Government of **Western Australia**
Department of **Water and Environmental Regulation**

Groundwater-dependent ecosystems of the

Dampier Peninsula

Royalties for Regions groundwater investigation

Environmental water report series
Report no. 29
August 2017

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For more information about this report, contact Robyn Loomes, Environmental Water Planning.

Disclaimer

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Contents

Figures

Tables

Summary

Demand for water in Western Australia is increasing alongside economic expansion and population growth. With this increasing demand an understanding of water availability is essential to underpin regional growth, opportunities for local economies and communities and to support groundwater-dependent ecosystems.

Across the Dampier Peninsula in the west Kimberley, hydrogeological information and knowledge about the dependency of ecosystems on groundwater resources has been studied less than in other potential growth areas in the state. The peninsula was therefore identified as one of six priority areas under the Department of Water's Royalties for Regions groundwater investigation initiative and allocated $2.865 million over four years. This study focuses on the central west of the peninsula.

The department's hydrogeological investigation work focused on the regional unconfined aquifer known as the Broome Sandstone and was supported by intensive ecological studies. Together these investigations have improved our understanding of the issues and risks relevant to groundwater abstraction on the Dampier Peninsula. This work will inform the review of allocation limits and provide greater certainty for people wanting to obtain a groundwater licence, help streamline licence approvals and support regional development, as well as ensure effective water resource management into the future.

This report presents the findings of the ecological investigations, specifically the identification, characterisation and mapping of the groundwater-dependent ecosystems.

Forming good relationships with traditional owner groups (Goolarabooloo, Nyul Nyul and Jabirr Jabirr people) through a series of meetings and on-country visits early in the project meant we could involve local people in our work, benefit from their knowledge and share our technical experience.

We identified and investigated five types of groundwater-dependent ecosystem; that is, wetlands, creeks, springs, phreatophytic vegetation and monsoon vine thickets (Table S1). In selecting potential study sites we considered existing mapping, published ecological data and environmental and cultural values.

Our work focused on groundwater-dependent vegetation because permanent waterbodies are scarce across the study area. Studying vegetation also offered a more consistent approach that was easily extrapolated across the peninsula.

Working closely with the project hydrogeologists we were able to draw heavily on the outcomes of their work (Searle & Degens 2017) to help us determine the water sources used by groundwater-dependent ecosystems. Groundwater dependence ranged from coastal wetlands using very shallow local aquifers, to springs and creeks supported by regional groundwater.

The hydrogeological results also helped us characterise each type of groundwater-dependent ecosystem not only by species composition, but also by hydrological

regimes and soil types (see Table S1). This will simplify any future groundwater-dependent ecosystem studies on the Dampier Peninsula and potentially the broader Kimberley region by helping field officers identify different types of potential groundwater-dependent ecosystems in locations where hydrogeological information is not available.

Combining outcomes of both the ecological and hydrogeological studies we developed maps to ensure land owners and other stakeholders have access to the project's major findings and can easily use them.

A groundwater-dependent ecosystem probability map (see Figure S1) was developed by combining our vegetation distribution data, previous survey information and existing mapping and modelling it against depth to groundwater and other factors. This map shows areas where additional work on groundwater-dependent ecosystems may be needed before a groundwater licence can be issued.

A water opportunity map (see Figure S2) was developed to summarise and extrapolate the project's findings into one visual product. Here we overlayed various spatial layers including groundwater-dependent ecosystems, depth to groundwater, saltwater interface, location of a newly discovered confined layer and existing groundwater users. This map indicates areas where groundwater abstraction proposals may have fewer approval constraints associated with an application for a groundwater licence.

This project has greatly improved our understanding of groundwater and dependent ecosystems of the Dampier Peninsula. It is a starting point as in most cases additional site-specific work will be required to license groundwater abstraction. The department may require further investigations of shallow groundwater systems to verify groundwater-dependence of springs, monsoon vine thickets and creeks, shallow drilling, installation of groundwater level loggers and groundwater sampling. As demand increases across the peninsula, a water allocation plan is likely to be needed to ensure that consistent, equitable and sustainable allocation decisions are made and to support the system as a whole.

Table S1 Characterising groundwater-dependent ecosystems of the Dampier Peninsula

GDE type	Dominant vegetation community	Soil type	Groundwater source and depth	Surface water source	Sites
Wetland					
	M. alsophila woodland	Clay to sandy clay	Local aquifer, < 5 m	Rain and runoff	Oval west, Triangle, Boolamon, Wibbijagun north
	M. dealbata woodland	Sand to clayey sand	Regional aquifer, < 5 m	Runoff and ground	Oval east, Ngadalargin Wibbijagun north-west
	Mixed *M. dealbata/ M. alsophila* woodland	Clayey sand	Local aquifer, < 5 m	Drainage line	Flow Dam, Ngadalargin east
Creek					
	Fringing *M. nervosa/ M. viridiflora* with *M. alsophila*	Sand (alluvium)	Regional aquifer, 0 m	Spring	Illelang, Jabirr Jabirr
	M. dealbata/ *C. bella* woodland	Sand (alluvium)	Regional aquifer, < 5 m	Ground and drainage line	Illelang, Bindingangun
	M. viridiflora very open woodland	Sandy clay	Local aquifer, < 5 m	Drainage line	Bobbis Crk
Spring					
	M. dealbata woodland	Sand	Regional aquifer, 0 m	Spring	Banana Well
	Fringing *M. viridiflora* with *P. spiralis*	Sandy clay	Regional aquifer, 0 m	Spring	Bobbis Crk Springs, Pandanus, Town
Monsoon vine thicket					
	Characteristic MVT species (see Appendix D)	Sand to sandy clay	Regional aquifer, < 10 m	n/a	Kardilakin, Rurrjaman, Mudoodon
Phreatophytic vegetation					
	M. dealbata woodland	Sand	Regional aquifer, < 5 m	n/a	Illelang woodland, Kurrukurugun
	M. dealbata and/or *C. bella* woodland	Sand	Regional aquifer, < 10 m	n/a	Banana Well west, Moorak, Black Tank, Bindingangun west
Non GDE					
	L. grandiflorus woodland	Sand to sandy clay	n/a	Rain and runoff	Rubabunan, Kurrukurugun fringe
	E. tectifica/ C. greeniana woodland	Pindan	> 30 m	n/a	DPB06, DPB03, DPB07, Pump 69
	M. alsophila woodland	Clayey sand	n/a	Tidal	Mouths of Bindingangun, Illelang, Julyulkun

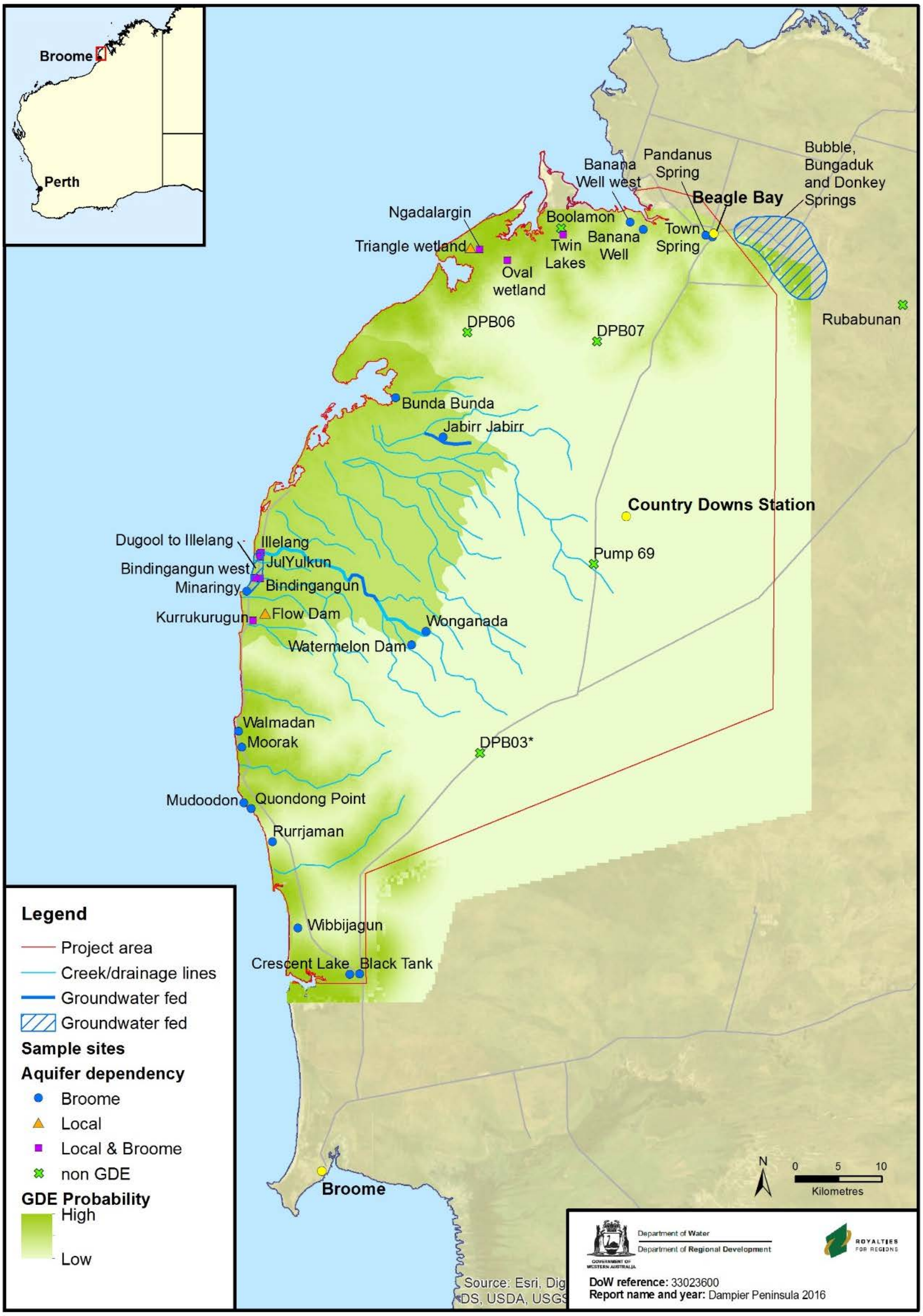


Figure S1 Groundwater-dependent ecosystem study sites and their aquifer dependency and Groundwater-dependent ecosystem probability map

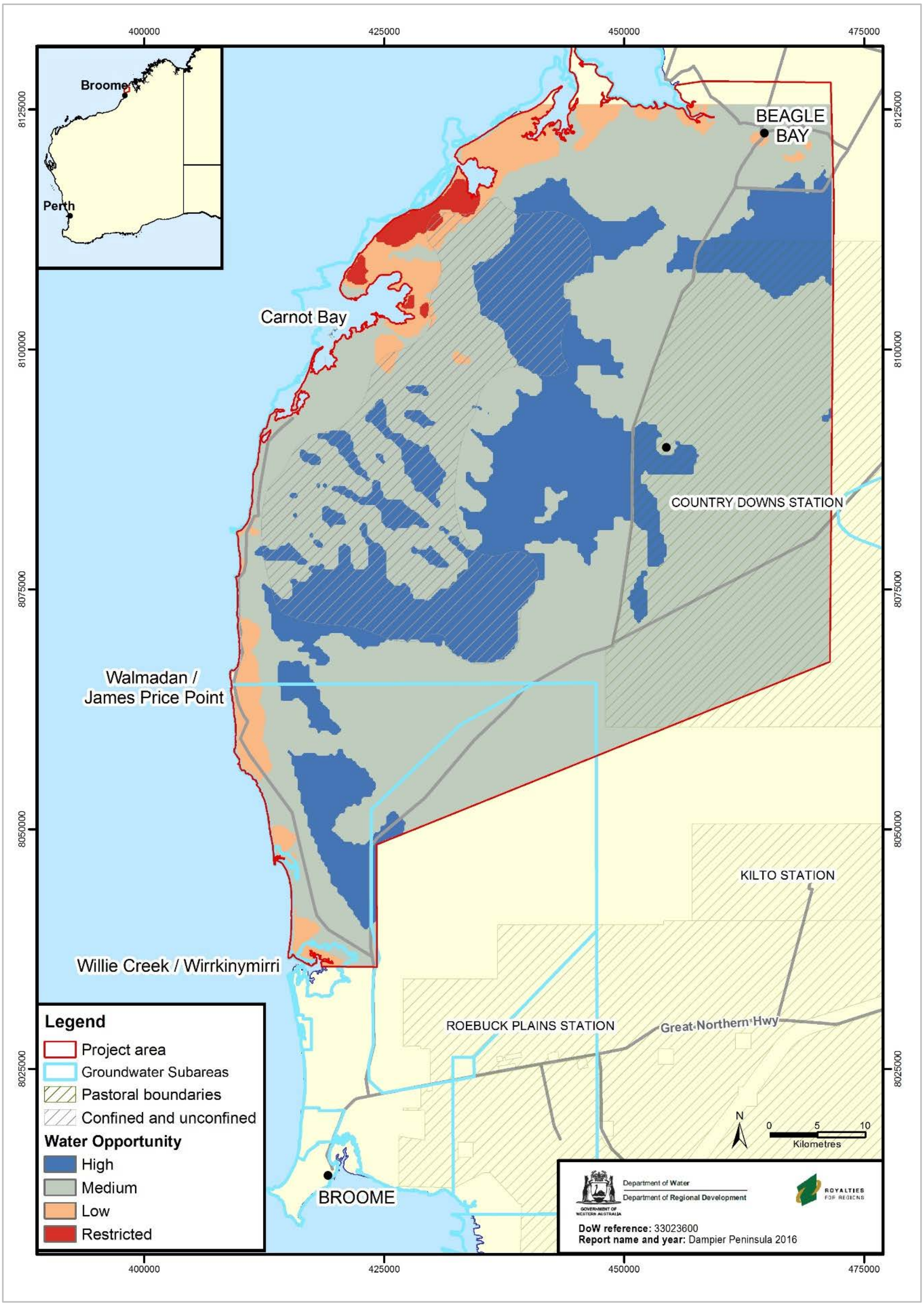


Figure S2 Water opportunity map

1 Introduction

1.1 Project context

Successful growth of regional communities through expansion of agriculture, industry and regional development will in part depend on access to reliable and secure water supplies.

The former Department of Water, now the Department of Water and Environmental Regulation, is responsible for regulating and managing the state’s water resources for sustainable productive use. In line with our strategic focus to assess and advise on water information, water availability and supply options to meet current and future demand, we accessed Royalties for Regions (RfR) funding to investigate groundwater in six priority areas across Western Australia. The funds were management though an agreement with the former Department of Regional Development. The groundwater investigations aimed to identify and establish long-term water sources in areas of population growth, agriculture and mining.

The Dampier Peninsula was identified as one of the six priority areas and $2.865 million was allocated over four years.

1.2 Purpose of this study

This study investigated the dependency of Dampier Peninsula wetlands and vegetation communities on groundwater. It was part of the Dampier Peninsula groundwater investigations project and relied heavily on the results of its drilling and groundwater sampling program (Searle & Degens 2017).

In summary, this study:

- identified and described 30 potential groundwater-dependent ecosystems, their ecological values and cultural connection with water
- determined the likelihood of the ecosystems being groundwater dependent
- determined which, if any, groundwater resource (aquifer) the ecosystems are likely to be accessing
- characterised different groundwater-dependent ecosystem types by water sources, species composition and soil types
- extrapolated results to map groundwater-dependent ecosystems across the study area
- synthesised results to develop a water opportunity map
- made recommendations for further work.

The hydrogeological and ecological investigations have improved our understanding of the issues and risks associated with groundwater abstraction on the Dampier Peninsula. The results of this work, specifically the identification and mapping of groundwater-dependent ecosystems, will inform how we allocate and license water from the peninsula. This will provide guidance for licence applicants and support licence assessment.

The new information from the ecological and hydrogeological investigations will be used to develop a combined groundwater allocation plan for Broome and the Dampier Peninsula.

2 The Dampier Peninsula

2.1 Study area

The Dampier Peninsula is located in the south-west Kimberley region, more than 2250 km north of Perth (Figure 1). It is defined as the area north of a line from Broome in the south-west corner to Derby in the east. The Indian Ocean surrounds the west and north of the peninsula, and King Sound is off the eastern coast.

