preferential recharge via runaway holes in karst terrain has also been observed for the carbonate aquifers in the Daly region. Regardless of the mechanism, very few studies have been conducted in northern Australia to quantify recharge; and those that have generally relate to a very small area. Preliminary estimates of diffuse recharge rates were recently determined as part of the CSIRO Northern Australia Sustainable Yields project; using a combination of climate, soil and vegetation covers and a one-dimensional Soil-Vegetation-Atmospheric-Transfer model, recharge was estimated to range between <1 mm/yr and >200 mm/yr (Crosbie et al., 2009). Lowest recharge was determined for the most arid regions with vertisol soils and annual grasses (e.g., much of the Flinders-Leichhardt region), whereas highest recharge was generally associated with wet tropic climates and more permeable soil types.

Groundwater discharge occurs primarily via evapotranspiration from shallow water tables, and to a lesser extent via discharge to rivers and streams, and to the marine environment. Again very little is known about groundwater discharge mechanisms in northern Australia, particularly groundwater interactions with surface water and the associated ecosystem dependence upon groundwater.

#### 3.4.2.1 Groundwater discharge on the Dampier Peninsula of Western Australia

##### 3.4.2.2 Introduction

The Dampier Peninsula is located in northern Western Australia, north of the town of Broome. It covers a total area of approximately 157 000 square kilometres and measures approximately 175 kilometres from north to south and 150 kilometres from east to west (Figure 3.27). The water resources of the Dampier Peninsula are under increasing demand due to various proposals to develop areas for tourism, horticulture, forestry and infrastructure projects (DoW, 2009). The aim of this document is to summarise the currently available literature relevant to the potential study of groundwater discharge features on the Dampier Peninsula.

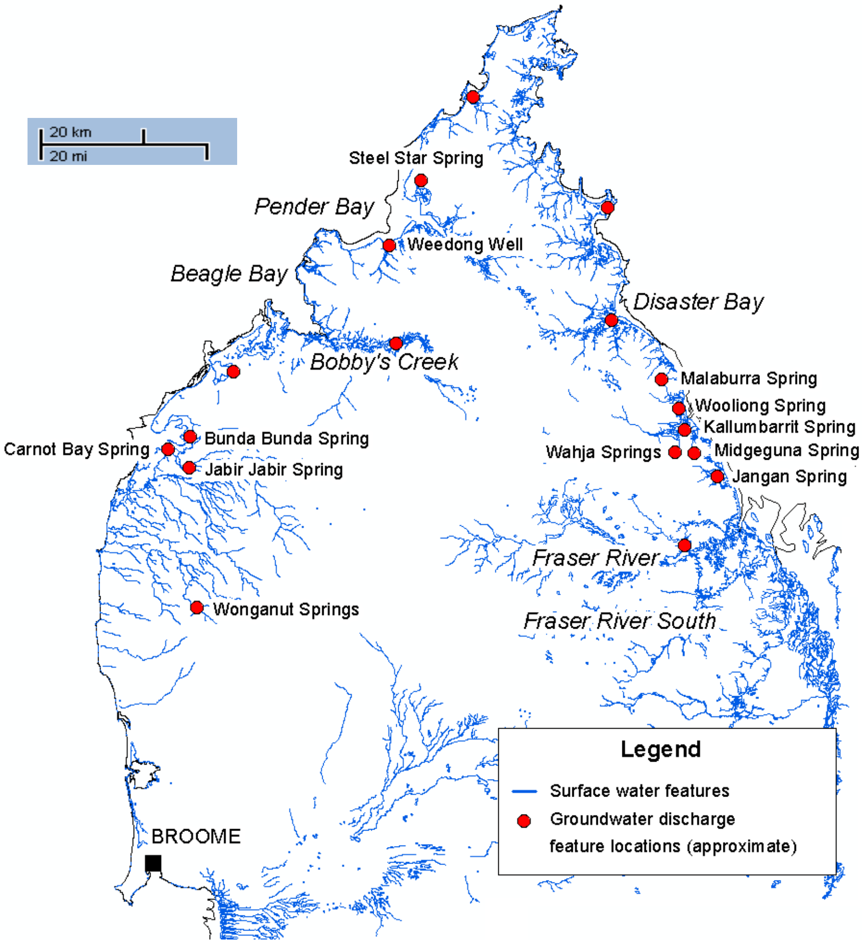



**Figure 3.27. Schematic map of Dampier Peninsula region showing the main surface water features and coastal springs (reproduced from (Rockwater Proprietary Limited, 2004))**

#### 3.4.2.3 Climate and Topography

For the purposes of the recent Northern Australia Sustainable Yields project, the Dampier Peninsula was included in the Fitzroy region, which features a mean annual rainfall of 560 mm, most of which (approximately 500 mm) falls between November and April. This region also features a strong north-south rainfall gradient (decreasing from 960 to 380 mm/yr) and a mean annual potential ET of 1980 mm (CSIRO, 2009c). Topographic relief across the Dampier Peninsula varies from 0 to 245 mAHD; higher elevations are located roughly in the centre of the Peninsula. The relatively flat slopes grading away from the centre of the Peninsula are incised by surface drainage lines that are ephemeral in nature (DoSD, 2010).

#### 3.4.2.4 Land use

The dominant land uses on the Dampier Peninsula are livestock grazing, indigenous use and conservation (CSIRO, 2009c). Land use on the southern half of the peninsula is predominantly grazing, including six pastoral stations (Country Downs, Kilto, Mount Jowlaenga, Roebuck Plains, Water Bank, and Yeeda). Land use on the northern end of the peninsula is predominantly by over 70 indigenous communities, the four largest being Ardyaloon (One Arm Point), Lombadina, Djarandjin, and Beagle Bay. Recent horticultural developments on the Dampier Peninsula have included trial plantations of native species as well as agroforestry trials of sandalwood species (DoW, 2009).

#### 3.4.2.5 Vegetation

The dominant vegetation type on Dampier Peninsula is Eucalyptus woodland (CSIRO, 2009c). Other vegetation types present include mangroves, coastal dune communities, rainforest assemblages, samphire, ephemeral grasslands and herblands, tussock grasslands and sedgelands, and various other woodland communities (DoW, 2009; Graham, 2001). Of particular interest to studies of groundwater discharge on the Dampier Peninsula are coastal dune communities and perennial wetlands. The coastal dunes of the Dampier Peninsula support a significant number of dispersed communities of monsoonal vine thickets, comprising a total area of approximately 1000 ha. These vine thickets occur on the leeward slopes of coastal dunes and are listed as threatened ecological species (DoW, 2009; Graham, 2001). Spatio-temporal data obtained from the Department of Water (WA) have recently been examined in order to identify vegetation features that are persistent throughout the year.

#### 3.4.2.6 Surface water

Drainage patterns of the Dampier Peninsula are dominated by small peripheral drainage lines, some of which support tidal mudflat and mangrove communities, particularly within the northern Dampier Peninsula. As a result of the prevailing meteorological conditions, most of the Dampier Peninsula is arid and the rivers are ephemeral, flowing only following infrequent heavy rainfall events. Due to the extensive Pindan sandplain soils, few drainage features, low elevation, and heavy seasonal (summer) rainfall patterns, surface water flows on the Dampier Peninsula are largely dominated by sheet flooding (DoSD, 2010). Surface water runoff is only generated after heavy summer rainfall and is quickly discharged. In the east and the northwest, streams are incised, and in the Coulomb Point-Cape Baskerville and Fraser River areas, a more rugged topography has developed with the streams cutting into and exposing the underlying sandstone. Some of the streams in the Point Coulomb Nature Reserve are intermittent, and fed for part of the dry winter season by spring flow from a perched aquifer; a few permanent streams are maintained from the same aquifer (Laws, 1991).

#### 3.4.2.7 Geology

The Dampier Peninsula is located within the larger Canning Basin and the geology of the area is predominantly of sedimentary origin (DoW, 2009). Surface geology on the peninsula is mainly regolith with some sandstone on the east coast (CSIRO, 2009c). The rocks and sediments interpreted to underlie the Dampier Peninsula comprise Precambrian age rocks overlying metamorphosed sediments and crystalline intrusive rocks. These are overlain by a sequence of Ordovician to Cretaceous Age lithified sediments, which are themselves overlain by Tertiary to Quaternary Age chemical precipitates and unconsolidated and partially consolidated sediments (DoSD, 2010).

#### 3.4.2.8 Hydrogeology

Groundwater on the Dampier Peninsula occurs in a range of aquifers and aquitards. The most utilised aquifer is the Broome Sandstone which is separated from the underlying aquifers by an aquitard, the Jarlemai Siltstone, which itself is underlain by the confined Wallal Sandstone aquifer. Overlying the Broome sandstone are Quaternary eolian sand aquifers, which are believed to contain significant perched groundwater. The coastal dunes immediately north of Broome are believed to be in hydraulic continuity with the Broome Sandstone, and are therefore provide an important source of recharge to the underlying Broome Sandstone (Laws, 1991).

#### 3.4.2.9 Eolian Sand Aquifer

Eolian sands of Quaternary age extend over an area of about 500 $km^2$ in the north of the Dampier Peninsula and form a major perched aquifer which overlies the Broome Sandstone. The thickness of these sands is unknown but may be up to 10 m. Recharge to the sands is by direct percolation of rainfall. The rate of recharge has been estimated from chloride ratios to be approximately 6.5% of rainfall. Groundwater salinities in the eolian sand aquifer are very low, ranging from 70 to 120 mg/L TDS. The groundwater is believed to be of sodium-chloride type, containing significant (approximately 30 mg/L) quantities of silica, which is possibly present as aluminium silicate (Laws, 1991).

#### 3.4.2.10 Broome Sandstone Aquifer

The Broome Sandstone aquifer is a multi-layered, unconfined aquifer system typically comprised of unconsolidated coarse-grained sandstone and conglomerates with intervening minor lenses of siltstone and claystone and thin coal seams. The relatively coarser grained materials produce higher yields and better quality water than the lower permeability siltstone, claystone and coal seams. Despite the aquifer being comprised of several water-bearing zones, there is little vertical difference in groundwater elevations between these water-bearing zones (Laws, 1991). Groundwater levels in the Broome Sandstone are approximately 2 m AHD near the coast, reflecting an unconfined aquifer with groundwater flow to the sea (Rockwater, 2004). From limited available data, groundwater levels inland are believed to form a mound in the centre of the Dampier Peninsula up to an elevation of approximately 60 m AHD (DoSD, 2010). Regional groundwater flow in the Broome Sandstone aquifer is influenced by topography and the location of groundwater recharge and discharge areas. Horizontal hydraulic head gradients are reported to be relatively flat, at around $4 \times 10^{-4}$ near the coast (Laws, 1991).

Groundwater recharge to the Broome Sandstone aquifer is by direct rainfall where the Broome Sandstone outcrops, by leakage from overlying Pindan soils (present over much of the peninsula) and coastal dune sands, and by infiltration of surface water from wetlands and drainage systems. Groundwater recharge is believed to vary throughout the peninsula according to rainfall intensity, depth to water table, location of drainage systems and the permeability of the Broome Sandstone materials (DoSD, 2010). Recharge to the Broome Sandstone aquifer was estimated from chloride ratios and from interpretation of aquifer flow nets to be approximately 4 to 5% of rainfall (Laws, 1991). Groundwater discharge on the peninsula typically occurs into the ocean over a saline interface at the coast. Some discharge via seepage faces along the coast and evapotranspiration is also believed to occur (DoSD, 2010). Groundwater storage in the Broome Sandstone has been estimated at approximately 84 x $10^9$ $m^3$ (Laws, 1991).

Groundwater salinities in the Broome Sandstone aquifer are in the range of 250 to 500 mg/L TDS (DoSD, 2010). The groundwater is essentially a sodium chloride type, with occasional high levels of bicarbonate. Observed concentrations of magnesium and sulphate are believed to be related to saline water, either from the coastal saltwater wedge or from entrapped seawater around the formerly more extensive tidal inlets. Silica levels are very high, ranging from 18 to 119 mg/L. In station and private bores, nitrate levels are frequently in excess of 40 mg/L, probably due to nitrate fixation by native plant species (Laws, 1991).

#### 3.4.2.11 Wallal Aquifer

The Wallal aquifer is interpreted to lie between the elevations of -400 to -600 m AHD (Rockwater, 2004). It is confined or semi-confined by the Jarlemai Siltstone which forms an aquitard and separates it from the overlying Broome Sandstone aquifer (Laws, 1991). The Wallal aquifer includes the sedimentary sequences of the Alexander Formation (a fine-grained, weakly cemented sandstone) and the Wallal Sandstone (a fine to coarse-grained, poorly consolidated sandstone). Intervening lenses of siltstone are present in the Alexander Formation and Wallal Sandstone. Artesian pressures have been observed in bores at Broome and Cable Beach, suggesting the aquifer may be artesian along the west coast of the peninsula (Laws, 1991). Recharge is believed to occur via direct rainfall where the Alexander Formation and Wallal Sandstone outcrop and from leakage from overlying aquifers such as the Broome Sandstone (DoSD, 2010). To date, a lack of data has prevented a quantitative assessment of recharge rates, but a recharge rate of about 3% of rainfall has previously been suggested (Laws, 1991). Regional groundwater flows in a westerly direction, likely discharging off the coast (DoSD, 2010). Groundwater salinity is believed (based on limited information) to range from around 1500 to 5500 mg/L TDS (which is typically higher than the Broome Sandstone aquifer) and is of sodium-chloride type. Noticeable concentrations of sulphate, calcium and magnesium have also been observed (Laws, 1991).

#### 3.4.2.12 Groundwater Use

The Dampier Peninsula is located within the Canning-Kimberley Groundwater Area. Groundwater abstraction is currently subject to licensing under the Rights in Water and Irrigation Act 1914 (DoSD, 2010). There are 10 groundwater licences (predominantly extracting from the Broome Sandstone aquifer) on the Dampier Peninsula outside the Broome groundwater area, with annual extraction totalling around 0.35 GL. The groundwater is used for a variety of purposes including agroforestry, community water supply, petroleum exploration and road infrastructure maintenance (DoSD, 2010).

#### 3.4.2.13 Mound Springs

Mound springs and perennial wetlands are a feature of the Dampier Peninsula, supporting unique assemblages of floral and faunal species. They possess cultural significance to indigenous communities and are recognised food gathering sites (DoW, 2009). Several of these sites have been classified (by the Department of Environment and Conservation WA) as being ecosystems at risk, including springs at Bunda-Bunda, Disaster Bay, and Lolly Well, as well as the Willie Creek wetlands (DoW, 2009). Bunda-Bunda springs and Willie Creek wetlands have also been classified as being of national significance (DoW, 2009). From this literature review it may be noted that there currently exists very little information with regards to the hydrology of the Dampier Peninsula mound springs, and of the hydrogeology and hydrogeochemistry of the Peninsula more generally.

#### 3.4.2.14 Possible Conceptualisations

The mechanism by which groundwater is discharged at mound springs on the Dampier Peninsula is not currently well understood. In the absence of detailed hydrochemical analyses, which would enable improved characterisation of the hydrology of the springs, two mechanisms have previously been proposed. Firstly, it has been suggested that numerous springs originate from the perched Eolian sands aquifer (Laws, 1991). Such discharges may occur where either (a) an abutment is present between the aquifer and a relatively low permeability formation (Figure 3.28), or (b) a break in slope occurs, such as seen on the leeward side of coastal dunes (Figure 3.29). It is therefore possible that some groundwater discharge features such as coastal vine thickets may be accessing perched phreatic groundwater.

Alternatively, it has been observed that the confined Wallal aquifer features artesian pressures in locations in the west of the Dampier Peninsula (Laws, 1991). Under natural conditions, artesian pressures require the presence of high-transmissivity geological features in order for groundwater flow to reach the surface (Figure 3.30). Given the presence of numerous east-west faults on the Dampier Peninsula, it is therefore suggested that features such as mound springs may be dependent upon surface discharge of artesian flow from the Wallal aquifer.

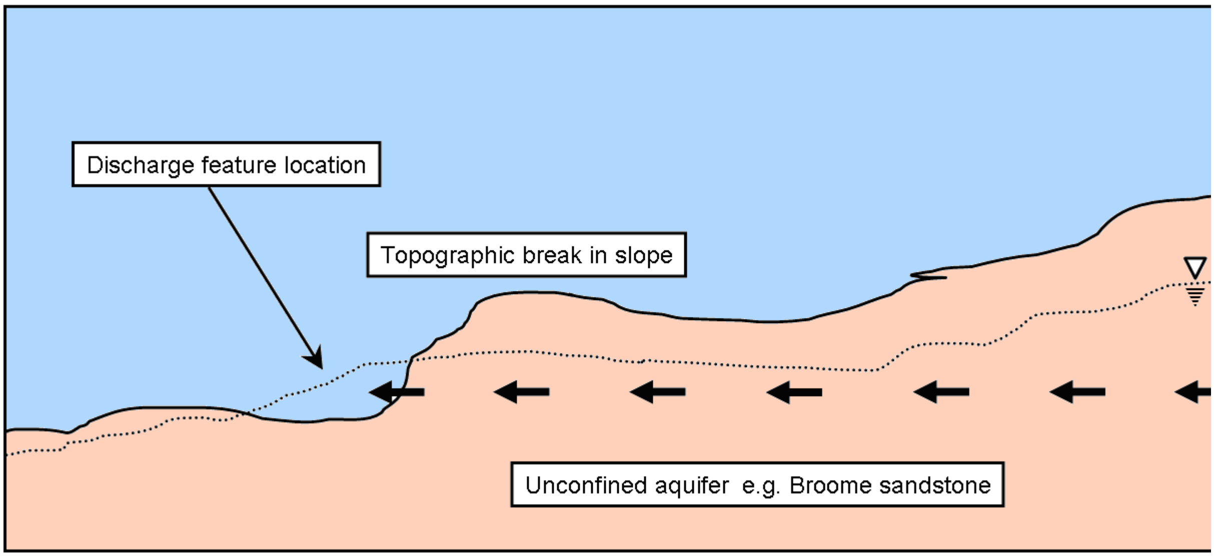



**Figure 3.28. Surface groundwater discharge from a perched unconfined aquifer due to aquifer abutment**

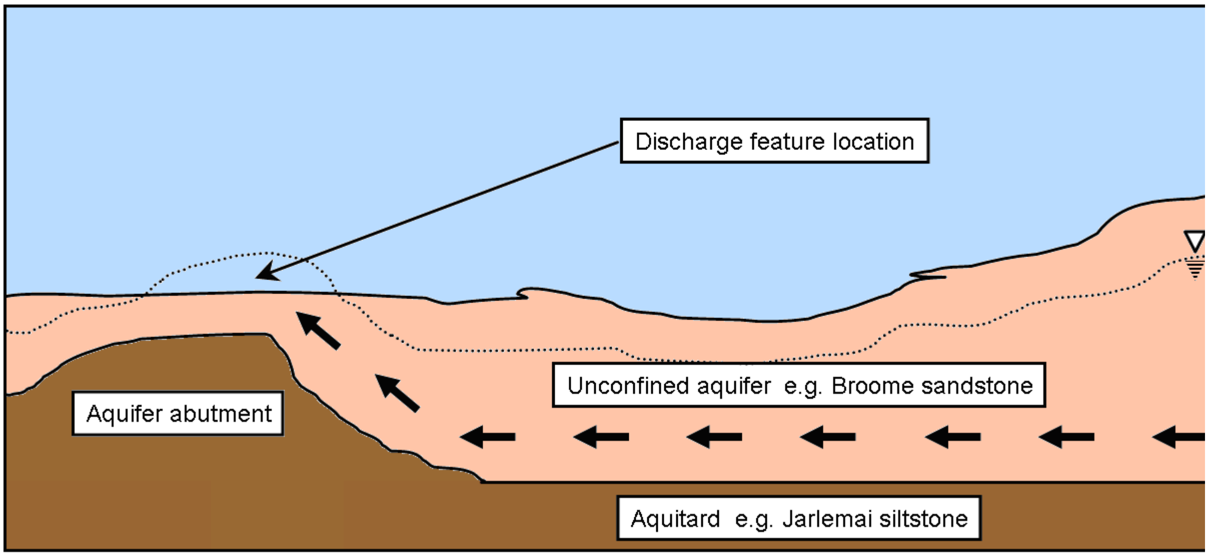



**Figure 3.29. Surface groundwater discharge from a perched unconfined aquifer due to break in topographic slope**

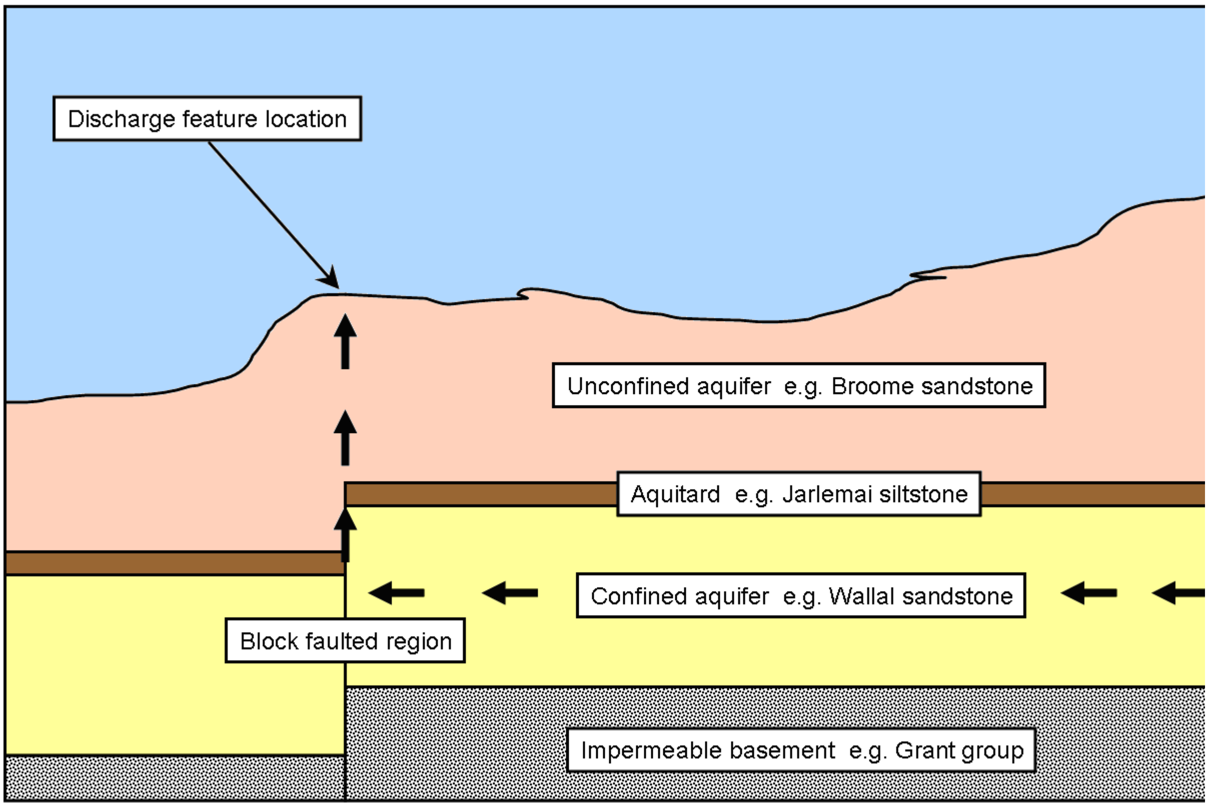



**Figure 3.30. Surface groundwater discharge from a confined artesian aquifer due to high transmissivity faults**

#### 3.4.2.15 Proposed Hydrogeological Investigations

Firstly, it is suggested that all available information relating to production and observation bores on the Dampier Peninsula be collated. From these data, the spatial distribution of potentiometric water levels may be mapped for all relevant hydrogeological units. These results may then be used to infer the directions and magnitudes of groundwater flow gradients. The Department of Water (WA) are currently undertaking a review of all relevant hydraulic and geological information.

Secondly, in order to better characterise the groundwater discharge features of the Dampier Peninsula, it is suggested that the following data collection be undertaken. Water sampling would enable the hydrochemical composition of various discharge features to be determined. These analyses could then be compared to the known compositions of the eolian sands, Broome sandstone and Wallal aquifers, in order to confirm or exclude potential water sources for groundwater discharge features. Groundwater age tracers could also be sampled in order to estimate the ages of the water discharged. For samples in which hydrochemistry alone is insufficient to characterise groundwater origin, age tracers may serve to distinguish between aquifers of similar chemistry; for example, between the eolian sand and Broome sandstone aquifers.

### 3.4.2.16 Surface water regimes (Service 1)

#### 3.4.2.16.1 Queensland

In four of the catchments in Queensland (Mitchell, Leichhardt, Flinders and Gilbert) river flow was modelled using the IQQM program, set up by the Department of Environment and Resource Management to support the Queensland Water Resource Planning Process (Petheram et al., 2009a). As part of the NASY project runoff in the above catchments was derived for the 77 year period from 1890 to 2008 (Petheram et al., 2009b) and the results used as input to a river model which includes water storages and abstractions (Petheram et al., 2009a). The water sharing rules used in this model were taken from the draft Gulf Resource Operations Plan (DNRW, 2008) and the level of development included in some of the model runs is based on the full use of existing entitlements. To describe the current surface hydrological conditions in these catchments we report on three scenarios:

- Scenario AN – historical climate without any of the existing development entitlements.
- Scenario C –future climate and no development of water resources.
- Scenario D – future climate and full development of water entitlements

The current level of water use in these catchments is unknown, but must be somewhere between no use of water entitlements and full use of water entitlements.

**Historical climate**

The Flinders-Leichardt region receives an annual average rainfall of 493 mm, most of which (96%) falls in the November to April wet season. Across the region there is a strong north–south gradient in annual rainfall, ranging from 812 mm in the north to 331 mm in the south. Potential evapotranspiration (PET) is very high across the region, averaging 1939 mm/year, with highest rates occurring in the wet season. PET generally remains higher than rainfall throughout the year resulting in year-round water-limited conditions.

The Gilbert and Mitchell region receives an average of 965 mm of rainfall per annum, most of which (95%) falls in the wet season. Across the region there is a strong north-west to south-east gradient in annual rainfall, ranging from 1615 mm in the north-west to 714 mm in the south-east. Potential evapotranspiration (PET) is very high across the region, averaging 1905 mm/year and varies moderately across the seasons. PET is higher than rainfall for most of the year resulting in water-limited conditions, with the exception of the period January to March, when more rain falls than can potentially be evaporated.

**Leichardt River**

The Leichhardt catchment (Figure 3.31) extends from the headwaters of the river basin that includes Rifle Creek south of Mount Isa, to the mouth of the Leichhardt River on the Gulf of Carpentaria north-east of Burketown. The most downstream flow monitoring station is the Floraville gauge (913007). The tributaries of the Leichhardt system include Alexandra River, Paroo Creek, Gunpowder Creek, Mistake Creek, Gorge Creek, Rifle Creek, Fiery Creek and Doughboy Creek. This river system is represented in the IQQM model by 42 river sections and 122 nodes (see Petheram et al., 2009b). Thirty-one of these nodes are water accounting nodes which are used for simulating water-harvesting rules in the lower section of the basin. There are also five large storages and four smaller in-stream storages in the model. The maximum volume of water that can currently be extracted from this river under the draft *Gulf Resource Operations Plan* is given in Table 3.1. Unsupplemented water is defined as surface water that is not sourced from a water storage that is able to regulate or control supply to users. Agriculture, mining and town waters supplies have approximately equal water abstraction entitlements, around 31 to 33 GL $year^{-1}$ each.

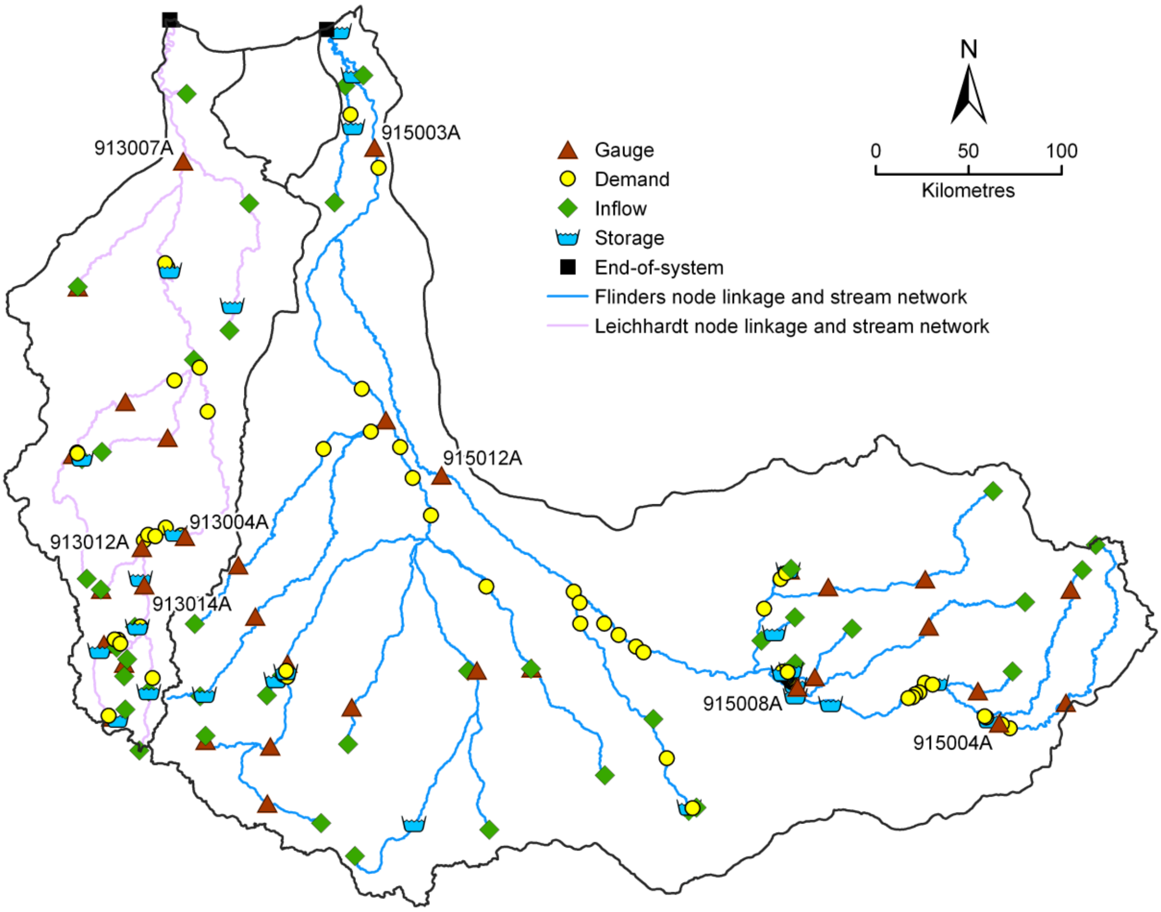



**Figure 3.31. Schematic diagram the Leichhardt river system model (pink lines) and the Flinders river system model (blue lines) including the location of gauging stations, main demand nodes and storages (reproduced from Petheram et al., (2009a)).**

The mean annual water balance of the Leichardt river system with historical climate and full entitlement use is shown as Scenario A* in Table 3.4. Most of the flow in this catchment is ungauged (89%) with diversions (at maximum current entitlements) that would amount to 43% of losses between the catchment inflow and outflow. Unattributed fluxes in Table 3.4 are the modelled river losses, estimated during calibration of the IQQM model such that flow is conserved between upstream and downstream gauging stations. Further details of the IQQM model setup and application in this catchment are given by Petheram et al., (2009).

**Table 3.4. The river system model mean annual water balance under Scenario A* for the Leichardt, Flinders, Gilbert and Mitchell Rivers (reproduced from Petheram et al., (2009a)).**

| | Leichardt | Flinders | Gilbert | Mitchell |
|---|---|---|---|---|
| | GL year$^{-1}$ | | | |
| Inflows | | | | |
| Subcatchments | | | | |
| Gauged | 233 | 536 | 775 | 2879 |
| Ungauged | 1808 | 2404 | 5094 | 10676 |
| **Sub-total** | **2041** | **2940** | **5868** | **13555** |
| Diversions | | | | |
| Agriculture | | | | |
| General Security | 7.8 | 13.1 | 3.0 | **-** |
| Unsupplemented | 23.6 | 86.7 | 18.7 | 29.8 |
| Mining | | | | |
| High Security | 29.4 | - | 6.6 | - |
| Unsupplemented | 3.8 | - | 0.4 | 10.1 |
| Town Water Supply | | | | |
| High Security | 32.3 | 3.3 | - | - |
| Unsupplemented | - | 0.0 | 0.0 | 0.2 |
| Other Uses | | | | |
| High Security | 13.9 | 2.5 | 0.2 | 20.0 |
| Unsupplemented | **-** | 1.4 | **-** | 14.9 |
| **Sub-total** | **111.0** | **107** | **29.0** | **75.0** |
| Outflows | | | | |
| End-of-system flow | 1785 | 1982 | 5304 | 12023 |
| **Sub-total** | **1785** | **1982** | **5304** | **12023** |
| Net evaporation | | | | |
| Major storages | 71.6 | 10 | 5 | 26.9 |
| Other Storages | 1.2 | - | - | 1.8 |
| **Sub-total** | **72.8** | **10** | **5** | **28.7** |
| Unattributed fluxes | **72** | **841** | **530** | **1428** |

### Standard high and low flow metrics

Analysis of high and low flow metrics were undertaken at four locations (913012A, 913004A, 913007A and 913014A) which correspond to stream gauging sites within the Leichhardt River catchment, Figure 3.31. In this section we report and interpret the results for one of these locations; results for the other three locations are given in Appendix A.

The standard high and low flow metric analysis results for the Leichhardt River are shown in Table 3.5 for the most downstream gauge at Floraville Homestead (913007A). Based on Scenario AN, most of the flow (96%) occurs during the wet season, with the river having a long average annual zero flow period of 153 days. The greatest changes in annual and wet season flow (>28% increase) occur under Scenarios Cwet and Dwet. Changes to dry season flow are extreme under both Cwet (66% increase) and Cdry (39% reduction). The combination of development and driest climate results in more than a 30% reduction in annual stream flow.

