



Government of **Western Australia**
Department of **Water**

Yule River - ecological values and issues

Ecological water requirements

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Ecological water requirements

Looking after all our water needs

Department of Water

Environmental water series

Report no. 18

October 2010

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October 2010

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ISBN 978-1-921789-35-9 (print)

ISBN 978-1-921789-36-6 (online)

ISSN 1833-6582 (print)

ISSN 1833-6590 (online)

Acknowledgements

This report was prepared by Mike Braimbridge from the Department of Water's Environmental Water Planning section. The author acknowledges the input and comments provided by Michelle Antao, Robyn Loomes and Fiona Lynn. This project is part funded by the Australian Government's Water for the Future initiative.



Australian Government
Water for the Future

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The recommended reference for this publication is:

Braimbridge, M, 2010, *Yule River: ecological values and issues*, Environmental water report series, Report no. 18, Department of Water, Government of Western Australia.

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Summary

This document summarises the values associated with ecosystems dependent on groundwater from the Yule River alluvial aquifer. The project area is centred around the existing Yule River Borefield which has been in operation since 1967 as one of the sources that supplies Port Hedland. As with most Pilbara alluvial aquifers, the system relies on river flow, predominantly generated from cyclone derived rainfall, as the main source of recharge to the aquifer.

River pools, riparian vegetation and aquifer ecosystems are the ecosystems identified as reliant on groundwater to meet their water requirements, at least in part. Terrestrial fauna is indirectly reliant on groundwater, with a number of species preferentially using or relying on habitat provided by groundwater-dependent ecosystems (GDEs).

The GDEs described for the Yule River aquifer are comparable in terms of types and composition with ecosystems occurring on similar systems in the Pilbara. River pool and riparian vegetation communities within the study area have been impacted by grazing pressure and weed invasion. They are considered to be of local conservation significance only.

The links between the ecosystems and the aquifer are described as conceptual models. Eco-hydrological linkages considered to represent the key linkages between the ecosystems and hydrogeology have been identified as objectives for revising ecological water requirements (EWRs) for the system.

The ecological water requirements will be a key input into the determination of an allocation limit for the system which will also consider the social and cultural water requirements and consumptive demand for water. A revised management and monitoring framework will be developed and the operating rules for the resource reviewed.

Allocation planning for the Pilbara coastal ports and towns is underway and scheduled to be completed in 2012.

1 Introduction

1.1 Purpose of this document

This document reviews the available information on the ecosystems of the lower Yule River focusing on those linked to the underlying alluvial aquifer. The links between the ecosystems of the lower Yule River and the hydrogeology of the system (eco-hydrological links) are described as conceptual models, and key links identified as objectives for determining ecological water requirements (EWRs).

This information will provide a framework to determine the system's EWRs. Ultimately it will also support the revision of allocation limits and rules to manage the potential impacts of water abstraction on the system and its dependent ecosystems.

1.2 Project area

The Yule River is located approximately 40 km west of Port Hedland (Figure 1). The area of focus for this project is the section of the Yule River downstream of the North West Coastal Highway to the old highway crossing. This area includes the existing Yule Borefield and an approximately 30 km section of the lower Yule River. Some ecological survey work has extended further upstream and downstream of this area to provide broader catchment information.

Like many other river systems in the Pilbara the lower reaches on the coastal plain overlies an alluvial aquifer. This aquifer has been utilised as a supply source for Port Hedland since 1967. The area is part of an operating pastoral lease, Mundabullangana Station, and also supports a range of ecosystems some of which rely on the groundwater, at least in part, for their water requirements.

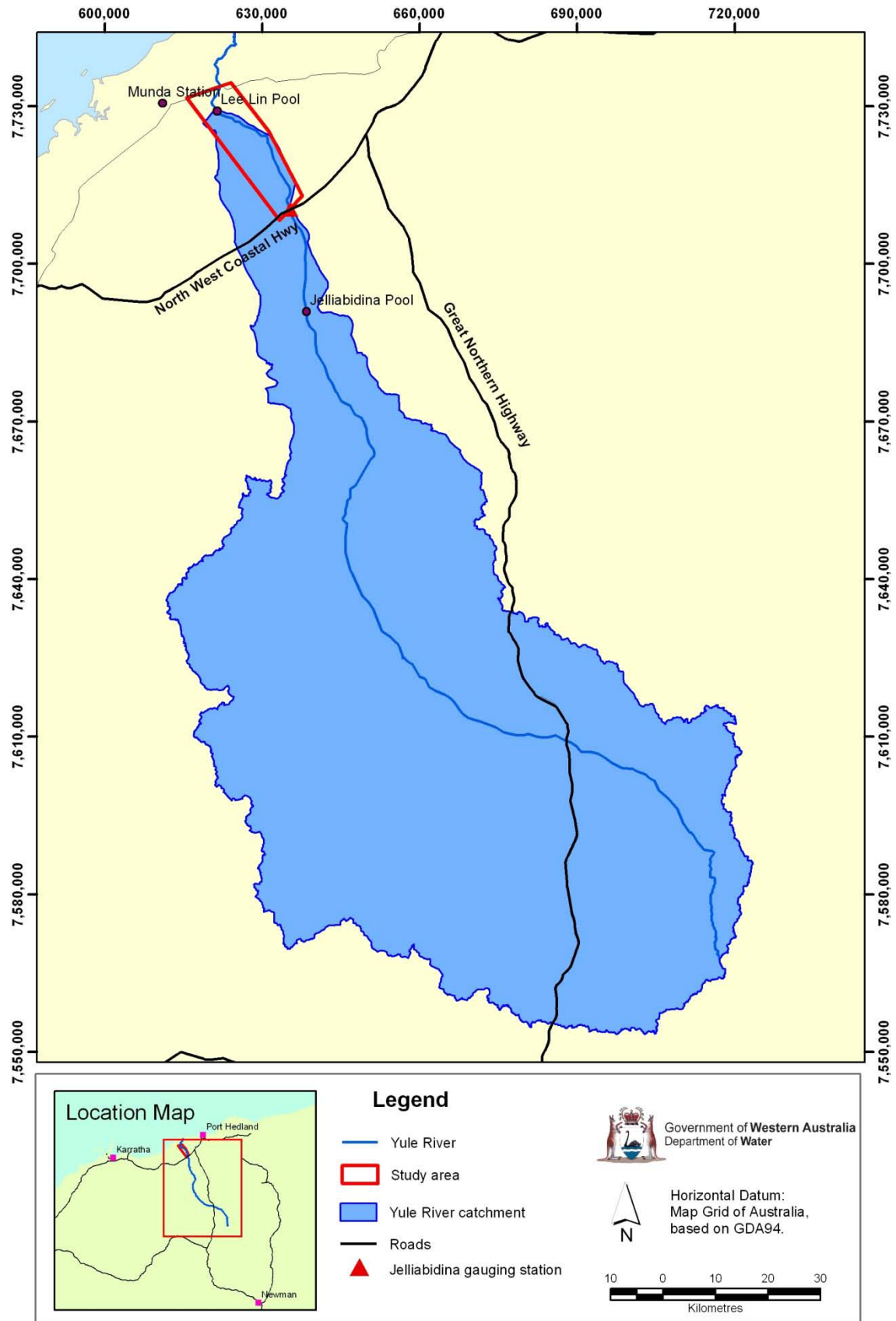


Figure 1 Yule River catchment and study area

1.3 Hydrology

Yule River is approximately 217 km long and has a catchment area of 12 000 km² draining from the Chichester and Mungaroona ranges to the coast. The lower Yule River gauging station (Jelliabidina Well gauging station) is located immediately upstream of the study area where the river crosses the North West Coastal Highway. The current period of record is 35 years extending from 1973 to 2010 (excluding 2003 and 2004) (Figure 2).

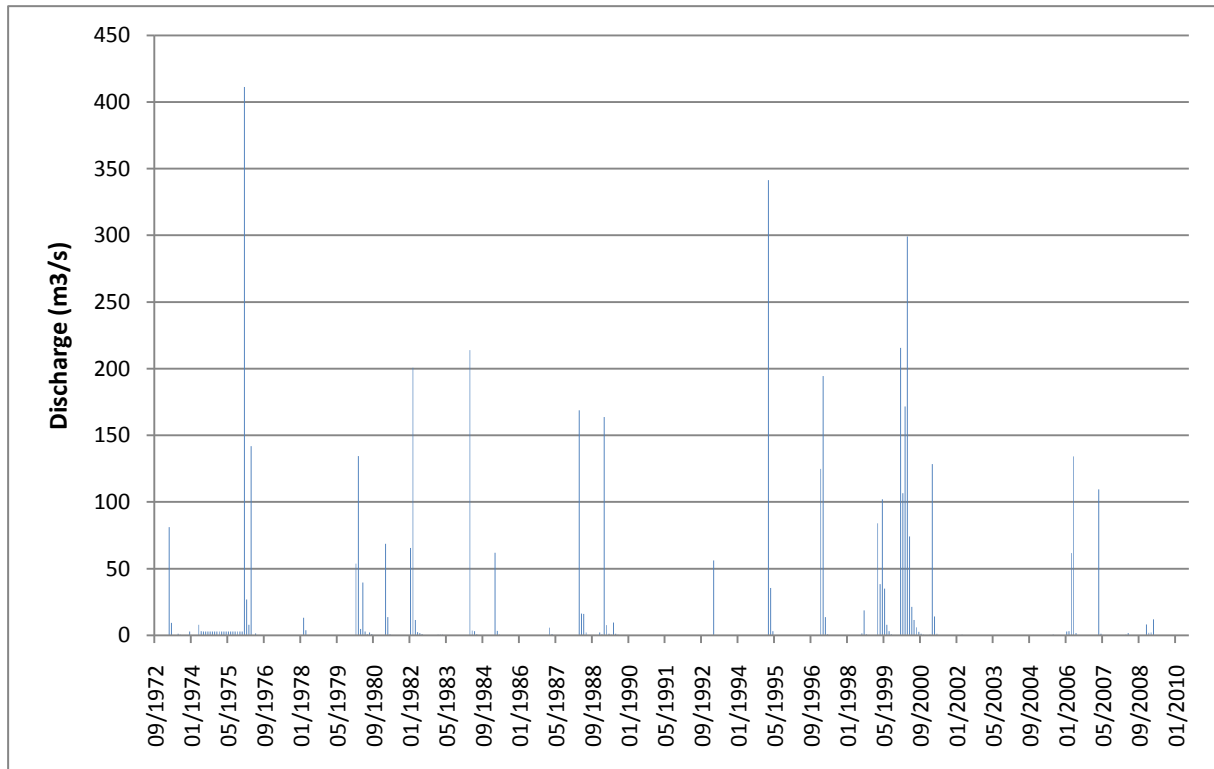


Figure 2 Monthly mean discharge for the Jelliabidina Well gauging station on the Yule River for the available record (1973 to 2010)

The Yule River is an ephemeral system characterised by a highly variable and unpredictable flow regime across years. Recorded mean and median annual flows are 332 GL and 135 GL respectively. A maximum annual discharge of 1823 GL was recorded in 2000, whilst no or low flows (less than 10 percent of the mean annual flow) have been recorded in 13 years.