This study focuses on the peninsula’s central west, an area from Beagle Bay in the north to Willie Creek in the south, running east from the coast to the middle of Country Downs pastoral station (Figure 1). Initial interest in the study area stemmed from the location of the state government’s proposed industrial precinct at James Price Point, 50 km north of Broome.

2.2 Current groundwater management

The Department of Water and Environmental Regulation is responsible for regulating and managing Western Australia’s water resources for sustainable productive use. We do this by defining allocation limits, setting licence conditions, and through ongoing monitoring and analysis. In areas of low water use, or low pressure on the resources, site specific licence conditions are applied. When an area has higher water use or more pressure on the resource, detailed allocation plans are developed. Allocation plans enable individual use while protecting the resource as a whole for social, ecological and economic benefits.

The study area covers parts of the groundwater areas of Broome (Town Water Reserve and Roebuck subareas) and Canning-Kimberley (Canning-Pender subarea) (Figure 1). The Broome groundwater area is located on the south-west corner of the Dampier Peninsula, and occupies 1743.28 km^2 (Figure 1). The town of Broome uses groundwater for its public drinking water supply, as well as for horticulture, watering of parks and gardens, and other domestic and industrial uses. Within the Broome groundwater area, the Broome aquifer has an allocation limit of 51.27 GL/year.

The Canning-Pender subarea of the Canning-Kimberley groundwater area covers 11 332.8 km^2 – the majority of the Dampier Peninsula (Figure 1). At present, all licensed groundwater use in this subarea is from the Broome aquifer, and there is no known abstraction from the Wallal aquifer. The main groundwater uses in the subarea are for horticulture, irrigated pasture (at Kilto station) and water supplies for Aboriginal communities. The allocation limit for the Broome aquifer in the Canning-Pender subarea is 50 GL/year.

An allocation plan was developed in 1994 for the Broome groundwater area where groundwater use is relatively high (WAWA 1994). However, across most of the project area and broader Dampier Peninsula, abstraction is low and the population sparse; thus overall pressure on the resource is currently low. These areas are not covered by an allocation plan and are managed through the licensing process.

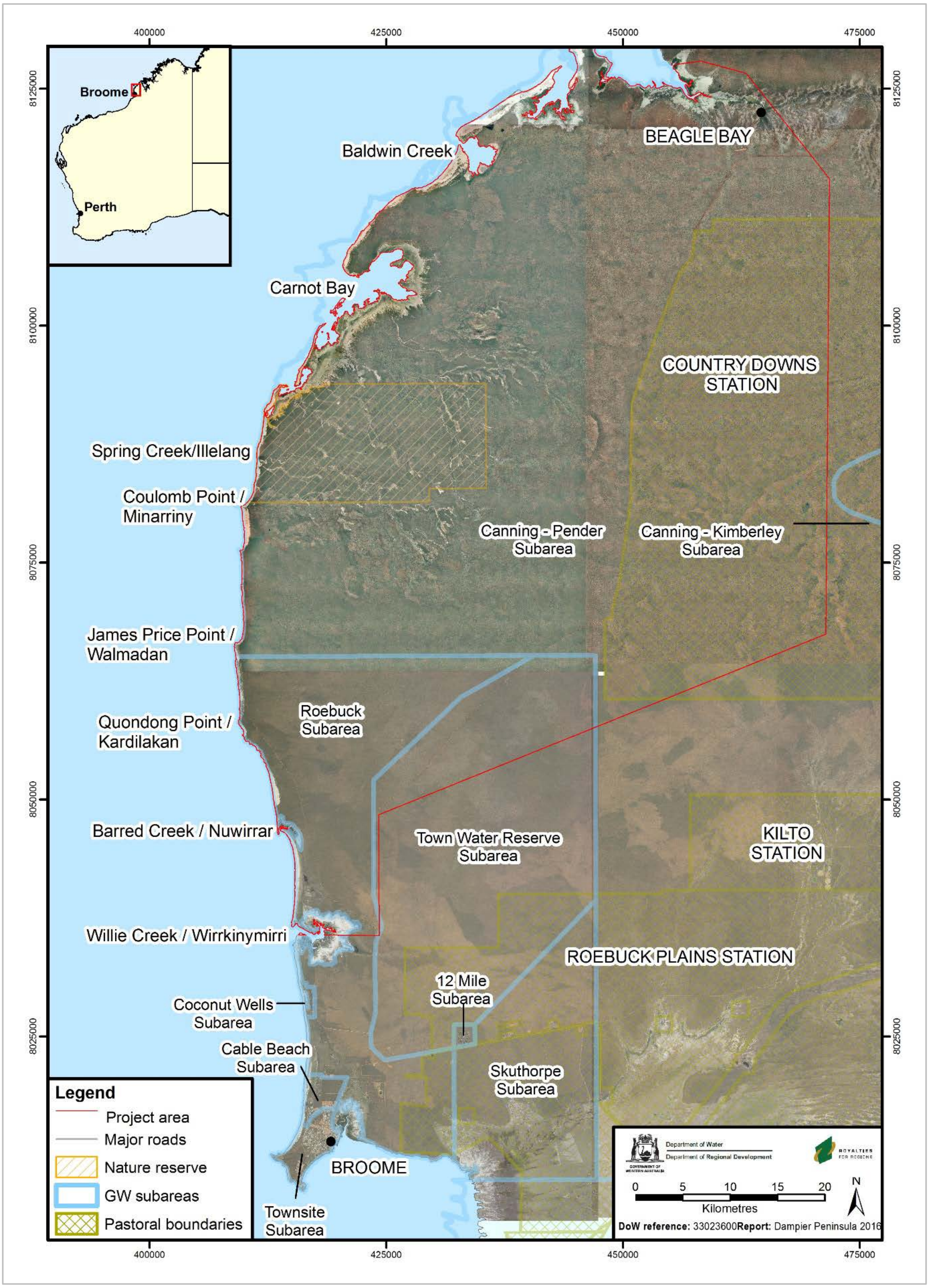


Figure 1 Groundwater areas and subareas within the study area

2.3 Climate

The Dampier Peninsula’s climate is classified as subtropical characterised by hot, wet summers and warm, dry winters. The wet season extends from December to March with about 90 per cent of average annual rainfall occurring during this period. This is opposed to the dry season when a relatively small amount of rain falls and the mean temperature and humidity are significantly lower.

Rainfall across the study area is highly variable (Figure 2). The central part of the study area is topographically higher and has the highest mean annual rainfall: 945 mm measured at Country Downs Station. Broome, in the study area’s south, has an annual mean rainfall of 611 mm (Bureau of Meterology 2015), while Beagle Bay, in its north, has an average of 772 mm. Across the Dampier Peninsula the annual potential evaporation is high (2700 mm).

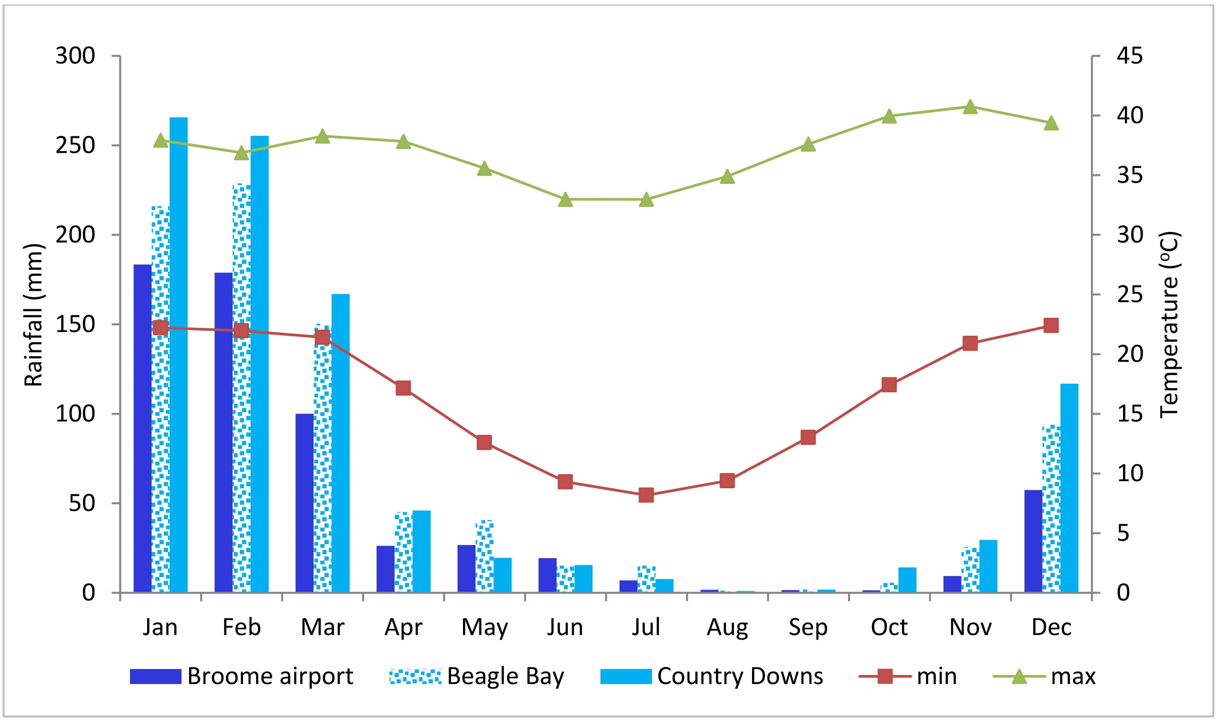


Figure 2 Broome, Country Downs and Beagle Bay average monthly rainfall and Broome temperature (1940–2014)

Extreme rain events are common during the wet season; these are driven by low pressure and associated with high wind speeds and flooding. It is these weather systems that drive groundwater recharge in the region. Although the recent climate (1996–2010) has been wetter than the historical climate, occasionally a wet season will not deliver significant rain resulting in very low aquifer recharge (Department of Water 2012; Searle 2012). This was the case during the 2014–15 and 2015–16 wet seasons which were significantly drier than average (Figure 3). However, the 2016–17 wet season has seen higher than average rainfall.

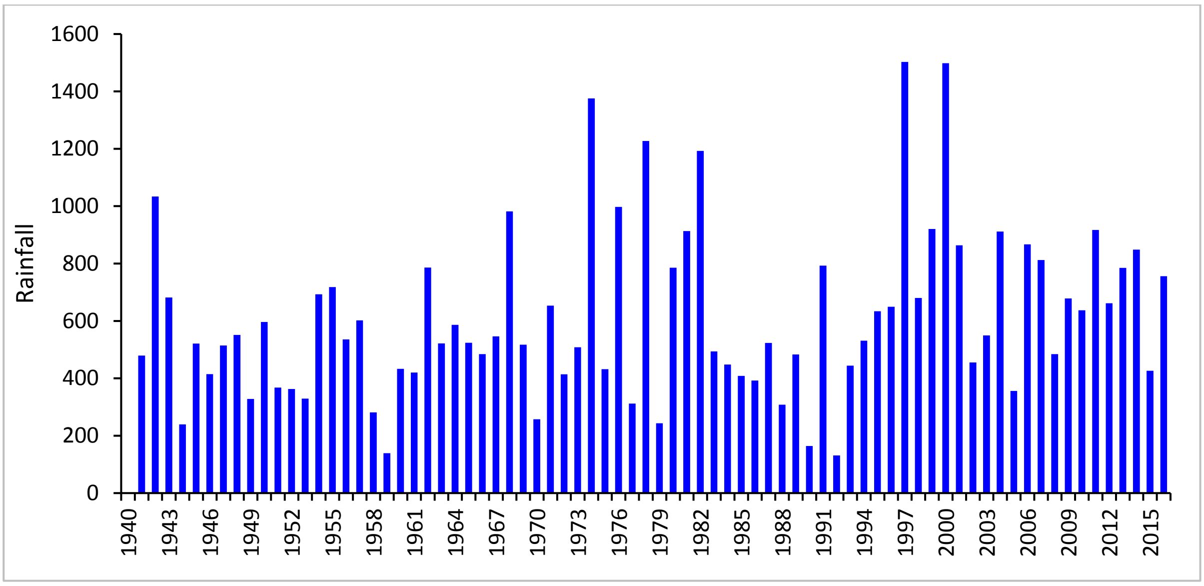


Figure 3 Total annual rainfall at Broome airport (1940–2016)

2.4 Geomorphology

The Dampier Peninsula is about 175 km long (north–south) and 130 km wide (east–west). It is gently domed, rising to 245 mAHD towards the centre. Around the coastline are narrow sandy beaches, sand dunes, platforms of compacted sediments and extensive mudflats (Laws 1984; Searle 2012). A thin veneer of red silty sandy soil, commonly known as pindan sands, covers most of the peninsula.

Drainage lines are poorly developed. Sheet flooding is the main drainage pattern, with much of the water infiltrating to groundwater (Laws 1984; Searle 2012). There are numerous ephemeral creeks that only flow after heavy summer rainfall. Several permanent creeks begin at springs and seepages in the centre of the peninsula, and flow west to discharge in the Indian Ocean. Groundwater-dependent surface waters, including mound springs, are also known to exist, although their locations, connectivity to groundwater systems and values have not been comprehensively investigated.

The Ramsar-listed Roebuck Bay on the south-west coast is a tidal mudflat, extending 30 km inland. Along the western coastline numerous wetlands have formed at seepage faces, including some lake basins (Mathews, Semeniuk et al. 2011).

2.5 Hydrogeology

The unconfined regional Broome Sandstone aquifer, commonly called the Broome aquifer, is mostly fresh and the largest shallow aquifer across most of the Dampier Peninsula. It flows radially from the centre of the peninsula, with depth to water varying from less than 10 m around the coast to more than 100 m inland. Connectivity between the Broome aquifer, shallow surface (surficial) aquifer and various ecosystems were investigated in this study.

In the eastern part of the peninsula, the largest shallow aquifer is the Wallal Sandstone aquifer, commonly called the Wallal aquifer. It is generally unconfined and subcrops near the surface, with water levels ranging from 25 m below ground level to 2 m above ground level (where confined).

The Wallal aquifer also occurs in the western part of the peninsula within the project area, where it is overlain and confined by the Jarlemai Siltstone. Here, the top of the Wallal aquifer is up to 400 m below ground level, with artesian heads up to 39 m above ground level. Groundwater in the Wallal aquifer is fresh to saline.

In 2012 the former Department of Water reviewed the groundwater resources of the Dampier Peninsula with a particular focus on the performance of the Broome Sandstone aquifer (Searle 2012). We assessed the aquifer’s performance by analysing groundwater level and water quality monitoring information. Groundwater resources were generally showing little signs of impact from current use, with the exception of some subareas of the Broome groundwater area. Changes in water quality (salinity) in the Town Water Reserve sub-area indicate that upper limits to sustainable abstraction may have been reached (Searle 2012).

3 Ecological values

Groundwater-dependent ecosystems are at least partially dependent on groundwater for their existence and health. They can rely on groundwater directly (e.g. phreatophytic vegetation using groundwater from shallow watertables) or indirectly (e.g. wetland vegetation or aquatic ecosystems sustained by groundwater discharge to the surface) (Eamus, Froend et al. 2006).

The ecological values of numerous groundwater-dependent ecosystems of the Dampier Peninsula have been described and listed as being of international, national or regional conservation significance. Groundwater-dependent ecosystems of significance include monsoon vine thickets, wetlands, mound springs and the threatened flora and fauna they support. We considered a number of spatial datasets (Appendix A) to identify and map known ecological values.

3.1 Monsoon vine thickets

Monsoon vine thickets (MVT) are a remnant rainforest community found on the slopes of coastal sand dunes between Broome and Derby (English 2010). The ‘monsoon vine thickets on the coastal sand dunes of the Dampier Peninsula’ represent the most southern occurrences of rainforest in Western Australia. They are listed by the former Department of Parks and Wildlife (DPAW) as a threatened ecological community (TEC) and were recently listed as endangered under the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999*. This is due to the presence of vegetation assemblages that are distinct from other rainforest communities found throughout the Kimberley and northern Australia.