The greatest impact on the low flow characteristics at this location come from the combination of development and dry climate (Ddry). Under such conditions the number of days of zero flow increases by 25% (52 days/year). Impacts on low flow are also high under the wet climate and development (Dwet) with the number of days of zero flow decreasing by 37 days/year.

Changes to the flow regime at high flows are more modest with only Scenario Ddry resulting in the number of days above the high flow threshold and the number of high flow events reducing by more than 25%. The wet season rate of rise increased by 27% under Scenario Cwet and decreased by 33% under Scenario Ddry. The wet season rate of fall was reduced by 30% by the combination of dry climate and development (Ddry).

**Table 3.5. Standard metrics for changes to flow regime on the Leichhardt River at Floraville Homestead under Scenarios C and D relative to Scenario AN. Red text indicates changes of more than 25% relative to Scenario AN.**

| Leichhardt - Leichhardt River at Floraville Homestead, Gauge No. 913007A | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Standard metrics | Units | AN | Cwet | Cmid | Cdry | Dwet | Dmid | Ddry |
| | | | change from Scenario A | | | | | |
| General metrics | | | | | | | | |
| Annual flow (mean) | GL | 1368 | +30% | +19% | -23% | +18% | +8% | -33% |
| Wet season flow (mean)* | GL | 1315 | +28% | +19% | -22% | +18% | +9% | -32% |
| Dry season flow (mean)** | GL | 63.9 | +66% | +23% | -39% | +38% | -3% | -55% |
| Low flow metrics | | | | | | | | |
| Low flow threshold (discharge exceeded 90% of the time in Scenario A) | GL/d | 0 | | | | | | |
| Number of days below low flow threshold (mean) | d/y | 153 | -8.8 | -0.5 | +24.6 | +37.1 | +41.8 | +52.2 |
| Duration of flow events below low flow threshold (mean) | d/y | 23.7 | +0.3 | -0.8 | +1.1 | +0.2 | +0.5 | 0 |
| Number of events below low flow threshold (mean) | events/y | 6.48 | -0.4 | +0.2 | +0.7 | +1.5 | +1.6 | +2.2 |
| Number of days of zero flow (mean) | d/y | 153 | -8.8 | -0.5 | +24.6 | +37.1 | +41.8 | +52.2 |
| High flow metrics | | | | | | | | |
| High flow threshold (discharge exceeded 5% of the time in Scenario A) | GL/d | 11.9 | | | | | | |
| Number of days above high flow threshold (mean) | d/y | 18.3 | +2.6 | +1.7 | -2.9 | +0.3 | -0.4 | -4.9 |
| Duration of flow events above high flow threshold (mean) | d/y | 5.39 | +0.2 | +0.1 | +0.1 | +0.3 | 0 | +0.5 |
| Number of events above high flow threshold (mean) | events/y | 3.39 | +0.4 | +0.3 | -0.6 | -0.1 | -0.1 | -1.1 |
| Wet season rate of rise (mean) | GL/d | 3.35 | +0.9 | +0.7 | -0.7 | +0.5 | +0.3 | -1.1 |
| Wet season rate of fall (mean) | GL/d | 2.02 | +0.5 | +0.5 | -0.5 | +0.3 | +0.3 | -0.6 |

*Wet season covers the six months from November to April
**Dry season covers the six months from May to October
nm – not modelled

## Flinders River

The Flinders catchment (Figure 3.31) extends from the headwaters in the east upstream of Hughenden on the Flinders River and in the west upstream of Cloncurry on Cloncurry River, to the mouth of the Flinders River on the Gulf of Carpentaria west of Karumba. The Cloncurry River joins the Flinders River just upstream of the outlet to the ocean. The Walkers Bend gauge (915003A) is the most downstream flow monitoring station in the system. The tributaries of the Flinders system include Porcupine Creek, Betts Creek, Dutton River, Mountain Creek, Stawell River and Woolgar River which contribute to the Flinders River flows and Malbon River, Williams River, Gilliat River, Julia Creek, Corella River and Dugald River which contribute to the Cloncurry River flows.

The Flinders river system is represented in the IQQM model by 55 river sections and 170 nodes. Twelve of these nodes are water demand nodes which are used for simulating water-harvesting rules in the lower section of the basin. There are two main storages represented in the model, Corella Dam and Chinaman Creek Dam, and ten smaller in-stream storages.

The maximum volume of water that can currently be extracted from this river under the draft *Gulf Resource Operations Plan* is given in Table 3.4. Agriculture has the largest water allocation in this catchment (98% of all entitlements), with town waters supplies and other uses having 3 to 4 GL year$^{-1}$ each.

The mean annual water balance of the Flinders River system with historical climate and full entitlement use is shown as Scenarios A* in Table 3.4. Again most of the flow in this catchment is ungauged (82%) with diversions (at maximum current entitlements) that would amount to 11% of losses between the catchment inflow and outflow. Unattributed fluxes or modelled river losses are much greater than the total planned diversions at 88% of all losses between the catchment inflow and outflow (Table 3.4). Further details of the IQQM model setup and application in this catchment are given by Petheram et al., (2009a).

## Standard high and low flow metrics

Analysis of high and low flow metrics were undertaken at four locations (915003A, 915004A, 915008A and 915012A) which correspond to stream gauging sites within the Flinders River catchment, Figure 3.31. In this section we report and interpret the results for one of these locations; results for the other three locations are given in Appendix A.

The standard high and low flow metric analysis results for the Flinders River are shown in Table 3.6 for the most downstream gauge at Walkers Bend (915003A). Based on Scenario AN, annual flows are dominated by the wet season contribution (97%). This location also experiences a long average annual zero flow period of 245 days/year. Annual, wet season and dry season flow increase greatly under Scenario Cwet although these increases are not quite as large with the addition of development entitlements (Dwet). The dry climate scenarios (Cdry and Ddry) result in large reductions (>25%) in annual flow mainly as a result of reduced wet season flow.

**Table 3.6. Standard metrics for changes to flow regime on the Flinders River at Walkers Bend under Scenarios C and D relative to Scenario AN. Red text indicates changes of more than 25% relative to Scenario AN.**

| Flinders - Flinders River at Walkers Bend, Gauge No. 915003A | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Standard metrics | Units | AN | Cwet | Cmid | Cdry | Dwet | Dmid | Ddry |
| | | | change from Scenario A | | | | | |
| General metrics | | | | | | | | |
| Annual flow (mean) | GL | 2023 | +32% | +2% | -25% | +28% | -2% | -29% |
| Wet season flow (mean)* | GL | 1968 | +30% | +2% | -25% | +26% | -2% | -29% |
| Dry season flow (mean)** | GL | 72.7 | +83% | -2% | -15% | +75% | -9% | -21% |
| Low flow metrics | | | | | | | | |
| Low flow threshold (discharge exceeded 90% of the time in Scenario A) | GL/d | 0 | | | | | | |
| Number of days below low flow threshold (mean) | d/y | 245 | -5.7 | +2.2 | +9.1 | +5.7 | +13.7 | +20.9 |
| Duration of flow events below low flow threshold (mean) | d/y | 67.0 | -0.1 | +2.3 | +2 | +1.5 | +2.5 | +6 |
| Number of events below low flow threshold (mean) | events/y | 3.66 | -0.1 | -0.1 | 0 | 0 | +0.1 | 0 |
| Number of days of zero flow (mean) | d/y | 245 | -5.7 | +2.2 | +9.1 | +5.7 | +13.7 | +20.9 |
| High flow metrics | | | | | | | | |
| High flow threshold (discharge exceeded 5% of the time in Scenario A) | GL/d | 26.0 | | | | | | |
| Number of days above high flow threshold (mean) | d/y | 18.2 | +3.3 | +0.5 | -3.4 | +2.6 | -0.4 | -4.3 |
| Duration of flow events above high flow threshold (mean) | d/y | 8.46 | +1.4 | +0.2 | -0.3 | +1.2 | -0.1 | -0.7 |
| Number of events above high flow threshold (mean) | events/y | 2.16 | 0 | 0 | -0.3 | 0 | 0 | -0.4 |
| Wet season rate of rise (mean) | GL/d | 6.69 | +1.5 | +0.6 | -1.5 | +1.5 | +0.9 | -1.2 |
| Wet season rate of fall (mean) | GL/d | 4.06 | +0.8 | +0.6 | -0.9 | +1 | +0.7 | -0.8 |

*Wet season covers the six months from November to April
**Dry season covers the six months from May to October
nm – not modelled

Changes to the low flow conditions at this location are relatively modest with the biggest change to the number of days of zero flow being less than 10% (Scenario Ddry). The number of low flow events changed very little and there were only modest increases in the duration of low flow events (Table 3.6).

Changes to the high flow regime were also modest with Scenario Ddry resulting in the largest reduction in the number of days above the high flow threshold (24%). The greatest increase in the duration of events above the high flow threshold occurred under Scenario

Cwet (16%) and the greatest decrease occurred under Scenario Ddry (8%). The wet season rate of rise changed only modestly across all scenarios.

**Gilbert River**

The Gilbert catchment (Figure 3.32) extends from the headwaters adjacent to the Burdekin catchment, to the mouth of the Gilbert River on the Gulf of Carpentaria. The Miranda Downs gauge on the Gilbert River (917009A) is the most downstream flow monitoring station in the system. However, this gauge was closed in 1989. The most downstream flow monitoring station which is still open is the Rockfields gauge on the Gilbert River (917001D). The Gilbert River is the principal stream, and major tributaries are: Copperfield River, Einasliegh River, Etheridge River, Robertson River, Percy River, Little River, McKinnons Creek, Elizabeth Creek and Agate Creek.

The Gilbert river system is represented in the IQQM model by 43 river sections and 182 nodes. Eleven of these nodes are water demand nodes which are used for simulating water-harvesting rules in the lower section of the basin. There is only one major main storage the Copperfield Dam which was constructed on the Copperfield River during 1984 to provide an assured freshwater supply for the Kidston Gold Mine. Although the mine is now closed, the storage capacity of the dam (21,000 ML) is included in the river model.

The maximum volume of water that can currently be extracted from this river under the draft *Gulf Resource Operations Plan* is given in Table 3.1. Agriculture has the largest water allocation in this catchment (75 of all entitlements), with a mining entitlement of 7 GL year$^{-1}$ and on significant town water supply.

The mean annual water balance of the Gilbert River system with historical climate and full entitlement use is shown as Scenarios A* in Table 3.4. Again most of the flow in this catchment is ungauged (87%) with diversions (at maximum current entitlements) that would amount to 5% of losses between the catchment inflow and outflow. Unattributed fluxes or modelled river losses dominate (at 94%) the losses between the catchment inflow and outflow (Table 3.4). Further details of the IQQM model setup and application in this catchment are given by Petheram et al., (2009a).

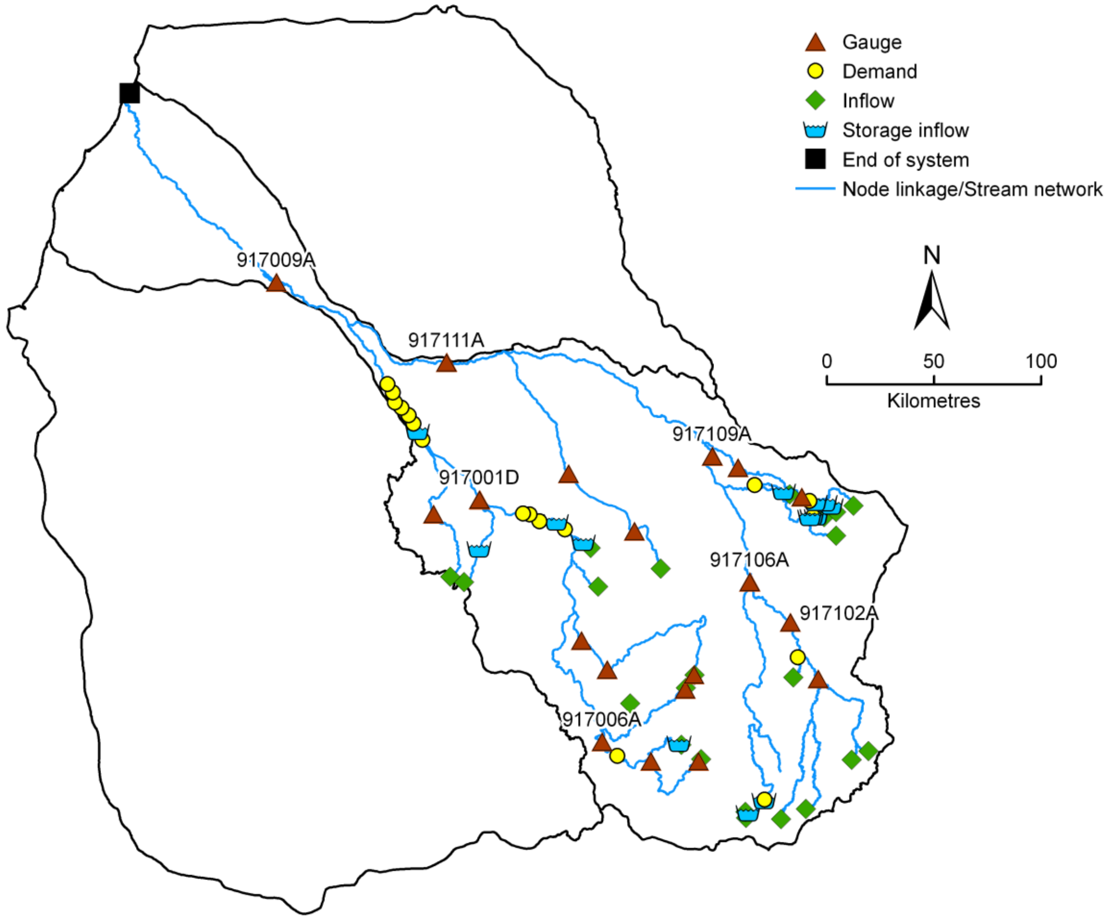



**Figure 3.32. Schematic diagram the Gilbert river system model (blue lines) including the location of gauging stations, main demand nodes and storages (reproduced from Petheram et al.,(2009a)).**

### Standard high and low flow metrics

Analysis of high and low flow metrics were undertaken at four locations (917001D, 917009A, 917102A and 917109A) which correspond to stream gauging sites within the Gilbert River catchment, Figure 3.32. In this section we report and interpret the results for one of these locations; results for the other three locations are given in Appendix A.

The standard high and low flow metric analysis results for the Gilbert River system are shown in Table 3.7 for the Gilbert River at Miranda Downs (917009A). Based on Scenario AN, nearly all of the flow (99%) occurs during the wet season, with the river having a long average annual zero flow period of 123 days. The greatest changes in dry season flow occur under Scenarios Cdry and Ddry with reductions in flow of 31% and 33%, respectively. Mean annual flows increase by 23% under Scenario Cwet and decrease by 15% under Scenario Ddry.

The impact of development and climate change on low flows metrics at this location is relatively modest. The greatest increases in the number of zero flow days arise from Scenarios Cdry (11%) and Ddry (18%). The duration and number of low flow events changes only slightly across scenarios.

The number of days above the high flow threshold shows only limited variation across the different scenarios as does the duration and number of high flow events. The greatest change in the high flow metrics relative to Scenario AN is an increase in the rate of rise by more than 50% and a decrease in the rate of fall of 30% under Scenario Cwet.

**Table 3.7. Standard metrics for changes to flow regime on the Gilbert River at Miranda Downs under Scenarios C and D relative to Scenario AN. Red text indicates changes of more than 25% relative to Scenario AN.**

| Gilbert - Gilbert River at Miranda Downs, Gauge No. 917009A | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Standard metrics | Units | AN | Cwet | Cmid | Cdry | Dwet | Dmid | Ddry |
| | | | change from Scenario A | | | | | |
| General metrics | | | | | | | | |
| Annual flow (mean) | GL | 3724 | +23% | +7% | -15% | +22% | +7% | -15% |
| Wet season flow (mean)* | GL | 3704 | +23% | +8% | -14% | +22% | +7% | -15% |
| Dry season flow (mean)** | GL | 47.1 | +21% | -1% | -31% | +18% | -4% | -33% |
| Low flow metrics | | | | | | | | |
| Low flow threshold (discharge exceeded 90% of the time in Scenario A) | GL/d | 0 | | | | | | |
| Number of days below low flow threshold (mean) | d/y | 123 | -3.5 | -0.6 | +14.1 | +6 | +9.5 | +22 |
| Duration of flow events below low flow threshold (mean) | d/y | 33.0 | 0 | 0 | +1.7 | +2.6 | +1.3 | +2.6 |
| Number of events below low flow threshold (mean) | events/y | 3.73 | -0.1 | 0 | +0.2 | -0.1 | +0.1 | +0.4 |
| Number of days of zero flow (mean) | d/y | 123 | -3.5 | -0.6 | +14.1 | +6 | +9.5 | +22 |
| High flow metrics | | | | | | | | |
| High flow threshold (discharge exceeded 5% of the time in Scenario A) | GL/d | 39.5 | | | | | | |
| Number of days above high flow threshold (mean) | d/y | 18.3 | +2.3 | +0.7 | -1.8 | +2.2 | +0.6 | -2.1 |
| Duration of flow events above high flow threshold (mean) | d/y | 4.77 | +0.3 | 0 | -0.1 | +0.2 | 0 | -0.2 |
| Number of events above high flow threshold (mean) | events/y | 3.83 | +0.2 | +0.1 | -0.3 | +0.3 | +0.1 | -0.3 |
| Wet season rate of rise (mean) | GL/d | 21.6 | +6.5 | +1.6 | -3.7 | +6.7 | +1.7 | -3.6 |
| Wet season rate of fall (mean) | GL/d | 12.7 | +3.8 | +1 | -1.7 | +4.1 | +1 | -1.6 |

*Wet season covers the six months from November to April
**Dry season covers the six months from May to October
nm – not modelled

**Mitchell River**

The IQQM model for this catchment (Figure 3.33) does not extend over the whole Mitchell River basin, but excludes the upper catchment areas of the Mitchell and Walsh rivers which are included in the *Barron Water Resources Plan* area, and these catchments are modelled in the Barron River IQQM. The upstream limits of the model are the Walsh River at the

Flatrock stream flow recorder and the Mitchell River at AMTD 601.2 km. The simulated outflows from the Barron River IQQM at these locations become the inflows to the Mitchell River IQQM. Inflows include inter-valley transfer from the Barron River for irrigation diversions in the upper reaches of the Walsh and Mitchell rivers. The net average annual diversion from the Barron system is 6.2 GL year$^{-1}$ (diversions less transfers). The downstream limit of the model is the mouth of the Mitchell River. The stream gauging station at Koolatah (919009A) is the most downstream location at which flow records are available. This station monitors flow from approximately two-thirds of the river basin. The Mitchell River is the principal stream and major tributaries of the Mitchell River are the Palmer, Walsh, Lynd and Tate rivers.

Grazing is the predominant land use over the basin. Some irrigated agriculture is practised in the upper reaches of the Walsh and Mitchell rivers, where irrigation supplies are obtained from the Mareeba-Dimbulah Water Supply Scheme. Within the area modelled the main consumptive water uses are small-scale irrigation and small mines.

The Mitchell river system is represented in the IQQM model by 27 river sections and 124 nodes. Five of these nodes are water demand nodes which are used for simulating water-harvesting rules in the lower section of the basin. There is only one major storage, Southedge Dam, and five smaller in-stream storages, are represented in the model.

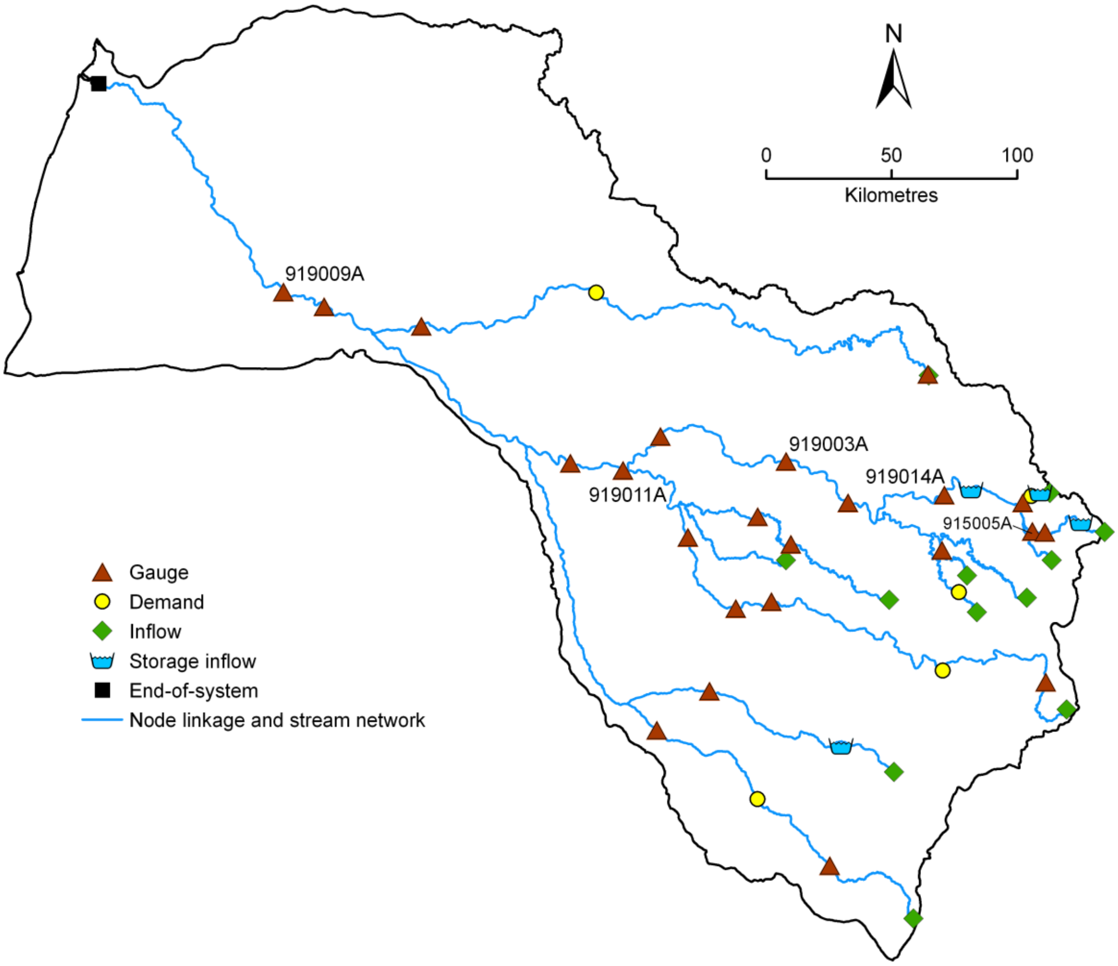



**Figure 3.33. Schematic diagram the Mitchell river system model (blue lines) including the location of gauging stations, main demand nodes and storages (reproduced from Petheram et al., (2009a)).**

The maximum volume of water that can currently be extracted from this river under the draft *Gulf Resource Operations Plan* is given in Table 3.4. Agriculture has the largest water allocation in this catchment (40% of all entitlements), with a mining entitlement of 10 GL year$^{-1}$ and a further 25 GL year$^{-1}$ for other uses.

The mean annual water balance of the Gilbert River system with historical climate and full entitlement use is shown as Scenarios A* in Table 3.4. Again most of the flow in this catchment is ungauged (79%) with diversions (at maximum current entitlements) that would amount to 5% of losses between the catchment inflow and outflow. Unattributed fluxes or modelled river losses dominate (at 93%) the losses between the catchment inflow and outflow (Table 3.4). Further details of the IQQM model setup and application in this catchment are given by Petheram et al., (2009a).

**Standard high and low flow metrics**

Analysis of high and low flow metrics were undertaken at four locations (919011A, 919014A, 919009A and 919311A) which correspond to stream gauging sites within the Mitchell River catchment, Figure 3.33. In this section we report and interpret the results for one of these locations; results for the other three locations are given in Appendix A.

The standard high and low flow metric analysis results for the Mitchell River system are shown in Table 3.8 for the Mitchell River at Koolatah (919009A). Under Scenario AN annual flow into this location is highly dominated by wet season flows (97%). Annual and seasonal flows do not change much under Scenario Cmid (4 to 16%) compared to Scenario AN, but there are large increases under Scenario Cwet (33 to 41%). Under Scenario Cdry there are large decreases in wet season flow (25%) and dry season flow (37%) compared to Scenario AN. The introduction of the development scenarios had only a small additional impact on top of the climate scenarios.

Under Scenario Cdry, there is almost twice the number of days with flow that is below the low flow threshold as defined by Scenario AN and this increases by a further 10 days with the addition of development entitlements. The number of days of zero flow more than doubles under Scenario Cdry and more than triples under Scenario Ddry. The duration and number of events below the low flow threshold also increases for these scenarios.

Compared to Scenario AN, there are large increases and decreases in the high flow threshold exceedance under scenarios Cwet and Cdry respectively, with little change under Scenario Cmid. The development scenarios add little impact to the flow regime relative to the climate scenarios. The wet season rate of rise changed only modestly across all scenarios, with the exception of Cwet and Dwet, where the rate of rise increased by 42% and the rate of fall increased by 38%.

**Table 3.8. Standard metrics for changes to flow regime on the Mitchell River at Koolatah under Scenarios C and D relative to Scenario AN. Red text indicates changes of more than 25% relative to Scenario AN.**

| Mitchell - Mitchell river at Koolatah, Gauge No. 919009A | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Standard metrics | Units | AN | Cwet | Cmid | Cdry | Dwet | Dmid | Ddry |
| | | | change from Scenario A | | | | | |
| General metrics | | | | | | | | |
| Annual flow (mean) | GL | 6786 | +41% | -4% | -25% | +40% | -6% | -26% |
| Wet season flow (mean)* | GL | 6602 | +41% | -5% | -25% | +40% | -6% | -26% |
| Dry season flow (mean)** | GL | 164 | +33% | +16% | -34% | +29% | +13% | -37% |
| Low flow metrics | | | | | | | | |
| Low flow threshold (discharge exceeded 90% of the time in Scenario A) | GL/d | 0.045 | | | | | | |
| Number of days below low flow threshold (mean) | d/y | 36.5 | -10.2 | +4.8 | +35.5 | -3.7 | +13.5 | +44.7 |
| Duration of flow events below low flow threshold (mean) | d/y | 18.6 | -2.1 | -0.8 | +8.7 | -1.8 | +1 | +10.5 |
| Number of events below low flow threshold (mean) | events/y | 1.96 | -0.4 | +0.4 | +0.7 | 0 | +0.6 | +0.8 |
| Number of days of zero flow (mean) | d/y | 6.13 | -2.4 | +2.2 | +14.5 | -0.2 | +6.2 | +21.3 |
| High flow metrics | | | | | | | | |
| High flow threshold (discharge exceeded 5% of the time in Scenario A) | GL/d | 105 | | | | | | |
| Number of days above high flow threshold (mean) | d/y | 18.4 | +7.4 | -1 | -4.8 | +7.2 | -1.3 | -4.9 |
| Duration of flow events above high flow threshold (mean) | d/y | 7.75 | +1.6 | +0.1 | -1 | +1.6 | -0.1 | -1 |
| Number of events above high flow threshold (mean) | events/y | 2.38 | +0.4 | -0.1 | -0.4 | +0.4 | -0.1 | -0.4 |
| Wet season rate of rise (mean) | GL/d | 8.73 | +3.7 | -0.5 | -1.8 | +3.7 | -0.5 | -1.8 |
| Wet season rate of fall (mean) | GL/d | 5.96 | +2.3 | -0.3 | -1.2 | +2.3 | -0.4 | -1.1 |

*Wet season covers the six months from November to April
**Dry season covers the six months from May to October
nm – not modelled

#### 3.4.2.16.2 Western Australia

In three catchments in Western Australia (Fitzroy, King Edward and Charnley) river flow was modelled using an ensemble calibration of the rainfall-runoff models Sacramento and IhacresClassic (Petheram et al., 2009b). As part of the NASY project runoff in the above catchments was derived for the 77 year period from 1930 to 2008 (Petheram et al., 2009b). In the Fitzroy catchment there was also additional groundwater recharge modelling carried out using the WAVES model (Zhang and Dawes, 1998). Currently there is comparatively little surface water abstraction in the above catchments so no future development scenarios were reported in the NASY project. The only exception is in the Fitzroy catchment where the combined volume of existing groundwater allocations from the fractured rock aquifers and the Canning Basin amount to about 20 GL/year. To describe the current surface hydrological conditions in these catchments we report two of the scenarios analysed in the NASY project, Scenario A and Scenario C:

- Scenario A – historical climate (1930 to 2007) and current development. This scenario is used as a baseline for comparison with all other scenarios.
- Scenario C – future climate (~2030) and current development.

**Historical climate**

The Fitzroy (WA) region receives an average of 577 mm of rainfall over a September to August water year, most of which (534 mm) falls in the November to April wet season. Across the region there is a strong north–south gradient in annual rainfall, ranging from 963 mm in the north to 383 mm in the south. Over the first half of the historical (1930 to 2007) period, annual rainfall has been relatively constant at around 450 mm. The second half of the period has seen an increase in mean rainfall to approximately 650 mm. The highest yearly rainfall received was 1127 mm which fell in 2000, and the lowest was 249 mm in 1953. Historical potential evapotranspiration (PET) is very high across the region, averaging 2023 mm over a water year, and varies moderately across the seasons. PET generally remains higher than rainfall throughout the year resulting in year-round water-limited conditions.

The Kimberley region, where the Charnley and King Edward Rivers are located, receives an average of 950 mm of rainfall over a September to August water year, most of which (898 mm) falls in the November to April wet season. 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, 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 (CSIRO, 2009c).

**Charnley River**

The Charnley River, located in the Kimberley region of Western Australia, Figure 3.29, has its headwaters situated below Rocky Mountain in the Caroline Ranges and flows eastward across the Gardner Plateau and discharges into the Indian Ocean via Walcott Inlet. There are seven tributaries of the Charnley river these are; Pearson River, Maurice Creek, Synnot Creek, Kalumba Creek, Bayonet Creek, Maudie Creek and Kaangulman Creek. The Calder River also flows into Walcott inlet.

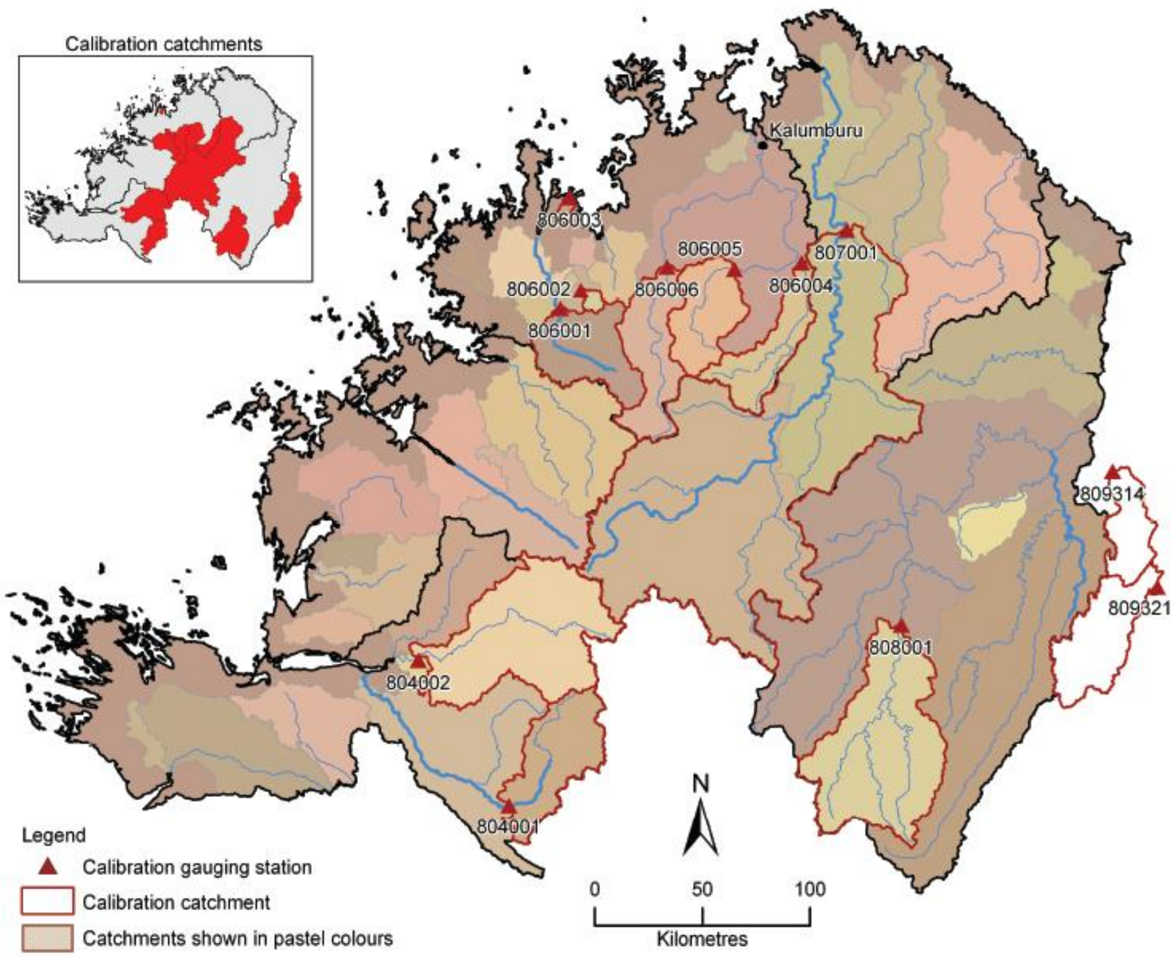



**Figure 3.34 Schematic diagram of the Kimberley region where the Charnley River and King Edward River are located (reproduced from CSIRO (2009c)).**

### Standard high and low flow metrics

Analysis of high and low flow metrics were undertaken at only one location (804002) in the Charnley River catchment, Figure 3.34. In this section we report and interpret the results for this location.

The standard high and low flow metric analysis results for the Charnley River are shown in Table 3.9 for the Panta Downs gauge (804002). Based on Scenario A, most of the flow (95%) occurs during the wet season, with the river rarely ceasing to flow. The greatest changes in annual, wet and dry season flow occurs under Scenario Cdry with reductions of >35%. There are no development scenarios reported for this location.