High flows typically occur during December to April, peaking in February (Figure 3). Low or no flow is typically experienced from May through to November.

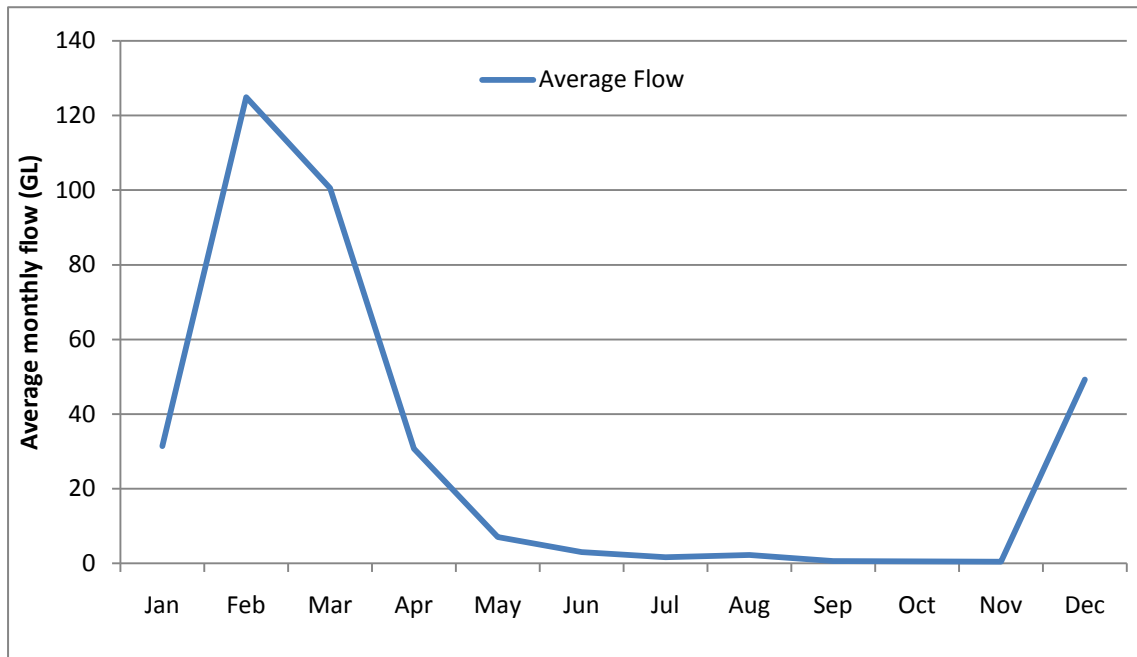


Figure 3 Average monthly flow recorded at Jelliabidina Well gauging station (709005)

1.4 Hydrogeology

The lower reaches of Yule River on the coastal plain overlie an alluvial aquifer of Quaternary and Tertiary sediments. The aquifer is thickest, up to 27 to 50 m, where paleochannels have been formed within the underlying Archaean granitoid-greenstone basement.

The main paleochannel trends north west crossing from the west to the eastern side of the Yule River beneath the current Yule Borefield. There are also branches off the main paleochannel on the north and south sides.

The alluvium consists of sands and gravels with clay lenses forming a semi confined aquifer in parts. There are also minor occurrences of calcrete but the alluvial sands and gravels are considered the main aquifer which has been investigated several times since 1967 (Whincup 1967; Forth 1972; Davidson 1976; MWH 2010).

Hydrographs from monitoring bores indicate that there is generally good connectivity throughout the aquifer system.

Groundwater flow in the aquifer is north towards the coast. Losses from the system include throughflow and evapotranspiration. Evapotranspiration (ET) is highest along the river where depth to groundwater is shallow and vegetation is dense. ET losses have previously been estimated to be 3.6 GL/yr for the borefield area and 5.4 GL/yr for the area between the borefield and the highway. At high aquifer levels the watertable intersects the river channel in places as either baseflow or discharge which sustains river pools.

Mean annual recharge has previously been estimated to be between 13.4 GL/yr (Whincup 1967) and 14.6 GL/yr (Forth 1972). Recharge is primarily the result of

infiltration of streamflow where the current river channel directly overlies the alluvial aquifer.

The data from the Jelliabidina gauging station provide the best indication of the reliability and variability of recharge. The station has a maximum recorded period of no flow of 37 months. In the period of record from 1973 to 2009 (excluding years with incomplete data) there were 13 years when annual flow was less than 10 percent of mean annual flow (MWH 2010). This indicates that in 1 in 3 years there is very low recharge to the aquifer (Haig 2009, MWH 2010).

1.5 Water use

A borefield to supply water to Port Hedland has been in operation at the Yule River since 1967. There are currently 10 production bores in operation at the borefield on the northern side of the river, operated by the Water Corporation (Figure 4). The water abstracted from the Yule River Borefield feeds into the Port Hedland supply scheme which is also supplied by the Namagoorie Borefield on the De Grey River.

The Water Corporation has a licenced allocation from the Yule River of 6.5 GL/yr with an interim additional 2.0 GL/yr. The additional 2.0 GL/yr is provided on basis that the Water Corporation completes a pumping trial that simulates abstraction of an annual total of 8.5 GL/yr and demonstrates:

- (i) the aquifer's capacity to supply this amount
- (ii) that this amount can be provided by the resource without significantly impacting dependent ecosystems.

The pumping trial commenced in December 2008 as a collaborative exercise involving the Water Corporation, Department of Water, University of Western Australia and University of Sydney (see section 3).

Annual abstraction since 2000 has averaged 4.8 GL/yr. In the 2009–2010 water year (April 2009 to March 2010) approximately 4.7 GL was abstracted. The highest annual abstraction was 6.4 GL in the 2003–2004 water year.

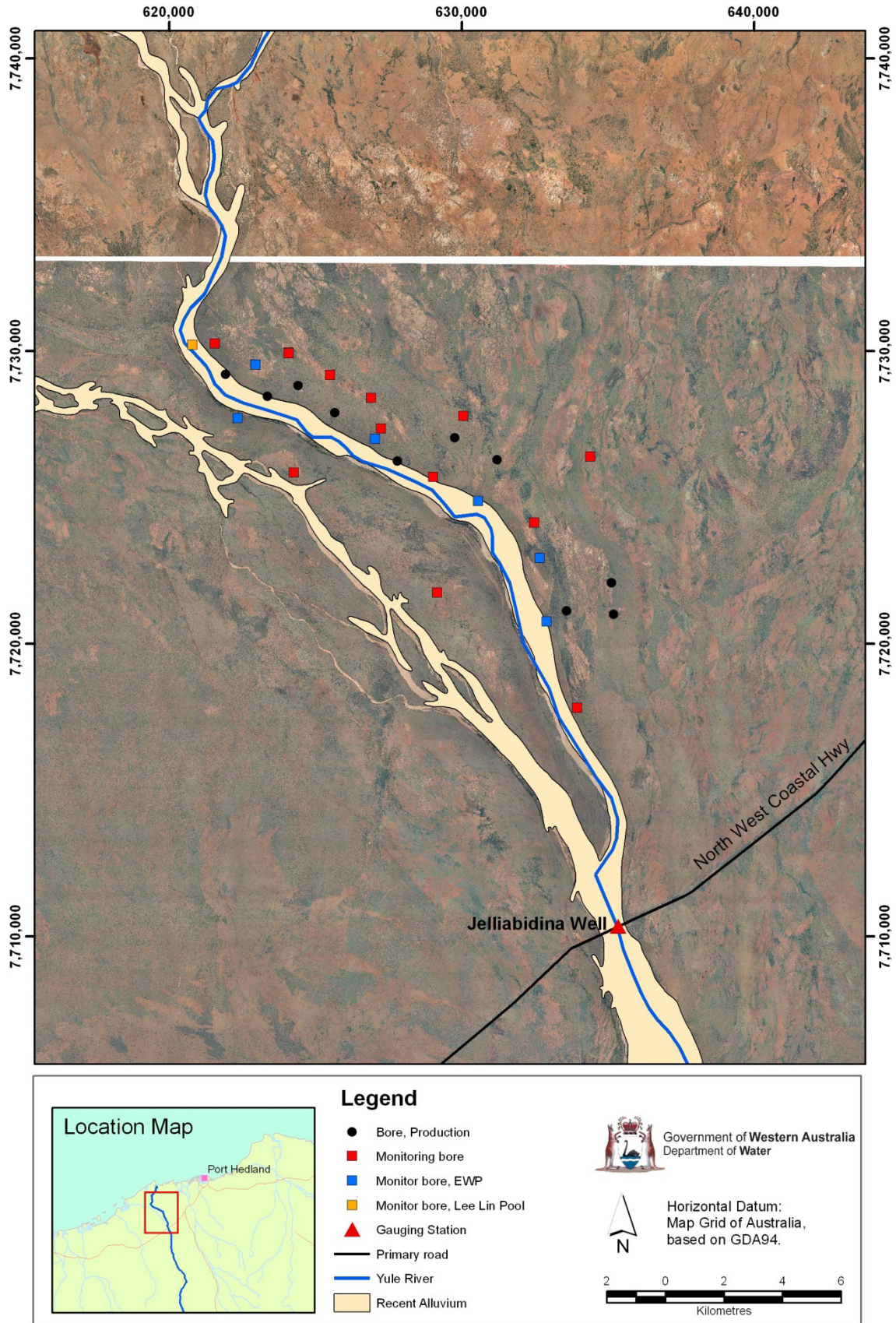


Figure 4 Yule River Borefield, production and monitoring bore distribution

1.6 Management of water abstraction and existing environmental water provisions

Overall management of the borefield is completed in accordance with an operating strategy required as a condition of the groundwater abstraction licence. The Water Corporation is required to operate the borefield in accordance with this strategy.

Management of abstraction impacts on groundwater-dependent ecosystems is via a set of environmental water provision (EWP) criteria. These criteria are set as trigger and minimum water levels in five EWP monitoring bores located across the borefield (Figure 4).

The criteria were developed based on ecological water requirements (EWRs). These were estimated using the historical groundwater level record for the borefield and predicted tolerances to minimum groundwater levels of key groundwater-dependent vegetation species (Maunsell 2003).

Trigger levels were established in monitoring bores at 0.25 m above the minimum recorded water level. When this trigger is reached the frequency of water level and ecological monitoring is to be increased from monthly and 6-monthly, respectively, to fortnightly and bimonthly.

As water levels approach the historic minimum the Water Corporation is required to modify the abstraction from the borefield to reduce abstraction pressure on the affected area. Minimum water levels have been set at 0.25 m below historic minimums. As well as modifying the pattern of take from the borefield, the Water Corporation is also required to implement restrictions on water users and implement contingency sources (Water Corporation 2008).