The vine thickets occur as isolated pockets of dense vegetation, varying in size from about 0.02 ha up to about 200 ha (English 2010). The average size is about 35 ha, and the most common size is about 10 ha. In total, just under 2700 ha of the vine thickets are known to occur on the peninsula.

The largest vine thickets on the Dampier Peninsula occur between Cape Borda and Packer Island (at the northernmost end of the peninsula), while those between Quondong Point and James Price Point probably form the second-largest continuous vine thickets (Biota Environmental Service 2009) (Figure 4).

Although the vine thickets’ occurrence has been mapped across the Dampier Peninsula (Figure 4), the communities of James Price Point are probably the most widely studied and understood. Here, the vine thickets occur as either closed-canopy, evergreen patches or semi-deciduous linear belts (Biota Environmental Service 2009) and it is likely that these two subgroups occur in other areas.

Local Aboriginal people know the vine thickets as Budan (Cedat & Duprat 2007), which is valued for supporting numerous species of birds and other fauna, catching fresh water and providing shelter from fires. Even in the dry season shallow groundwater is available for people, animals and plants (Cedat & Duprat 2007).

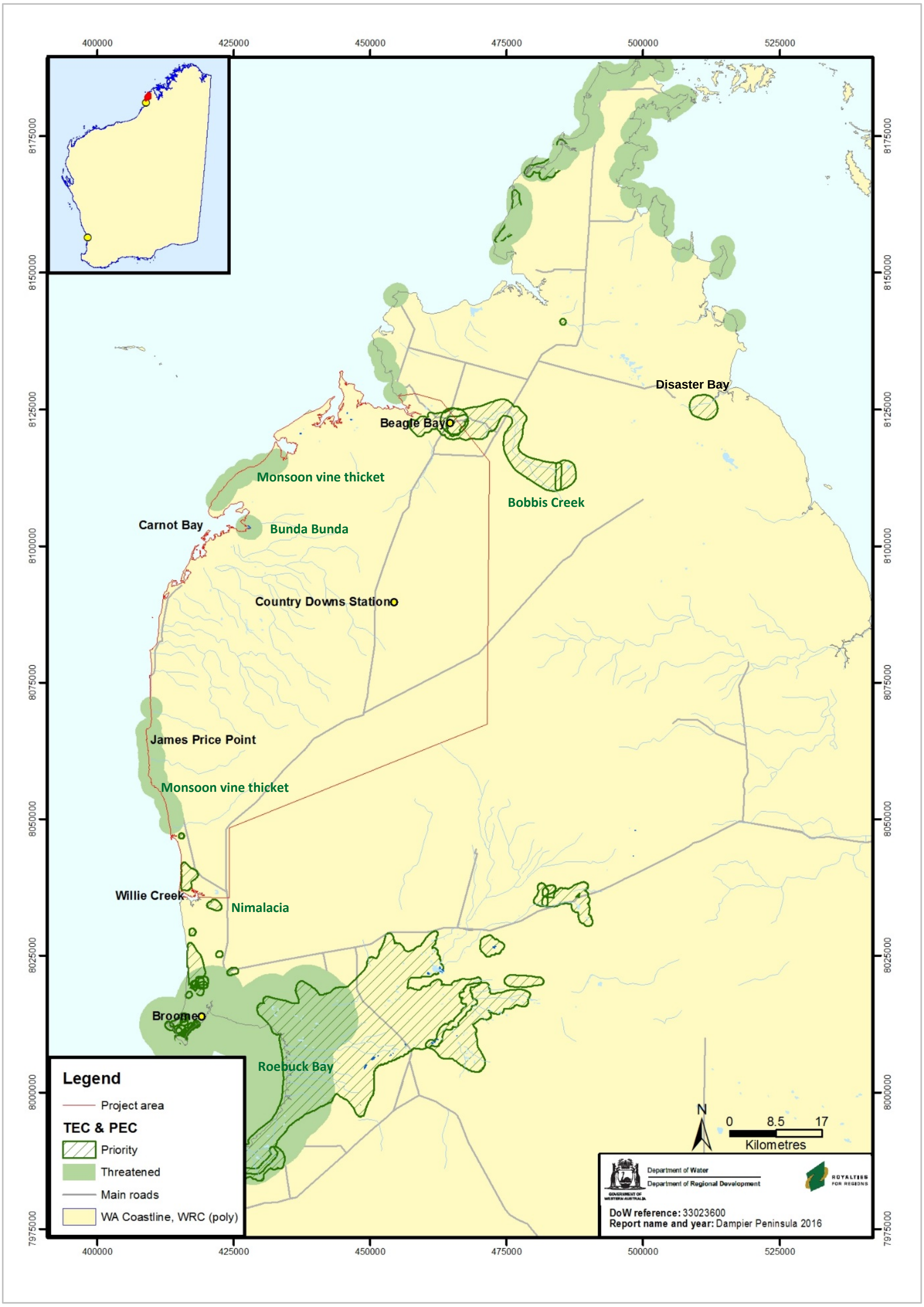


Figure 4 Wetlands, TECs and PECs of the Dampier Peninsula

Vine thickets contain many fleshy-fruited plants, providing an important food resource for wildlife such as agile wallabies, bowerbirds and fruit-doves (Biota Environmental Service 2009). Recently a breeding group of Gouldian finch (*Erythrura gouldiae*), an endangered species, was recorded in vine thickets on the Dampier Peninsula (pers comm Jan Lewis, Broome Bird Observatory).

3.2 Mound springs

Mound springs occur along the coast and creek lines where the Broome Sandstone is thought to discharge from depth through the overlying alluvium to the surface (Mathews et al. 2011). The groundwater in the springs is under pressure and stands slightly higher than the watertable (Rockwater 2004). The springs may rise as much as two metres above the surrounding plains and may form local groundwater mounds superimposed on the watertable (Rockwater 2004).

The locations of 20 mound springs have been confirmed along Bobbis Creek near Beagle Bay with others occurring elsewhere on the peninsula (Figure 4). The Bobbis Creek sites are some of the few areas of permanent fresh water on the peninsula. These sites support a high number of plant species with restricted distributions, many of which are listed as priority flora.

Lolly Well Springs is located on Bobbis Creek, less than 2 km from the Bobbis Creek Community. The spring is listed as a Priority 3 ecological community – priority ecological communities (PECs) are recognised by DPAW as high conservation value but not afforded the same level of protection as TECs (Ecologia Environmental 2004a). The springs comprise wetland vegetation complexes as well as numerous low organic mound springs.

Bunda Bunda Mound Springs is situated near Carnot Springs Community in the Coloumb Point Nature Reserve (Figure 4). It is listed in the Directory of Important Wetlands (DIWA) (ref no. WA016) as a freshwater spring of outstanding cultural significance (Environment Australia 2001) and is also listed as a TEC. The site includes a large mound area of about 20 ha and a small mound area of about 2 ha on tidal mudflats (Department of Water 2009). Bunda Bunda supports dense rainforest on large raised peaty swamps that resemble islands.

Other mound springs are known to occur on the peninsula’s west coast between Beagle and Carnot bays, further north inland from Pender Bay and on the east side at Disaster Bay. The organic mound spring communities of Disaster Bay are listed as TECs.

3.3 Wetlands

Roebuck Bay, situated to the south of the current study area (Figure 4), was designated a Wetland of International Importance under the Ramsar Convention in June 1990. It is one of less than 20 soft-bottomed intertidal mudflats worldwide that support very large numbers of migratory shorebirds, and is a primary staging and over-wintering area for their annual southwards migrations (Bennelongia 2009). Roebuck Bay is also listed in the DIWA (Environment Australia 2001).

The Willie Creek wetland system (Wirrkinmere) is also listed in the DIWA. The wetlands include seasonal/intermittent saline lakes, permanent freshwater ponds (< 8 ha) and marshes and swamps with emergent vegetation waterlogged for most of the growing season (Environment Australia 2001). The wetlands were listed based on them meeting the following criteria:

- a good example of a wetland type occurring within a biogeographic region in Australia
- a wetland which is important as the habitat for animal taxa at a vulnerable stage in their lifecycles, or provides a refuge when adverse conditions such as drought prevail
- being of outstanding historical or cultural significance.

Nimalaica Clay Pan is part of the Willie Creek wetland system. It is a unique, almost permanent freshwater lake located inland of Willie Creek (Department of Parks and Wildlife 2016) (Figure 4). It is listed as a Priority 4 (ii) ecological community – recognised by DPAW as of high conservation value, but not afforded the same level of protection as a TEC.

Culla Culla Creek (north of Wonganarda) is described as an unusual spring site and listed as an ‘ecosystem at risk’ in the DIWA (Environment Australia 2001).

3.4 Flora and fauna of conservation significance

At the international scale, migratory species are recognised by international treaties such as the Japan-Australia Migratory Bird Agreement (JAMBA) and China-Australia Migratory Bird Agreement (CAMBA). Endangered animals are listed and their conservation status reviewed by the International Union for the Conservation of Nature (IUCN).

The *Environment Protection and Biodiversity Conservation Act 1999* provides for the protection of certain species. The Act references a list of species that are considered to be critically endangered, endangered, vulnerable, conservation dependent, extinct or extinct in the wild.

Declared Rare Flora (DRF) and fauna are also protected under the Western Australian *Biodiversity Conservation Act 2016.* Priority flora are assigned to one of four priority categories. Fauna in need of species protection are assigned to one of four distinct schedules and/or DPAW priority categories.

Previous surveys within the study area (Ecologia Environmental 2005) either observed, or listed as probably occurring, nine fauna species of international significance, three of national significance and three of state significance. In addition, two flora species of national and three of state significance have also been identified (Ecologia Environmental 2004a).

We searched online databases (Department of Environment 2000; Department of Environment 2015; Department of Parks and Wildlife 2016) to develop lists of flora and fauna species of conservation significance (see Appendices A and B).

Threatened and priority flora and fauna

Internationally listed fauna

On the Dampier Peninsula there are 29 bird and six turtle species listed under various international agreements. The habitat requirements of at least one bird species, *Erythrura gouldiae* (Gouldian finch; endangered) includes permanent fresh water and/or fringing woodlands along watercourses and *Melaleuca* swamps (Department of Environment 2000).

National listed fauna and flora

Eleven fauna species listed under the *Environment Protection and Biodiversity Conservation Act 1999* are likely to occur in the Dampier Peninsula area, comprising six birds, four mammals and a reptile.

Three of the listed bird species, namely *Erythrotriorchis radiates* (red goshawk), *Calidris ferruginea* (curlew sandpiper) and *Rostratula benghalensis* subsp. *Australis* (Australian painted snipe) may rely on groundwater-dependent wetlands and riparian vegetation (Skroblin & Legge 2012; Department of Environment 2015). The northern quoll (mammal) at times may also depend on these habitats, given that in parts of Queensland it is more likely to be present near permanent water sources (Department of Environment 2015). *Macrotis lagotis* (greater bilby) may also be found in these habitats.

Two flora species are listed as threatened. One of these, *Pandanus spiralis* var. *flammeus,* is associated with springs or shallow groundwater.

State listed fauna and flora

There are nine different listed priority or threatened fauna species, five birds, two mammals and two reptiles. The habitat requirements of *Erythrura gouldiae* (Gouldian finch) are discussed above.

Two of the 30 priority species listed in the study area may rely on habitats that depend on groundwater. The water lily, *Nymphoides beaglensis* (P3)*,* is found in permanent waterholes (Department of Parks Wildlife 2015) and *Lophostemon grandiflorus* subsp. *grandiflorus* (P3) is known from damp habitats associated with swamps and seepages.

Vegetation communities (PECs)

Vegetation complex 67 – grasslands, tall bunch grass savannah, sparse low tree; ribbon grass (*Chrysopogon* spp.), paperbarks (*Melaleuca* spp.) – occurs across the broader Bobbis Creek area (Figure 4).

Vegetation complex 73 – grasslands, short bunch grass savannah, grass; salt watermarine couch (*Sporobolus virginicus*) – occurs across a large wetland basin north of Willie Creek (Wibbijagun) (Figure 4).

4 Cultural and heritage values

4.1 Aboriginal cultural values

The Kimberley law bosses, or elders, are responsible for passing traditional culture (law) down to succeeding generations to keep the country and the people safe (Rau, Rau et al. 2013).

We worked on-country with the Nyul Nyul and Goolarabooloo peoples of the Dampier Peninsula throughout the project's field component. We also visited numerous potential groundwater-dependent ecosystems with Jabirr Jabirr and Djabera Djabera people.

Aboriginal people have lived on the Dampier Peninsula for thousands of years, maintaining their semi-nomadic, traditional coastal lifestyle until the late 1800s when the pearling industry, missions and pastoral stations were established (Birrell 2002). In 1884, the first priest arrived to serve the Catholics in the Kimberley and to convert the Aboriginal people (Birrell 2002). The missions gave rise to the settlement of people in the towns of Beagle Bay, Lombadina and Cygnet Bay from the 1890s.

The Beagle Bay mission and Catholic school were established in the land of the Nyul Nyul people by French Trappist monks in the early 1890s. In 1901 Pallotine Fathers from Germany took over the mission and in 1907, the St John of God Sisters began to run a mission school.

In 1976 Beagle Bay became a self-governing community. The Catholic Church remains an important part of the community.

Goolarabooloo

The law and culture of the Goolarabooloo people is encoded and materialised in its coastal Song Cycle path (Landvision Pty Ltd 2007). This is the starting point for other Song Cycle paths which travel east across the Kimberley and to the east coast of Australia. The Goolarabooloo people gave special permission for the reproduction of their Song Cycle map for use in this document (Figure 5).

> The fundamental integrity of the Song Cycle path relies on it staying the same as during Bugarregarra (dreamtime, creation time) and the Goolarabooloo have worked hard to maintain the country as it was when it was handed to them. Bugarregarra is an ongoing creative process where past, present and future are now. The Song Cycle path is kept alive by the law keepers through ceremony to maintain the living quality of the whole system. The Goolarabooloo family also maintain their section of the Song Cycle in their country by being part of the law and culture, living in, singing, dancing and walking the country – *Phil Roe (senior Goolarabooloo law man).*

The Song Cycle is made up of 'sites' – camping, ceremonial, seasonal food places, vegetation for ceremonial use, trees, plants, ochre, land and water resources – all that is needed to support life (Landvision Pty Ltd 2007).

Written by elders

The Songline travels North - South constantly branching off to the east. This section belongs to the total Song Cycle starting at One Arm Point and finishing south of La Grange

Figure 5 Song Cycle path (reproduced by DWER with permission of the Goolarabooloo people)

There are six creek systems that flow from the centre of the peninsula westward to the ocean. These creeks are extremely culturally significant as they are part of the Song Cycle path and sustain the living qualities of the country and all Song Cycle sites. This is why the Goolarabooloo people call the water ‘living water’ and point out that it is common sense to maintain the quality of the water and hence, the country (Phil Roe, pers comm).

Trees and shrubs of cultural importance are associated with the Song Cycle. These include Garnborr (*Melaleuca dealbata),* Yaari (*Corymbia zygophylla),* Gungkarra (*Carissa lanceolata*), Gumumu (*Santalum lanceolatum*) and Mirda (*Gyrocarus americanus).* They grow between rocks which can be Muurruu (inhabit a certain danger) and springs. Springs can be called Jila (living freshwater), Umban (living freshwater on the beach) or Ingu (seasonal freshwater swamps) (Cedat & Duprat 2007). An ‘area’ of freshwater, for example Willie Creek wetlands or Wonganarda Springs, is known as Billara.

The Goolarabooloo people have walked tourists along part of the Song Cycle – the Lurujarri Heritage Trail – since 1987, teaching them to look after country and fostering trust, friendship and empathy between the indigenous community and the wider Australian and international communities (Rau, Rau et al. 2013).

Nyul Nyul

Wetlands in Nyul Nyul country (around Beagle Bay) are very important as a water source and are also strongly connected to the identity of the Nyul Nyul people (Dobbs, Davies et al. 2015). Waterholes, lakes and springs are associated with cultural meaning, sites and stories and have remained important through the changing ways of life since European settlement. Wetlands also provide drinking water and places for fishing and hunting (Dobbs, Davies et al. 2015).

