Government of Western Australia
Department of Water

Lower De Grey River: ecological values and issues

Environmental water report series - Report no. 12

Looking after all our water needs

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Environmental water report series
Report no. 12
January 2010

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January 2010

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

ISBN 978-1-921675-90-4 (print)
ISBN 978-1-921675-91-1(online)

Acknowledgements

This report was prepared by Robyn Loomes and Mike Braimbridge from the Department of Water's Environmental Water Planning section. The authors acknowledge the input and comments provided by Fiona Lynn, Darryl Abbott and Hazli Koomberi.

Australian Government
Water for the Future

This project is part funded by the Australian Government's $12.9 billion *Water for the Future* initiative.

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The recommended reference for this publication is:

Loomes, R & Braimbridge, M 2010, *Lower De Grey River: ecological values and issues*, Environmental water report series, Report no. 12, Department of Water, Government of Western Australia.

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1 Introduction

Water is a defining feature of the semi-arid Pilbara region. Water management is vital to the beliefs and way of life of the region's Aboriginal people, to its towns and ports, and to the pastoral, mining and tourism industries.

The Pilbara mining industry's expansion has seen increased water demand from inland mining operations and coastal town and port supplies. Coastal demand is placing pressure on current water sources.

The Geological Survey of Western Australia investigated alluvial sediments across the Pilbara in the 1960s and 1970s, identifying the Lower De Grey River as a potential groundwater supply for Port Hedland.

The Namagoorie borefield, commissioned in 1979, is situated on the De Grey. The Water Corporation operates the borefield as part of the Port Hedland water supply scheme and is currently licensed to abstract 7.0 GL/yr. Although a second borefield (Bulgarene) has been proposed downstream of the Namagoorie, at the time of writing it remains reserved for future public use but there is no current intention to develop it. This coupled with existing usage (scheme supply and mining) places the resource under significant demand pressure.

The Water Corporation undertook a series of ecological studies as part of the environmental impact assessment process for the proposed Bulgarene borefield. These studies confirmed the occurrence of the following groundwater-dependent ecosystems associated with the De Grey River aquifer:

- riverine pools
- riparian vegetation
- aquifer ecosystems.

In this ecological values and issues report we identify and describe groundwater-dependent ecosystems in the lower De Grey River area using available information and additional (limited) field studies. We then use existing hydrological and biological data and updated vegetation mapping and transect data to conceptualise the groundwater dependence of key ecosystems, enabling us to formulate management objectives.

The outcomes of this work will be considered in the development of ecological water requirements (EWRs) and ultimately a water allocation plan.

2 Biophysical setting

The De Grey River basin is located north-east of Port Hedland in the Pilbara region. Covering an area of approximately 50 000 km^2, it is the largest river by volume in the region (based on mean annual flow). The EWR study area is near the existing Namagoorie borefield, downstream of the confluence with the Shaw River (Figure 1).

The biophysical environment of the De Grey River has been described previously in van Dam et al. (2005), Strategen (2006), Goater and Horgan (2006), Water Corporation (1998) and Haig (2009). The following information summarises these reports and includes updated climatic and hydrological data.

2.1 Climate

The Pilbara region's climate is classified as semi-arid to arid with hot dry conditions most of the year. Average maximum monthly temperatures recorded at the Port Hedland Airport meteorological station exceed 35°C from October to March and fall to 27°C in July (Figure 2). Monthly minimums range from 12°C in July to 25.5°C in January and February.

Average annual rainfall (1900–2008) in the region is generally low (Strelley: 325 mm; Pardoo: 298 mm). It is also highly variable because it depends on summer cyclones and autumn thunderstorms, with most rainfall occurring between November and March. In addition, the heat and clear skies result in average evaporation greatly exceeding rainfall. High evaporation and low rainfall cause an extreme moisture deficit across the region.

A number of meteorological stations are positioned near the De Grey River. Figures 3 and 4 show the long-term annual rainfall (1900–2008) and average monthly rainfall and evaporation recorded at the Strelley and Pardoo stations. Although data were also available for stations closer to the study area (De Grey Station, Strelley pumping station), the datasets used here were the most complete.

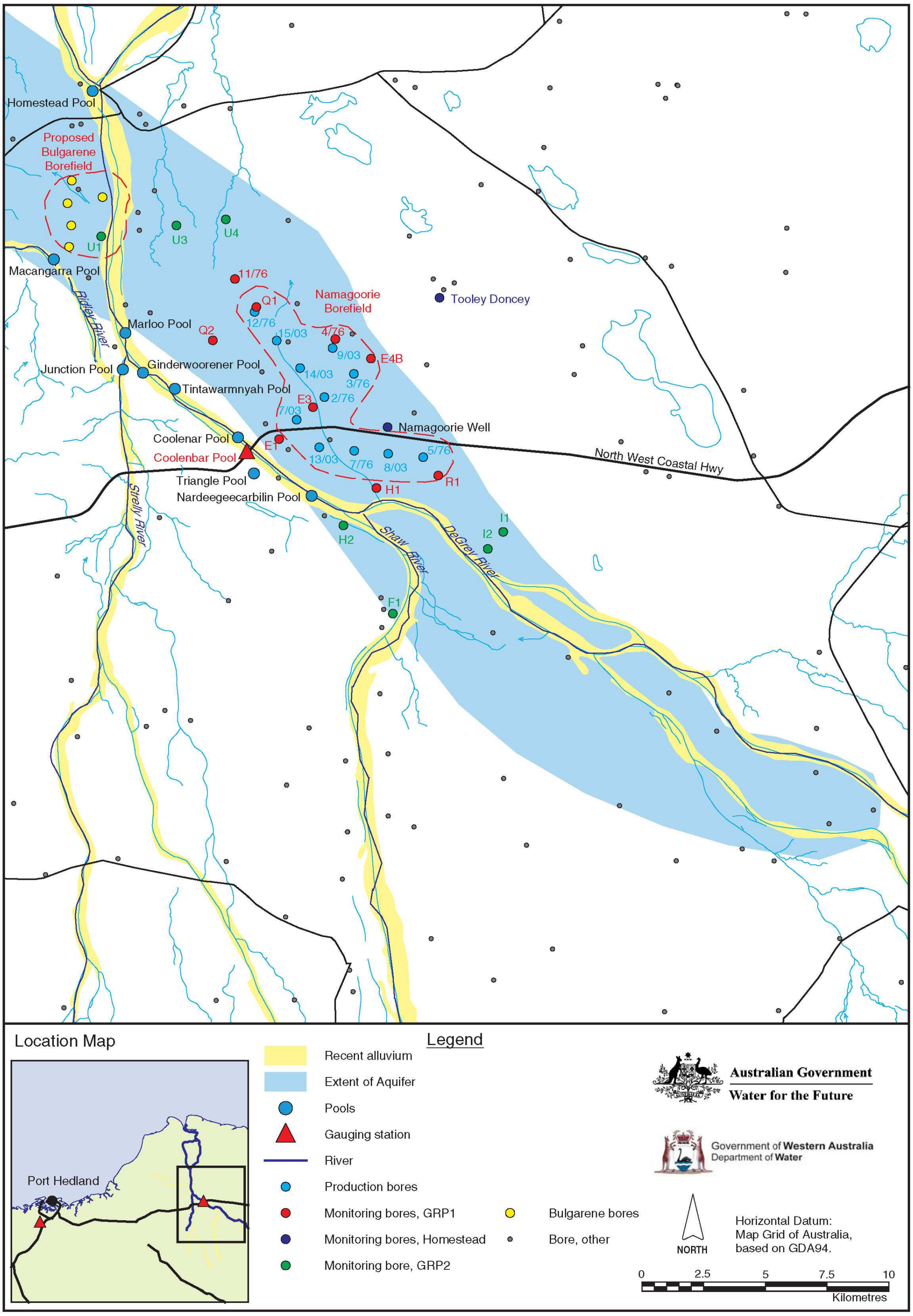

Figure 1 De Grey River borefield (from Haig 2009)

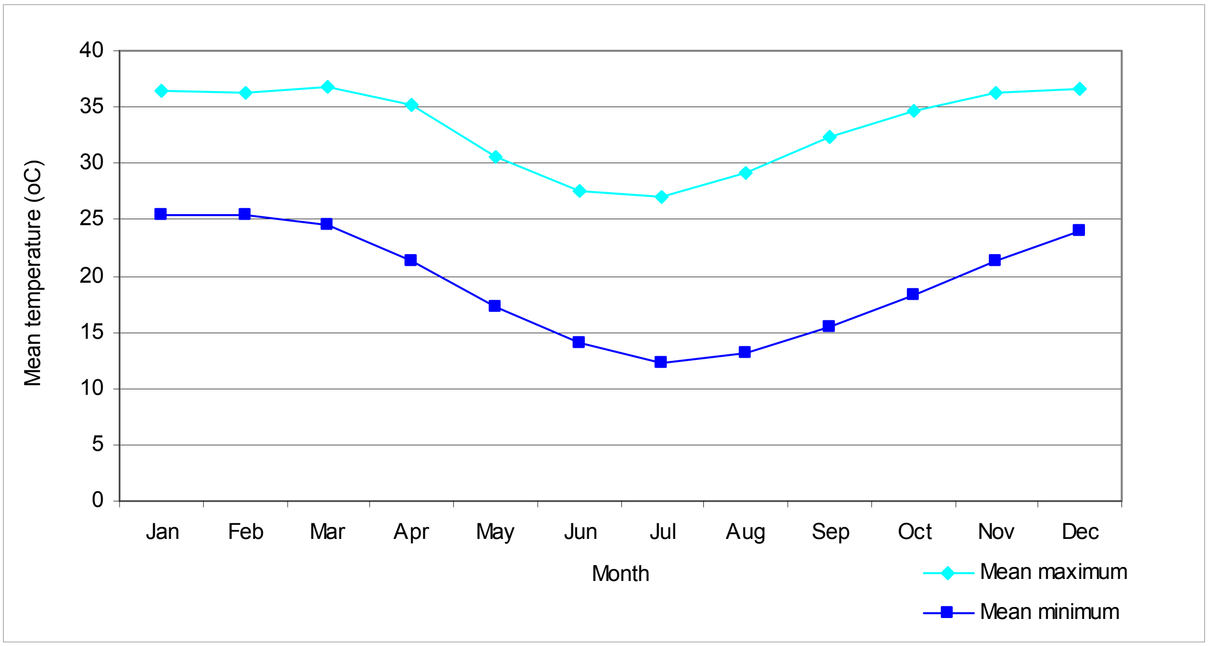

Figure 2 Mean monthly temperatures from Port Hedland Airport (1948–2009)

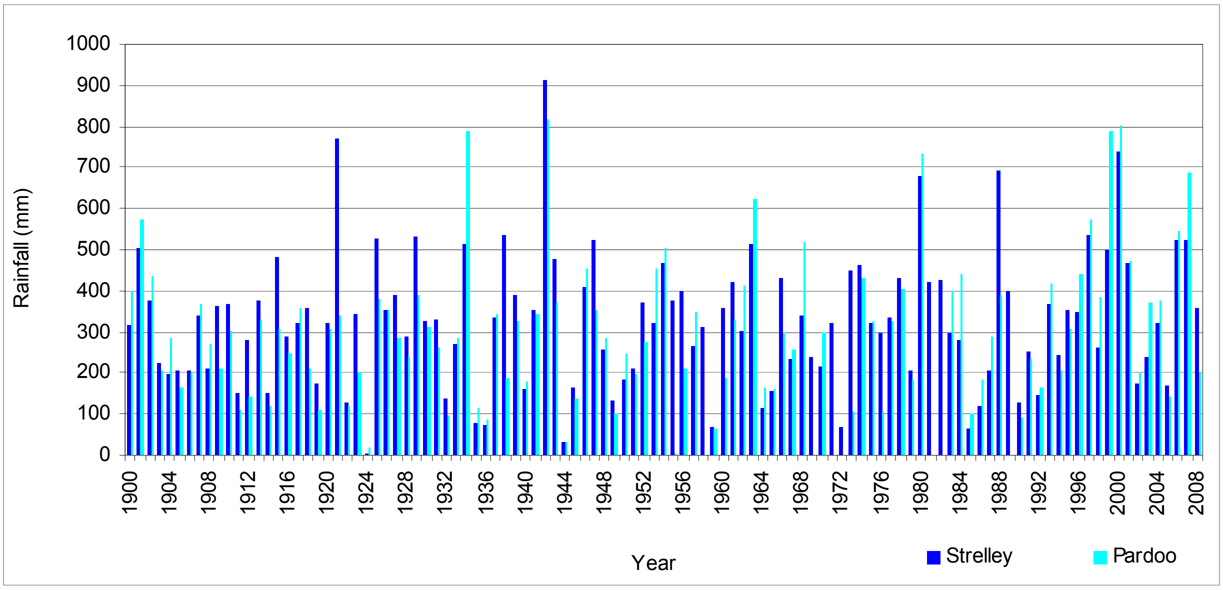

Figure 3 Long-term annual rainfall (1900–2008) for selected meteorological stations near the De Grey study area

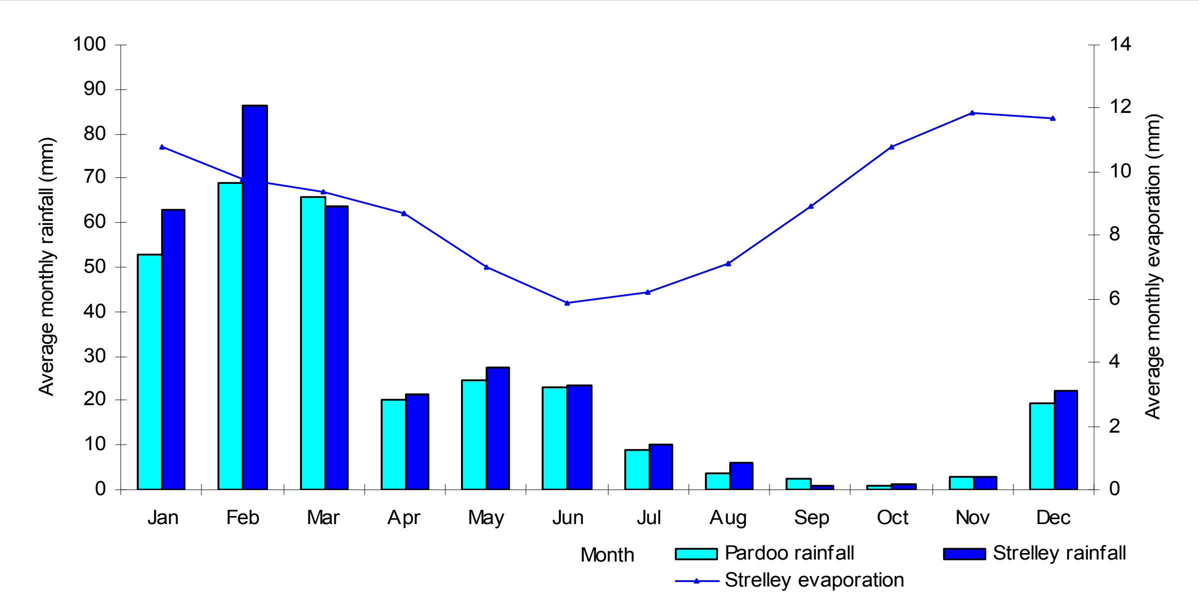

Figure 4 Monthly average rainfall (mm) and evaporation (mm) (1900–2008) for selected meteorological stations near the De Grey study area)

2.2 Physiography and geomorphology

The area surrounding the lower De Grey River consists of dissected highlands, extensive gravel plains and a wide alluvial plain leading westward onto a narrow coastal plain, with a small desert area that extends onto the south-western edge of the Canning Basin. The bedrock consists of Archaean metasediments, granites and volcanics: it outcrops extensively in the Ord Ranges and Ellarine Hills and also underlies the alluvial plain at depth (Table 1; Figure 5) (Dames & Moore 1978). Although the Mesozoic sediments do not outcrop in the area, they are present beneath the northern part of the Namagoorie borefield. Cainozic sediments exist as discontinuous patches of pisolite and calcrete of Tertiary age, with alluvium of Quaternary age to a depth of about 40 m on the De Grey River plain.

Table 1 Stratigraphic units of the lower De Grey River (from Haig 2009)

Era	Period	Rock unit	Lithology
Cainozoic	Quaternary	Alluvium	Alluvial clay, silt, sand, gravel conglomerate
	Tertiary	Paleochannel	Alluvium, pisolite and calcrete
Mesozoic	Early Cretaceous	Broome	Sandstone, shale and sandstone
Unconformity			
Archaean		Greenstone	Metasediments and volcanic rocks
		Granite	Granite and intrusive rocks

The De Grey River has a north-west-flowing drainage pattern, with major tributaries being the Shaw, Strelley, Coongan, Oakover and Nullagine rivers. Small creeks and erosion channels run from the ranges and plains of the Chichester, Goldsworthy, Isabella and Gregory ranges, forming the river's headwaters. Closer to the study area, the Strelley East and West branches feed the Ridley River, which wraps around the Ord Ranges before draining north-west (Worley Parsons 2005). From here the De Grey widens (1 km) and becomes a well-developed coastal drainage system.

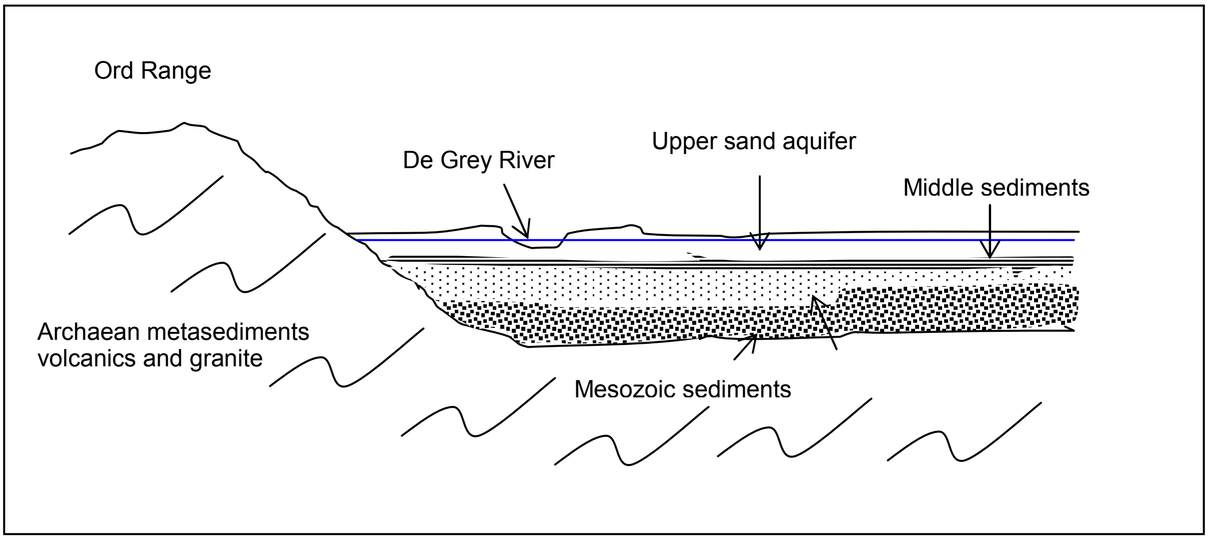

Figure 5   Geological cross-section (adapted from Dames & Moore 1978)

2.3 Hydrogeology

The Geological Survey of Western Australia investigated alluvial sediments in the area between 1969 and 1972 as a potential water supply for Port Hedland (Davidson 1974). Forty-nine exploration drill holes into the alluvium and underlying bedrock formed the basis of the investigations. This and subsequent studies have led to a relatively comprehensive understanding of the De Grey's hydrogeology, although further work is being undertaken in conjunction with the current study.