2 Identification and description of groundwater-dependent ecosystems

2.1 Revising the existing estimate of ecological water requirements

The current project will revise the previous EWR assessment using information that has since become available including:

- the recently completed numerical groundwater model of the Yule alluvial aquifer (MWH 2010)
- a digital elevation model derived from LiDAR (Light Detection and Ranging) data combined with hydrological data to characterise depth to water
- additional pool and bore monitoring data including six years of monitoring data from bores specifically established in 2004 to better represent water levels adjacent to riparian vegetation
- mapping and assessment of pool permanency using remote sensing across the Pilbara (including the lower Yule River) completed by the Department of Water
- development of a database summarising the distribution of key riparian species in relation to depth to groundwater at Yule River and at similar alluvial systems across the Pilbara (Loomes 2010)
- results of investigations into the ecology of riverine pools (water quality, macroinvertebrates and fish) (Morgan et al. 2009; Pinder & Leung 2009)
- preliminary results of the Yule pumping trial (see section 3).

This information has been incorporated, where applicable, into this report.

2.2 Defining groundwater-dependent ecosystems

Groundwater-dependent ecosystems rely on groundwater directly (for example, stygofauna or phreatophytic vegetation using water from shallow watertables) or indirectly (for example, wetland vegetation or aquatic ecosystems sustained by groundwater discharge).

Conceptual models describing the links between ecosystems, groundwater and hydrological support mechanisms have been developed based on previous studies (Maunsell 2003; Braimbridge et al. 2010; Loomes & Braimbridge 2010), the results of monitoring programs and information collected for this study.

The previous EWR study (Maunsell 2003) identified and assessed three groundwater-dependent ecosystems:

- riverine ecosystem
- riparian ecosystem

- aquifer ecosystem.

These ecosystems have also been the focus of the current EWR project. The degree and types of groundwater dependency have not changed in the intervening years.

2.3 Riverine ecosystems

Like most Pilbara rivers the Yule River is an ephemeral system with intermittent surface flows typically resulting from cyclone derived rainfall. In between flows, the river is reduced to a series of isolated pools.

Mapping and assessment of river pools conducted by the department using remote sensing identified 14 pools of varying permanency within the project area (Table 1). The biggest and most permanent pools in close proximity to the borefield are Lee Lin and the pool(s) located where North West Coastal Highway crosses the Yule River (Figure 5).

Table 1 Pools recorded for the lower Yule project area

Pool name (if known)	Oct 99	Jan 02	Feb 03	Oct 03	Jun 04	Jan 05	Defined permanency
	Estimated inundation area (m ²)						
Lee Lin	15 749	12 609	412 834	20 744	43 274	1270	Permanent
Unknown	8180	9435	63 409	19 475	22 590	1895	Permanent
Unknown	32 759	9470	39 654	19 549	31 479	0	Semi-permanent
Unknown	17 650	635	20 184	14 500	13 250	0	Semi-permanent
Unknown	4435	0	6340	1270	635	0	Semi-permanent
Unknown	0	8195	412 834	26 380	28 870	4420	Semi-permanent
Unknown	2525	0	14 455	3785	5035	0	Semi-permanent
Unnamed				145	145		
Hwy Pool	33 274	0	241 094	359	364	67 049	Semi-permanent
Unnamed				145	145		
Hwy Pool	30 125	0	241 094	359	364	0	Semi-permanent
Unknown	635	0	18 294	8200	0	0	Intermittent
Unknown	0	0	11 340	1895	0	0	Intermittent
Unknown	0	0	15 754	1900	2525	0	Intermittent
Unknown	0	0	117 309	635	24 524	0	Intermittent
Meedanar	2530	0	0	635	635	0	Intermittent

The pool mapping assessed the permanency of river pools based on their occurrence across seven sets of Landsat imagery spanning 1999 to 2007. Pools were defined as permanent if they were present across all image sets; semi-

permanent if present in 60 to 99 percent of image sets; and intermittent if present in <60 percent of image sets.

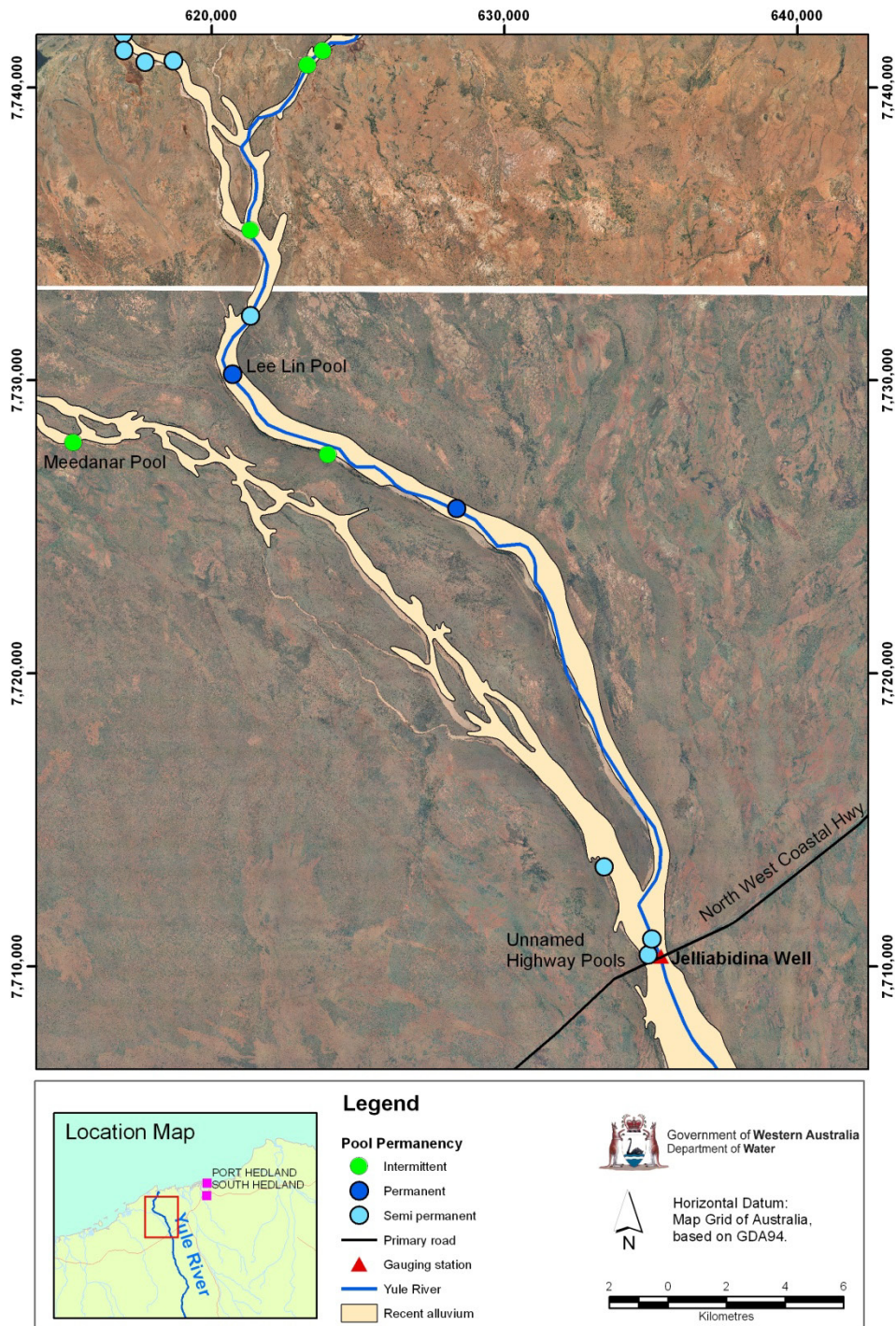


Figure 5 Distribution and permanency of river pools in the lower Yule River

Regionally, many Pilbara rivers, as a result of grazing and altered fire regimes, now carry large sand bed-loads due to increased runoff volumes and velocities in large parts of their catchments (Van Vreeswyk et al. 2004). The sandy bed of the Yule River is likely to be highly mobile during river flows and pools may migrate over time. However, anecdotal evidence suggests that pools such as Jelliabidina, Lee Lin and pools at the North West Coastal Highway have remained relatively stable in terms of position for up to ten years. Further analysis of longer term satellite imagery could confirm this.

Conceptual link to groundwater

The conceptual model of the connectivity of the pools of the lower Yule River to groundwater fits the general conceptual model developed and applied to other coastal alluvial systems in the Pilbara such as the De Grey, Robe and Fortescue rivers.

The direction of interaction between surface and groundwater changes seasonally in response to flooding, evaporation from pools or transpiration of groundwater by vegetation. As shown in the conceptual diagrams below, the permanence of the interaction is determined by the level of the groundwater in relation to the base height of the pool.

When the river is in flood there is connectivity between pools, the floodplains and the riparian zone (Figure 6). This hydrological connectivity allows biota, nutrients and carbon to disperse or migrate through the system. Large areas of the river and floodplain may become briefly inundated resulting in a spike in productivity and provision of temporary habitat for aquatic flora and fauna and water birds (Bunn et al. 2006). During river flow events, groundwater is recharged from the surface water and the watertable rises. These events are important triggers for dispersal and recruitment of riparian vegetation and aquatic flora and fauna.

During periods of no flow (Figure 7) the hydraulic gradient between the groundwater and the pools reverses and groundwater discharges into the pools. Intermittent pools begin to dry out as the watertable drops below the base height of the pool and the groundwater becomes disconnected.

Drought conditions and declining groundwater levels result in shallower pool depths and semi-permanent pools becoming disconnected from the groundwater (Figure 8). This greatly reduces the area of aquatic habitat available for macroinvertebrates, fish and macrophytes.

Permanent pools that have a demonstrated long-term connectivity to the groundwater are expected to be maintained by groundwater discharge during these drought periods. These pools provide critical habitat and are an important refuge for native flora and fauna during drought periods. In addition they facilitate relatively high 'in pool' productivity during these periods (compared to adjacent areas) and are likely to sustain productivity in surrounding areas (Douglas et al. 2005; Bunn et al. 2006).