> Water is the lifeline of our country, Nyul Nyul country, and everybody knows that. It’s not only good drinking water but also a part of our culture and heritage. This is one of the luckiest countries I know. If we look after the land and water it’s going to look after us back – *Preston Cox (Nyul Nyul ranger).*

4.2 Heritage values

Registers of the National Estate and Heritage Places

Coulomb Point Nature Reserve (Cape Bertholet), 45 km south of Beagle Bay, was listed on the National Estate in 2001 due to its importance as fauna habitat. It is a declared A Class Reserve for the conservation of flora and fauna (Figure 4) and is a known breeding area for endangered species including *Macrotis lagotis* (greater bilby), *Onychogalea unguifera* (nail-tailed wallaby) and *Isoodon auratus autatus* (golden-backed bandicoot).

Beagle Bay Mission Church (Sacred Heart Church) has cultural heritage significance related to the work of the missionaries and ongoing value to the Beagle Bay community.

5 Approach to identifying groundwater-dependent ecosystems

Previous investigations identified several potentially groundwater-dependent ecosystems on the Dampier Peninsula. Ecosystems that are likely to be directly dependent on groundwater include monsoon vine thickets and phreatophytic terrestrial or riparian vegetation. Those that may be indirectly dependent include springs, wetlands and creeks.

Although we assessed wetlands, springs and creeks, this study focused on groundwater-dependent vegetation, given permanent waterbodies are scarce across the study area. Studying vegetation also offered a more consistent approach that was easily extrapolated across the peninsula.

In addition to groundwater-dependent sites we also selected a non-groundwater-dependent, or reference, site. This meant we could compare results between dependent and non-dependent sites and identify which characteristics were most likely related to the presence of groundwater (e.g. species composition, vegetation health and tree hydration).

In this section we describe our approach for short-listing our study sites and detail the methods we followed during the investigations.

5.1 Site selection

A list of potential ecological study sites was made using a desktop review of available information (literature review) and geospatial data (spatial datasets, Normalised Difference Vegetation Index and depth to groundwater), as well as discussions with stakeholders.

The literature review was followed by site visits to determine ecosystem type and suitability for surveys (including access, need for cultural survey and heritage clearances).

Reviewed literature

We reviewed the available literature as a starting point for identifying potential groundwater-dependent ecosystems and their level of dependence on groundwater. Studies carried out across the peninsula in the past include:

- coarse scale mapping of vegetation across the Kimberley region (Beard 1979)
- description of Dampier Peninsula vegetation (McKenzie & Kenneally 1983)
- flora, fauna and groundwater-dependent ecosystem surveys and assessments for Tropical Timbers plantation 20 km south-east of Beagle Bay (Ecologia Environmental 2004a; Ecologia Environmental 2004b)
- vegetation, flora, fauna and groundwater-dependent ecosystem surveys and assessments at James Price Point for the proposed Browse Basin LNG

project (ENV Australia 2008; Biota Environmental Service 2009; Biota Environmental Service 2009; SKM 2011; Biota Environmental Service 2011a; Biota Environmental Service 2011b)

- remote mapping of wetlands (Boggs 2011)
- review of freshwater seepages (Mathews, Semeniuk et al. 2011)
- mapping and monitoring of monsoon vine thickets (Harding 2009; Threatened Species Scientific Committee 2013)
- vegetation and soil mapping along the Lurujarri Heritage Trial from Gantheanume Point to Bindingangun on the peninsula’s west coast (Cedat & Duprat 2007).

Relevant studies have also been carried out in other areas of northern Australia. These include work on potentially groundwater-dependent tropical woodlands and monsoon vine thickets to determine ecosystem water balances and tree water use (Cook, Hatton et al. 1998; O’Grady, Eamus et al. 2002).

This body of work provided a strong basis for our investigations. It helped us develop our approach to identifying groundwater-dependent ecosystems on the Dampier Peninsula and to determine their level of dependence.

Spatial datasets

We considered geospatial information (Appendix A) to map known groundwater-dependent ecosystems and ecological values and to help identify potential groundwater-dependent ecosystems. Specifically, existing spatial datasets were used to overlay aerial photographs with vegetation mapping, waterbodies, hydrological information and geological maps. Other layers were used to determine the conservation significance of specific areas.

Normalised Difference Vegetation Index

We used the Normalised Difference Vegetation Index (NDVI) to help identify areas of vegetation that may be using groundwater. The NDVI is strongly correlated with primary productivity and plant growth. It uses satellite imagery to detect photosynthesis (growth) of varying intensity. Plant growth during periods of low surface and soil water availability is potentially an indicator of groundwater use. Outputs can be used to extrapolate the presence of groundwater-dependent vegetation across a study area.

Depth to groundwater

Vegetation communities in Western Australia’s north west are known to access groundwater to depths of up to 15 m (Loomes 2010). Where groundwater-level data were available, we used it to further refine our list of potential study sites.

Indigenous knowledge and values

The Dampier Peninsula study area covers traditional countries of several Aboriginal groups – the Goolarabooloo, Jabirr Jabirr, Djabera Djabera and Nyul Nyul – who have thousands of years of lived knowledge and experience of their lands.

Early consultation with the traditional owners of the area was critically important as it meant we were able to:

- inform local people about our work in the area and work with them to select appropriate study sites
- develop meaningful relationships and understanding between Aboriginal groups and Department of Water and Environmental Regulation personnel
- develop funding agreements to train and engage Goolarabooloo and Nyul Nyul people in ongoing water-level monitoring and various fieldwork campaigns.

A series of initial meetings were held in Broome and Beagle Bay to advise people of the project. Following the meetings, on-country visits were organised through the Kimberley Land Council (KLC) and the State Agency Funding Agreement (SAFA). We also met directly with the Goolarabooloo people. Visits were undertaken in stages to gain approval for different rounds of groundwater drilling – deep and shallow.

Some of the traditional owners were initially concerned that the project was only investigating groundwater supplies for the proposed industrial development at James Price Point north of Broome. At that stage, the Nyul Nyul people were reluctant to be involved. However, we continued to meet with them and develop our relationship and they went on to play a very important role in our field work. Unfortunately, not working in Nyul Nyul country (north and north-west of the study area) for the first year of the project meant we could not fully investigate the springs and other potential groundwater-dependent systems associated with Bobbis Creek.

5.2 Methods

This section describes the methods used in the field to identify and describe groundwater-dependent ecosystems. We relied heavily on the outcomes of the hydrogeological work that formed the backbone of the Dampier Peninsula Royalties for Regions investigations.

Ecological methods ranged from those that were time consuming and needed expensive equipment to those that were relatively quick and inexpensive. All techniques used metrics associated with water availability to better understand the connection between ecosystems and groundwater. The approaches and methods used at each site are tabulated in Appendix C.

The hydrogeological work we considered included airborne electromagnetics (AEM), bore logs, groundwater tracers (radon, CFCs and carbon isotopes) and analysis of surface and groundwater isotopes. A full description of these techniques and results are presented in Searle and Degens (2017).

We have broken the methods into:

- identifying and describing probable groundwater-dependent ecosystems
- determining groundwater-dependence and potential water sources
- developing study-wide datasets.

Identifying and describing groundwater-dependent ecosystems

Vegetation community and dominant species

Describing a vegetation community type defines the structural forms of the vegetation in terms of the dominant plant form and the percentage of crown or foliage cover of the tallest plant layer. Overstorey species (trees) generally form the basis of vegetation community descriptions.

In this project we described the dominant vegetation at two scales: site and transect/ plot. The most dominant and/or common species identified across the sites are listed below with their traditional and common names, and are described further in Appendix D:

- *Melaleuca dealbata* (Garnborr) – freshwater paperbark
- *Melaleuca alsophila* (Murrga or Gooloongoorr) – saltwater paperbark
- *Corymbia bella* (Goonoor) – weeping ghost gum
- *Lophostemon grandiflorus* (Lardik) – freshwater mangrove
- *Melaleuca nervosa* (Nimalgoon)
- *Melaleuca viridiflora* (Walamangarr) – broad leaf paperbark
- *Diospyros humilis* (Birimbiri) – ebony wood
- *Pandanus spiralis* (Mangban).

Site conditions

It is important to describe the abiotic (physical) conditions of a site as these can be a key factor in determining vegetation type, distribution and overall condition. A suite of information was collected at each site, including:

- fire history
- flood/inundation history
- stock disturbance
- access tracks.

Transects/plots

We set up marked transects (or plots) to capture areas of vegetation representative of the wider ecosystem or community type of interest. More detailed assessments across entire sites were impractical due to the size of sites (e.g. entire wetlands) and time and budget constraints.

Transects generally ran perpendicular to wetlands/springs/creeks or upgradient from the lowest-lying areas of phreatophytic vegetation and monsoon vine thickets.

Depending on the width of the fringing vegetation, transects were either made up of a single plot, contiguous plots of the same size or plots set up wherever a change in vegetation community type occurred (Figure 6). The longest transect was 180 m long while others were only 20 m long. Plots were generally 20 x 20 m.

Species distribution

The distribution of known phreatophytic (groundwater-dependent) species across a transect/site can be a good indicator of groundwater availability and be used to identify groundwater-dependent ecosystems. For example, the north-west tree species *Melaleuca argentea* generally occurs in areas where the depth to groundwater is less than 10 m (Loomes 2010). Over time, the expansion or contraction of a species distribution may also reflect changes in water availability.

Measuring ranges is done by simply using a tape measure and noting the start and end of key species' distributions in relation to a wetland/creek, a low point where the watertable is shallowest or to a bore.

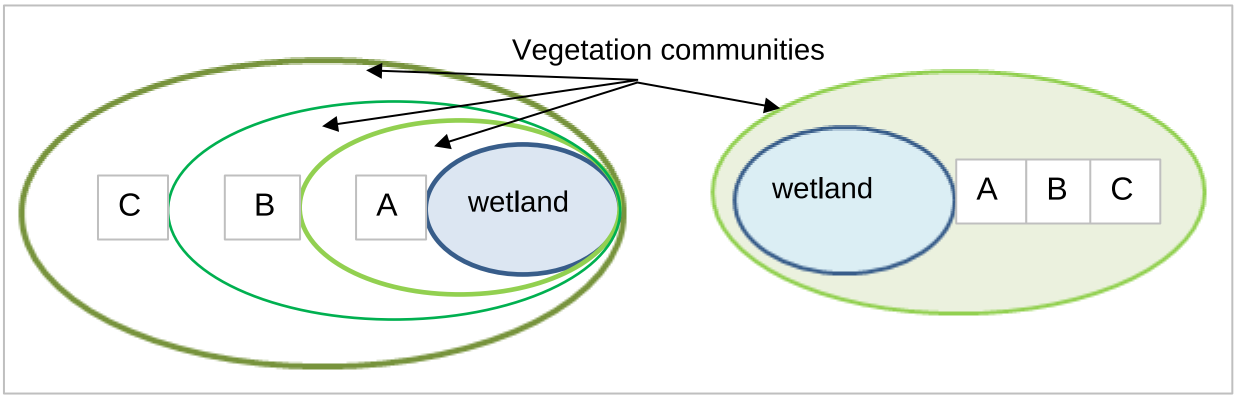


Figure 6 Example of monitoring plots (A, B and C) at change of community type (left) and contiguous plots in the same community type (right)

Vegetation (canopy) condition

As overstorey species tend to persist in highly disturbed plant communities when most other native species disappear, trees are generally suitable indicators of ecosystem condition. Our approach followed one that has been used for up to 20 years in south-west Western Australia to monitor changes in vegetation condition related to changes in water availability over time (Loomes & Froend 2007). For this project it provided a baseline or general idea of the current health of potential groundwater-dependent ecosystems.

Canopy assessments were undertaken on every tree within the study plots. The approach incorporates three aspects of canopy condition: foliage density, proportion of dead branches and degree of epicormic growth (see crown assessment procedure diagram in Appendix E). A score was given for each component (9, 7, 5, 3 or 1 for foliage density and proportion of dead branches and 5, 4, 3, 2 or 1 for epicormic growth) are then combined to provide an overall score out of 23. The higher the score, the better the condition of the tree.

We also measured the diameter of each tree as a record of approximate age class distribution. Diameter was measured at approximately 1.5 m from ground level – known as diameter at breast height (DBH).

Determining groundwater dependence

Depth to groundwater

The presence of groundwater-dependent ecosystems can be inferred by the depth to groundwater. If the watertable is within the rooting depth of the vegetation, this is a good indication that the vegetation is using groundwater. It is widely accepted that at depths of less than 10 m, vegetation is highly likely to be dependent on groundwater for some of the time (Eamus et al, 2006). At depths greater than 10 m, the volume of soil and thus available soil moisture increases and dependence on groundwater can decrease. As we had not previously worked on the peninsula and were unsure of tree rooting depth in the region, we considered areas with depths to groundwater of up to 15 m.

There were no existing monitoring bores at any of the detailed investigation sites. However, deep and/or shallow bores were installed at some sites during the project's drilling program (Oval Wetland, Jabirr Jabirr, Ngadalargin, Triangle and DBP06 in Figure 8). To determine depth to groundwater at the remaining sites – with the exception of Banana Well – we hand-augered to the watertable at the end of the wet season and again at the end of the dry. Although this told us where the watertable sat, it did not provide any information on which aquifer it was (if any) or indicate whether the watertable was perched.

Once the depth to groundwater across a site was determined we overlayed the distribution of key species to define their water-level ranges. To do this we measured the elevation at the start and end of each species range across each site using a staff and dumpy level, as shown in Figure 7. The measured depths to groundwater were then added to the elevation to determine a minimum and maximum depth to groundwater for each key species at each site.

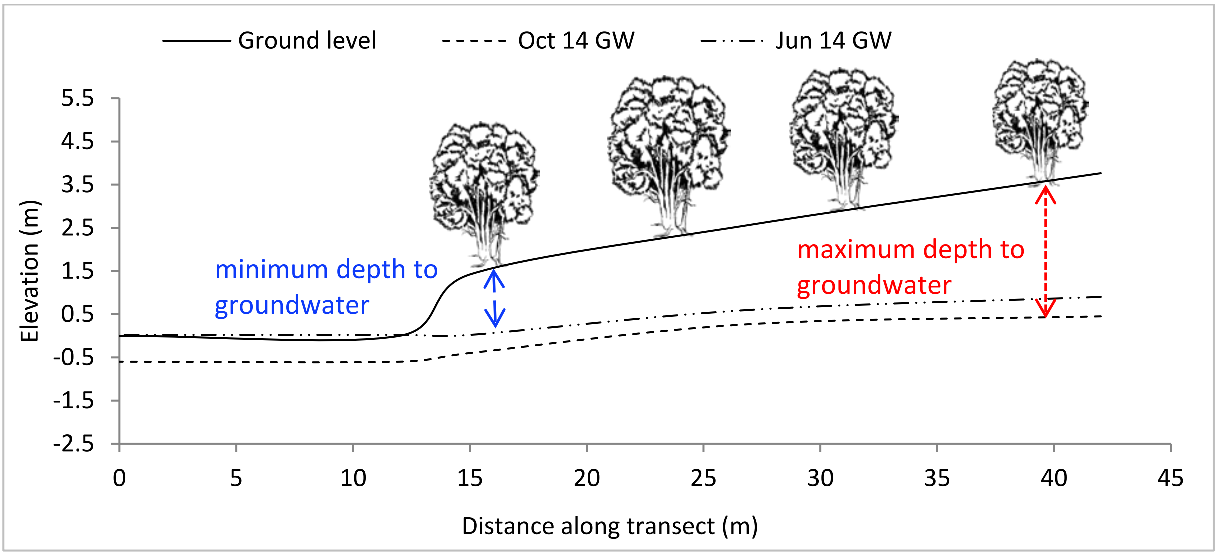


Figure 7 Example of determining depth to groundwater (GW) across a site

Foliage cover – canopy photography

Foliage cover (FC) is the percentage of a given area covered by the leaf area of the canopy. A change in FC over time (seasonally or inter-annually) may indicate plant response to changes in water availability. If FC remains high throughout the year, vegetation may have permanent access to groundwater. Percentage foliage cover is synonymous with leaf area index (LAI).

There are various methods to measure FC and LAI including using remote sensing; however, for this project we used digital photography. Photos were taken across each of our marked plots. To ensure total coverage photo spacing was 5 m, which resulted in 25 photos per 20 x 20 m plot.