The alluvial De Grey aquifers may be connected with underlying aquifers in the Mesozoic sediments, which may form part of the West Canning Basin. However, the Mesozoic sediments of the De Grey area are rich in clay and silt and therefore low yielding (Haig 2009).

Aquifers

The current river channel overlies a paleochannel, although paths deviate in some areas (Figure 1). The existing Namagoorie borefield is on the northern edge of the paleochannel.

Worley Parsons (2005) identified three distinct units, described as the ‘upper sand aquifer’, ‘middle sediments’ and ‘basal gravel/sand aquifer’ (Figure 5). The upper sand aquifer generally occurs within the current channel. It is less defined than the deeper aquifer and is usually only suitable for stock and domestic use. The middle sediments, separating the upper and lower aquifers, comprise 5 to 20 m of sandy clay or clayey sand. The basal gravel/sand aquifer, within the palaeochannel, is the most productive of the two aquifers. It generally occurs at depths below 30 m, ranging in thickness from about 20 to 40 m (Worley Parsons 2005). The unit varies from sand to gravel and clayey gravel towards the basement and is likely to be connected to the upper aquifer. Both aquifers are thought to be largely unconfined (Davidson 1974).

Current use

The Namagoorie borefield, located 75 km east of Port Hedland on the east side of the De Grey River, was commissioned in 1979 to supplement supply to the Port Hedland water supply scheme. The borefield comprises 11 production bores and 18 monitoring bores and is licensed to abstract 7 GL/yr.

Comparison of total annual abstraction and water levels from bore E1, which is close to the production bores, shows no clear relationship between abstraction and groundwater levels (Figure 6).

Abstraction increased significantly after 1995. Since that time (excluding 2009 due to incomplete data) use has averaged 6 GL/yr, but went as high as 7.2 GL/yr in 2003. Although production has been stepped down since 2004–05 (after the Port Hedland hot-briquetted iron facility closed), this is only expected to be temporary as the demand for water resources from the mining industry and associated infrastructure increases.

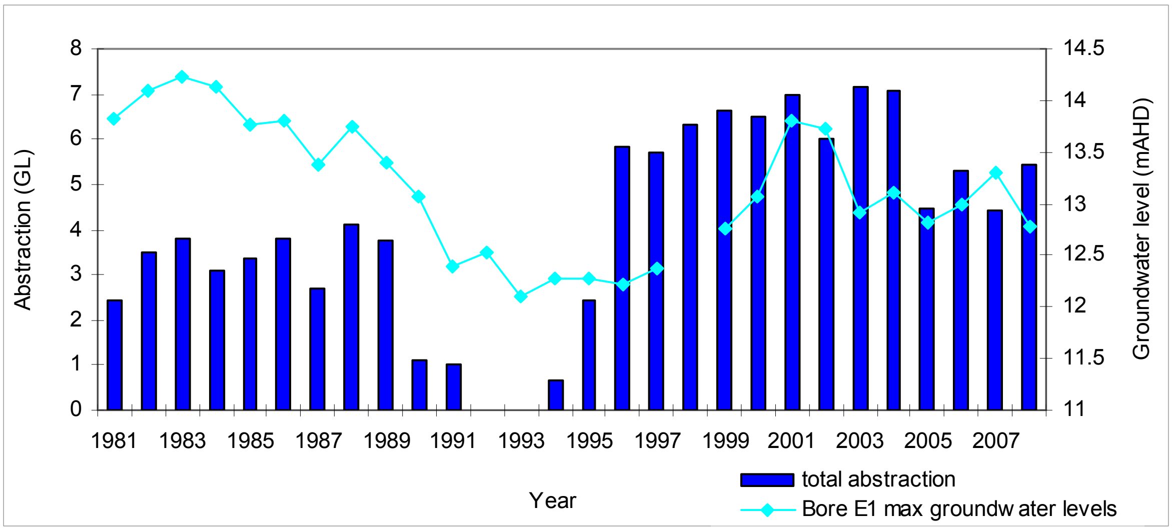

Figure 6 Namagoorie borefield total annual abstraction 1981–2009 (July)

Groundwater

Since 1974 groundwater levels have been monitored at numerous bores screened within the basal gravel/sand aquifer across the study area (25 at Bulgarene; 12 at Namagoorie). Data indicate the watertable typically occurs 5 to 11 m below the ground surface (Figure 7). Selected bores show a decline in the watertable between 1974 and 1980, followed by a general increase to 1996 when levels then dropped to near-historic lows before rising again. This trend closely mirrors surface water flows and hence rainfall (Figure 8).

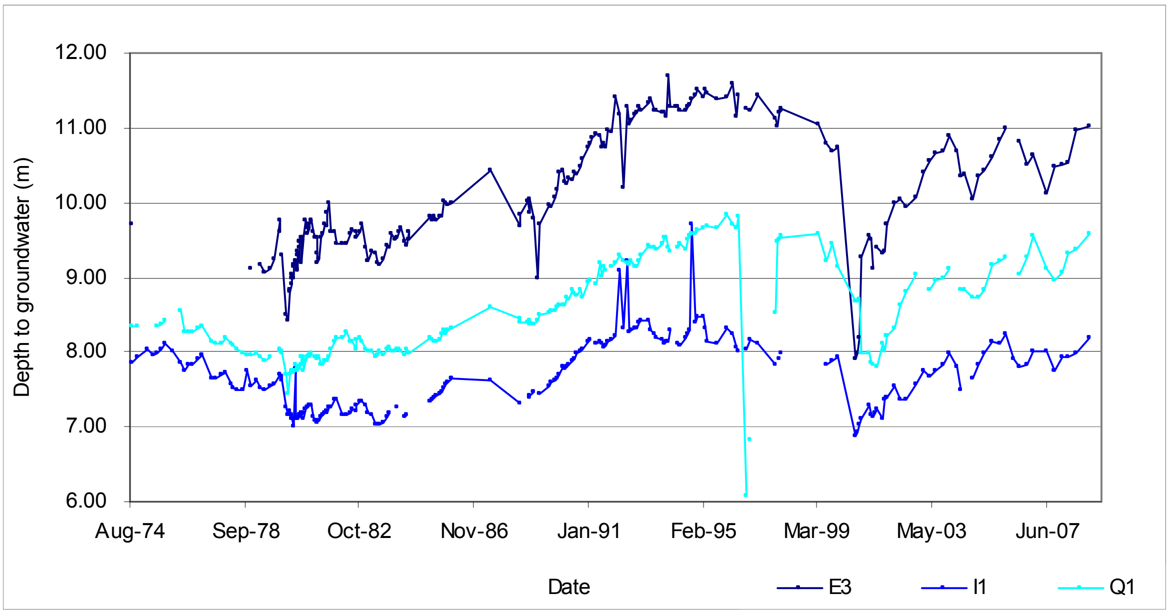

Figure 7 Selected Namagoorie monitoring bore hydrographs (1974–2009)

Groundwater outflow occurs at the northern end of the study area (Martin 1996; Worley Parsons 2005). Before the borefield was developed, throughflow was estimated as 5900 m^3/day or 2.2 GL/yr, which translated to 560 m^3/day/km for a 10.5 km section of the palaeochannel north of the De Grey channel and downstream of the Shaw River confluence (Davidson 1974). By December 1995, abstraction had flattened the hydraulic gradient north of the borefield, reducing outflow to 230 m^3/day/km (Martin 1996).

Abstraction also altered water level contours, resulting in additional inflow to the borefield, particularly between the borefield and the De Grey. Martin (1996) thought it likely that the borefield was inducing additional groundwater flow for about 3 km downstream of the Great Northern Highway, although this was based on limited data.

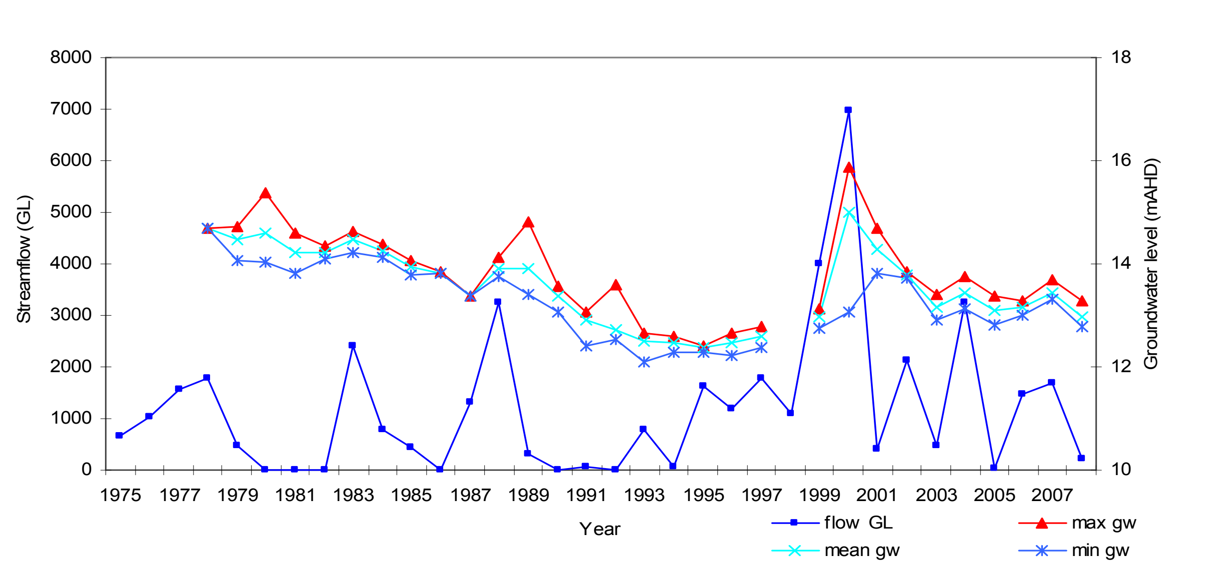

Figure 8 Annual streamflow and groundwater levels (bore E3) 1975–2008

River flow and aquifer recharge and storage

Based on mean and median annual flows and coefficients of variation, the De Grey is the largest and most reliable of the gauged Pilbara rivers (Table 2) (Ruprecht & Ivanescu 2000). Median annual flows of the De Grey (1062 GL) are an order of magnitude higher than the next largest rivers in the region, the Ashburton (534 GL) and the Yule (136 GL), despite similar rainfall. This is most likely a function of the De Grey's large drainage basin (56 890 km^2) and inflows from tributaries, including the Strelley, Shaw, Coongan, Oakover and Nullagine rivers. Although the longest number of consecutive months during which no flow was recorded is 19 months, this occurred in the only year of no measured flow during the 30-year flow record (Haig 2009).

Flooding of the De Grey and other main ephemeral tributaries in the region, specifically the Shaw, Ridley and Strelley rivers, is the greatest source of De Grey aquifer recharge (Worley Parsons 2005). Direct rainfall recharge is thought to be relatively insignificant due to low annual rainfall, high evaporation and the low infiltration capacity of the clayey floodplain soils away from the riverbeds.

Since 1974 flows and stage heights have been recorded at Coolenar Pool gauging station (701003) near the Great Northern Highway (Figure 9). Pool levels have also been measured at several sites (Bulgarene, Homestead, J96, Marloo and Muccangarra pools).

Flow primarily occurs in late summer and extends into late winter, although in exceptional years flow has been perennial (Pinder & Leung 2009). The long-term mean annual flow at Coolenar Pool (1975–2007) is 1396 GL. Although the alluvium receives river flow-events above the mean average one in every three years, one in six years the total annual flow is very low (<10 GL).

Table 2 Major river flows in the Pilbara (from Ruprecht & Ivanescu 2000)

River	**Gauging station number**	**Catchment area (km^2)**	**Mean rainfall (mm)** [4]	**Mean annual flow (GL)**	**Median annual flow (GL)**	**CV**[1]
Ashburton	706003	71 387	300	922	534	1.32
Cane	707005	2326	400	88	65	0.80
Robe	707002	7104	500	87	18	1.70
Fortescue[2]	708002	14 629	450	215	51	1.40
Fortescue[3]	708003	18 371	400	255	97	1.31
Maitland	709004	1948	375	40	14	2.08
Harding	709001	1058	400	39	23	1.30
Sherlock	709003	4581	400	164	40	1.60
Yule	709005	8427	400	350	136	1.40
Turner	709010	885	400	29	5	1.20
De Grey	**710003**	**56 890**	**400**	**1430**	**1062**	**1.10**
Shaw	710229	6501	400	328	151	1.60
Coongan	710204	3736	400	112	68	1.30

[1] CV: coefficient of variation [2] station 708002 at Gregory Gorge [3] station 708003 at Jimbegnyinoo
[4] based on mean annual isohyets

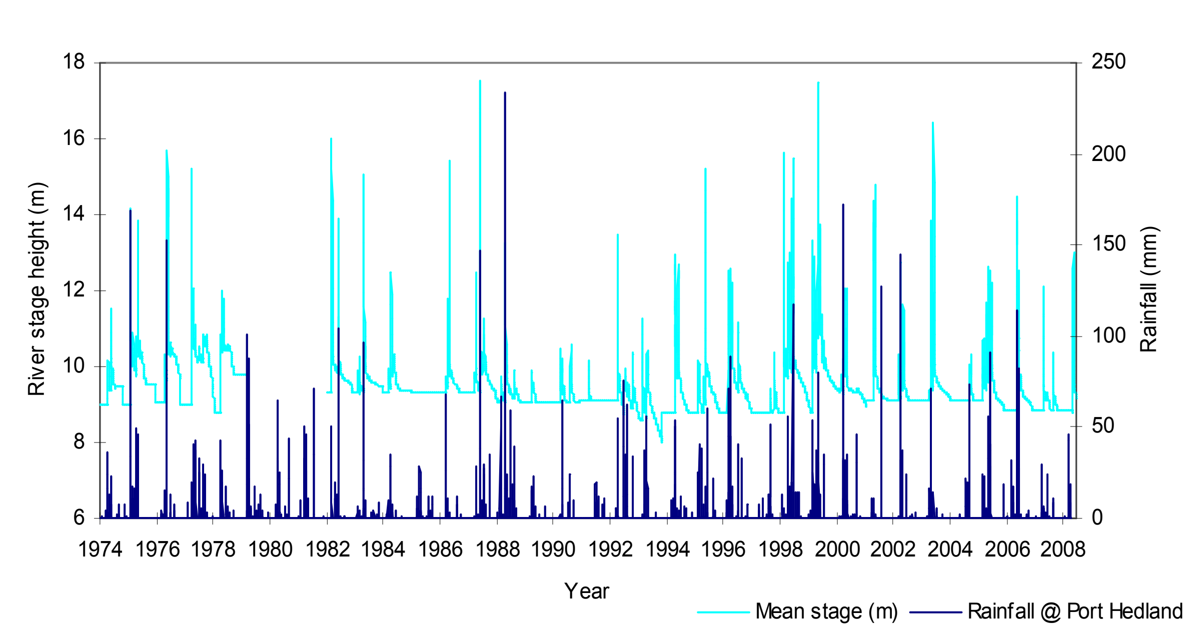

Figure 9 Coolenar Pool daily stage height and Port Hedland rainfall (1974–2008)

Water balance

Davidson (1974) estimated a groundwater balance along a 25 km stretch of the river, running from the north end of the existing borefield to 10 km upstream of the Shaw River confluence (170 km^2) (Table 3).

Total recharge from the De Grey and Strelley rivers was estimated as 15.6 GL/yr and rainfall inputs as 1.4 GL/yr. Transpiration along the river is the highest contributor to discharge, estimated as 50 per cent of pan evaporation (Davidson 1974). Applying a transpiration of 1.25 m over 11 km^2 (estimated vegetated area) resulted in an estimated volume of 13.75 GL/yr. Pool evaporation estimated from a pan evaporation rate of 2.5 m/yr, over a pool area of 0.25 km^2, resulted in a loss of 0.63 GL/yr.

Table 3 De Grey annual water balance before abstraction (from Davidson 1974)

Inputs (GL)		**Outputs (GL)**	
Recharge – De Grey and Strelley	15.60	Transpiration	13.75
Rainfall	1.40	Pool evaporation	0.63
		Groundwater outflow	2.20
Total	17.00		16.58

2.4 Vegetation and flora

The De Grey study area lies within the Abydos Plain physiographic unit in the Pilbara region's Fortescue Botanical District. Beard (1975) conducted broadscale vegetation mapping. He identified the dominant vegetation types as sclerophyll riverine woodland along creeks, bordered by plains of mixed grass and spinifex with scattered trees, and spinifex steppe in the west of the study area.

Although riparian and grassland vegetation of the De Grey area was mapped by Halpern Glick Maunsell (HGM) (1998) and Strategen (2006), in 2009 staff from the Department of Water extended the mapping to cover the current study area (Figure 10). No 'declared rare' or 'priority' flora species were recorded in these surveys.

The De Grey and major tributaries are fringed by *Eucalyptus camaldulensis* and *Melaleuca argentea* woodland over a sparse understorey of smaller trees and shrubs (HGM 1998). Where the woodland spreads out onto floodplains, *E. victrix* and occasional *Corymbia flavescens* replace *E. camaldulensis* and *M. argentea*, forming a tree-savanna over a ground layer of grasses that are dense and predominantly exotic (Beard 1975) (see Appendix A for photos of community types).

The grass and spinifex layers of the plains are dominated by the exotic grass *Cenchrus ciliaris* (buffel grass) and *Triodia pungens* (soft spinifex), with tree species including *Atalaya hemiglauca, E. victrix, C. flavescens* and *Lysiphyllum cunninghamii* (Strategen 2006). Poaceae, Mimosaceae, Fabaceae and Myrtaceae are the dominant vascular plant families, with the most common species in the study area including *C. ciliaris, A. hemiglauca, E. camaldulensis* and *Carissa lanceolata*.

