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

Ecological water requirements of the

Yule River aquifer

Looking after all our water needs

Environmental water report series
Report no. 24
September 2013

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October 2013

ISSN 1833-6582 (print)
ISSN 1833-6590 (online)

ISBN 978-1-921992-31-5 (print)
ISBN 978-1-921992-32-2 (online)

Recommended reference

Braimbridge, M & Loomes, R 2013, *Ecological water requirements of the Yule River aquifer*, Environmental water report series, report no. 24, Department of Water, Perth.

Acknowledgements

The Department of Water thanks the following for their contribution to this publication.

This report was written by Mike Braimbridge and Robyn Loomes. The authors would also like to thank Michelle Antao for her input and Adrian Goodreid and Rob Donohue for comments on drafts. The report includes summarised results from the Yule Pumping trial and the authors would therefore like to thank Sebastian Pfautsch, Pauline Grierson, Andrew Jones, Jacquie Bellhouse, Elizabeth Mclean, Tarryn Turnbull, Mark Adams, Kel Baldock and Scott Walker.

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Disclaimer

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Summary

The ecological water requirement (EWR) has been described for groundwater-dependent ecosystems on the lower Yule River alluvial aquifer.

The EWR has been described by determining thresholds for a set of hydro-ecological linkages. The linkages were developed from conceptual models of links between groundwater-dependent ecosystems and the groundwater regime completed in 2010 as Stage I of this project (Braimbridge 2010).

We have used the results of an approximately 2.5 year groundwater pumping trial to support the determination of thresholds for riparian vegetation, the main groundwater-dependent ecosystem at the site. Thresholds for river pools, the other main ecosystem for which EWR have been described, were set through analysis of historical water regimes and with results of studies in similar environments.

The EWR for the lower Yule has been described to incorporate inter-annual variation in water availability (for ecosystems) that is a characteristic of the Yule River aquifer and other alluvial aquifers in the Pilbara region. River flow, which is the main source of recharge to the alluvial aquifer, has been used to incorporate this variability through the development of ‘recharge classes’ based on the correlation between river flow and groundwater levels.

This approach describes the EWR in a way that reflects the variable water regime of the site, incorporating periods of drought and increased stress on ecosystems and sporadic periods of high water availability and productivity.

The approach developed will also enable variability in thresholds to be incorporated into a management framework for the water resource, including in any applicable water allocation plans (described elsewhere).

1 Introduction

Ecological water requirements (EWR) are the water regimes required to maintain dependent ecosystems at a low level of risk (Water and Rivers Commission 2000). They are a key consideration in the water allocation process, which aims to balance the consumptive demand for water with the needs of ecosystems and other in-situ values.

The Department of Water has developed an allocation plan for the Pilbara groundwater area that includes the Yule River alluvial aquifer. The description of the EWR as reported here has supported the revision of the aquifer's allocation limit.

The federal government's *Water for the Future program* partially funded the investigative work of this project.

1.1 Purpose of this document

This document describes the EWR for groundwater-dependent ecosystems (GDE) associated with the Yule alluvial aquifer.

Ecological water requirements have been determined for river pool and riparian vegetation ecosystems.

This report provides a brief description of the project area, including hydrology, hydrogeology and ecosystems summarised from earlier stages of this project (refer to Braimbridge 2010 *Yule River – ecological values and issues* for more detail). The key outputs presented in this report are the description of the EWR and the methods used to determine them.

1.2 Project stages

The ten steps we followed to describe the EWR and how we will manage impacts on dependent ecosystems are shown in Table 1.

Steps 1 to 4 were completed in 2010 as the first stage of the project and are summarised in the values and issues report (Braimbridge 2010). In this stage we identified GDEs, developed conceptual models of their interaction with groundwater and identified hydro-ecological linkages. The linkages describe the critical parts of the water regime that maintain important ecological features and processes.

We have used the linkages as the ecological objectives for describing the EWR for the system.

Table 1 Steps for setting and implementing EWRs

Steps	Reporting stage
1. Identify potential GDE.	Stage I: Values and Issues paper (Complete – Braimbridge 2010)
2. Assess conservation significance of GDE.	
3. Develop conceptual models to describe links between groundwater and ecosystems.	
4. Identify key components of the groundwater regime that support key components and processes for GDE–hydro-ecological linkages.	
5. Select representative sites (Section 3.3).	Stage II: EWR report
6. Determine thresholds for ecosystem response to changed water availability (Section 4).	
Develop recharge classes (Section 5).	
7. Develop EWR for sites – Apply thresholds to site-specific data and incorporate recharge classes.	
8. Determine EWP (environmental water provision), allocation limit and operating rules.	Allocation plan and supporting documents (2013)
9. Develop a monitoring program.	Operating strategy and allocation plan monitoring program (in preparation)

During this project we developed an approach to describing the EWR that takes into account the variable nature of the climate and groundwater regime in the Yule aquifer. This approach includes 'recharge classes' – a way of specifying a variable EWR linked to climate, which has allowed us to vary the EWR depending on annual recharge to the aquifer.

How the thresholds and recharge classes were developed and are to be applied is detailed in following sections.

1.3 Study area

The project area is the section of the Yule River downstream of the North West Coastal Highway approximately 40 km west of Port Hedland (Figure 1). This area is part of an operating pastoral lease, Mundabullangana Station.

This section of the Yule River overlies an alluvial aquifer that has been used as a water source to supply Port Hedland since 1967.

Climate

The Pilbara region's climate is classified as semi-arid to arid with hot, dry conditions most of the year. Average annual evaporation (greater than 3000 mm/yr) greatly exceeds rainfall (Table 2).

Rainfall is mainly associated with summer/autumn cyclones and thunderstorms with approximately 70% falling during the wet season between November and March. Average total annual rainfall recorded in the Yule study area is low (318 mm), highly episodic and variable between years.

Table 2 Yule rainfall data summary (1900-2012)

Rainfall statistic	Mundabullangana (BoM station 004024)
Average annual rainfall	318 mm
Median annual rainfall	297 mm
Maximum annual rainfall	778 mm
Minimum annual rainfall	6 mm

Hydrology

The Yule River is approximately 217 km long and has a catchment area of 12 000 km^2 draining from the Chichester and Mungaroona ranges to the coast. The Jelliabidina gauging station (Jelliabidina Well – WIN reference number 709005) is located where the North West Coastal Highway crosses the river.

The Yule River is an ephemeral system characterised by highly variable and unpredictable flow (Figure 2). High flows typically occur between December and April, matching the seasonal distribution of rainfall (Figure 3). The maximum annual discharge of 1823 GL was recorded in 2000.

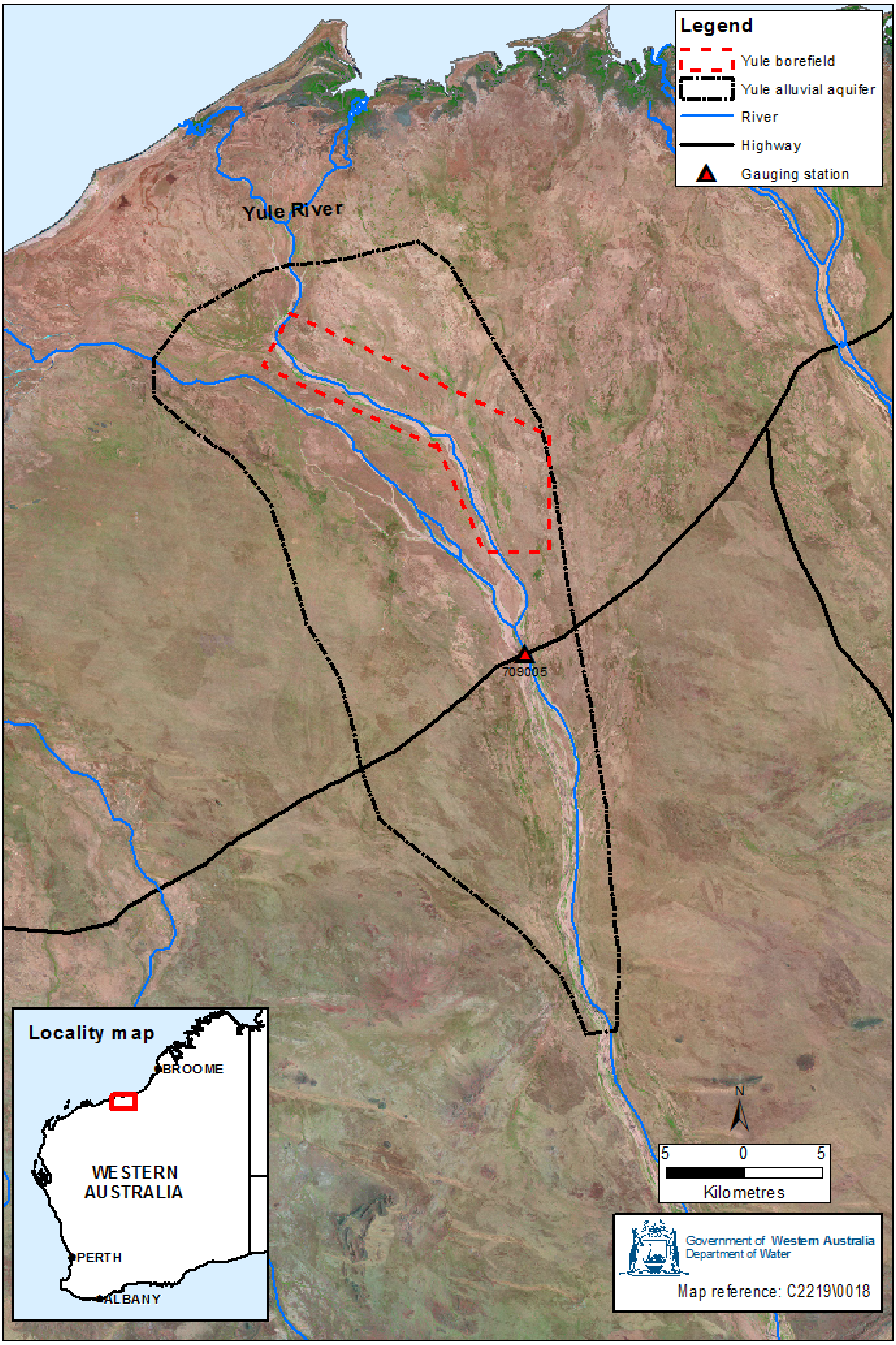


Figure 1 Lower Yule River study area

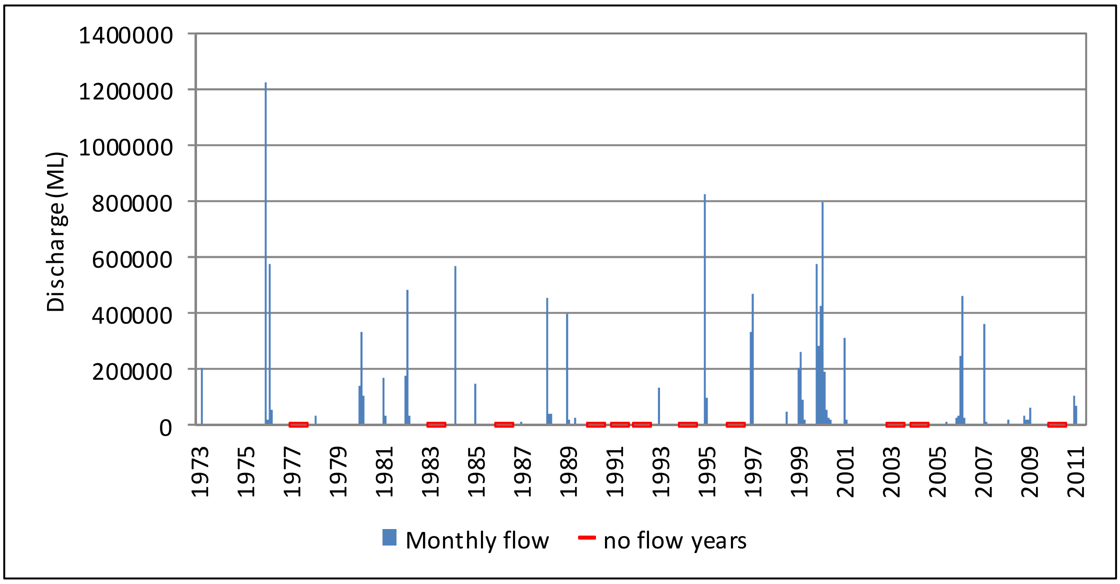


Figure 2 Total monthly discharges for the Jelliabidina Well gauging station (1973–2011)

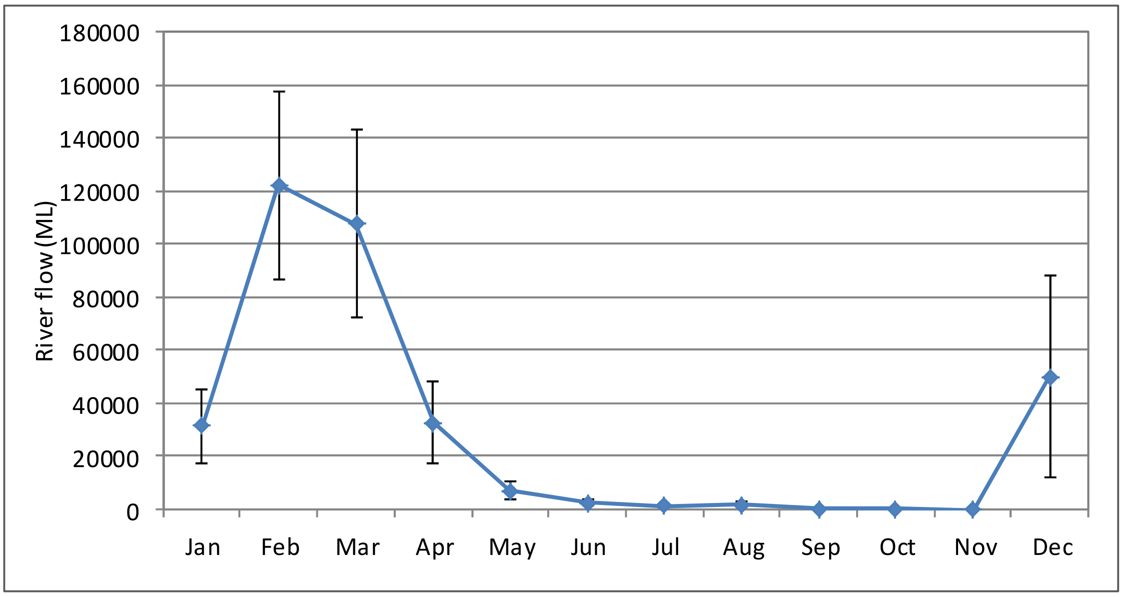


Figure 3 Average monthly flow for the Jelliabidina Well gauging station (error bars represent standard error for monthly means)

Seasonally there is typically little or no flow from May to November. There are also periods of no or low flow that extend across wet seasons. We have referred to these periods and years with no or low flow (less than 10% of mean annual flow) over the wet season as ‘drought years’. Excluding years when data is not available, there have been 13 drought years since records began in 1973. The longest period of no flow on record lasted 37 months (recorded from late 1989 to early 1993; Table 3).

Table 3 Yule flow statistics for the period of record 1973–2010

Flow statistic	Jelliabidina (Gauging station – 709005)
Maximum recorded flow	1823 GL in 2000
Mean annual flow	331 GL
Median annual flow	105 GL
Maximum no flow duration	37 months (Nov 1989–Jan1993)
Number of low flow years (total annual flow <10% mean annual flow)	13
Mean annual no flow months	7.5
Median annual no flow months	7

Hydrogeology

The lower reaches of the Yule River on the coastal plain overlie an alluvial aquifer of Quaternary and Tertiary sediments (Whincup 1967; Forth 1972; Davidson 1976; MWH 2010). The aquifer is thickest, up to 50 m, where palaeochannels have been formed within the underlying Archaean granitoid-greenstone basement.

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.

Mean annual recharge has previously been estimated as 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. Recharge from direct infiltration of rainfall is considered relatively minor.

Given the role of streamflow as the primary source of recharge to the aquifer, the variability in streamflow also means that recharge is highly variable. The data from the Jelliabidina gauging station provide the best indication of the reliability and variability of recharge. Based on the frequency of no or low flow years (discussed in the previous section, 13 years out of 37 years record) there is very low recharge to the aquifer in approximately 1 in 3 years (Haig 2009; MWH 2010).

Recharge as a result of river flow results in mounding of groundwater under the river, then gradual declines through lateral and downstream throughflow and losses via evapotranspiration. Evapotranspiration is highest along the river where the groundwater is shallowest and vegetation is most dense.

Surface discharge to the river as baseflow is an additional, albeit short-lived, loss from the aquifer when groundwater levels are high. As groundwater levels decline, direct discharge to the river channel is restricted to isolated pools where the river bed intersects the water table.

The depth to water table varies spatially and temporally with proximity to the river (and recharge areas) and time since recharge. In bores along the river (2004 series of vegetation monitoring bores) the range in groundwater levels has been up to 7 m (for monitoring data from 2005 to 2011). In the same set of bores groundwater levels have varied within a single year by as much as 5 m.

Current groundwater use

The Yule alluvial aquifer has been used as a water supply source for Port Hedland since 1967. There are currently 10 production bores operated by the Water Corporation across the Yule River borefield located downstream of the North West Coastal Highway (Figure 1). Abstraction since 2000 has averaged 4.8 GL/yr. The highest annual abstraction was 6.4 GL in the 2003–04 water year (1 April to 31 March; Figure 4).

Until 2012 the Water Corporation had an annual entitlement of 6.5 GL/yr with an interim additional entitlement of 2 GL/yr. The additional 2 GL/yr was provided (since 2003) on the basis that the corporation complete a pumping trial (see below) to test the aquifer's capacity to provide a total of 8.5 GL/yr while managing impacts on dependent values.

Since 2003 the borefield operating strategy has included environmental water provision (EWP) water level criteria and prescribed responses for managing the potential impacts of groundwater abstraction on the ecosystems dependent on the aquifer. The EWP criteria were based on minimum historical water levels and predicted tolerances of key vegetation species available at the time (Maunsell 2003). The key limitations of the existing EWP criteria are:

- the groundwater data used to establish the criteria were from bores up to 1 km from the ecosystems they were used to monitor and were not established to monitor impacts on the ecosystems
- the knowledge of key riparian vegetation species' tolerances to changes in water availability was limited and not site specific.

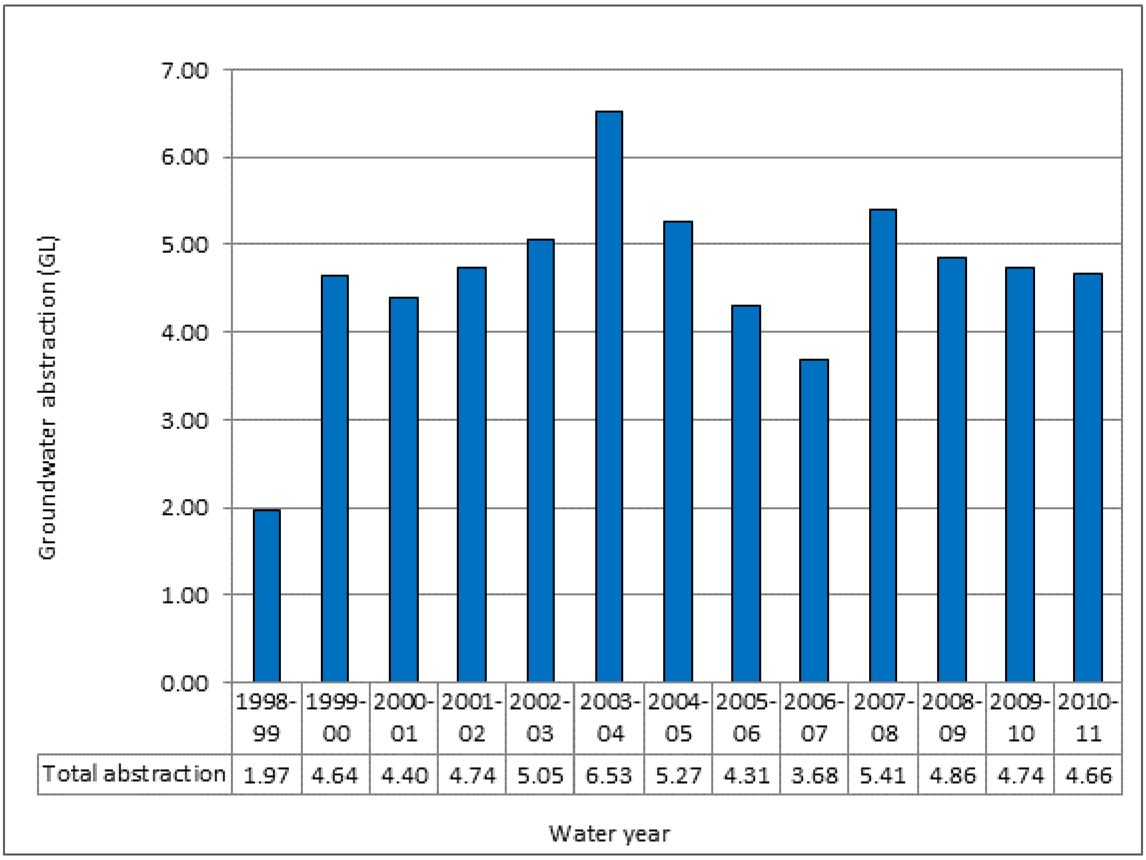


Figure 4 Total water year (April to March) abstraction by the Water Corporation from the Yule Borefield from 1998-99 to 2010-11

Yule pumping trial

The Yule pumping trial ran from December 2008 to April 2011. It was run as a collaborative exercise involving the Water Corporation, Department of Water, The University of Western Australia, University of Sydney and later Astron Environmental. The results have been incorporated into this EWR study (Section 4.1). The trial aimed to simulate increased rates of abstraction from the aquifer and monitor the response of the aquifer and groundwater-dependent ecosystems. Monitoring of ecosystems response focused on the riparian vegetation. The monitoring techniques and results of monitoring are discussed in detail in Appendix A.