Photos were processed in MATLAB using a script developed by CSIRO (Macfarlane, Hoffman et al. 2007). The software differentiates sky pixels from tree canopy and converts this to FC for each photo.

To determine the degree of change in FC between seasons, we took the photos at the end of wet season (May/June) and again at the end of the dry season (Oct/Nov).

Isotopes

The isotopes of water, oxygen-18 (δ^{18}O) and deuterium ($\delta\,^{2}$H) can be used to help determine sources of water used by vegetation (Richardson et al. 2011). Because the isotopic signature of water changes as it moves between the atmosphere (rain), soil, groundwater and vegetation, comparing the isotopic composition of potential sources (groundwater, surface water, rain and soil water) with plant xylem composition can indicate the water source (Richardson et al. 2011).

We took the following samples during the dry season when soil water was depleted and vegetation reliance on groundwater was increased:

- plants – small twigs cut and wrapped in cling wrap

- soil water – soil samples from various depths
- surface water – extracted directly from wetlands or rivers where present
- groundwater – taken from a bore/piezometer screened just below the watertable
- rainwater – collected in a rain gauge sealed with paraffin oil to prevent fractionation (enrichment from evaporation)
- dew – runoff collected in a plastic bag connected to a ‘catcher’.

Dew was collected opportunistically as it was very humid during the sampling period and it may have been available for use by the vegetation. Groundwater samples were also taken from bores across the broader study area during the hydrogeological investigation program.

All samples were stored in air-tight containers, refrigerated and sent to a commercial lab in Perth for analysis. Once analysed, the isotopic signatures of the twigs were compared with that of the various water sources (ground, surface, rain and/or soil) available at each site. The source closest in signature to the twig was considered most likely to be the water source. In some instances there was evidence of a mix of water sources; in others, there was no match between twigs and potential sources.

This method was not intended to replace other approaches, but rather to complement them (O’Grady, Eamus et al. 2002) as substantial supporting evidence is required before a clear picture of tree water use can be developed.

Shoot and soil water potential

Shoot water potential is a measure of plant hydration. Plants with roots accessing a good water supply (such as the watertable) are likely to be well hydrated. If trees are well hydrated during the dry season – when it is unlikely they have access to surface or soil water – it is considered they are at least partially groundwater dependent.

Soil water potential is directly related to plant water availability and uptake from the soil profile. Shoot water potential must be less (more negative) than soil water potential at the soil/root interface for water to move into the plant.

Measured during the day, shoot water potential indicates how a plant is balancing water loss from the leaves with water uptake through the roots. During the night, however, leaf pores (stomata) close, and the plant’s hydration comes into equilibrium with the amount of water in the soil surrounding the roots. Therefore, pre-dawn shoot water potential is a measure of water supply to the roots.

Matching soil and pre-dawn shoot water potentials can help identify the main depths of water uptake. For this study, shoots from individual plants were cut just before dawn and then stored in sealed snap lock bags in an esky or portable refrigerator. The water potential of each shoot was later measured in the lab using a Scholander-type (model PMS 1000) pressure chamber (uses Nitrogen gas) and the pressure at which sap is forced out of the cut stem surface was recorded (-MPa).

During bore installation (described below) or hand-augering, we took soil samples from varying depths, generally at the surface, then every 0.2 m to 1.0 m and then every 0.5 m to the watertable. Soil samples were sent to the lab for analysis of soil water potential, gravimetric moisture content (per cent) and for chloride (as a measure of salinity).

Soil moisture probes

Capacitance (soil moisture) probes allow us to track the movement of rain down through the soil profile (wetting front) in the wet season. This means we can determine when groundwater recharge starts and develop a relationship between rainfall and recharge.

We installed probes (Senetek EnviroSCAN series II RS232) at Kurrukurugun, Walmadan, Oval Wetland and DPB06 (Figure 8). Probes were inserted into hand augered, custom piezometers to a maximum depth of 2 m (length of probes) and configured to log soil moisture content at varying depths (generally 0.3, 0.6, 0.9, 1.2, 1.5, 1.7, 1.9 and 2.1 m) at six-hour intervals.

Data was recorded to a circuit board within the probe and required downloading every three months. Unfortunately two of the probes – DPB06 and Kurrukurugun – were burnt in bushfires during the 2015 dry season and all data post-March 2015 were lost.

Airborne Electromagnetics (AEM)

An AEM survey, using specialised helicopter-based equipment, was conducted over the study area between August and November 2012.

The equipment recorded electromagnetic fields in the ground, helping to identify the saltwater interface (where sea water meets fresh groundwater), potential freshwater-bearing sands of the Broome Sandstone aquifer, clay layers and the base of the Broome aquifer. This survey helped the department decide where to drill the deep investigation bores.

Although regional-scale flight lines were used for broader survey, we also identified several wetlands and other potential groundwater-dependent ecosystems (e.g. springs) for more targeted surveys. As a result there were some wetlands with short, closely spaced flight lines that did not penetrate the ground as deeply. These data were used to help define the source of groundwater – deep regional or shallow, localised aquifers – accessed by a number of potential groundwater-dependent ecosystems.

Hydrogeological investigations

Drilling

Drilling and construction of monitoring and investigation bores were completed for the hydrogeological investigations (Searle & Degens 2017). Deep drilling (eight bores) of up to 429 mbgl targeted the base of the Broome aquifer. Shallow drilling (24 bores) of up to 10.5 mbgl focused on groundwater around potential groundwater-dependent ecosystems. Where soil samples were collected from shallow bores for soil moisture and isotope analysis, the sonic drilling method was used. This kept sediment cores intact, ensuring unmixed samples could be taken from the appropriate depths.

Sampling program

In addition to the installation of bores and hand-augered piezometers, an extensive program of water sampling and monitoring was conducted throughout the project (see Searle & Degens 2017 for details). Samples were collected from rainfall, groundwater and surface water, and water-level loggers (both groundwater and surface water) were installed for the project's duration.

Bulk rainfall was collected over two wet seasons (2013–14, 2014–15) and sampled for major ions and isotopes ($\delta^{18}O$ and $\delta^{2}H$), and event-based rainfall samples were collected during the 2013–14 wet season and analysed for $\delta^{18}O$ and $\delta^{2}H$.

Sampling for groundwater quality was carried out in three main campaigns: July 2014, October to November 2014 and March to April 2015. The bores sampled included those drilled for the project, 12 existing bores and two water supply bores on Country Downs Station. Several water supply bores in Aboriginal communities were also sampled in 2013.

The physical properties measured at the time of sampling included temperature, electrical conductivity or EC (TDS), pH, dissolved oxygen and oxidation-reduction potential. Samples were also taken for major ions and constitutes, nutrients, $\delta^{18}O$ and $\delta^{2}H$ and radio-carbon dating (Carbon-14). A subset of shallow bores near discharge points were sampled for Radon-222 and a total of 22 shallow bores for CFCs. Deeper bores were sampled for Helium-4.

Surface water was sampled during the groundwater sampling campaigns and opportunistically in the early wet season to capture streams and wetlands. A similar suite of physical properties (to groundwater) were measured in-situ and samples collected for major ions, nutrients, Radon-222 and $\delta^{18}O$ and $\delta^{2}H$.

Carbon-14 and Helium-4 are used to estimate groundwater age. Radon-222 helps identify fresh groundwater discharge into surface waters. Chloride (chloride mass balance), CFCs and Carbon-14 are used to estimate groundwater recharge from rainfall. As with isotopes collected during the ecological work, $\delta^{18}O$ and $\delta^{2}H$ sampled from groundwater, rain and surface water helped determine water sources.

In August 2015, longitudinal sampling of Illelang (Spring Creek) baseflow was carried out to identify where groundwater discharges along the creek and to characterise this discharge. Sampling was conducted over two days at 32 locations from one of several springs feeding the head of the creek (Watermelon Dam) to the creek mouth (Figure 8). A helicopter was used to drop off and pick up field officers at points along the creek each day, although much of it was traversed on foot. This enabled close inspection of flow coupled with spot measurements of physical properties to help choose where to sample. In-situ physical and flow measurements were taken at each site with samples taken for major ions, $\delta^{18}O$ and $\delta\,^{2}H$ and Radon-222. Springs were also measured and sampled (including for ^{14}C) when it was possible to obtain fresh discharge without the influence of creek water.

Monitoring program

Groundwater-level monitoring was carried out in several ways. A series of bores (17) across the study area were equipped with automated water-level loggers (In-Situ Level TROLL 400) that were complemented with regular bore-level measurements by the traditional owners (Goolarabooloo and Nyul Nyul rangers).

Surface water level and quality loggers were installed in the lower reaches of Illelang and Bindingangun. Water-level loggers were also installed at Oval, Ngadalargin and Triangle wetlands and Watermelon Dam (Figure 7).

Developing study-wide vegetation datasets

Vegetation data collected through the approaches described above were used to develop study-wide datasets; that is, tree canopy condition, canopy density (foliage cover), depth to groundwater of key species and shoot water potential. As these methods are known measures of groundwater dependence, we used across-site comparison of results to further identify and describe potential for groundwater dependence.

Overstorey condition data were assessed on a plot by plot basis, with averages calculated by plot and site and rated as poor (1–5), moderate (6–11), good (12–17) and very good (18–23).

Per cent foliage cover was calculated on a plot by plot basis with the cover of each plot rated as very open (< 20%), open (20–40%), moderate (40–60%), dense (60–80%) or closed (> 80%).

Depth to groundwater ranges and shoot water potentials were assessed on a site by site basis.

6 Groundwater-dependent ecosystems - results and discussion

Following completion of the desktop review and on-country site visits, we selected 12 potential groundwater-dependent sites and one non-groundwater-dependent reference site (DPB06) for intensive field investigations (Table 1, Figure 8). It is noteworthy that the NDVI was largely ineffective in identifying groundwater-dependence, as the pindan soils across much of the study area retained enough moisture to ensure most of the vegetation remained green and dense year-round.

In this section we first discuss the study-wide datasets (see Table 1 for site name abbreviations for figures 10 to13). We then describe each of the 13 study sites in terms of the type of groundwater-dependent ecosystem, location and general site description, including distribution of dominant species and depth to groundwater. We then outline the specific work undertaken and summarise the key findings.

Table 1 Groundwater-dependent ecosystem study sites

GDE type	Name & abbreviation	Easting	Northing	Description
Wetland				
	Oval wetland* (DPB04)	440680	8098970	Freshwater wetland
	Flow Dam (FLD)	412588	8078523	Excavated flow line
	Wibbijagun (WIB)	416391	8042048	Seasonal freshwater wetland
	Ngadalargin (NGD)	437475	8120701	Seasonal brackish wetland
	Triangle wetland* (TRI)	436397	8120861	Freshwater wetland
Creek				
	Illelang (ILL) &	412121	8085573	Fed by springs/seepages
	Watermelon Dam (WAT)	429579	8074884	Excavated spring
	Bindingangun (BIN)	412034	8082602	Fed by inland springs/seepages
	Jabirr Jabirr (JJB)	433234	8098970	Fed by inland springs/seepages
Spring				
	Banana Well (BWE)	456399	8122980	Excavated spring
Monsoon vine thicket				
	Mudoodon (MOO)	410127	8056560	Monsoon vine thicket (TEC)
	Walmadan (WAL)	409536	8064848	Monsoon vine thicket (TEC)
Phreatophytic vegetation				
	Kurrukurugun* (KUR)	411187	8077708	Woodland on freshwater flow line
Pindan reference (non-groundwater dependent)				
	DPB06*	435995	8111110	Woodland on deep pindan soils

*project names

Figure 8 Groundwater-dependent ecosystem study sites

In addition to the study-wide datasets, we also considered soil and shoot water potentials, soil moisture, soil chloride and isotope data to determine if the vegetation sampled at each site was likely to be using groundwater. If the vegetaton was considered groundwater-dependent, we then considered all available data (including AEM) and results from the hydrogeological investigations (Rothery 2016; Searle & Degens 2017) to decide if the wider ecosystem was actually groundwater-dependent and if so, which groundwater source it was accessing.

For all sites except Banana Well, we provide a conceptual diagram showing distribution of key vegetation species in relation to minimum and maximum recorded water levels – level of inundation and/or depths to groundwater. All figures show vegetation running upgradient from the lowest elevation to the highest. Figure 9 is a key to the species depicted in the conceptual diagrams. Photographs of each site are presented in Appendix F.

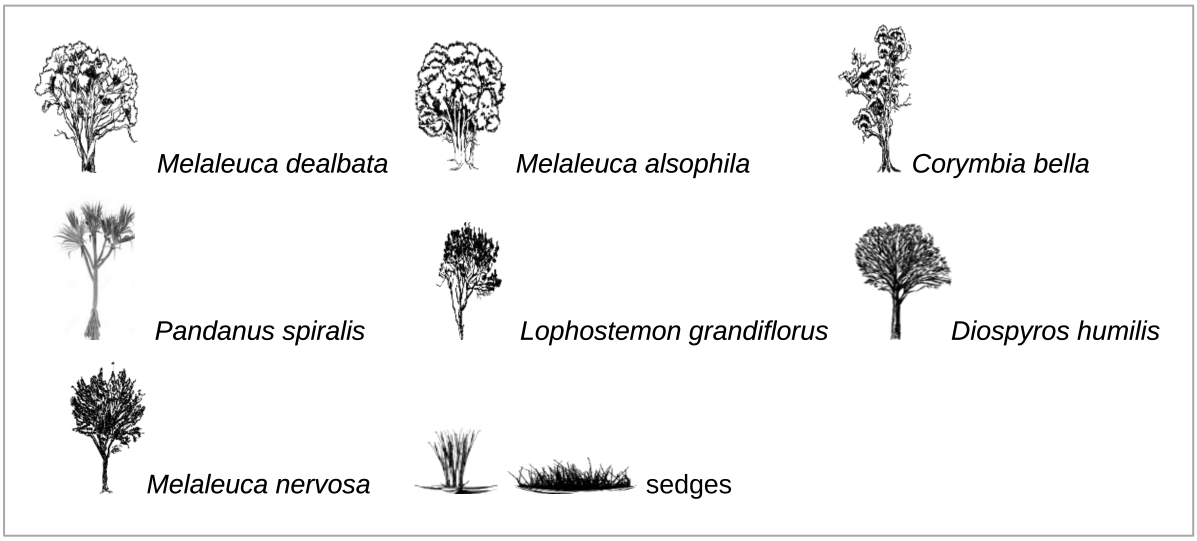


Figure 9 Key to vegetation species in conceptual diagrams

6.1 Study-wide vegetation datasets

Canopy condition

Canopy condition (tree health) was only assessed as part of site descriptions when sites were first established. This was generally at the end of the wet season (May/June) in 2014 or 2015. As a result trees would have been well hydrated and most likely at their healthiest. This also meant we could not compare condition between wet (high water availability) and dry (low water availability) seasons.

Average canopy condition was recorded over a total of 30 vegetation plots (Figure 10). No canopies were classified as being in poor or average condition, eight were in good condition (score of 12–17) and the remainder were considered to be in very good condition (score > 17).

Trees in the single plot at Ngadalargin wetland received the lowest score (14.5), followed by plot A at Wibbijagun wetland north (15.1). *Melaleuca alsophila* was the only species recorded in these plots. The highest scores were recorded for plot D at DPB04-2 (20), Jabirr Jabirr (20.2) and Walmadan (20.5).

Foliage cover

Although we aimed to assess foliage cover at the end of both the wet and dry seasons, to allow comparisons between them, only 14 of the 23 plots were assessed in both seasons (Figure 11).

Foliage cover ranged from very open to moderate, with no dense (60–80% cover) or closed (> 80% cover) canopies recorded (Figure 11). Of note is that the non-groundwater-dependent reference site, DPB06, was one of the more open plots at the end of the wet season along with some plots that may have been recently inundated: DPB04-1 plot A, Ngadalargin wetland, Triangle wetland and Wibbijagun north plot A.

There was no significant change in foliage cover across the dry season, with canopies of many plots actually becoming slightly denser, possibly as the sites dried out. The exceptions were Triangle wetland, which had a significant increase in density, and Kurrukurugun, which was partly burnt in a bushfire in September 2014 and therefore had a more open canopy. This suggests most sites still had access to a water source during the dry season and were likely to be groundwater-dependent.