The greatest impact on the low flow characteristics at this location occur under Scenario Cdry. Compared to Scenario A, the number of days below the low flow threshold more than doubles under Scenario Cdry, although there is little change to number of zero flow days.

Changes to the flow regime at high flows are modest for Scenarios Cwet and Cmid, however, Scenario Cdry results in a 40% reduction in the number of days above the high flow threshold. The number and duration of high flow events and the rates of rise and fall during the wet season shows little variation for Scenario Cwet and Cmid relative to Scenario A, however modest variation (<20%) for these same metrics was observed for Scenario Cdry.

**Table 3.9. Standard metrics for changes to flow regime on the Charnley River at Panta Downs under Scenarios C and D relative to Scenario A. Red text indicates changes of more than 25% relative to Scenario A.**

| Charnley - Charnley River at Panta Downs, Gauge No. 804002 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Standard metrics | Units | A | Cwet | Cmid | Cdry | Dwet | Dmid | Ddry |
| | | | change from Scenario A | | | | | |
| General metrics | | | | | | | | |
| Annual flow (mean) | GL | 744 | +5% | -2% | -35% | nm | nm | nm |
| Wet season flow (mean)* | GL | 704 | +5% | -3% | -35% | nm | nm | nm |
| Dry season flow (mean)** | GL | 34.5 | +9% | +2% | -37% | nm | nm | nm |
| Low flow metrics | | | | | | | | |
| Low flow threshold (discharge exceeded 90% of the time in Scenario A) | GL/d | 0.033 | | | | | | |
| Number of days below low flow threshold (mean) | d/y | 36.5 | -4.1 | +2.5 | +45.9 | nm | nm | nm |
| Duration of flow events below low flow threshold (mean) | d/y | 74.0 | -6.6 | -0.7 | +9.5 | nm | nm | nm |
| Number of events below low flow threshold (mean) | events/y | 0.494 | 0 | 0 | +0.5 | nm | nm | nm |
| Number of days of zero flow (mean) | d/y | 1.17 | 0 | 0 | +0.2 | nm | nm | nm |
| High flow metrics | | | | | | | | |
| High flow threshold (discharge exceeded 5% of the time in Scenario A) | GL/d | 10.6 | | | | | | |
| Number of days above high flow threshold (mean) | d/y | 18.3 | +1.3 | -0.8 | -7.5 | nm | nm | nm |
| Duration of flow events above high flow threshold (mean) | d/y | 8.23 | +0.1 | -0.2 | -2 | nm | nm | nm |
| Number of events above high flow threshold (mean) | events/y | 2.22 | +0.1 | 0 | -0.5 | nm | nm | nm |
| Wet season rate of rise (mean) | GL/d | 1.94 | +0.1 | 0 | -0.4 | nm | nm | nm |
| Wet season rate of fall (mean) | GL/d | 1.23 | 0 | 0 | -0.4 | nm | nm | nm |

*Wet season covers the six months from November to April
**Dry season covers the six months from May to October
nm – not modelled

## Fitzroy River

The Fitzroy catchment (Figure 3.35) covers almost 94,000 km$^2$ and extends from the headwaters in the King Leopold ranges, draining west for a distance of 730 km into King Sound. There are several flow monitoring stations in the catchment from Dimond Gorge in the east (802137) to the Looma gauge (802007) in the west. There are numerous tributaries in the Fitzroy system including the Margaret River, Christmas Creek, Hann River, Sandy Creek, Geegully Creek, Little Fitzroy River, Collis Creek, Adcock River, Cunninghame River, Yeeda River, Mudjalla Gully and Minnie River.

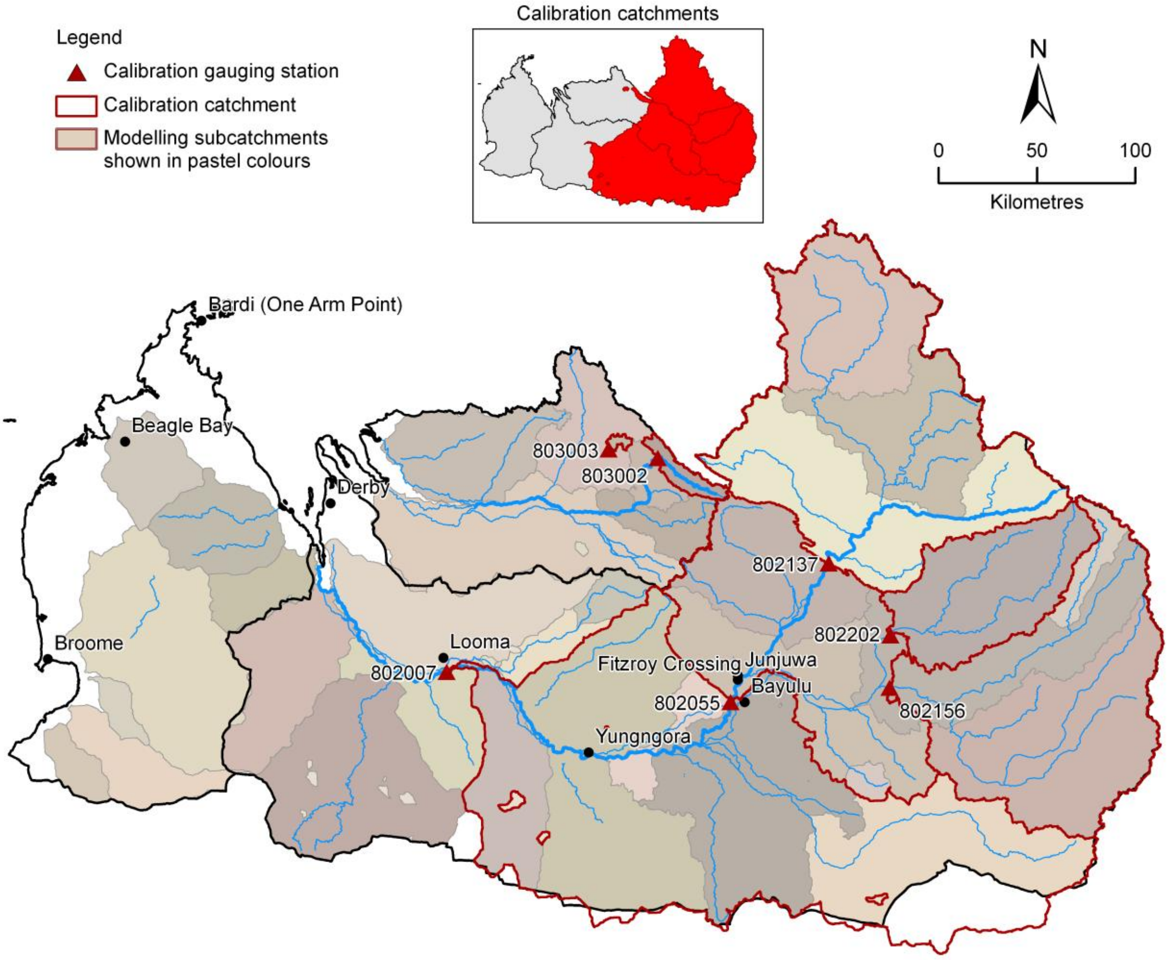



**Figure 3.35 Schematic diagram of the Fitzroy River system (blue lines) including the location of gauging stations Also shown are the NASY runoff modelling sub-catchments, with the inset highlighting (in red) the extent of the calibration catchments (reproduced from CSIRO (2009c)).**

**Standard high and low flow metrics**

Analysis of high and low flow metrics were undertaken at four locations (902055, 8020003, 802137 and 802007) which correspond to stream gauging sites within the Fitzroy River catchment, Figure 3.35. In this section we report and interpret the results for one of these locations; results for the other three locations are shown in Appendix A.

The standard high and low flow metric analysis results for the Fitzroy River are shown in Table 3.10 for Fitzroy Barrage gauge (802003). It is important to note that at this location, unlike other reported gauge locations, was not a model calibration point, therefore these results should be treated with some caution until more in depth analysis is undertaken.

Based on Scenario A, most of the flow (98%) occurs during the wet season, with the river ceasing to flow for 79 days of the year, on average. The greatest changes in annual, wet and dry season flow occurs under Scenario Cdry with reductions of >35%. There are no development scenarios reported for this location.

**Table 3.10. Standard metrics for changes to flow regime on the Fitzroy River at Fitzroy Barrage under Scenarios C and D relative to Scenario A. Red text indicates changes of more than 25% relative to Scenario A.**

| Fitzroy - Fitzroy River at Fitzroy Barrage, Gauge No. 802003 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Standard metrics | Units | A | Cwet | Cmid | Cdry | Dwet | Dmid | Ddry |
| | | | change from Scenario A | | | | | |
| General metrics | | | | | | | | |
| Annual flow (mean) | GL | 7693 | +18% | -3% | -35% | nm | nm | nm |
| Wet season flow (mean)* | GL | 7521 | +17% | -4% | -35% | nm | nm | nm |
| Dry season flow (mean)** | GL | 165 | +23% | +2% | -65% | nm | nm | nm |
| Low flow metrics | | | | | | | | |
| Low flow threshold (discharge exceeded 90% of the time in Scenario A) | GL/d | 0 | | | | | | |
| Number of days below low flow threshold (mean) | d/y | 79.0 | +0.8 | +1.5 | +39 | nm | nm | nm |
| Duration of flow events below low flow threshold (mean) | d/y | 83.3 | +0.8 | +2.7 | +30.2 | nm | nm | nm |
| Number of events below low flow threshold (mean) | events/y | 0.95 | 0 | 0 | +0.1 | nm | nm | nm |
| Number of days of zero flow (mean) | d/y | 79.0 | +0.8 | +1.5 | +39 | nm | nm | nm |
| High flow metrics | | | | | | | | |
| High flow threshold (discharge exceeded 5% of the time in Scenario A) | GL/d | 114 | | | | | | |
| Number of days above high flow threshold (mean) | d/y | 18.3 | +1.8 | -0.7 | -6.4 | nm | nm | nm |
| Duration of flow events above high flow threshold (mean) | d/y | 11.5 | 0 | -1.1 | -2.3 | nm | nm | nm |
| Number of events above high flow threshold (mean) | events/y | 1.58 | +0.2 | +0.1 | -0.3 | nm | nm | nm |
| Wet season rate of rise (mean) | GL/d | 16.1 | +4.6 | +0.3 | -1.2 | nm | nm | nm |
| Wet season rate of fall (mean) | GL/d | 7.99 | +1.3 | -0.1 | -1.2 | nm | nm | nm |

*Wet season covers the six months from November to April
**Dry season covers the six months from May to October
nm – not modelled

The greatest impact on the low flow characteristics at this location occur under Scenario Cdry (Table 3.10). Compared to Scenario A, the number of days of zero flow increases by 50% under Scenario Cdry and the average duration of low flow events increased by 36%. There was little change to low flow metrics under Scenarios Cwet and Cmid.

Changes to the flow regime at high flows were small for Scenarios Cwet and Cmid, however, Scenario Cdry results in a 34% reduction in the number of days above the high flow threshold. The number and duration of high flow events during the wet season shows little variation for all Scenarios. Relative to Scenario A, the wet season rate of rise increased by more than 25% for Scenario Cwet.

**Site specific flow metrics**

Fitzroy River at Fitzroy Barrage

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

- for flows at which fish could negotiate the Camballin Barrage - the mean number of days per year where stage height exceeded 11.0 m (equivalent to 8.0 GL/day)
- for complete barrage inundation of Camballin Barrage and unobstructed fish passage - the mean number of days per year where stage height exceeded 12.3 m (equivalent to a discharge of 28.8 GL/day).

Under Scenario A there were found to be 70 days per year (on average) where flows exceeded 8.0 GL/day and fish passage could commence (Table 3.11). There is little change to the exceedance of this flow threshold under Scenarios Cmid and Cwet, but there is a moderate decrease (24%) in this threshold exceedance under Scenario Cdry. Under Scenario A, flow was above the higher flow threshold of 28.8 GL/day threshold for 42 days per year on average. Under Cmid and Cwet there is little change to the exceedance of this flow but there is a 26% decrease in this threshold exceedance under Scenario Cdry. Therefore fish passage across the barrage would be restricted under Scenario Cdry.

The scenario indicating the largest changes to flow in Table 3.11 is Cdry and this matches with the scenario with the largest impact in the standard metrics for Fitzroy Barrage (Table 3.10). This observation increases confidence in the ability of the standard metrics to represent processes than might affect ecological process for north Australian rivers.

**Table 3.11. Site specific metrics on the Fitzroy River at Fitzroy Barrage under Scenarios C and D relative to Scenario A. Red text indicates changes of more than 25% relative to Scenario A.**

| Fitzroy - Fitzroy River at Fitzroy Barrage, Gauge No. 802003 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Site specific metrics | Units | A | Cwet | Cmid | Cdry | Dwet | Dmid | Ddry |
| | | | change from Scenario A | | | | | |
| Fish passage across Fitzroy Barrage possible | | | | | | | | |
| Number of days with flows above 8.0 GL/d | d/y | 70 | +3 | -1.5 | -17 | nm | nm | nm |
| Fish passage across Fitzroy Barrage unimpeded | | | | | | | | |
| Number of days with flows above 28.8 GL/d | d/y | 42 | +2.4 | -1.1 | -11.3 | nm | nm | nm |

nm – not modelled

### King Edward River

The King Edward River (Figure 3.34) covers 8400 km$^2$ and extends for a distance of 220 km to its mouth at south Napier Broome Bay. The are several flow monitoring stations in the catchment including Morgan River at Moondoalnee (806005), King Edward River at Mt Reid, (806006) and Carson River at Old Theda (806004). The river has seven tributaries including; Carson River, Drum Creek, Noolawayoo Creek, Coondillah Creek and Hair Creek.

### Standard high and low flow metrics

Analysis of high and low flow metrics were undertaken at three locations (8060004, 806005 and 806006) which correspond to stream gauging sites within the King Edward River catchment, Figure 3.34. In this section we report and interpret the results for one of these locations; results for the other two locations are shown in Appendix A.

The standard high and low flow metric analysis results for the King Edward River are shown in Table 3.12 for the Mt Reid gauge (806006). Based on Scenario A, most of the flow (94%) occurs during the wet season. Annual and seasonal flows do not change much under Scenario Cmid (<4%) compared to Scenario A, but there are moderate decreases under Scenario Cdry (>24%). Under Scenario Cwet annual and seasonal flows increase by about 10%. There are no development scenarios for this location.

Under Scenario Cdry, there is almost twice the number of days with flow that is below the low flow threshold as defined by Scenario A. The number of days of zero flow more than doubles under Scenario Cdry, but is reduced by more than 25% under Scenario Cwet. The duration of events below the low flow threshold increased by more than 40% under Scenario Cdry.

Compared to Scenario A, there is a large decreases (37%) in the high flow threshold exceedance under Scenario Cdry. The number of events exceeding the high flow threshold was also greatly reduced (28%) under this scenario. The wet season rate of rise and fall varied only slightly across Scenarios.

**Table 3.12. Standard metrics for changes to flow regime on the King Edward River at Mt Reid under Scenarios C and D relative to Scenario A. Red text indicates changes of more than 25% relative to Scenario A.**

| King Edward - King Edward River at Mt Reid, Gauge No. 806006 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Standard metrics | Units | A | Cwet | Cmid | Cdry | Dwet | Dmid | Ddry |
| | | | change from Scenario A | | | | | |
| General metrics | | | | | | | | |
| Annual flow (mean) | GL | 231 | +10% | -3% | -24% | nm | nm | nm |
| Wet season flow (mean)* | GL | 216 | +10% | -4% | -24% | nm | nm | nm |
| Dry season flow (mean)** | GL | 13.9 | +9% | 0% | -26% | nm | nm | nm |
| Low flow metrics | | | | | | | | |
| Low flow threshold (discharge exceeded 90% of the time in Scenario A) | GL/d | 0.001 | | | | | | |
| Number of days below low flow threshold (mean) | d/y | 36.5 | -7.8 | +3.4 | +29 | nm | nm | nm |
| Duration of flow events below low flow threshold (mean) | d/y | 68.6 | -3.4 | +4.6 | +28.4 | nm | nm | nm |
| Number of events below low flow threshold (mean) | events/y | 0.53 | -0.1 | 0 | +0.1 | nm | nm | nm |
| Number of days of zero flow (mean) | d/y | 14.7 | -5 | +2.8 | +21.1 | nm | nm | nm |
| High flow metrics | | | | | | | | |
| High flow threshold (discharge exceeded 5% of the time in Scenario A) | GL/d | 3.16 | | | | | | |
| Number of days above high flow threshold (mean) | d/y | 18.3 | +2.1 | -1 | -6.8 | nm | nm | nm |
| Duration of flow events above high flow threshold (mean) | d/y | 5.77 | +0.4 | -0.2 | -0.8 | nm | nm | nm |
| Number of events above high flow threshold (mean) | events/y | 3.17 | +0.1 | -0.1 | -0.9 | nm | nm | nm |
| Wet season rate of rise (mean) | GL/d | 0.88 | +0.1 | 0 | +0.2 | nm | nm | nm |
| Wet season rate of fall (mean) | GL/d | 0.47 | 0 | 0 | 0 | nm | nm | nm |

*Wet season covers the six months from November to April
**Dry season covers the six months from May to October
nm – not modelled

#### 3.4.2.16.3 Northern Territory

In three of the four catchments in the Northern Territory (East Alligator, Finniss, and South Alligator) river flow was modelled using an ensemble calibration of the rainfall-runoff models Sacramento and IhacresClassic (Petheram et al., 2009b). As part of the NASY project runoff in the above catchments was derived for the 77 year period from 1930 to 2008 (Petheram et al., 2009b). The forth catchment in the Northern Territory is the Daly, which was modelled using a combined surface water and groundwater model which was designed and run by the Northern Territory Government Department of Natural Resources, Environment, the Arts and Sport (Knapton et al., 2010).

To describe the current surface hydrological conditions in these catchments we report three of the scenarios analysed in the NASY project, Scenario A, Scenario C and Scenario D:

- Scenario A – historical climate (1930 to 2007) and current development. This scenario is used as a baseline for comparison with all other scenarios.
- Scenario C – future climate (~2030) and current development.
- Scenario D – future climate (~2030) and likely future development

**Historical climate**

The Daly River region receives an average of 1020 mm of rainfall over the September to August water year, most of which (975 mm) falls in the November to April wet season. Across the region there is a north–south gradient in annual rainfall, ranging from 1485 mm in the north to 670 mm in the south. Annual rainfall has been steadily increasing throughout the historical (1930 to 2007) period, from an average of around 560 mm to 1230 mm. The highest yearly rainfall received was 1640 mm, which fell in 1974, and the lowest was 500 mm in 1952 (CSIRO, 2009c).

The Van Diemen region, which includes the East Alligator, Finniss, and South Alligator Rivers, receives an average of 1390 mm of rainfall over the September to August water year, most of which (1327 mm) falls in the November to April wet season. Across the region there is a strong north–south gradient in annual rainfall, ranging from 1695 mm in the north to 1155 mm in the south. Over the historical (1930 to 2007) period, annual rainfall has been gradually increasing from an initial average of around 1100 mm to approximately 1400 mm later in the period. The highest yearly rainfall received was 1942 mm which fell in 2000, and the lowest was 765 mm in 1952 (CSIRO, 2009c).

**Daly River**

The Daly River, 200 km to the south of Darwin, is one of the largest perennial rivers of northern Australia, with a catchment area of just over 53,000 km$^2$. Dry season flow is dominated by input from groundwater from two underlying limestone aquifers which have an intervening siltstone aquitard. The catchment contains a number of important rivers, including the Katherine, Flora, Edith and Douglas Rivers, which have tourism and conservation value.

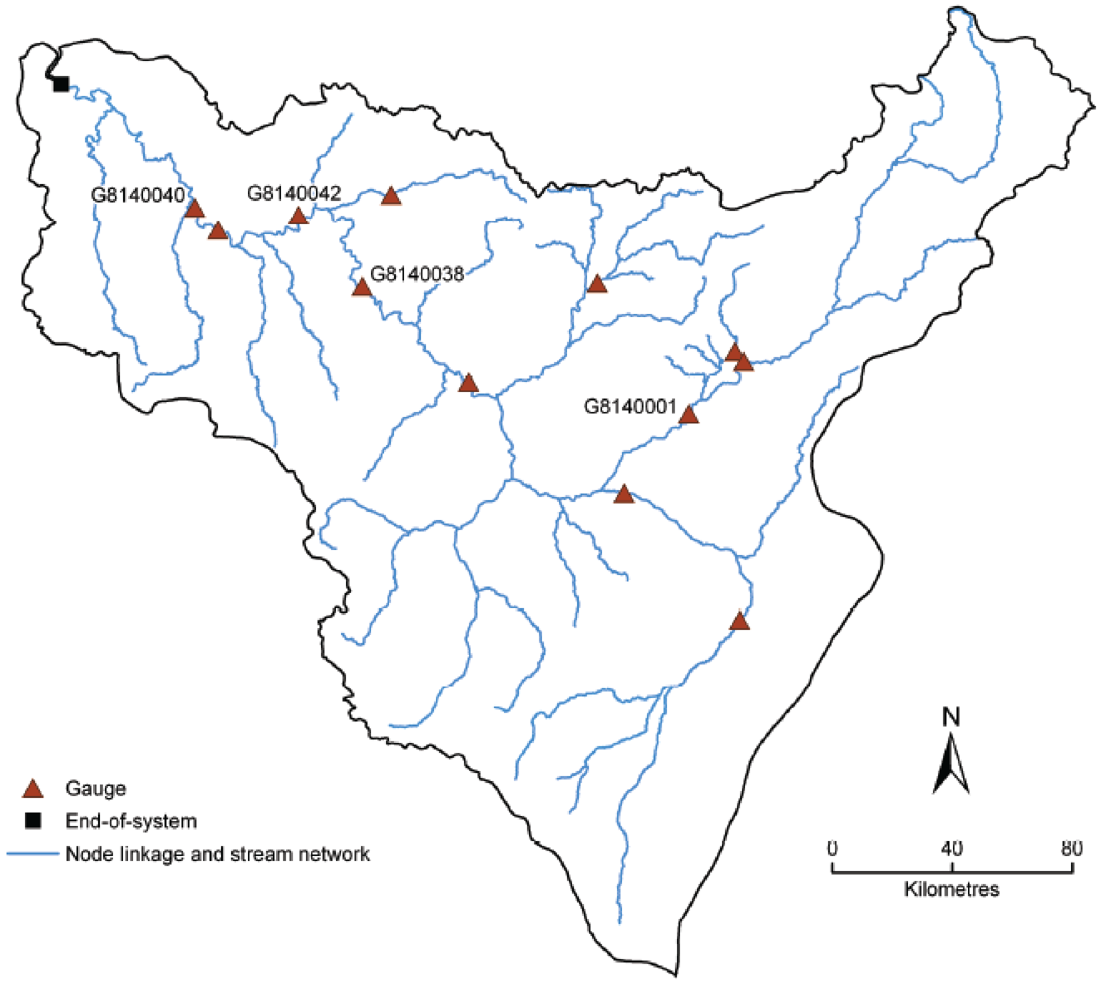



**Figure 3.36 Schematic diagram of the Daly River system (blue lines) including the location of gauging stations (reproduced from CSIRO (2009c)).**

### Standard high and low flow metrics

Analysis of high and low flow metrics were undertaken at four locations (8140038, 8140040, 8140042 and 8140001) which correspond to stream gauging sites within the Daly River catchment, Figure 3.36. In this section we report and interpret the results for one of these locations; results for the other three locations are given in Appendix A.

The standard high and low flow metric analysis results for the Daly River are shown in Table 3.13 for the Oolloo Road Crossing gauge (8140038). Based on Scenario A, most of the flow (91%) occurs during the wet season. Annual and seasonal flows do not change much under Scenario Cmid when compared to Scenario A, but there are large increases under Scenario Cwet (22 to 31%) and large decreases under Scenario Cdry (21 to 31%). Changes to annual and seasonal flows under scenarios Dwet, Dmid and Ddry, when compared to Scenario A, are similar to those under Scenario C, indicating very little additional impact on the hydrological regime as a result of proposed development.

The number of days when flow is less than the low flow threshold decreases moderately under Scenario Cmid compared to Scenario A, but there is a large increase in low flow days under Scenario Cdry and a large decrease in low flow days under Scenario Cwet. The number of days when flow is less than the low flow threshold also decreases moderately under Scenario Dmid, when compared to Scenario A. Scenario Dwet is similar to Cwet indicating little impact from proposed development, but there is a larger increase in low flow days under Scenario Ddry when compared to Scenario Cdry. There were no zero flow days at this location under any scenario.

Compared to Scenario A there is little change in high flow threshold exceedance under Scenario Cmid. Under Scenario Cwet high flow exceedance increases by 27% from Scenario A; conversely, there is a large decrease in high flow days under Scenario Cdry. The wet season rates of rise and fall are greatly increased under the wet climate scenarios and are greatly decreased under the dry climate scenarios.

**Table 3.13. Standard metrics for changes to flow regime on the Daly River at Oolloo Road Crossing under Scenarios C and D relative to Scenario A. Red text indicates changes of more than 25% relative to Scenario A.**

| Daly - Daly River at Oolloo Road Crossing, Gauge No. G8140038 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Standard metrics | Units | A | Cwet | Cmid | Cdry | Dwet | Dmid | Ddry |
| | | | change from Scenario A | | | | | |
| General metrics | | | | | | | | |
| Annual flow (mean) | GL | 5434 | +31% | -3% | -32% | +31% | -3% | -33% |
| Wet season flow (mean)* | GL | 4950 | +31% | -3% | -33% | +31% | -3% | -33% |
| Dry season flow (mean)** | GL | 206 | +22% | -3% | -17% | +21% | -5% | -22% |
| Low flow metrics | | | | | | | | |
| Low flow threshold (discharge exceeded 90% of the time in Scenario A) | GL/d | 0.72 | | | | | | |
| Number of days below low flow threshold (mean) | d/y | 36.6 | -28.6 | +7.7 | +48.1 | -26.6 | +15.9 | +66.6 |
| Duration of flow events below low flow threshold (mean) | d/y | 33.6 | -7.5 | -3.7 | +13.8 | -5 | +4 | +17.9 |
| Number of events below low flow threshold (mean) | events/y | 1.09 | -0.8 | +0.4 | +0.7 | -0.7 | +0.3 | +0.9 |
| Number of days of zero flow (mean) | d/y | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| High flow metrics | | | | | | | | |
| High flow threshold (discharge exceeded 5% of the time in Scenario A) | GL/d | 92.4 | | | | | | |
| Number of days above high flow threshold (mean) | d/y | 18.3 | +5 | -0.7 | -7.8 | +5 | -0.6 | -7.8 |
| Duration of flow events above high flow threshold (mean) | d/y | 7.93 | +1.4 | -0.3 | -1.8 | +1.4 | -0.3 | -1.8 |
| Number of events above high flow threshold (mean) | events/y | 2.30 | +0.2 | 0 | -0.6 | +0.2 | 0 | -0.6 |
| Wet season rate of rise (mean) | GL/d | 9.22 | +2.4 | -0.5 | -3.6 | +2.7 | -0.7 | -3.6 |
| Wet season rate of fall (mean) | GL/d | 4.97 | +1.5 | -0.2 | -1.5 | +1.7 | -0.2 | -1.6 |

*Wet season covers the six months from November to April
**Dry season covers the six months from May to October
nm – not modelled

**Site specific flow metrics**

Daly River at Oolloo Road Crossing

The reports by Erskine et al. (2004; 2003) summarise the results from five projects within the National River Health Environmental Flow Initiative (described in section 3.3.1.4.2). The aim of these projects was to provide recommendations on environmental flows consistent with maintaining the biota and wider ecosystem values of the Daly River. These projects made a range of environmental stream flow recommendations and some of these were suitable for assessment under this project's scenario analysis. The work by Georges et al. (2002) reported in Erskine et al. (2004; 2003) gives data for the success of Pig-Nosed Turtle (Carettochelys insculpta) nesting and their main food source, the aquatic macrophyte Vallisneria nana. In these reports turtle nesting success and *V. nana* bed occurrence are related to Daly River flow at the Oolloo Gauge (8140038). The Erskine et al. (2004) report recommends that at least 80 percent of flow should exceed 1.04 GL/day to provide habitat for Pig-Nosed Turtles and *V. nana.* When flow drops to these levels extraction should cease. Erskine et al. (2003) also reviewed the existing data on riparian vegetation water use along the Daly River and concluded that all of the riparian vegetation water use could be met by maintaining a stream flow of less than 0.17 GL/day during the dry season, assuming no loss of stream flow to regional aquifers. Further details of these flow thresholds are described in section 3.3.1.4.2.

The specific metrics assessed under each scenario are:

- for Pig-Nosed Turtle nesting success and *V. nana* bed occurrence - the mean number of days per year at Oolloo Gauge (8140038) with flows below identified threshold of 1.04 GL/day
- for riparian vegetation water requirements - the mean number of days per year at Oolloo Gauge ((8140038) with flows below the identified threshold of 0.17 GL/day.

For the flow threshold for protecting Pig-Nosed Turtle and the number of *V. nana* beds it was found that under Scenario A there is an average of 151 days per year when conditions are below the threshold (Table 3.14). This number decreases greatly under Cwet and Dwet. There is little change to the number of days below the identified threshold under scenarios Cmid and Dmid. The greatest increase in days below the threshold for the nesting success of the Pig-Nosed Turtle and the number of *V. nana* beds is under scenarios Cdry and Ddry with 30 and 37 percent increases, respectively. These changes would result in a reduction in the number of *V. nana* beds, a decline in the nesting success of the Pig-Nosed Turtle and an large increase in the period of time where water extraction should be limited.

The minimum flow requirement to maintain transpiration requirements of riparian vegetation has been reported by Erskine et al. (2003) to be 0.17 GL/day at the Oolloo Crossing gauge. The flow threshold analysis showed that flow levels were maintained above this level under all scenarios, so there is likely to be little or no impact of climate or development on transpiration of riparian vegetation in this river reach (Table 3.14).

**Table 3.14. Site specific metrics on the Daly River at Oolloo Road Crossing under Scenarios C and D relative to Scenario A. Red text indicates changes of more than 25% relative to Scenario A.**

| Daly - Daly River at Oolloo Road Crossing, Gauge No. G8140038 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Site specific metrics | Units | A | Cwet | Cmid | Cdry | Dwet | Dmid | Ddry |
| | | | change from Scenario A | | | | | | |
| Daly River Middle Reaches - Pig-Nosed Turtle nesting habitat suitability and *V. nana* bed occurrence | | | | | | | | | |
| Number of days with flows below 1.04 GL/d | d/y | 150 | -49.4 | +9.8 | +45.2 | -47.5 | +13.3 | +56.3 |
| Daly River Middle Reaches – Riparian vegetation water requirement | | | | | | | | | |
| Number of days with flows below 0.17 GL/d | d/y | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Daly River at Mt Nancar

In an ecological risk assessment for the Daly River, Bayliss et al. (2008) concluded that water extraction was a key threat to environmental flows in the Daly River. They used barramundi catch data to assess the effects of stream flow on fish population abundance. Barramundi was selected as a suitable species as it is an important recreational and commercial fish and has a life cycle dependent on the connection between freshwater and estuarine ecosystems. Bayliss et al. (2008) related population abundance to catch per unit effort (CPUE) and used records of barramundi catch from commercial fisheries, tour operators and a fishing tournament which has been held over many years. All catch data were positively correlated to wet season flow for the same year, however the strongest relationship was found with fishing tournament CPUE. The derived relationship between wet season flow and population abundance (as defined by CPUE for the fishing tournament) offers an opportunity to assess potential population impacts for barramundi across the different climate and development scenarios. The metrics presented by Bayliss et al. (2008) relate to flow on the Daly River at Mt Nancar to fishing tournament CPUE using the following equation:

$$\text{Log}_{10}\text{CPUE} = 0.641 * \text{Log}_{10}\text{WetSeason Flow} - 5.31 \qquad \text{Equation 1.}$$

Note this relationship varies to that presented in Bayliss et al. (2008) as several years of new data have now been incorporated (Bayliss *pers. comm*..). Also, the period defined as the wet season by Bayliss et al. (2008) varies to that used in the rest of this document and includes the 7 months from October to April.

By determining average wet season flow for each of the climate scenarios it is then possible to determine the resultant CPUE using Equation 1. The results this analysis are shown in Table 3.15. There is little change in the average wet season flow or CPUE for both Cmid and Dmid scenarios, however, the Scenarios Cwet and Dwet result in an increase in wet season flow of 33% and increase in CPUE of 20%. Scenario Cdry and Ddry show an opposite trend, with a 33% reduction in average wet season flow and a corresponding decrease in CPUE of 23%. An interesting point to note is that percentage change in CPUE is not as large as the percentage change in wet season flow. This indicates that the increase or decrease in flow has a damped effect on CPUE.

Interestingly the scenarios indicating the largest changes to flow in the standard metrics for Mt Nancar (Appendix A) match well with those causing the biggest change in this site specific analysis. This observation increases confidence in the ability of the standard metrics to represent processes than might affect ecological process for north Australian rivers.

**Table 3.15. Site specific metrics related to barramundi catch on the Daly River at Mt Nancar under Scenarios C and D relative to Scenario A. Red text indicates changes of more than 25% relative to Scenario A.**

| Daly - Daly River at Mt Nancar, Gauge No. G8140040 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Site specific metrics | Units | A | Cwet | Cmid | Cdry | Dwet | Dmid | Ddry |
| | | | change from Scenario A | | | | | |
| Angler barramundi catch per unit effort | | | | | | | | |
| Wet season flow | GL/d | 7539 | +33% | -1% | -33% | +33% | -1% | -33% |
| Catch per unit effort | Fish/angling hr | 0.12 | +20% | -0.6% | -23% | +20% | -0.6% | -23% |

N.B. For this analysis table the wet season covers the 7 months from October to April

Further site specific metrics related to nesting density of magpie geese was also presented for the Daly River at Mt Nancar by Bayliss et al. (2008). This metric compares the total wet season (October to April in this case) flow with nesting density. A relationship fitted to wet season flow and nesting density data showed that nesting density falls to between 0-6/km$^2$ when total wet season flow is less than 6900 GL. Above this point nesting density shows a positive trend with increasing wet season flow to peak levels of 25-30/km$^2$. Peak nesting densities continued to increase until wet season flow exceeded 11000 GL. Bayliss et al.