2 Groundwater-dependent ecosystems

Groundwater-dependent ecosystems are ecosystems that rely on groundwater directly (e.g. stygofauna or phreatophytic vegetation using groundwater from shallow watertables) or indirectly (e.g. wetland vegetation or aquatic ecosystems sustained by groundwater discharge; Richardson et al. 2011). Groundwater-dependent ecosystems may not use groundwater continuously, possibly only relying on it seasonally or periodically.

2.1 Groundwater-dependent ecosystems in the Yule study area

Three types of groundwater-dependent ecosystems were described in detail in Stage 1 of this project – *Lower Yule River: ecological values and issues* (Braimbridge 2010):

- riparian ecosystems
- river pools
- aquifer ecosystems.

A brief description of each and how they are linked to groundwater has been provided here.

Riparian vegetation

The Yule River and floodplain are vegetated by woodlands of *Eucalyptus camaldulensis, E. victrix* and *Melaleuca argentea* (Halpern Glick and Maunsell 1998; Maunsell 2003; Figure 5). The riparian vegetation communities are similar in structure and composition to riparian communities elsewhere in the Pilbara (Beard 1975; Van Vreeswyck et al. 2004; Loomes 2010). The woodlands vary in density along and away from the river from dense to open woodland.

Conceptual link to groundwater

The distribution of riparian communities along the river coincides with areas inundated during flooding and where the depth to groundwater is shallow (Figure 6).

Flood flows are important as triggers for recruitment, distribution of nutrients throughout the riparian zone and replenishment of soil water and/or bank storage in the unsaturated zone (Roberts et al. 2000; Pettit & Froend 2001; Bunn et al. 2006).

However, during periods of no flow (or rainfall) soil moisture levels in the unsaturated zone gradually decline and the riparian overstorey becomes increasingly reliant on groundwater to meet its water requirements. During extended periods of no flow (droughts), continued access to groundwater is critical in sustaining these vegetation communities.

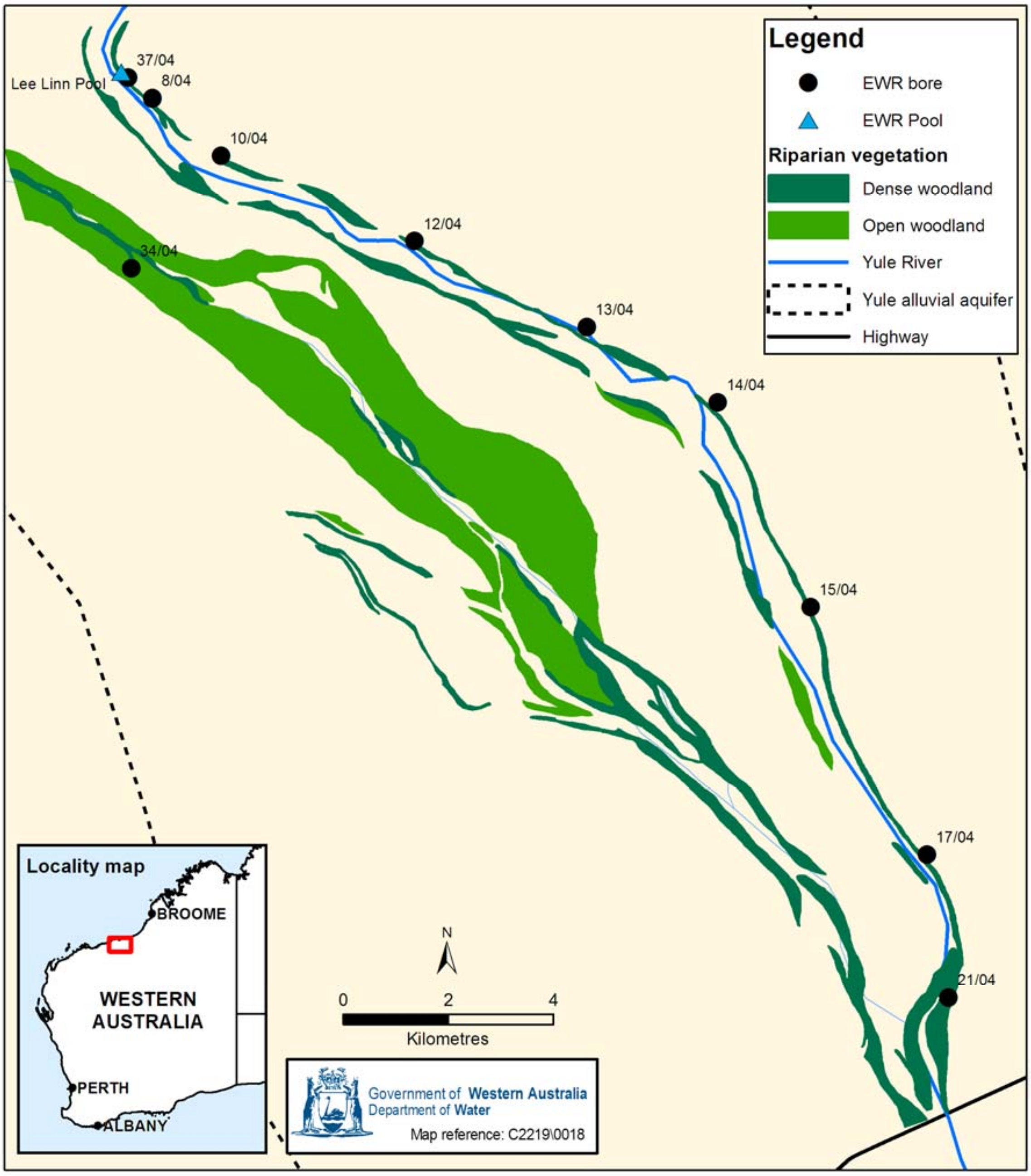


Figure 5 Vegetation communities for the Yule River study area (taken from Halpern Glick and Maunsell 1998).

Tolerance to altered water availability

Variable water availability and drought is a dominant feature of many Pilbara ecosystems including riparian woodlands in many locations. Riparian overstorey species have adaptations/responses that allow some capacity to cope with periods of low water availability but also need periods of higher water availability to maintain individual and community vigour. The maximum depth to groundwater, the rate of water level change, the frequency of low groundwater levels and the duration of periods of low groundwater levels will affect:

- the vigour of established vegetation

- the resilience of vegetation to recover from drought periods
- the recruitment and establishment of new individuals (Roberts et al. 2000).

Data from the Yule borefield show that the depth to groundwater underneath riparian vegetation ranges from 9.2 m below ground level to near surface. This is consistent with analysis of data from similar coastal systems in the Pilbara which found that riparian vegetation communities like those on the lower Yule River typically occur in zones where the maximum depth to groundwater is less than 10 m (Loomes 2010). Different species typically occupy different (but overlapping) parts of this groundwater range reflecting their sensitivity to change in groundwater levels and maximum rooting depth.

Tree physiology monitoring conducted as part of the groundwater pumping trial at the Yule borefield examined the response of dominant tree species to altered water availability. The results were used to directly inform the development of the EWR for the Yule River. The trial and results are discussed in detail in Section 4.1 (and Appendix A).

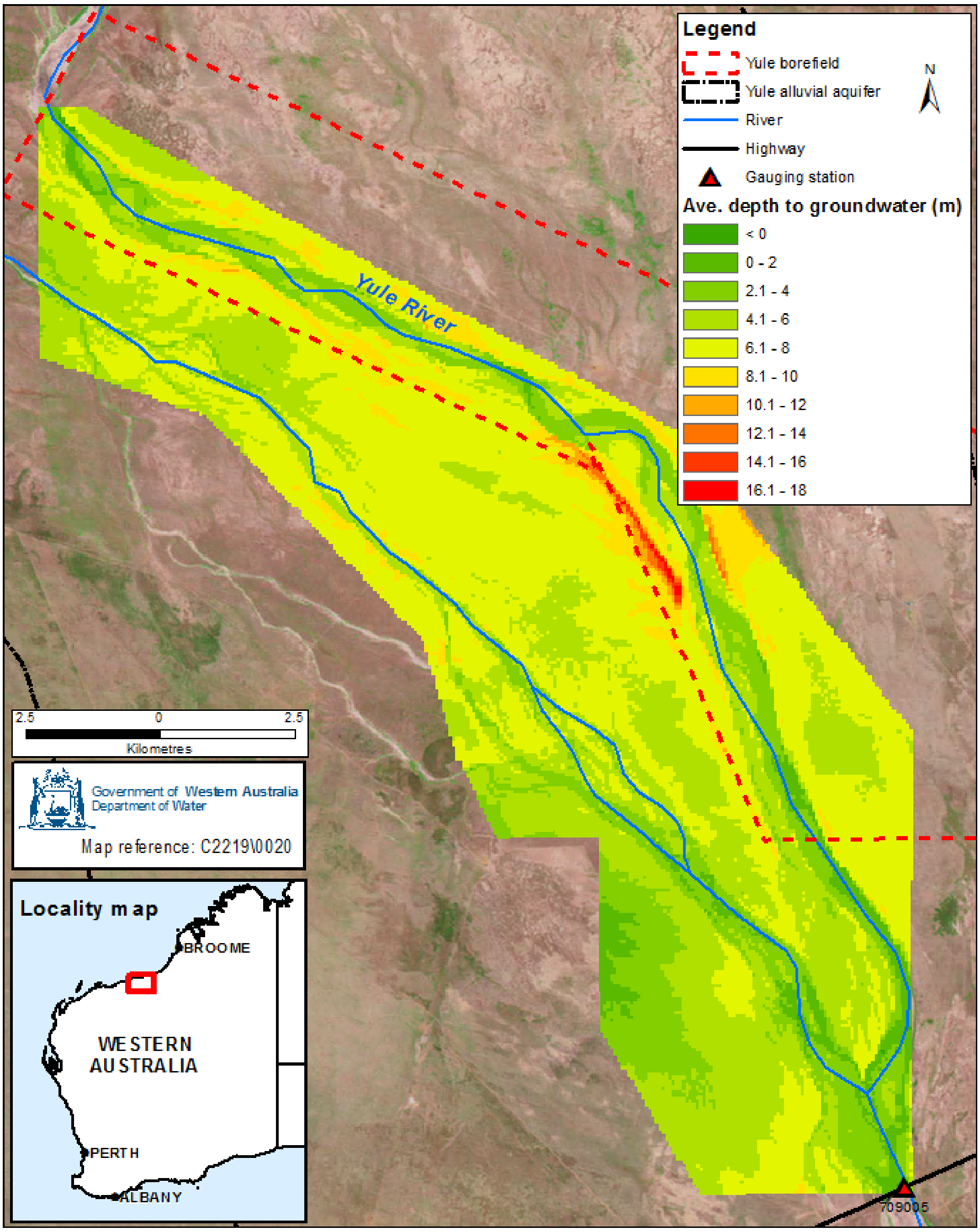


Figure 6 Depth to groundwater across the Yule River study area

Fauna

The *Pilbara biological survey* found that Pilbara riparian woodlands, particularly those with permanent pools, provide habitat for particular suites of birds and bats (and other mammals) which roost in riparian woodlands and feed on insects attracted to the river pools (McKenzie & Bullen 2009; Burbidge et al. 2010).

A range of fauna are known to or are likely to utilise the riparian woodlands (and river pools) of the Yule River. A combined study on the Yule and De Grey rivers from 1998 recorded two threatened bird species and two threatened reptile species from river and riparian ecosystems (HGM 1998). Recent work to support proposed expansion of the borefield recorded traces of the *EPBC* listed northern quoll (*Dasyurus hallucatus*) indicating it is likely to be present in the area and utilise the riparian woodland as habitat.

River pool ecosystems

The Yule River is an ephemeral system with intermittent flows. In between flows, the river is reduced to a series of pools. Fourteen pools of varying permanency were identified within the project area (Figure 7). Pools were defined as permanent if they were present across all image sets, semi-permanent if present in 60 to 99% and intermittent if present in <60% of image sets (Appendix B).

The pools support aquatic ecosystems of freshwater and marine fish species, macroinvertebrates, waterbirds and aquatic flora.

Conceptual link to groundwater

The river pools are connected to and interact with the underlying alluvial aquifer where groundwater along the river is shallow and intersects the river bed. The direction of interactions between surface and groundwater changes seasonally in response to flooding, evaporation from pools and declining groundwater levels between recharge events.

During river flow events, groundwater is recharged from the surface water and the watertable rises. Flooding and inundation result in a spike in productivity and provision of temporary habitat for aquatic flora and fauna and water birds (Bunn et al. 2006). These events are important triggers for dispersal and recruitment of riparian vegetation and aquatic flora and fauna.

During periods of no flow the hydraulic gradient between the groundwater and the pools reverses and groundwater discharges into the pools.

No flow conditions result in declining groundwater levels, shallower pools and semi-permanent pools becoming disconnected from the groundwater. This greatly reduces the area of aquatic habitat available for macroinvertebrates, fish and macrophytes.

Permanent pools that have continued connectivity with groundwater are critical habitat and are important refuges for flora and fauna during extended no flow or drought periods. In addition, they retain relatively high ‘in pool’ productivity (compared to adjacent areas) and are likely to sustain productivity in surrounding areas (Douglas et al. 2005; Bunn et al. 2006).

The continued input of groundwater to permanent pools is important to maintain adequate habitat and water quality during the dry season and extended droughts.

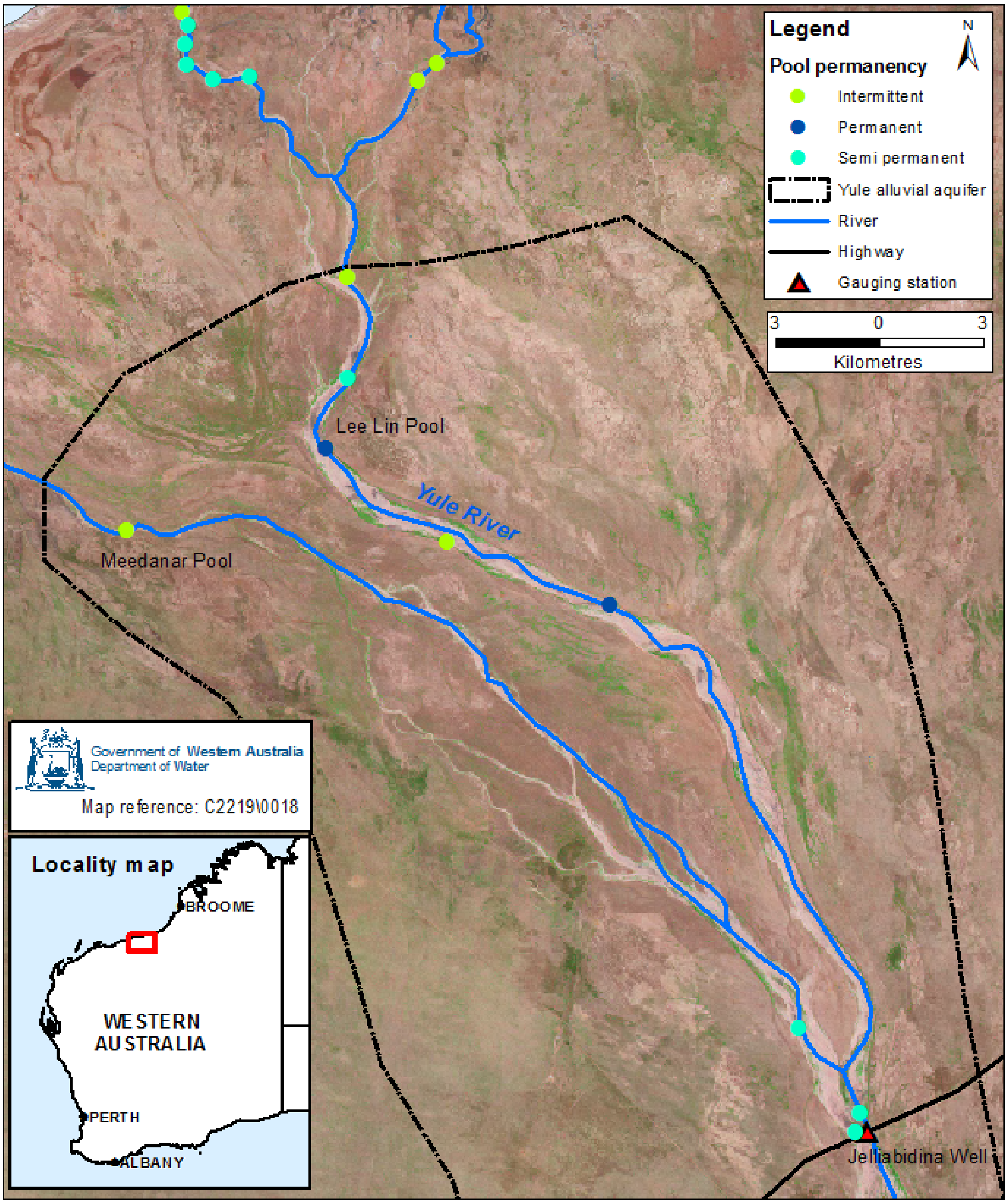


Figure 7 Distribution and permanency of river pools in the lower Yule River

Ecology

The patterns of diversity of fish fauna within the Yule catchment were similar to other systems in the Pilbara with lower reaches supporting more species than the middle and upper reaches (due in part to the presence of marine and estuarine species in the lower reaches; Morgan et al. 2009). Previous regional or targeted fish surveys in the Pilbara have found that pool stability and habitat diversity are key determinants of fish species richness (Beesley 2006; Morgan et al. 2009).

Six freshwater species with a range of habitat requirements and preferences occur within the project area including species with preference for deeper more permanent pools such as the northern eel (*Anguilla bicolor*) and the bony bream (*Nematolosa erebi*; Pusey et al. 2004).

Macroinvertebrate assemblages in the Yule River are similar in composition and abundance to the lower reaches of similar systems in the Pilbara including the De Grey and the lower Fortescue rivers (Pinder & Leung 2009). Macroinvertebrate species richness is strongly related to habitat diversity and the presence of macrophyte beds.

Overall the fish and macroinvertebrate assemblages of the lower Yule River are similar in terms of composition to similar lowland systems in the region. No species of restricted distribution were recorded.

Within the catchment permanent pools maintain refuges important for freshwater fish between flow events. The contribution of groundwater maintains the permanence, size, water quality and instream habitat.

Aquifer ecosystems

Alluvial aquifers similar to the Yule River aquifer elsewhere in the Pilbara have been found to support diverse stygofaunal assemblages (Eberhard et al. 2005; Reeves et al. 2007). There is currently no published information available on stygofauna specifically from the Yule aquifer.

Information on habitat requirements for stygofauna, in terms of which parts of the aquifers they utilise, and tolerances of differing water qualities, is very limited. This has prevented us from determining thresholds or limits of acceptable change in the water regime. Given this lack of understanding EWR have not been described specifically for stygofauna. By default EWR for riparian vegetation and pool ecosystems should support stygofauna. That is, by maintaining groundwater levels within the range to support riparian vegetation and pools, the habitat for stygofauna should be maintained.

Conservation significance and value of systems

Riparian vegetation provides habitat for fauna, helps maintain waterway condition and functionality, and contains species and represents habitat types that are restricted in distribution across the region. Although riparian systems of the Yule River are well represented across the region and modified by grazing they are locally important in supporting fauna, especially birds, bats and some mammal and reptile species.

The pools of the Yule River support fish and macroinvertebrate assemblages representative of aquatic ecosystems in coastal portions of other Pilbara rivers. Permanent pools provide refuge for fauna during drought periods and act as sources of colonisers during floods and high flows.

2.2 Hydro-ecology linkages

From the review of the groundwater-dependent ecosystems and the conceptual models for groundwater–ecosystem interaction (Stage I of the project), we have developed a set of hydro-ecology linkages (Braimbridge 2010). The linkages identify parts of the groundwater regime that are important for key ecological features and processes (e.g. riparian vegetation, fish, macroinvertebrates).

We have intentionally focused on the groundwater regime as this relates directly to the management of water abstraction from the borefield.

The linkages have been grouped by ecological features of riparian and river pool ecosystems and are briefly described below (Table 4).

Table 4 Hydro-ecological linkages for riparian vegetation and river pool ecosystems

GDE	Ecological feature /Hydro-ecological linkage
Riparian ecosystems	*Riparian vegetation* 1. Minimum groundwater levels to sustain phreatophytic vegetation during dry and drought periods when groundwater is the primary source available to meet their water requirements[1]. 2. Periods of high water availability for groundwater dependent vegetation to maintain resilience of established vegetation and allow establishment of new vegetation.[2]
River pools	*Fauna* 3. Areas of permanent pools consistent with regional seasonality to maintain pool stability and as refuges for fish and other fauna. 4. Sufficient areas of inundated shallow macrophyte habitat available for macroinvertebrates, small-bodied fish and juveniles of large-bodied fish. 5. Sufficient deeper habitat permanently inundated and available for mature and large-bodied fish. 6. Sufficient depth in deeper pools to maintain water quality in deeper pools[3].