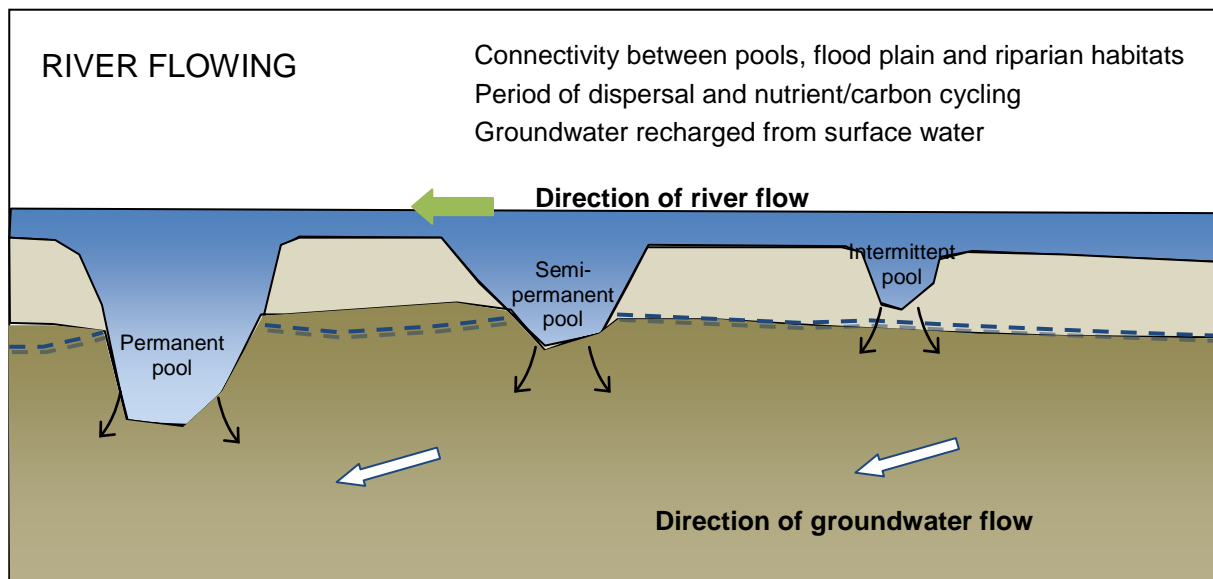


Figure 6 Conceptual diagram of a longitudinal cross-section of the Yule River during a river flow event

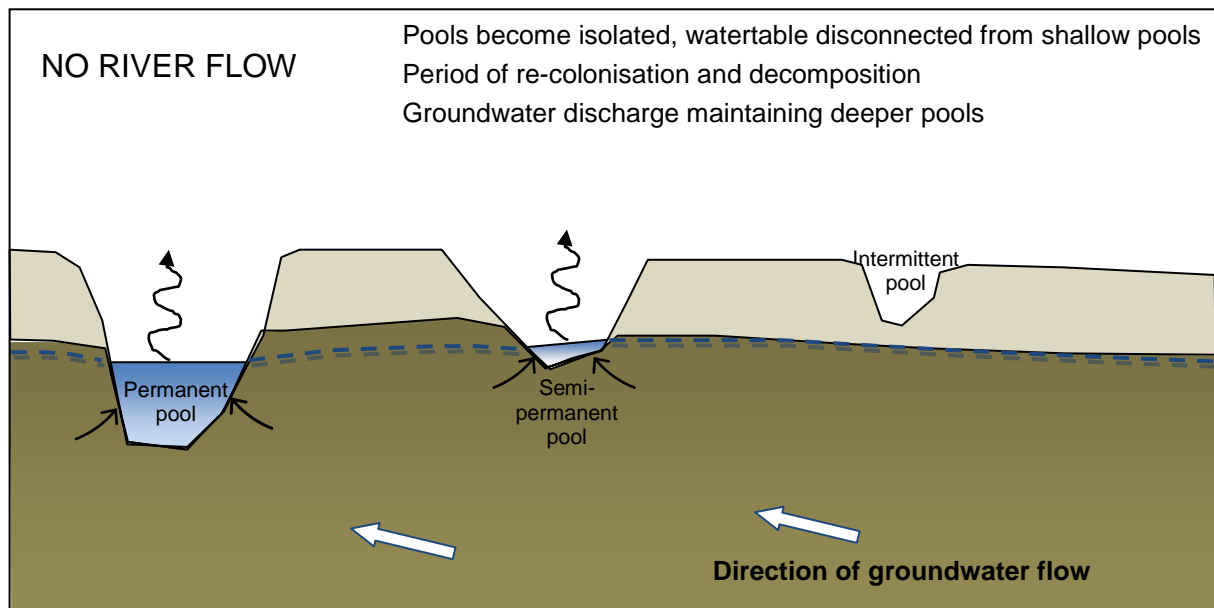


Figure 7 Conceptual diagram of a longitudinal cross-section of the Yule River during a period of no river flow

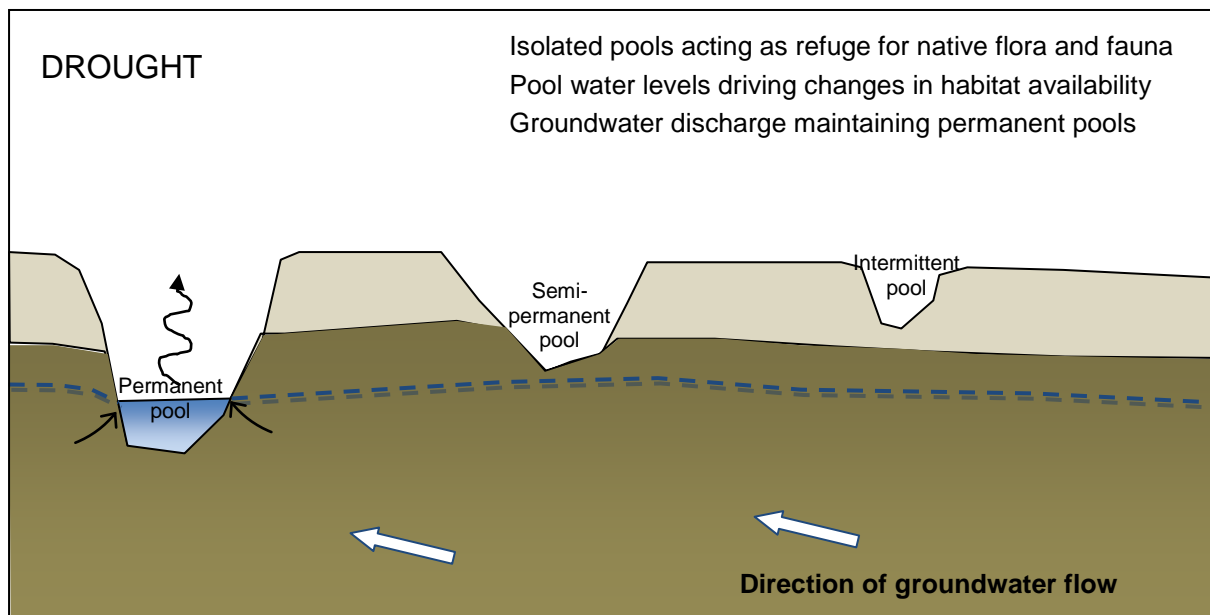


Figure 8 Conceptual diagram of a longitudinal cross-section of Yule River during a drought period

Ecology

Fish fauna

Six species of freshwater fish and ten marine/estuarine species have been recorded from the Yule River (Table 2) (Morgan et al. 2009). Consistent with other coastal systems in the Pilbara the lower reaches of the Yule River have a higher diversity of fish fauna than the middle or upper reaches. This is in part due to the presence of marine/estuarine species. The lower reaches act as a nursery for marine and estuarine species which are much less common in middle reaches and absent in the upper reaches. The lower reaches also provide habitat for all the freshwater species within the catchment whereas the headwaters or upper reaches support far fewer species.

The spangled perch (*Leiopotherapon unicolor*) and rainbow fish (*Melanotaenia australis*) are able to rapidly colonise temporary pools and shallower areas. These species are found throughout the system including minor tributaries and headwaters. Populations of these species in tributaries and headwaters are relatively dynamic across catchments and fluctuate with water availability.

Table 2 Fish species recorded for Yule River (Morgan et al. 2009)

Common name (Scientific name)	Freshwater/Marine	Recorded in 2009 survey
Barred grunter (<i>Amniataba percooides</i>)	freshwater	+
Indian short finned eel (<i>Anguilla bicolour</i>)*	freshwater	
Spangled perch (<i>Leiopotherapon unicolor</i>)	freshwater	+
Western rainbow fish (<i>Melanotaenia australis</i>)	freshwater	+
Bony bream (<i>Nematalosa erebi</i>)	freshwater	+
Hyrtl's tandan (<i>Neosilurus hyrtlui</i>)*	freshwater	
Giant herring (<i>Elops hawaiiensis</i>)	Marine/estuarine	+
Oxeye herring (<i>Megalops cyprinoides</i>)	Marine/estuarine	+
Milkfish (<i>Chanos chanos</i>)*	Marine/estuarine	
Sea mullet (<i>Mugil cephalus</i>)	Marine/estuarine	+
Barramundi (<i>Lates calcarifer</i>)*	Marine/estuarine	
Mangrove jack (<i>Lutjanus argentimaculatus</i>)*	Marine/estuarine	
Silver biddy (<i>Gerres subfasciatus</i>)*	Marine/estuarine	
Yellowtail trumpeter (<i>Amniataba caudavittata</i>)*	Marine/estuarine	
Striped butterflyfish (<i>Selenotoca multifasciata</i>)	Marine/estuarine	+
Empire gudgeon (<i>Hypseleotris compressa</i>)	Marine/estuarine	+

* Denotes species previously recorded from Yule River but not recorded during 2009 survey.

Other freshwater fish species are restricted to or have habitat preferences for deeper, more permanent pools which are largely restricted to middle and lower reaches. For example, the northern eel (*Anguilla bicolour*) and bony bream (*Nematolosa erebi*) are species that preferentially inhabit or are restricted to stable, larger, deeper pools (Table 3) (Beesley 2006; Morgan et al. 2009).

Pool stability, connectivity to the estuary and habitat complexity are important in maintaining species richness for fish (Beesley 2006). Permanent stable pools appear to have relatively stable fish communities. For example, Jelliabidina Pool (approximately 20 km upstream of the North West Coastal highway) had very similar fish assemblages in spring 2001 and spring 2008 (Morgan et al. 2009). The

maintenance of permanent pools and permanent habitat through the contribution of groundwater is considered to be vital in portions of Yule River on the coastal plain (Morgan et al. 2009).

The tolerance of fish to lower water quality, including levels of dissolved oxygen, differs between species. Buffering of extremes in levels of dissolved oxygen, temperature and salinity through connection to or contribution of groundwater is considered to be vital in maintaining fish populations, particularly for those species less tolerant to low DO levels (Morgan et al. 2009).

Reduction in water levels and reduction in pool size can lead to increased predation of fish by predatory fish and bird species. In-stream vegetation provides habitat for fish to evade predation and also supports more diverse macroinvertebrate assemblages which in turn sustain fish assemblages. The presence of riparian and in-stream vegetation (macrophytes) is considered important in maintaining habitat for fish.

All species, regardless of habitat preferences or life-history suitability to different zones within the river, rely on permanent refuge pools during periods of extended drought. Maintenance of suitable habitat within the context of a variable and dynamic climate is essential to maintaining fish populations within the catchment.