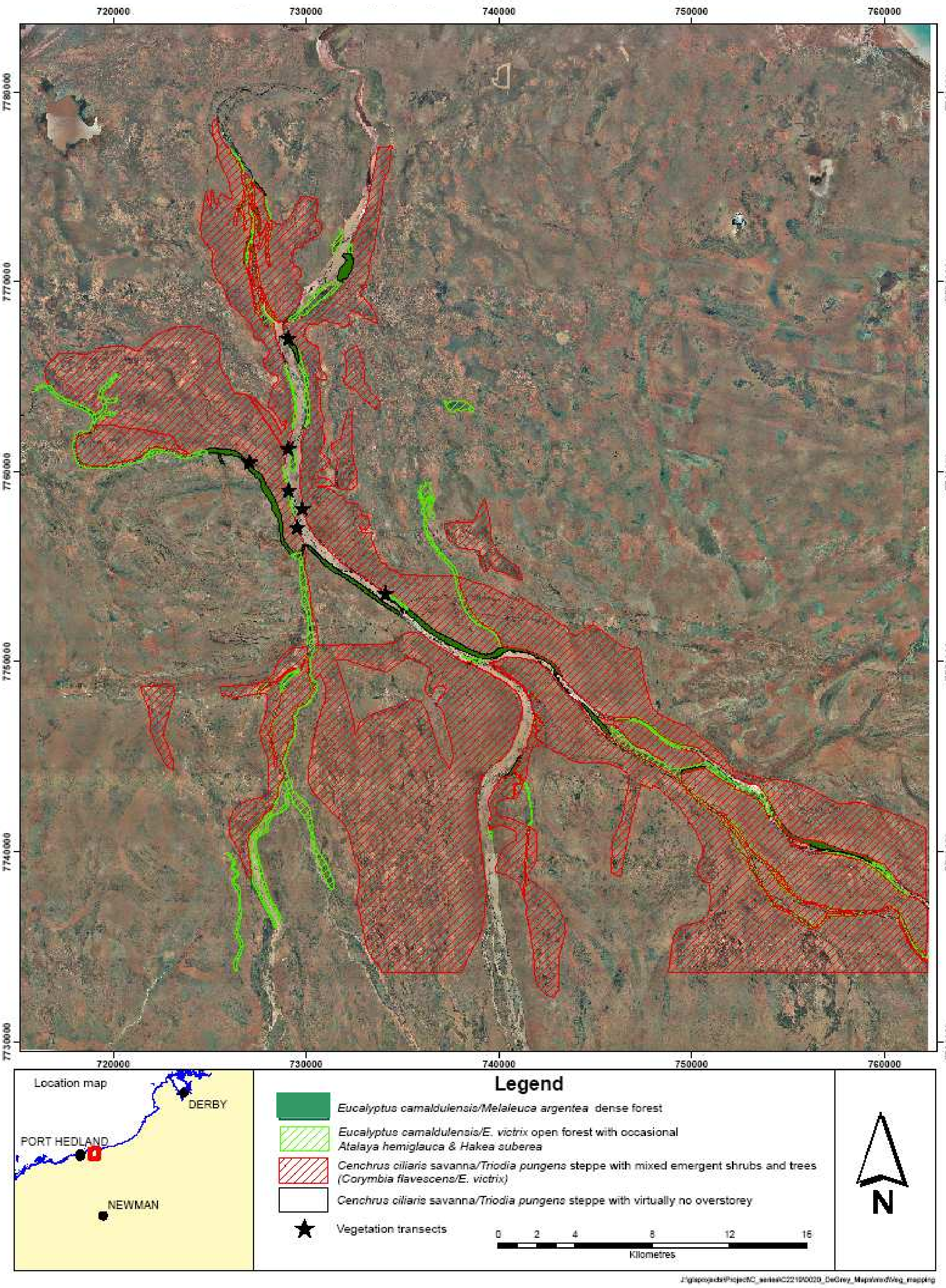

Figure 10 Vegetation mapping (adapted from Strategen 2006)

2.5 Fauna

Numerous fauna surveys have been undertaken in the De Grey study area. Fish and/ or macroinvertebrates were sampled on the De Grey and its tributaries as part of previous borefield development and regional characterisation studies (van Dam et al. 2005; Massini & Walker 1989; AUSRIVAS 2004; Dames & Moore 1978; HGM 1998; Kay et al. 1999; Massini 1988; Morgan et al. 2003; Pinder & Leung 2009). Van Dam et al. (2005) assessed hydrological processes that maintained the ecological values of river pools and the sensitivity of fish and macroinvertebrates to water regime change (see Section 3.1). Most recently Pinder and Leung (2009) investigated the relationship between aquatic invertebrates and habitat variables that may be affected by groundwater drawdown.

HGM (1998) undertook fauna trapping and non-systematic fauna surveys at 14 sites within the borefield area. Outback Ecology Services (2004) reviewed those survey results and other published material and searched relevant databases and archives. On the basis of known species distributions and the habitats available (pools, riverine forest and savanna/steppe), species of up to 145 birds, 97 reptiles, nine frogs, one turtle and 26 native and 12 introduced mammals may occur within the survey area. After this review Outback Ecology Services (2004) assessed fauna sensitivity to changes in pool water regimes and riverine vegetation habitat (see Section 3.2).

A pilot survey was undertaken to determine the presence of stygofauna within the area of the proposed Bulgarene borefield and the wider De Grey catchment (Goater & Horgan 2006). Although stygofauna were only collected from four of the 23 bores surveyed, this may be symptomatic of the bore locations rather than representative of distributions across the wider catchment.

Ten bores within the study area have also been surveyed as part of the *2002–2009 Pilbara region biological survey* of the Department of Environment and Conservation (DEC). Data are yet to be published.

2.6 Land use and cultural values

The De Grey River area's potential as pastoral land was recognised by FT Gregory in 1861 (Anon. 1886). In 1863 a small party journeyed overland from Cossack and *'finding a large scope of good country…'* established the region's first sheep station on the De Grey. Although today cattle are grazed in preference to sheep, the station remains operational.

The De Grey River study area lies within the De Grey pastoral lease (Strategen 2006). Cattle graze over the area and the river pools are used for stock watering. Overgrazing by livestock and feral species such as pigs, donkeys and camels is regarded as the greatest threat to the regional environment and may contribute to soil erosion and river sedimentation (van Dam et al. 2005).

Mining occurs across the catchment, with numerous mines in the following reaches:

- upper (Woody Woody, Nullagine Gold and Sulphur Springs)
- middle (Moly Mines)
- lower (Atlas).

Mining impacts may arise through abstraction for operations and/or dewatering activities discharging to nearby creeks (WRC 2004).

The De Grey River's pools are important to the Ngarla people, traditional owners of the land incorporating the borefields (van Dam et al. 2005). Over the wider study area there are two other traditional owner groups, the Warrarn and Njamal, for whom permanent pools hold significance.

The pools are used for fishing, swimming, hunting, collecting, camping, teaching, meetings and ceremonial activities. Cultural values will be discussed further in a separate report.

3 Identification and description of groundwater-dependent ecosystems

The shallow alluvial aquifer of the De Grey River area supports groundwater-dependent ecosystems of three different types and their associated biotic elements:

- wetlands (riverine pools) – aquatic macrophytes, phytoplankton, fish, macroinvertebrates and terrestrial vertebrate fauna
- riparian (river baseflow) – phreatophytic vegetation and dependent terrestrial fauna
- aquifer ecosystems – stygofauna.

The following information describes the De Grey's groundwater-dependent ecosystems, the communities/species they support, their conservation values and likely level of groundwater dependence. Conceptual models are then used to illustrate the hydrological support mechanisms of biotic communities in and adjacent to six key riverine pools (Homestead, J96, Bulgarene, Marloo, Coolenar, Muccangarra).

3.1 Wetland ecosystems

Hydrology

Numerous pools of varying permanence, size, depth and stability occur along the De Grey, Ridley, Shaw and Strelley rivers (Figure 11). An examination of key pool and bore hydrographs illustrates a high degree of connection between the aquifers and many permanent pools, including J96 Pool (Figure 12), Marloo Pool and Homestead Pool (Worley Parsons 2005). Semi-permanent and intermittent pools are also hydraulically connected to the shallow aquifer and are maintained by groundwater flow between flood events (Worley Parsons 2005).

Dames and Moore (1978) identified at least 20 pools within the Namagoorie borefield area, of which five were considered permanent or near-permanent. Recent pool mapping by the Department of Water suggests there are 30 permanent, 28 semi-permanent and 32 intermittent pools within the study area (DoW 2009). Pools <25 m in width were not identified in the mapping process (due to resolution of the imagery used), so the number of each pool type may actually be larger.

Although pools have been classified by permanence, the large flows that often occur in the De Grey are likely to have significant impacts on river morphology and to frequently alter the physical characteristics of pools. For example, station owners reported that Bulgarene Pool had 'moved' 100 m downstream in recent times (van Dam et al. 2005).

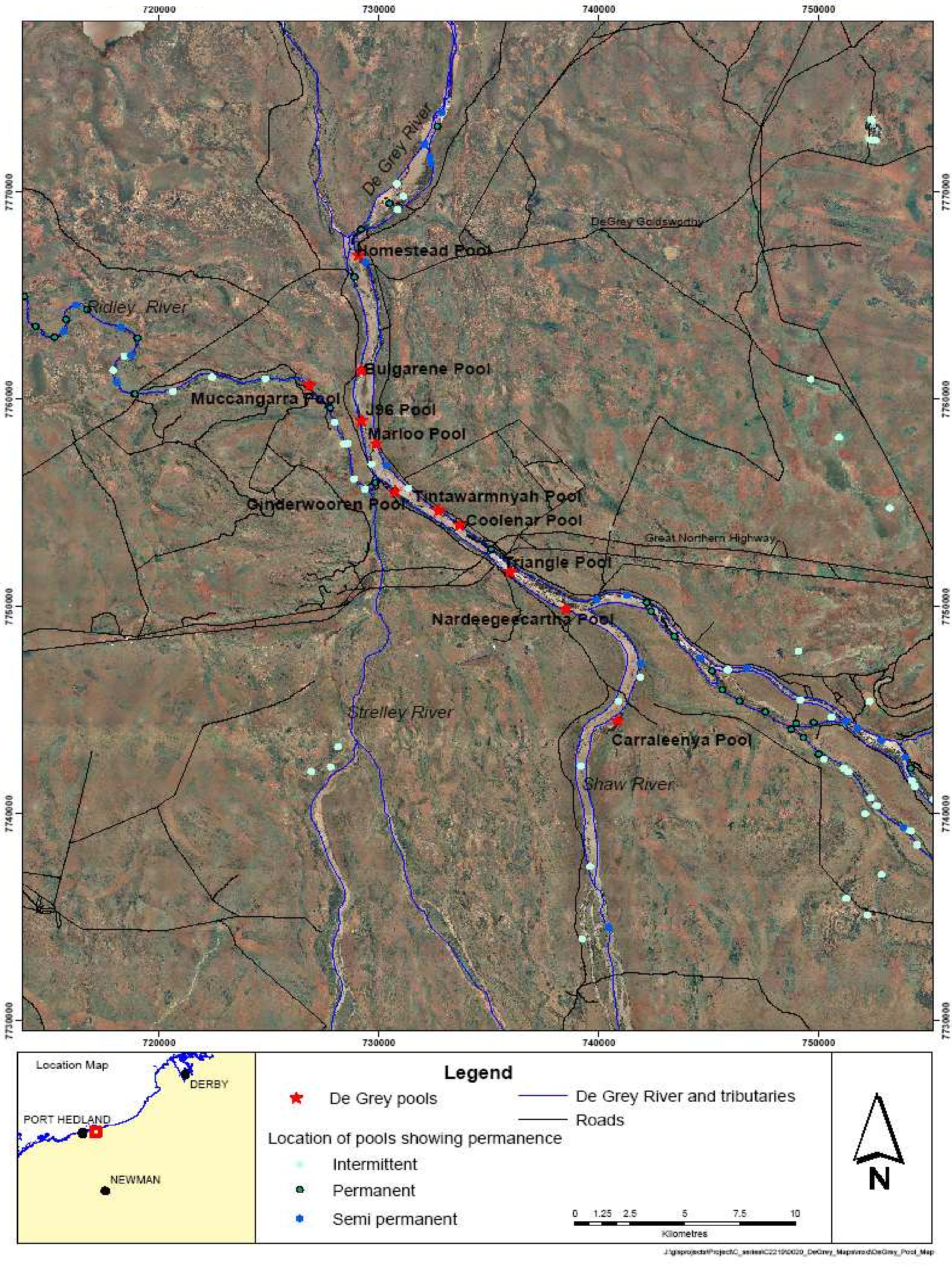

Figure 11 Location and permanence of De Grey River pools.

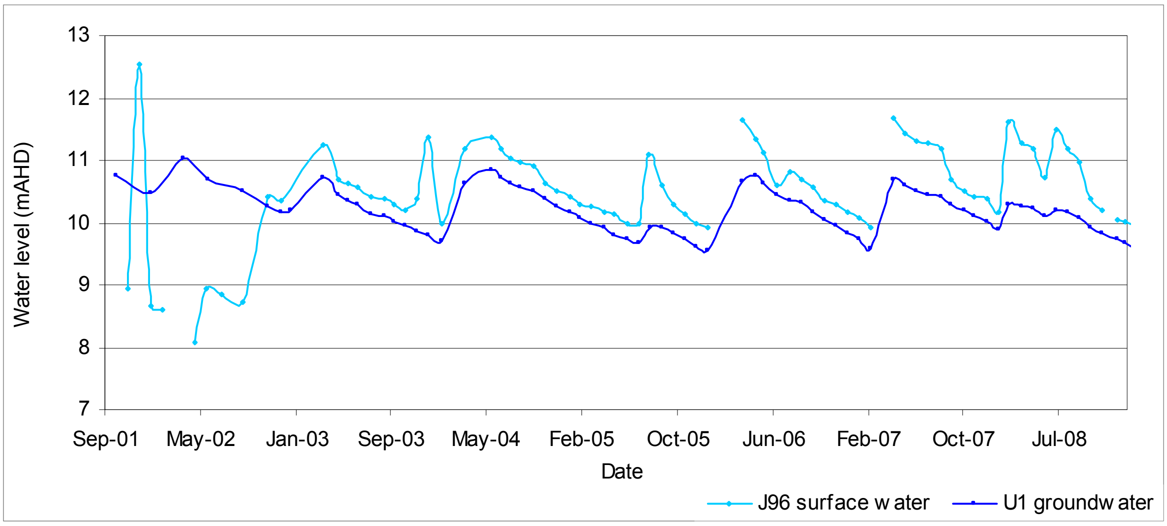

Figure 12 Relationship between groundwater at bore U1 and surface water levels at J96 Pool.

Ecology

The river pools support freshwater and marine fish species, macroinvertebrates, terrestrial vertebrate fauna, phytoplankton and aquatic macrophytes. Pool depth is thought to be more relevant to the ecology than pool size, as deeper pools (>2 m) hold water longer than intermediate (1–2 m) or shallow pools (<1 m), providing greater refuge value (van Dam et al. 2005).

Fish

Twenty of the 33 fish species known in the Pilbara have been recorded in the De Grey. Ten of these spend their entire lives in fresh water, four live predominantly in fresh water yet migrate to marine water to spawn (catadromous) and six are marine vagrants, spending most of their lives in coastal or oceanic waters, but occasionally venturing into freshwater environments (van Dam et al. 2005).

Van Dam et al. (2005) found a clear distinction between deep/intermediate and shallow pools with respect to fish diversity, richness and composition on the De Grey. This finding is consistent with studies elsewhere in the Pilbara (Morgan et al. 2009), where large-bodied species and adult fish were found to be generally restricted to more permanent deep/intermediate pools because they had greater habitat diversity, carrying capacity and refuge values.

The more permanent and stable deeper pools are the preferred habitat of a number of freshwater fish species, including the northern eel (*Anguilla bicolour*), bony bream (*Nematalosa erebi*), catfish (*Neosilurus hyrtlii*) and salmon catfish (*Arius graeffei*). Although the rainbow fish (*Melanotaenic australis*) also inhabits permanent pools, it is capable of rapidly colonising temporary pools and shallow areas. Spangled perch (*Leioptherapon unicolour*) and banded grunter (*Amniataba percoids*) can also rapidly colonise temporary pools and shallows, with anecdotal evidence that the latter is capable of surviving in mud during drought (HGM 1998).

Table 4 describes freshwater fish habitat requirements or preferences taken from Beesley (2006), Morgan et al. (2003), Pusey et al. (2004), HGM (1998), Massini (1988) and Dames and Moore (1978).

Table 4 Freshwater fish species recorded from the De Grey River.

Species	**General description and habitat preferences**
Northern eel (*Anguilla bicolour*)	A long-lived species estimated to reach maturity at 10 to 25 years. Once mature it migrates to the tropical deep sea to spawn. Only breeds once. Strongly restricted to permanent pools due to life history requirement for long-term stability.
Murchison River hardyhead (*Craterocephalus cuniceps*)	Permanent pools in either clear or turbid conditions. An extremely hardy species capable of surviving hypersaline conditions and a wide temperature range.
Salmon catfish (*Arius graeffei*)	A relatively long-lived species with relatively late maturity. Requires deep pools for incubation of eggs and larvae. Found mainly in deeper parts of permanent pools.
Rainbow fish (*Melanotaenic australis*)	Found throughout the Pilbara and Kimberley and into the Northern Territory in a wide range of habitats including shallow pools, streams and margins of deep pools. Relatively tolerant of a range of environmental conditions. Can rapidly colonise temporary pools.
Bony bream (*Nematalosa erebi*)	A widespread and common species of northern Australia and the inland rivers of south-eastern Australia. A detritivore commonly found in deep water in permanent and temporary pools. Susceptible to low dissolved oxygen.
Catfish (*Neosilurus hyrtlii*)	Very widespread species found across northern Australia where it inhabits a wide range of habitats. Mainly found in permanent pools.
Carp gudgeon (*Hypseleotris compressa*)	Found in flowing streams; congregates around fallen logs and other vegetative debris.
Spangled grunter/perch (*Leioptherapon unicolour*)	Widespread. Prefers lotic conditions but can achieve high abundances in large, deep, permanent pools. Can tolerate a range of environmental conditions. May survive in mud during drought.
Banded grunter (*Amniataba percoids*)	Widespread across northern Australia. Generally found in fresh flowing water. Large adults more common in deep, permanent pools; however, can rapidly colonise temporary pools.

Macroinvertebrates

Fifty-four macroinvertebrate taxa have been recorded from the De Grey system including two taxon not recorded elsewhere in the Pilbara: the beetle family Hydrochidae and the dragonfly family Macromiidae (van Dam et al. 2005). Although some taxa – predominantly the non-insects (Mollusca, Crustaceae, Acarina, Nematoda and Oligochaeta) – are at risk following pool drying, most De Grey taxa are either resistant to desiccation or avoid it through short life cycles completed in the course of the annual wet-dry season (van Dam et al. 2005).

Van Dam et al. (2005) found a difference in community structure between shallow and intermediate/deep pools. Although changes in pool depth may alter species composition, it is believed the De Grey's overall biodiversity would not be affected unless all pools were to dry out simultaneously.