(2008) suggest that beyond the flow level it is possible that nest density declines due to nest drowning. It is also worth noting that whilst the timing of onset of wet season rainfall may trigger nesting in magpie geese and so ultimately influence annual nest density and recruitment success, the amount of rainfall throughout the remainder of the wet season is also critical in that it needs to be sufficient in order to ensure completion of the nesting cycle, and to produce adequate food for goslings, adults and yearlings before the next wet season rains.

The derived relationship between wet season flow and nesting density (for a total of 22 years) offers another opportunity to assess potential population dynamics for magpie geese across the different climate and development scenarios. The specific metrics assessed under each scenario are:

- Number of years where wet season flows exceed the lower threshold of 6900 GL – beyond this threshold floodplain inundation and nesting density increases.
- Number of years where wet season flows exceed the upper threshold of 11000 GL – beyond this threshold floodplain inundation is considered too deep and nest drowning occurs.

The results this magpie geese metric analysis are shown in Table 3.16. Under Scenario A half of the number of years modelled (22 years) had wet season flow greater than the lower threshold. Of these 11 years, 5 had wet season flow greater than the higher threshold above which nest density declines. Of the total 22 years of analysis 27% of years (n = 6) fell within the optimal wet season flows for nesting density i.e. between 6900 and 11000 GL. Under Scenarios Cwet and Dwet the number of days above the high threshold increased by 14% (3 years) indicating the potential for nesting density decline due to nest drowning. There was little change under Cmid and Dmid. Under Scenario Cdry and Ddry the number of years within the optimal range was 4 (down 18%); this was due mainly to a reduction of the number of years above the lower threshold.

Interestingly this is one of the few metrics which report negative impacts of very high flows. The scenarios indicating the largest changes to flow in the standard metrics for Mt Nancar (Appendix A) match well with those causing the biggest change in this site specific analysis. However, in this instance the impact of the dry scenarios appears to be more significant than the standard site specific analysis would suggest.

**Table 3.16. Site specific metrics related to magpie goose nesting on the Daly River at Mt Nancar under Scenarios C and D relative to Scenario A. Red text indicates changes of more than 25% relative to Scenario A.**

| Daly - Daly River at Mt Nancar, Gauge No. G8140040 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Site specific metrics | Units | A | Cwet | Cmid | Cdry | Dwet | Dmid | Ddry |
| | | | change from Scenario A | | | | | |
| Number of years above nesting density thresholds | | | | | | | | |
| Total wet season flow greater than low threshold of 6900 GL | Years | 11 | +3 | 0 | -6 | +3 | 0 | -6 |
| Total wet season flow greater than high threshold of 1100 GL | Years | 5 | +3 | 0 | -4 | +3 | 0 | -4 |

N.B. For this analysis table the wet season covers the 7 months from October to April. Total number of wet seasons for analysis is

## East Alligator River

The East Alligator River covers an area of 14,500 km$^2$ and is approximately 160 km long. After rising in the northern part of the Arnhem Land Plateau, it flows with tributary streams towards the north-west through magnificent canyons towards the Van Diemen Gulf which it meets at Point Farewell. The major rivers in the catchment include Cooper Creek and Magela Creek.

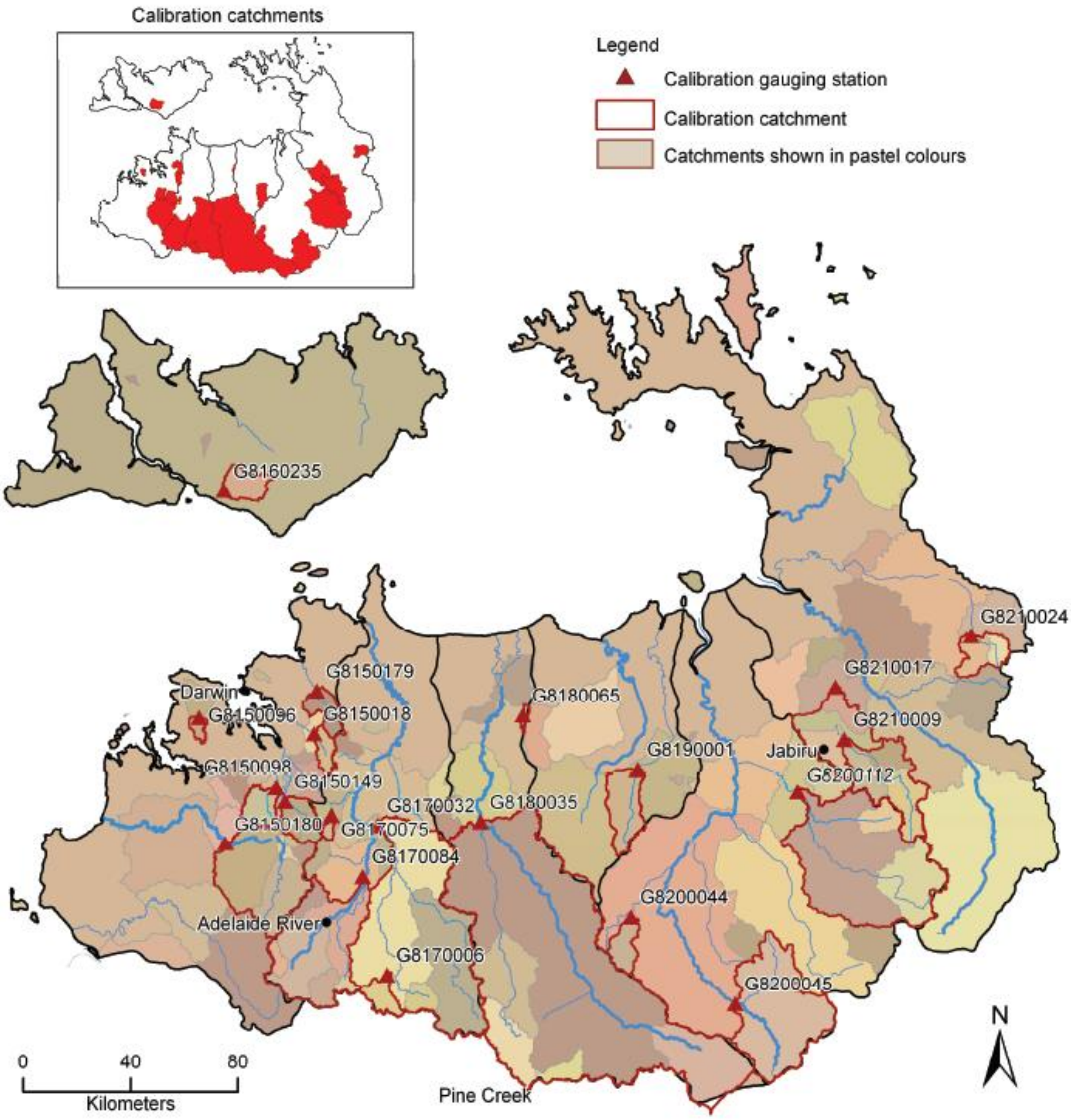



**Figure 3.37 Schematic diagram of the Van Diemen region where the East Alligator, Finniss and South Alligator rivers are located (reproduced from Petheram et al., (2009b)).**

### Standard high and low flow metrics

Analysis of high and low flow metrics were undertaken at four locations (8210024, 8210007, 8210017 and 8210009) which correspond to stream gauging sites within the East Alligator River catchment, Figure 3.37. In this section we report and interpret the results for one of these locations; results for the other three locations are given in Appendix A.

The standard high and low flow metric analysis results for the East Alligator River are shown in Table 3.17 for the Magela Creek Plains gauge at Jabiluka (8210017). Based on Scenario

A, most of the flow (92%) occurs during the wet season, with periods of zero flow occurring during the dry season. The greatest changes in annual and wet season flow occurs under Scenario Cwet, with increases of more than 43%. Under Scenario Cdry, annual and seasonal flow decreased by at least 37% relative to Scenario A. There are no development scenarios reported for this location.

The greatest impact on the low flow characteristics at this location occur under Scenario Cdry. Under this scenario, the number of days of zero flow increased by more than 42% and the duration of zero flow events increased by 50%. The number of days of zero flow was reduced by nearly 30% under Scenario Cwet.

Changes to the flow regime at high flows are greater than 46% for Scenarios Cwet and Cdry. The number of days above the high flow threshold and duration of events does not change much for any of the scenarios relative to Scenario A. The rates of rise and fall during the wet season shows changes of greater than 25% for both Scenario Cwet and Cdry.

**Table 3.17. Standard metrics for changes to flow regime on the Magela Creek Plains at Jabiluka under Scenarios C and D relative to Scenario A. Red text indicates changes of more than 25% relative to Scenario A.**

| East Alligator - Magela Creek Plains at Jabiluka, Gauge No. G8210017 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Standard metrics | Units | A | Cwet | Cmid | Cdry | Dwet | Dmid | Ddry |
| | | | change from Scenario A | | | | | |
| General metrics | | | | | | | | |
| Annual flow (mean) | GL | 252 | +43% | +0% | -40% | nm | nm | nm |
| Wet season flow (mean)* | GL | 231 | +47% | 0% | -42% | nm | nm | nm |
| Dry season flow (mean)** | GL | 6.78 | +16% | +2% | -37% | nm | nm | nm |
| Low flow metrics | | | | | | | | |
| Low flow threshold (discharge exceeded 90% of the time in Scenario A) | GL/d | 0 | | | | | | |
| Number of days below low flow threshold (mean) | d/y | 73.2 | -21.9 | +0.8 | +30.7 | nm | nm | nm |
| Duration of flow events below low flow threshold (mean) | d/y | 67.9 | -15.2 | +5.2 | +33.3 | nm | nm | nm |
| Number of events below low flow threshold (mean) | events/y | 1.08 | -0.1 | -0.1 | -0.1 | nm | nm | nm |
| Number of days of zero flow (mean) | d/y | 73.2 | -21.9 | +0.8 | +30.7 | nm | nm | nm |
| High flow metrics | | | | | | | | |
| High flow threshold (discharge exceeded 5% of the time in Scenario A) | GL/d | 4.22 | | | | | | |
| Number of days above high flow threshold (mean) | d/y | 18.3 | +9.6 | -0.6 | -8.5 | nm | nm | nm |
| Duration of flow events above high flow threshold (mean) | d/y | 14.2 | +1.8 | -1.3 | +1.8 | nm | nm | nm |
| Number of events above high flow threshold (mean) | events/y | 1.29 | +0.5 | +0.1 | -0.7 | nm | nm | nm |
| Wet season rate of rise (mean) | GL/d | 0.31 | +0.1 | 0 | -0.1 | nm | nm | nm |
| Wet season rate of fall (mean) | GL/d | 0.21 | +0.1 | 0 | -0.1 | nm | nm | nm |

*Wet season covers the six months from November to April
**Dry season covers the six months from May to October
nm – not modelled

**Finniss River**

The Finniss River catchment covers an area of 9,060 km$^2$. The river is located about 70km south of Darwin and flows generally westwards and meets the sea at Fog Bay. The Finniss Floodplain and Fog Bay system near the mouth is a wetland of national significance. This area supports a modified, but relatively intact floodplain with extensive paperbark swamps. The site supports some of the best floating mat vegetation communities in the NT and the permanent billabongs in the north east are a major breeding ground for Saltwater and Freshwater crocodiles (Environment Australia, 2001).

**Standard high and low flow metrics**

Analysis of high and low flow metrics were undertaken at five locations (8150010, 8150018, 8150097, 8150098, and 8150180) which correspond to stream gauging sites within the Finniss River catchment, Figure 3.37. In this section we report and interpret the results for one of these locations; results for the other four locations are given in Appendix A.

**The standard high and low flow metric analysis results for the Finniss River are shown in** Table 3.18 for the Gitchams gauge (8150180). Under Scenario A, annual flow into this location is dominated by wet season flows (96 percent). Annual and seasonal flows do not change under Scenario Cmid compared to Scenario A, but there are large increases under Scenario Cwet (19 to 28%) and large decreases under Scenario Cdry (24 to 28%). There are no reported development scenarios for the area upstream of this location.

Compared to Scenario C, the number of days when flow is less than the low flow threshold does not change very much under Scenarios Cmid, but there is a large decrease in low flow days under Scenario Cwet, and a very large increase in low flow days under Scenario Cdry. Zero flow days are rare at this location and this does not change much under any scenario.

Under Scenarios Cmid, high flow threshold exceedance does not change much from Scenario A. Conversely, there is a large increase in high flow days under Scenario Cwet and a large decrease in high flow days under the Scenario Cdry. The duration and number of high flow events changes only moderately under Scenario Cwet and Cdry and rates of rise and fall show little difference from Scenario A.

**Table 3.18. Standard metrics for changes to flow regime on the Finniss River at Gitchams under Scenarios C and D relative to Scenario A. Red text indicates changes of more than 25% relative to Scenario A.**

| Finniss - Finniss River at Gitchams, Gauge No. G8150180 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Standard metrics | Units | A | Cwet | Cmid | Cdry | Dwet | Dmid | Ddry |
| | | | change from Scenario A | | | | | |
| General metrics | | | | | | | | |
| Annual flow (mean) | GL | 426 | +28% | +0% | -24% | nm | nm | nm |
| Wet season flow (mean)* | GL | 411 | +28% | +0% | -24% | nm | nm | nm |
| Dry season flow (mean)** | GL | 12.7 | +19% | 0% | -28% | nm | nm | nm |
| Low flow metrics | | | | | | | | |
| Low flow threshold (discharge exceeded 90% of the time in Scenario A) | GL/d | 0.015 | | | | | | |
| Number of days below low flow threshold (mean) | d/y | 36.5 | -22.6 | +2.2 | +39.6 | nm | nm | nm |
| Duration of flow events below low flow threshold (mean) | d/y | 46.9 | -15.3 | -0.3 | +32.3 | nm | nm | nm |
| Number of events below low flow threshold (mean) | events/y | 0.78 | -0.3 | +0.1 | +0.2 | nm | nm | nm |
| Number of days of zero flow (mean) | d/y | 0.79 | 0 | 0 | 0 | nm | nm | nm |
| High flow metrics | | | | | | | | |
| High flow threshold (discharge exceeded 5% of the time in Scenario A) | GL/d | 6.96 | | | | | | |
| Number of days above high flow threshold (mean) | d/y | 18.3 | +5.7 | 0 | -5.8 | nm | nm | nm |
| Duration of flow events above high flow threshold (mean) | d/y | 6.86 | +1.1 | +0.2 | -1.3 | nm | nm | nm |
| Number of events above high flow threshold (mean) | events/y | 2.66 | +0.4 | -0.1 | -0.4 | nm | nm | nm |
| Wet season rate of rise (mean) | GL/d | 0.71 | +0.2 | 0 | 0 | nm | nm | nm |
| Wet season rate of fall (mean) | GL/d | 0.48 | +0.1 | 0 | 0 | nm | nm | nm |

*Wet season covers the six months from November to April
**Dry season covers the six months from May to October
nm – not modelled

### South Alligator River

The South Alligator River has a catchment area of 11,600 km$^2$ and the river itself is about 160 km long. It rises north of Mount Stow on the Arnhem Land plateau and flows north-westerly in a valley containing a number of disused uranium mines developed between 1955 and 1965. It also meets the sea in the Van Diemen Gulf. The entire river and its catchment are contained and protected in Kakadu National Park.

### Standard high and low flow metrics

Analysis of high and low flow metrics were undertaken at four locations (8200044, 8200045, 8200111 and 8200112) which correspond to stream gauging sites within the South Alligator River catchment, Figure 3.37. In this section we report and interpret the results for one of these locations; results for the other three locations are given in Appendix A.

The standard high and low flow metric analysis results for the South Alligator River are shown in Table 3.19 for the Nourlangie Creek gauge (8200112) at Kakadu Highway. Based on Scenario A, most of the flow (96%) occurs during the wet season, with the river ceasing to flow for 101 days of the year, on average. The greatest changes in annual and wet season flow occurs under Scenario Cwet, with increases of >25%. Annual and seasonal flows under Scenario Cdry are reduced by 23%. There are no development scenarios reported for this location.

The greatest impact on the low flow characteristics at this location occur under Scenario Cdry. Compared to Scenario A, the number of days of zero flow increases by 30% under Scenario Cdry and the average duration of low flow events increased by 25%. There were more moderate changes to low flow metrics under Scenarios Cwet and Cmid.

Under Scenarios Cmid, high flow threshold exceedance does not change much from Scenario A. Conversely, there is a large increase in high flow days under Scenario Cwet and a large decrease in high flow days under the Scenario Cdry. The duration and number of high flow events changes only moderately under Scenario Cwet and Cdry. Relative to Scenario A, the wet season rate of rise increased by more than 25% for Scenario Cwet and did not change at all for other Scenarios.

**Table 3.19. Standard metrics for changes to flow regime on the Nourlangie Creek At Kakadu Highway under Scenarios C and D relative to Scenario A. Red text indicates changes of more than 25% relative to Scenario A.**

| South Alligator - Nourlangie Creek At Kakadu Highway, Gauge No. G8200112 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Standard metrics | Units | A | Cwet | Cmid | Cdry | Dwet | Dmid | Ddry |
| | | | change from Scenario A | | | | | |
| General metrics | | | | | | | | |
| Annual flow (mean) | GL | 816 | +25% | 0% | -23% | nm | nm | nm |
| Wet season flow (mean)* | GL | 783 | +26% | 0% | -23% | nm | nm | nm |
| Dry season flow (mean)** | GL | 13.5 | +4% | +1% | -23% | nm | nm | nm |
| Low flow metrics | | | | | | | | |
| Low flow threshold (discharge exceeded 90% of the time in Scenario A) | GL/d | 0 | | | | | | |
| Number of days below low flow threshold (mean) | d/y | 101 | -11.9 | +4.9 | +31.4 | nm | nm | nm |
| Duration of flow events below low flow threshold (mean) | d/y | 99.7 | -12.8 | -2.6 | +24.6 | nm | nm | nm |
| Number of events below low flow threshold (mean) | events/y | 1.01 | 0 | +0.1 | +0.1 | nm | nm | nm |
| Number of days of zero flow (mean) | d/y | 101 | -11.9 | +4.9 | +31.4 | nm | nm | nm |
| High flow metrics | | | | | | | | |
| High flow threshold (discharge exceeded 5% of the time in Scenario A) | GL/d | 12.1 | | | | | | |
| Number of days above high flow threshold (mean) | d/y | 18.3 | +6.9 | -0.1 | -5.5 | nm | nm | nm |
| Duration of flow events above high flow threshold (mean) | d/y | 9.84 | +1.4 | -0.1 | -1.2 | nm | nm | nm |
| Number of events above high flow threshold (mean) | events/y | 1.86 | +0.4 | 0 | -0.4 | nm | nm | nm |
| Wet season rate of rise (mean) | GL/d | 0.70 | +0.2 | 0 | 0 | nm | nm | nm |
| Wet season rate of fall (mean) | GL/d | 0.477 | +0.2 | 0 | 0 | nm | nm | nm |

*Wet season covers the six months from November to April
**Dry season covers the six months from May to October
nm – not modelled

#### 3.4.2.16.4 Conclusions

- Stream flow in northern rivers and the environmental assets they support is extremely seasonal and ecosystems are adapted to the prevailing conditions. In unregulated streams the vast majority (> 90 percent) of total annual flow occurs during the wet season months (November to April). Ecosystems have adapted to environments with persistent dry season flow and have become dependent on this flow. This leads to a high level of endemism across north Australia.

- There is a general lack of quantitative relationships between flow and specific ecological flora and fauna in the NAWFA reporting area. As a result the consequence of flow changes on ecological systems is largely unknown. The few existing site-specific thresholds used here demonstrate the value of such information and resources for development of more of these thresholds and associated relationship are best targeted at areas containing high priority ecological assets that may come under significant development pressure.
- In the absence of species specific thresholds, standard metrics, derived solely from the river flow regime, provided useful guideline information and have the advantage that they enable comparisons within and between regions. The selected metrics relate mainly to the high and low flow conditions which are important drivers of floodplain and in-stream ecosystem structure and processes in northern Australia.
- For locations where both site specific and standard metrics were available it was found that the standard metrics adequately reflected the directions (and to some degree magnitude) of potential change derived for the site specific metrics.
- Low flows under dry climate change scenarios are likely to be altered significantly. Some areas are likely to experience considerable increases in the duration of low and zero flows which may have major ecological impacts. Combining climate change with development pressures can exacerbate changes to low flow conditions.
- Flooding is an important factor that sustains many environmental assets by providing connectivity across the floodplain and facilitating migration. Under dry climate change scenarios flood frequency can be reduced greatly and this may have impacts on provision of habitat and breeding grounds. Under wet climate change conditions flooding may become much more frequent and this could have both positive and negative impacts depending on flow requirements of different species.
- Despite the fact that there are large areas of groundwater dependant ecosystems in northern Australia there are no known locations with quantitative groundwater related ecological metrics. Further monitoring of the interactions between groundwater level and the functioning of ecosystems is therefore recommended.
- It is also worth noting that any change in river flow is likely to result in changes to water quality including sediment and nutrient loads, water temperature and dissolved

oxygen levels. These changes in turn may also affect productivity and habitat quality and as such should be carefully considered in future investigations.

### 3.4.2.17 In-steam pools as ecological refugia (Service 3)

#### 3.4.2.17.1 LandSat Results and Discussion

**Fitzroy, Western Australia**

The evolution of pools in the central 275 km reach of the Fitzroy River during three contrasting years is shown in Figure 3.38, along with the daily discharge recorded at the Fitzroy Barrage (gauge No. 802003) during the same three years. The wettest year was 2006 and analysis of the LandSat data on 20 March 2006 showed the river to be one continuous reach. As the dry season started and flows declined, pool numbers increased steadily, reaching a maximum of 194 on 27 August (day 239). After this date, pool numbers declined to 107 on 1 December (day 316), just before the start of the next wet season. There was less rainfall in the 2008 wet season and as a result at the beginning of this dry season the river had one long (142km) continuous reach and already contained ~ 50 pools. Pool numbers increased more rapidly than in 2006, but by 1 September (day 245) had reached a peak of 216, broadly similar to the peak pool number in 2006. River flows were extremely low in 2005 and pool numbers grew very rapidly in the early dry season and had exceeded 200 as early as 20 May (day 214). However, pool numbers did not continue to increase, but rather stayed around 170 (± 5%)  for the rest of the dry season.

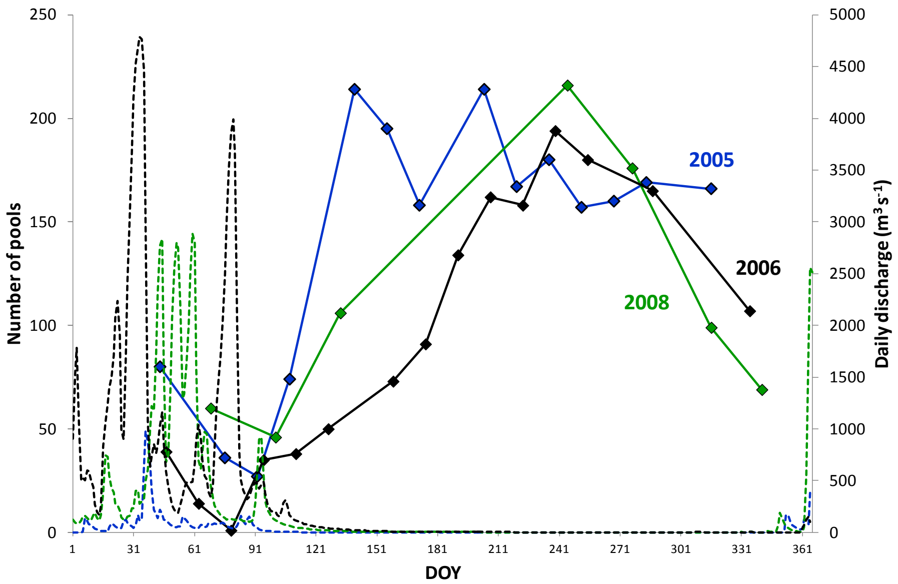



**Figure 3.38 The development of pools in the Fitzroy River, WA during three years; 2005 (blue), 2006 (black) and 2008 (green). Also shown is the daily discharge (dashed**

**lines) recorded at the Fitzroy Barrage (gauge No. 802003) during the same three years.**

The similarity in pool numbers around mid August (day 230), despite the very different preceding wet seasons, suggests that flow in this river at this time may be largely ground water fed. This is consistent with the conclusion from river water chemistry sampling at this time of year in this river (Harrington et al., 2011). The decline in pool numbers after mid-August suggests that the groundwater feed is not sufficient to maintain all the pools in the river and some of the smaller pools are drying up and disappearing (see below).

Figure 3.39 shows the seasonal change in total pool area during 2005, 2006 and 2008. Given that the river was continuous on 20 March 2006, the ‘bank full’ area of the river on this day (4529 ha) was taken to be 100% and total pool areas on other days are expressed as a percentage of the area on 20 March 2006. Pool area decreased rapidly at the start of the 2006 dry season and then continued to decline, but more slowly from early May onwards. Total pool area began both of the 2005 and 2008 dry seasons well below 100% and remained below the 2006 pool area for the rest of the dry season. At the time of peak pool numbers (mid August - day 230) total pool areas range from ~ 25% in 2005, 28% in 2008 and 35% in 2006. At the end of the dry seasons pool area remained above 24% in 2005 and 2006, but collapses to only 7% of the bank full area in the driest year of 2008.

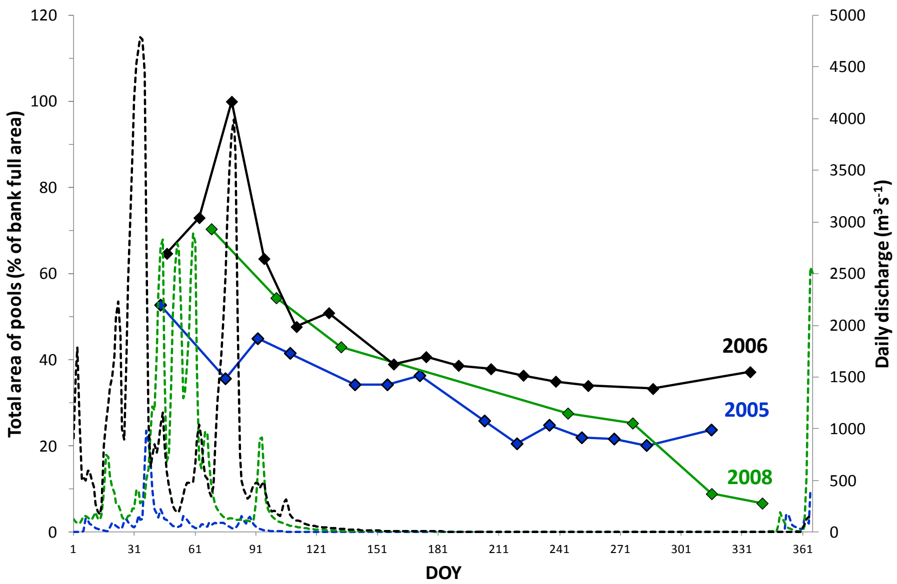



**Figure 3.39 The seasonal change in total pool area in the Fitzroy River, WA during three years; 2005 (blue), 2006 (black) and 2008 (green). Also shown is the daily discharge (dashed lines) recorded at the Fitzroy Barrage (gauge No. 802003) during the same three years.**

The relationships between (a) pool number and (b) total pool area and daily flow in the Fitzroy river are shown in Figure 3.40 for all three years (2005, 2006 and 2008). Pool numbers increase to around 50 when the river flow drops below ~ 500 $m^3 s^{-1}$. At much lower flows (below ~50 $m^3 s^{-1}$) there is a very rapid increase in pool numbers and commensurate rapid decrease in total pool area (Figure 3.40b). If aquatic biota in this river reach are adversely affected by low flows, then these low flow thresholds could be used to assess when these conditions occur within this river reach.

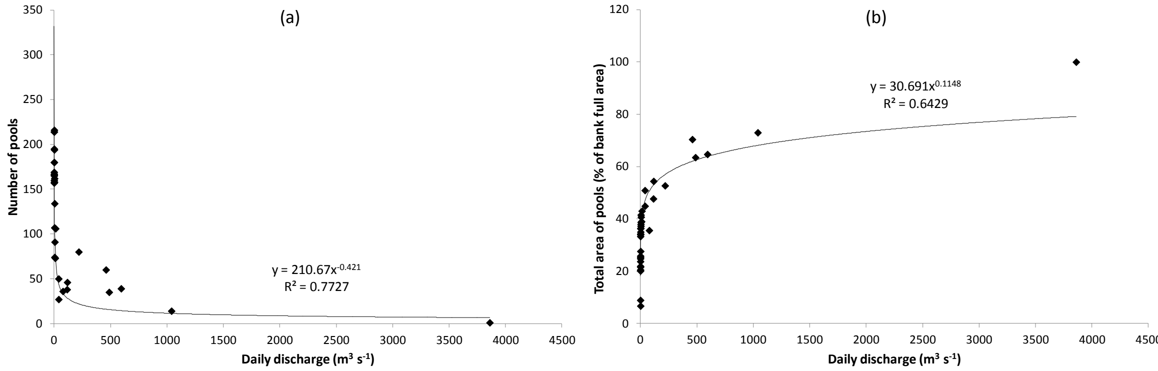



**Figure 3.40 The relationship between (a) pool number and (b) total pool area and flow recorded at the Fitzroy Barrage (gauge No. 802003) during 2005, 2006 and 2008.**

A description of the pool length distributions in each year is given in Figure 3.41 and the data are summarised in Table 3.20. In the driest year (2005) the season begins with one long (138 km) continuous river reach and 26 pools ranging in size from 0.1 to 6.2 km (median size 0.4 km). By mid August (peak pool number) the long river reach has broken up into pools, and the longest of these is 11.1 km. There are very many more small pools (< 0.5 km) with a secondary peak in pool size around 2 km (Figure 3.41a). At the end of the dry season the decline in pool numbers (Table 3.20) is mainly due to the disappearance of small pools (Figure 3.41a). During the drier year of 2008 there were more small pools at the start of the dry season, but fewer pools of this size at the end of the dry season. The distributions of pool sizes around mid-August (day 230 - peak pool numbers) were quite similar in 2005 and 2008. In contrast, the pool size distribution in the driest year (2005) showed the greatest number of small pools from mid-August onwards.

The summary of reach and pool lengths in Table 3.20 shows some interesting features. The median pool size is generally between 0.3 and 0.5 km, reflecting the large number of small pools. Significantly greater pool sizes only occurred towards the end of the wettest year (2006), when the median pool size rose to just over 1 km. Maximum pool sizes were in the range 4 to 13 km and the minimum pool size of 90 m is a reflection of the analysis technique which ignores pools which contain less than 4 pixels (pixel = 30 x 30 m). The total length of in-stream water bodies (reaches plus pools) is similar at the start of each year, shortest towards the end of the driest year and longest at the end of the wettest year. The total water length at the end of 2008 appears to be anomalously low and further analysis of the LandSat imagery at this time needs to be carried out.

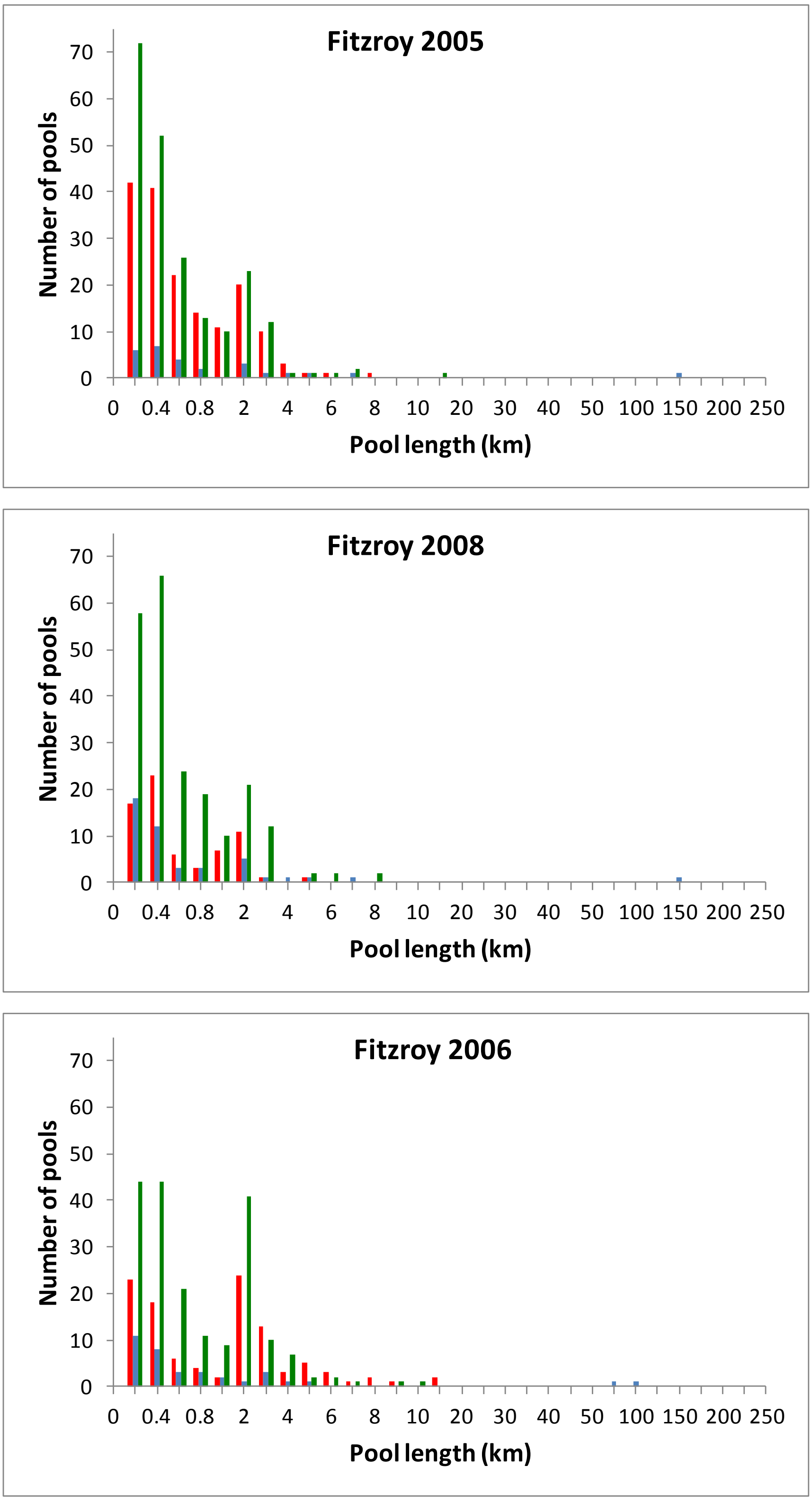



**Figure 3.41 The distribution of pool lengths at the start of the dry season (blue), at peak pool number (green) and at the end of the dry season (red) in the Fitzroy River. Following Georges et al., (2002), pools longer than 20km are referred to as river reaches.**

**Table 3.20 A summary of the length of pools and river reaches in the Fitzroy River during 2005, 2006 and 2008.**

| Year | period | date | pool number | reach number | reach length (km) | pool length (km) | | | total length (reach+pool) (km) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | median | minimum | maximum | |
| 2005 | start of dry season | 2-Apr | 26 | 1 | 138.3 | 0.40 | 0.12 | 6.2 | 166.2 |
| (dry) | peak pool number | 23-Jul | 214 | 0 | - | 0.30 | 0.09 | 11.1 | 154.3 |
| | end of dry season | 12-Nov | 166 | 0 | - | 0.40 | 0.09 | 7.1 | 129.6 |
| 2008 | start of dry season | 10-Apr | 45 | 1 | 142.0 | 0.29 | 0.09 | 6.3 | 174.6 |
| | peak pool number | 1-Sep | 216 | 0 | - | 0.33 | 0.09 | 8.0 | 153.7 |
| | end of dry season | 6-Dec | 69 | 0 | - | 0.33 | 0.09 | 4.9 | 43.4 |
| 2006 | start of dry season | 5-Apr | 33 | 2 | 148.9 | 0.33 | 0.09 | 4.3 | 174.9 |
| (wet) | peak pool number | 27-Aug | 194 | 0 | - | 0.46 | 0.09 | 9.6 | 194.7 |
| | end of dry season | 1-Dec | 107 | 0 | - | 1.02 | 0.09 | 13.0 | 184.1 |

**Mitchell, Queensland**

Figure 3.42 shows how the pools developed in the central 243km reach of the Mitchell River during 2005, along with the daily discharge recorded at the Gamboola river gauge (No. 919011A) during the same year. 2005 was a fairly dry year in this catchment and the river reach analysed started the dry season with 3 long river reaches (25km, 27km and 105km) and around 60 pools (Table 3.21). Pool numbers increased steadily as the dry season progressed and reached a maximum of ~ 230 towards the end of September (day 264). After this time pool numbers decreased despite the small increase in river flow around day 300. The late dry season decline in pool numbers is similar to that observed in the Fitzroy River and is likely to be associated small pools disappearing as the groundwater feed becomes insufficient to sustain all of the pools in the river bed.