Table 3 Description of freshwater fish habitat requirements or preferences (Beesley 2006; Dames & Moore 1984; Pusey et al. 2004)

Species	General description and habitat preferences
Bony bream (<i>Nematalosa erebi</i>)	A widespread and common species of northern Australia and inland rivers of south-eastern Australia. A detritivore commonly found in deep water in permanent and temporary pools. Susceptible to low dissolved oxygen.
Eel (<i>Anguilla bicolor</i>)	A long-lived species that is estimated to reach maturity at 10 to 25 years. Once mature it migrates to the tropical deep sea to spawn. Only breeds once. Strongly restricted to permanent pools due to life-history requirement for long-term stability.
Hyrtl's tandan (<i>Neosilurus hyrtlii</i>)	Very widespread species found across northern Australia in a wide range of habitats. In the Fortescue it is mainly found in permanent pools.
Western rainbow fish (<i>Melanotaenia australis</i>)	Found throughout the Pilbara and Kimberley and into the Northern Territory in a wide range of habitats including shallow pools, streams and the margins of deep pools. Relatively tolerant of a range of environmental conditions.
Spangled perch (<i>Leiopotherapon unicolor</i>)	Very widespread and abundant across northern Australia in a wide range of habitats. Species is considered hardy and tolerant of a wide range of environmental conditions. It is often found in tributaries and upstream reaches.
Barred grunter (<i>Amniataba percoides</i>)	Widespread across northern Australia but not recorded from the De Grey River. Found in a wide range of habitats but may be susceptible to low dissolved oxygen concentrations.

Macroinvertebrates

The macroinvertebrate assemblages in the pools of the lower Yule River are similar in composition and abundance to those in similar systems in the Pilbara such as the lower Fortescue and lower De Grey (Pinder & Leung 2009; Maunsell 2003). Within the lower Yule pools sampled by Pinder and Leung (2009), Jelliabidina Pool had the highest total species richness.

Lee Lin Pool located at the northern end of the current borefield, was very small when sampled and highly impacted by cattle with the lowest species richness (Pinder & Leung 2009). The relatively high species richness in Jelliabidina Pool and comparatively low richness in Lee Lin Pool are likely to be due to the greater habitat diversity in Jelliabidina.

No species of restricted distribution were recorded in Yule River. The species recorded were generally common and recorded from similar systems across the Pilbara (Pinder & Leung 2009; Maunsell 2003).

This is consistent with the conclusions drawn by Pinder and Leung (2009) who found that the macroinvertebrate populations in pools on the coastal sections of Pilbara rivers sampled were not substantially different to those further inland and species were generally (with the exception of those associated with springs) unlikely to be restricted to particular pool or rivers.

Parameters such as maximum pool depth, sample depth, pool size and pool permanence did not explain differences in macroinvertebrate populations very well (Pinder & Leung 2009). That is, it was not possible to set firm thresholds to maintain macroinvertebrate populations using these parameters.

However, habitat diversity and the presence of macrophyte beds were strongly related to macroinvertebrate species richness with a greater habitat diversity supporting greater numbers of macroinvertebrates and a more diverse population (Pinder & Leung, 2009). In order to maintain populations, habitat diversity and macrophyte beds should be maintained.

Water quality

Water quality in pools on the Yule River is generally within the range of that recorded elsewhere in lowland/coastal sections of Pilbara rivers. The pools are slightly alkaline with a pH range of 7.6 – 8.9, moderately warm and moderately turbid (Morgan et al. 2009; Pinder & Leung 2009). The results are consistent with results of sampling conducted on the lower Fortescue and lower De Grey rivers.

Nutrient values were, however, elevated in the pools on Yule River compared to those sampled elsewhere by Pinder and Leung (2009). Levels of total nitrogen and total phosphorous were elevated in five of the six pools sampled on the lower Yule. No specific water quality guidelines exist for the Pilbara at present but as an indication, Pinder and Leung (2009) compared values recorded with ANZECC trigger values for tropical lowland rivers. Both TN and TP values were higher than the ANZECC trigger levels. Chlorophyll a values for pools on Yule River were also above default trigger values suggested by ANZECC/ARMCANZ (2000). The high chlorophyll values are likely to be related to high nutrient levels, the result of impacts from cattle.

Conservation significance

The pools of the Yule River are representative of aquatic ecosystems in coastal portions of other Pilbara rivers. The Yule River supports fish and macroinvertebrate assemblages that are well represented in similar systems.

Within the catchment, permanent pools maintain refuges important for freshwater fish species which can very rarely move between catchments.

While there are permanent pools upstream that in most years provide refuge from which populations can recolonise areas downstream (such as Jelliabidina and at the North West Coastal Highway), it is difficult to predict how the catchment scale population would cope with the loss of pools within the borefield area. Therefore, pools like Lee Lin Pool should be maintained within the context of the naturally dynamic climate.

2.4 Riparian ecosystems

The vegetation of the project area is consistent with previous regional assessments (Beard 1975; Van Vreeswyk et al. 2004) and work conducted by the department in similar systems across the Pilbara. Away from the river channel the vegetation is typically characterised as tussock or hummock grassland of *Triodia* spp. with mixed Acacia shrubs. Riparian and floodplain vegetation are typically woodlands of *Eucalyptus camaldulensis* and *E. victrix* with some *Melaleuca argentea* over mixed shrubs and grasses often dominated by *Cenchrus ciliaris* (Figure 9).

Previous baseline environmental surveys of the study area which paid particular attention to vegetation potentially impacted by a reduction in groundwater levels mapped seven main vegetation types within the study area (Figure 10) (Halpern, Glick & Maunsell 1998; Maunsell 2003).

Of these seven vegetation types, two communities restricted to the riparian zone are regarded as potentially groundwater-dependent:

- *E. camaldulensis* and *M. argentea* overstorey forest
- *E. camaldulensis* and *E. victrix* open woodland.



Figure 9 Riparian forest on the banks of the Yule River

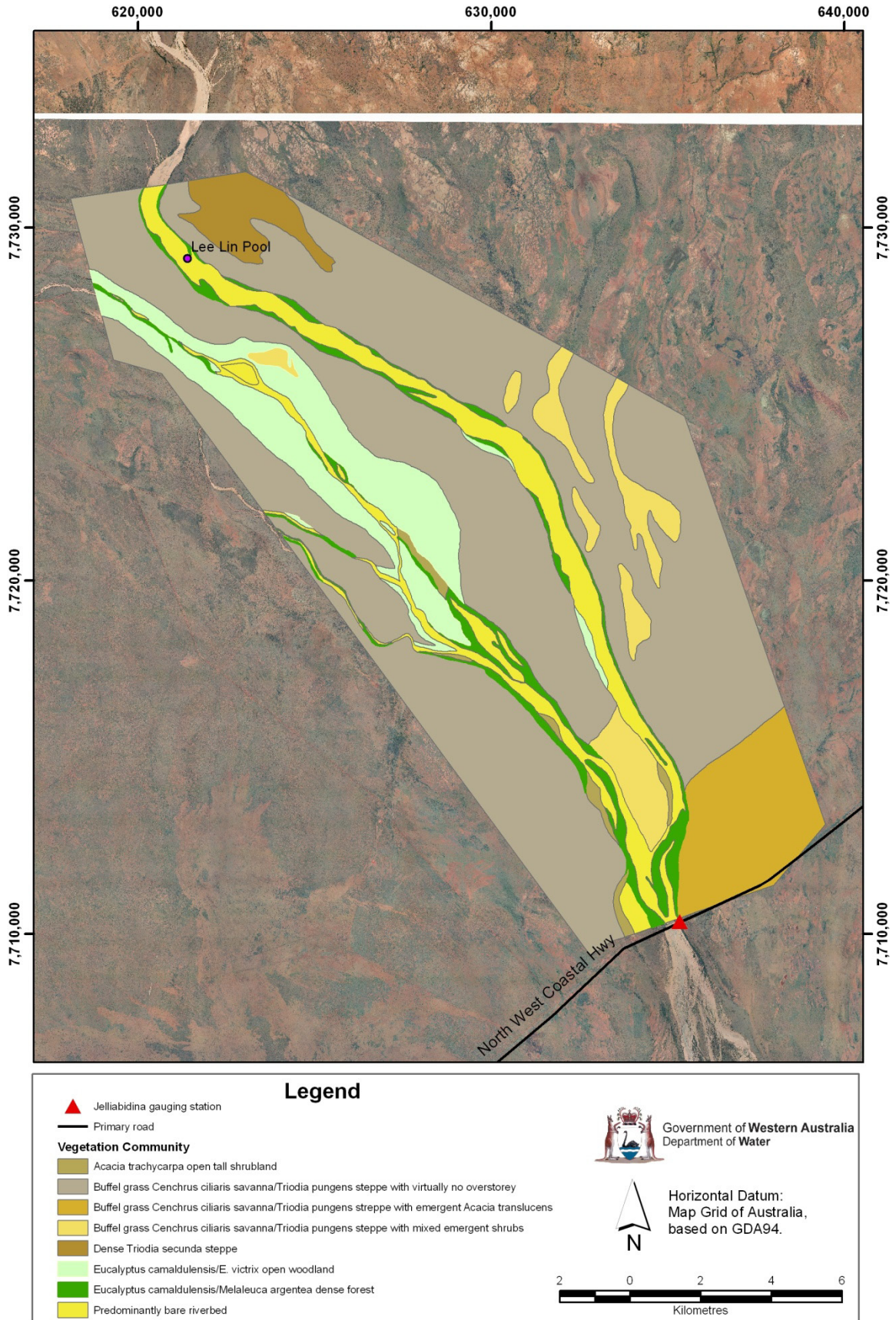


Figure 10 Vegetation map of lower Yule River

Conceptual link to groundwater

A conceptual model of groundwater dependency of riparian vegetation (Figure 11) along the Yule River study area has been developed using vegetation mapping, depth to groundwater mapping, analysis of hydrological conditions and comparison with similar systems elsewhere in the Pilbara.

The distribution of riparian vegetation generally coincides with areas with a shallow depth to groundwater and areas inundated during flooding. Flood flows are important triggers for recruitment, distribution of nutrients throughout the riparian zone and replenishment of soil water and/or bank storage in the unsaturated zone.

The shallow depth to groundwater in the alluvium and especially along the river provides areas where deep rooted vegetation can access groundwater. In periods between rainfall and/or surface flow recharging the unsaturated zone, deep rooted vegetation is accessing groundwater to satisfy, at least in part, its water requirements.