Pinder and Leung (2009) agreed to some extent, concluding that pool depth, size and permanency were correlated to macroinvertebrate communities; yet not to the extent that would allow thresholds to be recognised. Their study indicated that other components of the physical and chemical environment – water chemistry, the cover, density and composition of macrophytes, sediment composition, organic material and aspects of the hydrological cycle – also influenced invertebrate communities. The most important drivers (although not strongly correlated) of both species richness and community composition were shown to be macrophyte cover and biomass, sediment type and nutrient loads. Pinder and Leung (2009) concluded it was important to maintain habitat diversity and adequate conditions in a variety of pools within the catchment to ensure the present suite of species persisted.

Vertebrate fauna

Although the De Grey pools provide distinct isolated habitat for fish (discussed previously) and a single freshwater turtle species (*Chelodina steindachneri*), they are also used opportunistically by a larger number of vertebrate species (HGM 1998). Waterbirds, waders and frogs are most strongly associated with this habitat type, with reptiles and both native and introduced mammals using the pools for foraging, shelter and drinking. Saltwater crocodiles have also been noted in the estuarine zone. Many of these species are mobile and capable of moving to other water sources in dry conditions.

Permanent pools may also be important to the productivity of surrounding landscapes. During the dry season, the abundance of flying adult insects in the riparian zone is likely to be much higher than the nearby steppe and savanna, providing important food sources for terrestrial consumers such as bats, reptiles, birds and spiders (Douglas et al. 2005).

Flora

Previous phytoplankton surveys (Massini & Walker 1989; Dames & Moore 1978; Massini 1988) recorded at least 29 species on the De Grey River (van Dam et al. 2005). Cyanophyta (blue-green algae) and Chlorophyta (green algae) generally dominate the flora with Bacillariophyceae (diatoms) also common.

Van Dam et al. (2005) concluded that water quality and pool size during the dry season had a greater impact on phytoplankton communities than pool depth, but that increased turbidity could also have an effect.

Although not common to all pools, macrophytic vegetation is an important ecological component of the De Grey, providing food and habitat for fauna. This was supported in the findings of a recent aquatic invertebrate habitat study (Pinder & Leung 2009), which concluded that species richness increased with increased biomass and cover of submerged macrophytes. Macrophytes are of increased importance in the De Grey, where pool substrates are relatively sandy and provide little habitat diversity.

To date at least seven of the 12 recorded Pilbara macrophyte species have been identified on the De Grey. The green macroalgae, *Chara* sp., which may have restricted distribution across the Pilbara, has also been recorded (van Dam et al. 2005). The most dominant species, *Vallisneria nana, Potamogeton pectinatus* and *Myriophyllum* sp., are submerged root angiosperms typically found only in permanent pools. *Schoenoplectus littoralis*, an emergent macrophyte (sedge), is found in similar conditions. *V. nana* provides important habitat for aquatic fauna and occurs at a depth range of 0–1.3 m, with maximum densities found at depths of 0.6 m (George et al. 2002).

Macroalgae reproduce by oospores, while all recorded aquatic macrophyte species reproduce by seed and some also by other means such as stem pieces, tubers and rhizomes (van Dam et al. 2005). Oospores and seed represent the most effective means of propagation for aquatic plants in ephemeral systems, providing resilience against prolonged drought.

Water quality

The De Grey’s surface water quality has not been comprehensively assessed, although data exists from van Dam et al. (2005) and Pinder and Leung (2009), as well as from earlier studies (AUSRIVAS 2004; Dames & Moore 1978; Massini 1988; Massini & Walker 1989).

Unlike other river systems in which salinity increases with distance downstream, the situation in the De Grey is much more variable – with pool water quality reflecting that of the local groundwater. For example, Dames and Moore (1978) found saline groundwater surrounding a saline pool on the ‘J’ line of bores, and a fresh pool in an area of fresh groundwater near the Goldsworthy railway bridge. These results suggest that once flow ceases, the pools are maintained by groundwater from adjacent parts of the aquifer.

Van Dam et al. (2005) and Pinder and Leung (2009) assessed key physico-chemical parameters across 12 and eight pools respectively. Both studies found alkaline conditions (pH ~8-9) and generally clear waters (low turbidities); however salinities varied, with the earlier study reporting relatively high levels (EC measured as mS/cm) and the latter finding fresh water (TDS as mg/L) in all pools. This may be due to different measures of salinity or differences in the timing of sampling.

As part of the current assessment, Department of Water staff measured key physico-chemical parameters in June 2009 in a subset of the previously assessed pools (Table 5). As the 2009 measurements were taken in pools close to established vegetation monitoring transects and not at the exact sites assessed by van Dam et al. (2005) or Pinder and Leung (2008), comparisons between 2009 and previous years were limited.

There was generally little temporal difference in physico-chemical parameters, yet there were some results of note. Although water temperatures were higher in the earlier assessments, this was most likely the result of sampling later in the season when ambient air temperatures would also have been higher. Dissolved oxygen (DO%), pH and conductivity (EC) were generally lower in 2009. It is likely that this reflects the influence of relatively fresh groundwater inflow during 2009 compared with more saline surface water inputs following high flows before the 2004 study. Commander, Martin and Doherty (2004) reported similar findings across the region, describing groundwater and pool salinities above normal recorded levels following large flow events and/or during exceptionally wet years.

Although groundwater quality can also have a major influence on surface water during periods of low flow (as shown by 2009 EC results for Muccangarra Pool), it is also variable. Groundwater salinity in Pilbara coastal aquifers generally increases with distance from the active channel due to decreasing recharge. However, in the De Grey, fresh water is available beyond the active channel due to the presence of the palaeochannel (Haig 2009). Despite this, a wide range of salinities exists in the area, ranging from 0–500 mg/L TDS along the Shaw River and its confluence with the De Grey and north of the Ridley River confluence, to >3000 mg/L TDS in an area of higher elevation west of the Ridley River (Haig 2009).

Table 5 Physico-chemical parameters measured in 2004, 2008 and 2009.

Pool*	temp			pH			EC (mS/cm)			DO%		
	04	08	09	04	08	09	04	08	09	04	08	09
Homestead	24.3	29.4	-	8.6	9.0	-	1.4	-	-	82	-	-
Bulgarene	22.7	-	-	7.4	-	-	1.1	-	-	27	-	-
J96												
– channel	-	27.1	22.2	-	8.9	7.98	-	-	1.05	-	-	96.8
– main pool	28.7	-	24	8.6	-	8.44	1.9	-	1.53	123	-	109
Coolenar												
– downstream	-	-	16.9	-	-	8.66	-	-	1.49	-	-	86.2
– highway xing	-	-	19.5	-	-	8.86	-	-	1.53	-	-	126
Muccangarra	27.2	29.3	21.3	8.1	8.0	7.95	3.5	-	0.81	101	-	75.8
Unnamed pool (MX)	-	-	21.3	-	-	7.92	-	-	0.94	-	-	104
Junction	29.6	29.1	-	8.5	7.6	-	1.85	-	-	138	-	-
Namagoorie	25.6	30.1	-	8.5	8.6	-	1.8	-	-	107	-	-
Coongeenariner	27.6	27	-	8.4	8.4	-	1.7	-	-	131	-	-
Wardoo-moondene	27	28	-	7.9	8.7	-	1.6	-	-	86	-	-

*unless otherwise specified, parameters were measured at the edge of the pool.

Although conductivity remains generally higher than the ARMCANZ & ANZECC (2000) range reported for slightly to moderately disturbed wetland ecosystems, it is not uncommon for north-west Western Australian wetlands to have natural salinities higher than those in other regions.

Despite relatively good water quality, the De Grey pools are under pressure from surrounding land use. Pastoral activities across the catchment have the potential to degrade and thin native vegetation. This can lead to soil erosion and mobilisation of sediments, which in turn may cause pool infilling (van Dam et al. 2005). Stock access also has the potential to affect water quality, physically damage pool banks and cause further competition with native fauna for water resources.

Van Dam et al. (2005) and Pinder and Leung (2009) also measured nutrient levels – specifically total nitrogen (TN) and total phosphorus (TP) – linked to water quality problems including toxic algae blooms, hypoxia and declines in habitat values. Results showed the lowest concentrations were recorded in 2005 following a high flow event. This suggests that nutrient levels vary with time since the previous flushing event (high flow), however the season of survey and grazing pressures are also important.

Variations in water quality are also influenced by catchment geology. For example, high nitrate levels upstream in the Nullagine and Oakover rivers are mobilised in flow events, increasing levels in the De Grey (D Abbott pers. comm. 2009).

Sensitivity and conservation significance

Sensitivity

A desk-based sensitivity assessment of all fauna species known or thought to occur in the study area was conducted, taking into account potential impacts of groundwater decline on river pools and river vegetation (Outback Ecology Services 2004). Each species was assigned to one of three categories as described in Bamford (2003):

- low sensitivity – show no preference for river pools or riverine vegetation
- moderate sensitivity – make some use of habitat associated with river pools or riverine vegetation
- high sensitivity – dependent on river pools and riverine vegetation and associated habitats.

The study identified species of 19 reptiles, 22 mammals and 89 birds with moderate sensitivity to groundwater decline (Outback Ecology Services 2004). Of these one mammal and five birds are of conservation significance (Table 6). Nine frog species, one reptile species and 46 bird species were considered to have high sensitivity to groundwater decline, including 12 birds of conservation significance.

Conservation significance

The De Grey River, from the confluence of the Nullagine and Oakover rivers to the Indian Ocean at Poissonnier Point, is listed in the *Directory of important wetlands in Australia* (Environment Australia 2001). The river meets three of the six criteria for inclusion in the directory, namely:

- it is a good example of a wetland type occurring within a biogeographical region of Australia
- it is a wetland which plays an important ecological or hydrological role in the natural functioning of a major wetland system/complex
- the wetland is of outstanding historical or cultural significance.

The area includes approximately 4500 ha of tidal wetlands consisting of mudflats, coastal flats, mangroves and about 22 km of tidal reaches (MWH Australia Pty Ltd 2007). Because mangroves are present, the De Grey is also recognised as a wetland of subregional significance (Kendrick & Stanley 2002). Carawine Gorge on the Oakover River and Skull Springs and Running Waters on the Davis River – all in the upper catchment of the De Grey – are also wetlands of subregional importance. In addition, at the extreme eastern extent of the De Grey River catchment, Rudall River and Savoury Creek are listed as a wild rivers (DoW 2009b).

The De Grey pools represent the some of the largest permanent river pools in north-western Australia (Environment Australia 2001). Dames and Moore (1978) stated that the 'aquatic ecosystem is better developed in the De Grey River pools than in any other part of the northern or eastern Pilbara'. The pools are known or thought to support the following fauna:

- 54 of 101 macroinvertebrate taxa/families recorded in the Pilbara, including two new to the region (van Dam et al. 2005)
- 20 of 33 Pilbara fish fauna, probably the most diverse in the region (van Dam et al. 2005)
- nine species of frog, 145 birds (32 of conservation significance), 38 mammals (four of conservation significance) and 98 reptiles (two of conservation significance) may occur in the study area (Outback Ecology Services 2004).

Table 6 Fauna of conservation significance sensitive to groundwater decline (Outback Ecology Services 2004)

Taxon	**Level of sensitivity to groundwater decline**	
	Moderate	High
Mammals	• Pilbara leaf nose bat (*Rhinonicteris aurantius*)	–
Birds	• White-bellied sea-eagle (*Haliaeetus leucogaster*) • Rainbow bee-eater (*Merops ornatus*) • Fork-tailed swift (*Apus paciflicus*) • Barn swallow (*Hirundo rustica*) • Peregrine falcon (*Falco peregrinus*)	• Great egret (*Ardea alba*) • Cattle egret (*Ardea ibis*) • Australian painted snipe (*Rostratula benghalensis*) • Sharp-tailed sandpiper (*Calidris acuminata*) • Curlew sandpiper (*Calidris ferruginea*) • Broad-billed sandpiper (*Limicola falcinellusi*) limited records • Marsh sandpiper (*Tringa stagnatillis*) • Red-necked stint (*Calidris ruficollis*) • Little curlew (*Numenius minutus*) • Lesser sand plover (*Charadrius mongolus*) • Oriental plover (*Charadrius veredus*) • Oriental pratincole (*Glareola maldivarum*)

Van Dam et al. (2005) deemed that the ecological values of deep pools (>2 m) in terms of fish and macroinvertebrates were higher than those of intermediate pools, which were in turn greater than the values of shallow pools. Deep pools provide refugia for resident species during dry periods, with intermediate pools offering additional carrying capacity and recruitment habitat for the same species during wetter times.

3.2 Riparian ecosystems

Ecology

The De Grey study area lies within the Pilbara region's Fortescue Botanical District (Beard 1975). HGM (1998) mapped four main vegetation types in the area, of which two support species commonly regarded as groundwater dependent:

- river red gum (*Eucalyptus camaldulensis*) and cadjeput (*Melaleuca argentea*) overstorey with varying understorey, fringing the river
- river red gum (*E. camaldulensis*) and coolibah (*Eucalyptus victrix*) on the floodplains.

Groundwater-dependent vegetation

The riparian tree species *E. camaldulensis* and *M. argentea* are widespread across floodplains in the Pilbara and the De Grey study area, with *E. victrix* common slightly higher in the landscape. These species are the most studied and understood of Pilbara riparian species.

Previous studies indicate that the shallow planform root system of *M. argentea* is adapted to areas of shallow groundwater (2–3 mbgl; m below ground level) and the species has difficulties adjusting to short periods of dry conditions (Graham 2001; Strategen 2006).

E. camaldulensis is also commonly associated with shallow depths to groundwater (2–5 mbgl), although it has been recorded where groundwater is up to 21 mbgl (Landman 2001). The bimorphic root system (surface lateral roots and a tap root) of this species enables it to access both groundwater and water held in the unsaturated, vadose zone above the watertable. Although *E. camaldulensis* is reported to be capable of sinking new tap roots in response to groundwater decline, drawdown of >10 m over a prolonged period may cause irreversible stress (Woodward-Clyde 1997).

Although both *E. camaldulensis* and *M. argentea* are phreatophytic (Muir Environmental 1995), it is thought they will access surface/flood water where available (O'Grady et al. 2002). Surface/flood waters also play an important role in reproductive morphology, with the period of greatest seedfall for both species timed to coincide with receding floodwaters (Pettit & Froend 2001). This ensures moist sediments are available to support seed germination and survival. Flood frequency is important because the small seeds of *E. camaldulensis* dry out quickly and do not become incorporated into the seedbank (Pettit & Froend 2001). Flood frequency and intensity also drives size and age class structure: immature, small individuals can be removed in relatively low-intensity flows and mature trees in large events.

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

The tree species *Sesbania formosa, Atalaya hemiglauca, Ficus aculeata* and *Corymbia flavescens* also occur in the riparian and floodplain zones. Although less well studied than other riparian species, their habitat preferences suggest they are poorly adapted to low moisture availability and likely to be accessing groundwater. *S. formosa* is restricted to alluvium and creek lines or rivers (Paczkowska & Chapman 2000), indicating the potential for a high level of groundwater use. *A. hemiglauca* occurs on floodplains and clayey soils, and *C. flavescens* along drainage lines and floodplains, suggesting a lower degree of groundwater use. *F. aculeata* occurs on floodplain margins and creek edges as well as in gorges and at the base of cliffs (DEC 2009), suggesting a preference for moisture-rich environments and, at the De Grey, an opportune use of groundwater rather than obligate dependence.

Fauna

E. camaldulensis/M. argentea woodlands and forests fringing the De Grey provide habitat for terrestrial fauna, including reptiles, mammals and avifauna. Although most species would not be directly affected by groundwater decline, any loss of habitat may have an indirect impact.

Bird fauna relying on the riparian vegetation for feeding, breeding and habitat are thought to be sensitive to groundwater regime change (Outback Ecology Services 2004). Although they are mobile and can relocate to other suitable areas, there is the potential for over-population of habitats and overall reduction in carrying capacity.

Bats and some small mammal species are also relatively sensitive. Of the small mammals, *Dasyurus hallucatus* (northern quoll) and *Ningaui timealeyi* (Pilbara ningaui) are believed to be the most sensitive due to their preference for habitats associated with creek and drainage lines (Outback Ecology Services 2004). Any of the bat species known from the area, such as *Nyctophilus arnhemensis* (northern long-eared bat), *N. bifax daedelus* (eastern long-eared bat), *N. geoffroyi* (lesser long-eared bat), *Chalinolobus gouldii* (Gould's wattled bat) or *Scotorepens greyii* (little broad-nosed bat), are likely to rely on riverine vegetation for habitat and to feed on invertebrates living in tree canopies (Outback Ecology Services 2004).

Vegetation condition

Condition assessments were carried out in conjunction with vegetation community mapping by HGM (1998) and Strategen (2006). HGM also undertook biannual tree-stress monitoring at 10 sites across the Bulgarene borefield during 2000, 2001 and 2002 (HGM 2001a; HGM 2001b; HGM 2002b; HGM 2002a).

HGM (1998) assessed vegetation condition based on the ratio of introduced to native species, the nature and degree of disturbance and the degree of change to community structure. Results showed vegetation along the river banks was in very good condition, possibly due to the greater availability of water. However, other vegetation was classified as completely degraded. Exotic species were found to dominate the understorey across the study area.

The purpose of the HGM biannual monitoring program was to detect biological responses of indicator species (overstorey) to groundwater extraction. Results showed a decline in tree health from December 2000 to August 2002 for *E. camaldulensis*, *E. victrix* and *M. argentea*. Above-average rainfall before the initial assessment and below-average rainfall at the end of the monitoring period were thought to be the cause (HGM 2002b).

Strategen (2006) assessed the tree-canopy condition of *E. camaldulensis* and *M. argentea* at 10 transects along the De Grey as part of a study into the sensitivity of vegetation to groundwater decline. Six of the transects were re-assessed in June 2009 as part of the current EWR project (appendices B and C).

Comparison of the 2004 and 2009 results showed an increase in mean canopy condition across all re-assessed transects (Figure 13; Appendix B). This may simply be a result of different individuals undertaking the assessment or may reflect an increasing trend in groundwater levels (see Section 2.3).

Results from the current monitoring also showed that some trees had collapsed and others had been lost from transects, most likely as a result of high-flow events. Exotic species continued to dominate the understorey as reported by HGM (1998) and Strategen (2006). Although the understorey of most transects remained dominated by the exotic grasses *Cenchrus ciliatus* and *Cynodon dactylon*, species richness at all sites was greater during the 2009 assessment (Appendix B).

Although these data provide some insight into temporal changes in vegetation condition, monitoring techniques are somewhat subjective and subsequent analyses insufficient to fully explore relationships between changes in groundwater levels and vegetation health. The use of quantitative techniques, such as tree water use (sapflow and associated methods) and water sources accessed (deuterium analysis), would provide greater insight into the relationship between the dominant species at the De Grey (*E. camaldulensis* and *M. argentea*) and response to changes in groundwater availability. However, these methods are expensive and time consuming and are beyond the scope of the current study.