The seasonal change in total pool area during 2005 in this catchment is shown in Figure 3.43. The earliest suitable (largely cloud free) LandSat data for this year was 25 February and even though the river was not fully continuous, the ‘bank full’ area of the river on this day (2995ha) was taken to be 100% and total pool areas on other days are expressed as a percentage of the area on 25 February 2005. Pool area decreased steadily during the dry season reaching a minimum of 53% on 21 September, the same day when the peak number of pools was observed (Figure 3.42). After this date total pool area increased, even though the number of pools declined. The small increase in flow around day 300 therefore increased the size of the pools at the end of the dry season and this is confirmed by the pool length analysis described below.

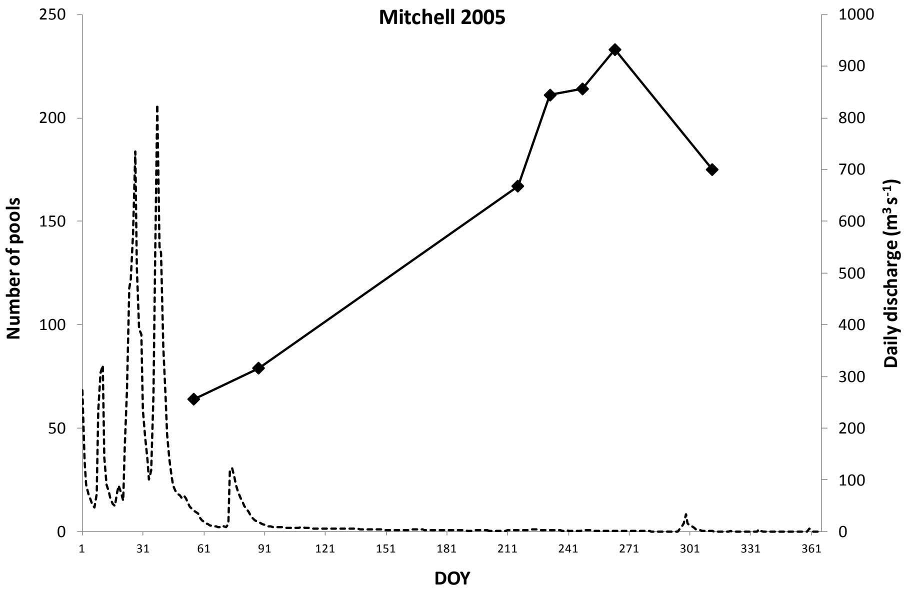



**Figure 3.42 The development of pools in the Mitchell River, QLD during 2005. Also shown is the daily discharge (dashed lines) recorded at the Gamboola river gauge (No. 919011A) during the same year.**

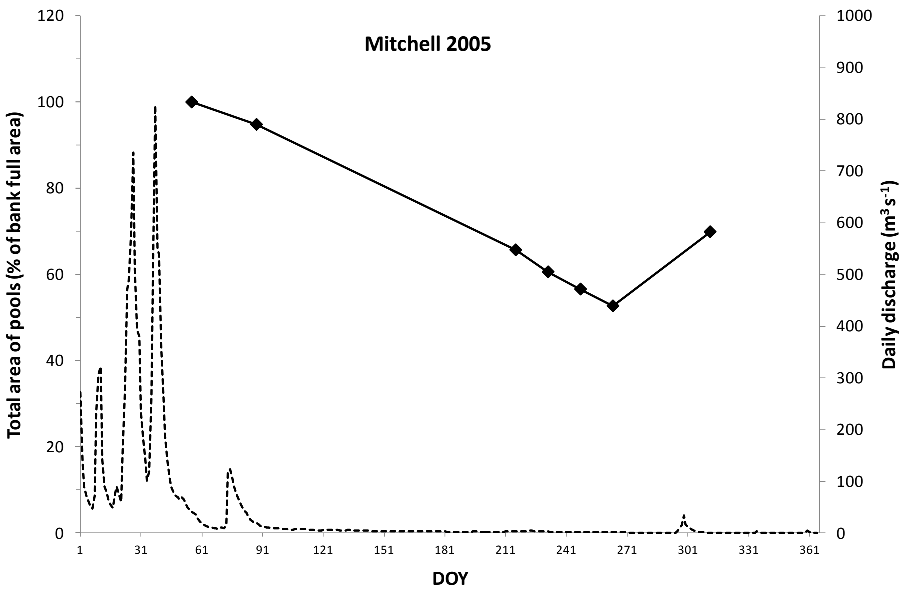



**Figure 3.43 The seasonal change in total pool area in the Mitchell River, QLD during 2005. Also shown is the daily discharge (dashed lines) recorded at the Gamboola river gauge (No. 919011A) during the same year.**

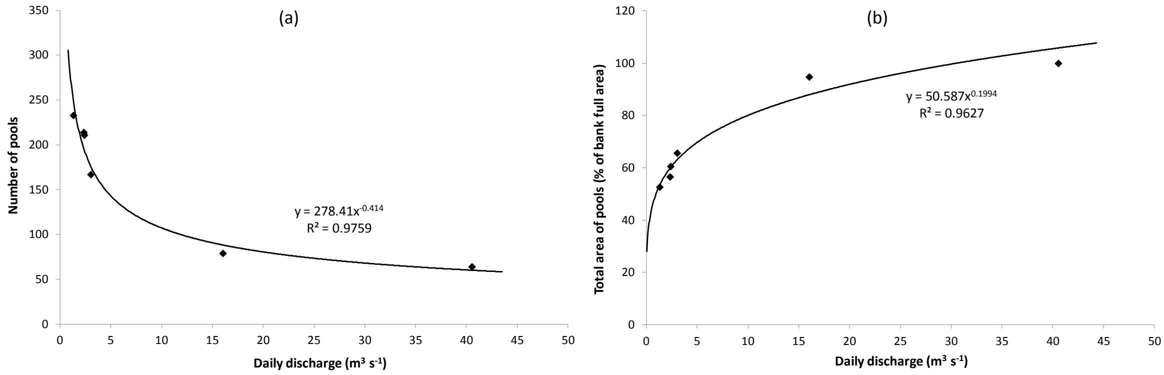



**Figure 3.44 The relationship between (a) pool number and (b) total pool area and flow recorded at the Gamboola river gauge (No. 919011A) during 2005.**

The relationships between (a) pool number and (b) total pool area and daily flow in the Mitchell river are shown in Figure 3.44 for 2005. As in the Fitzroy River, pool numbers increase and total pool area decreases as flow declines. From this single year analysis it is more difficult to identify a sharp threshold, which may not even exist. Further information on the condition of key aquatic biota in this river reach and how these vary with flow rate are needed to identify ecological thresholds for water management purposes.

Figure 3.45 shows how the pool lengths varied in the Mitchell River during 2005 and the data are summarised in Table 3.21. The season begins with one long (105 km) continuous river reach, two other sizable reaches (25 km and 27 km) and 61 pools ranging in size from 0.1 to 8.7 km (median size 0.26 km). By September (peak pool number) the long river reach has broken up into pools, and the longest of these is 12.5 km. There are very many more small pools (< 0.5 km) with a secondary peak in pool size around 2 km (Figure 3.44a). At the end of the dry season the small increase in flow (Figure 3.43) sustains and even increases the number and size of larger pools and the decline in pool numbers at this time is mainly due to the disappearance of small pools. This is confirmed in Table 3.21, which shows median pool size increasing to 0.56 km at the end of the dry season and the total pool length also increasing.

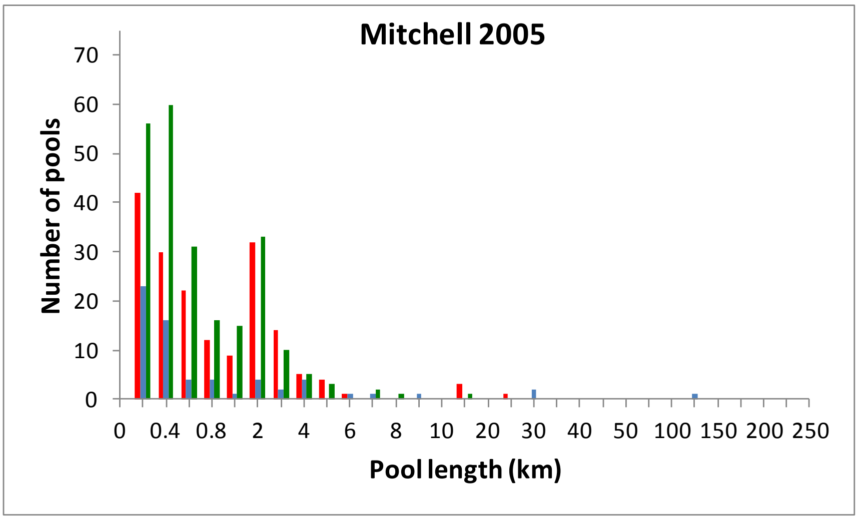



**Figure 3.45 The distribution of pool lengths at the start of the dry season (blue), at peak pool number (green) and at the end of the dry season (red) in the Mitchell River. Following Georges et al., (2002), pools longer than 20km are referred to as river reaches.**

**Table 3.21 A summary of the length of pools and river reaches in the central section of the Mitchell River during 2005.**

| Year | period | date | pool number | reach number | reach length (km) | pool length (km) median | minimum | maximum | total length (reach+pool) (km) |
|---|---|---|---|---|---|---|---|---|---|
| 2005 | start of dry season | 25-Feb | 61 | 3 | 157.4 | 0.26 | 0.09 | 8.7 | 215.9 |
| | peak pool number | 21-Sep | 233 | 0 | - | 0.41 | 0.09 | 12.5 | 198.2 |
| | end of dry season | 8-Nov | 175 | 1 | 22.1 | 0.56 | 0.09 | 12.6 | 222.5 |

### Daly, Northern Territory

Figure 3.46 shows how the pools developed in the central 171km reach of the Daly River during 2000, along with the daily discharge recorded at the Beeboom river gauge (No. 8140042) during the same year. The year 2000 was chosen to allow comparison of pool numbers with the ground survey and pool modelling work of Georges et al., 2002. The river started the dry season as one continuous reach and there were no pools. This continuous reach started to break up as the dry season progressed and by the mid-late dry season (day 251) there were 35 pools and one remaining river reach ~49 km long (Table 3.22). After this time pool numbers continued to increase to 41 at the end of the dry season.

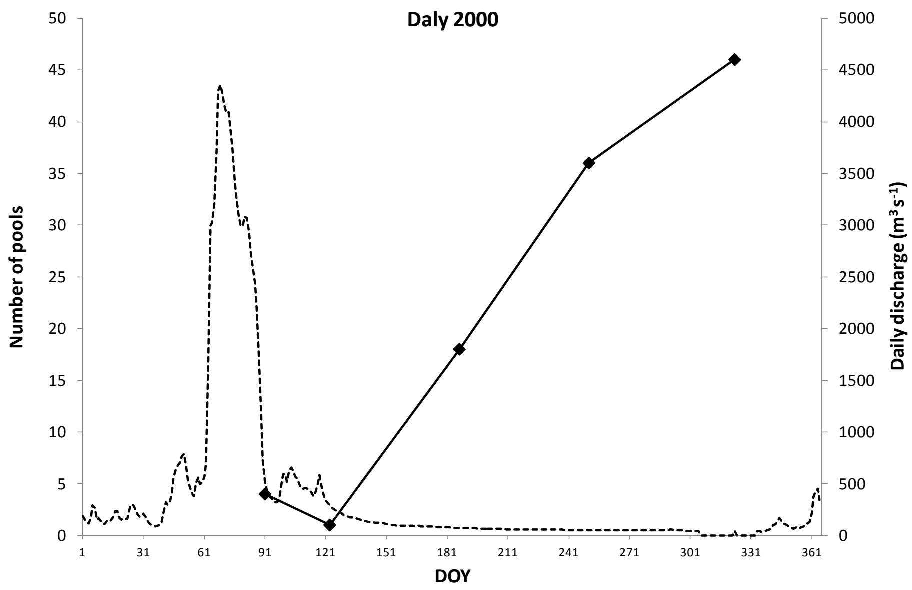



**Figure 3.46 The development of pools in the Daly River, QLD during 2000. Also shown is the daily discharge (dashed lines) recorded at the Beeboom river gauge (No. 8140042) during the same year.**

Pool numbers are much smaller in the Daly River, compared to the Fitzroy and Mitchell Rivers, and this is a reflection of the relatively high flows maintained in this river during the dry season. The absence of a late dry season decline in pool numbers (similar to that observed in the Fitzroy and Mitchell Rivers) may also mean that the groundwater feed in this river is sufficient to sustain all of the pools in the river bed. Georges et al., (2002) reported a peak pool number of 33 in the Daly middle reaches, slightly less than we found in the current study. However, we have analysed a much longer river reach and it would be necessary to carry out further analyses on the same river reaches to make any further comparison between the two studies.

The seasonal change in total pool area during 2000 in the Daly River is shown in Figure 3.47. Analysis of LandSat data on 2 May 2000 showed that the river was one continuous reach, so the ‘bank full’ area of the river on this day (1768 ha) was taken to be 100% and total pool areas on other days are expressed as a percentage of the area on 2 May 2000. Pool area decreased slowly during the dry season, but only reaching a minimum of 73% on 18 December, shortly before the start of the next wet season.

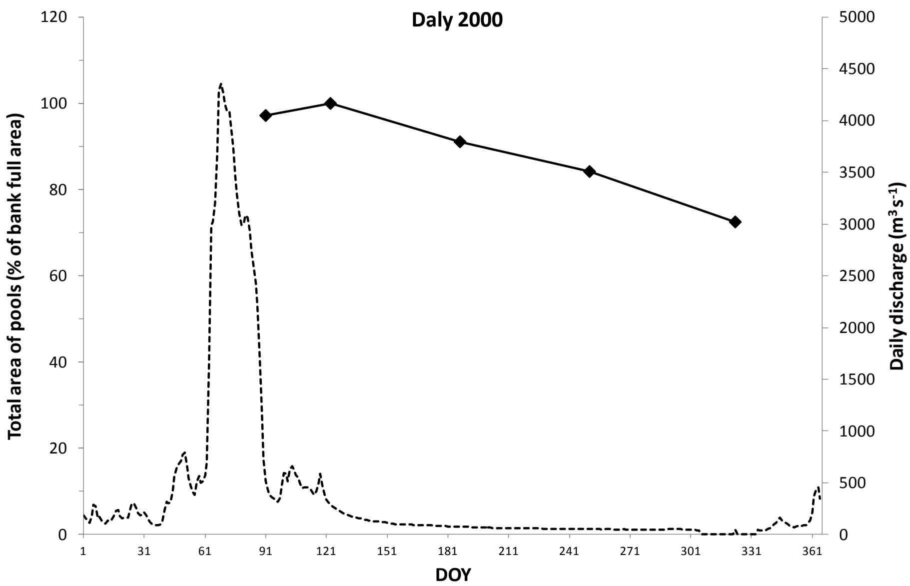



**Figure 3.47 The seasonal change in total pool area in the Daly River, QLD during 2000. Also shown is the daily discharge (dashed lines) recorded at the Beeboom river gauge (No. 8140042) during the same year.**

**Table 3.22 A summary of the length of pools and river reaches in the central section of the Daly River during 2000.**

| Year | period | date | pool number | reach number | reach length (km) | pool length median | pool length minimum (km) | pool length maximum | total length (reach+pool) (km) |
|---|---|---|---|---|---|---|---|---|---|
| 2000 | start of dry season | 2-May | 0 | 1 | 127.0 | - | - | - | 127.0 |
| | mid-late dry season | 7-Sep | 35 | 1 | 48.7 | 0.89 | 0.09 | 13.7 | 137.0 |
| | end of dry season | 18-Dec | 41 | 1 | 56.2 | 1.31 | 0.12 | 9.5 | 141.0 |

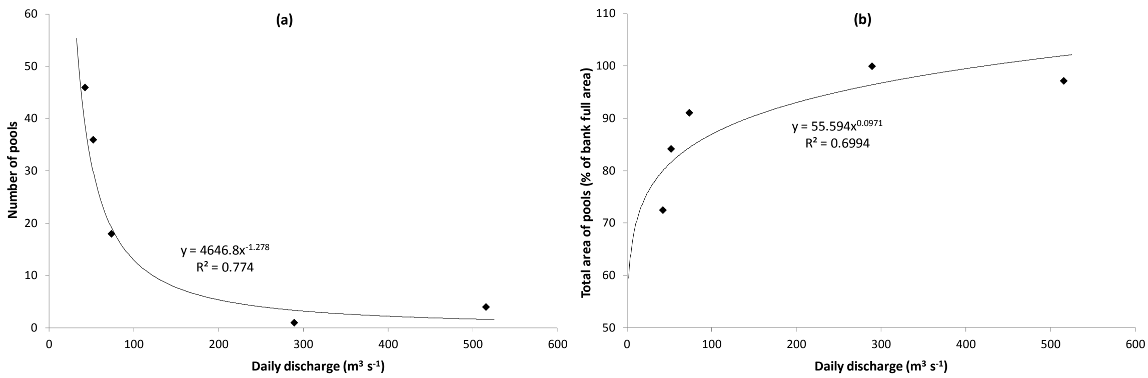



**Figure 3.48 The relationship between (a) pool number and (b) total pool area and flow recorded at the Beeboom river gauge (No. 8140042) during 2000.**

The relationships between (a) pool number and (b) total pool area and daily flow in the Daly River are shown in Figure 3.48 for 2000. As in the Fitzroy River and Mitchell Rivers, pool numbers increase and total pool area decreases as flow declines. Again from this single year analysis it is difficult to identify a sharp threshold, however, the increase in pool numbers found here appears to start at a much higher river flow (~50-100 $m^3$ $s^{-1}$) than the flow rates (~15-20 $m^3$ $s^{-1}$) reported by Georges et al., (2002) below which pools started to form in the Daly middle reaches. It should be noted however, that George et al. used flow data from a different gauge (Dorisvale) than the one used in the present study (Beeboom).

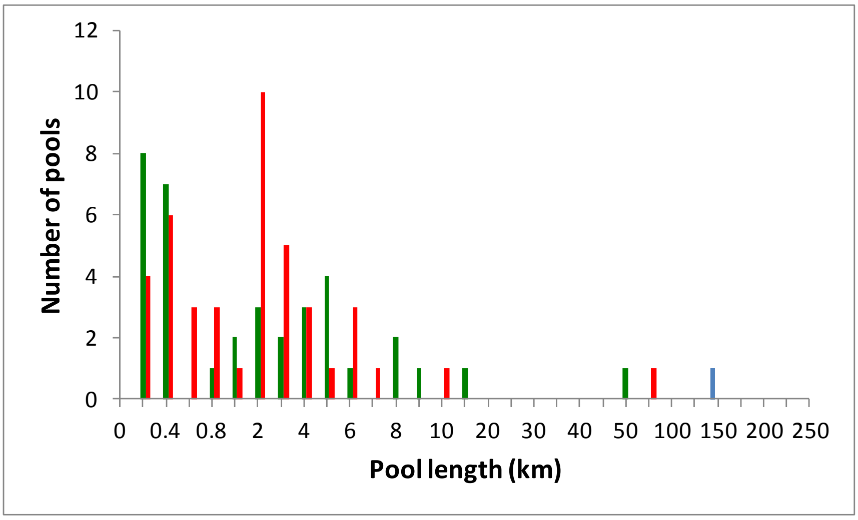



**Figure 3.49 The distribution of pool lengths at the start of the dry season (blue), mid to late dray season (green) and at the end of the dry season (red) in the Daly River. Following Georges et al., (2002), pools longer than 20km are referred to as river reaches.**

Figure 3.46 shows how the pool lengths varied in the Daly River during 2000 and the data are summarised in Table 3.22. The season begins with one long (127 km) continuous river reach, but by mid-late dry season this has broken up into one reach 49 km long and a number of pools, most of which were less than 1 km long. Georges et al., (2002) also found that most of the pools in the Daly middle reaches were of 1 to 2 km in length. By the end of the dry season there remained one long river reach and 41 pools, the median size of which had increased to 1.3 km, largely because of an increase in the number of pools in the 2 to 3 km range (Figure 3.49).

#### 3.4.2.17.2 Conclusions

- In the Fitzroy River the preceding wet season affects the rate at which pools form in the early dry season, but the late dry season pool number is insensitive to wet season flow. This implies that groundwater is the primary source of base flow in this river at this time.
- Both the Fitzroy and Mitchell Rivers show a decline in pool numbers at the end of the dry season. This may be due to the disappearance of small pools which cannot be sustained by groundwater flow at this time.
- Many more pools form in the Fitzroy and Mitchell rivers than in the Daly River. This is because flows are much lower for longer in the two former rivers and a greater groundwater contribution in the Daly River.
- Most of the pools in all three rivers analysed are relatively small (~ 200 to 600 m in length) and the number of small pools generally increases as the dry season progresses.
- There are reasonably good relationships between pool numbers or total pool area and flow, but the relationships are quite different for each river. Some of these relationships may be useful for setting ecologically acceptable low flows, however, additional information on the response of key aquatic biota to pool characteristics is needed to quantify these thresholds.

### 3.4.2.18 Flood extent and wetland connectivity

#### 3.4.2.18.1 Results

**Model Calibration**

A comparison of water heights at four key locations (e.g. Fitzroy Crossing, Noonkanbah, Fitzroy Barrage and Looma) is shown in Figure 3.50 for the flood event in 2002. The overall agreement between measured and simulated stage heights is fairly good except at Noonkanbah. The matching of peak arrival at all four locations is good which confirms accurate prediction of the flood wave speed. Figure 3.51 shows a typical comparison between simulated and MODIS detected inundated areas at: a) near peak inundation and b) recession stages of floods. In case of near peak flooding, it shows a reasonably good match alongside the Fitzroy River. However, a large number of water cells that appeared in the vicinity of the Margaret River were not visible in the Satellite image. One of the reasons might be the large pixel size of MODIS data (250 m grid). Other reasons might include dense vegetation on land that potentially hides shallow water bodies.

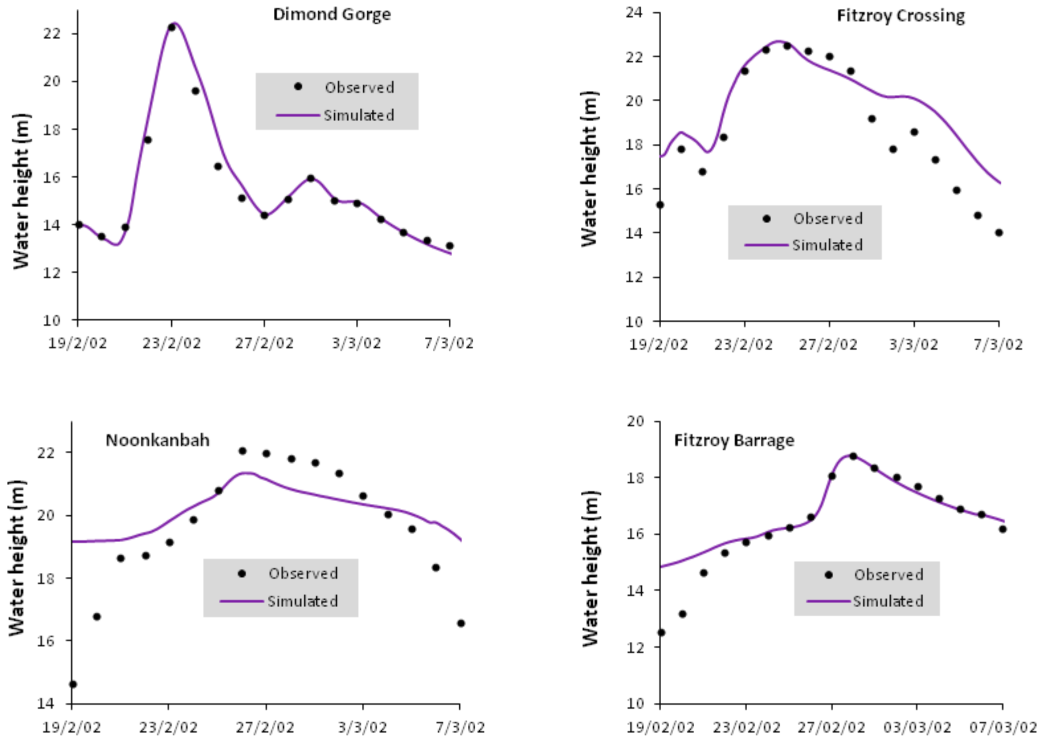



**Figure 3.50 Comparison between observed and model simulated stage heights at 4 stream gauge locations in the floodplain.**

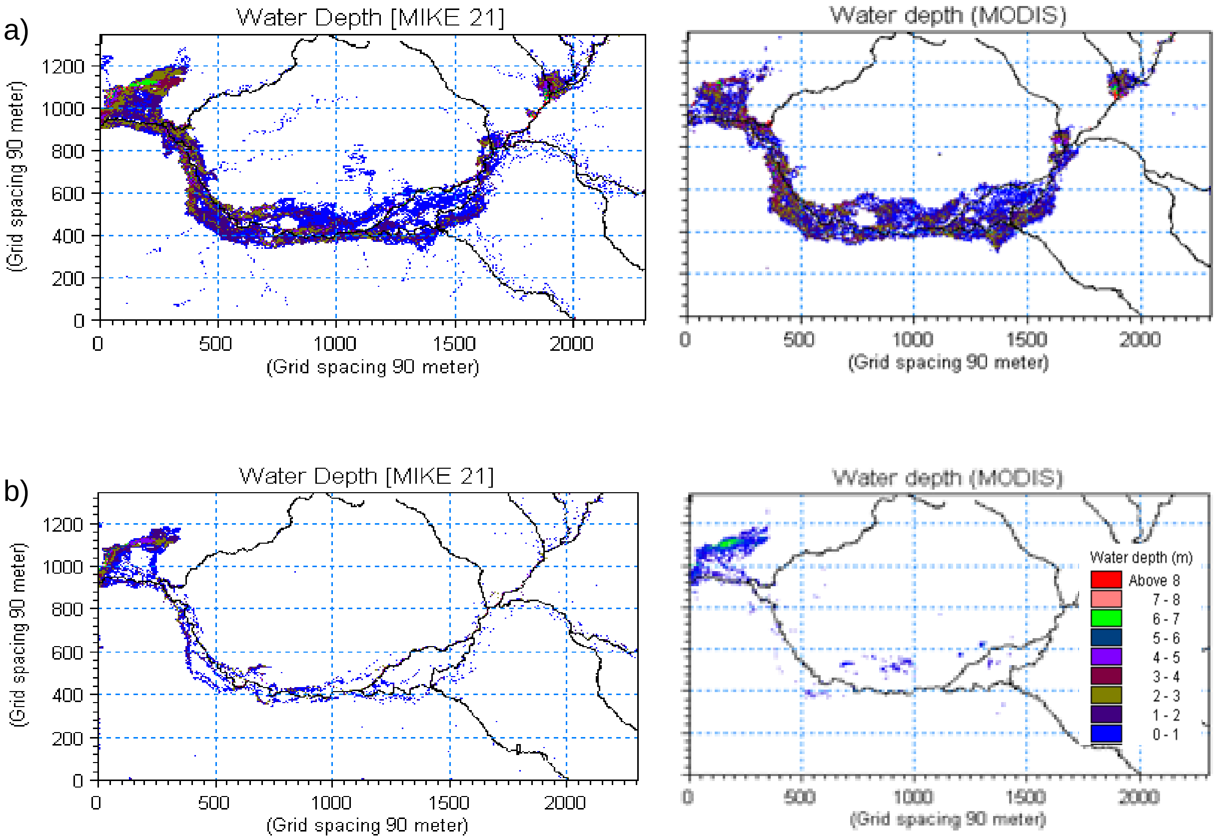



**Figure 3.51 Comparison between model simulated and MODIS detected inundations in the central floodplain on (a) 27 Feb 2002 and (b) 8 Mar 2002.**

### Inundation area

Figure 3.52 shows a time series of inundation area covering the periods of rising, peak and falling stages. MODIS detected inundation areas and a comparison with simulated inundations can be seen on the same figure. Simulated inundation areas are generally large especially during the flood recession. One of the reasons may be the poor representation of stream channels that leads to less flow through the channel thus increasing overbank flows. This problem has been partly solved by lowering the elevation of stream grids. It is also possible that MODIS detection could be poor due to cloud cover, or the MODIS large pixel size does not detecting small water features. We also indentified the areas that were inundated for a day or more during the flood. Figure 3.53 is an example of such results that also shows the maximum inundation depth for the entire simulation period (40 days). Other than the Fitzroy, the Margaret River has large inundation areas on both sides of its river banks. Flooding alongside of the major creeks is either small in area or low in depth.