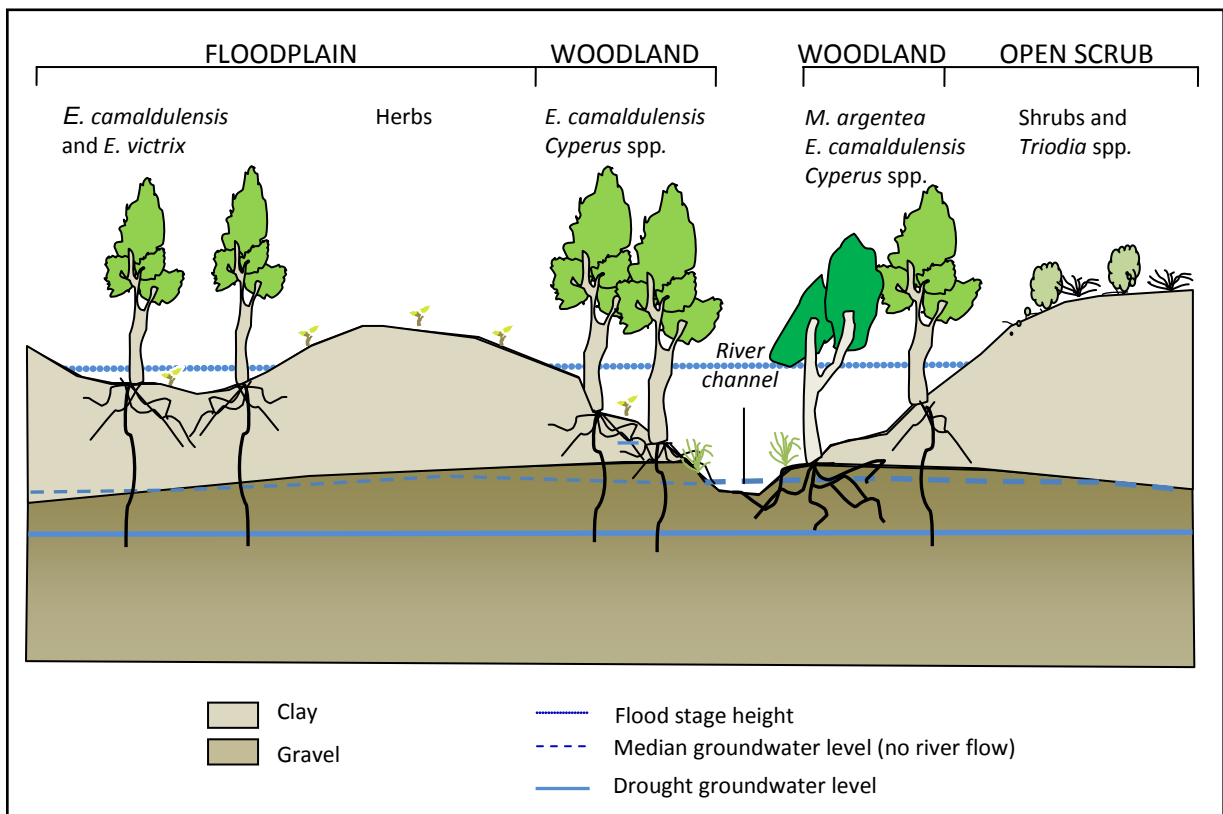


Figure 11 Conceptual groundwater dependence of riparian vegetation of Yule River

The distribution of vegetation communities identified as potentially groundwater-dependent (see above) generally supports this model when compared to the mapping of depth to groundwater (Figure 12). Average depths to groundwater along the course of the river are typically in the range of 0 – 4.0 m. Inter-annual fluctuations are in the order of 2.0 m with maximum declines from average groundwater level being about 2.5 m (that is, maximum depth to groundwater ~6.5 m).

At these shallow depths to groundwater, dominant tree species such as *E. camaldulensis* are highly likely to be accessing groundwater. The ability of the vegetation to adapt to groundwater decline beyond these groundwater levels is dependent upon water available in the unsaturated zone and species physiology. For example, how quickly their roots will grow, the maximum depths to which roots will grow and the species' ability to cope with lower water availability.

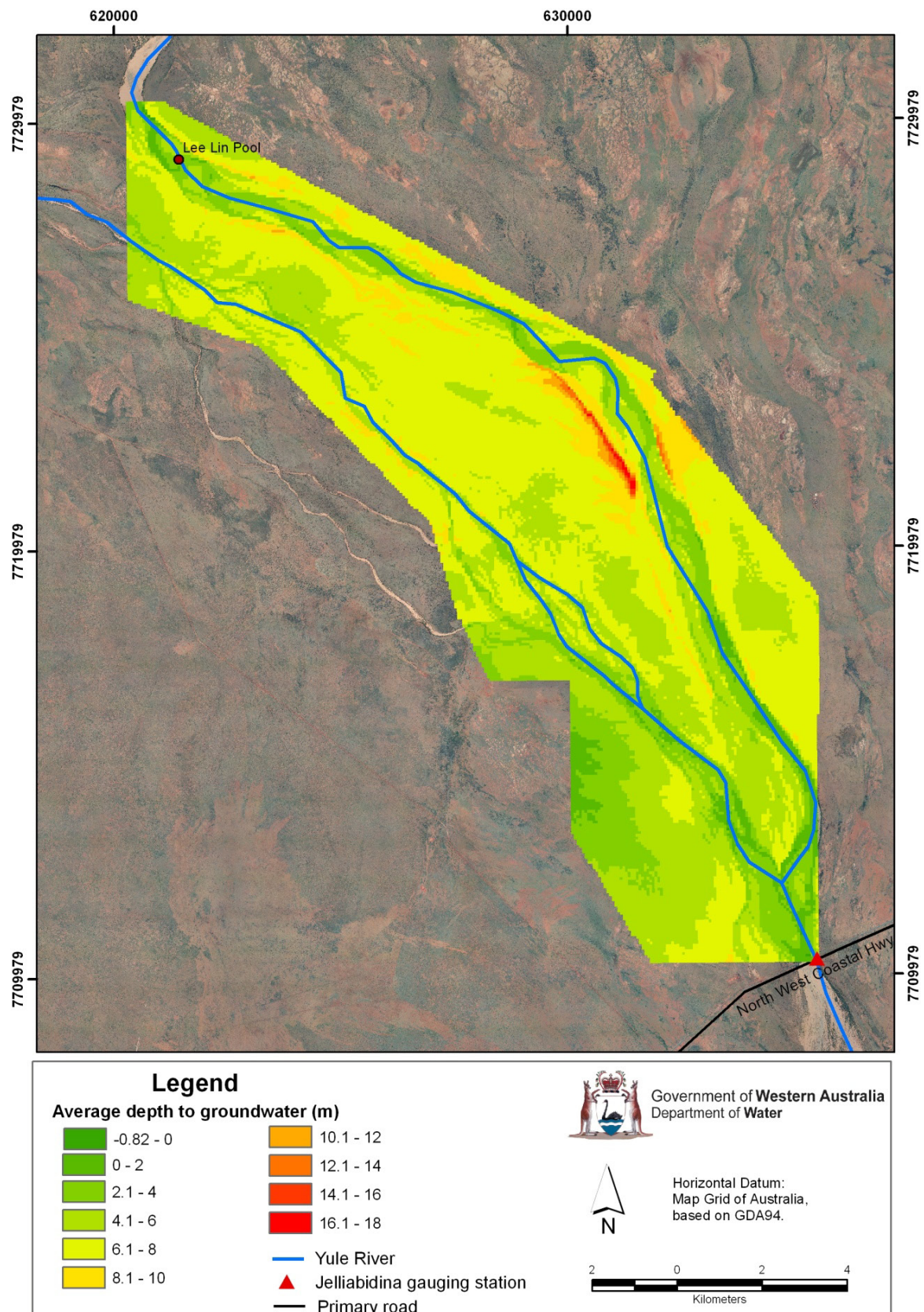


Figure 12 Depth to groundwater map of the lower Yule River

Ecology

The Department of Water has conducted further investigations to develop our understanding of the relationship between groundwater availability and vegetation occurrence. In addition to depth to groundwater mapping, this has included establishment and surveying of vegetation transects and development of ecological ranges for vegetation species (Loomes 2010).

The survey of six vegetation transects established as part of the Yule pumping trial recorded approximately 70 species of terrestrial vegetation from 24 families of vascular plants. The species and families recorded were consistent with previous surveys at the Yule (Halpern Glick Maunsell 1998; Maunsell 2003). No priority or declared rare species were recorded.

Groundwater-dependent species

A number of species in the Pilbara region are largely restricted to the relatively mesic environments typically associated with riparian zones and wetlands. Three of the most common in terms of distribution and dominance in riparian and floodplain communities are useful indicator species: *M. argentea*, *E. camaldulensis* and *E. victrix*. These species are the most studied of Pilbara riparian species in terms of plant water requirements.

Data from vegetation transects across the riparian zone adjacent to monitoring bores combined with similar transects at other sites across the Pilbara has allowed the development of a database of the ranges in depth to groundwater for common riparian species (Loomes 2010) (Table 4).

Previous studies indicate that the shallow planiform root system of *M. argentea* is adapted to areas where surface water is present or groundwater is very shallow (maximum 2.0 to 3.0 m below surface). The depth to water level ranges predicted from Department of Water transects were mostly consistent with association of *M. argentea* with areas of shallow watertable. The depth to groundwater predicted for the Yule Borefield ranges from 5.96 to 0.03 m below surface. The species is reported to have difficulty adjusting to short periods of dry conditions or reductions in water availability (Graham 2001; Strategen 2006).

E. camaldulensis is also commonly associated with shallow depths to groundwater (approximately 2.0 to 5.0 m; Table 4), but has been recorded where groundwater is up to 21 m below surface (Landman 2001). The bimorphic root system (surface lateral roots and a tap root) of this species enables it to access both groundwater and water held in the unsaturated, vadose zone above the watertable.

The tolerance of the species to changes in groundwater availability is likely to be strongly influenced by the local conditions. Although *E. camaldulensis* is reported to be capable of sinking new tap roots in response to groundwater decline, drawdown of > 10 m over a prolonged period may cause irreversible stress (Woodward-Clyde 1997). Deaths of *E. camaldulensis* have been recorded in the Millstream delta when the depth to groundwater increased beyond 5 m.

Although both *E. camaldulensis* and *M. argentea* are reported to be phreatophytic (Muir Environmental 1995), they will access surface water/floodwater where available (O'Grady et al. 2002).

E. victrix is commonly reported to be found in drier areas than *E. camaldulensis* and *M. argentea* (Muir Environmental 1995). Although considered to be tolerant of long periods of drought and less susceptible to drawdown, this species appears sensitive to prolonged inundation (Strategen 2006).

Table 4 Ecohydrological ranges for dominant riparian tree species (for water level data 2004-2009)

Species	Absolute range in Yule monitoring bores (m below ground surface)	Regional absolute range (m below ground surface)	Regional mean range (m below ground surface)
<i>Eucalyptus camaldulensis</i>	9.21 m to 0.51 m	9.21 m to -1.56 m	4.92 m to 1.81 m
<i>Eucalyptus victrix</i>		7.47 m to -1.56 m	4.03 m to 2.18 m
<i>Melaleuca argentea</i>	5.96 m to 0.03 m	7.71 m to -1.22 m	3.87 m to 1.15 m

These results are consistent with the comparison between the depth to groundwater and vegetation community mapping discussed above. The distribution of vegetation in relation to depth to groundwater provides an indication of the magnitude of change or range in depth to groundwater which species may be able to tolerate. However, the rate of water level (or water availability) change, the frequency of low groundwater levels and the duration of periods of low groundwater levels are also important considerations. All of these factors will affect:

- the vigour of established vegetation
- the resilience of vegetation to recover from drought periods
- the recruitment and establishment of new individuals.

Conservation significance

Riparian vegetation performs important ecosystem services such as maintaining bank stability for flood and sedimentation mitigation, providing an important source of carbon for instream ecosystems, potentially supplementing productivity in adjacent areas during droughts and maintaining water quality in the pools and aquifer through biofiltration. Riparian ecosystems also provide habitat to terrestrial species particularly bird and bat species and act as corridors for fauna movement.