Linkage 1: Minimum groundwater levels to sustain phreatophytic vegetation during dry and drought periods

The water requirements of the riparian vegetation are met at least in part by access to groundwater through maintenance of local water tables. During drought periods,

[1] & [3] In response to additional information this linkage has been reworded since Phase I of the project reference Braimbridge (2010)

[2] In response to additional information this linkage has been added since Phase I of the project.

when soil moisture becomes depleted, continued access to groundwater to meet the water requirements of vegetation is critical.

The magnitude and rate of water level change and the frequency and duration of low water levels are all likely to be important considerations for phreatophytic vegetation.

Linkage 2: Periods of higher water availability for groundwater-dependent vegetation

Periods of higher water availability are important for the recruitment and establishment of new individuals and the resilience of established vegetation to recover from drought periods.

Groundwater levels in the Yule alluvial aquifer fluctuate with the region's dynamic climate. Riparian ecosystems have adapted to cope with droughts and recover during wet periods. The EWR has been described to reflect this and therefore includes requirements for high groundwater levels.

Linkage 3: Areas of permanent pools consistent with regional seasonality

Pilbara rivers experience an underlying seasonality with high variability between years, particularly when longer-term droughts occur. At the river scale, the proportion of pools retaining water is important because persistent pools provide refuge for fauna and act as sources of colonisers once the dry season or drought ends (Bunn et al. 2006). Maintaining groundwater input into river pools consistent with seasonal and inter-annual variations in groundwater levels will be critical to satisfying this linkage.

Linkage 4: Macrophytes inundated and available as habitat

Macrophytes provide important habitat for fish and macroinvertebrates in the Yule River pools that would otherwise be habitat poor (Pinder & Leung 2009). The presence of macrophyte beds in river pools is a strong driver of macroinvertebrate richness and diversity (Pinder & Leung 2009).

Many macrophytes reproduce by seed that is resilient to frequent or extended periods of drought (van Dam et al. 2005). However, it is important that they remain inundated and available as habitat during dry periods. Again, maintenance of groundwater input into river pools will be important to satisfying this linkage.

Linkage 5: Deeper pools available as habitat

River pool stability is an important driver of Pilbara fish community structure (van Dam et al. 2005; Beesley 2006; Dobbs & Davies 2009; Morgan et al. 2009). Deeper pools are not only capable of supporting a greater number and diversity of fish, but also persist longer during drought periods providing drought refuges. Continued groundwater input, particularly during extended no flow periods, is critical to maintaining deep pools and maintaining the permanence of pools.

Linkage 6: Sufficient depth in deeper pools to maintain water quality in deeper pools

Adequate pool size and depth can also reduce the risk of nutrient enrichment and anoxia through buffering extreme changes in temperature and evapoconcentration.

Provision of deep pool habitat will satisfy hydro-ecological linkages 5 for fauna and 6 for water quality (Table 4).

3 Approach to determining EWR

3.1 Overview

The hydro-ecology linkages described above have guided the determination of the EWR for the Yule aquifer. Using the linkages we have defined the parts of the groundwater regime that are critical to maintaining robust functioning ecosystems.

Each linkage has had a threshold defined at a set of representative sites across the project area. The thresholds are defined in terms of groundwater or pool level(s). Some of the thresholds are also defined in terms of a timing or duration. The thresholds represent groundwater or pool water levels beyond which we've found, or predict, there is an increased risk to the ecosystem or part of the ecosystem.

Given that the water regime in the lower Yule River is highly variable, periods of increased 'stress', as well as sporadic high productivity, are inevitable and are part of natural variation. Therefore, even in the absence of groundwater abstraction some thresholds and linkages will not be met in every year.

We have developed a method to deal with this variability by linking the application of thresholds to seasonal climate. The EWR we've described is therefore dynamic and varies with climate.

3.2 How we determined thresholds

Defining thresholds is a critical part of establishing EWR. For groundwater-dependent ecosystems on the Yule aquifer we used a combination of approaches to define thresholds.

The results of the Yule pumping trial and the associated field experiment were a vital input to define the thresholds related to linkages for riparian vegetation.

For other linkages we have used thresholds from literature and previous studies. Where existing thresholds were not available, we have developed them from analysis of the historic water regime.

In all cases we have applied thresholds to sites along the river using a combination of observed and modelled groundwater and surface water data (Appendix C summarises the data available for description of EWR). Each site has thresholds expressed as measurable water levels in a nearby monitoring bore.

3.3 Site selection

Ten sites, representative of riparian vegetation and/or river pool ecosystems, were selected to give an appropriate spread across the existing borefield area, potential future expansion areas and reference sites not affected by abstraction (Figure 5 & Table 5).

Sites were selected based on biological survey results and availability of data. All are associated with shallow groundwater bores monitored since March 2005.

All sites have riparian vegetation representative of communities that occur along the river (see Figure 5). Vegetation transects were established at all sites either as part of earlier EWR studies (Maunsell 2003), ongoing vegetation health monitoring (associated with the borefield operation) or as part of this study.

Table 5 Yule EWR site details

Site reference (Bore number)	GDE represented	Distance from nearest pool (m)	Data availability		
			Observed water levels (month/year)	Modelled water levels (month/year)	Vegetation Transect
8/04	Riparian vegetation	-	3/05–10/11	1/72–11/10 10/10–8/63	✓
10/04	Riparian vegetation	-	3/05–10/11	1/72–11/10 10/10–8/63	✓
12/04	Riparian vegetation	-	3/05–10/11	1/72–11/10 10/10–8/63	✓
13/04	Riparian vegetation and Unnamed pool	550	3/05–10/11		✓
14/04	Riparian vegetation	-	3/05–10/11	1/72–11/10 10/10–8/63	✓
15/04	Riparian vegetation	-	3/05–10/11		✓
34/04	Riparian vegetation	-	3/05–10/11		✓
37/04	Riparian vegetation and Lee Lin Pool	- 80	2/04–3/12 3/05–10/11	1/72–11/10 10/10–8/63	✓
17/04	Riparian vegetation	-	3/05–10/11	1/72–11/10 10/10–8/63	✓
21/04	Riparian vegetation and Highway Pool	1500 2000	3/05–10/11	1/72–11/10 10/10–8/63	✓

Site 37/04 is located close to Lee Lin Pool, one of the few semi-permanent to permanent pools in the borefield area. Bore 21/04 is located approximately 2 km north of the North West Coastal Highway bridge over the river and Highway Pool.

3.4 How we combine thresholds and describe the EWR

To deal with the highly variable groundwater regimes in the Yule aquifer we have developed and applied a framework that links the EWR to the climate which drives this variability.

The framework uses the relationship between river flow, as the key source of recharge, and groundwater levels to define the climate variability and incorporate variability into the EWR. Wet season river flow was analysed to define 'recharge classes'. These classes are used to link thresholds to climate – to determine which thresholds are applicable in the following year. So drought thresholds are applicable in years when recharge was low and thresholds related to higher water levels are applicable in years when recharge was high. The result is an EWR that is defined by a changing set of thresholds that are considered likely to be met in the following seasons.

How we developed this framework and how it will be applied are described in Section 5.

4 Determining thresholds

For each linkage we have described how we determined thresholds to meet the linkage. We have also described how the thresholds were calculated for each applicable EWR site. River pools were only present at two (of ten) sites so linkages relating to aquatic ecosystems were only applied at these sites.

4.1 Thresholds for riparian vegetation (Yule pumping trial)

Linkage 1: Minimum groundwater levels to sustain phreatophytic vegetation during dry and drought periods when groundwater is the primary source available to meet their water requirements.

Approach

We determined minimum groundwater level thresholds needed to sustain riparian vegetation during dry and drought periods using the results the groundwater pumping trial. The trial methods and results are described in greater detail in Appendix A.

During the trial, monitoring was conducted at control (bore 17/04), impact (bore 10/04) and intermediate (bore 14/04) sites. The monitoring focused on the responses of the dominant riparian species *Eucalyptus victrix/camaldulensis*[4] and *Melaleuca argentea* to changes in water availability. Monitoring at the control and impact sites included continuous logging of tree water use (using heat ratio method to estimate sapflow velocity e.g. Burgess et al*.* 2001) and groundwater (water levels monitored using data loggers). Eight monitoring campaigns were also conducted between March 2009 and April 2011, collecting data on a range of parameters related to tree water status (including leaf water potential, projected foliage cover and qualitative health assessments; see for example Eamus et al*.* 2006 for explanation of techniques) and soil moisture content.

By comparing the observed stress responses in the vegetation at the control and impact sites with groundwater levels and other data we were able to identify thresholds for low, medium and high risk of impact to vegetation from decline in groundwater levels.

Results

Groundwater levels declined (depth to groundwater increased) progressively over the course of the trial from March 2009 to January 2011, exceeding previous maximum depth to groundwater at the monitoring sites and equalling or exceeding previous maximums across much of the borefield (Figure 8).

[4] Eucalypt species were treated as a functional group. DNA analysis of leaf samples collected in the field confirmed a mix of *Eucalyptus camaldulensis* and *E. victrix* from trees identified as *E. camaldulensis* based on morphology (see Appendix A).

Soil water availability (above the saturated water table) also progressively declined during the course of the trial until early 2011.

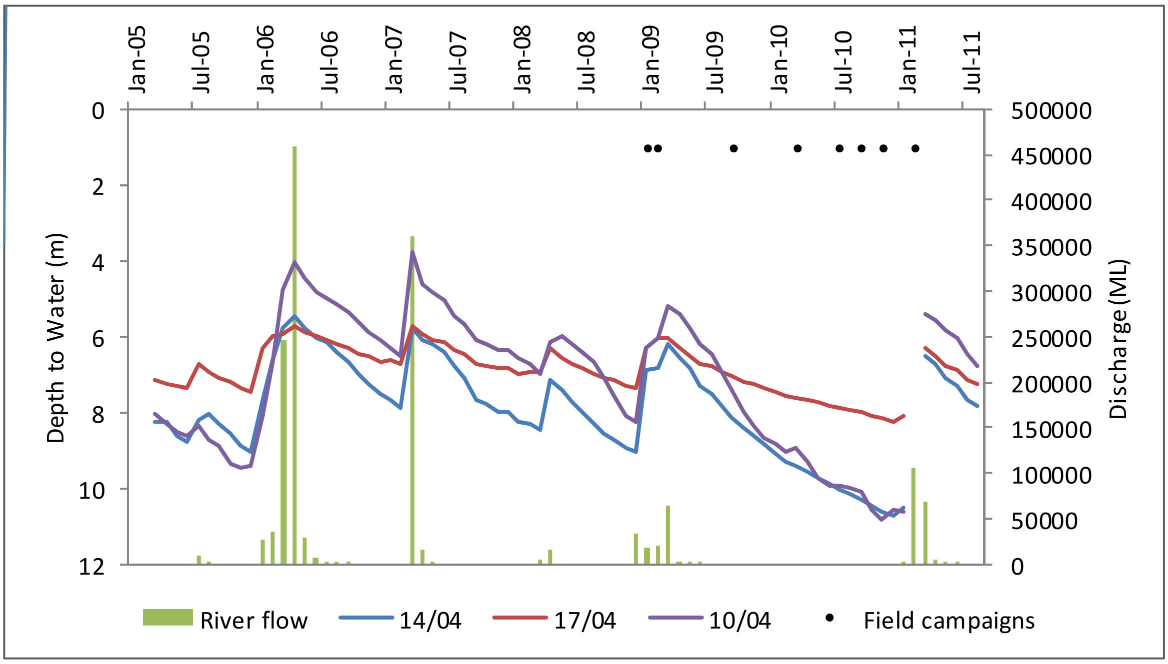


Figure 8 Groundwater level (as depth to groundwater) and river flow (as monthly total discharge) for control, impact and intermediate impact sites from March 2005 to August 2011

Monitored vegetation parameters showed increasingly negative responses in the vegetation over the course of the trial as water availability declined. The response ultimately indicated what has been interpreted as signs of tree water stress as demonstrated by:

- Tree water use (sapflow): Rates of tree water use across both sites (control and impact) declined over the course of the trial corresponding with the decline in water availability. Declines were greater at the impact site compared to the control site. Midday depressions in rates of sapflow at the impact site indicated water availability was limiting transpiration, particularly under severe weather conditions.
- Leaf water potential: Pre-dawn leaf water potential provides an indication of the water status of vegetation. Leaf water potential across both sites declined (became more negative) from May 2010 onwards with significantly greater declines at the impact site (Figure 9). Hourly measurement of leaf water potential (5:00 am to 5:00 pm) during November 2010 indicated stomatal closure at the impact site by 8:00 am (Figure 10). This was interpreted as a response to limited water availability and an indication of impaired plant functionality at this site. Pre-dawn and midday readings were similar at the impact site for November 2010 and January 2011 sampling. This was considered to indicate that the vegetation was unable to rehydrate overnight and had become disconnected from the groundwater. This response was not evident at the control site.
- Canopy condition and density: Projected foliage cover and qualitative health assessments also indicated declining condition over the course of the trial and

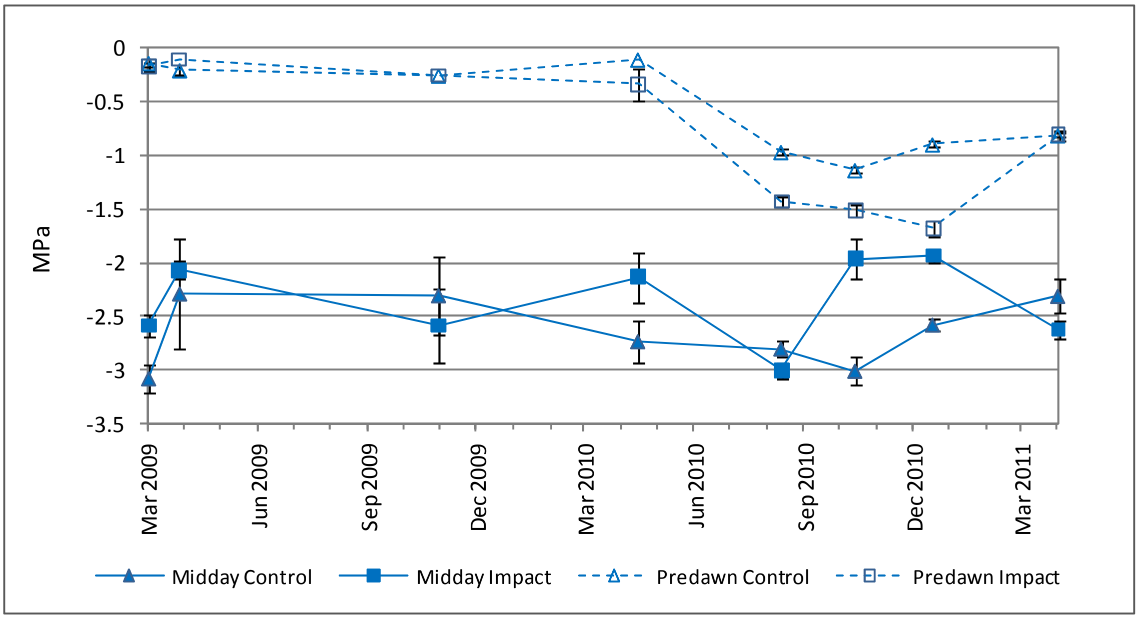
greater signs of water stress during late 2010/early 2011 at the impact site compared to the control site.

The monitoring results allowed us to identify three levels of vegetation response with associated maximum depths to groundwater. We have interpreted the different levels of response as associated with a risk of permanent impact to the vegetation. These have been defined as:

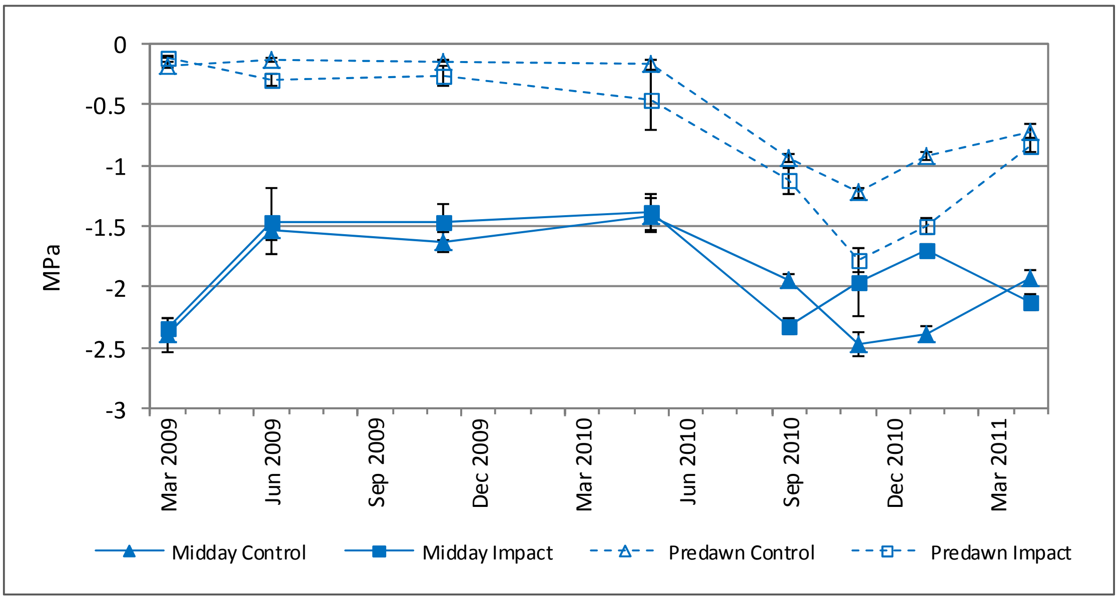
- Low response/low risk: For groundwater levels up until the May 2010 monitoring campaign vegetation response was consistent with low levels of water stress. The changes in water availability during this period (December 2008 to April 2010) were within the range normally experienced within the project area and were not considered to pose a risk to vegetation condition.
- Medium response/medium risk: For groundwater levels for the May and September 2010 monitoring campaigns vegetation response increased coinciding with decreased water availability.
- High response/high risk: For groundwater levels during the November 2010 and January 2011 campaigns vegetation response was increased and at the impact site indicated a stressed response in the vegetation and impaired plant functionality.

The responses in groundwater levels and vegetation (based on observation at least) measured at the impact site during the course of the trial were matched elsewhere across the borefield. Groundwater levels in monitoring bores at all other EWR sites within the borefield showed declines similar to the impact (bore 10/04) and intermediate (14/04) sites. Isolated deaths of mature *Eucalyptus* trees and complete leaf loss (and potential deaths) in stands of *Melaleuca argentea* saplings were observed within the borefield early in 2011. These were attributed to the water availability conditions in the preceding months and were considered to confirm that groundwater levels across the borefield had reached critically low levels during the trial.

We used groundwater levels immediately prior to the May and November 2010 campaigns to represent levels of risk/response. That is, depths to groundwater less than those recorded before the May campaign, when indications of a 'stress' response were initially observed, present a low level of risk of permanent impact to vegetation. Similarly, if depths to groundwater exceeded those recorded prior to the November campaign, a more severe, potentially high risk response in the vegetation, similar to that observed during the trial, could be expected.