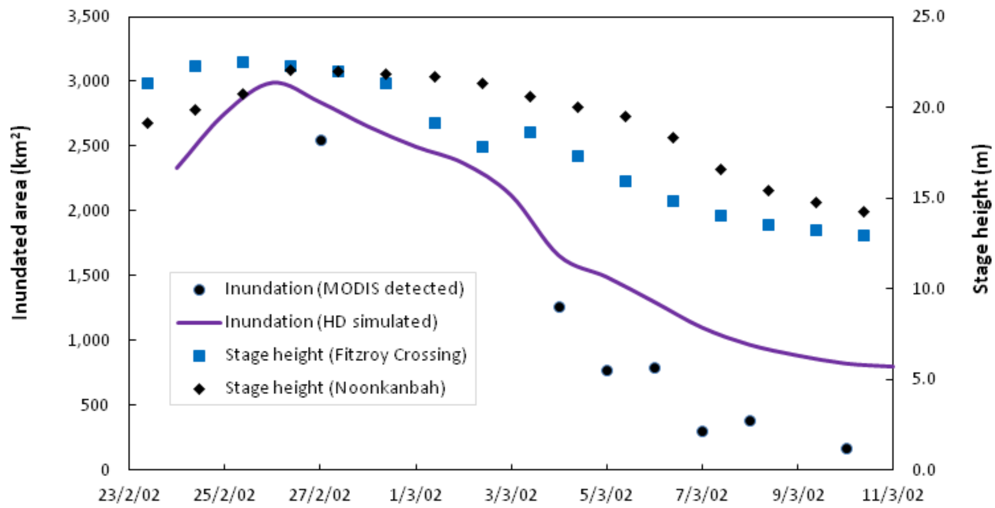



**Figure 3.52 Comparison between simulated and Satellite (MODIS) detected inundation areas during the February-March 2002 flood (Note: all water cells in the river and on the floodplain are included in inundation calculation)**

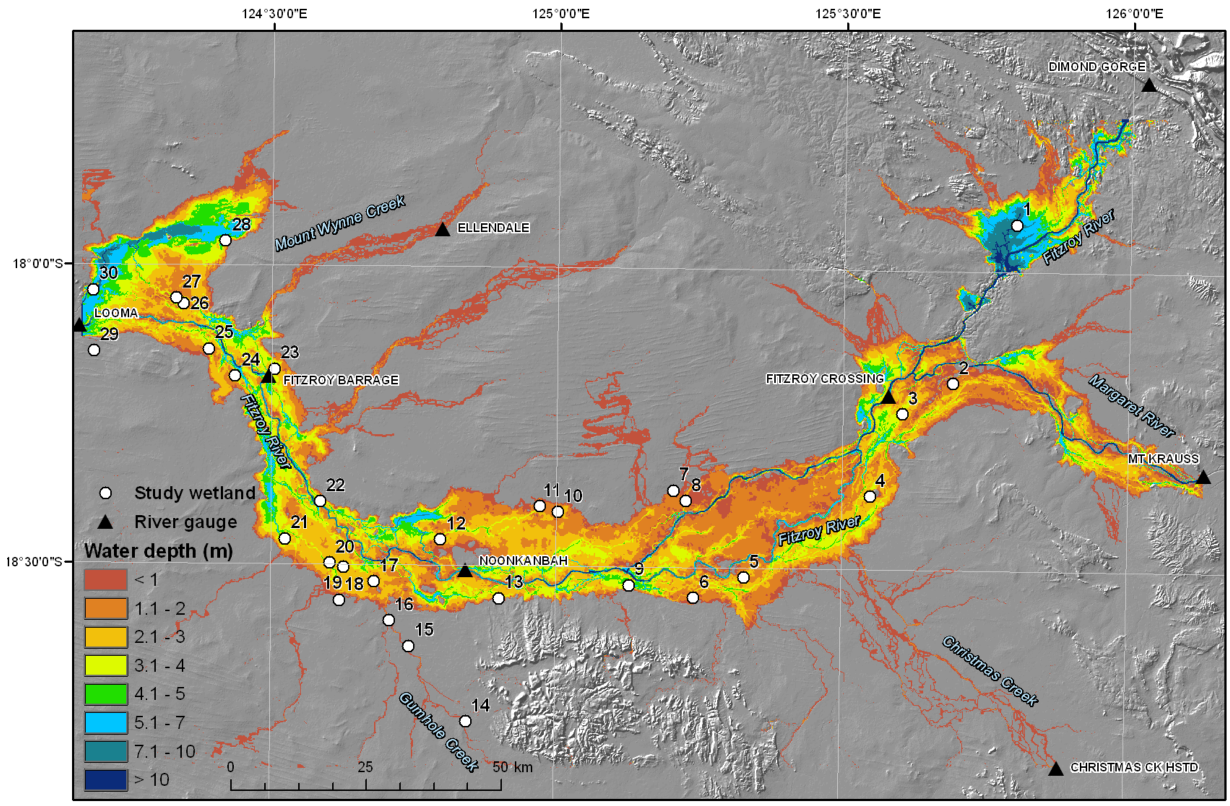



**Figure 3.53 Simulated inundation area and maximum inundation depth across the floodplain for the flood event in 22 Feb- 5 Mar 2002. Maximum depths were calculated using time series of 6 hourly water depths at each grid.**

### Inundation duration

Duration of inundation is another ecologically important aspect of floods on wetland habitats. It is mainly governed by the hydrological regime and partly by topography of the floodplain. We used six hourly flood depth information derived from the HD model to calculate inundation duration and a typical example is shown in Figure 3.54. In general, duration of inundation is longer in the lower part of the floodplain, especially near Looma. This is primarily due to flat land topography in this region compared with upper part of the floodplain. Importantly we note that inundation alongside of the Margaret River is very short, typically 2-3 days, even during a large flood in 2002.

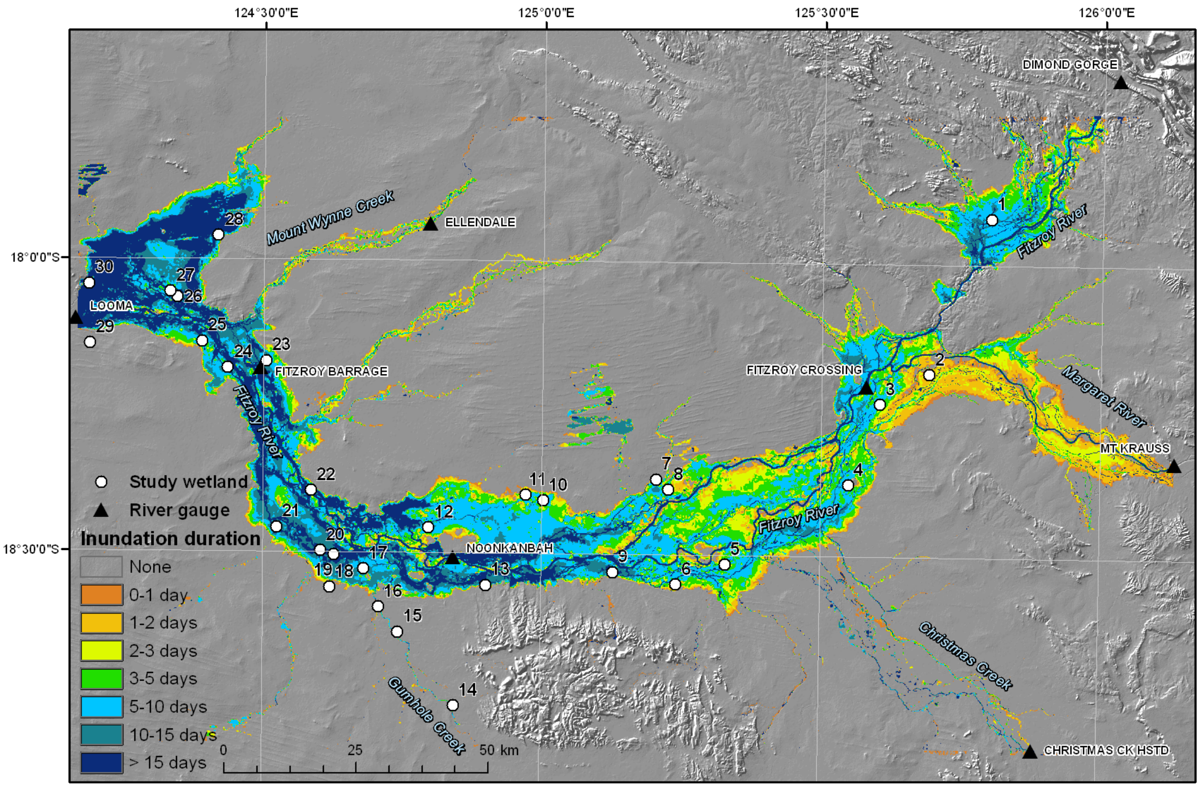



**Figure 3.54 A typical example of the spatial variation in inundation duration across the floodplain for the flood event in 2002**.

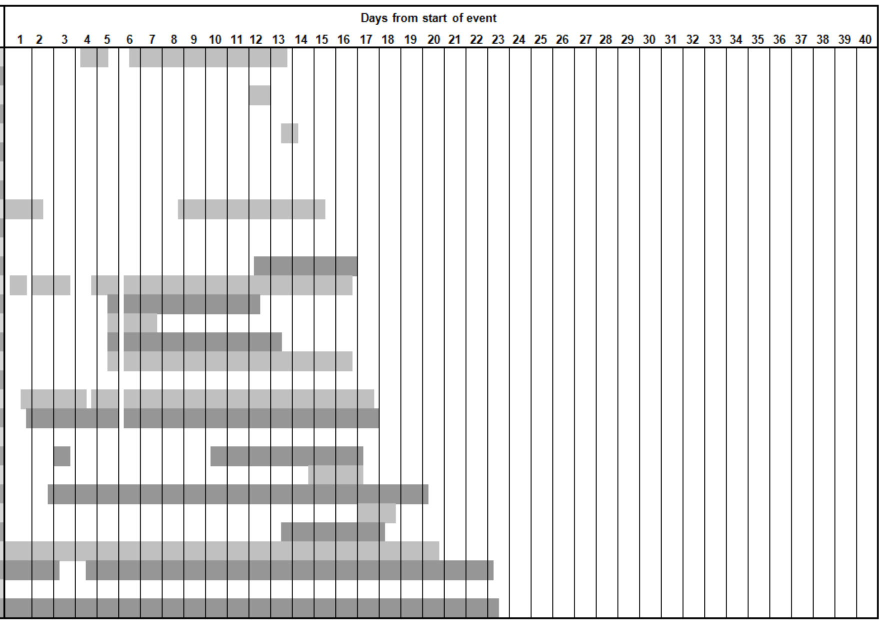
### Wetland connectivity

The summaries of connection timing and the duration of connection of the wetlands to the Fitzroy River are shown in Figure 3.55 for the flood events of 2002 and 2007. As indicated previously, larger floods produce longer duration of flooding, and they also create longer duration of connectivity. It shows 10 out of 30 wetlands did not connect to the river by overbank flows during the 2007 event which was a relatively small flood (1.5 year ARI). More wetlands, however, connected to the river during the larger 2002 flood event (14 year ARI). Three wetlands (e.g. Peaceful Lagoon, Lake Daley and Sandhill Swamp) did not connect to the river during this large flood event. The main reason is their location either on elevated land (e.g. Lake Daley) or great distance from the river (e.g. Peaceful lagoon). It is interesting to note that Peaceful lagoon was not connected to the river during the 2002 flood but was connected during the smaller 2001 flood. This is caused by spatial variation in local runoff due to rainfall heterogeneity. It can also be seen that Gumhole Billabong, which is located 26km from the river, yet still connects with it during floods. This wetland is actually located on-stream in the Gumhole Creek (a tributary of the Fitzroy River) which often connects the river during the wet season. In general, wetlands that are located in the lower part of the study area (i.e. in between Looma and Noonkanbah) experience longer connection with the river. This is consistent with the duration of inundation as seen in Figure 3.54.

Result also shows that flood events having more than one peak produce much longer duration of connection even if the second peak is small in magnitude. Such an example of connectivity behaviour is shown in Figure 3.56 for the flood event in 2001. It can be seen that several wetland connected to the river for a very long duration (above 30 days) and some reconnected to the river after disconnection following the first peak.

a) Flood 2007

| ID | Wetland | Duration (days) | Distance (km) |
|---|---|---|---|
| 1 | Duck Hole | 8.5 | 6.3 |
| 2 | Lilyhole Billabong | 0.0 | 0.0 |
| 3 | Coorie Billabong | 1.0 | 6.8 |
| 4 | Jillyardie Waterhole | 0.0 | 0.0 |
| 5 | Pelican Billabong | 0.8 | 11.5 |
| 6 | Sevenmile Billagong | 0.0 | 0.0 |
| 7 | Patersons Dam | 0.0 | 0.0 |
| 8 | Quanbun Billabong | 0.0 | 0.0 |
| 9 | Red Billabong | 8.5 | 2.1 |
| 10 | Mallallah Swamp I | 0.0 | 0.0 |
| 11 | Mallallah Swamp II | 0.0 | 0.0 |
| 12 | Sandy Billabong | 4.8 | 8.7 |
| 13 | Balwynah Pool | 14.3 | 3.6 |
| 14 | Gumhole Billabong | 6.8 | 48.9 |
| 15 | Peaceful Lagoon | 2.0 | 36.1 |
| 16 | Duckhole Billabong | 7.8 | 19.9 |
| 17 | Goosehole Billagong | 11.0 | 10.9 |
| 18 | SandHill Swamp | 0.0 | 0.0 |
| 19 | Backhouse Waterhole | 15.8 | 9.6 |
| 20 | Slaughter Hole | 16.0 | 11.5 |
| 21 | Quonga Waterhole | 0.0 | 0.0 |
| 22 | Broken Wagon Pool | 7.8 | 1.1 |
| 23 | Troys Lagoon | 2.5 | 1.7 |
| 24 | Ligligin Waterhole | 17.5 | 4.5 |
| 25 | Ninemile Pool | 1.8 | 3.9 |
| 26 | Yallamungie Pool | 4.8 | 3.7 |
| 27 | Camballin Floodplain | 20.0 | 9.3 |
| 28 | Le Lievre Swamp | 21.3 | 25.9 |
| 29 | Lake Daley | 0.0 | 0.0 |
| 30 | Upper Liveringa Pool | 22.8 | 5.5 |




b) Flood 2002

| ID | Wetland | Duration (days) | Distance (km) |
|---|---|---|---|
| 1 | Duck Hole | 15.3 | 5.7 |
| 2 | Lilyhole Billabong | 1.5 | 8.6 |
| 3 | Coorie Billabong | 6.0 | 4.5 |
| 4 | Jillyardie Waterhole | 5.8 | 4.9 |
| 5 | Pelican Billabong | 7.8 | 5.1 |
| 6 | Sevenmile Billagong | 2.8 | 4.0 |
| 7 | Patersons Dam | 6.0 | 15.8 |
| 8 | Quanbun Billabong | 5.3 | 12.9 |
| 9 | Red Billabong | 14.3 | 1.9 |
| 10 | Mallallah Swamp I | 4.0 | 14.1 |
| 11 | Mallallah Swamp II | 5.5 | 12.7 |
| 12 | Sandy Billabong | 11.5 | 6.9 |
| 13 | Balwynah Pool | 18.0 | 3.1 |
| 14 | Gumhole Billabong | 1.8 | 42.3 |
| 15 | Peaceful Lagoon | 0.0 | 0.0 |
| 16 | Duckhole Billabong | 7.3 | 12.1 |
| 17 | Goosehole Billagong | 11.5 | 4.8 |
| 18 | SandHill Swamp | 0.0 | 0.0 |
| 19 | Backhouse Waterhole | 17.8 | 5.5 |
| 20 | Slaughter Hole | 17.3 | 7.0 |
| 21 | Quonga Waterhole | 6.5 | 8.6 |
| 22 | Broken Wagon Pool | 15.5 | 0.9 |
| 23 | Troys Lagoon | 9.5 | 1.7 |
| 24 | Ligligin Waterhole | 18.5 | 2.8 |
| 25 | Ninemile Pool | 11.0 | 3.1 |
| 26 | Yallamungie Pool | 12.8 | 3.6 |
| 27 | Camballin Floodplain | 22.0 | 7.8 |
| 28 | Le Lievre Swamp | 24.5 | 23.4 |
| 29 | Lake Daley | 0.0 | 0.0 |
| 30 | Upper Liveringa Pool | 28.3 | 5.4 |

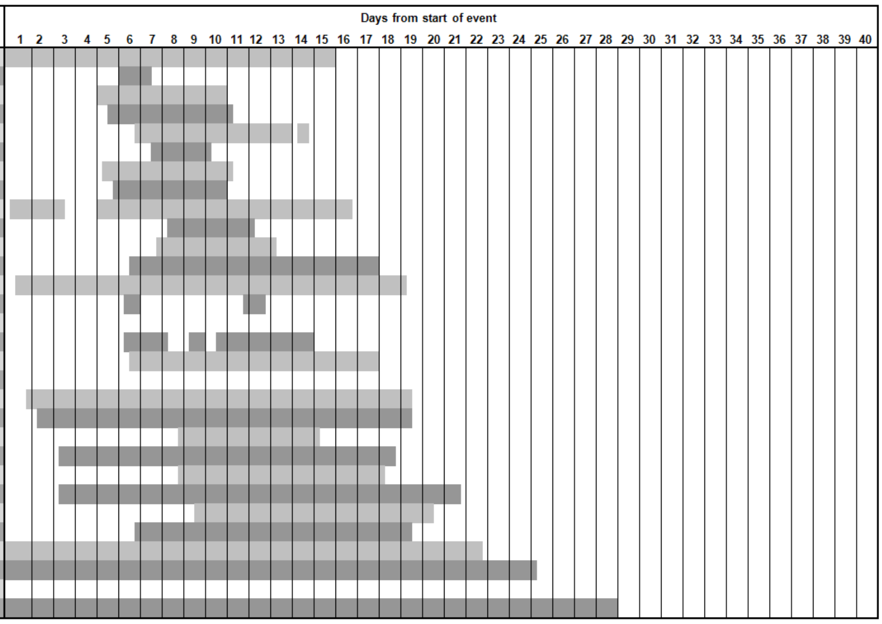



**Figure 3.55 Timing and duration of connectivity of wetlands to the Fitzroy River for floods of different magnitudes, a) 2007 flood (1.5 year ARI) and b) 2002 flood (14 year ARI)**

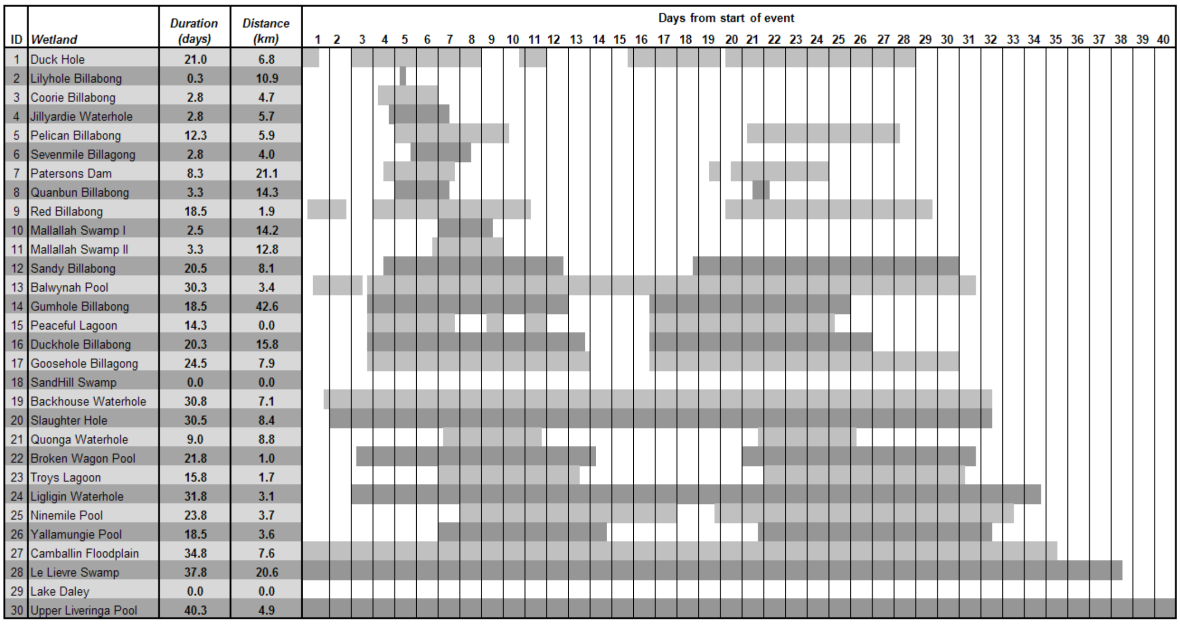



**Figure 3.56 Connectivity behaviour for an event having two flood peaks (flood 2001, see Figure 3.19)**

#### 3.4.2.18.2 Conclusions

This study of hydrological connectivity in the Fitzroy catchment has demonstrated how a hydrodynamic model can be used to quantify connectivity between floodplain wetlands and the main river channel. This method can be used to derive the timing, duration and frequency of connectivity of a range of wetlands on the floodplain. The duration of wetland connectivity ranges from 1 to 40 days per flood and is not only related to distance from the main river channel, but also the topography between the wetland and river. Some wetlands connect in relatively small and frequent floods and others only connect in much larger, less frequent floods. Wetlands in the lower part of the floodplain tend to have greater connectivity because of the longer duration of inundation in this area. It should also be noted that spatial variability in rainfall (and thus runoff) can influence the connectivity status of individual wetlands.

The study provides an overview of the connectivity status for the major wetlands in the Fitzroy floodplain. The information could be useful to future studies on (i) movement and recruitment patterns of fish during floods (ii) wetland habitat characteristics and (iii) biodiversity of individual wetlands.

## 3.5 OVERALL CONCLUSIONS AND RECOMMENDATIONS

Summary of the main conclusions and recommendations for each of the five study areas;

**1. Review of broad scale surface-groundwater interactions in northern Australia including the Dampier peninsula in Western Australia**.

a. Groundwater information is very scarce across northern Australia and for most of the region it is therefore only possible to make broad scale assessments of groundwater resources and their recharge by surface drainage. Preliminary estimates of diffuse recharge rates range between <1 mm $yr^{-1}$ and >200 mm $yr^{-1}$; with the lowest rates in the most arid regions with vertisol soils and annual grasses (e.g., much of the Flinders-Leichhardt region), and the highest rates generally associated with wet tropic climates and more permeable soil types.

b. Across northern Australia, typically more than 90% of annual rainfall and runoff occurs during the wet season and during this period groundwater recharge occurs via a combination of diffuse infiltration of rainfall, floodplain inundation and leakage from losing streams and rivers. In the subsequent dry season, river flows recede rapidly and the majority of surface water features cease to flow or even dry completely before the following wet season. There are, however, several iconic perennial rivers in northern Australia that rely on significant groundwater input (up to 50%) through the dry season – notable inclusions are the Daly River and Roper River (NT), the Fitzroy River (WA) and many of the rivers on Cape York peninsula (QLD). Other regions where dry season flows are dependent on groundwater include the Kimberley, Ord-Bonaparte, Arafura, Northern Coral region and the South-West & South-East gulf regions.

c. Potential changes in annual diffuse groundwater recharge due to climate change (relative to modelled historical recharge) are predicted to vary from +39% to -5%. In terms of surface water features that are dependent (to some extent) upon groundwater discharge, the impacts of climate change will be more immediate to those which are fed by shallow, local unconfined aquifers (e.g. the Flinders-Leichhardt, Mitchell and Kimberley regions). Conversely, the impacts of climate change will be delayed for surface water features that are fed by deep, regional aquifers (e.g. the Daly and Fitzroy regions). In some areas with significant levels of current groundwater extraction (e.g. the Darwin Rural Area), despite increases in diffuse recharge under a future climate, groundwater levels are likely to continue to decline and may threaten a number of groundwater dependent ecosystems in the area.

d. Development impacts on groundwater have only been estimated in very few locations. For example, in the Daly catchment with the high degree of interconnection between the Daly River and the adjacent aquifers, the greatest impacts to groundwater resources from increased development will occur in parts of aquifers that are distal to the rivers; that is, groundwater extraction will lead to large drawdown of water levels in the aquifers that cannot be mitigated through increased leakage from the rivers.

e. From the brief review of the groundwater characteristics of the Dampier Peninsula in Western Australia, it is clear that many of the springs in this Peninsula are fed by groundwater and there are several possible mechanisms by which this occurs. Progress in identifying which mechanisms apply to which springs could be made by (i) collating and analysing the disparate groundwater information associated with a number of production and observation bores on the Peninsula and (ii) the collection of water samples from the springs for hydro-chemical identification of the source aquifers.

**RECOMMENDATIONS**

Despite a broad general knowledge of the locations of significant groundwater discharge to rivers and streams in northern Australia, there are several fundamental knowledge gaps around the nature of interactions in complex geological environments, and how these systems will respond to potential future climate change and increased water resource development. Specific examples that warrant focussed research include:

- mound Spring ecosystems on the Dampier Peninsula;
- ‘rejected recharge’ and artesian springs from the Great Artesian Basin that sustain dry season flows in rivers on Cape York Peninsula; and
- spring-fed rivers in carbonate aquifers of the South East Gulf region.

**2. Review of the surface water regimes in key Queensland catchments.**

a. The Queensland rivers (Leichardt, Flinders, Gilbert and Mitchell) are highly seasonal and dominated by rainfall and flows that occur during the wet season. These rivers are also prone to flooding in the wet season, but they also have long periods of zero flow in the dry season.

b. The (theoretical) implementation of full use of existing water allocation entitlements in these Queensland rivers will generally increase the number of zero flow days experienced along the river, especially in the Leichardt catchment. However, the impact on high flow threshold exceedence is much smaller, and again the Leichardt catchment appears to be the only one with significant reductions in high flows under development.

c. The greatest impact on river system flows under full development will be felt in the Leichardt River, where abstractions would increase the naturalised loss of flow in the river by 43%. The equivalent figures for the other Queensland rivers are; Flinders (11%), Gilbert (5%) and Mitchell (5%).

d. Any climate change in the region will bring additional perturbations to the flow in these rivers and these are summarised in the section below.

**RECOMMENDATIONS**

- Much of the gauged river flow data in northern Australia is too poor in quality or based on too short a duration of observations for accurate discharge estimation, especially at high and low flows (Petheram et al., 2009b). This is why we were unable to provide any reliable flow analysis for the Norman River. Substantial effort is required to (a) sustain and enhance current gauging stations in northern Australia and (b) carry out rigorous flow calibration, particularly at high and low flows.
- The river modelling and climate and development scenarios for Queensland are different from those used in other regions in northern Australia. It is therefore recommended that future modelling of runoff be undertaken using a consistent and robust set of methods and scenarios.
- In Queensland (and other regions in northern Australia) there is no comprehensive information on current levels of actual water use (rather than entitlements and/or permits). Further effort is therefore required to establish what current water use levels are in order to assess current and future ecological impacts.

**3. Hydro-ecological linkages and how these may be affected by climate change and/or development.**

a. Stream flow in northern rivers is extremely seasonal with the vast majority (> 90 percent) of total annual flow occurs during the wet season months (November to April). The aquatic ecosystems that are dependent on these river flows are adapted to the prevailing conditions, responding to both wet season high flows and the long dry season low flows.

b. There is a general lack of quantitative relationships between flow and specific ecological flora and fauna in the NAWFA reporting area. As a result the consequence of flow changes on ecological systems is largely unknown. The few existing site-specific thresholds used here demonstrate the value of such information and resources for development of more of these thresholds and associated relationships are best targeted at areas containing high priority ecological assets that may come under significant development pressure.
c. In the absence of species specific thresholds, standard metrics, derived solely from the river flow regime, provided useful guideline information and have the advantage that they enable comparisons within and between regions. The selected metrics relate mainly to the high and low flow conditions which are important drivers of floodplain and in-stream ecosystem structure and processes in northern Australia.
d. In general, exceedence of high and low flow thresholds in most northern rivers under future climate scenarios are quite large and likely to have a significant impact on associated aquatic biota. The implementation of additional development water entitlements in Queensland can exacerbate the climate impact, but the relatively modest development water requirements reported for NT and WA developments do not usually add much further impact on high and low river flows.
e. For locations where both site specific and standard metrics were available it was found that the standard metrics adequately reflected the directions (and to some degree magnitude) of potential change derived for the site specific metrics.
f. Low flows under dry climate change scenarios are likely to be altered significantly. Some areas are likely to experience considerable increases in the duration of low and zero flows which may have major ecological impacts. Combining climate change with development pressures can exacerbate changes to low flow conditions.
g. Flooding is an important factor that sustains many environmental assets by providing connectivity across the floodplain and facilitating migration. Under dry climate change scenarios flood frequency can be reduced greatly and this may have impacts on provision of habitat and breeding grounds. Under wet climate change conditions flooding may become much more frequent and this could have both positive and negative impacts depending on flow requirements of different species.

## RECOMMENDATIONS

- Where specific high priority aquatic biota may be at risk from climate change and/or development pressure, studies need to be carried out to quantify the relationship between the species in question and key aspects of the river flow regime that it is dependent on.

- Despite the fact that there are large areas of groundwater dependant ecosystems in northern Australia there are no known locations with quantitative groundwater related ecological metrics. Further monitoring of the interactions between groundwater level and the functioning of ecosystems is therefore recommended. The work described below on dry season pools that are sustained by groundwater is a good example of such monitoring.
- It is also worth noting that any change in river flow is likely to result in changes to water quality including sediment and nutrient loads, water temperature and dissolved oxygen levels. These changes in turn may also affect productivity and habitat quality and as such should be carefully considered in future investigations.

**4. A remote sensing study of in-stream pools as ecological refugia.**

a. In the Fitzroy River the preceding wet season affects the rate at which pools form in the early dry season, but the late dry season pool number is insensitive to wet season flow. This implies that groundwater is the primary source of base flow in this river at this time.
b. Both the Fitzroy and Mitchell Rivers show a decline in pool numbers at the end of the dry season. This may be due to the disappearance of small pools which cannot be sustained by groundwater flow at this time.
c. Many more pools form in the Fitzroy and Mitchell rivers than in the Daly River. This is because (i) flows are much lower for longer in the two former rivers and (ii) there ois a greater groundwater contribution in the Daly River.
d. Most of the pools in all three rivers analysed are relatively small (~ 200 to 600 m in length) and the number of small pools generally increases as the dry season progresses.
e. There are reasonably good relationships between pool numbers or total pool area and flow, but the relationships are quite different for each river. Some of these relationships may be useful for setting ecologically acceptable low flows, however, additional information on the response of key aquatic biota to pool characteristics is needed to quantify these thresholds.

**RECOMMENDATIONS**

- The accuracy of the pool numbers and size (especially of small pools) determined using the relatively coarse LandSat data (30m) needs to be assessed. This can be done by comparing the LandSat results with those derived using higher resolution imagery (e.g. Ikonos) and/or ground survey.
- The current analysis of the LandSat data gives useful information on the total number of pools in a river reach, however, further analysis is recommended to determine the rates of production and loss of specific pools along a river reach. This will help identify the locations of specific pools that may be of local significance (both ecologically and culturally) as well as confirming whether the loss of small pools occurs throughout the dry season, or only towards the end of it.
- It may also be possible to determine pool (surface) temperatures using LandSat data and it is recommended that this is investigated as a means of assessing how the suitability of pool habitats evolves as the dry season progresses. Additional information on the response of key aquatic biota to pool characteristics (size, depth, temperature) is needed to quantify thresholds above or below which undesirable ecological impacts occur.

**5. Prediction of flood extent and associated wetland connectivity.**

a. We have demonstrated how a hydrodynamic model can be used to quantify connectivity between floodplain wetlands and the main river channel. This method can be used to derive the timing, duration and frequency of connectivity of a range of wetlands on the floodplain.

b. In the Fitzroy catchment, the duration of wetland connectivity ranges from 1 to 40 days per flood and is not only related to distance from the main river channel, but also the topography between the wetland and river. Some wetlands connect in relatively small and frequent floods and others only connect in much larger, less frequent floods. Wetlands in the lower part of the floodplain tend to have greater connectivity because of the longer duration of inundation in this area.

c. The study provides an overview of the connectivity status for the major wetlands in the Fitzroy floodplain. The information could be useful to future studies on (i) movement and recruitment patterns of fish during floods (ii) wetland habitat characteristics and (iii) biodiversity of individual wetlands.

## RECOMMENDATIONS

- The current hydro-dynamic flood simulations tend to hold water on the floodplain for longer than is detected at stream gauges or in remotely sensed flood images. Further analysis is therefore needed to see if the fault lies entirely within the hydro-dynamic model and if so, a solution derived.
- Hydro-dynamic models are costly and time consuming to set up and so an alternative method for quantifying wetland connectivity should be investigated. Potential options include the use of remotely sensed flood area and relating this to gauged river flow. This method could be tested in catchments where hydro-dynamic models already exist, e.g. the Fitzroy in Western Australia and the Tully-Murray catchments in Queensland.
- Further information is required on the role of flood pulse connectivity on a number of important ecological responses such as fish migration and recruitment between and within individual wetlands.

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# APPENDIX A - STANDARD METRICS FOR CHANGES TO FLOW REGIME

## A1.1 SUMMARY

This appendix contains the results of the standard metrics analysis for all reporting locations in Queensland, Northern Territory and Western Australia. Locations of all sites and detailed descriptions of the selection of suitable metrics for assessing changes to flow regime under different climate and development scenarios are given in Chapter 3 of this report. Detailed descriptions of the changes in flow regime at one or more locations within each selected river catchment are given in Section 3.1.4.17.1. In the tables below red text is used to highlight metrics where changes to the flow regime from Scenario A are greater than 25%.