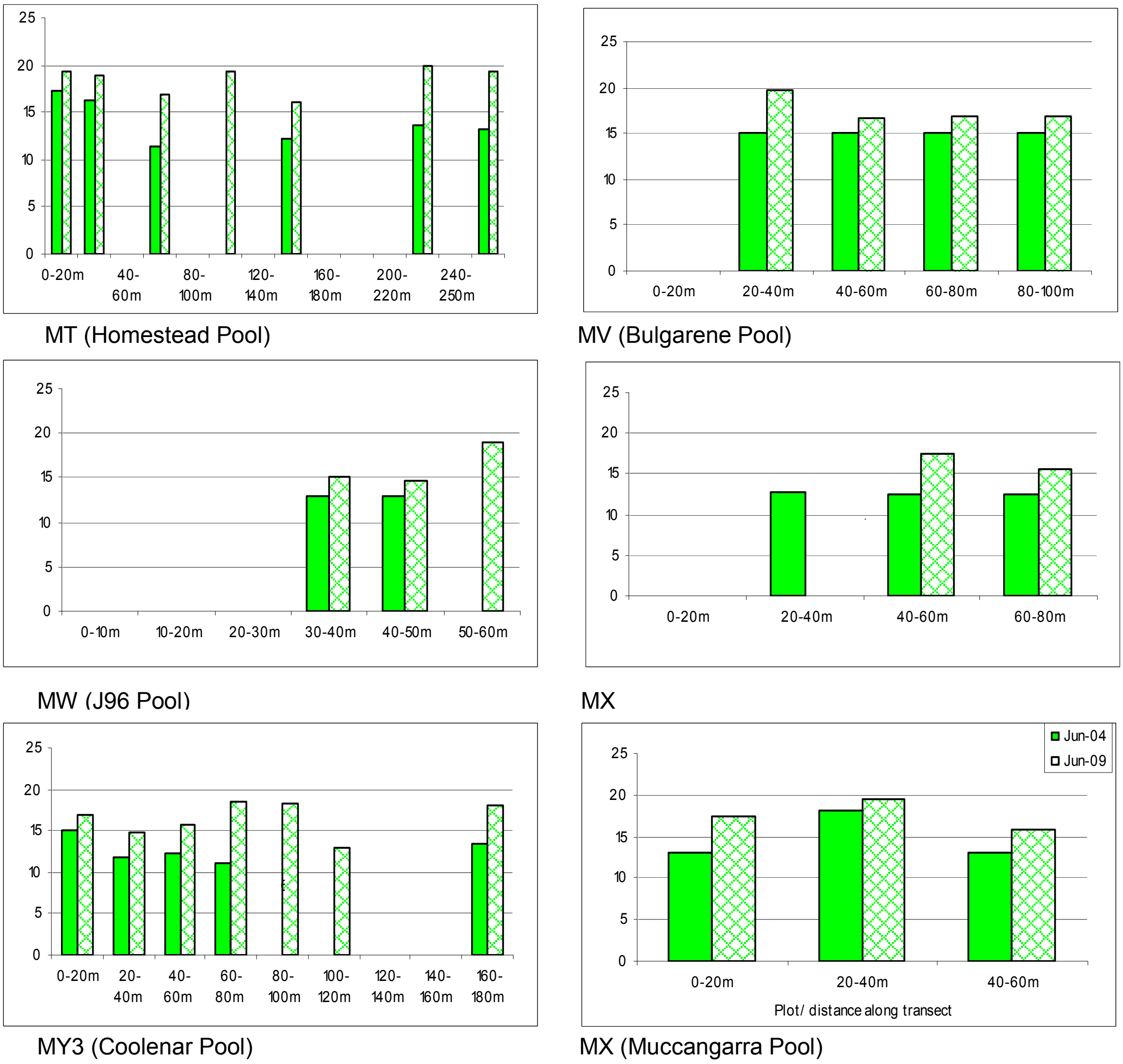

Figure 13 Comparison of mean tree health between June 2004 and June 2009.

Conservation significance

Searches of DEC's Threatened (Declared Rare) Flora and the Western Australian Herbarium Specimen databases identified 12 priority species in the general area. None of these species have been identified in vegetation surveys to date (Strategen 2006); however, *Abutilon trudgenii, Acacia glaucocaesia* and *Euphorbia clementii* are known from the study area. Although *A. glaucocaesia* may occur on floodplains (DEC 2009), as a woody shrub it is likely to have a shallow root system – suggesting it is not groundwater dependent. *A. trudgenii* is also a herbaceous species and unlikely to be phreatophytic. *E. clementii* is generally found on gravelly hillsides or stony grounds (DEC 2009) and is therefore also unlikely to be phreatophytic.

3.3 Aquifer ecosystems

Aquifers in the Pilbara region have been associated with diverse subterranean fauna. Although most studies in the region have been of calcrete aquifers, recent surveys of the alluvial De Grey aquifer have also yielded stygofauna (Goater & Horgan 2006).

In a recent survey, taxa from three higher taxonomical groups were identified: class Oligochaeta, class Maxillopoda (order Harpacticoida), and class Malacostraca (order Amphipoda) (Goater & Horgan 2006). Although stygofauna were only collected from four (17/96, 20/96, I2 and Q2) of the 23 bores surveyed, this may be symptomatic of the bore locations rather than representative of distributions across the wider catchment. Conservation status of these fauna was undetermined.

Twelve stygofauna taxa were identified when potential impacts of mining in the nearby Ord Ranges were assessed. Although none of the study sites were within the De Grey alluvial aquifers, this finding suggests stygofauna are widespread across the study area.

Ten bores within the study area have also been surveyed as part of the DEC's *2002–2009 Pilbara region biological survey*. Data are yet to be released.

3.4 Conceptual models of groundwater dependence

Depth to groundwater is often the most important attribute at sites relying on subsurface provision of groundwater (phreatophytic vegetation), whereas depth and frequency of inundation appear most important to ecosystems relying on both surface expressions of groundwater and overland flows of surface waters (floodplains, wetlands, baseflow rivers) (Eamus et al. 2006).

In this study, ground and pool water levels, combined with surface elevations (vegetation transects and bathymetry), vegetation mapping (riparian and aquatic) and occurrence of pool biota (fish and macroinvertebrates), have been used to model a conceptual understanding of groundwater dependence.

As biota and water quality have been assessed at the five pools where pool water levels are monitored (Homestead, Bulgarene, J96, Marloo and Muccangarra), these pools have been selected as the key sites along with Coolenar Pool (see Figure 11). Conceptual models for each site depict groundwater-dependent ecosystems reliant on subsurface and/or surface expressions of groundwater.

Coolenar Pool

Coolenar Pool (Figure 14) is located at the crossing of the Great Northern Highway. Although this pool's biota has not been assessed, Strategen (2006) established a vegetation monitoring transect (MY3) towards the pool's downstream extent.

Elevations measured across the transect have been combined with a lithological cross-section of the adjacent E-line bores (Haig 2009) to depict surface elevations and lithology across a line running approximately 5.7 km east from the crossing. Groundwater levels from bore 7/04 and three of the E-line bores (E1, E3 and E4) as well as surface water levels from Coolenar Pool were used to determine recent (2002–08) mean maximum and minimum levels across the site. Vegetation mapping and MY3 transect data were then used to depict vegetation distribution.

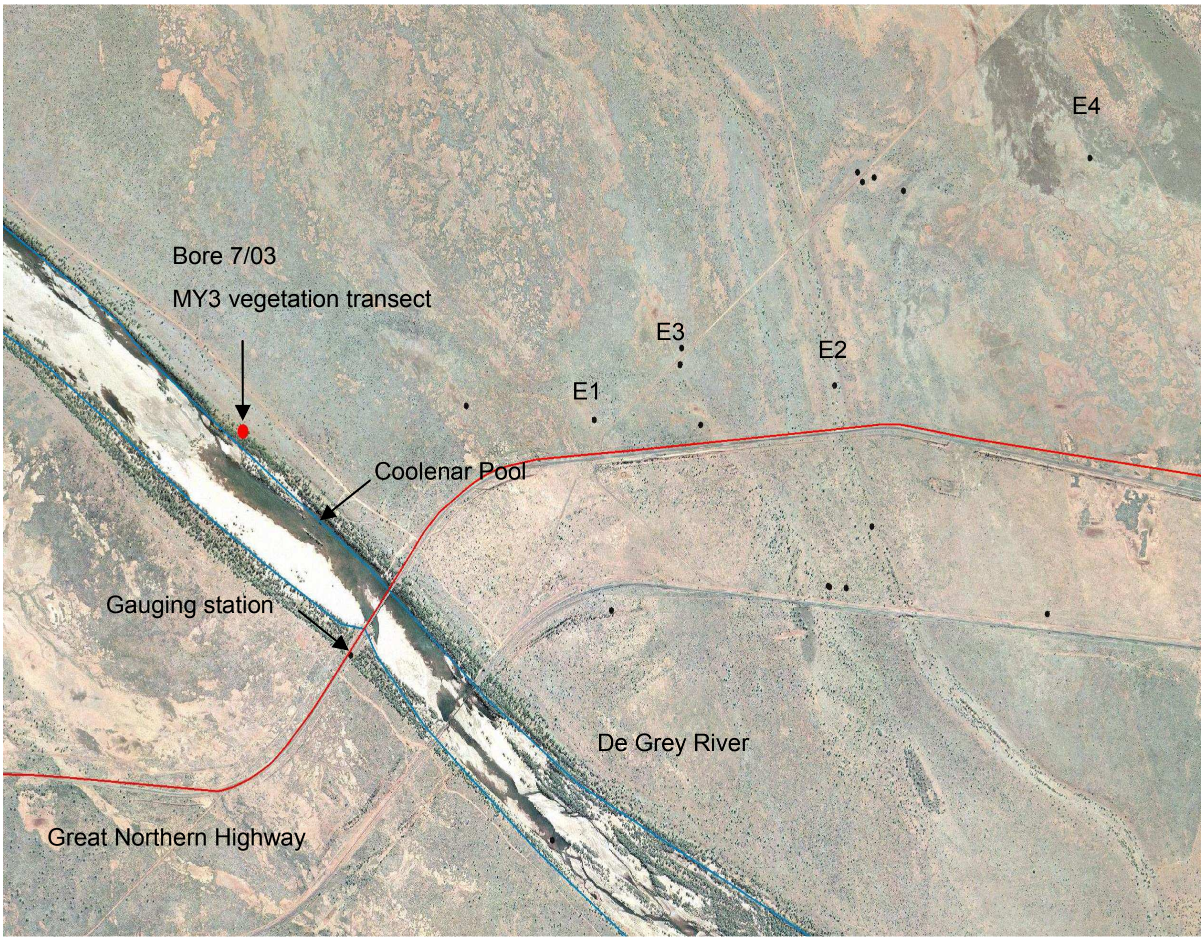

Figure 14 Location of Coolenar Pool, bores, gauging station and vegetation transect.

The conceptual model shows average depths to groundwater (2002–08) of the E-line bores, ranging from a minimum of 7.38 m and a maximum of 7.55 m at E4, to 10.3 m and 10.7 m at E3 (Figure 15). Average depths (2005–08) at bore 7/04 (near the pool and vegetation transect) range from 5.99 m to 7.53 m.

In this area the groundwater table exists entirely within the recent alluvium. This is supported by stratigraphy from bore 7/04, which indicates a silt/sand/clay layer to a depth of 8 m with gravel/clay/sand to 18 m.

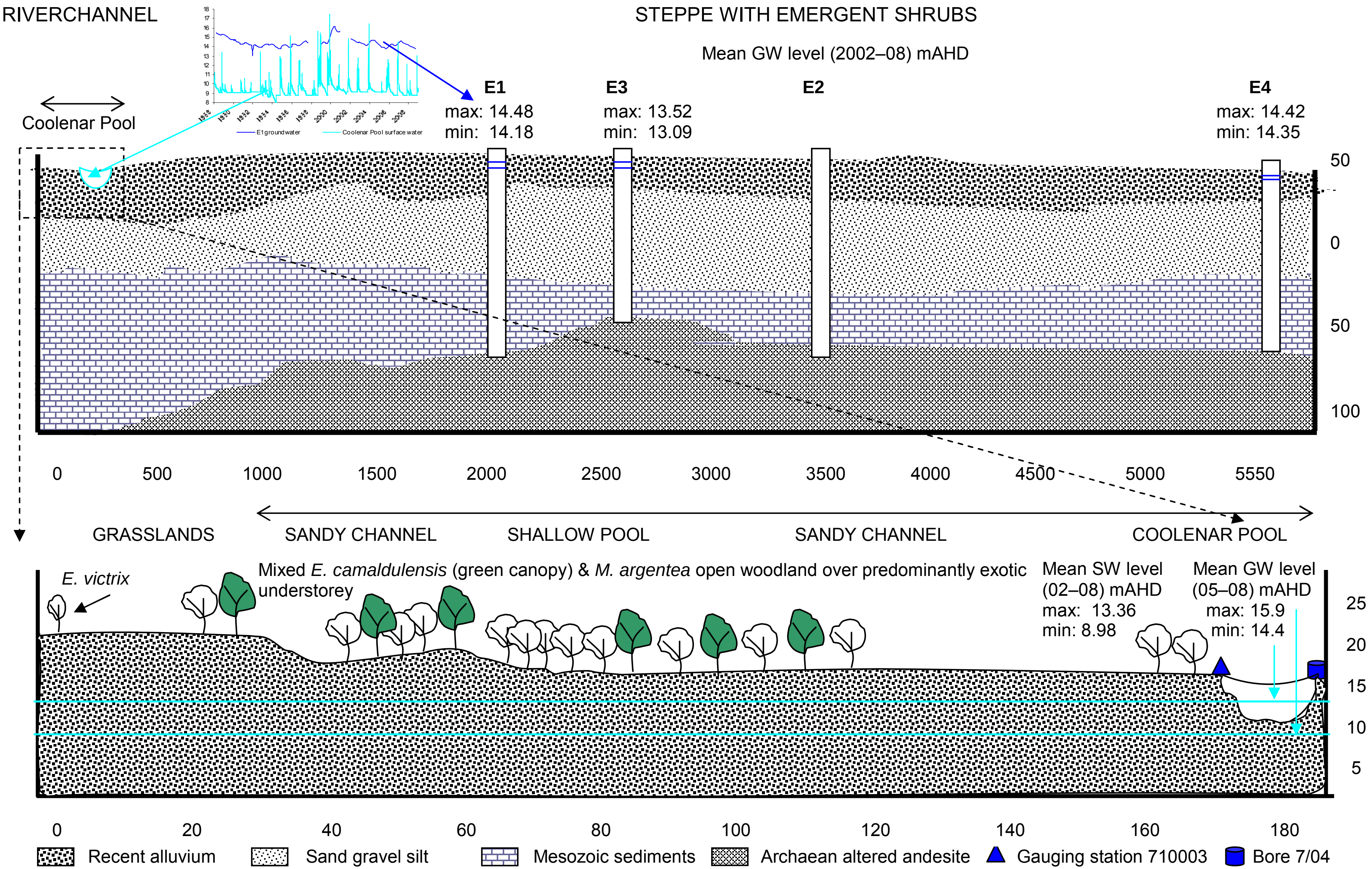

Figure 15 Conceptual groundwater dependence of Coolenar Pool.

As pool bathymetry is currently unknown, depth cannot be accurately determined; however, stage height data suggests Coolenar Pool can reach depths of greater than 8 m when in full flood, reducing to 1–2 m during dry periods (Figure 15).

As previously discussed, the riparian tree species *E. camaldulensis* and *M. argentea* are phreatophytic (groundwater dependent). Minimum and maximum elevations (mAHD) at which each species occurred across the MY3 transect were measured to determine their elevational distribution. These values were then compared with mean groundwater levels (2005–08) to determine current ranges in depth to groundwater as follows:

- *Melaleuca argentea*: -0.36 m to 5.94 m
- *Eucalyptus camaldulensis*: -0.41 m to -5.04 m.

At shallow depths to groundwater (0–3 m) *E. camaldulensis* and *M. argentea* are highly groundwater dependent, with individuals at greater depths (3–6 m) showing slightly less dependence. However, it is probable that *E. victrix* and *C. flavescens* individuals also exhibit a degree of dependence when they occur where the watertable is less than 10 m below the ground surface.

Although macrophytes have not been surveyed specifically, dense beds of *Potamogeton pectinata* were noted along the pool's edge near the highway crossing. Fauna surveys have not been carried out to date; however, the size and apparent permanency of Coolenar Pool suggests it would support fish, macroinvertebrate and bird populations similar to other permanent pools of the same size. There is also anecdotal evidence of saltwater crocodiles occasionally moving upriver during flood events and being stranded in the pool as flood waters recede.

Marloo Pool

Marloo Pool is downstream of the highway crossing on the east bank of the main channel. Pinder and Leung (2009) and van Dam et al. (2005) assessed water quality and pool biota, describing the pool as likely to be permanent to semi-permanent and to support fish, macroinvertebrates and aquatic macrophytes. Strategen (2006) recorded species distribution and condition across a vegetation transect.

To develop a conceptual model for this site, elevations measured across the transect have been combined with water levels from Marloo Pool (mean maximum and minimum, 2004–08) and vegetation transect data.

The conceptual model (Figure 16) shows surface water levels range from 12.23 mAHD to 13.88 mAHD. Although van Dam et al. (2005) recorded a maximum depth of 3.4 m, pool bathymetry is currently unknown and actual depth cannot be determined. Groundwater data from a nearby bore (Marloo Bore) were not available.

Elevational distributions of *E. camaldulensis* and *M. argentea* across the transect were measured previously (Strategen 2006). Extrapolation of pool water level data allows calculation of the current (2002–08) depth to groundwater ranges for each species across the vegetation transect as follows:

- *Melaleuca argentea*: -0.90 m to -2.80 m
- *Eucalyptus camaldulensis*: -1.10 m to -4.60 m.

At these shallow depths to groundwater, *E. camaldulensis* and *M. argentea* are likely to be highly groundwater dependent. However, *F. opposita* also occurs where the watertable is less than 10 m below the ground surface, suggesting a degree of groundwater use.