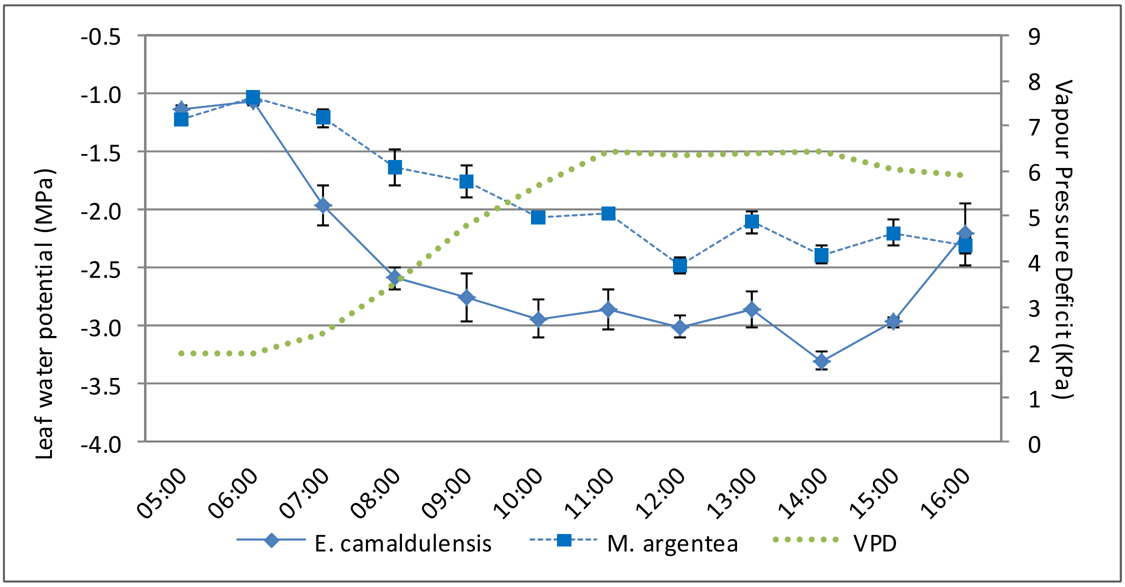


a)

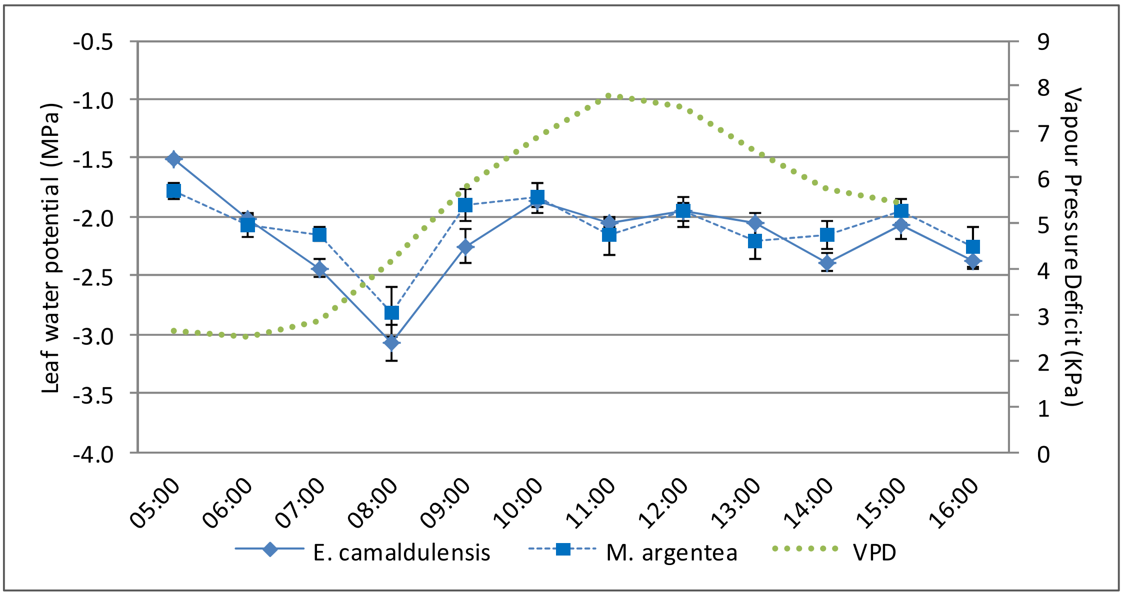


b)

Figure 9 Pre-dawn and midday leaf water potential measurements for (a) Eucalyptus victrix/camaldulensis *and (b)* Melaleuca argentea *for measurement campaigns completed over the trial period*



a)



b)

Figure 10 Diurnal leaf water potential for Control (a) and Impact (b) sites from November campaign

We compared historic depths to groundwater from all EWR sites with depths recorded immediately prior to the May 2010 campaign – to represent depth to groundwater for the medium risk/response – and the November 2010 campaign – to represent depth to groundwater for the high level of risk/response (Table 6).

Recorded depths to groundwater for the high risk threshold at the majority of EWR sites were found to approximately coincide with the 95th percentile groundwater depths. For the medium risk threshold depth to groundwater recorded across the EWR sites fell between the 80th and 90th percentiles of the groundwater depth distributions.

Based on these results we have adopted the 95th percentile of depth to groundwater as the high risk threshold for groundwater-dependent vegetation across the site. The 80th percentile has been adopted as a medium risk threshold. The 80th percentile was chosen (instead of 90th) to provide an earlier warning of potential water stress response.

Adopting these percentiles as thresholds, instead of absolute maximum depths to groundwater (such as groundwater levels should not exceed 10.59 m at all sites) or changes in depth to groundwater, makes the thresholds relative measures of the range of depths to groundwater. This is an advantage when applying thresholds to different sites with a potentially different range in variability in groundwater levels.

During the trial the depth to groundwater was greater than the medium risk threshold for 6 months in total and exceeded the high risk threshold for 4 months. We have used these durations as maximum durations, beyond which we expect the vegetation response would exceed that observed during the trial and the risk of permanent impact be increased.

Table 6 Probability of ranked depth (m) to groundwater levels for EWR sites (using data set 1/3/05 to 29/4/11)

	Bore site									
Cumulative probability[5]	**8/04**	**10/04**	**12/04**	**13/04**	**14/04**	**15/04**	**17/04**	**21/04**	**34/04**	**37/04**
0.01	5.97	3.77	3.87	3.46	5.47	4.45	5.70	3.81	2.02	5.93
-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-
0.75	9.43	8.69	6.57	5.64	8.76	7.43	7.33	5.47	5.68	9.39
0.77	9.45	8.71	6.58	5.75	8.84	7.54	7.35	5.49	5.74	9.43
0.78	9.61	8.82	6.73	5.76	8.88	7.59	7.35	5.49	5.77	9.44
0.79	9.63	8.91	6.86	5.83	8.96	7.69	7.36	5.49	5.84	**9.56**
0.81	9.64	8.95	6.91	5.95	9.07	7.71	7.36	5.51	5.86	9.65
0.82	**9.78**[6]	9.07	7.00	6.07	9.07	7.73	7.46	5.55	5.87	9.71
0.84	9.83	**9.32**	7.13	6.10	9.11	**7.84**	7.47	5.62	5.95	9.78
0.85	9.97	9.38	7.22	6.33	9.29	7.88	7.55	5.71	6.02	9.81
0.86	10.13	9.41	7.32	6.49	9.42	7.94	7.60	5.75	**6.10**	9.86
0.88	10.19	9.48	**7.63**	**6.74**	**9.59**	7.98	**7.68**	5.76	6.18	9.95
0.89	10.26	9.72	7.95	6.98	9.75	8.00	7.75	**5.84**	6.24	9.98
0.90	10.27	9.92	8.31	7.20	9.89	8.10	7.82	5.91	6.30	10.06
0.92	10.29	9.93	8.52	7.43	10.04	8.22	7.87	5.97	6.35	10.17
0.93	10.33	10.01	8.66	7.55	10.14	8.29	7.92	6.01	6.43	10.19
0.95	10.46	10.12	8.93	7.74	10.29	8.41	7.99	6.05	***6.54***	10.26
0.96	***10.78***[7]	***10.58***	***9.36***	***7.97***	***10.49***	***8.58***	8.09	6.12	6.62	***10.40***
0.97	10.83	10.59	9.49	8.09	10.52	8.69	***8.11***	***6.23***	6.68	10.55
0.99	10.92	10.61	9.60	8.20	10.60	8.76	8.17	6.31	6.75	10.60
1.00	11.03	10.81	9.73	8.22	10.71	8.79	8.24	6.37		10.65
Calculated percentiles										
95%	10.59	10.30	9.10	7.83	10.37	8.48	8.03	6.08	6.48	10.32
80%	9.64	8.93	6.89	5.90	9.03	7.70	7.36	5.50	5.83	9.61

Recommendations

We determined thresholds of response in dominant riparian tree species to altered water availability from the results of the groundwater pumping trial and associated monitoring. Thresholds for medium and high risk of impact from declining groundwater levels were found to coincide with the 80th and 95th percentiles of depth to groundwater level distributions. For the most part the riparian vegetation appeared to recover from the brief periods experienced (6 and 4 months) of depth to groundwater slightly (up to 0.5 m) greater than medium and high risk thresholds.

[5] Cumulative probability was calculated based on the ranked depth to groundwater level distributions for each bore/EWR site. Light shaded row highlights the approximate 80th percentile and the dark shaded row highlights 95th percentile.

[6] Figures in bold text are depth to groundwater levels recorded immediately before the May 2010 campaign

[7] Figures in bold and italics are depth to groundwater levels recorded before the November 2010 campaign

However, based on a response of vegetation observed during the trial frequent and prolonged exposures to depth to groundwater greater than the high risk threshold are considered likely to cause permanent decline in ecosystem condition.

Groundwater levels should be maintained above the high risk of impact threshold to sustain the phreatophytic riparian vegetation. Incorporating medium and high risk thresholds into a dynamic EWR related to climate will help to maintain ecosystem condition.

The medium and high risk thresholds for this linkage for each of the ten EWR sites are shown in Table 7 as depth to groundwater (m) and groundwater levels (mAHD).

Table 7 Medium and high risk of impact thresholds to maintain minimum groundwater levels for riparian vegetation

Site	Medium risk threshold		High risk threshold	
	Depth to groundwater (m)	Groundwater level (mAHD)	Depth to groundwater (m)	Groundwater level (mAHD)
8/04	9.64	9.23	10.59	8.28
10/04	8.93	9.87	10.30	8.50
12/04	6.89	14.31	9.10	12.10
13/04	5.90	17.51	7.83	15.58
14/04	9.03	18.79	10.37	17.45
15/04	7.70	23.12	8.48	22.34
17/04	7.36	28.96	8.03	28.29
21/04	5.50	32.04	6.08	31.46
34/04	5.83	10.05	6.48	9.40
37/04	9.61	8.89	10.32	8.18

Linkage 2: Periods of high water availability for groundwater-dependent vegetation to maintain resilience of established vegetation and allow establishment of new vegetation

Maintenance of robust functioning riparian vegetation communities will require periods of relatively high water availability to allow recovery of established vegetation and recruitment of new individuals.

Approach

We have used the results of the trial to look at vegetation response following recovery of groundwater levels and longer-term groundwater level data for the borefield to set thresholds for this linkage. We used the median monthly depth to groundwater (or 50th percentile) as a measure of groundwater levels for periods when water availability to phreatophytic vegetation should not be limiting and allow recovery and facilitate recruitment of riparian tree species.

Results

In February and March 2011 groundwater levels across the borefield recovered following river flow events and recharge to the aquifer. Leaf water potential recorded in April showed recovery of vegetation water status, with levels similar to those recorded in September 2010.

Water levels post-recharge in February/March were above 50th percentile groundwater levels for all of the monitoring sites. The 50th percentile groundwater levels have been exceeded in 6 out of 7 years (available data 2005–11) for the control and impact sites. We used modelled historical groundwater levels to check the occurrence of higher groundwater levels. Not surprisingly the 50th percentiles over longer-term data were exceeded in approximately 50% of years.

Recommendations

To help maintain ecosystem resilience and recruitment it is important that periods of high groundwater levels are maintained. Threshold levels based on the 50th percentile depth to groundwater (Table 8) should be exceeded during years with average or greater recharge.

Table 8 Threshold groundwater levels to maintain high water availability

Site	**8/04**	**10/04**	**12/04**	**13/04**	**14/04**	**15/04**	**17/04**	**21/04**	**34/04**	**37/04**
50th percentile DTW (m)	8.06	6.59	5.81	5.08	7.99	6.62	6.84	5.01	5.20	8.15

4.2 Thresholds for river pools

Linkage 3: Surface water expression consistent with regional seasonality to maintain pools as refuges

Maintaining areas of permanent surface water consistent with regional seasonality will maintain pool stability and provide refuges for fish, macroinvertebrates and other fauna.

Representative permanent and semi-permanent pools should be maintained as drought refuges, consistent with seasonality and inter-annual variation in levels and depths – lower during dry seasons and higher during wet seasons. Drying and re-filling of semi-permanent and intermittent pools on the lower Yule River will meet the lifecycle requirements of aquatic fauna.

Approach

Pool mapping assessed the permanency of river pools based on their occurrence across seven sets of Landsat imagery selected during dry periods (no surface water flow) between 1999 and 2007. Pools were defined as permanent if they were present across all image sets, semi-permanent if present in 60 to 99% and intermittent if present in <60% of image sets (Appendix B).

Based on this analysis and records of pool levels Lee Lin Pool was classed as semi-permanent. The pool dried out in 2010 during the pumping trial corresponding with the extended no flow/no recharge period (23 months) and historically low groundwater levels across the borefield. Monitoring data for the pool indicate it has retained some surface water in almost all other years but the data set is relatively limited (2005 to current).

Surface water levels measured at Lee Lin Pool since 2005 are strongly correlated (r^2 = 0.70) with groundwater levels from bore 37/04. This suggests there is connectivity between groundwater and surface water (Figure 11).

Surface water monitoring data at no flow levels is not available for Highway Pool. We have used groundwater levels recorded in the nearest bore, bore 21/04 as a surrogate for surface water levels (during no flow periods) in Highway Pool.

In addressing this linkage we have used surface water level data for Lee Lin Pool and groundwater data for bore 21/04 to describe seasonality in surface water expression of groundwater.

To represent the historic range in pool levels, 5th, 50th and 90th percentiles of Lee Lin Pool water level and groundwater level for bore 21/04, were calculated (Table 9; Figure 12). These have been used to represent low, average and high water availabilities respectively.

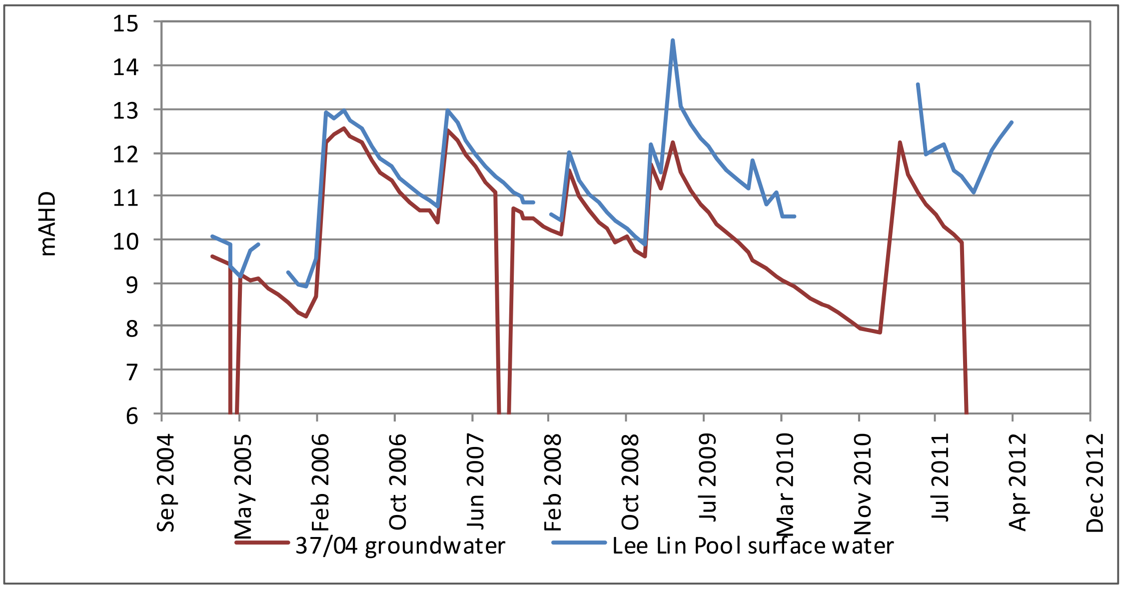


Figure 11 Relationship between water levels at bore 37/04 and Lee Lin Pool

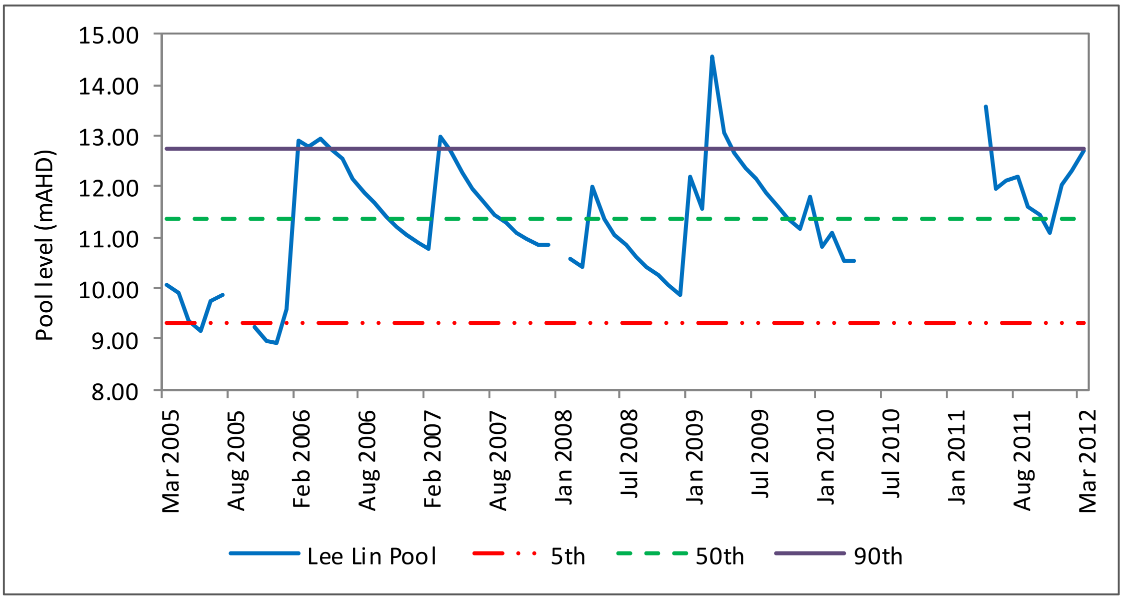
Recommendations

Maintaining water levels in the range of percentiles in Table 8 will maintain the bulk of inter-annual and seasonal variation at the pools. This will ensure the provision of river pool habitat consistent with the historical water regime. Minimum levels of at least 9.31and 31.48 mAHD should be maintained at Lee Lin Pool and bore 21/04 (Highway pools) respectively. Application of thresholds from year to year should be related to climate (see Section 5). Application of 5th and 50th percentiles is most relevant to defining EWR for groundwater input into the pools and management of impacts of groundwater abstraction.

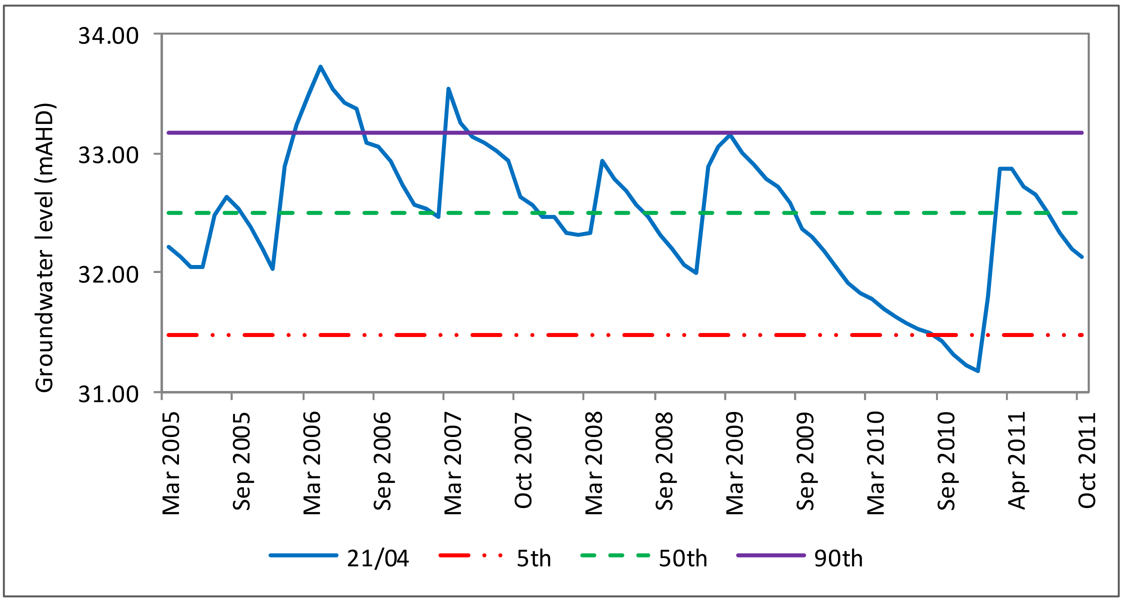
Pool bathymetry should be surveyed (at Lee Lin and Highway pools) to improve our ability to predict pool permanence and pool depth. Water levels in Highway Pool should be monitored below the cease to flow levels of the pool and the correlation with nearby bores tested to confirm connectivity with groundwater.

Table 9 Historical pool and representative groundwater levels

	Percentile pool water-level (mAHD)		
	5th	50th	90th
Lee Lin	9.31	11.38	12.76
Bore 21/04 (Highway pools)	31.48	32.50	33.17



(a)



(b)

Figure 12 Pool and groundwater level percentiles (a) Lee Lin Pool, (b) bore 21/04 – Highway pools

Linkage 4: Macrophytes inundated and available as habitat

Pools of the lower Yule River support submerged macrophytes which provide important habitat for macroinvertebrates and small fish. Ensuring macrophytes are present and available as habitat will help to maintain macroinvertebrate and fish fauna.

Approach

Thresholds for minimum water depths needed to maintain macrophyte habitat are not specifically available for the Pilbara. In the absence of these we have looked at pool depth and compared this to thresholds for macrophyte habitat identified elsewhere, such as for the lower Ord River where a minimum depth of 45 cm (based on expert panel advice) was used as a threshold (Braimbridge & Malseed 2007).

The depths of Lee Lin Pool and Highway Pool are not monitored. However, maximum depth was recorded during macroinvertebrate surveys in 2008 (Pinder & Leung 2009). The maximum recorded depth at Lee Lin this time was 0.76 m. Using this depth and measured surface water levels we have back calculated the maximum depths of Lee Lin Pool across the period of pool level monitoring.

A maximum depth of 1.20 m was recorded at Highway Pool during the survey. We have used groundwater levels and the spot measurement of maximum depth from bore 21/04 to back calculate approximate pool depth for Highway Pool.