## A1.2 QUEENSLAND

### A1.2.1 Leichardt River

**Table A1. Standard metrics for changes to flow regime on the Leichhardt River at Doughboy Creek under Scenarios C and D relative to Scenario AN.**

| Leichhardt - Leichhardt River at Doughboy Creek, Gauge No. 913014A | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Standard metrics | Units | AN | Cwet | Cmid | Cdry | Dwet | Dmid | Ddry |
| | | | change from Scenario A | | | | | |
| General metrics | | | | | | | | |
| Annual flow (mean) | GL | 204 | +41% | +24% | -23% | +7% | -9% | -48% |
| Wet season flow (mean)* | GL | 190 | +40% | +23% | -21% | +8% | -8% | -46% |
| Dry season flow (mean)** | GL | 15.3 | +62% | +40% | -42% | 0% | -15% | -69% |
| Low flow metrics | | | | | | | | |
| Low flow threshold (discharge exceeded 90% of the time in Scenario A) | GL/d | 0 | | | | | | |
| Number of days below low flow threshold (mean) | d/y | 54.8 | -0.9 | -0.6 | +1.2 | +75.6 | +78.2 | +85.6 |
| Duration of flow events below low flow threshold (mean) | d/y | 50.8 | -0.8 | -0.6 | +1.1 | +30.1 | +29.2 | +33.6 |
| Number of events below low flow threshold (mean) | events/y | 1.08 | 0 | 0 | 0 | +0.5 | +0.6 | +0.6 |
| Number of days of zero flow (mean) | d/y | 54.8 | -0.9 | -0.6 | +1.2 | +75.6 | +78.2 | +85.6 |
| High flow metrics | | | | | | | | |
| High flow threshold (discharge exceeded 5% of the time in Scenario A) | GL/d | 1.05 | | | | | | |
| Number of days above high flow threshold (mean) | d/y | 19.1 | +3.9 | +1.8 | -3.1 | -1.8 | -3.6 | -8 |
| Duration of flow events above high flow threshold (mean) | d/y | 3.65 | +0.5 | +0.3 | -0.2 | 0 | -0.2 | -0.8 |
| Number of events above high flow threshold (mean) | events/y | 5.22 | +0.4 | +0.1 | -0.6 | -0.5 | -0.7 | -1.3 |
| Wet season rate of rise (mean) | GL/d | 1.74 | +0.6 | +0.3 | -0.3 | +2.3 | +1.7 | +0.4 |
| Wet season rate of fall (mean) | GL/d | 0.89 | +0.3 | +0.2 | -0.2 | +0.8 | +0.6 | +0.1 |

*Wet season covers the six months from November to April
**Dry season covers the six months from May to October
nm – not modelled

## Table A2. Standard metrics for changes to flow regime on the Leichhardt River at Miranda Creek under Scenarios C and D relative to Scenario AN.

| Leichhardt - Leichhardt River at Miranda Creek, Gauge No. 913004A | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Standard metrics | Units | AN | Cwet | Cmid | Cdry | Dwet | Dmid | Ddry |
| | | | change from Scenario A | | | | | |
| General metrics | | | | | | | | |
| Annual flow (mean) | GL | 358 | +41% | +22% | -22% | +5% | -13% | -53% |
| Wet season flow (mean)* | GL | 335 | +39% | +21% | -21% | +6% | -12% | -51% |
| Dry season flow (mean)** | GL | 24.8 | +64% | +37% | -42% | -5% | -26% | -80% |
| Low flow metrics | | | | | | | | |
| Low flow threshold (discharge exceeded 90% of the time in Scenario A) | GL/d | 0 | | | | | | |
| Number of days below low flow threshold (mean) | d/y | 144 | -5.2 | -0.9 | +13.4 | +141.6 | +144.4 | +152.9 |
| Duration of flow events below low flow threshold (mean) | d/y | 31.9 | -0.1 | +0.4 | +1.7 | +23.3 | +22.7 | +25.5 |
| Number of events below low flow threshold (mean) | events/y | 4.51 | -0.1 | -0.1 | +0.2 | +0.7 | +0.8 | +0.7 |
| Number of days of zero flow (mean) | d/y | 144 | -5.2 | -0.9 | +13.4 | +141.6 | +144.4 | +152.9 |
| High flow metrics | | | | | | | | |
| High flow threshold (discharge exceeded 5% of the time in Scenario A) | GL/d | 2.71 | | | | | | |
| Number of days above high flow threshold (mean) | d/y | 18.3 | +4.1 | +1.9 | -3 | -2.4 | -4.4 | -9.4 |
| Duration of flow events above high flow threshold (mean) | d/y | 3.78 | +0.5 | +0.3 | -0.1 | +0.6 | +0.2 | -0.4 |
| Number of events above high flow threshold (mean) | events/y | 4.83 | +0.4 | +0.1 | -0.7 | -1.2 | -1.3 | -2.2 |
| Wet season rate of rise (mean) | GL/d | 2.63 | +0.9 | +0.5 | -0.5 | +2.3 | +1.7 | -0.1 |
| Wet season rate of fall (mean) | GL/d | 1.40 | +0.5 | +0.3 | -0.3 | +0.6 | +0.3 | -0.3 |

*Wet season covers the six months from November to April
**Dry season covers the six months from May to October
nm – not modelled

## Table A3. Standard metrics for changes to flow regime on the Leichhardt River at Julius Dam Tailwater under Scenarios C and D relative to Scenario AN.

| Leichhardt - Leichhardt River at Julius Dam Tailwater, Gauge No. 913012A | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Standard metrics | Units | AN | Cwet | Cmid | Cdry | Dwet | Dmid | Ddry |
| | | | change from Scenario A | | | | | |
| General metrics | | | | | | | | |
| Annual flow (mean) | GL | 280 | +41% | +23% | -22% | -8% | -24% | -64% |
| Wet season flow (mean)* | GL | 260 | +39% | +22% | -21% | -6% | -22% | -61% |
| Dry season flow (mean)** | GL | 21.3 | +61% | +38% | -42% | -24% | -40% | -90% |
| Low flow metrics | | | | | | | | |
| Low flow threshold (discharge exceeded 90% of the time in Scenario A) | GL/d | 0 | | | | | | |
| Number of days below low flow threshold (mean) | d/y | 188 | -6.8 | -2.5 | +14.1 | +146.7 | +149.9 | +159.9 |
| Duration of flow events below low flow threshold (mean) | d/y | 17.6 | +0.1 | +0.1 | -0.3 | +136.7 | +150.3 | +240 |
| Number of events below low flow threshold (mean) | events/y | 10.7 | -0.4 | -0.2 | +1 | -8.5 | -8.7 | -9.3 |
| Number of days of zero flow (mean) | d/y | 188 | -6.8 | -2.5 | +14.1 | +146.7 | +149.9 | +159.9 |
| High flow metrics | | | | | | | | |
| High flow threshold (discharge exceeded 5% of the time in Scenario A) | GL/d | 2.11 | | | | | | |
| Number of days above high flow threshold (mean) | d/y | 18.3 | +4.1 | +2.1 | -3 | -4.9 | -6.7 | -11.8 |
| Duration of flow events above high flow threshold (mean) | d/y | 3.52 | +0.5 | +0.2 | -0.1 | +1.9 | +1.6 | +1.2 |
| Number of events above high flow threshold (mean) | events/y | 5.19 | +0.4 | +0.3 | -0.8 | -2.7 | -2.9 | -3.8 |
| Wet season rate of rise (mean) | GL/d | 1.87 | +0.7 | +0.4 | -0.4 | +8.1 | +7.3 | +5.5 |
| Wet season rate of fall (mean) | GL/d | 1.04 | +0.4 | +0.2 | -0.2 | +1.5 | +1.2 | +0.3 |

*Wet season covers the six months from November to April
**Dry season covers the six months from May to October
nm – not modelled

### A1.2.2 Flinders River

## Table A4. Standard metrics for changes to flow regime on the Flinders River at Etta Plains under Scenarios C and D relative to Scenario AN.

| Flinders - Flinders River at Etta Plains, Gauge No. 915012A | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Standard metrics | Units | AN | Cwet | Cmid | Cdry | Dwet | Dmid | Ddry |
| | | | change from Scenario A | | | | | |
| General metrics | | | | | | | | |
| Annual flow (mean) | GL | 1030 | +36% | -12% | -27% | +29% | -19% | -34% |
| Wet season flow (mean)* | GL | 1006 | +35% | -12% | -28% | +28% | -19% | -35% |
| Dry season flow (mean)** | GL | 33.6 | +76% | -13% | -5% | +63% | -25% | -18% |
| Low flow metrics | | | | | | | | |
| Low flow threshold (discharge exceeded 90% of the time in Scenario A) | GL/d | 0 | | | | | | |
| Number of days below low flow threshold (mean) | d/y | 273 | -4.1 | +3.2 | +5.9 | -1.1 | +6.6 | +9.7 |
| Duration of flow events below low flow threshold (mean) | d/y | 69.8 | -1.7 | +3.5 | +1 | -1.7 | +4.9 | +1.8 |
| Number of events below low flow threshold (mean) | events/y | 3.91 | 0 | -0.1 | 0 | +0.1 | -0.2 | 0 |
| Number of days of zero flow (mean) | d/y | 273 | -4.1 | +3.2 | +5.9 | -1.1 | +6.6 | +9.7 |
| High flow metrics | | | | | | | | |
| High flow threshold (discharge exceeded 5% of the time in Scenario A) | GL/d | 9.59 | | | | | | |
| Number of days above high flow threshold (mean) | d/y | 18.3 | +2.8 | -1.1 | -2.7 | +1.1 | -2.7 | -4.5 |
| Duration of flow events above high flow threshold (mean) | d/y | 8.48 | +0.4 | -0.6 | -1.1 | +0.2 | -1.1 | -1.5 |
| Number of events above high flow threshold (mean) | events/y | 2.16 | +0.2 | 0 | 0 | +0.1 | -0.1 | -0.2 |
| Wet season rate of rise (mean) | GL/d | 6.47 | +2.5 | -0.6 | -1.7 | +2 | -1.1 | -1.9 |
| Wet season rate of fall (mean) | GL/d | 3.42 | +1.2 | -0.3 | -0.8 | +1.2 | -0.3 | -0.8 |

*Wet season covers the six months from November to April
**Dry season covers the six months from May to October
nm – not modelled

## Table A5. Standard metrics for changes to flow regime on the Flinders River at Richmond under Scenarios C and D relative to Scenario AN.

| Flinders - Flinders River at Richmond, Gauge No. 915008A | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Standard metrics | Units | AN | Cwet | Cmid | Cdry | Dwet | Dmid | Ddry |
| | | | change from Scenario A | | | | | |
| General metrics | | | | | | | | |
| Annual flow (mean) | GL | 367 | +35% | -20% | -30% | +30% | -25% | -35% |
| Wet season flow (mean)* | GL | 357 | +34% | -20% | -31% | +29% | -24% | -35% |
| Dry season flow (mean)** | GL | 13.4 | +76% | -24% | -13% | +67% | -32% | -21% |
| Low flow metrics | | | | | | | | |
| Low flow threshold (discharge exceeded 90% of the time in Scenario A) | GL/d | 0 | | | | | | |
| Number of days below low flow threshold (mean) | d/y | 257 | -5.1 | +4.1 | +4.9 | +17.7 | +28.7 | +29.8 |
| Duration of flow events below low flow threshold (mean) | d/y | 66.9 | -1.5 | +0.8 | +0.4 | -2.4 | +1.7 | +1.1 |
| Number of events below low flow threshold (mean) | events/y | 3.84 | 0 | 0 | +0.1 | +0.4 | +0.3 | +0.4 |
| Number of days of zero flow (mean) | d/y | 257 | -5.1 | +4.1 | +4.9 | +17.7 | +28.7 | +29.8 |
| High flow metrics | | | | | | | | |
| High flow threshold (discharge exceeded 5% of the time in Scenario A) | GL/d | 1.97 | | | | | | |
| Number of days above high flow threshold (mean) | d/y | 18.3 | +3.3 | -2.2 | -3.3 | +0.8 | -4.4 | -5.3 |
| Duration of flow events above high flow threshold (mean) | d/y | 5.80 | +0.4 | -0.1 | -0.2 | +0.3 | -0.2 | -0.3 |
| Number of events above high flow threshold (mean) | events/y | 3.16 | +0.3 | -0.3 | -0.5 | 0 | -0.7 | -0.8 |
| Wet season rate of rise (mean) | GL/d | 4.05 | +1.3 | -0.6 | -1 | +1.7 | -0.5 | -0.7 |
| Wet season rate of fall (mean) | GL/d | 2.42 | +0.8 | -0.4 | -0.6 | +0.9 | -0.3 | -0.4 |

*Wet season covers the six months from November to April
**Dry season covers the six months from May to October
nm – not modelled

## Table A6. Standard metrics for changes to flow regime on the Flinders River at Hughenden under Scenarios C and D relative to Scenario AN.

| Flinders - Flinders River at Hughenden, Gauge No. 915004A | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Standard metrics | Units | AN | Cwet | Cmid | Cdry | Dwet | Dmid | Ddry |
| | | | change from Scenario A | | | | | |
| General metrics | | | | | | | | |
| Annual flow (mean) | GL | 100 | +36% | -20% | -32% | +27% | -28% | -39% |
| Wet season flow (mean)* | GL | 94.8 | +35% | -19% | -33% | +26% | -27% | -40% |
| Dry season flow (mean)** | GL | 5.94 | +67% | -24% | -14% | +57% | -34% | -25% |
| Low flow metrics | | | | | | | | |
| Low flow threshold (discharge exceeded 90% of the time in Scenario A) | GL/d | 0 | | | | | | |
| Number of days below low flow threshold (mean) | d/y | 258 | -3.1 | +3.9 | +4.3 | +30.9 | +40.6 | +41.4 |
| Duration of flow events below low flow threshold (mean) | d/y | 32.7 | -0.3 | +2 | +1.3 | +29 | +31.5 | +30.7 |
| Number of events below low flow threshold (mean) | events/y | 7.88 | 0 | -0.3 | -0.2 | -3.2 | -3.2 | -3.2 |
| Number of days of zero flow (mean) | d/y | 258 | -3.1 | +3.9 | +4.3 | +30.9 | +40.6 | +41.4 |
| High flow metrics | | | | | | | | |
| High flow threshold (discharge exceeded 5% of the time in Scenario A) | GL/d | 1.02 | | | | | | |
| Number of days above high flow threshold (mean) | d/y | 18.3 | +2.9 | -2.3 | -3.7 | +0.2 | -5.4 | -6.9 |
| Duration of flow events above high flow threshold (mean) | d/y | 4.00 | +0.4 | -0.2 | -0.3 | +0.3 | -0.2 | -0.4 |
| Number of events above high flow threshold (mean) | events/y | 4.57 | +0.2 | -0.4 | -0.6 | -0.3 | -1.2 | -1.4 |
| Wet season rate of rise (mean) | GL/d | 0.97 | +0.3 | -0.2 | -0.3 | +0.7 | +0.1 | -0.1 |
| Wet season rate of fall (mean) | GL/d | 0.47 | +0.1 | -0.1 | -0.1 | +0.3 | 0 | -0.1 |

*Wet season covers the six months from November to April
**Dry season covers the six months from May to October
nm – not modelled

### A1.2.3 Gilbert River

## Table A7. Standard metrics for changes to flow regime on the Einasleigh River at Cowana Lake under Scenarios C and D relative to Scenario AN.

| Gilbert - Einasleigh River at Cowana Lake, Gauge No. 917109A | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Standard metrics | Units | AN | Cwet | Cmid | Cdry | Dwet | Dmid | Ddry |
| | | | change from Scenario A | | | | | |
| General metrics | | | | | | | | |
| Annual flow (mean) | GL | 1147 | +14% | +5% | -10% | +13% | +4% | -11% |
| Wet season flow (mean)* | GL | 1131 | +14% | +5% | -9% | +12% | +4% | -11% |
| Dry season flow (mean)** | GL | 25.2 | +23% | -2% | -39% | +21% | -3% | -41% |
| Low flow metrics | | | | | | | | |
| Low flow threshold (discharge exceeded 90% of the time in Scenario A) | GL/d | 0 | | | | | | |
| Number of days below low flow threshold (mean) | d/y | 110 | +1 | +0.9 | +3 | -14.5 | -13.7 | -6.5 |
| Duration of flow events below low flow threshold (mean) | d/y | 28.6 | +0.2 | 0 | +0.8 | -10.3 | -9.6 | -6.5 |
| Number of events below low flow threshold (mean) | events/y | 3.86 | 0 | 0 | 0 | +1.4 | +1.2 | +0.8 |
| Number of days of zero flow (mean) | d/y | 110 | +1 | +0.9 | +3 | -14.5 | -13.6 | -6.5 |
| High flow metrics | | | | | | | | |
| High flow threshold (discharge exceeded 5% of the time in Scenario A) | GL/d | 11.7 | | | | | | |
| Number of days above high flow threshold (mean) | d/y | 18.3 | +2.2 | +0.4 | -1.6 | +2 | +0.2 | -2 |
| Duration of flow events above high flow threshold (mean) | d/y | 5.41 | -0.2 | +0.1 | +0.2 | -0.2 | +0.1 | +0.2 |
| Number of events above high flow threshold (mean) | events/y | 3.39 | +0.5 | 0 | -0.4 | +0.5 | 0 | -0.5 |
| Wet season rate of rise (mean) | GL/d | 6.39 | +1.8 | +0.4 | -0.8 | +1.3 | +0.1 | -1 |
| Wet season rate of fall (mean) | GL/d | 3.21 | +0.8 | +0.2 | -0.4 | +0.7 | 0 | -0.5 |

*Wet season covers the six months from November to April
**Dry season covers the six months from May to October
nm – not modelled

### Table A8. Standard metrics for changes to flow regime on the Einasleigh River at Carpentaria Downs under Scenarios C and D relative to Scenario A.

| Gilbert - Einasleigh River at Carpentaria Downs, Gauge No. 917102A | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Standard metrics | Units | AN | Cwet | Cmid | Cdry | Dwet | Dmid | Ddry |
| | | | change from Scenario A | | | | | |
| General metrics | | | | | | | | |
| Annual flow (mean) | GL | 496 | +4% | -2% | -9% | +4% | -3% | -10% |
| Wet season flow (mean)* | GL | 492 | +5% | -2% | -9% | +4% | -3% | -10% |
| Dry season flow (mean)** | GL | 8.82 | -3% | 0% | -23% | -4% | -1% | -24% |
| Low flow metrics | | | | | | | | |
| Low flow threshold (discharge exceeded 90% of the time in Scenario A) | GL/d | 0 | | | | | | |
| Number of days below low flow threshold (mean) | d/y | 94.1 | 0 | 0 | 0 | 0 | 0 | 0 |
| Duration of flow events below low flow threshold (mean) | d/y | 65.3 | 0 | 0 | 0 | 0 | 0 | 0 |
| Number of events below low flow threshold (mean) | events/y | 1.44 | 0 | 0 | 0 | 0 | 0 | 0 |
| Number of days of zero flow (mean) | d/y | 94.1 | 0 | 0 | 0 | 0 | 0 | 0 |
| High flow metrics | | | | | | | | |
| High flow threshold (discharge exceeded 5% of the time in Scenario A) | GL/d | 3.86 | | | | | | |
| Number of days above high flow threshold (mean) | d/y | 18.3 | +0.3 | -0.3 | -1.2 | -0.2 | -0.7 | -1.5 |
| Duration of flow events above high flow threshold (mean) | d/y | 5.81 | +0.1 | +0.1 | 0 | +0.1 | +0.1 | 0 |
| Number of events above high flow threshold (mean) | events/y | 3.14 | 0 | -0.1 | -0.2 | -0.1 | -0.2 | -0.2 |
| Wet season rate of rise (mean) | GL/d | 3.20 | +0.1 | -0.1 | -0.3 | +0.1 | -0.1 | -0.3 |
| Wet season rate of fall (mean) | GL/d | 1.48 | +0.1 | 0 | -0.1 | +0.1 | 0 | -0.1 |

*Wet season covers the six months from November to April

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

nm – not modelled

### Table A9. Standard metrics for changes to flow regime on the Gilbert River at Forest Home under Scenarios C and D relative to Scenario A.

| Gilbert - Gilbert River at Forest Home, Gauge No. 917001A | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Standard metrics | Units | AN | Cwet | Cmid | Cdry | Dwet | Dmid | Ddry |
| | | | change from Scenario A | | | | | |
| General metrics | | | | | | | | |
| Annual flow (mean) | GL | 1131 | +5% | -2% | -8% | +3% | -3% | -10% |
| Wet season flow (mean)* | GL | 1125 | +5% | -2% | -8% | +3% | -3% | -9% |
| Dry season flow (mean)** | GL | 15.1 | -2% | +2% | -19% | -6% | -2% | -22% |
| Low flow metrics | | | | | | | | |
| Low flow threshold (discharge exceeded 90% of the time in Scenario A) | GL/d | 0 | | | | | | |
| Number of days below low flow threshold (mean) | d/y | 168 | +0.2 | +0.2 | +1.1 | +2.1 | +2.2 | +2.8 |
| Duration of flow events below low flow threshold (mean) | d/y | 33.4 | 0 | -0.4 | -0.5 | -0.3 | -0.5 | -0.8 |
| Number of events below low flow threshold (mean) | events/y | 5.03 | 0 | +0.1 | +0.1 | +0.1 | +0.1 | +0.2 |
| Number of days of zero flow (mean) | d/y | 168 | +0.2 | +0.2 | +1.1 | +2.1 | +2.2 | +2.8 |
| High flow metrics | | | | | | | | |
| High flow threshold (discharge exceeded 5% of the time in Scenario A) | GL/d | 12.0 | | | | | | |
| Number of days above high flow threshold (mean) | d/y | 18.4 | +0.6 | -0.3 | -1.7 | +0.1 | -0.9 | -2 |
| Duration of flow events above high flow threshold (mean) | d/y | 3.77 | +0.1 | -0.1 | -0.3 | +0.1 | -0.1 | -0.4 |
| Number of events above high flow threshold (mean) | events/y | 4.87 | 0 | 0 | -0.1 | -0.1 | -0.1 | -0.1 |
| Wet season rate of rise (mean) | GL/d | 9.27 | +0.1 | -0.1 | -0.2 | 0 | -0.2 | -0.4 |
| Wet season rate of fall (mean) | GL/d | 5.47 | 0 | -0.1 | -0.2 | 0 | -0.1 | -0.3 |

*Wet season covers the six months from November to April

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

nm – not modelled

## A1.2.4 Mitchell River

### Table A10. Standard metrics for changes to flow regime on the Walsh River at Flat Rock under Scenarios C and D relative to Scenario AN.

| Mitchell - Walsh River at Flat Rock, Gauge No. 919311A | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Standard metrics | Units | AN | Cwet | Cmid | Cdry | Dwet | Dmid | Ddry |
| | | | change from Scenario A | | | | | |
| General metrics | | | | | | | | |
| Annual flow (mean) | GL | 644 | +22% | -1% | -34% | +22% | -1% | -34% |
| Wet season flow (mean)* | GL | 634 | +22% | -1% | -34% | +22% | -1% | -34% |
| Dry season flow (mean)** | GL | 9.97 | +19% | +24% | -36% | +19% | +24% | -36% |
| Low flow metrics | | | | | | | | |
| Low flow threshold (discharge exceeded 90% of the time in Scenario A) | GL/d | 0 | | | | | | |
| Number of days below low flow threshold (mean) | d/y | 140 | 0 | 0 | 0 | 0 | 0 | 0 |
| Duration of flow events below low flow threshold (mean) | d/y | 19.3 | 0 | 0 | 0 | 0 | 0 | 0 |
| Number of events below low flow threshold (mean) | events/y | 7.25 | 0 | 0 | 0 | 0 | 0 | 0 |
| Number of days of zero flow (mean) | d/y | 140 | 0 | 0 | 0 | 0 | 0 | 0 |
| High flow metrics | | | | | | | | |
| High flow threshold (discharge exceeded 5% of the time in Scenario A) | GL/d | 8.67 | | | | | | |
| Number of days above high flow threshold (mean) | d/y | 18.3 | +2.9 | -0.1 | -4.9 | +2.9 | -0.1 | -4.9 |
| Duration of flow events above high flow threshold (mean) | d/y | 6.20 | +0.6 | +0.1 | -0.5 | +0.6 | +0.1 | -0.5 |
| Number of events above high flow threshold (mean) | events/y | 2.95 | +0.2 | -0.1 | -0.6 | +0.2 | -0.1 | -0.6 |
| Wet season rate of rise (mean) | GL/d | 2.15 | +0.5 | -0.1 | -0.7 | +0.5 | -0.1 | -0.7 |
| Wet season rate of fall (mean) | GL/d | 1.18 | +0.3 | 0 | -0.4 | +0.3 | 0 | -0.4 |

*Wet season covers the six months from November to April
**Dry season covers the six months from May to October
nm – not modelled

### Table A11. Standard metrics for changes to flow regime on the Mitchell River at Cooktown Crossing under Scenarios C and D relative to Scenario AN.

| Mitchell - Mitchell River at Cooktown Crossing, Gauge No. 919014A | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Standard metrics | Units | AN | Cwet | Cmid | Cdry | Dwet | Dmid | Ddry |
| | | | change from Scenario A | | | | | |
| General metrics | | | | | | | | |
| Annual flow (mean) | GL | 795 | +20% | -6% | -29% | +14% | -13% | -35% |
| Wet season flow (mean)* | GL | 724 | +21% | -7% | -29% | +15% | -13% | -36% |
| Dry season flow (mean)** | GL | 71.1 | +11% | +3% | -24% | +4% | -4% | -31% |
| Low flow metrics | | | | | | | | |
| Low flow threshold (discharge exceeded 90% of the time in Scenario A) | GL/d | 0.095 | | | | | | |
| Number of days below low flow threshold (mean) | d/y | 36.5 | -3.7 | +5.7 | +37.7 | +11.2 | +22.6 | +55.6 |
| Duration of flow events below low flow threshold (mean) | d/y | 12.3 | -0.7 | +1 | +8 | +3.6 | +4.8 | +11.7 |
| Number of events below low flow threshold (mean) | events/y | 2.97 | -0.1 | +0.2 | +0.7 | 0 | +0.5 | +0.9 |
| Number of days of zero flow (mean) | d/y | 0 | 0 | 0 | 0 | +0.2 | +0.2 | +0.2 |
| High flow metrics | | | | | | | | |
| High flow threshold (discharge exceeded 5% of the time in Scenario A) | GL/d | 9.41 | | | | | | |
| Number of days above high flow threshold (mean) | d/y | 18.3 | +3.9 | -1.3 | -5.3 | +3.3 | -2.3 | -6.9 |
| Duration of flow events above high flow threshold (mean) | d/y | 5.52 | +0.7 | 0 | -0.6 | +0.7 | +0.1 | -0.8 |
| Number of events above high flow threshold (mean) | events/y | 3.31 | +0.3 | -0.2 | -0.7 | +0.2 | -0.5 | -0.9 |
| Wet season rate of rise (mean) | GL/d | 1.94 | +0.4 | -0.2 | -0.6 | +0.3 | -0.3 | -0.7 |
| Wet season rate of fall (mean) | GL/d | 0.98 | +0.2 | -0.1 | -0.3 | +0.1 | -0.2 | -0.3 |

*Wet season covers the six months from November to April
**Dry season covers the six months from May to October
nm – not modelled

**Table A12. Standard metrics for changes to flow regime on the Mitchell River at Gamboola under Scenarios C and D relative to Scenario AN.**

| Mitchell - Mitchell River at Gamboola, Gauge No. 919011A | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Standard metrics | Units | AN | Cwet | Cmid | Cdry | Dwet | Dmid | Ddry |
| | | | change from Scenario A | | | | | |
| General metrics | | | | | | | | |
| Annual flow (mean) | GL | 3483 | +39% | -4% | -27% | +37% | -7% | -29% |
| Wet season flow (mean)* | GL | 3376 | +39% | -5% | -27% | +37% | -7% | -29% |
| Dry season flow (mean)** | GL | 90.2 | +26% | +14% | -35% | +21% | +9% | -40% |
| Low flow metrics | | | | | | | | |
| Low flow threshold (discharge exceeded 90% of the time in Scenario A) | GL/d | 0.02 | | | | | | |
| Number of days below low flow threshold (mean) | d/y | 36.5 | -4.3 | +3.6 | +35.3 | +6 | +16.4 | +48.6 |
| Duration of flow events below low flow threshold (mean) | d/y | 18.0 | -2 | -1.5 | +5.5 | -1.2 | +1.8 | +8.8 |
| Number of events below low flow threshold (mean) | events/y | 2.03 | 0 | +0.4 | +1 | +0.5 | +0.6 | +1.1 |
| Number of days of zero flow (mean) | d/y | 22.8 | -3.1 | +3.2 | +28.4 | +7.4 | +14.8 | +42.6 |
| High flow metrics | | | | | | | | |
| High flow threshold (discharge exceeded 5% of the time in Scenario A) | GL/d | 49.8 | | | | | | |
| Number of days above high flow threshold (mean) | d/y | 18.3 | +5.4 | -0.8 | -4.4 | +5.2 | -1.2 | -4.9 |
| Duration of flow events above high flow threshold (mean) | d/y | 7.65 | +0.9 | -0.4 | -1.3 | +0.9 | -0.6 | -1.5 |
| Number of events above high flow threshold (mean) | events/y | 2.39 | +0.4 | 0 | -0.2 | +0.4 | 0 | -0.2 |
| Wet season rate of rise (mean) | GL/d | 6.74 | +2.9 | -0.2 | -1.5 | +2.8 | -0.3 | -1.5 |
| Wet season rate of fall (mean) | GL/d | 4.03 | +1.8 | -0.3 | -0.9 | +1.8 | -0.2 | -0.9 |

*Wet season covers the six months from November to April
**Dry season covers the six months from May to October
nm – not modelled

# A1.3 WESTERN AUSTRALIA

## A1.3.1 Fitzroy River

**Table A13. Standard metrics for changes to flow regime on the Fitzroy River at Dimond Gorge under Scenarios C and D relative to Scenario A.**

| Fitzroy - Fitzroy River at Dimond Gorge, Gauge No. 802137 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Standard metrics | Units | A | Cwet | Cmid | Cdry | Dwet | Dmid | Ddry |
| | | | change from Scenario A | | | | | |
| General metrics | | | | | | | | |
| Annual flow (mean) | GL | 1937 | +17% | -2% | -42% | nm | nm | nm |
| Wet season flow (mean)* | GL | 1891 | +17% | -2% | -41% | nm | nm | nm |
| Dry season flow (mean)** | GL | 39.1 | +30% | +1% | -60% | nm | nm | nm |
| Low flow metrics | | | | | | | | |
| Low flow threshold (discharge exceeded 90% of the time in Scenario A) | GL/d | 0.0002 | | | | | | |
| Number of days below low flow threshold (mean) | d/y | 36.2 | -1.5 | +2.3 | +35.8 | nm | nm | nm |
| Duration of flow events below low flow threshold (mean) | d/y | 36.6 | -2.4 | -1.3 | +18.8 | nm | nm | nm |
| Number of events below low flow threshold (mean) | events/y | 0.987 | 0 | +0.1 | +0.3 | nm | nm | nm |
| Number of days of zero flow (mean) | d/y | 1.70 | +0.1 | +0.3 | +4.8 | nm | nm | nm |
| High flow metrics | | | | | | | | |
| High flow threshold (discharge exceeded 5% of the time in Scenario A) | GL/d | 29.5 | | | | | | |
| Number of days above high flow threshold (mean) | d/y | 18.3 | +1.8 | -0.3 | -7.9 | nm | nm | nm |
| Duration of flow events above high flow threshold (mean) | d/y | 10.3 | +0.8 | +0.1 | -1.7 | nm | nm | nm |
| Number of events above high flow threshold (mean) | events/y | 1.78 | 0 | -0.1 | -0.6 | nm | nm | nm |
| Wet season rate of rise (mean) | GL/d | 3.72 | +1.5 | -0.1 | -1.2 | nm | nm | nm |
| Wet season rate of fall (mean) | GL/d | 1.96 | +0.6 | 0 | -0.7 | nm | nm | nm |

*Wet season covers the six months from November to April
**Dry season covers the six months from May to October
nm – not modelled

## Table A14. Standard metrics for changes to flow regime on the Fitzroy River at Fitzroy Crossing under Scenarios C and D relative to Scenario A.

| Fitzroy - Fitzroy River at Fitzroy Crossing, Gauge No. 802055 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Standard metrics | Units | A | Cwet | Cmid | Cdry | Dwet | Dmid | Ddry |
| | | | change from Scenario A | | | | | |
| General metrics | | | | | | | | |
| Annual flow (mean) | GL | 4685 | +20% | -3% | -38% | nm | nm | nm |
| Wet season flow (mean)* | GL | 4610 | +20% | -3% | -38% | nm | nm | nm |
| Dry season flow (mean)** | GL | 64.8 | +34% | +2% | -63% | nm | nm | nm |
| Low flow metrics | | | | | | | | |
| Low flow threshold (discharge exceeded 90% of the time in Scenario A) | GL/d | 0.001 | | | | | | |
| Number of days below low flow threshold (mean) | d/y | 36.5 | -4.4 | +2.9 | +41.9 | nm | nm | nm |
| Duration of flow events below low flow threshold (mean) | d/y | 58.6 | -9.1 | -2.4 | +16.9 | nm | nm | nm |
| Number of events below low flow threshold (mean) | events/y | 0.62 | 0 | +0.1 | +0.4 | nm | nm | nm |
| Number of days of zero flow (mean) | d/y | 1.12 | 0 | 0 | +0.1 | nm | nm | nm |
| High flow metrics | | | | | | | | |
| High flow threshold (discharge exceeded 5% of the time in Scenario A) | GL/d | 62.0 | | | | | | |
| Number of days above high flow threshold (mean) | d/y | 18.3 | +1.9 | -0.7 | -6.7 | nm | nm | nm |
| Duration of flow events above high flow threshold (mean) | d/y | 11.9 | -0.4 | -0.1 | -1.5 | nm | nm | nm |
| Number of events above high flow threshold (mean) | events/y | 1.53 | +0.2 | 0 | -0.4 | nm | nm | nm |
| Wet season rate of rise (mean) | GL/d | 8.40 | +3.1 | +0.1 | -2.3 | nm | nm | nm |
| Wet season rate of fall (mean) | GL/d | 4.20 | +1 | -0.3 | -1.4 | nm | nm | nm |

*Wet season covers the six months from November to April
**Dry season covers the six months from May to October
nm – not modelled

## Table A15. Standard metrics for changes to flow regime on the Fitzroy River at Looma under Scenarios C and D relative to Scenario A.

| Fitzroy - Fitzroy River at Looma (Kings Bore), Gauge No. 802007 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Standard metrics | Units | A | Cwet | Cmid | Cdry | Dwet | Dmid | Ddry |
| | | | change from Scenario A | | | | | |
| General metrics | | | | | | | | |
| Annual flow (mean) | GL | 6183 | +17% | -6% | -40% | nm | nm | nm |
| Wet season flow (mean)* | GL | 5936 | +16% | -7% | -39% | nm | nm | nm |
| Dry season flow (mean)** | GL | 235 | +22% | -1% | -57% | nm | nm | nm |
| Low flow metrics | | | | | | | | |
| Low flow threshold (discharge exceeded 90% of the time in Scenario A) | GL/d | 0.002 | | | | | | |
| Number of days below low flow threshold (mean) | d/y | 36.5 | -0.7 | +2.9 | +43 | nm | nm | nm |
| Duration of flow events below low flow threshold (mean) | d/y | 24.7 | +0.2 | +0.9 | +10.5 | nm | nm | nm |
| Number of events below low flow threshold (mean) | events/y | 1.48 | 0 | +0.1 | +0.8 | nm | nm | nm |
| Number of days of zero flow (mean) | d/y | 5.22 | -0.1 | +1.1 | +15.9 | nm | nm | nm |
| High flow metrics | | | | | | | | |
| High flow threshold (discharge exceeded 5% of the time in Scenario A) | GL/d | 92.0 | | | | | | |
| Number of days above high flow threshold (mean) | d/y | 18.3 | +2.4 | -1 | -6.9 | nm | nm | nm |
| Duration of flow events above high flow threshold (mean) | d/y | 20.1 | +0.1 | -0.6 | -3 | nm | nm | nm |
| Number of events above high flow threshold (mean) | events/y | 0.91 | +0.1 | 0 | -0.2 | nm | nm | nm |
| Wet season rate of rise (mean) | GL/d | 5.47 | +1.6 | -0.2 | -1.4 | nm | nm | nm |
| Wet season rate of fall (mean) | GL/d | 1.61 | +0.5 | -0.1 | -0.5 | nm | nm | nm |

*Wet season covers the six months from November to April
**Dry season covers the six months from May to October
nm – not modelled

## A1.3.2 King Edward River

### Table A16. Standard metrics for changes to flow regime on the Morgan River at Moondoalnee under Scenarios C and D relative to Scenario A.