Riparian vegetation at the Yule study area is very similar to vegetation communities along lowland or coastal plain portions of other Pilbara rivers such as the De Grey, Turner and Sherlock. Within the study area it has also been noticeably degraded through grazing and weed invasion.

Given the degraded nature of the ecosystems and absence of any threatened flora or species the conservation significance of the riparian ecosystems is considered to be locally significant. The local significance is recognising the restricted nature of riparian ecosystems across the Pilbara and their importance in terms of ecosystem services.

2.5 Fauna

The river pools and riparian ecosystems of Yule River provide habitat for terrestrial fauna, including reptiles, mammals and birds. Fifty-three bird species were recorded from the river and riparian ecosystems (in a combined survey of the lower Yule and lower De Grey rivers), including numerous waterbirds which utilise river pools when available (HGM 1998). The highest rates of individuals were recorded from large pools (HGM 1998). The riparian ecosystems provide important habitat including roosting habitat for waterbirds.

Two threatened bird species were recorded inhabiting the riparian forest (HGM, 1998): the Schedule 1 Grey Falcon *Falco hypoleucos* and the Schedule 4 Peregrine Falcon *Falco peregrinus*. In general, bird fauna relying on the riparian vegetation for feeding, breeding and habitat are thought to be sensitive to groundwater regime change (Outback Ecology Services 2004). Although they are mobile and can relocate to other suitable areas, there is the potential for over-population of habitats and overall reduction in carrying capacity.

Seventeen reptile species were recorded in surveys of the Yule and De Grey (HGM, 1998). An additional 79 species could potentially occur within the study area based on expected distributions and habitat requirements. Ten species were expected to utilise river pool ecosystems and 44 potentially occur within the riparian ecosystems including the Schedule 4 Woma Python (*Aspidites ramsayi*) and the Schedule 1 Pilbara Olive Python (*Liasis olivaceus*).

Large monitor species such as the Black-headed monitor (*Varanus tristis*) could be expected to drink from river pools and python species may be attracted to pools to hunt for prey. Many of the smaller reptiles recorded or expected to occur in the riparian ecosystems utilise trees for habitat (arboreal) or are found in leaf litter common in this habitat.

The river pool and riparian ecosystems are also potentially habitat to sixteen native mammals including 10 species of bats (HGM 1998). Riparian woodlands with permanent pools provide important habitat for bats which forage for insects attracted to river pools and some of which roost in the riparian woodland (McKenzie & Bullen 2009).

Although most species would not be directly affected by groundwater decline, any loss of habitat may have an indirect impact.

2.6 Aquifer ecosystems

Aquifers in the Pilbara region have been demonstrated to support diverse stygofaunal assemblages including porous alluvial aquifers (Eberhard et al. 2005). Coastal low lying aquifers, such as the Yule alluvial aquifer, were found to have assemblages distinct from upland sites (Reeves et al. 2007). There is, however, little specific information about the stygofauna of the Yule alluvial aquifer and sampling from this aquifer appears to have been limited.

This lack of specific information on the stygofauna of the study area and in general a lack of knowledge of stygofauna ecology within aquifers and tolerances to water level changes means there is insufficient information to develop a conceptual model of stygofauna groundwater dependence in the lower Yule. It is likely that they are responsive to changes in both the level and the quality of the groundwater. However, information on habitat requirements, in terms of different parts of aquifers, and tolerances of differing water qualities, is very limited and prohibits the determination of thresholds or limits of acceptable change.

3 Existing monitoring and pumping trial

Ongoing vegetation monitoring is undertaken by the Water Corporation as part of their licence requirements for the Yule Borefield. The objective of the program has been to monitor the potential impacts of groundwater abstraction on groundwater-dependent vegetation. Until recently the monitoring had largely applied a qualitative set of condition ratings based on the visual appearance of the vegetation. Unfortunately, this monitoring has yielded little useful information to assist management of the resource or improve our understanding of the ecosystem links to groundwater.

As a condition of increasing the licenced allocation available to the Water Corporation from 6.5 to 8.5 GL/yr, the Department of Water required that the Water Corporation complete a pumping trial for the resource. The aim of the trial was to test the resource's capacity to provide the increased allocation while maintaining adequate provision of water to dependent ecosystems.

The trial commenced late in 2008 as a collaborative exercise between the Water Corporation, Department of Water, University of Western Australia and University of Sydney. Pumping at a rate equivalent to 8.5 GL/yr commenced in April 2009 following a recharge event in February and a period of no pumping during March. Due to production bore and water main failures, the pumping rate was unable to be maintained throughout 2009. However, the trial continued and with the absence of a recharge event during the 2009–10, wet season aquifer levels exceeded 5-year low levels.

Monitoring completed as part of the trial has been extensive and included:

- continuous (15 min) logging of groundwater levels in monitoring bores
- soil moisture (neutron probe) and soil characterisation
- continuous logging of sapflow in *E. camaldulensis*, *E. victrix* and *M. argentea* at control and impact sites
- isotopic analysis of soil water, groundwater and vegetation samples to confirm the sources of water accessed by vegetation and the physiological responses of different species
- measurements of leaf water potentials, stomatal conductance and leaf gas exchange collected during four intensive campaigns across the project to date
- leaf or crown density measured at control and impact sites once during the trial in May 2010.

Only preliminary results are available from the trial at this stage but it is anticipated that these will be important in refining our estimation of ecological water requirements for the riparian vegetation of the Yule system.

4 Summary of ecological values

This study has identified three groundwater-dependent ecosystems in the lower Yule River study area, that is, riverine, riparian vegetation and aquifers. The components of these ecosystems, their conservation significance and their links to the aquifer have been described. Their ecological values are summarised in this section using the categories defined by Horwitz and Rogan (2003):

- biotic values – key species and/or communities (including rare or threatened biota)
- functional values – ecosystem services that maintain habitat for dependent populations or species
- land/waterscape values – contributions to landscape connectivity, habitat provision, representativeness and ecosystem resilience to disturbance.

Cultural values will be discussed in a separate report.

Riverine ecosystems

Recent pool mapping has identified two permanent pools, seven semi-permanent pools and five intermittent pools. These pools are of varying size and depth and provide a range of habitats.

Biotic values

The lower Yule River pools support flora and fauna consistent with similar coastal portions of rivers in the Pilbara.

Functional values

The pools maintain key ecological processes important to habitat provision including:

- water quality
- nutrient cycling associated with productivity
- decomposition of organic carbon required for food webs.

Land/waterscape values

The pools hold a number of broader scale and regional values. These include:

- connectivity – hydrological linking of pools plays an important role in the natural functioning of a major wetland system
- habitat provision – pools act as a drought refuge for native flora and fauna
- resilience – the health/condition of the wetlands allow them to absorb seasonal changes (drought/flood).

Riparian vegetation ecosystems

The pools and shallow groundwater adjacent to the lower Yule River support riparian vegetation, with groundwater sustaining deep rooted vegetation at least in part.

Biotic values

Although impacted by grazing the riparian zone contains eucalypt woodlands including vegetation species that are restricted to this type of habitat. It also provides habitat to terrestrial, bird, reptile and mammal fauna.

Functional values

The riparian vegetation maintains key ecological processes important to habitat provision including:

- maintenance of water quality through biofiltration
- soil/bank stabilisation
- supports food webs.

Landscape values

Riparian vegetation of Yule River supports the following landscape values:

- connectivity – vegetation provides corridors allowing fauna to move between habitats (for example, pools)
- habitat provision – vegetation provides direct habitat and refuge habitat during drought
- representativeness – vegetation communities are examples of riparian ecosystems of the region
- resilience – the health/condition of vegetation allow it to absorb seasonal changes (drought/flood).

Aquifer ecosystems

Biotic values

Aquifers in the Pilbara region have been associated with diverse subterranean fauna and are recognised as being important for the conservation of subterranean biodiversity (Eberhard et al. 2005). Coastal low lying alluvial aquifers such as the Yule River aquifer have been found to provide habitat for assemblages distinct from upland sites. The limited information available about stygofauna from the Yule River means an assessment of the biotic values is difficult. However, it is likely that the aquifer supports an assemblage comparable in diversity and abundance to similar systems.

Overall ecological value

The ecosystems supported by Yule River and the associated alluvial aquifer are considered to be of local conservation significance. The ecosystems are in general consistent with or comparable to those replicated on similar coastal plain sections of rivers elsewhere in the Pilbara. Riparian vegetation and river pool ecosystems within the study area have been impacted by grazing and weed invasion. Ecosystem functional values and landscape values are likely to be partially disrupted due to degradation.

5 Ecological management objectives

Formulating management objectives for a water resource system is an integral component of the allocation planning process. Objectives presented in this report are based solely on ecological values and issues identified during the review of ecological information. The objectives set here will frame the development of ecological water requirements. In developing an allocation plan, management objectives will also consider social, cultural and economic values.

This review has identified groundwater-dependent ecosystems of three different types associated with the lower Yule River – riverine, riparian vegetation and aquifer ecosystems. Management objectives are required to ensure that the functionality of these ecosystems is maintained and considered in future water resource planning.

The overall objective to guide the determination of ecological water requirements for the lower Yule River has been developed with the variable climate and the system's role as a refuge in mind. The broad objective for the EWR is to:

maintain the function, extent and condition of groundwater-dependent ecosystems in the context of a naturally variable climate.

This objective will be supported through the development of practical targets and performance indicators to ensure key ecosystem components and processes identified in this report are maintained. With this in mind, management objectives and parameters against which water requirements will be set and then measured have been identified.

The management objectives have focused on the parts of the hydrological regime that can be managed through water resource management and in particular through the management of groundwater abstraction.

Large flood events are important to Pilbara river systems such as the Yule River in a number of ways including:

- recharging groundwater
- triggering recruitment of riparian vegetation and movement of aquatic fauna
- redistributing carbon and nutrients within and around river and floodplain systems
- geomorphological processes in river channels.

However, large flood events are not influenced through the management of groundwater abstraction and therefore have not been included. That is, objectives to maintain the ecological functions performed by high flow events have not been developed as part of this process.

The determination of EWRs also does not include a separate consideration of water requirements for stygofauna due to the lack of knowledge on the habitat requirements for this group. It is anticipated that the water requirements determined

for other dependent ecosystems will, by maintaining aquifer levels within the range of tolerance of riparian vegetation and wetlands, also maintain adequate habitat for stygofauna within the aquifer.

Riverine ecosystems

The riverine ecosystems have been demonstrated to support a diverse aquatic biota with specific habitat requirements. River pools are also considered important in terms of supporting avifauna and other terrestrial fauna that are associated with this habitat. The role of permanent pools as a refuge for aquatic and terrestrial biota, particularly during drought periods, is considered particularly important in maintaining ecosystem processes and systems.

Groundwater contributions to the river pools are considered to be most critical during periods when surface water inputs are negligible.

To maintain the extent and diversity of river pool habitats the following management objectives need to be met within the context of a dynamic climate.