Estimated pool depths were analysed to determine if depths greater than 0.45 m were achieved under past water regimes. To characterise seasonal and inter-annual variation percentiles of pool depths were calculated. We have used 5th, 20th and 50th percentiles to represent drought, dry and average conditions respectively.

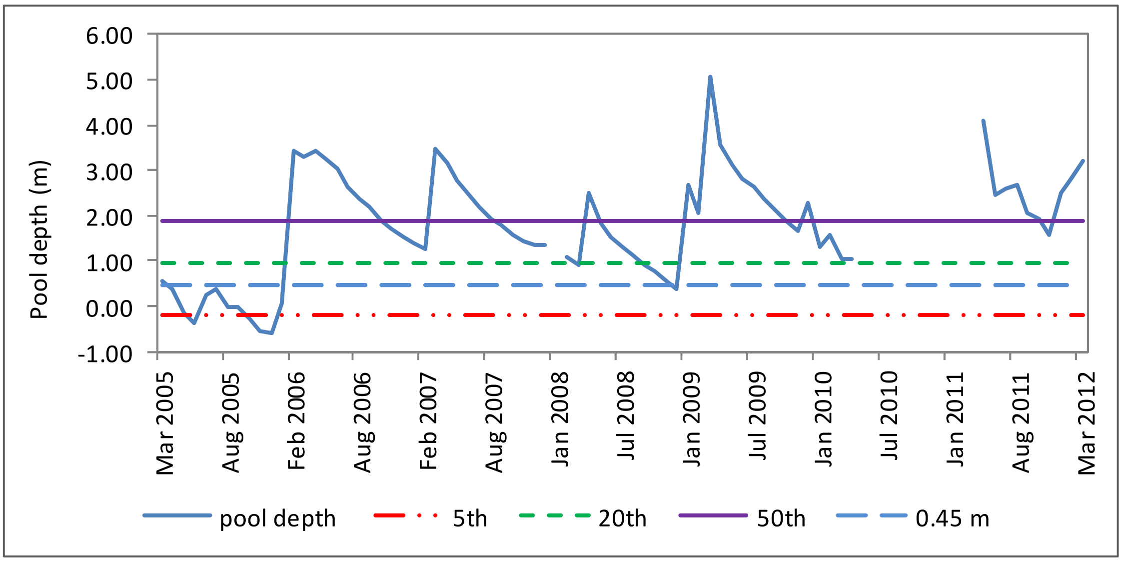
Results

The estimated minimum pool or groundwater levels required to maintain a depth of 0.45 m are:

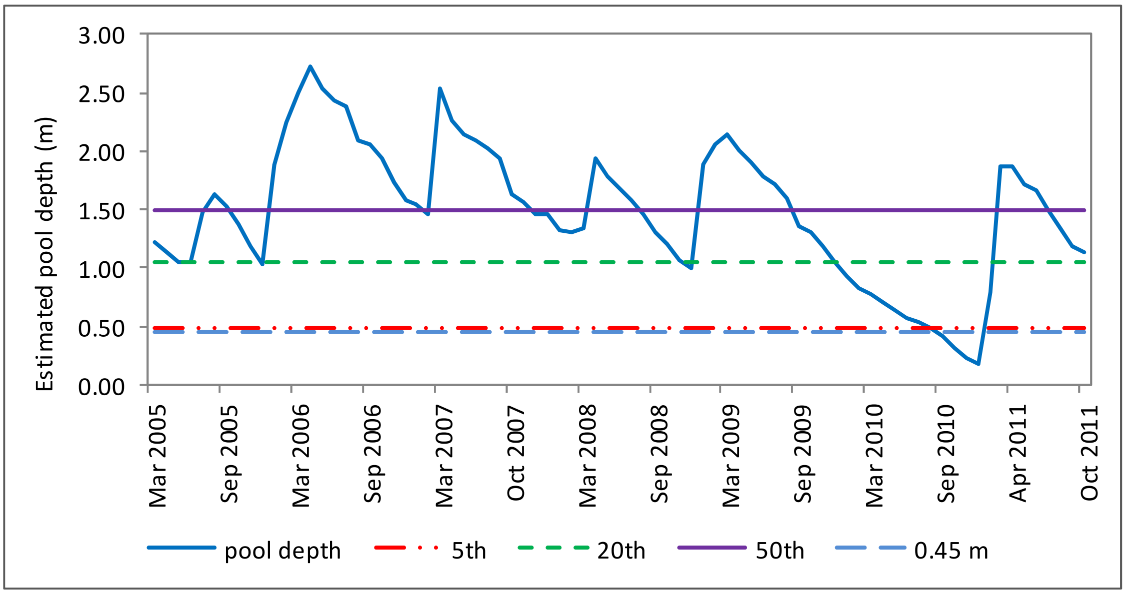
- 9.96 mAHD for Lee Lin Pool
- 31.45 mAHD at bore 21/04 for Highway Pool.

The 5th percentile for Lee Lin Pool was less than 0.45 m deep. This indicates that the threshold depth for provision of macrophyte habitat would not be met under drought conditions. Given that the pool dried out during 2010 this confirms that, under drought conditions, albeit exacerbated by groundwater abstraction, this threshold would not be met. However, in dry (20th percentile) and average (50th percentile) conditions, the pool was deeper than 0.45 m (Figure 13; Table 10).

The 5th, 20th and 50th percentiles of estimated depths of Highway pool were all greater than 0.45 m depth. However, the pool did dry out in late 2010 despite our estimate that some water (shallower than 0.45 m) would be retained in the pool at the groundwater levels experienced at this time (Figure 13).



(a)



(b)

Figure 13 *Pool depth percentiles and 0.45 m depth estimated for (a) Lee Lin Pool and (b) Highway Pool*

Table 10 Summarised macrophyte habitat depth requirement as estimated monthly pool depths and water levels (2005–10)

Pool	Percentile	Estimated pool depth (m)	Water level (mAHD)
Lee Lin	Threshold depth	0.45	9.96
	5th	0	9.31
	20th	0.94	10.45
	50th	1.86	11.38
Highway (bore 21/04)	Threshold depth	0.45	31.45
	5th	0.48	31.48
	20th	1.05	32.05
	50th	1.50	32.5

Recommendation

To meet the ecological threshold for hydro-ecological linkage 4 a minimum pool level of greater than 9.96 mAHD is required at Lee Lin Pool. For Highway Pool a minimum level of 31.45 mAHD measured at bore 21/04 is required.

Given the results of the comparison of these threshold water levels with estimated monthly pool depths, the threshold for Lee Lin Pool is not met in all years. This threshold should therefore not be applied at Lee Lin Pool in ‘drought’ years.

The threshold is estimated to be met in all years at Highway Pool, however given inaccuracy in estimating pool water levels the relationship between pool level and groundwater should be confirmed with surface water monitoring.

Linkage 5: Deeper pools available as habitat

Deep pools provide habitat for larger fish and are the preferred habitat for a subset of species. Pool depth is considered an important indicator of pool stability which has been found to be correlated with fish diversity.

Approach

Previous studies on the De Grey identified intermediate and deep pools as at least 1.2–1.5 m deep. Intermediate and deep pools supported larger (mean fish length), more (abundance) and more species of fish than shallow pools (van Dam et al. 2005).

We have applied a 1.5 m threshold (based on the De Grey study) to identify the occurrence of deep pool habitat for the Yule using the same approach used to determine the ecological thresholds for linkage 4. That is, we calculated maximum pool depths using maximum depth measurements from macroinvertebrate surveys and available monthly water level monitoring for Lee Lin Pool and bore 21/04. Estimated depths were again compared to 5th, 20th and 50th percentiles to provide an indication of how often thresholds for deep pool habitat have been met historically.

Results

The estimated minimum pool or groundwater levels required to maintain a depth of 1.50 m are:

- 11.01 mAHD for Lee Lin Pool
- 32.50 mAHD at bore 21/04 for Highway Pool.

The 50^{th} percentile of depth for Lee Lin was greater than 1.50 m and therefore suggests the pool provides deep pool habitat more than 50% of the time (Figure 14). Pool depths for Highway Pool are estimated to have been above 1.50 m in 50% of months (i.e. 50^{th} percentile equal to 1.50 m).

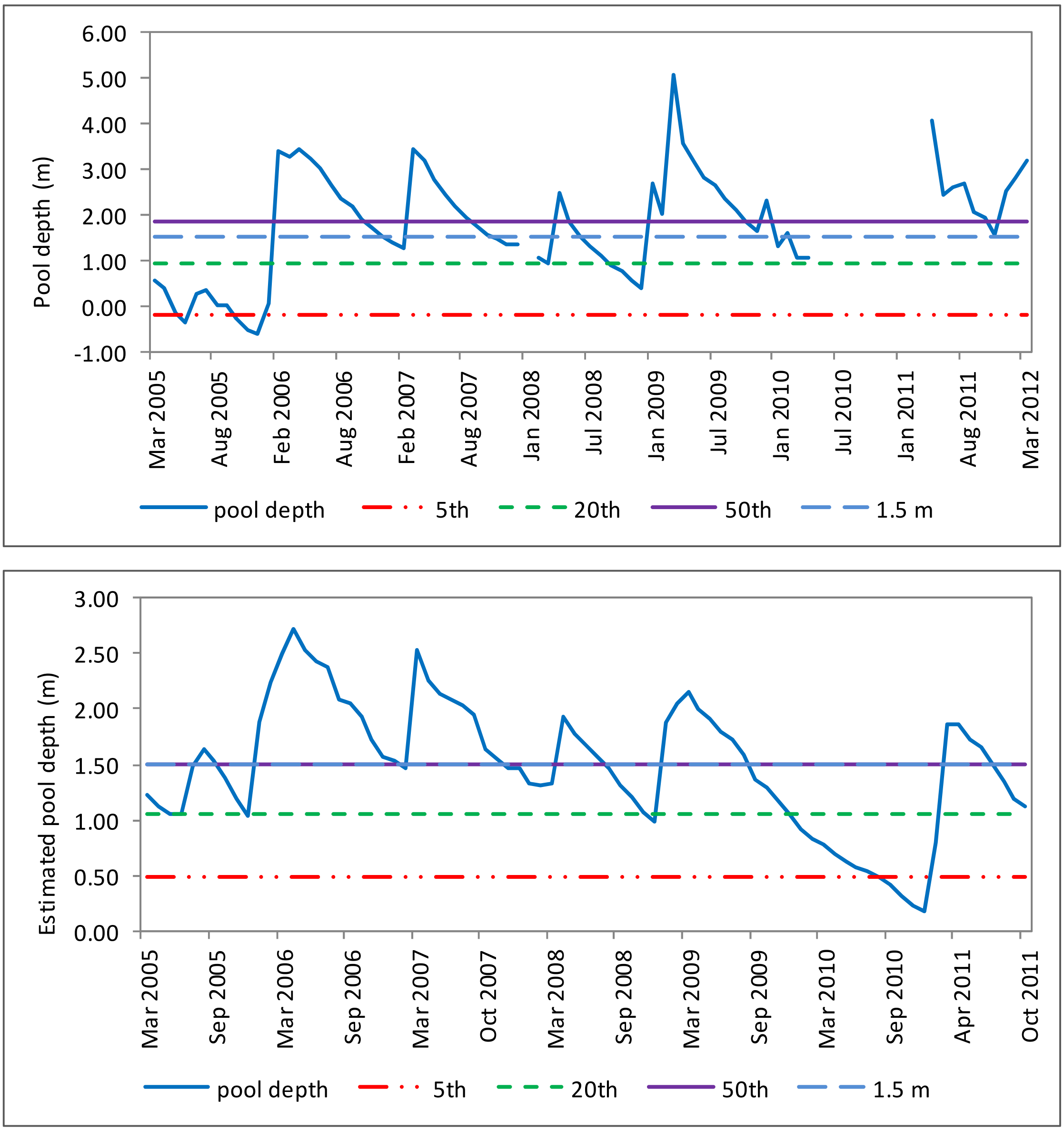


Figure 14 Pool depth percentiles and 1.50 m depth estimated for (a) Lee Lin Pool and (b) Highway Pool

Recommendation

To meet the ecological threshold for hydro-ecological linkage 5 a minimum pool level of greater than 11.01 mAHD is required at Lee Lin Pool. For Highway Pool a minimum level of 32.50 mAHD, measured at bore 21/04, is required.

The results indicate that deep pool habitat (>1.5 m) is not always available in the section of the Yule River within the project area. Maximum pool depths typically exceed 1.5 m in 'average' years or 50% of months or less. However, slightly shallower maximum pool depths 1.00 m or greater are provided in up to 80% of months (20^{th} percentile for both pools approximated 1.00 m maximum depth).

5 Recharge classes

Recharge classes were developed to determine which EWR thresholds should be applied and which linkages will be met in any given year. This approach recognises that climate and groundwater levels at the Yule River are naturally variable.

Given the frequency of droughts in the Yule catchment, it is unrealistic to set EWR thresholds that do not incorporate drought/water stress periods. We also recognised that maintaining groundwater levels at a bare minimum or drought groundwater level would put increased pressure on the ecosystems beyond what could be expected as part of natural variation. This would fail to recognise that a range of water levels are important in maintaining the overall health and resilience of the ecosystems.

Given the critical link between river flow and aquifer recharge, we have developed recharge classes based on river flow. The amount of groundwater recharge depends on a range of flow characteristics including the magnitude, duration and height of river flows. We looked at the correlation between groundwater levels and a range of flow parameters to see which one best predicted recharge. The groundwater data and flow parameters we assessed are shown in Appendix D.

Analyses used groundwater level data from two bores, 17/04 and 21/04, upstream of the Yule bore field to exclude the possible influence of groundwater abstraction. Correlations were calculated using recorded and modelled historical monthly groundwater data and average monthly flow data from the Jelliabidina gauging station. Whilst modelled data provided a longer, more complete dataset it introduced an additional source of uncertainty (modelling error) so we focused on results using recorded monthly groundwater data (2004–10).

Total water year (May to April) flow had the strongest correlation with minimum groundwater levels in the following dry season ($r^2 = 0.68$ for 17/04 and $r^2 = 0.58$ for 21/04). We used dry season minimum groundwater levels as the end of the dry is when critical groundwater EWR thresholds are most likely to be reached.

To establish recharge classes, we calculated total water year flows for the years 1975 to 2011 (excluding 1979, 2003, 2004 and 2005 for which no data were available), plotted a cumulative probability distribution curve and checked for ‘groupings’ (Figure 15; see Appendix E for data).

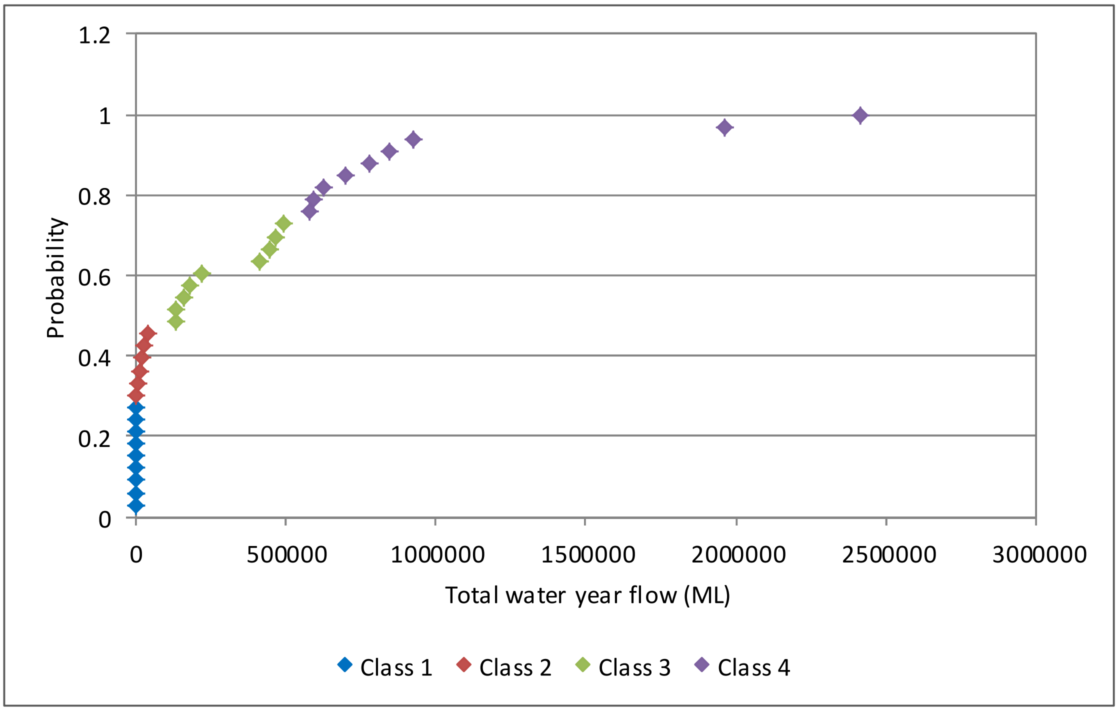


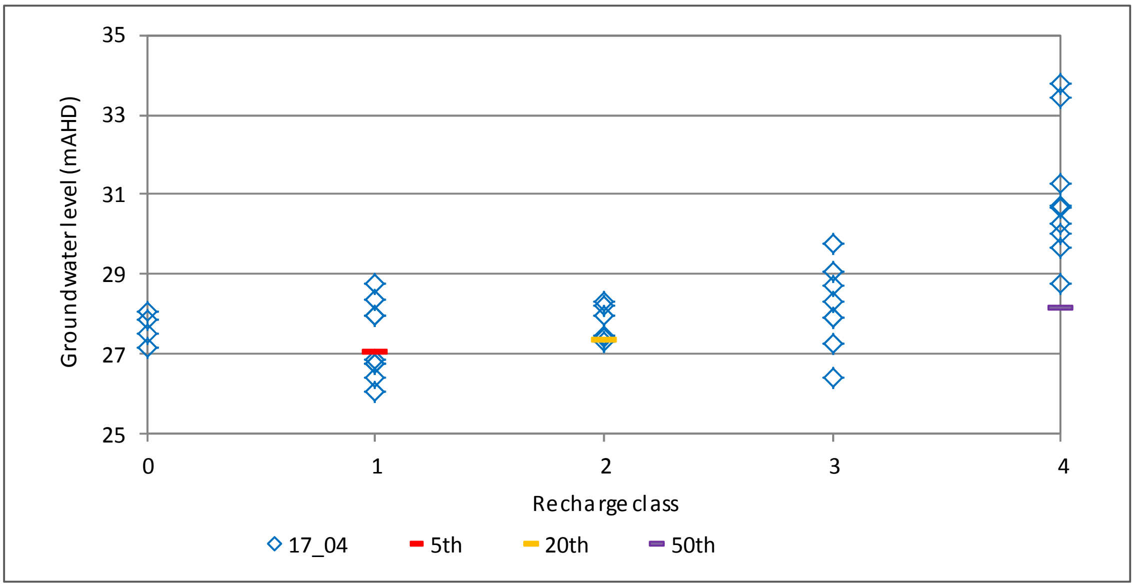
Figure 15 Total water year flow probability distribution curve (1975–2011)

Based on observation of groupings and trial and error the following recharge classes were defined:

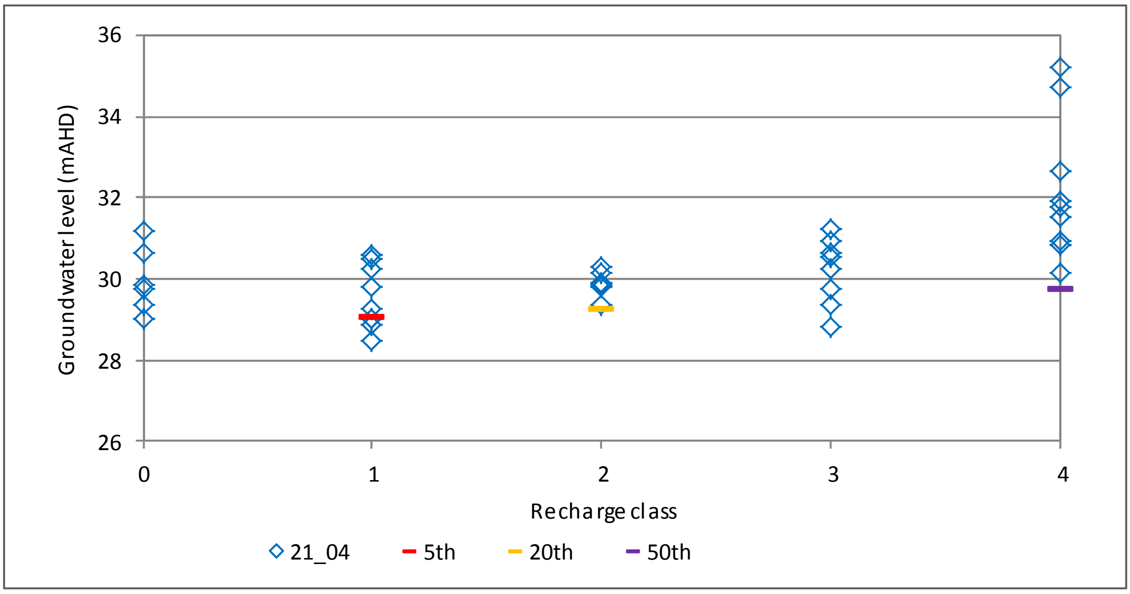
- Class 1 – drought: total water year (May to April) flow less than 3000 ML
- Class 2 – dry: total water year flow 3000 to 50 000 ML
- Class 3 – average: total water year flow 50 000 to 500 000 ML
- Class 4 – above average/ wet: total water year flow greater than 500 000 ML.