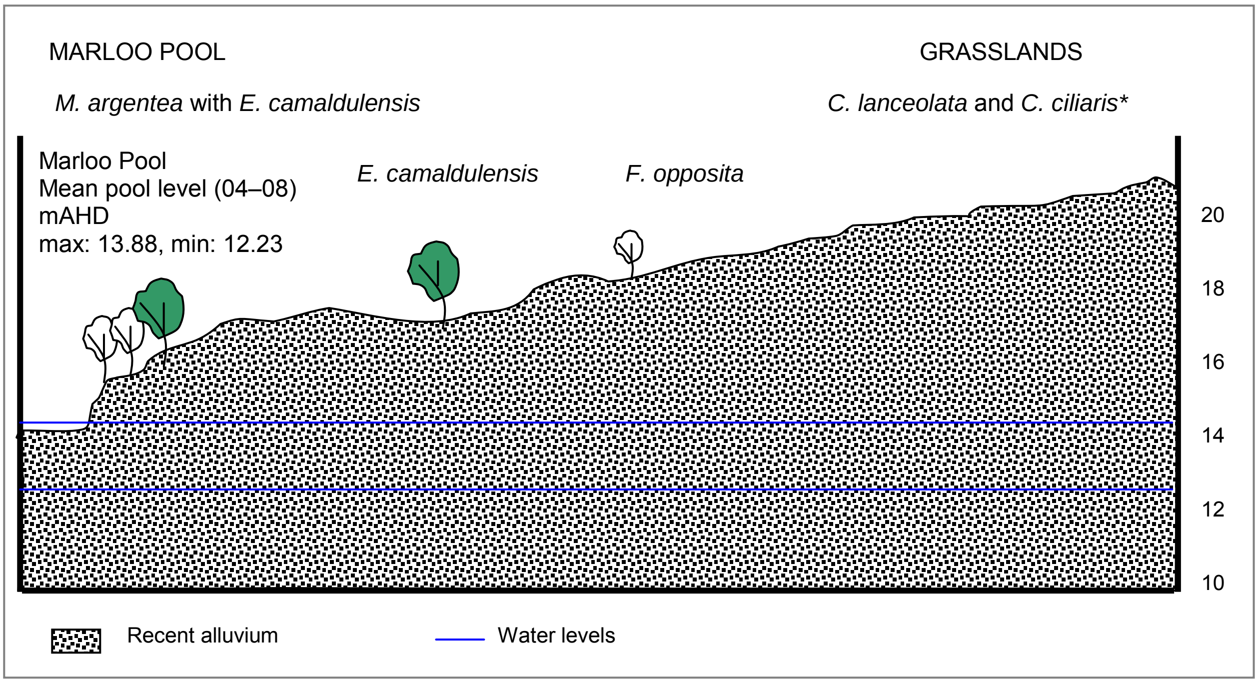

Figure 16 Conceptual groundwater dependence of Marloo Pool.

J96 Pool

J96 Pool is on the west side of the main De Grey channel downstream of Marloo Pool. Extensive areas of shallow water (<0.5 m) with a narrow zone of deeper water (up to 1.7 m) occur along the western bank (van Dam et al. 2005). Pinder and Leung (2009) and van Dam et al. (2005) assessed water quality, biota and vegetation. Although it was suggested that the pool might dry out in some years, it was found to support fish, macroinvertebrates and aquatic macrophytes.

The conceptual model was developed using site elevations measured across the MW vegetation transect (Strategen 2006), water levels from J96 Pool (2002–08), groundwater levels and elevations from nearby bore U1 (2002–08) and vegetation data.

The conceptual model (Figure 17) shows mean pool water levels range from 9.76 mAHD to 11.31 mAHD. Groundwater data from U1 (2002–08) showed mean levels similar to the pool, ranging from 9.77 mAHD to 10.77 mAHD. As pool bathymetry is currently unknown, actual depth cannot be determined; however, van Dam et al. (2005) recorded a maximum depth of 1.7 m. At this time (September 2004), the pool level was 10.91 mAHD and local groundwater was 10.51 mAHD.

The elevational distribution of *E. camaldulensis* and *M. argentea* and current pool level data (2002–08) were used to calculate depth to groundwater ranges for each species as follows;

- *Melaleuca argentea*: -0.29 m to -2.94 m
- *Eucalyptus camaldulensis*: -1.99 m to -5.34 m.

At these shallow depths to groundwater *E. camaldulensis* and *M. argentea* are highly groundwater dependent. However, it is probable that individual *F. opposita* and *A. hemiglauca* also exhibit a degree of dependence when they occur where the watertable is less than 10 m below the ground surface.

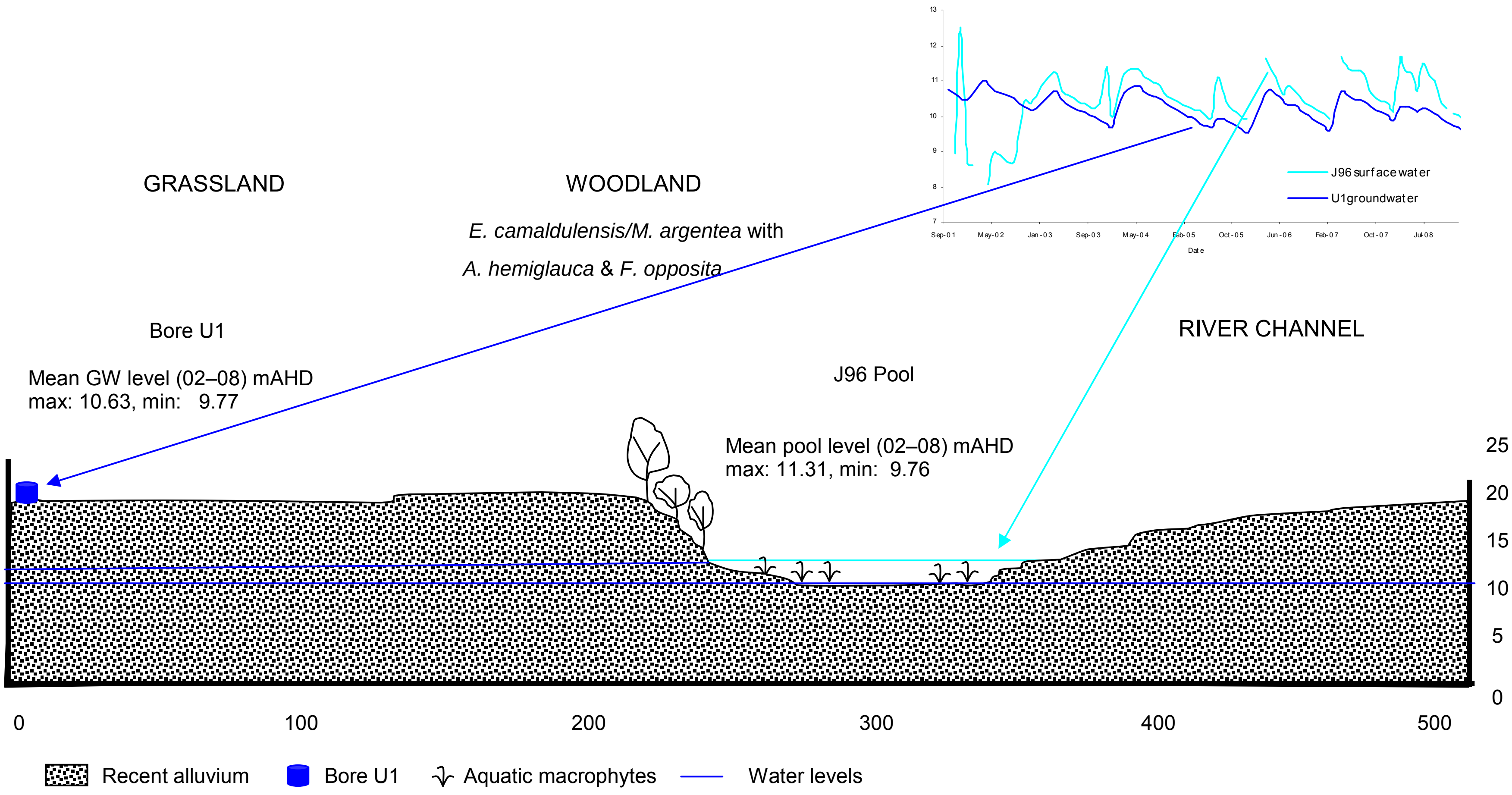

Figure 17 Conceptual groundwater dependence of J96 Pool and surrounds.

Bulgarene Pool

Bulgarene Pool is on the eastern side of the De Grey within the existing borefield. Although the pool is thought to dry out in most years and is unlikely to act as a drought refuge, when inundated it supports fish, macroinvertebrates and aquatic macrophytes.

Site elevations measured across the MV vegetation transect, water levels from Bulgarene Pool (2002–08), groundwater levels and elevations from nearby bore 8/04 (2002–08) and vegetation transect data were used to develop the conceptual model (Figure 18).

The model shows mean pool water levels (2002–08) range from 9.38 mAHD to 10.83 mAHD. As pool bathymetry is currently unknown, actual depth cannot be determined; however, van Dam et al. (2005) recorded a maximum depth of 0.62 m. Groundwater data from bore 8/04 (2005–09) showed mean levels ranging from 9.07 mAHD to 9.97 mAHD.

The elevational distribution of *E. camaldulensis* and *M. argentea* and current pool level data (2002–08) were used to calculate depth to groundwater ranges for each species as follows:

- *Melaleuca argentea*: +0.63 m to -7.07 m
- *Eucalyptus camaldulensis*: -5.57 m to -7.07 m.

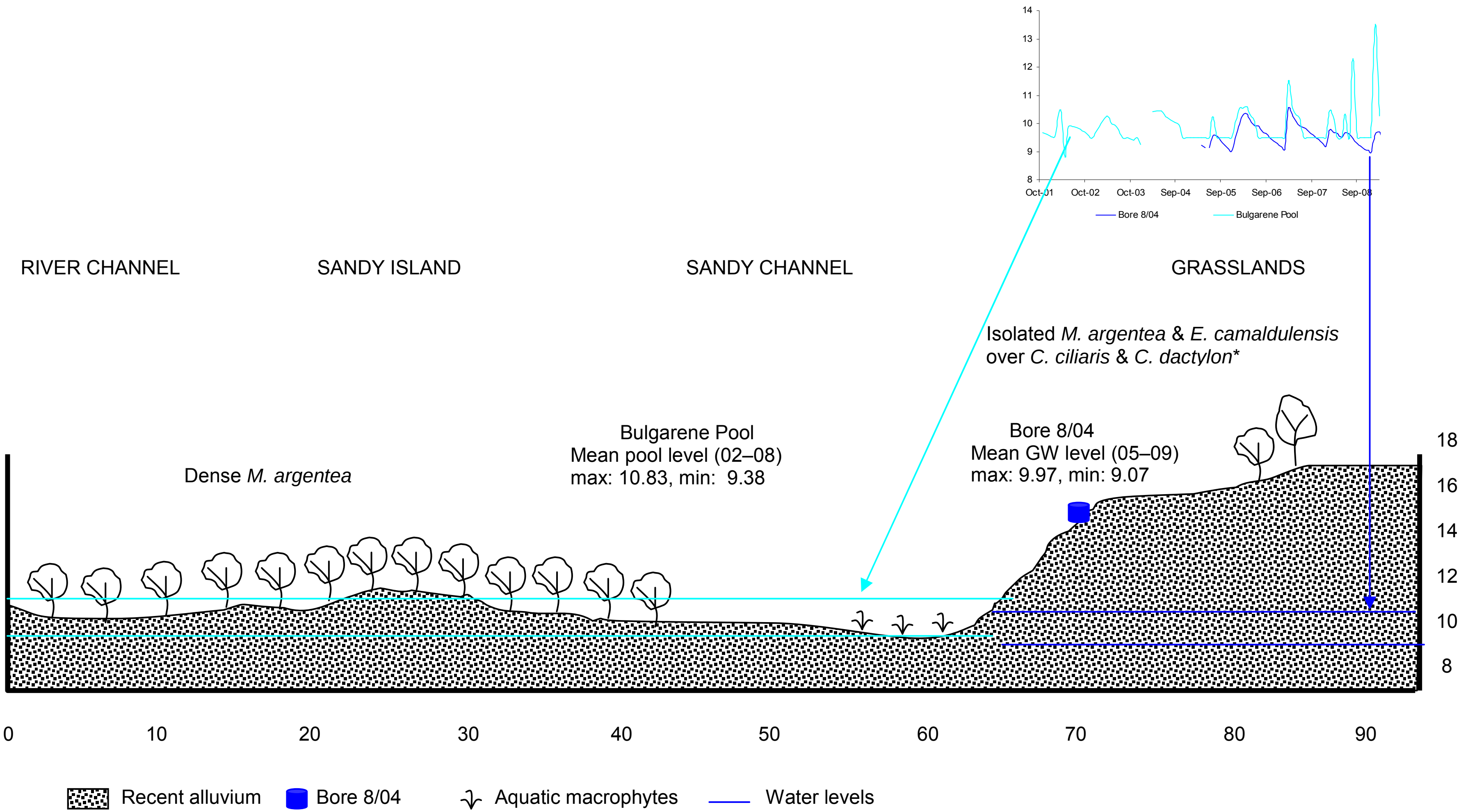

Figure 18 Conceptual groundwater dependence of Bulgarene Pool and surrounds.

Homestead Pool

Homestead Pool is a large (~25 ha) deep pool on the eastern bank of the river adjacent to the De Grey Station homestead. Water and biota were assessed by van Dam et al. (2005) and Pinder and Leung (2009) and a vegetation transect (MT) established upstream (Strategen 2006). As a deep permanent pool, Homestead Pool acts as an important drought refuge supporting fish, macroinvertebrates and aquatic macrophytes.

The conceptual model (Figure 19) was developed using vegetation transect data and elevations and pool water levels. The model shows mean groundwater levels (2002–08) ranged from 6.17 mAHD to 8.09 mAHD. Although pool bathymetry is unknown, van Dam et al. (2005) recorded a maximum depth of 3.73 m. They also noted extensive shallow areas at the upstream and downstream ends of the pool.

The elevational distribution of *E. camaldulensis* and *M. argentea* and recent pool level data (2002–08) were used to calculate depth to groundwater ranges for each species as follows:

- *Melaleuca argentea*: -1.81 m to -3.83 m
- *Eucalyptus camaldulensis*: -2.16 m to -7.33 m.

At shallow depths to groundwater (e.g. 0–3 m) *E. camaldulensis* and *M. argentea* are highly groundwater dependent, with individuals at greater depths (3–6 m) showing slightly less dependence. However, it is also probable that *F. opposita* individuals also exhibit a degree of dependence when they occur where the watertable is less than 10 m below the ground surface.

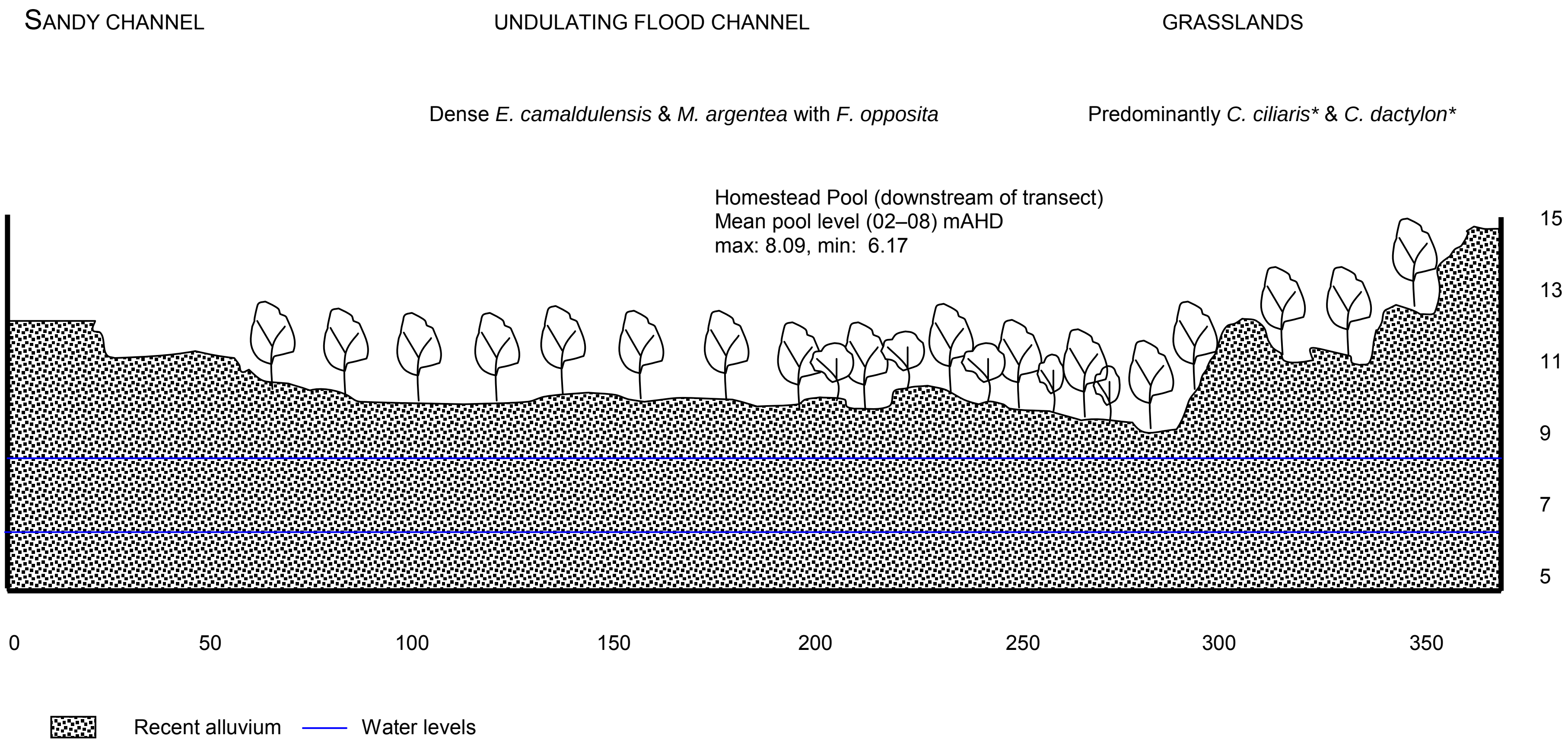

Figure 19 Conceptual groundwater dependence of Homestead Pool and surrounds.

Muccangarra Pool

Muccangarra Pool is a long, narrow, deep pool on the Ridley River west of the De Grey. It is of cultural significance to the Ngarla people. Van Dam et al. (2005) described Muccangarra as atypical of pools on the main river channel due to its well-defined nature and dense riparian vegetation. Based on the presence of flood debris on the downstream side of riparian trees and the ‘upstream lean’ of many individuals, van Dam et al. (2005) concluded that the Ridley River receives significant backflow when the De Grey is in flood. They also stated that a large rock bar at the downstream end is likely to help stabilise the pool.

Water and biota were assessed by van Dam et al. (2005) and Pinder and Leung (2009). They found, because of its size and depth, that Muccangarra acts as an important drought refuge for macroinvertebrates and fish. Although the depth of the pool excludes aquatic macrophytes from all but a few isolated and shallow backwater areas (van Dam et al. 2005), where beds do occur they are very dense (Pinder & Leung 2009).