| King Edward - Morgan River at Moondoalnee (Theda), Gauge No. 806005 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Standard metrics | Units | A | Cwet | Cmid | Cdry | Dwet | Dmid | Ddry |
| | | | change from Scenario A | | | | | |
| General metrics | | | | | | | | |
| Annual flow (mean) | GL | 184 | +12% | -5% | -22% | nm | nm | nm |
| Wet season flow (mean)* | GL | 177 | +12% | -5% | -22% | nm | nm | nm |
| Dry season flow (mean)** | GL | 6.74 | +13% | +0% | -33% | nm | nm | nm |
| Low flow metrics | | | | | | | | |
| Low flow threshold (discharge exceeded 90% of the time in Scenario A) | GL/d | 0.0002 | | | | | | |
| Number of days below low flow threshold (mean) | d/y | 36.6 | -3.9 | +3.9 | +24.1 | nm | nm | nm |
| Duration of flow events below low flow threshold (mean) | d/y | 37.1 | -1.1 | +2.4 | +22.8 | nm | nm | nm |
| Number of events below low flow threshold (mean) | events/y | 0.99 | -0.1 | 0 | 0 | nm | nm | nm |
| Number of days of zero flow (mean) | d/y | 20.5 | -2.3 | +4.1 | +22.3 | nm | nm | nm |
| High flow metrics | | | | | | | | |
| High flow threshold (discharge exceeded 5% of the time in Scenario A) | GL/d | 2.44 | | | | | | |
| Number of days above high flow threshold (mean) | d/y | 18.3 | +2.7 | -1.3 | -5.8 | nm | nm | nm |
| Duration of flow events above high flow threshold (mean) | d/y | 4.85 | +0.4 | -0.1 | -0.5 | nm | nm | nm |
| Number of events above high flow threshold (mean) | events/y | 3.77 | +0.2 | -0.2 | -0.9 | nm | nm | nm |
| Wet season rate of rise (mean) | GL/d | 0.74 | +0.1 | 0 | +0.1 | nm | nm | nm |
| Wet season rate of fall (mean) | GL/d | 0.39 | +0.1 | 0 | 0 | nm | nm | nm |

*Wet season covers the six months from November to April
**Dry season covers the six months from May to October
nm – not modelled

### Table A17. Standard metrics for changes to flow regime on the Carson River at Old Theda under Scenarios C and D relative to Scenario A.

| King Edward - Carson River at Old Theda, Gauge No. 806004 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Standard metrics | Units | A | Cwet | Cmid | Cdry | Dwet | Dmid | Ddry |
| | | | change from Scenario A | | | | | |
| General metrics | | | | | | | | |
| Annual flow (mean) | GL | 199 | +8% | -2% | -18% | nm | nm | nm |
| Wet season flow (mean)* | GL | 196 | +8% | -2% | -18% | nm | nm | nm |
| Dry season flow (mean)** | GL | 2.53 | +18% | +5% | -36% | nm | nm | nm |
| Low flow metrics | | | | | | | | |
| Low flow threshold (discharge exceeded 90% of the time in Scenario A) | GL/d | 0.0002 | | | | | | |
| Number of days below low flow threshold (mean) | d/y | 36.5 | -3.5 | +3.2 | +26.3 | nm | nm | nm |
| Duration of flow events below low flow threshold (mean) | d/y | 35.1 | -0.3 | +0.4 | +20.5 | nm | nm | nm |
| Number of events below low flow threshold (mean) | events/y | 1.04 | -0.1 | +0.1 | +0.1 | nm | nm | nm |
| Number of days of zero flow (mean) | d/y | 16.9 | -1.8 | +2.6 | +20.9 | nm | nm | nm |
| High flow metrics | | | | | | | | |
| High flow threshold (discharge exceeded 5% of the time in Scenario A) | GL/d | 2.93 | | | | | | |
| Number of days above high flow threshold (mean) | d/y | 18.3 | +1.6 | -0.7 | -5.7 | nm | nm | nm |
| Duration of flow events above high flow threshold (mean) | d/y | 5.29 | +0.1 | -0.1 | -0.8 | nm | nm | nm |
| Number of events above high flow threshold (mean) | events/y | 3.45 | +0.2 | -0.1 | -0.7 | nm | nm | nm |
| Wet season rate of rise (mean) | GL/d | 0.83 | 0 | 0 | +0.1 | nm | nm | nm |
| Wet season rate of fall (mean) | GL/d | 0.44 | 0 | 0 | 0 | nm | nm | nm |

*Wet season covers the six months from November to April
**Dry season covers the six months from May to October
nm – not modelled

# A1.4 NORTHERN TERRITORY

## A1.4.1 Daly River

### Table A18. Standard metrics for changes to flow regime on the Katherine River at Railway Bridge under Scenarios C and D relative to Scenario A.

| Daly - Katherine River at Railway Bridge, Gauge No. G8140001 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Standard metrics | Units | A | Cwet | Cmid | Cdry | Dwet | Dmid | Ddry |
| | | | change from Scenario A | | | | | |
| General metrics | | | | | | | | |
| Annual flow (mean) | GL | 920 | +26% | +1% | -23% | +26% | +0% | -23% |
| Wet season flow (mean)* | GL | 849 | +26% | +1% | -23% | +26% | +1% | -23% |
| Dry season flow (mean)** | GL | 21.5 | +18% | -3% | -21% | +10% | -11% | -29% |
| Low flow metrics | | | | | | | | |
| Low flow threshold (discharge exceeded 90% of the time in Scenario A) | GL/d | 0.057 | | | | | | |
| Number of days below low flow threshold (mean) | d/y | 36.6 | -29.5 | +4.7 | +47.4 | -10 | +35.1 | +79.3 |
| Duration of flow events below low flow threshold (mean) | d/y | 31.1 | -19.5 | +2.8 | +10.8 | +15.9 | +2.5 | +28.1 |
| Number of events below low flow threshold (mean) | events/y | 1.17 | -0.6 | 0 | +0.8 | -0.6 | +1 | +0.8 |
| Number of days of zero flow (mean) | d/y | 0 | 0 | 0 | 0 | 0 | 0 | +0 |
| High flow metrics | | | | | | | | |
| High flow threshold (discharge exceeded 5% of the time in Scenario A) | GL/d | 14.9 | | | | | | |
| Number of days above high flow threshold (mean) | d/y | 18.3 | +4.3 | +0 | -4.6 | +4.3 | +0.1 | -4.5 |
| Duration of flow events above high flow threshold (mean) | d/y | 5.40 | +0.8 | -0.1 | -0.6 | +0.8 | 0 | -0.7 |
| Number of events above high flow threshold (mean) | events/y | 3.39 | +0.3 | 0 | -0.5 | +0.3 | 0 | -0.5 |
| Wet season rate of rise (mean) | GL/d | 2.65 | +0.6 | -0.3 | -0.8 | +0.5 | -0.2 | -0.7 |
| Wet season rate of fall (mean) | GL/d | 1.29 | +0.6 | 0 | -0.2 | +0.6 | +0.1 | -0.2 |

*Wet season covers the six months from November to April
**Dry season covers the six months from May to October
nm – not modelled

### Table A19. Standard metrics for changes to flow regime on the Daly River at 2km downstream of Beeboom Crossing under Scenarios C and D relative to Scenario A.

| Daly - Daly River at 2km downstream of Beeboom Crossing, Gauge No. G8140042 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Standard metrics | Units | A | Cwet | Cmid | Cdry | Dwet | Dmid | Ddry |
| | | | change from Scenario A | | | | | |
| General metrics | | | | | | | | |
| Annual flow (mean) | GL | 6519 | +34% | -1% | -31% | +34% | 0% | -32% |
| Wet season flow (mean)* | GL | 5910 | +34% | -1% | -32% | +35% | -1% | -32% |
| Dry season flow (mean)** | GL | 308 | +25% | +1% | -14% | +26% | +1% | -17% |
| Low flow metrics | | | | | | | | |
| Low flow threshold (discharge exceeded 90% of the time in Scenario A) | GL/d | 1.04 | | | | | | |
| Number of days below low flow threshold (mean) | d/y | 36.5 | -31.8 | -6.7 | +27.5 | -31 | -5.8 | +38.4 |
| Duration of flow events below low flow threshold (mean) | d/y | 44.2 | -17.2 | -6 | +10.3 | -23 | -7 | +5 |
| Number of events below low flow threshold (mean) | events/y | 0.83 | -0.7 | 0 | +0.3 | -0.6 | 0 | +0.7 |
| Number of days of zero flow (mean) | d/y | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| High flow metrics | | | | | | | | |
| High flow threshold (discharge exceeded 5% of the time in Scenario A) | GL/d | 108 | | | | | | |
| Number of days above high flow threshold (mean) | d/y | 18.3 | +5.4 | -0.5 | -7.7 | +5.6 | -0.3 | -7.8 |
| Duration of flow events above high flow threshold (mean) | d/y | 8.96 | +0.8 | +0.2 | -2.2 | +1 | -0.1 | -1.8 |
| Number of events above high flow threshold (mean) | events/y | 2.04 | +0.4 | -0.1 | -0.5 | +0.3 | 0 | -0.6 |
| Wet season rate of rise (mean) | GL/d | 9.76 | +3.2 | +0.1 | -3.4 | +3.4 | -0.4 | -3.4 |
| Wet season rate of fall (mean) | GL/d | 5.48 | +2 | 0 | -1.8 | +2.1 | +0.1 | -1.7 |

*Wet season covers the six months from November to April
**Dry season covers the six months from May to October
nm – not modelled

## Table A20. Standard metrics for changes to flow regime on the Daly River at Mt Nancar under Scenarios C and D relative to Scenario A.

| Daly - Daly River at Mt Nancar, Gauge No. G8140040 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Standard metrics | Units | A | Cwet | Cmid | Cdry | Dwet | Dmid | Ddry |
| | | | change from Scenario A | | | | | |
| General metrics | | | | | | | | |
| Annual flow (mean) | GL | 8184 | +32% | -1% | -32% | +33% | -1% | -32% |
| Wet season flow (mean)* | GL | 7495 | +33% | -1% | -33% | +33% | -1% | -33% |
| Dry season flow (mean)** | GL | 360 | +23% | +1% | -14% | +24% | +1% | -17% |
| Low flow metrics | | | | | | | | |
| Low flow threshold (discharge exceeded 90% of the time in Scenario A) | GL/d | 1.20 | | | | | | |
| Number of days below low flow threshold (mean) | d/y | 36.6 | -31.7 | -7.2 | +25.5 | -30.6 | -6.1 | +35.4 |
| Duration of flow events below low flow threshold (mean) | d/y | 46.7 | -18.7 | -4.5 | +12.7 | -19.1 | -14.9 | +2 |
| Number of events below low flow threshold (mean) | events/y | 0.783 | -0.6 | -0.1 | +0.3 | -0.6 | +0.2 | +0.7 |
| Number of days of zero flow (mean) | d/y | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| High flow metrics | | | | | | | | |
| High flow threshold (discharge exceeded 5% of the time in Scenario A) | GL/d | 135 | | | | | | |
| Number of days above high flow threshold (mean) | d/y | 18.3 | +5.7 | -0.2 | -8.2 | +5.9 | 0 | -8.2 |
| Duration of flow events above high flow threshold (mean) | d/y | 9.13 | +2.8 | +0.1 | -1.9 | +2.9 | +0.4 | -1.9 |
| Number of events above high flow threshold (mean) | events/y | 2.00 | 0 | 0 | -0.6 | 0 | -0.1 | -0.6 |
| Wet season rate of rise (mean) | GL/d | 11.4 | +5.5 | +0.7 | -3.3 | +5.2 | -0.3 | -3.3 |
| Wet season rate of fall (mean) | GL/d | 6.66 | +2.2 | 0 | -2.5 | +2.4 | -0.1 | -2.5 |

*Wet season covers the six months from November to April
**Dry season covers the six months from May to October
nm – not modelled

## A1.4.2 East Alligator River

## Table A21. Standard metrics for changes to flow regime on the Magela Ck downstream of Jabiru under Scenarios C and D relative to Scenario A.

| East Alligator - Magela Ck downstream of Jabiru, Gauge No. G8210009 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Standard metrics | Units | A | Cwet | Cmid | Cdry | Dwet | Dmid | Ddry |
| | | | change from Scenario A | | | | | |
| General metrics | | | | | | | | |
| Annual flow (mean) | GL | 265 | +25% | 0% | -23% | nm | nm | nm |
| Wet season flow (mean)* | GL | 253 | +26% | 0% | -24% | nm | nm | nm |
| Dry season flow (mean)** | GL | 3.64 | -1% | +1% | -24% | nm | nm | nm |
| Low flow metrics | | | | | | | | |
| Low flow threshold (discharge exceeded 90% of the time in Scenario A) | GL/d | 0 | | | | | | |
| Number of days below low flow threshold (mean) | d/y | 156 | -14.9 | +2.2 | +22.9 | nm | nm | nm |
| Duration of flow events below low flow threshold (mean) | d/y | 128 | -13.5 | +10.6 | +32.4 | nm | nm | nm |
| Number of events below low flow threshold (mean) | events/y | 1.22 | 0 | -0.1 | -0.1 | nm | nm | nm |
| Number of days of zero flow (mean) | d/y | 156 | -14.9 | +2.2 | +22.9 | nm | nm | nm |
| High flow metrics | | | | | | | | |
| High flow threshold (discharge exceeded 5% of the time in Scenario A) | GL/d | 4.17 | | | | | | |
| Number of days above high flow threshold (mean) | d/y | 18.3 | +5.5 | -0.2 | -5.4 | nm | nm | nm |
| Duration of flow events above high flow threshold (mean) | d/y | 4.84 | +0.4 | +0.1 | -0.5 | nm | nm | nm |
| Number of events above high flow threshold (mean) | events/y | 3.78 | +0.7 | -0.1 | -0.8 | nm | nm | nm |
| Wet season rate of rise (mean) | GL/d | 0.54 | +0.1 | 0 | 0 | nm | nm | nm |
| Wet season rate of fall (mean) | GL/d | 0.43 | +0.1 | 0 | 0 | nm | nm | nm |

*Wet season covers the six months from November to April
**Dry season covers the six months from May to October
nm – not modelled

## Table A22. Standard metrics for changes to flow regime on the Magela Creek upstream of Bowerbird Waterhole under Scenarios C and D relative to Scenario A.

| East Alligator - Magela Creek upstream of Bowerbird Waterhole, Gauge No. G8210007 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Standard metrics | Units | A | Cwet | Cmid | Cdry | Dwet | Dmid | Ddry |
| | | | change from Scenario A | | | | | |
| General metrics | | | | | | | | |
| Annual flow (mean) | GL | 53.0 | +46% | -2% | -42% | nm | nm | nm |
| Wet season flow (mean)* | GL | 48.8 | +50% | -2% | -44% | nm | nm | nm |
| Dry season flow (mean)** | GL | 1.44 | +18% | +1% | -39% | nm | nm | nm |
| Low flow metrics | | | | | | | | |
| Low flow threshold (discharge exceeded 90% of the time in Scenario A) | GL/d | 0 | | | | | | |
| Number of days below low flow threshold (mean) | d/y | 117 | -22.4 | +0.2 | +29.9 | nm | nm | nm |
| Duration of flow events below low flow threshold (mean) | d/y | 111 | -21.3 | -1.2 | +25.1 | nm | nm | nm |
| Number of events below low flow threshold (mean) | events/y | 1.05 | 0 | 0 | 0 | nm | nm | nm |
| Number of days of zero flow (mean) | d/y | 117 | -22.4 | +0.2 | +29.9 | nm | nm | nm |
| High flow metrics | | | | | | | | |
| High flow threshold (discharge exceeded 5% of the time in Scenario A) | GL/d | 0.90 | | | | | | |
| Number of days above high flow threshold (mean) | d/y | 18.3 | +9.8 | -0.9 | -9 | nm | nm | nm |
| Duration of flow events above high flow threshold (mean) | d/y | 15.3 | +2.3 | -1.3 | -2.7 | nm | nm | nm |
| Number of events above high flow threshold (mean) | events/y | 1.19 | +0.4 | +0.1 | -0.5 | nm | nm | nm |
| Wet season rate of rise (mean) | GL/d | 0.06 | 0 | 0 | 0 | nm | nm | nm |
| Wet season rate of fall (mean) | GL/d | 0.04 | 0 | 0 | 0 | nm | nm | nm |

*Wet season covers the six months from November to April
**Dry season covers the six months from May to October
nm – not modelled

## Table A23. Standard metrics for changes to flow regime on the Cooper Creek downstream of Nabarlek under Scenarios C and D relative to Scenario A.

| East Alligator - Cooper Creek downstream of Nabarlek, Gauge No. G8210024 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Standard metrics | Units | A | Cwet | Cmid | Cdry | Dwet | Dmid | Ddry |
| | | | change from Scenario A | | | | | |
| General metrics | | | | | | | | |
| Annual flow (mean) | GL | 84.3 | +22% | -1% | -22% | nm | nm | nm |
| Wet season flow (mean)* | GL | 80.8 | +23% | -2% | -22% | nm | nm | nm |
| Dry season flow (mean)** | GL | 2.33 | +3% | -1% | -24% | nm | nm | nm |
| Low flow metrics | | | | | | | | |
| Low flow threshold (discharge exceeded 90% of the time in Scenario A) | GL/d | 0.0004 | | | | | | |
| Number of days below low flow threshold (mean) | d/y | 36.6 | -11.8 | +1.8 | +26.4 | nm | nm | nm |
| Duration of flow events below low flow threshold (mean) | d/y | 44.7 | -11.3 | -0.6 | +18.3 | nm | nm | nm |
| Number of events below low flow threshold (mean) | events/y | 0.82 | -0.1 | +0.1 | +0.2 | nm | nm | nm |
| Number of days of zero flow (mean) | d/y | 4.94 | -2 | +0.5 | +9.5 | nm | nm | nm |
| High flow metrics | | | | | | | | |
| High flow threshold (discharge exceeded 5% of the time in Scenario A) | GL/d | 1.18 | | | | | | |
| Number of days above high flow threshold (mean) | d/y | 18.3 | +6.1 | -0.5 | -5.3 | nm | nm | nm |
| Duration of flow events above high flow threshold (mean) | d/y | 4.02 | +0.4 | 0 | -0.4 | nm | nm | nm |
| Number of events above high flow threshold (mean) | events/y | 4.55 | +1 | -0.1 | -1 | nm | nm | nm |
| Wet season rate of rise (mean) | GL/d | 0.24 | 0 | 0 | 0 | nm | nm | nm |
| Wet season rate of fall (mean) | GL/d | 0.14 | 0 | 0 | 0 | nm | nm | nm |

*Wet season covers the six months from November to April
**Dry season covers the six months from May to October
nm – not modelled

### A1.4.3 Finniss River

**Table A24. Standard metrics for changes to flow regime on the Finniss River at Batchelor Dam Site under Scenarios C and D relative to Scenario A.**

| Finniss - Finniss River at Batchelor Dam Site, Gauge No. G8150010 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Standard metrics | Units | A | Cwet | Cmid | Cdry | Dwet | Dmid | Ddry |
| | | | change from Scenario A | | | | | |
| General metrics | | | | | | | | |
| Annual flow (mean) | GL | 146 | +30% | +1% | -26% | nm | nm | nm |
| Wet season flow (mean)* | GL | 141 | +30% | +1% | -26% | nm | nm | nm |
| Dry season flow (mean)** | GL | 3.69 | +21% | 0% | -34% | nm | nm | nm |
| Low flow metrics | | | | | | | | |
| Low flow threshold (discharge exceeded 90% of the time in Scenario A) | GL/d | 0.002 | | | | | | |
| Number of days below low flow threshold (mean) | d/y | 36.5 | -19.1 | +3.2 | +39.4 | nm | nm | nm |
| Duration of flow events below low flow threshold (mean) | d/y | 7.81 | -1.6 | -0.1 | +4 | nm | nm | nm |
| Number of events below low flow threshold (mean) | events/y | 4.68 | -1.9 | +0.5 | +1.8 | nm | nm | nm |
| Number of days of zero flow (mean) | d/y | 2.42 | -1.3 | +0.3 | +8.8 | nm | nm | nm |
| High flow metrics | | | | | | | | |
| High flow threshold (discharge exceeded 5% of the time in Scenario A) | GL/d | 2.13 | | | | | | |
| Number of days above high flow threshold (mean) | d/y | 18.3 | +6 | +0.2 | -5.9 | nm | nm | nm |
| Duration of flow events above high flow threshold (mean) | d/y | 5.19 | +0.7 | +0.1 | -1 | nm | nm | nm |
| Number of events above high flow threshold (mean) | events/y | 3.52 | +0.6 | 0 | -0.6 | nm | nm | nm |
| Wet season rate of rise (mean) | GL/d | 0.25 | +0.1 | 0 | -0.1 | nm | nm | nm |
| Wet season rate of fall (mean) | GL/d | 0.20 | +0.1 | 0 | 0 | nm | nm | nm |

*Wet season covers the six months from November to April
**Dry season covers the six months from May to October
nm – not modelled

**Table A25. Standard metrics for changes to flow regime on the East Finniss River at Rum Jungle under Scenarios C and D relative to Scenario A.**

| Finniss - East Finniss River at Rum Jungle, Gauge No. G8150097 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Standard metrics | Units | A | Cwet | Cmid | Cdry | Dwet | Dmid | Ddry |
| | | | change from Scenario A | | | | | |
| General metrics | | | | | | | | |
| Annual flow (mean) | GL | 27.8 | +30% | +1% | -23% | nm | nm | nm |
| Wet season flow (mean)* | GL | 27.2 | +31% | +1% | -23% | nm | nm | nm |
| Dry season flow (mean)** | GL | 0.37 | +15% | +2% | -34% | nm | nm | nm |
| Low flow metrics | | | | | | | | |
| Low flow threshold (discharge exceeded 90% of the time in Scenario A) | GL/d | 0 | | | | | | |
| Number of days below low flow threshold (mean) | d/y | 181 | -18.1 | +2.4 | +18.4 | nm | nm | nm |
| Duration of flow events below low flow threshold (mean) | d/y | 164 | -9.1 | +0.2 | +25.5 | nm | nm | nm |
| Number of events below low flow threshold (mean) | events/y | 1.10 | -0.1 | 0 | -0.1 | nm | nm | nm |
| Number of days of zero flow (mean) | d/y | 181 | -18.1 | +2.4 | +18.4 | nm | nm | nm |
| High flow metrics | | | | | | | | |
| High flow threshold (discharge exceeded 5% of the time in Scenario A) | GL/d | 0.41 | | | | | | |
| Number of days above high flow threshold (mean) | d/y | 18.3 | +6.1 | +0.3 | -4.8 | nm | nm | nm |
| Duration of flow events above high flow threshold (mean) | d/y | 4.41 | +0.8 | +0.3 | -0.4 | nm | nm | nm |
| Number of events above high flow threshold (mean) | events/y | 4.14 | +0.5 | -0.2 | -0.7 | nm | nm | nm |
| Wet season rate of rise (mean) | GL/d | 0.11 | 0 | 0 | 0 | nm | nm | nm |
| Wet season rate of fall (mean) | GL/d | 0.06 | 0 | 0 | 0 | nm | nm | nm |

*Wet season covers the six months from November to April
**Dry season covers the six months from May to October
nm – not modelled

## Table A26. Standard metrics for changes to flow regime on the Blackmore River at Tumbling Waters under Scenarios C and D relative to Scenario A.

| Finniss - Blackmore River at Tumbling Waters, Gauge No. G8150098 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Standard metrics | Units | A | Cwet | Cmid | Cdry | Dwet | Dmid | Ddry |
| | | | change from Scenario A | | | | | |
| General metrics | | | | | | | | |
| Annual flow (mean) | GL | 88.8 | +24% | +0% | -20% | nm | nm | nm |
| Wet season flow (mean)* | GL | 88.0 | +24% | +0% | -20% | nm | nm | nm |
| Dry season flow (mean)** | GL | 0.57 | +46% | -5% | -43% | nm | nm | nm |
| Low flow metrics | | | | | | | | |
| Low flow threshold (discharge exceeded 90% of the time in Scenario A) | GL/d | 0 | | | | | | |
| Number of days below low flow threshold (mean) | d/y | 160 | -15.7 | +5.1 | +24.7 | nm | nm | nm |
| Duration of flow events below low flow threshold (mean) | d/y | 134 | -4.7 | +9 | +37.4 | nm | nm | nm |
| Number of events below low flow threshold (mean) | events/y | 1.19 | -0.1 | 0 | -0.1 | nm | nm | nm |
| Number of days of zero flow (mean) | d/y | 160 | -15.7 | +5.1 | +24.7 | nm | nm | nm |
| High flow metrics | | | | | | | | |
| High flow threshold (discharge exceeded 5% of the time in Scenario A) | GL/d | 1.40 | | | | | | |
| Number of days above high flow threshold (mean) | d/y | 18.3 | +3.7 | 0 | -4.4 | nm | nm | nm |
| Duration of flow events above high flow threshold (mean) | d/y | 4.24 | +0.2 | +0.1 | -0.4 | nm | nm | nm |
| Number of events above high flow threshold (mean) | events/y | 4.31 | +0.6 | -0.1 | -0.7 | nm | nm | nm |
| Wet season rate of rise (mean) | GL/d | 0.29 | 0 | 0 | 0 | nm | nm | nm |
| Wet season rate of fall (mean) | GL/d | 0.19 | 0 | 0 | 0 | nm | nm | nm |

*Wet season covers the six months from November to April
**Dry season covers the six months from May to October
nm – not modelled

## Table A27. Standard metrics for changes to flow regime on the Elizabeth River at Stuart Highway under Scenarios C and D relative to Scenario A.

| Finniss - Elizabeth River at Stuart Highway, Gauge No. G8150018 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Standard metrics | Units | A | Cwet | Cmid | Cdry | Dwet | Dmid | Ddry |
| | | | change from Scenario A | | | | | |
| General metrics | | | | | | | | |
| Annual flow (mean) | GL | 48.4 | +26% | 0% | -21% | nm | nm | nm |
| Wet season flow (mean)* | GL | 46.5 | +27% | 0% | -21% | nm | nm | nm |
| Dry season flow (mean)** | GL | 1.53 | +9% | +1% | -27% | nm | nm | nm |
| Low flow metrics | | | | | | | | |
| Low flow threshold (discharge exceeded 90% of the time in Scenario A) | GL/d | 0.0003 | | | | | | |
| Number of days below low flow threshold (mean) | d/y | 36.5 | -18.5 | +4.2 | +26.8 | nm | nm | nm |
| Duration of flow events below low flow threshold (mean) | d/y | 41.3 | -12.5 | +0.4 | +22.8 | nm | nm | nm |
| Number of events below low flow threshold (mean) | events/y | 0.88 | -0.3 | +0.1 | +0.1 | nm | nm | nm |
| Number of days of zero flow (mean) | d/y | 11.4 | -7.7 | +1.9 | +15.3 | nm | nm | nm |
| High flow metrics | | | | | | | | |
| High flow threshold (discharge exceeded 5% of the time in Scenario A) | GL/d | 0.736 | | | | | | |
| Number of days above high flow threshold (mean) | d/y | 18.3 | +4.8 | -0.6 | -4.8 | nm | nm | nm |
| Duration of flow events above high flow threshold (mean) | d/y | 3.82 | +0.4 | -0.1 | -0.6 | nm | nm | nm |
| Number of events above high flow threshold (mean) | events/y | 4.78 | +0.6 | -0.1 | -0.6 | nm | nm | nm |
| Wet season rate of rise (mean) | GL/d | 0.20 | 0 | 0 | 0 | nm | nm | nm |
| Wet season rate of fall (mean) | GL/d | 0.11 | 0 | +0 | 0 | nm | nm | nm |

*Wet season covers the six months from November to April
**Dry season covers the six months from May to October
nm – not modelled

### A1.4.4 South Alligator River

#### Table A28. Standard metrics for changes to flow regime on the Jim Jim Creek At Oenpelli Road Crossing under Scenarios C and D relative to Scenario A.

| South Alligator - Jim Jim Creek At Oenpelli Road Crossing, Gauge No. G8200111 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Standard metrics | Units | A | Cwet | Cmid | Cdry | Dwet | Dmid | Ddry |
| | | | change from Scenario A | | | | | |
| General metrics | | | | | | | | |
| Annual flow (mean) | GL | 717 | +25% | +1% | -23% | nm | nm | nm |
| Wet season flow (mean)* | GL | 695 | +26% | +1% | -23% | nm | nm | nm |
| Dry season flow (mean)** | GL | 10.7 | +6% | +2% | -25% | nm | nm | nm |
| Low flow metrics | | | | | | | | |
| Low flow threshold (discharge exceeded 90% of the time in Scenario A) | GL/d | 0 | | | | | | |
| Number of days below low flow threshold (mean) | d/y | 105 | -14.3 | +3.6 | +31.6 | nm | nm | nm |
| Duration of flow events below low flow threshold (mean) | d/y | 79.3 | -5.7 | +8.8 | +41.6 | nm | nm | nm |
| Number of events below low flow threshold (mean) | events/y | 1.32 | -0.1 | -0.1 | -0.2 | nm | nm | nm |
| Number of days of zero flow (mean) | d/y | 105 | -14.3 | +3.6 | +31.6 | nm | nm | nm |
| High flow metrics | | | | | | | | |
| High flow threshold (discharge exceeded 5% of the time in Scenario A) | GL/d | 10.8 | | | | | | |
| Number of days above high flow threshold (mean) | d/y | 18.3 | +6.6 | +0.2 | -6 | nm | nm | nm |
| Duration of flow events above high flow threshold (mean) | d/y | 9.20 | +1.4 | +0.2 | -0.8 | nm | nm | nm |
| Number of events above high flow threshold (mean) | events/y | 1.99 | +0.4 | 0 | -0.5 | nm | nm | nm |
| Wet season rate of rise (mean) | GL/d | 0.64 | +0.2 | 0 | 0 | nm | nm | nm |
| Wet season rate of fall (mean) | GL/d | 0.42 | +0.1 | 0 | 0 | nm | nm | nm |

*Wet season covers the six months from November to April
**Dry season covers the six months from May to October
nm – not modelled

#### Table A29. Standard metrics for changes to flow regime on the Goodparla Creek At Coirwong Gorge under Scenarios C and D relative to Scenario A.

| South Alligator - Goodparla Creek At Coirwong Gorge, Gauge No. G8200044 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Standard metrics | Units | A | Cwet | Cmid | Cdry | Dwet | Dmid | Ddry |
| | | | change from Scenario A | | | | | |
| General metrics | | | | | | | | |
| Annual flow (mean) | GL | 23.3 | +28% | 0% | -28% | nm | nm | nm |
| Wet season flow (mean)* | GL | 23.1 | +29% | 0% | -28% | nm | nm | nm |
| Dry season flow (mean)** | GL | 0.0817 | +46% | +2% | -53% | nm | nm | nm |
| Low flow metrics | | | | | | | | |
| Low flow threshold (discharge exceeded 90% of the time in Scenario A) | GL/d | 0 | | | | | | |
| Number of days below low flow threshold (mean) | d/y | 193 | -15.4 | +3.3 | +23.8 | nm | nm | nm |
| Duration of flow events below low flow threshold (mean) | d/y | 118 | -8.5 | +2 | +29.8 | nm | nm | nm |
| Number of events below low flow threshold (mean) | events/y | 1.64 | 0 | 0 | -0.2 | nm | nm | nm |
| Number of days of zero flow (mean) | d/y | 193 | -15.4 | +3.3 | +23.8 | nm | nm | nm |
| High flow metrics | | | | | | | | |
| High flow threshold (discharge exceeded 5% of the time in Scenario A) | GL/d | 0.371 | | | | | | |
| Number of days above high flow threshold (mean) | d/y | 18.3 | +5.3 | -0.3 | -7.5 | nm | nm | nm |
| Duration of flow events above high flow threshold (mean) | d/y | 5.61 | +0.8 | 0 | -1 | nm | nm | nm |
| Number of events above high flow threshold (mean) | events/y | 3.26 | +0.4 | -0.1 | -0.9 | nm | nm | nm |
| Wet season rate of rise (mean) | GL/d | 0.05 | 0 | 0 | 0 | nm | nm | nm |
| Wet season rate of fall (mean) | GL/d | 0.03 | 0 | 0 | 0 | nm | nm | nm |

*Wet season covers the six months from November to April
**Dry season covers the six months from May to October
nm – not modelled

## Table A30. Standard metrics for changes to flow regime on the South Alligator River at El Sherana under Scenarios C and D relative to Scenario A.

| South Alligator - South Alligator River at El Sherana, Gauge No. G8200045 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Standard metrics | Units | A | Cwet | Cmid | Cdry | Dwet | Dmid | Ddry |
| | | | change from Scenario A | | | | | |
| General metrics | | | | | | | | |
| Annual flow (mean) | GL | 405 | +24% | 0% | -24% | nm | nm | nm |
| Wet season flow (mean)* | GL | 394 | +25% | 0% | -24% | nm | nm | nm |
| Dry season flow (mean)** | GL | 8.49 | +19% | +1% | -23% | nm | nm | nm |
| Low flow metrics | | | | | | | | |
| Low flow threshold (discharge exceeded 90% of the time in Scenario A) | GL/d | 0.004 | | | | | | |
| Number of days below low flow threshold (mean) | d/y | 36.5 | -14.6 | +1.9 | +34.1 | nm | nm | nm |
| Duration of flow events below low flow threshold (mean) | d/y | 33.1 | -5.4 | +0.9 | +24.8 | nm | nm | nm |
| Number of events below low flow threshold (mean) | events/y | 1.10 | -0.3 | 0 | +0.1 | nm | nm | nm |
| Number of days of zero flow (mean) | d/y | 1.01 | -0.2 | +0.1 | +0.2 | nm | nm | nm |
| High flow metrics | | | | | | | | |
| High flow threshold (discharge exceeded 5% of the time in Scenario A) | GL/d | 6.21 | | | | | | |
| Number of days above high flow threshold (mean) | d/y | 18.3 | +5.5 | -0.2 | -5.4 | nm | nm | nm |
| Duration of flow events above high flow threshold (mean) | d/y | 4.89 | +0.6 | +0.1 | -0.6 | nm | nm | nm |
| Number of events above high flow threshold (mean) | events/y | 3.74 | +0.6 | -0.1 | -0.7 | nm | nm | nm |
| Wet season rate of rise (mean) | GL/d | 0.91 | +0.2 | 0 | -0.1 | nm | nm | nm |
| Wet season rate of fall (mean) | GL/d | 0.58 | +0.1 | 0 | -0.1 | nm | nm | nm |

*Wet season covers the six months from November to April

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

nm – not modelled

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