Recharge classes were checked against modelled[8] historical groundwater levels (1972–2010) to see how well classes matched the occurrence of threshold levels (Figure 16). This confirmed that, in all recharge Class 4 years, groundwater levels were above the 50th percentile. In Class 3 years, all but two years minimum groundwater levels were above the 20th percentile and above the 20th percentile in all Class 2 years. There were some recharge Class 1 years in which the minimum groundwater levels were below the 5th percentile groundwater level. These results show that the defined recharge classes generally align with the distribution of minimum groundwater levels and the occurrence of groundwater levels below/above thresholds.

[8] We used modelled historical data in this instance to extend the number of years the predictive ability of recharge classes was checked against. Using observed data for these bores would only have allowed checks in 6 years while using modelled historical data allowed a check in 38 years.



(a)



(b)

Figure 16 Minimum groundwater levels for each recharge class at a) bore 17/04 and b) bore 21/04. Red bars represent 5th, 20th and 50th percentile groundwater level thresholds.

6 Ecological water requirements

6.1 Summary of EWR for the system

The EWR we have developed varies each water year based on river flow (as our estimate of the recharge to the aquifer). Total water year flow (from 1 May to 30 April) is used to determine a recharge class for the following year. Based on the recharge class, the applicable EWR thresholds are set. That is, not all thresholds apply every year and so not all the linkages are satisfied each year.

Table 11 sets out which thresholds apply in each recharge class. For example, in drought years when river flow has been below 3000 ML, the 95th percentile threshold for linkage 1 and 5th percentile for linkage 3 apply. If river flows are large (500 000 ML or greater), thresholds for linkages 2, 3, 5 and 6 are expected to be satisfied in full.

Thresholds for each site, for each linkage, are summarised in Table 12.

Table 11 Thresholds applied by recharge class

Linkage	Threshold	Recharge class	Applicable at site
1 – Minimum groundwater levels for riparian vegetation	Maximum depth to groundwater less than:		All
	95th percentile	1	
	80th percentile	2	
2 – Periods of higher water availability for riparian vegetation	Minimum depth to groundwater greater than: 50th percentile	4	All
3 – Groundwater levels to maintain pools	5th percentile	1	Lee Lin Pool, Bore 21_04
	50th percentile	3 & 4	
	90th percentile	4	
4 – Macrophyte habitat available	Minimum pool depth of 0.45 m	2	Lee Lin Pool
5 – Deep pool habitat available	Minimum pool depth of 1.5 m	3 & 4	Lee Lin Pool
6 – Water quality in pools maintained	Minimum pool depth 1.5 m	3 & 4	Lee Lin Pool

Table 12 EWR thresholds for each site and linkage

Site reference (Bore number)	Linkage and thresholds					
	1 – Minimum groundwater levels (mbgl)	2 – Higher water availability (mbgl)	3 – Maintain pools (mAHD)	4 – Macrophyte habitat (mAHD)	5 – Deep pool habitat (mAHD)	6 – Pool water quality (mAHD)
8/04	Medium risk 9.64 m High risk 10.59 m	8.10 m	NA	NA	NA	NA
10/04	Medium risk 8.93 m High risk 10.30 m	6.62 m	NA	NA	NA	NA
12/04	Medium risk 6.89 m High risk 9.10 m	5.81 m	NA	NA	NA	NA
13/04	Medium risk 5.90 m High risk 7.83 m	5.09 m	NA	NA	NA	NA
14/04	Medium risk 9.03 m High risk 10.37 m	8.00 m	NA	NA	NA	NA
15/04	Medium risk 7.70 m High risk 8.48 m	6.65 m	NA	NA	NA	NA
34/04	Medium risk 5.83 m High risk 6.48 m	5.19 m	NA	NA	NA	NA
37/04 (Lee Lin Pool)	Medium risk 9.61 m High risk 10.32 m	8.18 m	5^{th} percentile 9.31 m 50^{th} percentile 11.38 m	9.96 m	11.01 m	11.01 m
17/04	Medium risk 7.36 m High risk 8.03 m	6.84 m	NA	NA	NA	NA
21/04 (Highway Pool)	Medium risk 5.50 m High risk 6.08 m	5.04 m	5^{th} percentile 31.48 m 50^{th} percentile 32.50 m	31.45 m	32.50 m	32.50 m

Appendices

Appendix A Yule trial methods and results

Objective of the pumping trial

The objective of the pumping trial was to test the capacity of the resource to deliver an annual volume of 8.5 GL/yr. The intent was to test the capacity of the resource both in terms of the groundwater response and response of dependent ecosystems. Groundwater response data from the trial was used to revise the groundwater model for the aquifer and is not the focus of this report.

The ecological monitoring during the trial focused on riparian tree species. This was because they are the dominant groundwater dependent ecosystem at the site and the species occurring at the Yule River are common to riparian ecosystems across the Pilbara (and so results and knowledge gained could be transferable to other similar sites).

The trial ran from December 2008 to April 2011 as a collaboration between Department of Water, the Water Corporation, The University of Western Australia and the University of Sydney.

The agreed objectives of the ecological studies were:

- Characterise the sources of water used by key groundwater-dependent species.
- Inform or enable the development of ecological response functions of key groundwater-dependent species to altered hydrological regimes.
- Provide guidance on suitable monitoring techniques for groundwater dependent vegetation to facilitate ongoing management.

Design and data collection

The trial was designed on a before – after – control – impact (BACI) design. Site selection was based on availability and location of existing monitoring bores and distribution of suitable stands of riparian vegetation. An existing groundwater model developed by the Water Corporation was used to confirm whether control sites would be outside the zone of groundwater drawdown (Water Corporation 2009).

Based on the suitability of available groundwater monitoring bores and vegetation and informed by the results of the preliminary groundwater modelling the impact site was established at bore 10/04, an intermediary impact site was established at bore 14/04 and a control site established at bore 17/04.

River flow throughout the trial was monitored via the Department of Water's existing Jelliabidina gauging station (Jelliabidina Well – WIN reference number 709005).

Groundwater levels at control, impact and intermediate sites (and additional sites across the borefield) were monitored monthly by the Water Corporation. The Department of Water also installed un-vented pressure data loggers (*levelTroll 100* and later *levelTroll 300* water level sensors *In-situ Inc.*) to continuously record (15–30 minute intervals) groundwater levels. Data loggers were installed in the control, impact and intermediate sites and an additional seven vegetation monitoring bores across the borefield. Barometric pressure sensors (BaroTroll) were also installed at two sites (10/04 and 13/04) and used to correct water level data for atmospheric pressure as part of data calibration.

Soil moisture data was collected using a neutron probe accessing existing bore holes for sites 8/04, 10/04, 11/04, 13/04, 14/04, 16/04 and 17/04. Two to three access tubes were installed specifically for soil moisture monitoring amongst riparian vegetation (as distinct from bore locations up on the river bank) at the control, impact and intermediate sites. Soil profiles were collected from control, impact and intermediate sites and at sites adjacent to bores 11/04 and 13/04. Samples from soil cores were analysed to confirm soil moisture (for calibration) and properties (bulk density, field volumetric water content and hydraulic conductivity). Soil moisture data was collected using the neutron probe approximately monthly over the course of the trial.

Meteorological data was collected over the course of the trial from a weather station installed at the impact site. Air temperature (T, ^oC), relative humidity (RH, %), rainfall (mm), wind speed (ms^{-1}), wind direction (^oN) and photosynthetic radiation (PAR) were recorded by the station from October 2008 to the end of the trial.

Eco-physiological monitoring was undertaken initially by researchers from The University of Western Australia (UWA) and the University of Sydney (USyd) and then by Astron Environmental. Monitoring at the control and impact sites included continuous monitoring of tree water use (sapflow) and a series of eight intensive monitoring campaigns (Table A1). The monitoring focused on the responses of the dominant riparian species *Eucalyptus victrix, E. camaldulensis* and *Melaleuca argentea* to changes in water availability.

Sapflow derived estimates of tree water use followed the Heat Ratio Method (Burgess et al. 2001). Initially[9] three to five trees were instrumented at the control and impact sites following the same procedure and using the same equipment as described by Pfautsch et al. (2011). Probes were installed in above-ground stems and data was collected every 30 minutes. Stem cross sections were sampled in May 2010 to quantify sapwood area and allow tree water use to be estimated (Grierson et al. 2010).

[9] UWA and USyd monitoring included 3–5 trees of each species at each site. Astron monitoring later in the trial instrumented two trees of each species at each site.

Table A1 Monitoring campaigns conducted during the pumping trial

Campaign date	Monitoring conducted by
27–29/3/09	UWA/Usyd
21–24/4/09	UWA/Usyd
23–26/11/09	UWA/Usyd
10–15/5/10	UWA/Usyd
6–9/9/10	Astron
8–11/11/10	Astron
11–13/01/11	Astron
20–23/04/11	Astron

During the campaigns, additional parameters were measured:

- Leaf water potential (LWP) – Both pre-dawn and midday leaf water potentials were measured to assess the response of vegetation to changing water availability. Diurnal (hourly measurements over 12–24 hr periods) were measured to assess daily water stress cycles during the 2009, May 2010 and November 2010 campaigns.
- Leaf porometry – This is a measure of stomatal conductance or the degree of stomatal opening which is an important measure related to plant water status (Eamus et al. 2006).
- Isotopes – Leaf, groundwater and soil water samples taken to confirm sources of water used by vegetation (i.e. through analysis of ^{18}O and ^{2}H isotopes).

Leaf water potential was sampled using standard pressure bomb techniques with samples taken from each of the sapflux instrumented trees. Pre-dawn, midday and (during two campaigns) diurnal leaf water potentials were measured.

There was a change in methodology used in sampling LWP between the May and September campaigns with the change from UWA/Usyd to Astron environmental. LWP measurements up to May were taken immediately (within a few minutes) of stems being removed from the trees. Samples were taken from the top of the canopy using an elevated work platform. From September 2010 the sampling procedure was to remove the stems, store them in sealed bags in an esky immediately after collection, and measure LWP within 30 minutes of sampling. Samples were taken from the mid canopy.

Trees instrumented for sapflow and sampled for LWP also changed between May 2010 and September 2010 campaigns (refer to Astron 2011 for details).

Leaf porometry data was collected during campaigns from March 2009 until May 2010.

Later campaigns (from May 2010 onwards) also quantified canopy cover (using leaf area index) within all three of the monitoring sites (i.e. including the intermediate site 14/04) using photographic techniques (Macfarlane et al. 2007). Qualitative assessments of tree stress were also conducted at all sites (control, impact and intermediate) from September 2010 onwards (Astron 2011).

Additional data including stem water potential and leaf gas exchange were also collected during the trial but have not been reported here.

Statistical analyses of the trial results were constrained by changes in methodology and replication in key physiological measures, i.e. leaf water potential and sapflow. Repeated measures ANOVA of leaf water potential were the main analyses completed. Where interactions between factors were significant further analyses of main effects (repeated measures ANOVA) were also completed. Problems with continuity in replication of leaf water potential were overcome by focusing on the results for September 2010 onwards.

Results

River flow and groundwater levels

Groundwater levels at the start of the trial period (in December 2008) were comparatively low, following a virtually ‘failed’ 2007/2008 wet season (Figure A1). Low but sustained river flow in the 2008/09 wet season led to recovery in the groundwater levels over the first few months of 2009.

Groundwater levels declined (depth to groundwater increased) from March 2009 to January 2011. Over this period, the depth to groundwater in bores 10/04 and 14/04 increased by 5.40 m and 4.50 m (5.20 m to 10.61 m bgl and 6.21 m to 10.71 m bgl) respectively. In comparison, the depth to groundwater at the control site – bore 17/04 – increased by 2.22 m (from 6.02 m in March 2009 to 8.24 m bgl in January 2011).

Depths to groundwater from early 2010 onwards at all trial sites exceeded previous maximums (10/04 = 9.48 m, 14/04 = 9.07 m and 17/04 = 7.46 m bgl). Bores across the borefield with longer-term records indicated groundwater levels were near to or exceeded maximum historical recorded depths in late 2010/early 2011 (Figure A2).

River flow in February and March 2011 recharged the aquifer and groundwater levels recovered. From peak levels in late February–early March[10] groundwater declined through to April 2011. Groundwater levels remained relatively high across the borefield between January and April 2011.

[10] Groundwater data for these months is from data logger; rain meant the site wasn’t accessible for monthly water level monitoring.

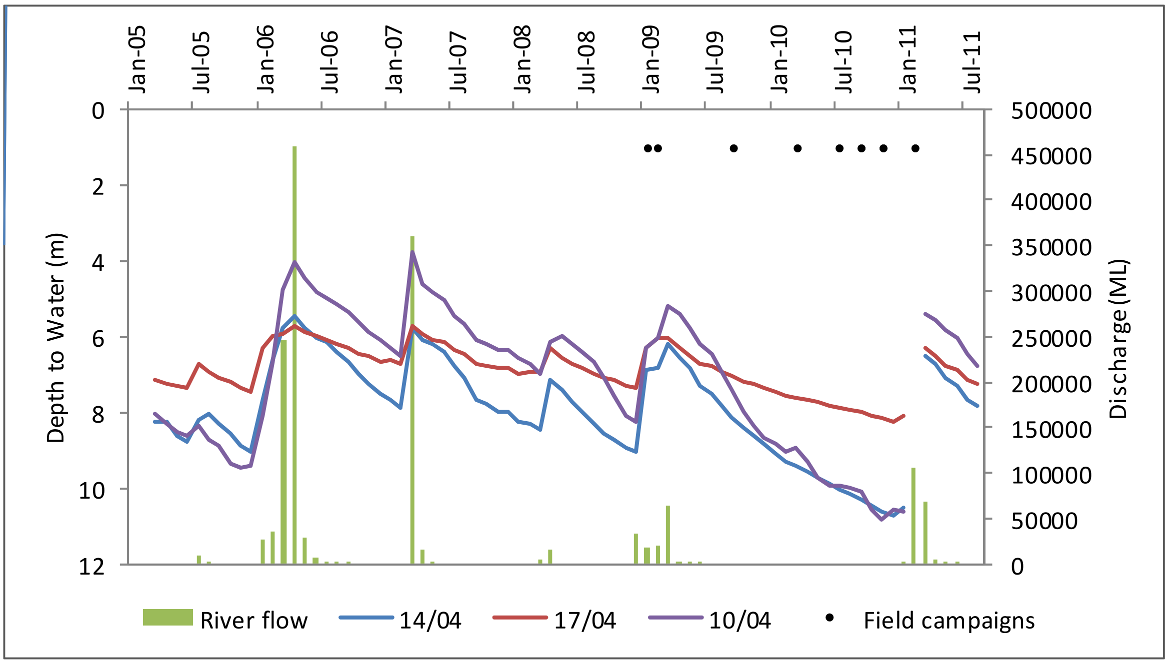


Figure A1 Groundwater level (as depth to groundwater) for control, impact and intermediate impact sites and river flow (as monthly total discharge) from March 2005 to August 2011

Riparian species

Eco-physiological data

DNA analysis of leaf samples from instrumented (sapflow) eucalypts at both control and impact sites confirmed a mix of *Eucalyptus camaldulensis* and *E. victrix* from trees thought to be *E. camaldulensis* (based on morphology). The results for these two species have therefore been combined and treated as a functional group (*E. victrix/camaldulensis*). Both species were occurring across the same zone within the river channel and along the river bank at both sites.

Monitored *E. victrix/camaldulensis* (*Eucalyptus* spp.) and *M. argentea* at control and impact sites showed declining water use, as estimated from sapflow velocities, over the trial period (Figure A3). There was some indication that water availability was affecting vegetation function at the impact site as early as November/December 2009. That is, at the impact site, tree water use on particularly hot dry days showed a midday depression suggesting trees were shutting stomata during the hottest part of the day to limit water use (Figure A4).

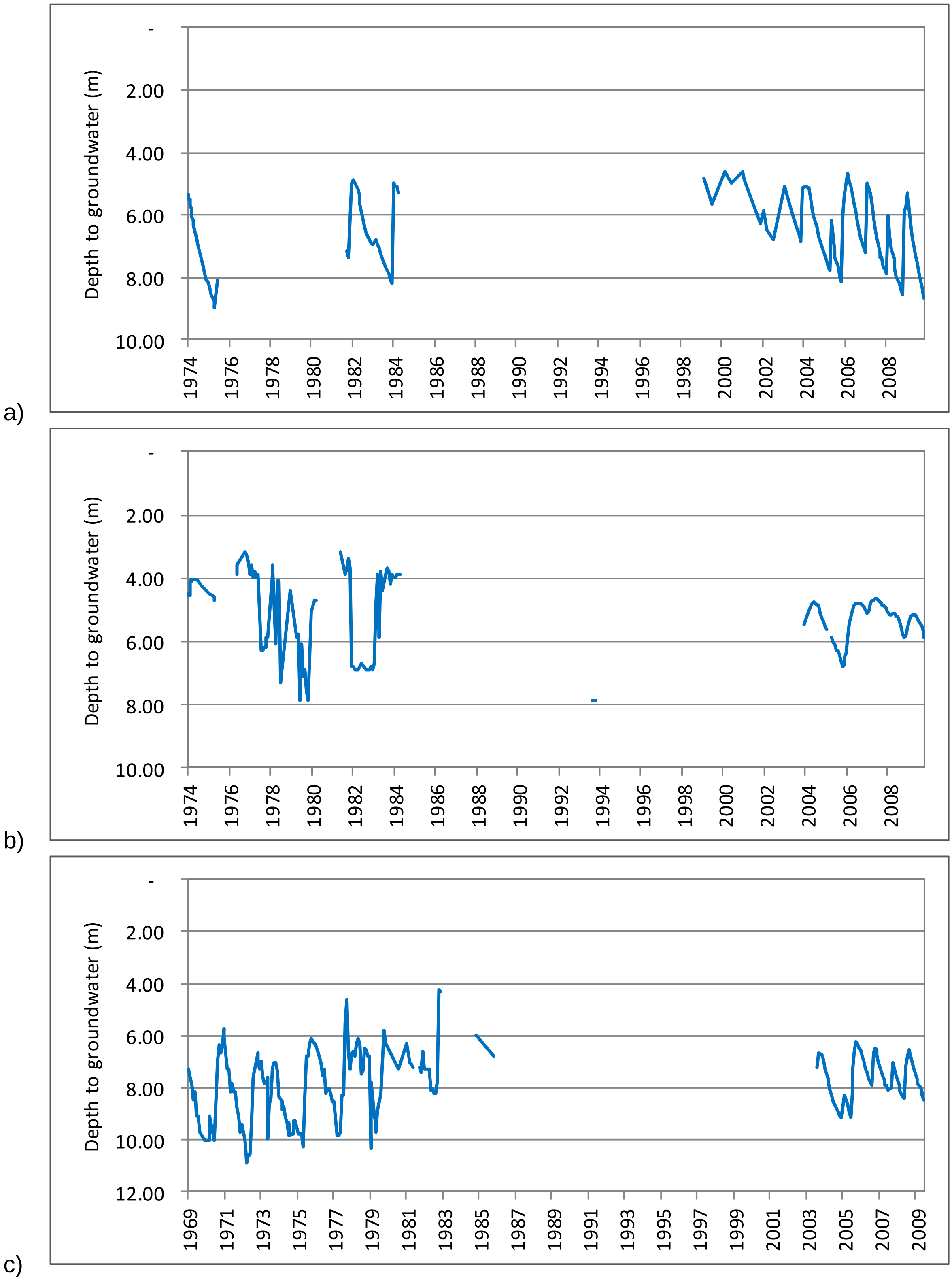


Figure A2 Groundwater level (as depth to groundwater) for long-term monitoring bores (a) 1/73 (b) 14/96 and (c) 5/67

Results of the campaigns from March to November 2009 did not show additional responses in vegetation to altered water availability. That is, leaf water potentials

(Figure A5) and stomatal conductance data did not show differences in response between control and impact sites or indicate additional signs of plant water stress.

The midday depressions in sapflow velocities (and tree water use) are considered a response to weather conditions in combination with relatively minor changes in water availability. Both groundwater levels and soil moisture (and plant available water content across most of the soil horizon) declined over this period (Figure A1 & Figure A6). However, these changes are within the normal range of groundwater levels at the site and are considered likely to be within the normal range of water availability.