Transect elevations (transect MZ) (Strategen 2006), vegetation data and pool water levels were used to develop a conceptual model of groundwater dependence (Figure 20). The model shows mean groundwater levels (2004–08) ranged from 8.81 mAHD to 10.47 mAHD. Although pool bathymetry is unknown, van Dam et al. (2005) recorded a maximum depth of 7.03 m, making Muccangarra the deepest pool assessed to date.

The elevational distribution of *E. camaldulensis* and *M. argentea* and updated pool level data (2004–08) were used to calculate depth to groundwater ranges for each species as follows:

- *Melaleuca argentea*: -0.23 m to -2.79 m
- *Eucalyptus camaldulensis*: -0.83 m to -7.41 m.

As with other pools, individuals over a watertable <3 m below the surface are likely to be highly groundwater dependent, with trees at greater depths showing lesser degrees of dependence.

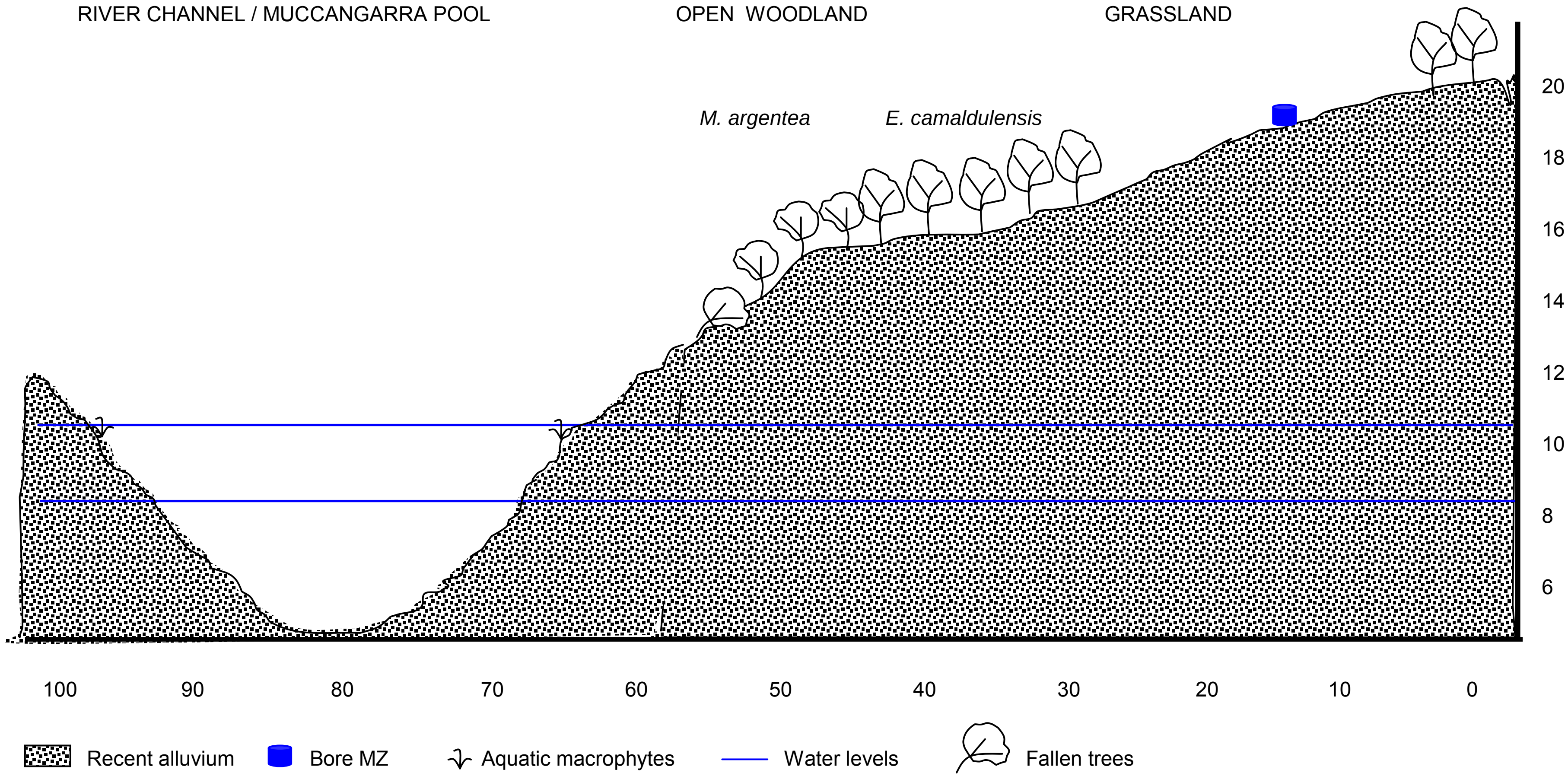

Figure 20 Conceptual groundwater dependence of Muccangarra Pool and surrounds.

3.5 Summary of ecological values

In this study, groundwater-dependent ecosystems of three different types have been identified and described in the De Grey River area: wetlands (riverine pools), riparian vegetation and aquifers. This section provides a summary of the ecological values of each type of groundwater-dependent ecosystem. Values are divided into the following categories following Horwitz and Rogan (2003):

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

Cultural values will be discussed in a separate report.

Wetlands

Numerous pools of varying size, depth and permanency occur along the De Grey, Ridley, Shaw and Strelley rivers. They are hydraulically connected to the aquifers and maintained by groundwater flow between flood events. Recent pool mapping (DoW 2009a) suggests there are 30 permanent, 28 semi-permanent and 32 intermittent pools within the study area.

Biotic values

The De Grey pools are known or thought to support the following flora and fauna:

- 29 species of phytoplankton
- seven of the Pilbara’s 12 known macrophyte species
- 54 of 101 macroinvertebrate taxa/families known to the region
- 20 of 33 Pilbara fish species (possibly most diverse in the region)
- nine frog species
- 145 bird species (32 of conservation significance)
- 38 mammal species (four of conservation significance)
- 98 reptile species (two of conservation significance).

Functional values

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

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

Land/waterscape values

The De Grey pools and the river itself hold a number of broader-scale and regional values. These include:

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

Riparian vegetation

The pools and shallow groundwater adjacent to the De Grey support two riparian vegetation community types:

- *Eucalyptus camaldulensis* (river red gum) / *Melaleuca argentea* (cadjeput) woodland/dense forest
- *Eucalyptus camaldulensis* (river red gum) and *E. victrix* (coolibah) on floodplains.

Biotic values

Riparian vegetation supports the following fauna:

- birds
- mammals, including up to five bat species
- reptiles
- macroinvertebrates.

Functional values

Riparian vegetation maintains key ecological processes important to habitat provision including:

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

Landscape values

Riparian vegetation of the De Grey supports the following landscape values:

- connectivity – vegetation provides corridors allowing fauna to move between habitats (e.g. pools)

- habitat provision – vegetation provides both direct habitat and refuge habitat during drought
- representativeness – vegetation communities are good examples of riparian ecosystems of the region
- resilience – the health/condition of vegetation allows it to absorb seasonal changes (drought/flood).

Aquifers

Biotic values

Aquifers in the Pilbara region have been associated with diverse subterranean fauna. Although studies within the De Grey's alluvial aquifers have been limited, stygofauna have been identified across the area.

4 Ecological management objectives

Formulating management objectives for a water resource system is an integral component of the allocation planning process. Objectives presented in this report are based solely on ecological values and issues identified during the review of ecological information. In the final allocation plan, management objectives will be informed by social, cultural and economic values.

Ecological management objectives influence all aspects of ecosystem management including:

- determining the study area
- identifying management triggers
- designing and implementing a monitoring program
- reporting of outcomes
- subsequent response of management within an adaptive management framework.

Without a clear statement of objectives, the success or otherwise of any management plan cannot be assessed. Because the stated objectives are often very general or conceptual in nature, the challenge is to translate them into practical targets and performance indicators that can be measured in the field. The management system must also be able to detect and correct mistakes before unacceptable damage is done.

This review has identified groundwater-dependent ecosystems of three different types associated with the De Grey River – riverine pools, riparian vegetation and aquifers – as well as their associated ecological values. Management objectives are now required to ensure these values are maintained and considered in future water resource planning.

The overarching management objective for the De Grey is to:

- maintain the ecological characteristics of the site in the context of a naturally variable climate*.*

The ecological investigations discussed in this report indicate that pools support a number of key ecosystem processes. These include the maintenance of:

- in-stream foodwebs (aquatic vegetation, macroinvertebrates etc.)
- fringing riparian vegetation
- floodplain vegetation
- pool water quality
- connectivity.

The following generic management objectives have been developed for the ecological components of the De Grey River pools that drive/maintain these processes:

Macroinvertebrates: maintain species richness and composition through maintenance of:

- macrophyte habitat inundated and available for a range of macroinvertebrate species
- available surface water expression consistent with regional seasonality.

Fish: maintain species richness and composition through maintenance of:

- shallow macrophyte habitat inundated and available for small-bodied fish and juveniles of large-bodied fish
- deeper habitat permanently inundated and available for mature and large-bodied fish species.

Frogs and reptiles: maintain species richness and composition through maintenance of:

- permanent surface water with seasonal fluctuation to provide frog and turtle habitat

Vegetation: maintain species richness, composition and extent through maintenance of:

- permanent inundation of pools to support aquatic macrophytes
- permanent available soil moisture and occasional inundation of all riparian and floodplain vegetation
- maintaining depth to groundwater within the range required by phreatophytic species and within the context of the regional climate.

Pool water quality: maintain water quality through maintenance of:

- sufficient depth in deep pools to ensure dissolved oxygen levels do not reduce to anoxia
- occasional high-level flows to scour the sediment.

The ecological management objectives described here, as well as the social and cultural values to be addressed in the future, will inform the development of ecological water requirements for the De Grey River. In this process they will be used to frame estimates of water requirements specifically related to those potentially impacted by groundwater abstraction. In addition, they will provide the basis for a potential future ecological monitoring program.

Appendices

Appendix A Photos

Plate 1 Dense Eucalyptus camaldulensis/Melaleuca argentea *forest at Homestead Pool (and high water mark in January 2010)*

Plate 2 Buffel grass dominated understorey near Homestead Pool.

Plate 3 Muccangarra Pool.

Plate 4   Floodplain south of the Great Northern Highway crossing.

Plate 5 Shaw River/De Grey River confluence.

Plate 6 Permanent pool south of Great Northern Highway crossing.

Appendix B Vegetation transect species lists and abundances 2009

Date	Transect	Quadrat	Distance	Comp	Coll.	Species	Abundance	% cover
23/06/2009	MT	1	0–20	MB		*Atalaya hemiglauca* (s)	23	0.5
	729579E	7766439N				*Cenchrus ciliaris*		20
					MB01	*Papilionacea* sp.	10	0.1
						Ficus opposita (s)	1	0.1
						Eucalyptus camaldulensis	1	0.2
						Passiflora foetida	1	0.1
						Cucumis melo	1	0.01
						Acacia sp.	1	0.1
		2	20–40	MB		*Atalaya hemiglauca* (s)	29	1
						Cenchrus ciliaris		1
						Cynodon dactylon		2
					MB01	*Papilionacea* sp.	4	0.02
						Ficus opposita (s)	3	1
						Cucumis melo	1	0.01
						Sida sp.	6	0.1
						Carissa lanceolata	1	1
		3	60–80	MB		*Atalaya hemiglauca* (s)	9	1
						Cenchrus ciliaris		2
						Cynodon dactylon		20
						Erythrina vespertilio	1	0.2
					MB03	*Tephrosia* sp.	1	0.05
						Solanum nigricans	2	0.05
					MB02	*Argemone ochroleuca*	43	0.5
						Eucalyptus camaldulensis	1	0.2
						Alternanthera nodiflora	1	0.01
		4	100–120	MB		*Cynodon dactylon*		60
					MB02	*Argemone ochroleuca*	15	0.1
						Alternanthera nodiflora	1	0.01
						Solanum nigricans	1	0.01
		5	140–160	MB		*Cynodon dactylon*		60
					MB02	*Argemone ochroleuca*	100	3
					MB03	*Tephrosia* sp.	1	0.05
						Ficus opposita (s)	1	0.5
						Eucalyptus camaldulensis (s)	2	0.25
			220	MB		*Cynodon dactylon*		10
						Eucalyptus camaldulensis	9	1
					MB02	*Argemone ochroleuca*	10	
					MB04	White one-sided	100	10
					MB03	*Tephrosia* sp.	1	0.1
			250	MB	MB04	White one-sided	150	10
						Cynodon dactylon		4
						Cenchrus ciliaris		0.1
						Eucalyptus camaldulensis (s)	17	3

Date	Transect	Quadrat	Distance	Comp	Coll.	*Species*	Abundance	% cover
23/06/2009	MV	1	20–40	MB		*Ficus opposita* (s)	8	0.5
	730154E	7763139N				*Cynodon dactylon*		20
						Eucalyptus camaldulensis (s)	2	0.05
						Cenchrus ciliaris		2
		2	40–60	MB		*Crotalaria novae-hollandiae*	3	0.05
						Cynodon dactylon		3
						Sesbania formosa (s)	1	0.02
		3	60–80	MB		*Ficus opposita* (s)	4	0.2
						Cynodon dactylon		3
						Cenchrus ciliaris		1
						Calotropis sp.	1	0.5
					MB06	*Ipomea muelleri*	1	0.8
						Eucalyptus camaldulensis	1	0.1
					MB05	*Urochloa* sp.		1
		4	80–100	MB		*Cynodon dactylon*		5
						Solanum nigricans	1	0.2
						Cenchrus ciliaris		2
					MB04	White one-sided	1	0.1
						Cyperus vaginatus	1	0.01
						Alternanthera nodiflora	2	0.05
24/06/2009	MW	1	0–10	MB		*Cenchrus ciliaris*		5
	729070E	2	10–20m	MB		*Cenchrus ciliaris*		5
	7761336N					*Corchorus* sp.	1	0.2
		3	20–30	MB		*Cenchrus ciliaris*		15
					MB03	*Tephrosia* sp.	2	0.1
		4	30–40	MB	MB03	*Tephrosia* sp.	8	1
						Cenchrus ciliaris		8
						Cynodon dactylon		2
		5	40–50	MB		*Cynodon dactylon*		3
						Atalaya hemiglauca (s)	1	0.2
						Acacia farnesiana	1	0.05
		6	50–60	MB		*Cynodon dactylon*		0.1
24/06/2009	MZ	1	0–20	MB	MB03	*Tephrosia* sp.	55	2
	727075E	7760395N				*Lysiphyllum cunninghamii* (s)	1	0.2
						Cenchrus ciliaris		1
		2	20–40	MB	MB03	*Tephrosia* sp.	37	4
						Cenchrus ciliaris		0.5
						Cynodon dactylon		2
		3	40–60	MB	MB03	*Tephrosia* sp.	13	1.5
						Cynodon dactylon		30
						Ficus opposita (s)	1	0.1
						Atalaya hemiglauca (s)	1	0.05
					MB04	White one-sided	1	0.05
						Carissa lanceolata	1	0.1
24/06/2009	MX	1	0–20	MB	MB03	*Tephrosia* sp.	18	15
	729059E	7759147N				*Ficus opposita* (s)	4	3
						Datura sp.	10	5
						Cynodon dactylon		25
						Atalaya hemiglauca (s)	1	0.1
						Cenchrus ciliaris		0.5
						Ipomea muelleri		0.2
						Burr	1	0.2
		2	20–40	MB	MB03	*Tephrosia* sp.	2	0.5
						Ficus opposita (s)	2	1
						Atalaya hemiglauca (s)	1	0.05
						Cynodon dactylon		10
						Cucumis melo	1	0.05
		3	40-60	MB		*Cynodon dactylon*		3
						Alternanthera nodiflora	1	0.05

Date	Transect	Quadrat	Distance	Comp	Coll.	*Species*	abundance	% cover
24/06/2009	MY3	1	0–20	MB		*Cenchrus ciliaris*		4
	734161E	7753618N			MB03	*Tephrosia* sp.	100+	60
		2	20–40	MB		*Cenchrus ciliaris*		6
					MB03	*Tephrosia* sp.	100+	15
						Ficus opposita (s)	5	1
						Parkinsonia aculeata	2	0.5
					MB02	*Argemone ochroleuca*	100+	2
					MB05	*Urochloa* sp.		0.2
						Burr	1	0.05
						Solanum nigricans	2	0.05
		3	40–60	MB		*Cynodon dactylon*		35
					MB06	*Ipomea muelleri*	5	0.5
					MB07	Pumpkin weed	1	0.01
					MB08	*Boerharvia*	1	0.01
					MB09	Succulent	3	0.05
						Atalaya hemiglauca (s)	2	0.15
					MB03	*Tephrosia* sp.	2	0.5
						Ficus opposita (s)	4	0.5
						Datura sp.	1	0.1
					MB05	*Urochloa* sp.		0.1
						Cenchrus ciliaris		0.2
		4	60–80	MB	MB03	*Tephrosia* sp.	6	1
						Atalaya hemiglauca (s)	1	0.05
					MB02	*Argemone ochroleuca*	40	2
						Cynodon dactylon		25
						Eucalyptus camaldulensis (s)	3	0.5
						Parkinsonia aculeata	1	0.1
						Melaleuca argentea (s)	10	1
		5	80–100	MB		*Eucalyptus camaldulensis* (s)	10	1
						Melaleuca argentea (s)	16	2
					MB04	White one-sided	3	0.1
					MB06	*Boerharvia*	1	0.1
					MB10	Candles	21	0.5
						Cynodon dactylon		10
						Urochloa sp.		0.2
						Aira cariophylla		0.5
		6	100–120	MB	MB03	*Tephrosia* sp.	1	0.5
						Melaleuca argentea (s)	2	0.1
						Cynodon dactylon		5
						Cucumis melo	1	0.05
						Cyperus vaginatus	1	0.05
		7	160–180	MB	MB03	*Tephrosia* sp.	3	0.1
						Cyperus vaginatus	1	0.05
						Cynodon dactylon		2