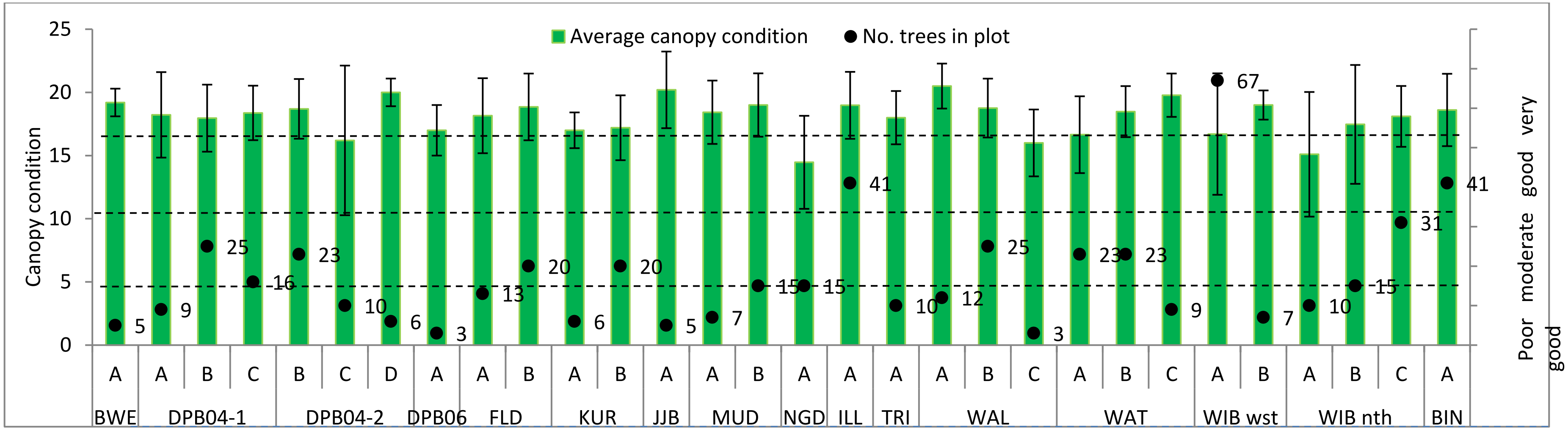


Figure 10 Average (with standard error) canopy condition by plot – study sites

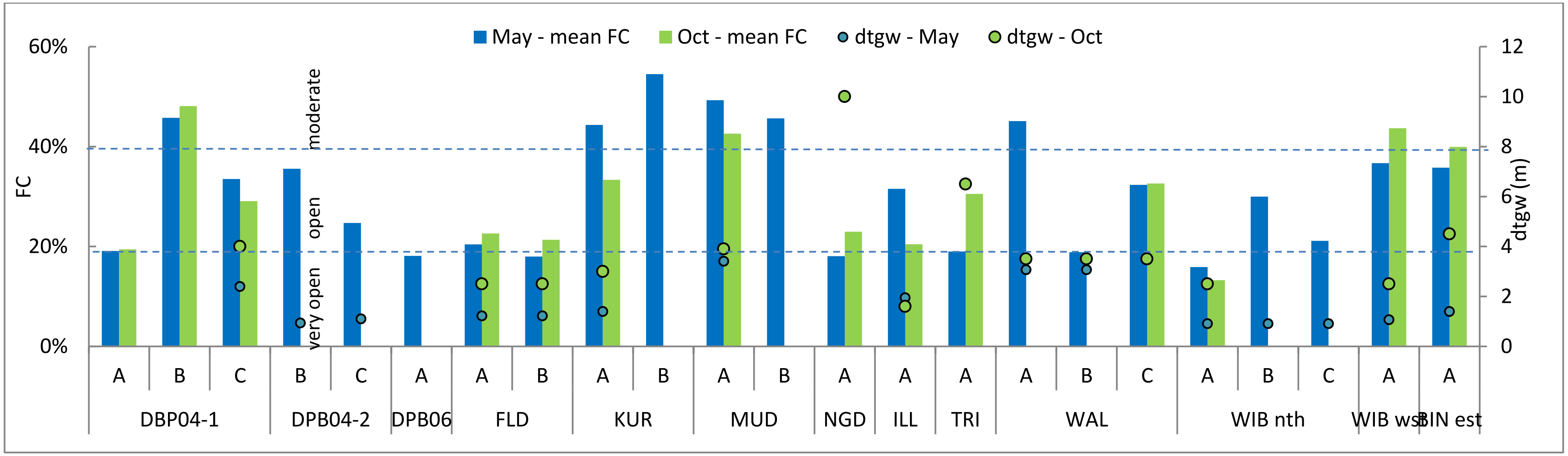


Figure 11 Average foliage cover (FC) and depth to groundwater (dtgw) by plot – study sites

Water depth ranges of key species

We estimated water-level ranges for eight overstorey species across 13 sites. The box and whisker graph (Figure 12) shows the ranges of each species at each plot. The solid bar (box) is the average range (minimum to maximum) across the site and the lines (whiskers) are the absolute minimum and maximum depths. Where there are no whiskers, only one individual occurred in the plot. A positive depth means the tree was inundated.

Only *Melaleuca dealbata* and *M. alsophila* were recorded in flooded conditions during the life of the project. Both species were inundated at Oval wetland (DPB04-1 and DPB04-2) with *M. alsophila* also inundated at Flow Dam.

The deepest and widest ranges of groundwater depth for *Corymbia bella, M. dealbata* and *M. nervosa* were recorded at Ngadalargin wetland. Groundwater was deepest for *Pandanus spiralis* and *Lophostemon grandiflorus* in the Mudoodon monsoon vine thicket and at Kurrukurugun respectively (Figure 12).

Overall *M. dealbata* and *M. alsophila* were found in areas of the shallowest groundwater (and/or presence of surface water) and *L. grandiflorus* and *Diospyros humilis* in the deepest groundwater. *C. bella, P. spiralis* and *M. nervosa* were generally found at immediate depths to groundwater.

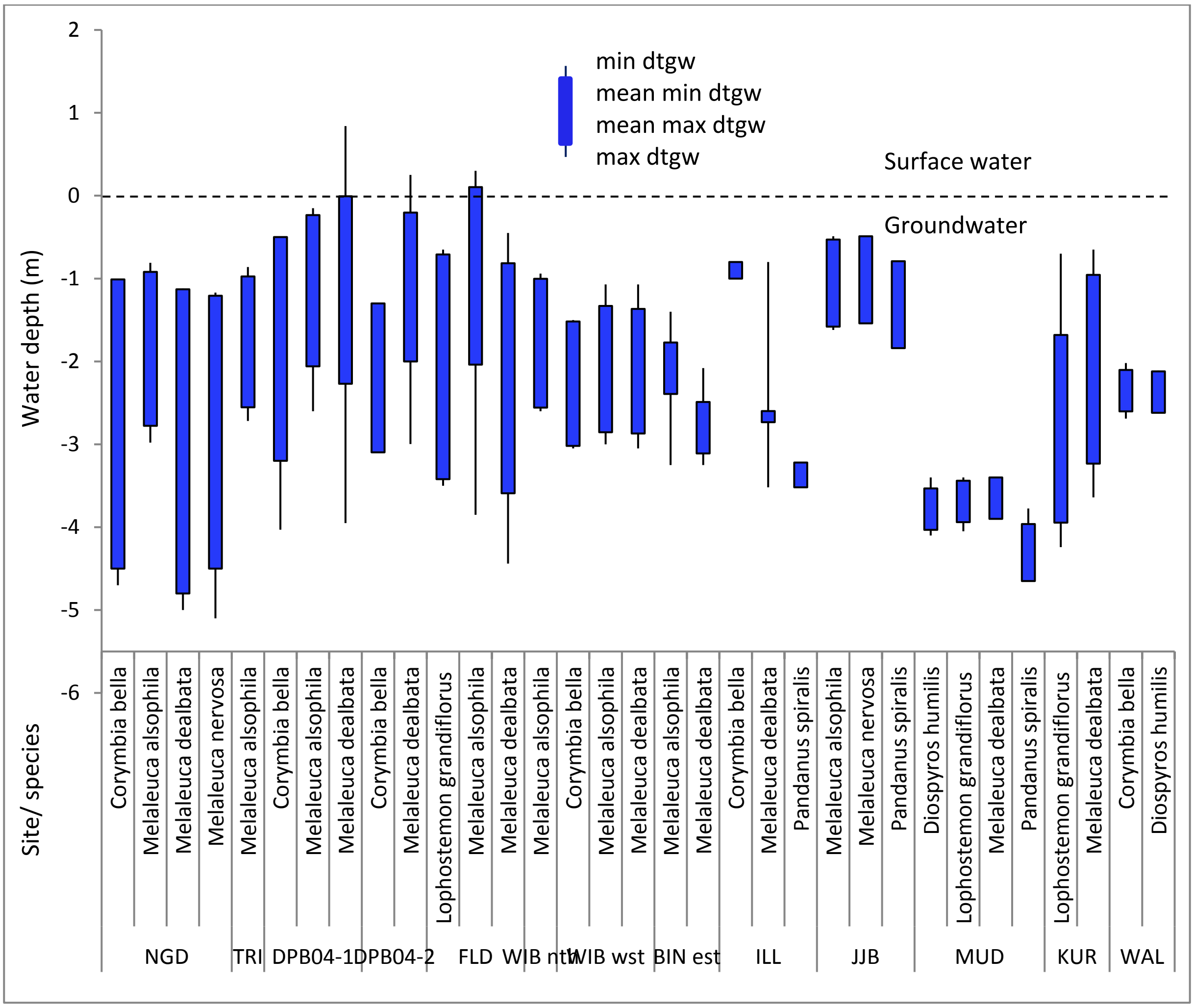


Figure 12 Water-depth ranges of key species – study sites

Shoot water potentials

We measured shoot water potentials of important overstorey species at the end of both the wet and dry seasons to allow comparisons between seasons (Figure 13). Three sites – Mudoodon, Walmadan and DPB04-2 (Oval wetland) – were only assessed at the end of the wet, so comparisons were not possible.

Although *M. dealbata* and *M. alsophila* were recorded at similar depths to groundwater across numerous sites, *M. dealbata* generally maintained higher levels of hydration across the dry season (i.e. shoot water potentials were less negative) (Figure 13). This may be due to the presence of *M. alsophila* in more brackish or saline areas and associated reduced uptake of groundwater.

M. dealbata, *M. alsophila* and *L. grandiflorus* sampled at Flow Dam showed the greatest decline in hydration across the dry season, despite the presence of shallow groundwater. The three *L. grandiflorus* here were in fact the most water stressed of all trees sampled across the study area (i.e. shoot water potentials were most negative). *L. grandiflorus* were also relatively water stressed at Kurrukurugun.

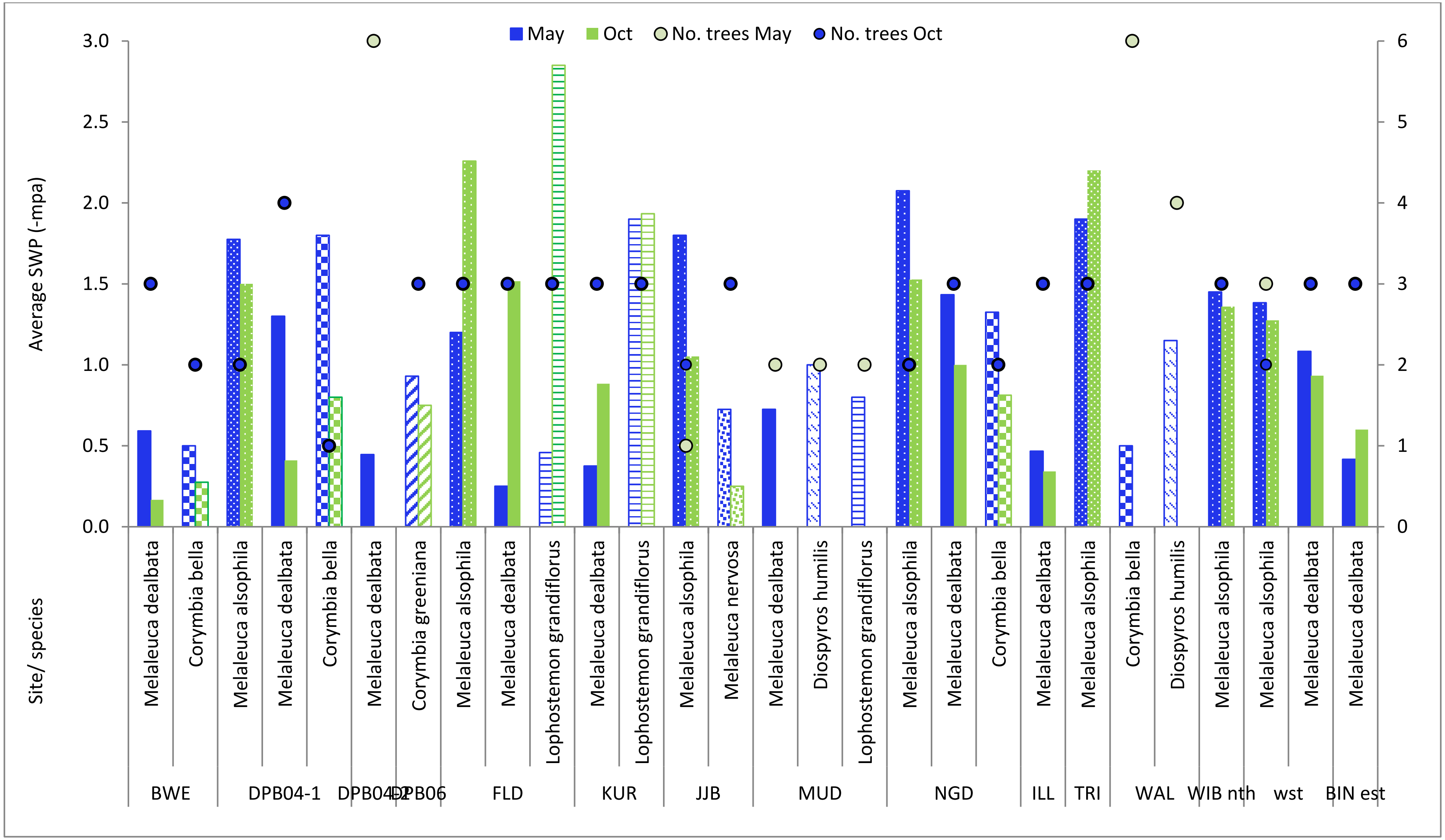


Figure 13 Shoot water potentials of key species – study sites

6.2 Ngadalargin wetland

Site description and methods

Ngadalargin wetland (Appendix F, Figure F1) is located in the north-west of the study area on a gently undulating plain behind coastal dunes between Baldwin Creek and Camp Inlet (Figure 14). Ngadalargin is semi-permanent, drying by the end of most dry seasons.

The vegetation fringing Ngadalargin is predominantly low woodland to low open-forest of *Melaleuca alsophila* with an understorey of annual grasses. On the lake's eastern side there is an isolated patch of *M. dealbata* and *Corymbia bella* with a stand of *M. nervosa* further from the water's edge. A 20 x 20 m plot was established here in May 2014 to capture both 'fresh' and 'saltwater' overstorey species.

A non-vented In-Situ Level TROLL 400 (water-level logger) and staff gauge were installed in the wetland in May 2014 (8011013) (Figure 14). In November 2014 contractors installed two shallow bores, NGB and NGC (80110245 and 80110250), about 80 m north of the vegetation plot. A third bore, NGA, could not be completed due to problems with the drill rig. A sonic rig was used so intact soil cores could be sampled for soil moisture and isotope analysis. A water-level logger was installed in the bore, and surface water and twig samples were collected at this time for isotope analysis.

Results

Drilling of bore NGC at Ngadalargin found a thin, perched, saline aquifer, which only persisted for a few months during the wet season. Bore NGB showed a second, but permanent aquifer that was deeper yet also saline. Before drilling of bore NGA was stopped at 30 metres below ground level (mbgl), it was found that groundwater was becoming fresher with depth – thought to be connected to the aquifer found in NGB. This is supported by the AEM results (Searle & Degens 2017).