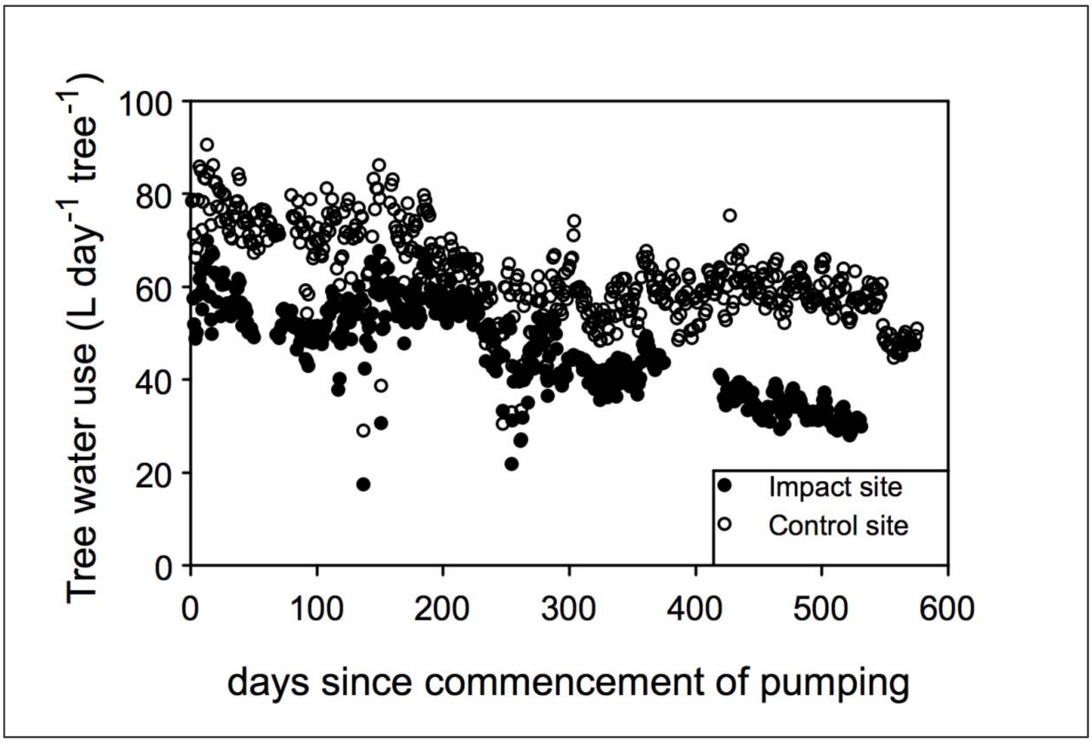


Figure A3 Average daily water use as estimated from sapflow of Eucalyptus victrix/camaldulensis *from 02/10/2008 to 10/05/2010*

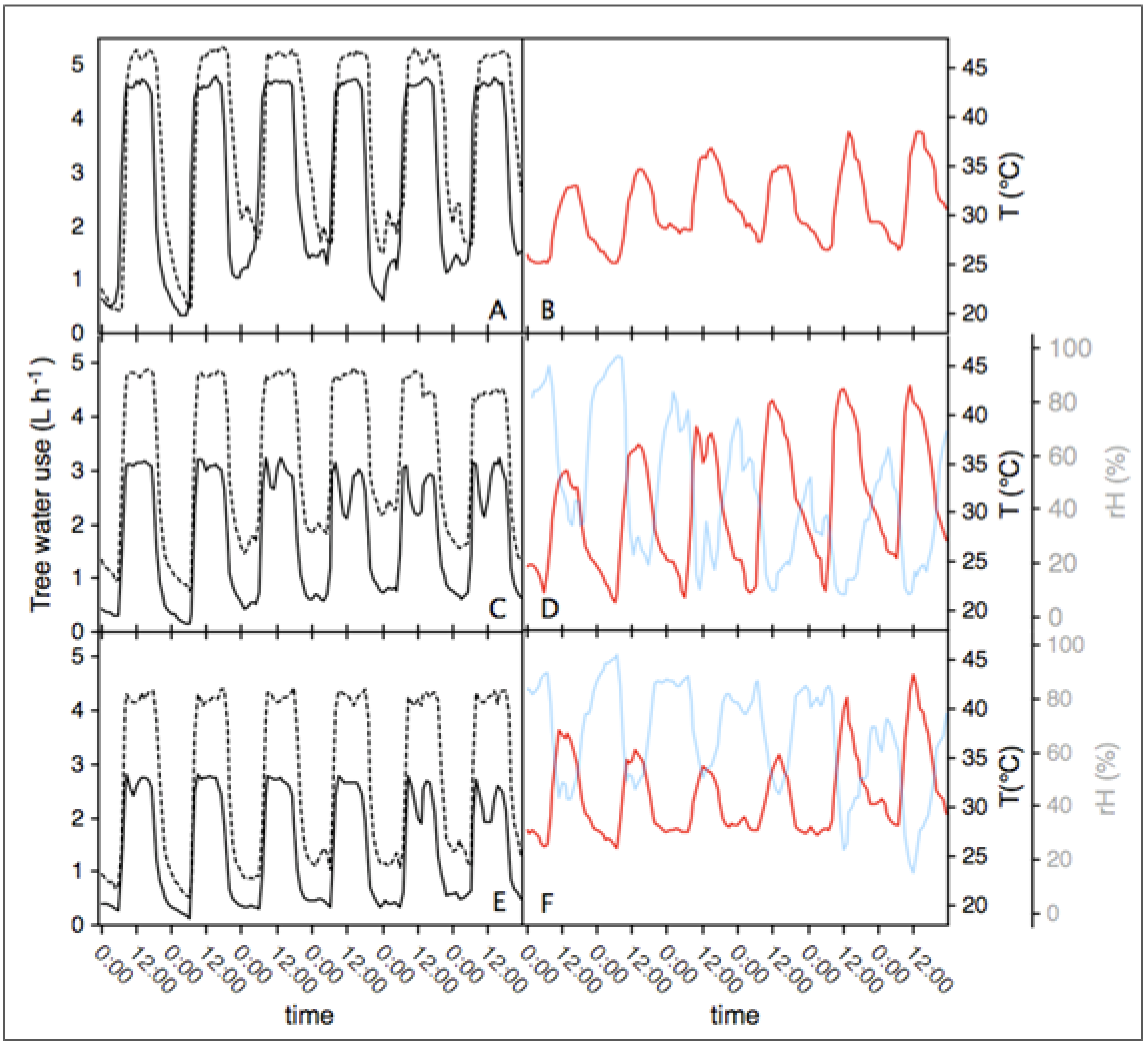
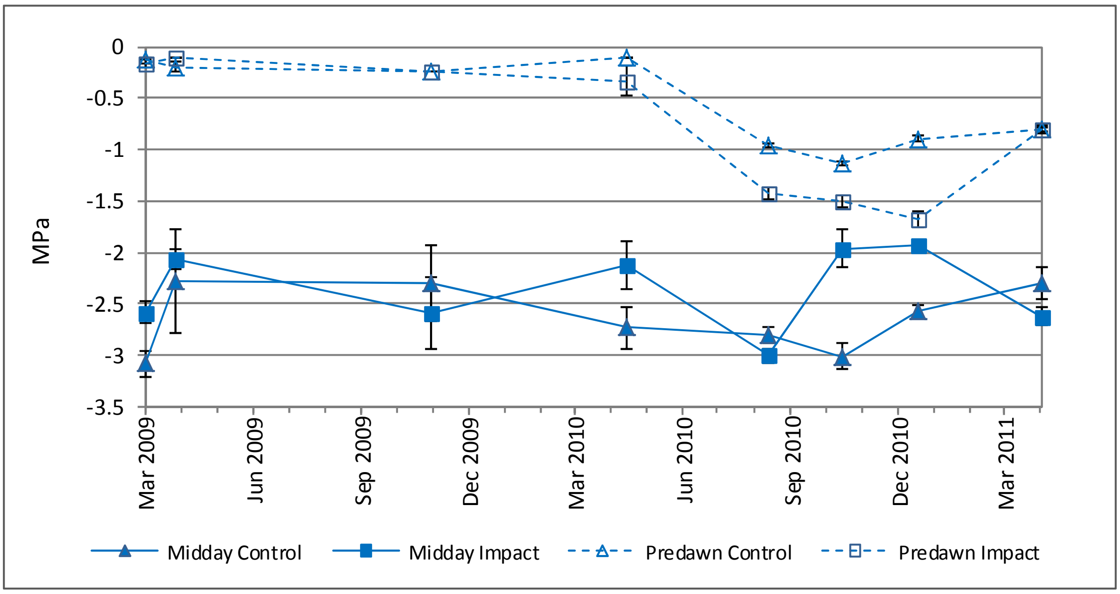


Figure A4 *Diurnal patterns of tree water use of* Eucalyptus spp. *at the control (dashed line) and impact (solid black line) sites. Average air temperatures (T, red line), and where available relative humidity (rH, blue line). Data shown was recorded at end of the 1st wet season (20–25/02/2009; panels A, B), end of the following dry season (27/11–02/12/2009; panels C, D) and the end of the 2nd wet season (20–25/02/2010; panels E, F).*

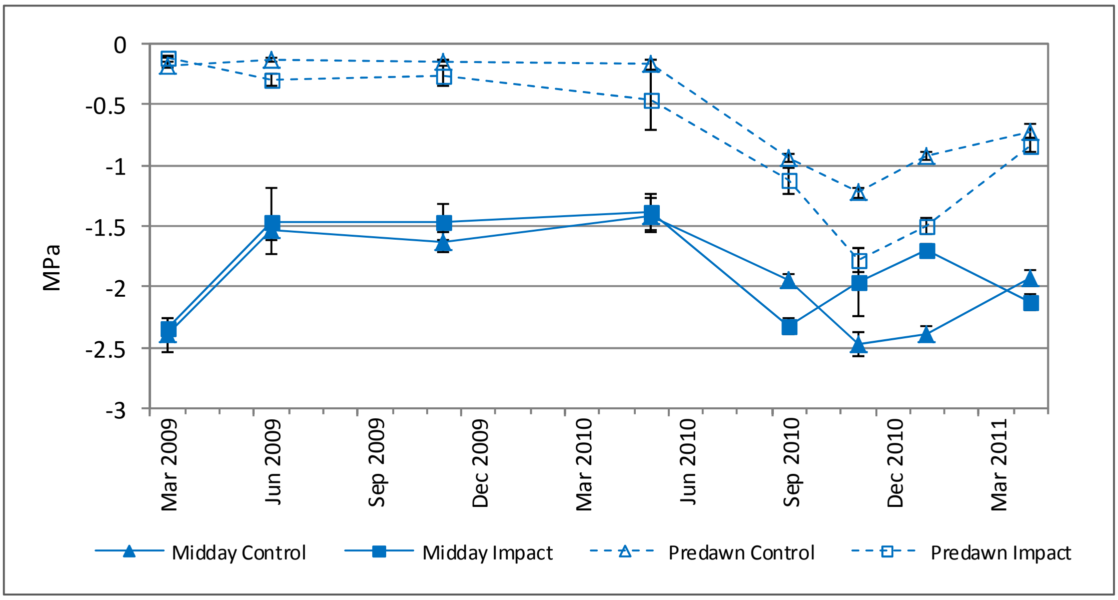
Most of the May 2010 campaign results were similar to previous campaigns however, leaf water potentials for smaller *Melaleuca argentea* at the impact site showed some early indications of increased water stress (E McLean pers. comm). Canopy thinning of *Eucalyptus* spp. was also observed visually across both sites during the May campaign. This is a common response in eucalypts (and other species) to water limitation (Eamus et al. 2006, Merchant et al. 2007) and is likely due to the prolonged no recharge/declining groundwater experienced across the project area. These results coincided with depths to groundwater exceeding previously recorded maximums at all three sites between January and May 2010. Soil moisture levels reached minimum levels recorded over the trial late (December) in 2010 (Figure A6).

Quantitative canopy cover data was collected for the first time during the May 2010 campaign.

This increasing stress response was confirmed by results of the September 2010 campaign which recorded pre-dawn leaf water potentials for *Eucalyptus* spp. at the impact site that were significantly more negative than the control site ($t(8) = 5.22$, $p = 0.001$; Figure A5).

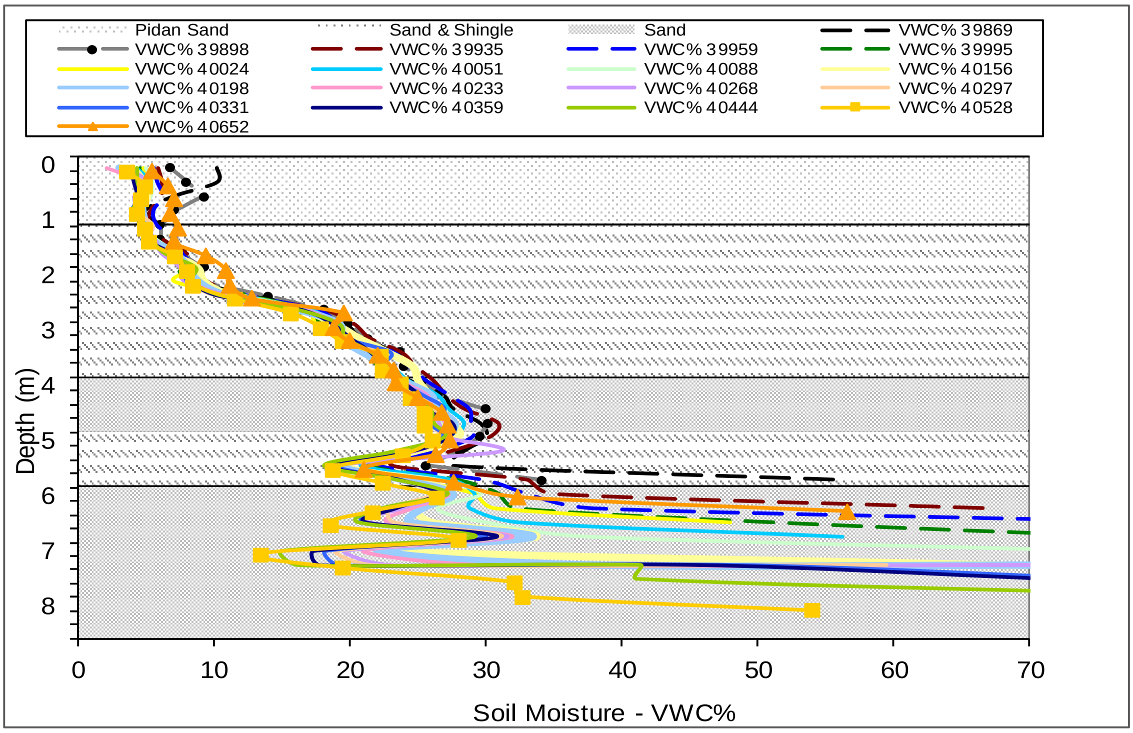


(a)

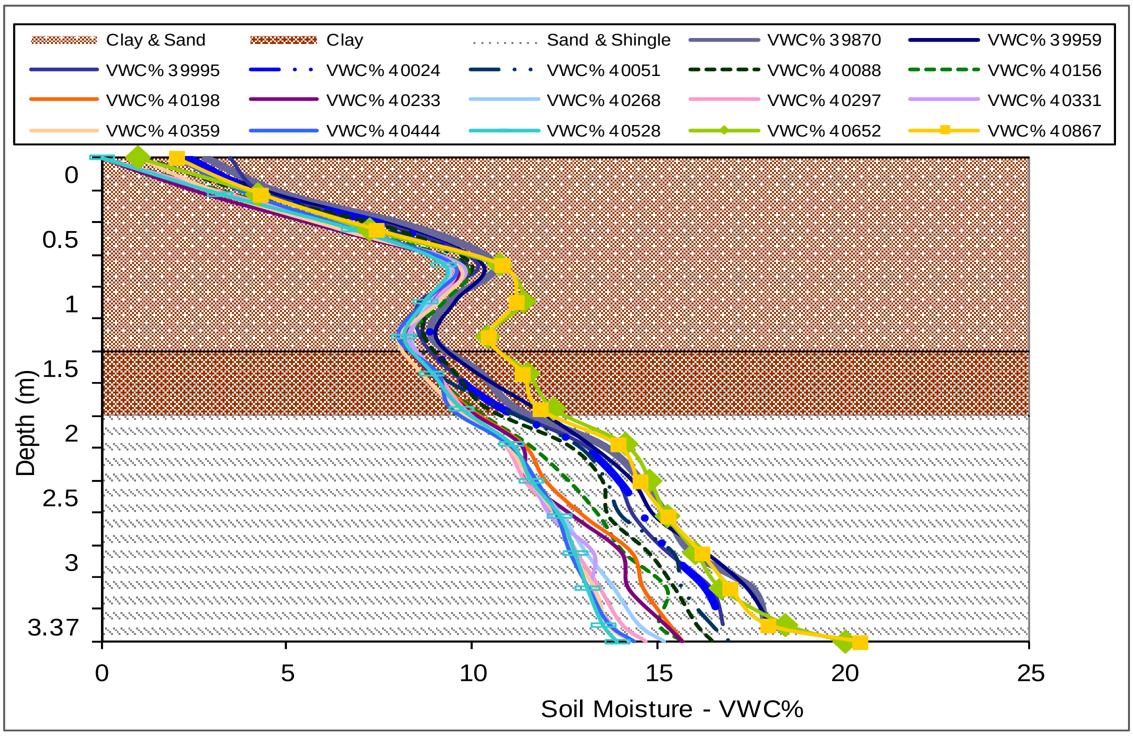


(b)

Figure A5 *Pre-dawn and midday leaf water potential measurements for (a)* Eucalyptus victrix/camaldulensis *and (b)* Melaleuca argentea *for measurement campaigns completed over the trial period*

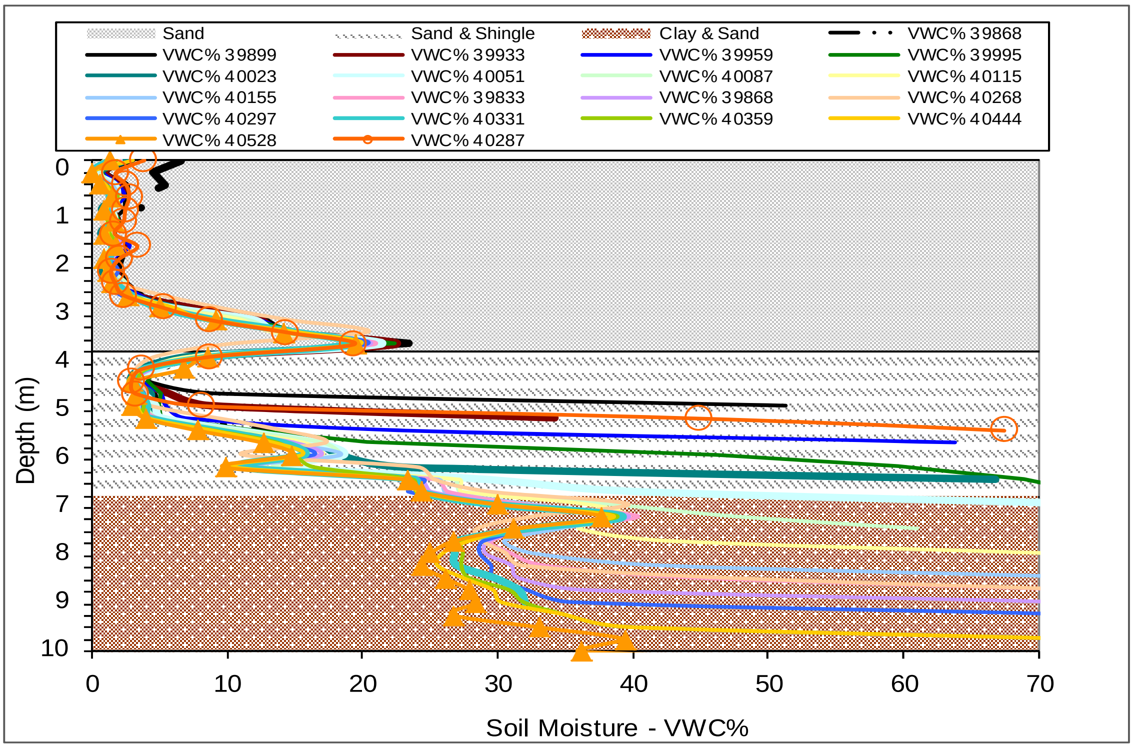

Pidan Sand
Sand & Shingle
Sand
VWC% 39869
VWC% 39898
VWC% 39935
VWC% 39959
VWC% 39995
VWC% 40024
VWC% 40051
VWC% 40088
VWC% 40156
VWC% 40198
VWC% 40233
VWC% 40268
VWC% 40297
VWC% 40331
VWC% 40359
VWC% 40444
VWC% 40528
VWC% 40652
Depth (m)
0
1
2
3
4
5
6
7
8
0
10
20
30
40
50
60
70
Soil Moisture - VWC%

a)


Clay & Sand
Clay
Sand & Shingle
VWC% 39870
VWC% 39959
VWC% 39995
VWC% 40024
VWC% 40051
VWC% 40088
VWC% 40156
VWC% 40198
VWC% 40233
VWC% 40268
VWC% 40297
VWC% 40331
VWC% 40359
VWC% 40444
VWC% 40528
VWC% 40652
VWC% 40867
Depth (m)
0
0.5
1
1.5
2
2.5
3
3.37
0
5
10
15
20
25
Soil Moisture - VWC%

b)

c)



d)