Appendix C Vegetation transect overstorey species health and diameter 2009

Homestead (MT); Co-ords: 729579E, 7766439N; Date: 23/06/09

Quad	Species	Tag	Distance on transect		DBH		Canopy cond	
			x (m)	y (m)	2004	2009	2004	2009
0-20m	*Ficus opposita*	1	10.4	13.2	12.7	15, 12	19	19
	Atalaya hemiglauca	2	12.2	8.45	25.8	24.8	19	19
		3	14.5	3	12.7	7	23	21
		NT	na	na	na	8.5, 15		19
	Eucalyptus camaldulensis	4	15.4	8	86.0	13.5, 84.4, 11.4, 15.5, 26.8	17	17
		5	17.3	1.7	10.2	7.5, 24	13	21
		6	17.1	4.5	8.0	8	13	19
		7	16.8	11.3	9.2	10.5	13	17
		8	17	16.9	5.3	11.5	21	21
20-40m	*Eucalyptus camaldulensis*	9	41.1	3.7	34.4	32.5, 55	13	15
		12	33.7	8	1.6	3	17	15
		13	33.7	14.4	1.3	8.5, 1.5	17	21
		NT	na	na	na	1.2, <1		19
	Atalaya hemiglauca	11	28	8.4	3.2	4, 4.7, 4	17	23
	Ficus opposita	10	28	11.2	34.7	22	17	21
40-60m	n/a							
60-80m	*Eucalyptus camaldulensis*	19	64	7.2	9.6	10.6	13	19
		26	68.1	2.6	60.5	50.5, 59.2, 35.7	17	19
		23	64.7	14.9	48.7	48.5, 13, 25.5	11	19
		22	71.8	14	27.1	4.5, 30.3	15	15
		18	72	16.6	5.4	5.8	9	15
		20	72.3	17.2	7	8	11	15
		15	75.6	12.1	5.4	16.4	11	11
		25	75.6	10.9	4.8	?	7	?
		17	76.5	7.6	9.5	11.3	11	15
		14	76.5	17.5	7	?	11	?
	Melaleuca argentea	21	72.9	11	22.3	22.3	15	19
		24	75.9	7.6	11.1	14, 5.8, 10.4, 6.2, 2, 3.3, 3.3	11	19
	Ficus opposita	10	28	11.2	34.7	22	17	21

Quad	Species	Tag	Distance on transect x (m)	Distance on transect y (m)	DBH 2004	DBH 2009	Canopy cond 2004	Canopy cond 2009
100-120m new plot	*Eucalyptus camaldulensis*					22.5		19
						32.5		21
						31.8		21
						26.8		19
						21.2		19
						28.4		21
						8.5		17
						34.2		19
						22		17
140-160m	*Eucalyptus camaldulensis*	27	140.3	8.8	24.8	27.0	11	19
		33	149.9	3.4	12.1	16.5	11	19
		34	149	8.4	8.9	7.0	7	13
		32	146.7	16	5.7	na	11	na
		35	151.8	7.5	5.7	na		na
		36	152	8.1	8.0	3.7, <2	11	19
		37	152	9.9	14.0	15.6, 6.3	15	21
		38	154.7	10.1	15.0	16.7, 2.3	17	17
		39	154.7	9.4	14.0	17.0	17	15
		40	158.7	6.9	6.4	5.9, <2	7	7
		41	154.7	3.5	4.8	5.0	7	11
		42	158.8	4.3	5.1	5.0	7	15
		43	158.8	5.9	14.0	15.3	15	17
		44	158.8	15.9	17.5	20.4	15	19
		NT	na	na	na	<2		11
	Melaleuca argentea	28	140.3	8.9	63.7	58.2, 31	13	15
		29	143.1	13	30.3	26.5	15	19
		30	143.1	11.5	16.6	15.0	15	21
		31	143.3	6.1	20.7	21.0	13	19
		NT	na	na	na	4.5		13
220-240m	*Eucalyptus camaldulensis*	400	220	17.3	14.6	10.0	15	21
		401	226.5	5	14.3	15.5	13	21
		402	229.9	1	15.3	23.1, <2, <2	13	19
		403	236.2	1.6	13.7	12.5	13	19
		404	232.2	7.4	29.9	31, 9.5	15	
		405	139.5	14.5	3.2	3.5	13	23
		NT	na	na	na	<2		17
		NT	na	na	na	7.1		21
		NT	na	na	na	12, 10.6		19
250-270m	*Eucalyptus camaldulensis*	406	252.8	6.3	1.6	<2	13	15
		407	252.8	13.9	1.6	<2	13	19
		408	259	9.3	4.5	7.3	13	21
		409	260	1.5	3.5	<2, <2, <2,	13	17
		410	263.6	8.2	3.2	3.0	13	18
		411	260.7	7.5	6.4	8.2, <2	13	21
		412	259	14	15.0	4, 19.7, 6, 2.2, 3, 8, 9	13	23
		413	262.6	16	31.5	22.2	15	21
		414	268.8	3.1	2.9	<2	13	15
		NT	na	na	na	13.8		23

Bulgarene (MV); Co-ords: 730154E, 7763139N; Date: 23/06/09

Quad	Species	Tag	Distance on transect		DBH		Canopy cond	
			x (m)	y (m)	2004	2009	2004	2009
20-40m	*Eucalyptus camaldulensis*	45	11	0.5	45.9	42.2	15	21
		49	10.2	18.9	101.9	96	15	19
	Melaleuca argentea	46	11.9	3.7	75.5	23, 74.4, 43.2	15	21
		47	11.8	10.7	50.6	52.1, 50.5, 49.5	15	19
		48	10.2	18	45.2	60	15	19
60-80m	*Melaleuca argentea*	50	52		56.4	49.9	15	19
		51	53		20.4	20.5	15	17
		52	54		12.7	12.5	15	17
		53	55		12.7	15	15	7
		54	56		15.3	16	15	19
		55	57		16.2	17	15	15
		56	58		14.6	13	15	17
		57	59		12.1	11.3	15	19
		89	59		22.3	18.5, 16.5, 37.5	15	17
		90	55		25.8	31	15	15
		NT	na		na	5, 3.3	na	17
		NT	na		na	8.2, <2, <2, <2	na	19
		NT	na		na	32.5	na	19
		60	61		11.5	11.9	15	17
		62	62		10.2	10.5	15	19
		63	66		14.3	14.8	15	15
		64	67		22.3	21	15	17
		65	68		18.2	18	15	19
		66	68		20.1	19.9, 12.3	15	19
		68	71		21.3	20.7	15	17
		69	72		28.7	27	15	13
		70	73		28.7	32.2	15	17
		71	74		30.3	26.6	15	17
		85	75		29.3	12.2, 12.2	15	15
		84	78		33.4	31	15	17
		83	79		27.7	24.8	15	17
		82	80		23.9	19.8	15	19
		94	74		13.4	14.5	15	17
		93	65		15.3	22.2	15	17
		92	68		36.0	24.8	15	17
		91	70		7.6	13	15	19
		88	79		13.4	15	15	17
		101	77		25.5	32	15	17
		103	79		14.3	17	15	11
		104	64		17.5	19.2	15	19
						17.3		7
80-100	*Melaleuca argentea*	59	63		19.4	16	15	19
		58	64		10.2	9	15	17
		61	65		13.1	13.5	15	21
		67	70		46.2	49.3	15	21
		72	76		26.4	15, 10.2	15	17
		81	81		9.2	10	15	19

Quad	Species	Tag	Distance on transect		DBH		Canopy cond	
			x (m)	y (m)	2004	2009	2004	2009
80-100	*Melaleuca argentea*	80	82		23.9	21.2	15	13
		79	83		14.3	16.5	15	15
		78	84		10.8	10.5	15	19
		77	85		17.5	17	15	21
		76	86		15.9	19	15	21
		75	87		20.7	19.5, 8.4, 36.8	15	15
		74	88		13.1	9.5	15	17
		73	89		16.9	<2, <2, <2, <2	15	9
		100	90		6.4	7.2	15	19
		99	91		14.3	13, 8.5, 5, 8.2, 7.8	15	19
		98	92		11.1	10.2, 3.5	15	13
		97	85		6.4	5	15	11
		96	86		20.7	13, 19	15	19
		95	84		14.3	14.8	15	17
		86	84		11.1	12.2	15	17
		87	85		8.9	8	15	19
		NT	na	na	na	39.6, 21.6	na	19
		NT	na	na	na	21	na	17
		NT	na	na	na	27.4	na	17

J96 (MW), Co-ords: 729070E, 7761336N, Date: 24/06/09

Quad	Species	Tag	Distance on transect		DBH		Canopy cond	
			x (m)	y (m)	2004	2009	2004	2009
0-10m	n/a							
10-20m	n/a							
20-30m	n/a							
30-40m	*Eucalyptus camaldulensis*	199	38	11.8	33.4	33.6	13	15
	Eremophila longifolia	200	33	16.1	42.9	5.3, 7.6, 3.8, 9.5, 7.9, 3.1, 2.6, 38	15	19
40-50m	*Eucalyptus camaldulensis*	196	43	13.7	55.2	51.7, 13.5	13	15
		193	44	15.5	40.4	38.5	13	17
		192	44	17.8	25.5	23, 24	11	15
		194	44.6	19.5	36.6	30.2	11	15
	Melaleuca argentea	198	46.5	1	118.4	148, 79.8	13	14
		197	15	49	124.1	128	15	13
		191	49.5	14	44.9	15.2, 12.4, 16.1, 8	15	13
50-60m	*Melaleuca argentea*	NT	na	na	na	78	na	19
		NT	na	na	na	42.8, 26.3, 23.6, 16	na	19

MX; Co-ords: 729059E, 7759147N; Date: 24/06/09

Quad	Species	Tag	Distance on transect x (m)	y (m)	DBH 2004	2009	Canopy cond 2004	2009
0-20m								
20-40m	*Eucalyptus camaldulensis*	240	26.9	1.1	49.7		11	
		241	26.9	5.2	66.6		15	
		242	26.9	16.8	65.3		11	
		243	29.2	19.5	9.9		13	
		244	33.2	16.5	22.3		11	
	Atalaya hemiglauca	245	30.3	1.2	20.4		15	
40-60m	*Eucalyptus camaldulensis*	246	47.8	1.1	62.1	60, 54.6	15	15
		247	46.2	8.4	42.7		11	
		248	45.6	11.2	77.1		11	
		250	46	17	56.4		13	
	Melaleuca argentea	249	44	17.2	14.0	13	13	17
		251	50.3	9	49.4	45.5	13	15
		252	50	5.7	52.2	50.6, 13.5	13	15
		253	50.7	2.1	29.9	31	11	19
		254	54.4	1.8	36.6	29.8	13	19
		255	50.7	3.6	38.5	12.9, 20, 23	11	19
		256	57	2.6	19.1	19.2	11	21
		257	57	2.6	18.2	18	13	17
		258	59.2	14.6	31.8	15.5, 13, 10	13	19
		257B	57	11.5	18.5	18.2	13	17
60-80m	*Melaleuca argentea*							
		259	63.3	17.4	18.5	20.1	13	17
		260	63.3	16	25.5	11.5, 14	13	19
		261	62	15.4	7.0	7.9	13	15
		262	61.5	3.8	20.7	21	13	21
		263	60.2	12.6	29.0	15.2, 9.1	13	17
		264	61.7	8	21.3	20.5	11	19
		265	60.2	5.8	17.5		13	
		266	60.2	5.8	24.5		11	
		267	60.2	3.8	17.5	28	11	19
		268	60.9	2	30.3	26.6, 22.7	13	17
		269	63.3	0	23.2		13	
		NT				47		7
		NT				66.1		17
		NT				77.2		17
		NT				81		9
		NT				42.5		11
		NT				11.3		15
		NT				9		15
		NT				8		15
		NT				14.5		17
		NT				13.8		15
		NT				12		13

Coolenar (MY3); Co-ord: 734161E, 7753618N; Date: 24/06/08

Quad	Species	Tag	Distance on transect		DBH		canopy cond	
			x (m)	y (m)	2004	2009	2004	2009
0-20m	*Eucalyptus victrix*	110	1	11	30.9	24.3	15	17
20-40m	*Melaleuca argentea*	109	31	9.8	52.2	52.4	10	19
		115	30.1	9.6	43.3	56	10	17
		119	30.8	13.8	43.6	41.5	13	11
	Acacia sp.	116	30.2	11.7	7.3	9.2, 9	11	19
		121	37.7	20.1	6.4	5.3	13	8
	Lysiphyllum cunninghamii	117	31	10.8	8.3	9.5, 7.6	11	15
	Atalaya hemiglauca	118	29.8	14.8	12.7	15.2	17	17
	Ficus opposita	105	37.2	11.7	28.7	18.8, 7.8	11	21
	Eucalyptus camaldulensis	120	33.3	20.1	65.3	64	11	19
		122	37.7	1.6	36.3	dead	13	0
40-60m	*Melaleuca argentea*	123	45.6	3.6	20.7	18.4	11	14
		124	48	1.8	46.2	41.8	11	16
		125	45.6	1.2	6.4	<2, ,2, <2, 3.6, 2.9, 3.4	13	21
		134	45.6	8.6	28.7	30.9	13	16
		133	48	5.8	9.6		11	
		132	49	3.4	50.3	18.4	13	12
		131	49.4	1.6	19.7	17.9, 5.7	11	15
		126	49	6.6	43.0	41.6	11	17
		130	49.4	7.9	25.5	20.6	13	21
		129	49.4	10.9	24.8	dead	11	dead
		128	49.4	11.8	44.6	42.5	13	21
		127	54	20.2	100.3	97	11	14
		NT	na	na	na	2, 2.8, <2, <2	na	19
		NT	53	2	na	14, <2	na	18
		NT	na	na	na	20, 36	na	14
	Eucalyptus camaldulensis	140	54	6.4	59.6	62	17	19
		139	54	4.1	21.3	20	11	12
		138	54.2	5	15.9	16.8	13	17
		135	56.1	0.5	35.0	36.5	11	15
60-80m	*Melaleuca argentea*	500	61.9	4.4	49.0	55.5, 24.4, 10, 15	7	17
		501	61.9	6.4	53.2	na	13	na
		502	63.5	5.3	58.9	na	13	na
		503	62	11.1	67.2	33.2, 20, 62	13	16
		504	61.9	18.4	21.7	13, 21.2	11	21
		505	67.1	16.7	11.1	na	11	na
		508	68	13.4	18.5	15.8	11	15
		509	69.7	13.6	15.3	14.5	13	20
		510	69	10	19.1	20.5	13	19
		511	69.7	9.8	23.9	25.4	11	19
		514	72.8	5.9	4.8	na	11	na
		515	73	7.3	3.5	<2, <2, <2	11	20
		516	71.6	9.3	18.2	na	11	na
		517	71.2	13.8	14.3	na	9	na
		518	72.4	13.9	17.2	na	9	na
		519	71.8	15.3	22.3	na	0	na
		520	71.8	16.6	20.4	na	9	na
		521	73	15.8	11.1	11	9	16
		522	75.5	18	19.1	14.5, 19.5	9	17
		523	75.5	14.9	14.0	na	11	na

Quad	Species	Tag	Distance on transect x (m)	y (m)	DBH 2004	2009	canopy cond 2004	2009
60-80m	*Melaleuca argentea*	524	77	18.2	28.7	9.1, 8.5, 5.3, <2	13	17
		525	78	17.4	22.0	32.9	13	17
		526	75.5	12.5	17.2	10.5	11	21
		526A	73	14.5	8.3	na	11	na
		529	72.9	5.2	8.0	8.3	13	17
		528	73	6	5.7	8.4	13	21
		530A	75.5	3.6	7.3	13.2, 5.5	13	19
		532	73	1	19.4	na	11	na
		NT	na	na	na	2.2	na	19
		NT	na	na	na	3.5	na	16
						2.5, 3, 3.8, 2.9, 2.4, <2, <2, <2, <2, <2, <2		18
	Eucalyptus camaldulensis	506	68	16.8	27.7	na	13	na
		507	68.6	16.4	32.2	na	13	na
		512	64.5	3.7	5.4	10	11	19
		513	69.7	8	3.5	7.5	13	21
		NT	na	na	na	5	na	19
		NT	na	na	na	6.8	na	21
	Sesbania formosa	530	75.5	3.2	9.55	na	11	na
80-100m	*Melaleuca argentea*		80.3	8.7	na	<2, 4.2, 4.5, 3.3	na	21
			84	8.5	na	2.1, 3.9	na	11
	Eucalyptus camaldulensis		82	8.2	na	13.4	na	21
			81.8	9.3	na	8.1	na	17
			100	9	na	12.2	na	21
100-120m	*Melaleuca argentea*		101	2	na	3.1, 2.5, <2, <2, <2, <2	na	13
~166	*Melaleuca argentea*	137	166		46.2	38.5, 58.3, 42.5	15	19
		136	166		32.5	21.4, 12.3, 13.8, 19.5, 13, 52	13	19
		141	166		63.7	31.6, 31, 17.5, 20.9, 15.5, 15.3, 11, 26.4, , 28.5, 12.9.9	13	16
		145	166		35.0	na	13	na

Muccangarra (MZ); Co-ords: 757075E, 7760395N; Date: 24/06/09

Quad	Species	Tag	Distance on transect		DBH		Canopy cond	
			x (m)	y (m)	2004	2009	2004	2009
0-20m	*Eucalyptus camaldulensis*	188	4.7	12.3	35.0	14.2	13	17
		186	5.9	7	4.8	na	13	na
		189	9.3	17.7	13.4	17, 34, 11, 6.5	13	17
		NT	na	na	na	5	na	19
	Atalaya hemiglauca	NT	na	na	na	34.0	na	17
		NT	na	na	na	11	na	17
		NT	na	na	na	6.5	na	17
20-40m	*Eucalyptus camaldulensis*	195	35	5.8	6.4	24	17	19
		185	36	7.8	8.6	na	17	na
		187	38.4	7.3	4.8	15.8	19	19
		190	38.4	7.3	4.8	19.7	19	19
		201	40	16.4	3.8	18.6	19	21
40-60m	*Eucalyptus camaldulensis*	202	43.3	1.2	21.3	na	13	na
		203	43.3	1.9	9.6	na	9	na
		204	46.9	1.5	26.4	na	15	na
		205	40	1.8	29.9	na	15	na
		206	45.3	1.4	5.7	na	9	na
		207	51.7	5.1	41.1	na	15	na
		208	51.7	6	16.9	na	15	na
		209	51.7	6.6	39.5	na	13	na
		211	50.5	8	7.3	na	11	na
		217	50.5	13.5	23.6	na	15	na
		218	50	9.7	6.4	na	13	na
		NT	43	12.5	na	3.2	na	17
		NT	40	6	na	9.3	na	17
		NT	44	16	na	12	na	17
		NT	40	17.1	na	6.7	na	17
		NT	52	19	na	10.9	na	19
		NT	51	10	na	27	na	19
		NT	46	na	na	5.7	na	17
		NT	53	na	na	12.3	na	13
	Melaleuca argentea	210	51.7	7.1	13.4	18.8	13	17
		212	53	7.9	9.9	17.5	13	17
		213	53.5	9.3	19.1	na	13	na
		214	53	11.5	21.7	na	13	na
		215	50.5	12.1	4.8	7.7	15	17
		216	53	13.5	20.4	na	13	na
		219	53	13.5	15.9	8.2	15	11
		220	53	13.6	3.2	5.2	13	17
		221	53	14.3	27.1	na	13	na
		222	53	14.6	27.7	na	13	na
		223	53.5	16.5	11.8	na	11	na
		224	53.5	16.5	15.9	na	11	na
		225	51.5	15.5	52.9	52	13	11
			58			2.5, <2, <2, <2, <2		13
			59			8.5, 7.1, 6, 14.5, 7.4		17
			59			27		17
			58			15, <2, <2, <2, <2		15
			58			8, 20		13
	Prosopis spp.	226	40	6.5	5.4	na	19	na

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