- 1 Maintain areas of permanent pools consistent with regional seasonality to maintain pool stability and as refuges for fish and other fauna.
 - a Parameters
 - (i) minimum aquifer level in the vicinity of river pools to maintain discharge/surface expression of groundwater
- 2 Maintain sufficient areas of inundated shallow macrophyte habitat available for macroinvertebrates, small-bodied fish and juveniles of large-bodied fish
 - a Parameters
 - (i) minimum pool depth and area to provide macrophyte habitat
 - (ii) minimum aquifer level to ensure sufficient contribution to pools
- 3 Maintain sufficient deeper habitat permanently inundated and available for mature and large-bodied fish.
 - a Parameters
 - (i) minimum pool depth and area to provide deep pool habitat
 - (ii) minimum aquifer level to ensure sufficient contribution to pools
- 4 Maintain sufficient depth in deeper pools to ensure dissolved oxygen levels do not reduce to anoxia.
 - a Parameters
 - (i) minimum aquifer level to ensure sufficient contribution to pools
 - (ii) suitable water quality in the aquifer
 - (iii) suitable pool water quality.

Riparian vegetation ecosystems

Riparian vegetation provides habitat and habitat corridors for avifauna and other terrestrial fauna. It is also important in maintaining waterway condition and

functionality. Riparian vegetation also contains species and represents habitat types that are restricted in distribution across the region.

Based on the conceptual model discussed previously the water requirements of the riparian vegetation are met at least in part by access to groundwater through maintenance of local watertables or soil moisture. During drought periods groundwater contributions to maintenance of vegetation is critical as it is likely to be the only source of water available.

The magnitude and rate of water level (or water availability) change, the frequency of low water levels and the duration of periods of low water levels are all likely to be important considerations for phreatophytic vegetation. All of these factors will affect:

- the vigour of established vegetation
- the resilience of vegetation to recover from drought periods
- the recruitment and establishment of new individuals.

To maintain the extent and diversity of riparian habitats, the following management objective needs to be met within the context of a dynamic climate and consistent with regional seasonality.

- 5 Sufficient water availability for groundwater-dependent vegetation, during periods of no surface water inputs, as provided by maintenance of watertable levels that are accessible to phreatophytic vegetation.
 - a Parameters
 - (i) minimum depth to watertable in areas of riparian vegetation
 - (ii) rate of change in groundwater levels in local bores
 - (iii) frequency and duration of periods of 'low' groundwater levels.

5.1 Ecological water requirements

The EWRs for the lower Yule River will be revised using the objectives and conceptual models presented here, supported by the recently completed numerical groundwater model (MWH 2010).

The ecological water requirements will be related to easily measured parameters such as bore water levels. The ecological water requirements will be a key input into the determination of an allocation limit for the system which will also consider the social and cultural water requirements and consumptive demand for water. A revised management and monitoring framework will be developed and the operating rules for the resource reviewed. The aim of estimating the ecological water requirements is to define rules to ensure sustainable management of the resource and have clearly set out links between monitoring, management and the understanding that underlies the ecological water requirements.

Glossary

Abstraction	The permanent or temporary withdrawal of water from any source of supply, so that it is no longer part of the resources of the locality.
Aquifer	A geological formation or group of formations capable of receiving, storing and transmitting significant quantities of water. Usually described by whether they consist of sedimentary deposits (sand and gravel) or fractured rock.
Biodiversity	Biological diversity or the variety of organisms, including species themselves, genetic diversity and the assemblages they form (communities and ecosystems). Sometimes includes the variety of ecological processes within those communities and ecosystems.
Biomass	The total amount of living material in a given habitat, population or sample. Specific measures of biomass are generally expressed in dry weight (after removal of all water from the sample) per unit area of land or unit volume of water.
Biota	The living organisms occupying a place together, for example, marine biota, terrestrial biota.
Detritivore	An organism that feeds on and breaks down dead plant or animal matter, returning essential nutrients to the ecosystem.
Ecological water requirement	Water regime needed to maintain the ecological values (including assets, functions and processes) of water-dependent ecosystems at a low level of risk.
Ecosystem	A community or assemblage of communities of organisms, interacting with one another and with the specific environment in which they live, for example, a lake. Includes all the biological, chemical and physical resources and the interrelationships and dependencies that occur between those resources.
Environment	Living things, their physical, biological and social surroundings, and the interactions between them.
Flow	Streamflow in terms of m ³ /s, m ³ /d or ML/a. May also be referred to as discharge
Food web	A series of organisms related by predator–prey and consumer–resource interactions; the entirety of interrelated food chains in an ecological community.
Groundwater	Water that occupies the pores and crevices of rock or soil beneath the land surface.
Groundwater-dependent ecosystems	An ecosystem that depends on groundwater for its existence and health.
Habitat	The area or natural environment in which an organism or population normally lives. A habitat is made up of physical factors such as soil, moisture, range of temperature and availability of light as well as biotic

	factors such as the availability of food and the presence of predators.
Hydrogeology	The hydrological and geological science concerned with the occurrence, distribution, quality and movement of groundwater, especially relating to the distribution of aquifers, groundwater flow and groundwater quality.
Invertebrate	An animal without a backbone.
Life cycle	The series of changes in the growth and development of an organism from its beginning as an independent life form to its mature state in which offspring are produced.
Macrophyte	A plant, especially an aquatic or marine plant, large enough to be visible to the naked eye.
Phreatophyte	A plant (often relatively deep rooted) that obtains water from a permanent ground supply or from the watertable.
Planiform	Having a flattened shape.
Stygofauna	Fauna that live within groundwater systems, such as caves and aquifers, or more specifically small, aquatic groundwater invertebrates.
Surface water	Water flowing or held in streams, rivers and other wetlands on the surface of the landscape.
Wetland	Areas that are permanently, seasonally or intermittently waterlogged or inundated with water that may be fresh or saline, flowing or static, including areas of marine water of which the depth at low tide does not exceed 6 m.

References

- ARMCANZ/ ANZECC (2000) Australian and New Zealand Guidelines for Fresh and Marine Water Quality. National Water Quality Management Strategy Paper No 4. Canberra, Australian and New Zealand Environment and Conservation Council and Agricultural and Resource Management Council of Australia and New Zealand
- Beard, J. (1975) Vegetation Survey of Western Australia: Pilbara. 1:1,000,000 Vegetation Series - Explanatory Notes to Sheet 5. Perth, University of Western Australia Press.
- Beesley, L. (2006) Environmental Stability: Its Role in Structuring Fish Communities and Life History Strategies in the Fortescue River, Western Australia. *School Of Animal Biology*. Perth, University of Western Australia.
- Braimbridge, M., Antao, M. & Loomes, R. (2010) Groundwater-dependent ecosystems for Millstream: ecological values and issues. *Environmental water report series, Report no. 13*. Department of Water, Government of Western Australia.
- Bunn, S. E., Thoms, M. C., Hamilton, S. K. & Capon, S. J. (2006) Flow variability in dryland rivers: boom, bust and the bits in between. *River Research and Applications*, 22, 179-186.
- Dames and Moore (1984) Millstream water management programme. Perth, Public Works Department.
- Douglas, M. M., Bunn, S. E. & Davies, P. M. (2005) River and wetland food webs in Australia's wet-dry tropics: general principles and implications for management. *Marine and Freshwater Research*, 56, 329-342.
- Eberhard, S. M., Halse, S. A. & Humphreys, W. F. (2005) Stygofauna in the Pilbara region, north-west Western Australia: a review. *Journal of the Royal Society of Western Australia*, 88, 167-176.
- Graham, J. (2001) The root hydraulic architecture of *Melaleuca argentea*. University of Western Australia.
- Haig, T. (2009) The Pilbara Coast Water Study. Perth, Department of Water, Hydrogeological record series, Report HG34.
- Halpern Glick Maunsell (1998) East Pilbara Water Supply Augmentation: Biological Assessment. Prepared for the Water Corporation. Perth, HGM.
- Horwitz, P. & Rogan, R. (2003) Ecological Values of Aquatic Macroinvertebrates from Wetlands of the Gnangara and Jandakot Mounds. Joondalup, Centre for Ecosystem Management, Edith Cowan University.
- Landman, P. (2001) Ecology and physiology of eucalypts and acacias in the Pilbara, WA. Botany Department. Crawley, University of Western Australia.
- Loomes, R. (2010) Determining water level ranges of Pilbara riparian species. *Environmental water report series, Report no. 17*. Department of Water, Government of Western Australia.

- Loomes, R. & Braimbridge, M. (2010) Lower De Grey River: ecological values and issues. *Environmental water report series, Report no. 12*. Department of Water, Government of Western Australia.
- Mausnell (2003) Ecological and social water requirements and impacts on other commercial users study - Yule Borefield, Port Hedland. Report prepared for the Water Corporation.
- McKenzie, N. L. & Bullen, R. D. (2009) The echolocation calls, habitat relationships, foraging niches and communities of Pilbara microbats. *Records of the Western Australian Museum, Supplement 78*, 123-155.
- Morgan, D., Ebner, B. & Beatty, S. (2009) Fishes in groundwater dependent pools of the Fortescue and Yule rivers; Pilbara, Western Australia. Freshwater fish group, Center for fish and fisheries research, Murdoch University.
- Muir Environmental (1995) Ecology of Millstream Delta vegetation: information review and interpretation. Perth, Water Authority of Western Australia.
- MWH (2010) Development of a subregional scale numerical groundwater model of the lower Yule catchment. Report prepared for the Department of Water.
- O'Grady, A. O., Eamus, D., Cook, P., Lamontagne, S., Kelly, G. & Hutley, L. (2002) Tree Water Use and Sources of Transpired Water in Riparian Vegetation Along the Daly River, Northern Territory. Canberra Department of Environment and Heritage.
- Outback ecology services (2004) Bulgarene Borefield (De Grey River) Port Hedland Water Supply - Terrestrial Fauna Study. Perth.
- Pinder, A. M. & Leung, A. (2009) Conservation status and habitat associations of aquatic invertebrates in Pilbara coastal river pools, report to the Department of Water. Department of Environment and Conservation, Science Division.
- Pusey, B., Kennard, M. & Arthington, A. (2004) *Freshwater Fishes of North-Eastern Australia*, Antahn, Qld, CSIRO Publishing.
- Reeves, J. M., De Deckker, P. & Halse, S. A. (2007) Groundwater ostracods from the arid Pilbara region of northwestern Australia: distribution and water chemistry. *Hydrobiologia*, 585, 99-118.
- Strategen (2006) Draft Bulgarene Borefield (De Grey River) Vegetation Sensitivity Study. A report to the Water Corporation. Perth.
- Van Vreeswyk, A. M. E., Payne, A. L., Leighton, K. A. & Hennig, P. (2004) An inventory and condition survey of the Pilbara region, Western Australia. *Technical Bulletin No. 92*. Department of Agriculture, Western Australia.
- Water Corporation (2008) Port Hedland regional water supply water resource management operation strategy. Infrastructure Planning Branch July 2008.
- Woodward-Clyde (1997) Newman Satellite Development of Orebody 23 Below the watertable: Consultative Environmental Review. Unpublished report prepared for BHP Iron Ore. Perth.

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