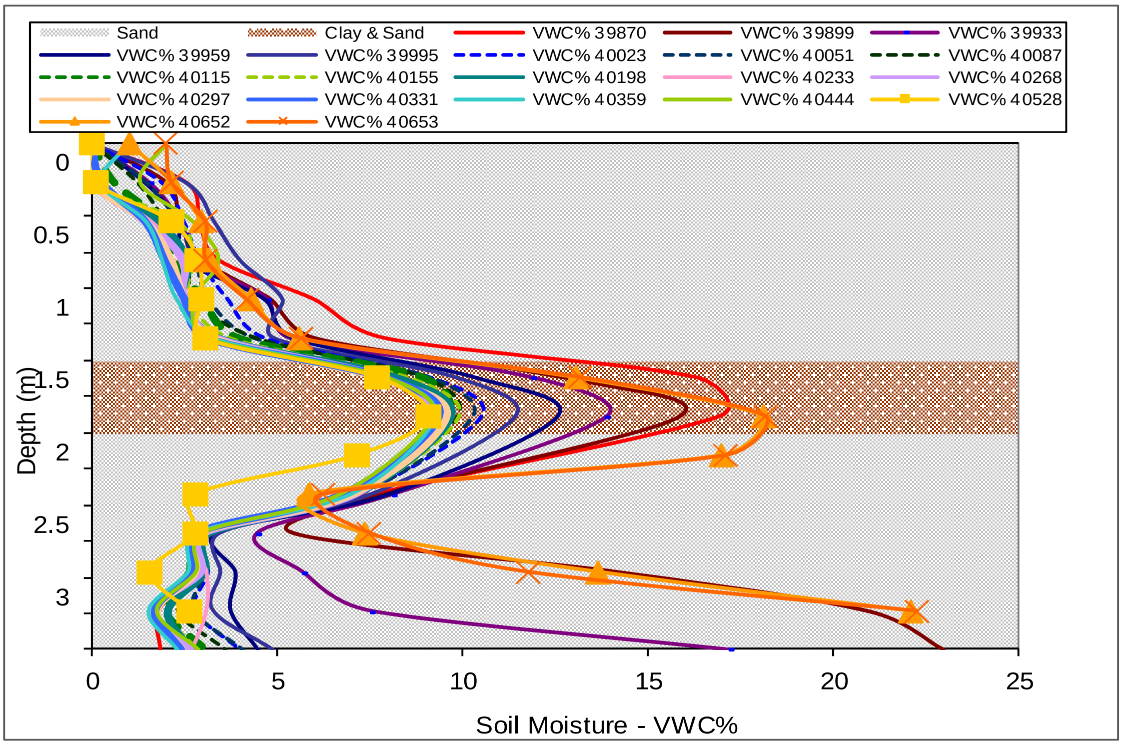


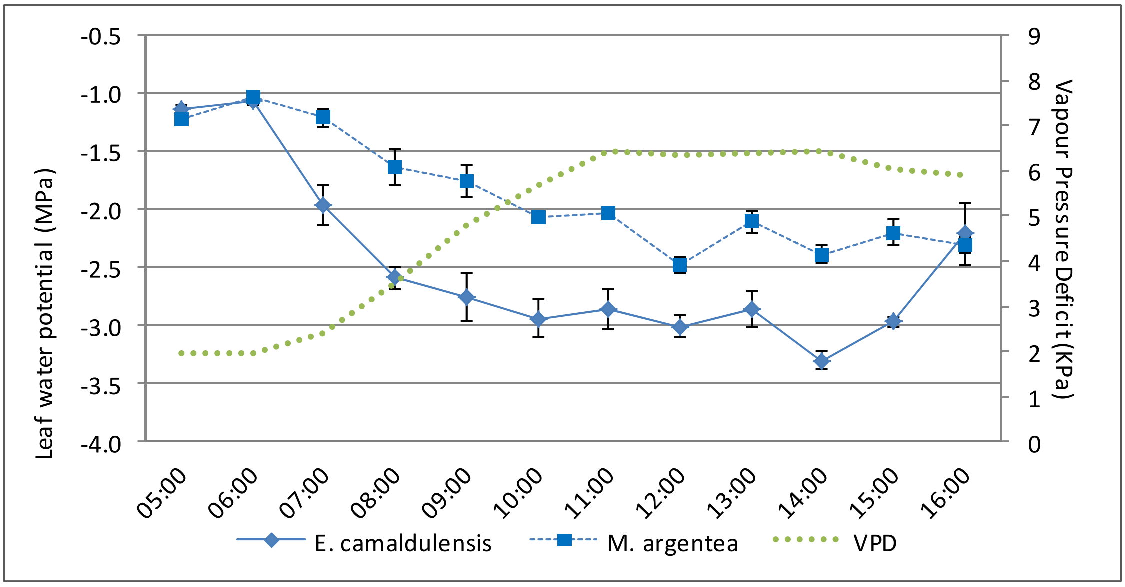
Figure A6 a) 17_04 bore b) 17_04 soil moisture tube 2 c)10_04 bore d) 10_04 soil moisture tube 2

Pre-dawn leaf water potentials for both species for campaigns after May 2010 were overall lower at the impact site compared with the control site (*Melaleuca argentea* $F(1,8) = 8.96$, $p = 0.017$, *partial* $\eta^2 = 0.53$ and *Eucalyptus victrix/camaldulensis* $F(1,8) = 98.49$, $p < 0.001$, *partial* $\eta^2 = 0.93$).

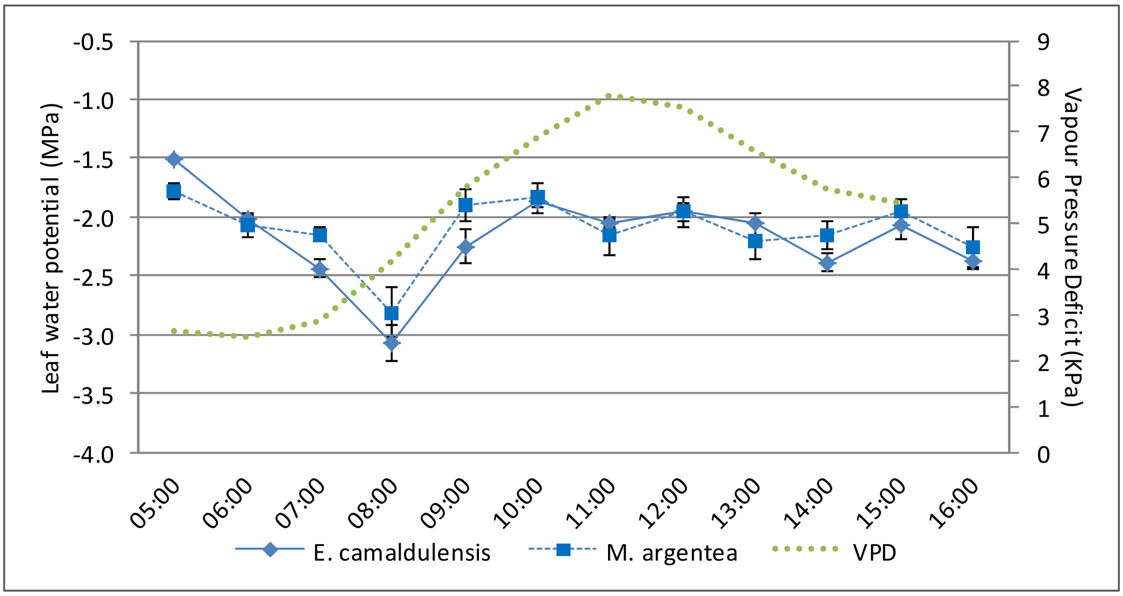
Monitoring results indicated that water stress increased between September and November 2010. For *M. argentea*, leaf water potentials (pre-dawn) recorded in November were lower than in September across control and impact sites ($F(1,8) = 92.19$, $p < 0.001$, *partial* $\eta^2 = 0.92$), indicating increasing water stress. For *Eucalyptus victrix/camaldulensis* the difference in pre-dawn leaf water potentials from September to November was significant only at the control site ($F(1,4) = 19.66$, $p = 0.011$, *partial* $\eta^2 = 0.831$).

Comparison of pre-dawn and midday leaf water potentials supports an increased water stress response between September and November 2010. Leaf water potentials at the impact site are similar for pre-dawn and midday readings during the November and January campaigns. This could be the result of vegetation not being able to rehydrate overnight. These results coincided with record low groundwater levels across the borefield and minimum soil moisture levels recorded for the trial period.

During the November 2010 campaign leaf water potential was measured hourly from 5:00 am to 5:00 pm. This provided additional detail on plant water use during the day. At the impact site leaf water potentials indicated stomatal closure by 8:00 am (Figure A7). The responses in leaf water potential at the impact site appear to indicate limited water availability and impaired plant functionality at this site.



a)



b)

Figure A7 Diurnal leaf water potential for Control (a) and Impact (b) sites from the November 2010 campaign

Declines in projected canopy cover were recorded across both control and impact sites from September to November 2010 (Astron 2011) but there was no change at the intermediate site.

Signs of water stress were still evident in January 2011. Pre-dawn and midday leaf water potentials at the impact site were still similar. There was slight recovery in pre-dawn leaf water potential between November 2010 and January 2011 for both species at the control site and *Melaleuca argentea* at the impact site. This may indicate some recovery in water status of the vegetation which could be in response to rainfall (in December and early January) and lower Vapour Pressure Deficit (VPD; due to increased humidity).

By the April 2011 campaign, groundwater levels and soil moisture availability had recovered to near pre-trial levels. Leaf water potential, canopy cover and qualitative health ratings all indicated that plant water status had recovered at the control, impact and intermediate sites.

Conclusions

Changes in methodology for sampling leaf water potential from May 2010 to September 2010 and onwards present some possible issues with interpretation of these results. However, midday leaf water potentials are comparable throughout the trial for *Eucalytpus victrix/camaldulensis*. This suggests that both techniques produced comparable results. Pre-dawn leaf water potentials for both species at both sites are lower (more negative) from September 2010 onwards coinciding with the change in sampling. Influence of the sampling technique on the results cannot be excluded. However, while the methodology may have influenced the absolute values for LWP (for pre-dawns) the relative change in time from September 2010 through to April 2011 was not influenced by changes in methodology. Neither were the diurnal recordings during November 2010 or comparisons between pre-dawn and midday values and lack of recovery of pre-dawn LWP during November 2010 and January 2011.

Trial results have demonstrated increasing vegetation response to prolonged declines in soil water and groundwater. The response in multiple vegetation parameters supported our conclusions that plant water status reached critical/near critical levels late in 2010/early 2011. This coincided with low water availability as demonstrated by record low water table levels across much of the borefield and low soil water availability.

We have used groundwater levels recorded prior to the May 2010 and November 2010 campaigns to define thresholds. That is, based on the results of the trial we predict that there is moderate risk of impact to vegetation from water stress if depths to groundwater greater than those experienced up until the May campaign are exceeded. We have also concluded that there is a high risk of impact to vegetation if depths to groundwater greater than those experienced up until November are exceeded.

Appendix B Details of river pools within the Yule project area

Pool name (if known)	Oct 99	Jan 02	Feb 03	Oct 03	Jun 04	Jan 05	Defined permanency
	Estimated inundation area (m²)						
Lee Lin	15 749	12 609	412 834	20 744	43 274	1 270	Permanent
Unknown	8 180	9 435	63 409	19 475	22 590	1 895	Permanent
Unknown	32 759	9 470	39 654	19 549	31 479	0	Semi-permanent
Unknown	17 650	635	20 184	14 500	13 250	0	Semi-permanent
Unknown	4 435	0	6 340	1270	635	0	Semi-permanent
Unknown	0	8 195	412 834	26 380	28 870	4 420	Semi-permanent
Unknown	2 525	0	14 455	3 785	5035	0	Semi-permanent
Unnamed Hwy Pool	33 274	0	241 094	145 359	145 364	67 049	Semi-permanent
Unnamed Hwy Pool	30 125	0	241 094	145 359	145 364	0	Semi-permanent
Unknown	635	0	18 294	8 200	0	0	Intermittent
Unknown	0	0	11 340	1 895	0	0	Intermittent
Unknown	0	0	15 754	1 900	2 525	0	Intermittent
Unknown	0	0	117 309	635	24 524	0	Intermittent
Meedanar	2 530	0	0	635	635	0	Intermittent

NB. Pool mapping assessed the permanency of river pools based on their occurrence across seven sets of Landsat imagery spanning 1999 to 2007. Pools were define as permanent if they were present across all image sets; semi-permanent if present in 60 to 99% of image sets; and intermittent if present in <60% of image sets.

Appendix C Data availability

Groundwater and surface water levels have been monitored across the study area since the late1960s as follows:

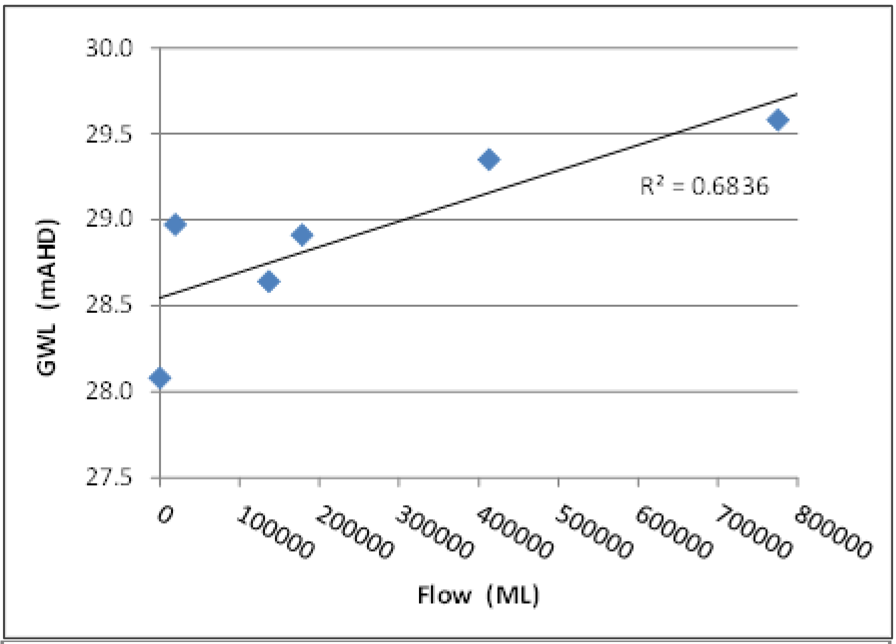
- daily streamflow and stage height data measured at Jelliabidina Well (709005) from 1972 (some periods of missing data)
- groundwater level data from 31 monitoring bores from the late 1960s (1988 to 1998 data missing)
- monthly (approximately) surface water levels from Lee Lin Pool from 2004 to present.

Water level monitoring data, results of previous hydrogeological investigations, results of airborne geophysics surveys, a digital elevation model (derived from LiDAR), bore stratigraphy, climate data and river flow records were used to develop a numerical groundwater model of the lower Yule alluvial aquifer (MWH 2010). This work was completed as part of a three year investigation and assessment project funded in part by the federal government's *Water for the Future program*. The model has been used to support revision of the EWR and the allocation limit for the aquifer.

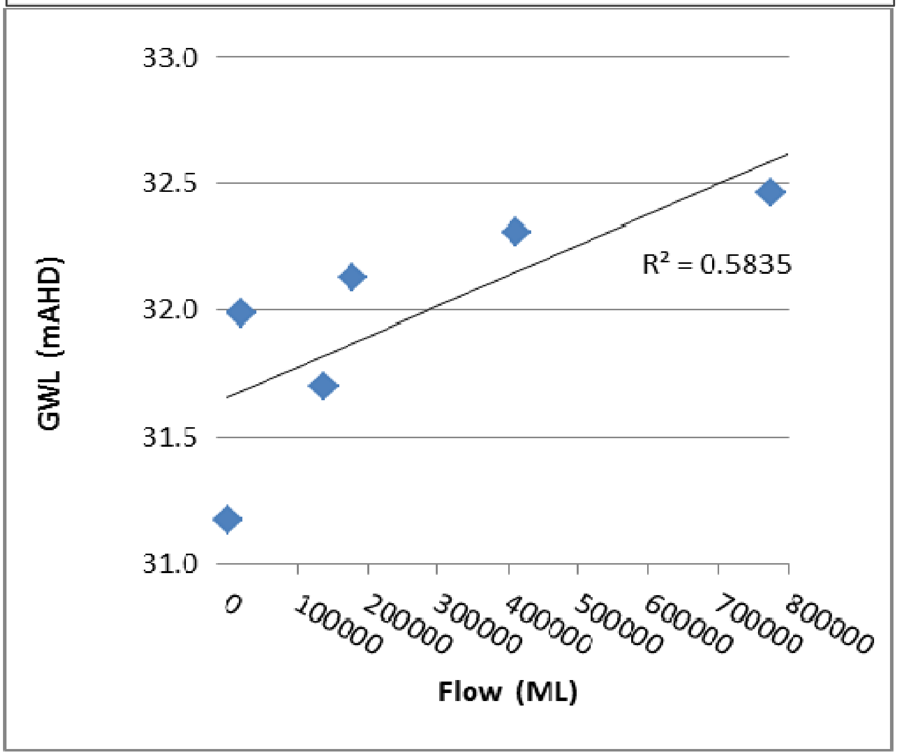
Appendix D Flow parameters and groundwater datasets used in recharge classes

Table D1 Flow parameters

Groundwater data (historic water year minimum)	Flow parameter
Modelled	Wet (Dec to Apr) total flow (ML)
Recorded	Wet (Dec to Apr) total flow (ML)
Modelled	Water year (May to April) total flow (ML)
Recorded	Water year (May to April) total flow (ML)
Recorded	2 year mean water year (May to April) flow (ML)
Recorded	2 year wet (Dec to Apr) total flow (ML)
Recorded	2 year water year (May to April) total flow (ML)
Modelled	Time since flow
Modelled	3 year wet (Dec to Apr) total flow (ML)
Modelled	3 year wet (Dec to Apr) mean flow (ML)
Modelled	3 year water year (May to April) total flow (ML)



a)



b)

Figure D1 Relationship between water year (May to April) total flow (ML) and groundwater levels at bores a) 17/04 and b)21/04

Appendix E Total water year flow volume, probability and recharge class

Year	Flow volume (ML)	Probability	Recharge Class	Water availability
1975	0	0.030303	1	Drought
1991	0	0.060606	1	
1992	0	0.090909	1	
1994	0	0.121212	1	
2002	21	0.151515	1	
1986	31	0.181818	1	
1996	211	0.212121	1	
1998	309	0.242424	1	
2010	523	0.272727	1	
1977	3601	0.30303	2	Dry
1983	6577	0.333333	2	
1987	15550	0.363636	2	
2008	19904	0.393939	2	
1990	26371	0.424242	2	
1978	42453	0.454545	2	
1993	135367	0.484848	3	Average
2009	137575	0.515152	3	
1985	164245	0.545455	3	
2011	179385	0.575758	3	
1981	222081	0.606061	3	
2007	413523	0.636364	3	
2001	448435	0.666667	3	
1989	467918	0.69697	3	
1988	493404	0.727273	3	
1984	580758	0.757576	4	Wet
1980	595959	0.787879	4	
1999	625064	0.818182	4	
1982	697248	0.848485	4	
2006	776184	0.878788	4	
1997	843327	0.909091	4	
1995	928316	0.939394	4	
1976	1964738	0.969697	4	
2000	2410905	1	4	
1979	No data			
2003	No data			
2004	No data			
2005	No data			

Appendix F Map disclaimer

Datum and projection information

Vertical datum: Australian Height Datum (AHD) Horizontal datum: Geocentric Datum of Australia 94

Projection: MGA 94 Zone 50

Spheroid: Australian National Spheroid

Project information

Client: Michael Braimbridge

Map Author: Michelle Antao

Filepath:

J:\gisprojects\Project\C_series\C2219\0018_Yule_Maps\mxd

Filename:

130515_Yule_Location_ERW_Report.mxd

130515_Yule_GDE_EWR_Report.mxd

130515_DTGW_ERW_Report.mxd

130515_Pools_EWR_report.mxd

Compilation date: 2013

Disclaimer

These maps are a product of the Department of Water, Water Resource Use Division and were printed as shown. These maps were produced with the intent that they be used for information purposes at the scale as shown when printing.

While the Department of Water has made all reasonable efforts to ensure the accuracy of this data, the department accepts no responsibility for any inaccuracies and persons relying on this data do so at their own risk.

Sources

The Department of Water acknowledges the following datasets and their custodians in the production of these maps:

Hydrography, Linear (Hierarchy) – DoW – 05/11/2007

Pools Pilbara – DoW – 2009

Road Centrelines – DoW – Current

Towns –DLI – Current WA Coastline, WRC (Poly) – DoW – 20/07/2006

WIN surface water sites – stream gauging, DoW, 2012

WIN groundwater sites – all, DoW, 2012

DWAID Aquifers, DoW

DWAID Groundwater areas,

Yule Vegetation Mapping - DoW project specific

Glossary

Abstraction The permanent or temporary withdrawal of water from any source of supply, so that it is no longer part of the resource of the locality.

Alluvium Fragmented rock transported by a stream or river and deposited as the river floodplain.

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.

Bore A narrow, normally vertical hole drilled in soil or rock to measure or withdraw groundwater from an aquifer.

Ecological water requirement The water regime needed to maintain ecological values of water-dependent ecosystems at a low level of risk.

Ecosystem A community or assemblage of communities of organisms, interacting with one another, and the specific environment in which they live and with which they also interact, e.g. 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/second, m^3/day or ML/annum. May also be referred to as discharge.

Groundwater Water that occupies the pores and crevices of rock or soil beneath the land surface.

Groundwater-dependent ecosystems An ecosystem that is dependent 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 food availability and the presences of predators.

Hydrology The study of water, its properties, movement, distribution and utilisation above, on or below the Earth’s surface.

Hydrogeology The hydrological and geological sciences 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.

Lifecycle	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.
Riparian vegetation	Plant communities along the river margins and banks or at the interface between land and a river or stream.
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.
Water regime	A description of the variation of flow rate or water level over time. It may also include a description of water quality.

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