Loggers in NGB and NGC showed groundwater levels remained lower than surface water levels in the wetland, except for immediately after large rainfall recharge events. Groundwater levels at bore NGB ranged from 4.0 to 0.6 mbgl between November 2014 and January 2015.

The local, perched groundwater (NGC) exceeded 10 400 mg/L TDS and was many times more saline than surface water, even at the end of the dry season when surface water quality ranged from 330 to 1300 mg/L TDS. This is supported by anecdotal evidence from the Nyul Nyul rangers that Ngadalargin wetland itself is a seasonal, brackish system.

The shallow, saline groundwater contained isotopic signatures that showed salts had been concentrated through tree use – transpiration, rather than direct evaporation.

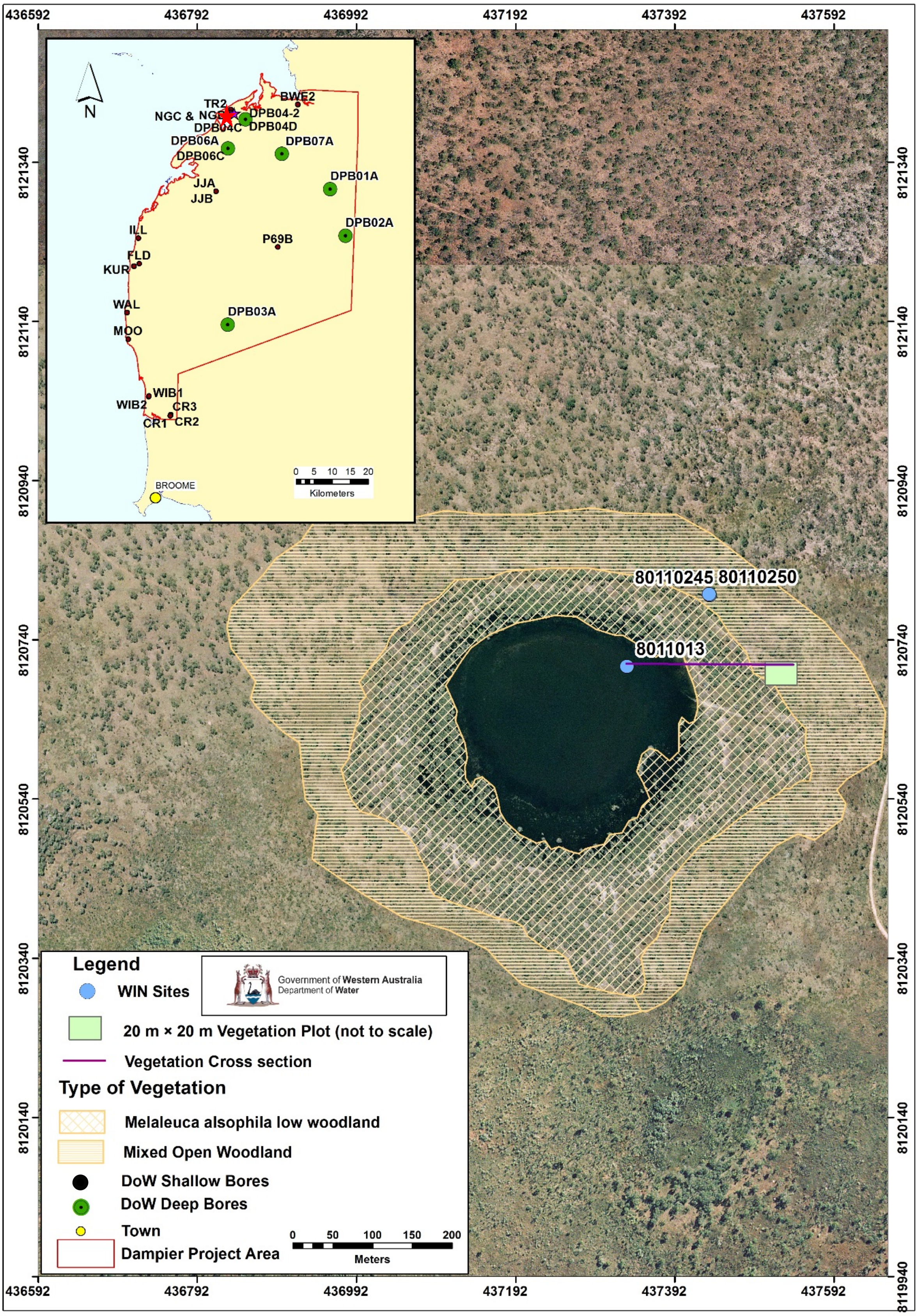


Figure 14 Ngadalargin wetland location, bore, vegetation and survey plot

Figure 15 shows the conceptual distribution of key species across an elevational gradient from the staff gauge to the bore (see Figure 9 for species key). The vegetation plot runs from 110 to 130 m. Water levels experienced by the four overstorey species were lowest in December 2014 and highest in January 2015. *C. bella* water levels ranged from 4.1 to 1.01 mbgl, *M. alsophila* from 2.98 to 0.81 mbgl, *M. dealbata* from 5.0 to 1.13 mbgl and *M. nervosa* from 5.1 to 1.2 mbgl (Figure 12).

The canopy condition of the *M. dealbata, M. alsophila* and *C. bella* forming the overstorey in the plot was rated as good, but was the lowest of all investigation sites (Figure 10). Although the canopy was very open, foliage cover increased over the 2014 dry season (Figure 11). There were no seedlings (< 2 cm DBH) or saplings (2–4 cm DBH) in the plot.

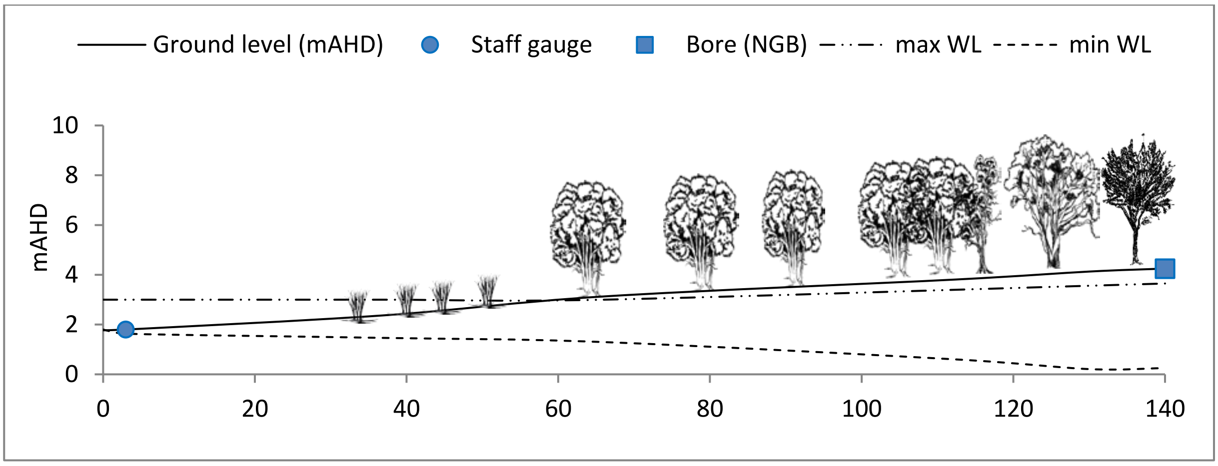


Figure 15 Water levels and vegetation distribution at the Ngadalargin wetland site

Trees were generally less hydrated at Ngadalargin than at other sites. This was illustrated by shoot water potentials of *M. dealbata* and *M. alsophila* being lower (more negative) than all sites at the end of the wet and among the lowest at the end of the dry (Figure 14).

Shoot water potential, soil moisture and chloride data from the shallow bore suggest the sampled wetland trees (Md-1, 2, 3 and Ma-1, 2 in Figure 16) were most likely accessing soil moisture from 3.5 mbgl and deeper. Isotope data supports this, with tree signatures closest to those of soil samples from 3.5 and 4.0 mbgl – despite also being close to soil moisture from 2.0 mbgl, water is unavailable to the roots at this depth as soils are too dry (Figure 17).

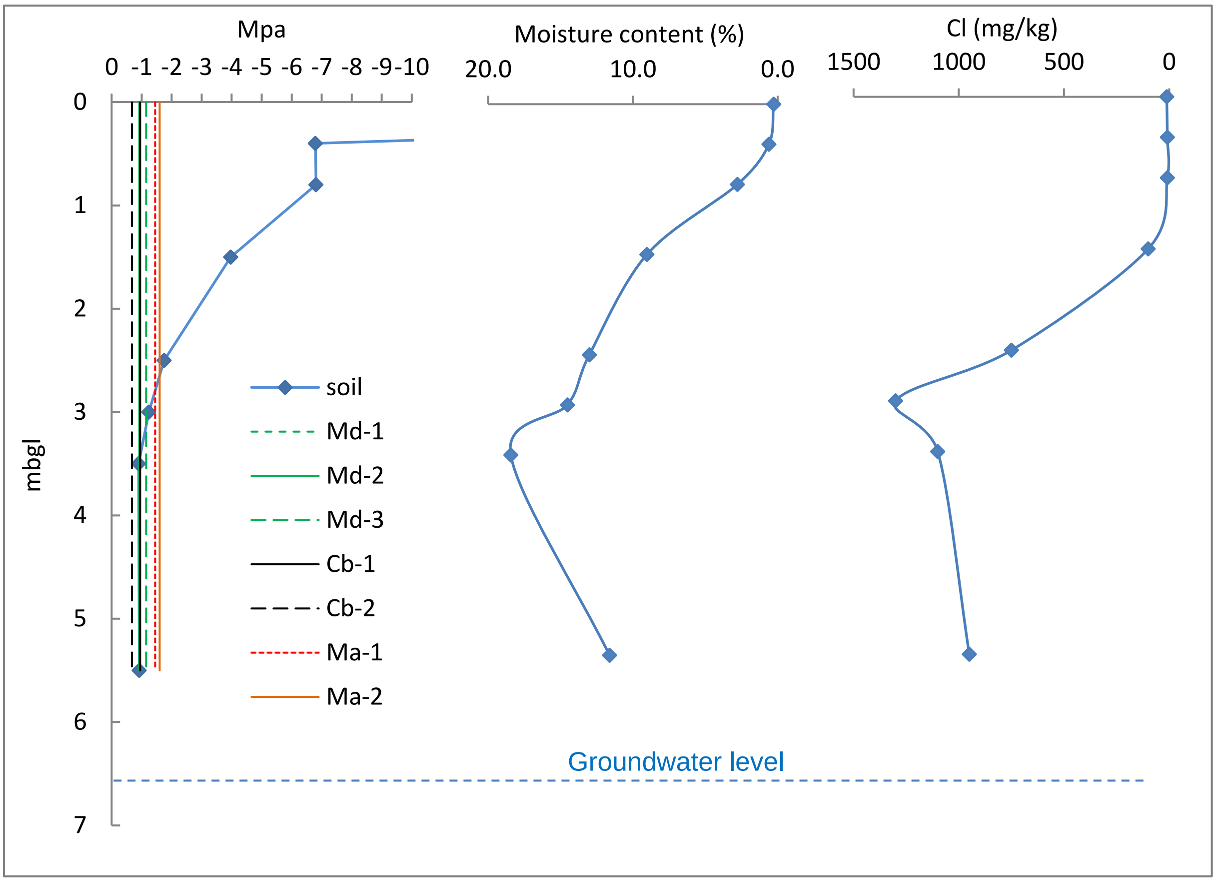


Figure 16 *Ngadalargin – soil and shoot water potential, soil moisture content and soil chloride with depth in bore NGB*

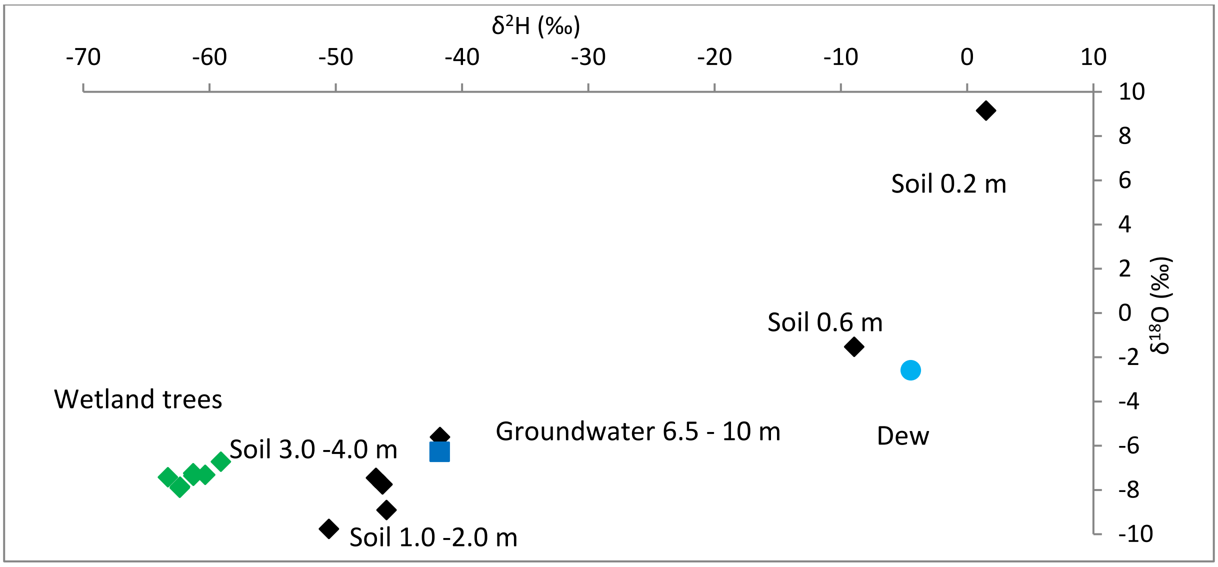


Figure 17 *Ngadalargin – Deuterium and Oxygen-18 isotope signatures of trees and potential water sources*

Is Ngadalargin wetland a groundwater-dependent ecosystem?

Saline groundwater underlies the *M. alsophila* fringing most of the wetland, in the form of a shallow perched aquifer and a deeper, more permanent aquifer. As a salt-tolerant species it appears able to use this water, storing salt just beneath the bark, possibly to excrete at a later stage. However, uptake of saline water is likely limited as illustrated by the trees being less hydrated than other species.

Given that only a small stand of freshwater tree species (*M. dealbata* and *C. bella*) is found on the wetland's eastern side, and that these species are less healthy and hydrated than at all other study sites, it is possible that fresh groundwater was not readily available. However, the freshness of groundwater at depth (at bore NGA) suggests there may be some connection to the regional Broome aquifer. It is thought that this is the same aquifer as NGB, which is only salty (at shallow depths) due to transpiration.

Therefore, although *M. alsophila* may be accessing the local, shallow saline aquifer, it is possible some connection to the regional groundwater table exists at Ngadalargin wetland. Whether or not the small number of *M. dealbata* and *C. bella* individuals are sitting above an area of greater connectivity to the fresher groundwater of the Broome aquifer is unclear.

6.3 Triangle wetland

Site description and methods

Triangle wetland (Appendix F, Figure F2) sits behind coastal dunes within 2 km of Camp Inlet. It is immediately west of Ngadalargin and the two are often connected during the wet season (Figure 18). As our 'project name' suggests, the lake is roughly triangular in shape. It is probably semi-permanent, forming as surface and subsurface flows bank up behind the extensive dune system along its western and northern boundaries. Freshwater inputs are also likely from rainfall-derived local aquifers formed in the dunes.

The vegetation fringing most of the wetland is low woodland of *Melaleuca alsophila,* with an understorey of annual grasses. However, there is very little to no overstorey along the lake's northern edge where a very wide band of mixed sedges occurs, including *Schoenoplectus subulatus*. This extends across the floodplain in the north-east. There are also isolated patches of *Typha domingensis* near the lake's western edges and at the base of the dunes in the north. A band of large *Albizia procuera* and other unidentified trees with isolated *Pandanus* sp. also occurs along the base of the dunes. A 20 x 20 m plot was established on the wetland's eastern side among *M. alsophila* (Figure 18).

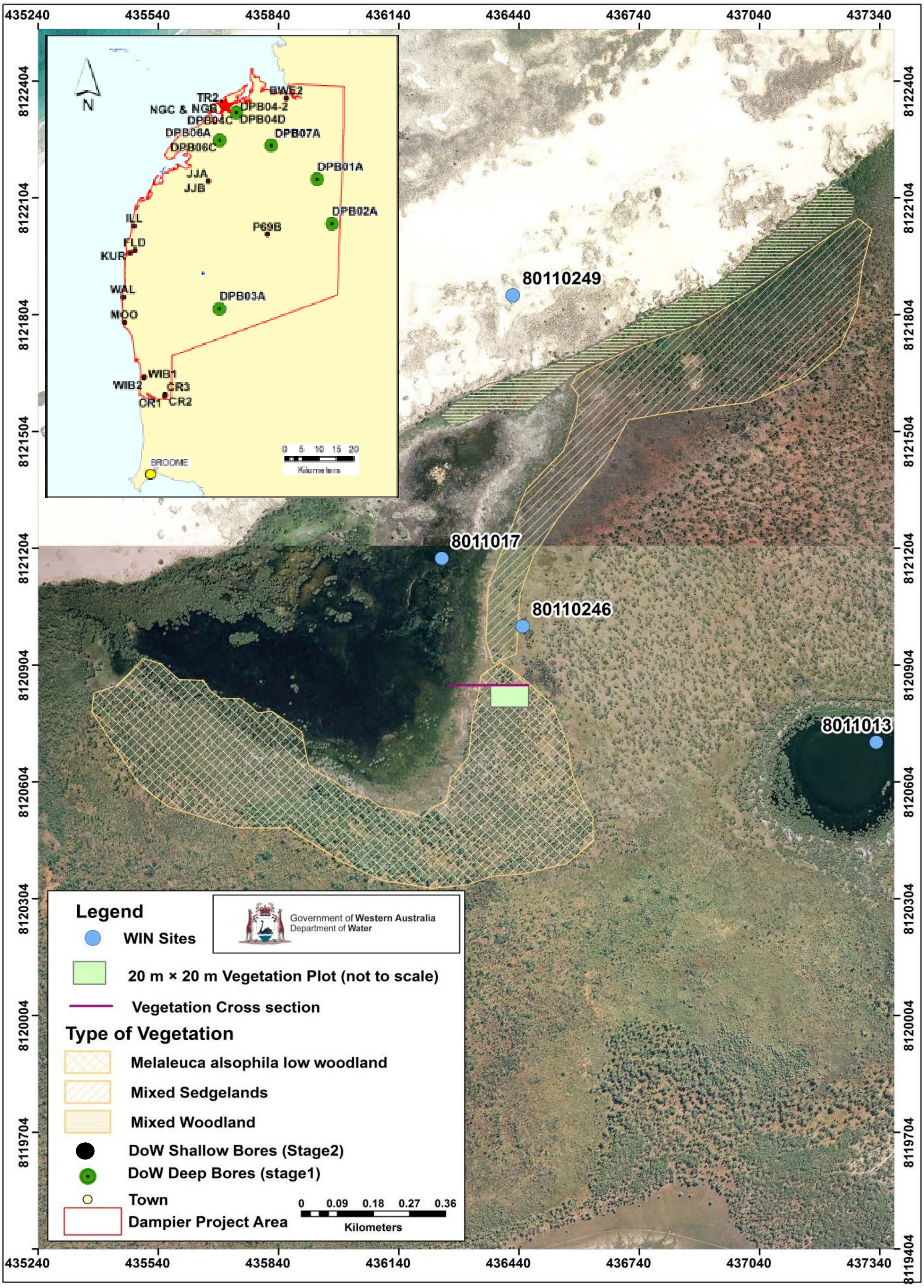


Figure 18 Triangle wetland location, bores, vegetation and survey plot

Contractors installed a shallow bore (80110246) equipped with a groundwater logger on the wetland's eastern side about 80 m north of the vegetation plot in October 2014 (Figure 18). A sonic rig was used so intact soil cores could be sampled for soil moisture and isotope analysis. Surface water and twig samples were also collected.

A surface water logger was also installed at a staff gauge in the wetland in May 2014 (8011017) and a shallow bore was hand augered in a dune swale to the west of the wetland (80110249) (Figure 18).

Results

No permanent shallow groundwater was found on Triangle wetland's eastern side during drilling. However, a perched (seasonal) watertable was found. At the time of bore installation the groundwater was saline (12 400 mg/L TDS) and was about 2.3 m deep, but depths ranged from 0.72 to 3.17 mbgl during the life of the project. Loggers showed groundwater levels in the bore remained lower than surface levels in the wetland, except for immediately after large rainfall recharge events.

The dune bore was constructed in sands with fresh (80 mg/L TDS), shallow groundwater at 1.9 mbgl. Levels in the dune bore were generally higher than both the bore water levels and the wetland.

Groundwater (12 400 mg/L TDS) was much more saline than surface water in the wetland, even at the end of the dry season (range 330 to 1300 mg/L TDS). This, along with relative water levels, indicated little to no groundwater input from the regional aquifer. Groundwater from the fresh dune aquifer could discharge into the wetland, and support the vegetation at the base of the dunes.

Figure 19 shows the conceptual distribution of key species across an elevational gradient from the staff gauge to the wetland bore (TR1). The vegetation plot runs from 165 to 185 m. Depth to groundwater experienced by the *M. alsophila* (Figure 12) ranged from maximum of 2.80 mbgl in December 2014 to a minimum of 0.97 mbgl in January 2015. The canopy condition of the *M. alsophila* forming the open overstorey of the Triangle wetland vegetation plot was rated as very good (figures 10 and 11). Fourteen *M. alsophila* seedlings and 12 saplings were recorded in the plot.

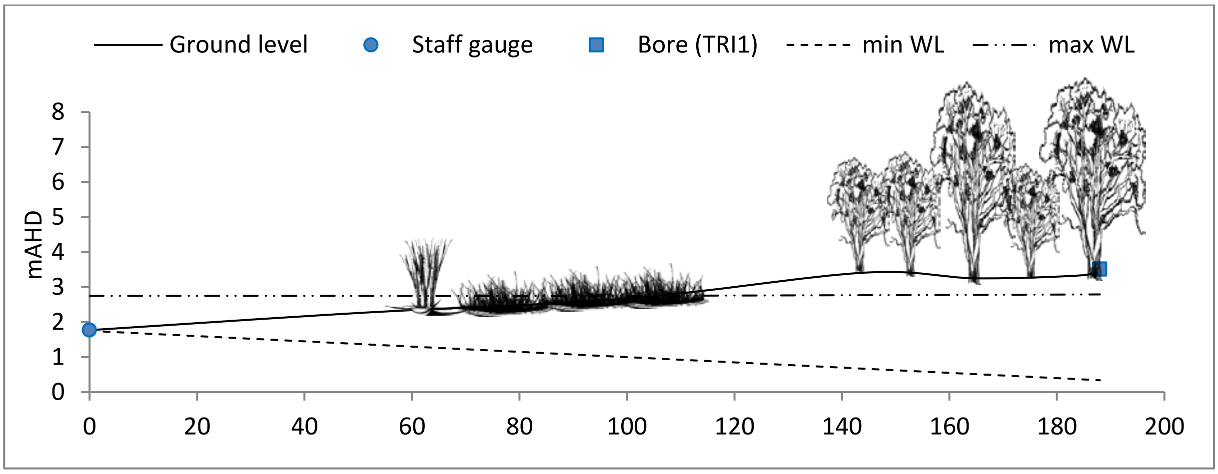


Figure 19 Water levels and vegetation distribution at the Triangle wetland site

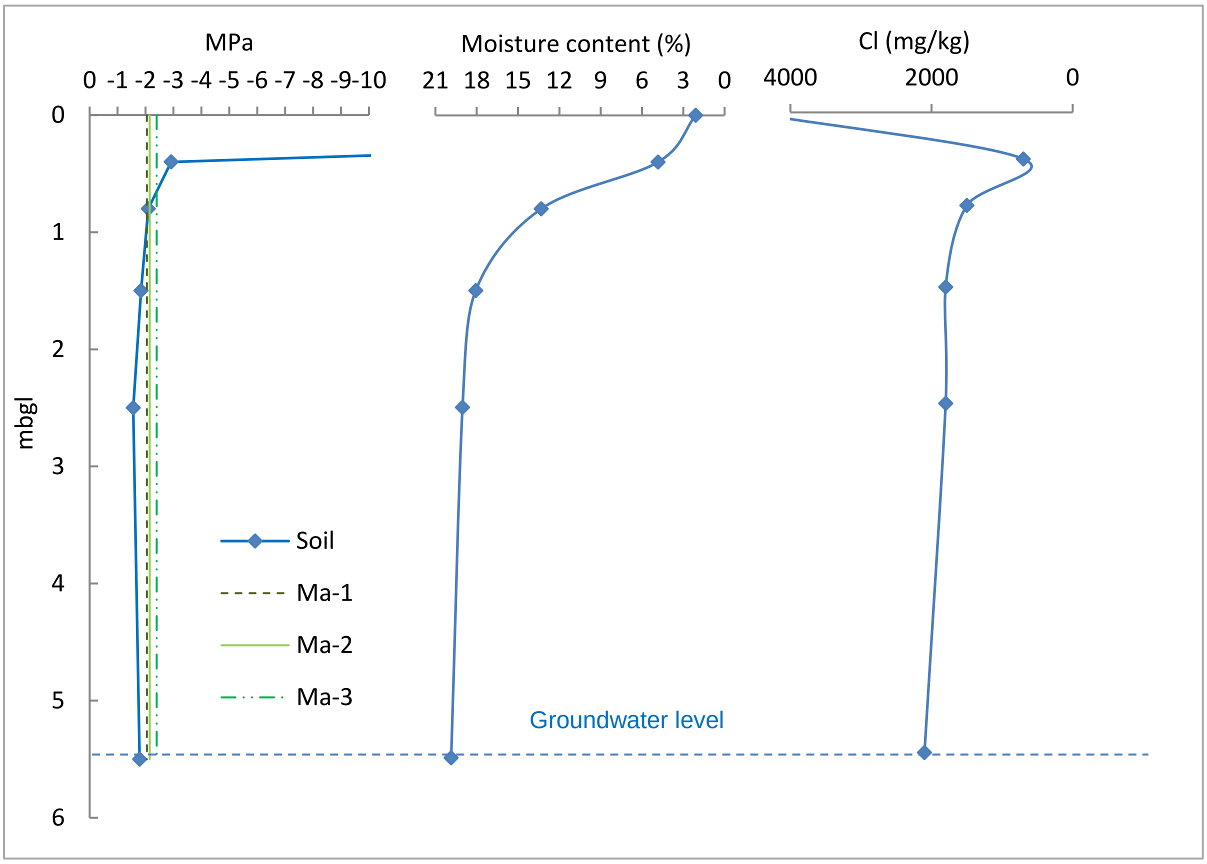


Figure 20 Triangle wetland – soil and shoot water potential, soil moisture content and soil chloride with depth

M. alsophila (Ma-1, 2, 3 in Figure 20) shoot water potentials were generally lower (more negative) at Triangle than at other sites, suggesting trees were less hydrated (Figure 13). However, at the end of the dry season the *M. alsophila* were accessing soil moisture from 0.6 to 5.5 mbgl even though it was brackish (Figure 20). Isotopic data support this and further indicate that trees were also using groundwater to 5.5 mbgl and deeper (Figure 21).

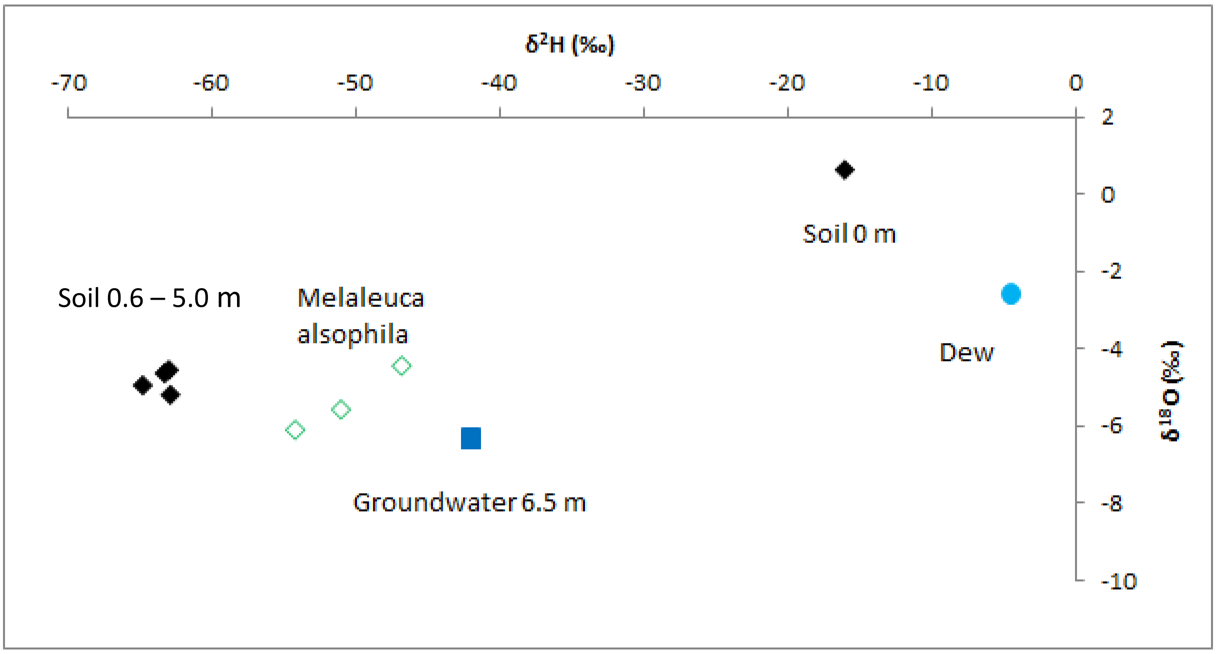


Figure 21 Triangle wetland – Deuterium and Oxygen-18 isotope signatures of trees and potential water sources

Is Triangle wetland a groundwater-dependent ecosystem?

The only freshwater species at Triangle wetland occurs at the base of the extensive dune system west of the lake. The dunes contain a local, shallow aquifer thought to form from direct rainfall. The watertable in the dunes is higher than the lake level, suggesting fresh water may flow into the wetland during the dry season. This supports the anecdotal evidence from the Nyul Nyul rangers that Triangle wetland itself is a semi-permanent, freshwater system.

However, the *M. alsophila* fringing most of the wetland sit over deeper brackish groundwater and are accessing soil and groundwater from 0.6 mbgl and deeper. This reliance on brackish water may explain why they are less hydrated than trees at other sites, even though they have access to greater reserves of moisture/water.

Salinity in the groundwater may be caused by transpiration (water use by trees), as indicated by the lack of enrichment in the stable isotopes of water (Searle & Degens 2017). Fresh water from within the dune system could discharge into the wetland, since water levels are generally higher in the dunes than in the wetland.

Therefore, although there are local groundwater inputs into Triangle wetland, it is unlikely to be connected to the regional Broome Sandstone aquifer.

6.4 Oval wetland

Site description and methods

This un-named circular wetland is about 3.5 km south-east of Ngadalargin. In very wet years it is probably connected to Ngadalargin and Triangle wetlands. Oval wetland (or DPB04) is permanent with a small pool of fresh water remaining at the end of every dry season (Appendix F, Figure F3).

The vegetation fringing the wetland's western and southern sides is predominantly *Melaleuca alsophila* open woodland with *M. dealbata* and *Corymbia bella* becoming dominant with distance from the wetland's western edge. However, *M. dealbata* of varying age classes form woodland around the lake's northern and eastern sides (Figure 22).

The wetland itself supports various aquatic plants including *Nymphaea violacea* (water lily), *Marsilia* sp. (Nardoo) and *Nymphoides indica* (marshwort). Several bird species have been noted along with fish, possibly *Chanos chanos* (milkfish).

Two transects, named for the bores installed there, were set up at Oval wetland: DPB04-1 in the south-west and DPB04-2 in the north (Figure 22). A surface water logger was installed in the wetland in June 2014 (8011003).

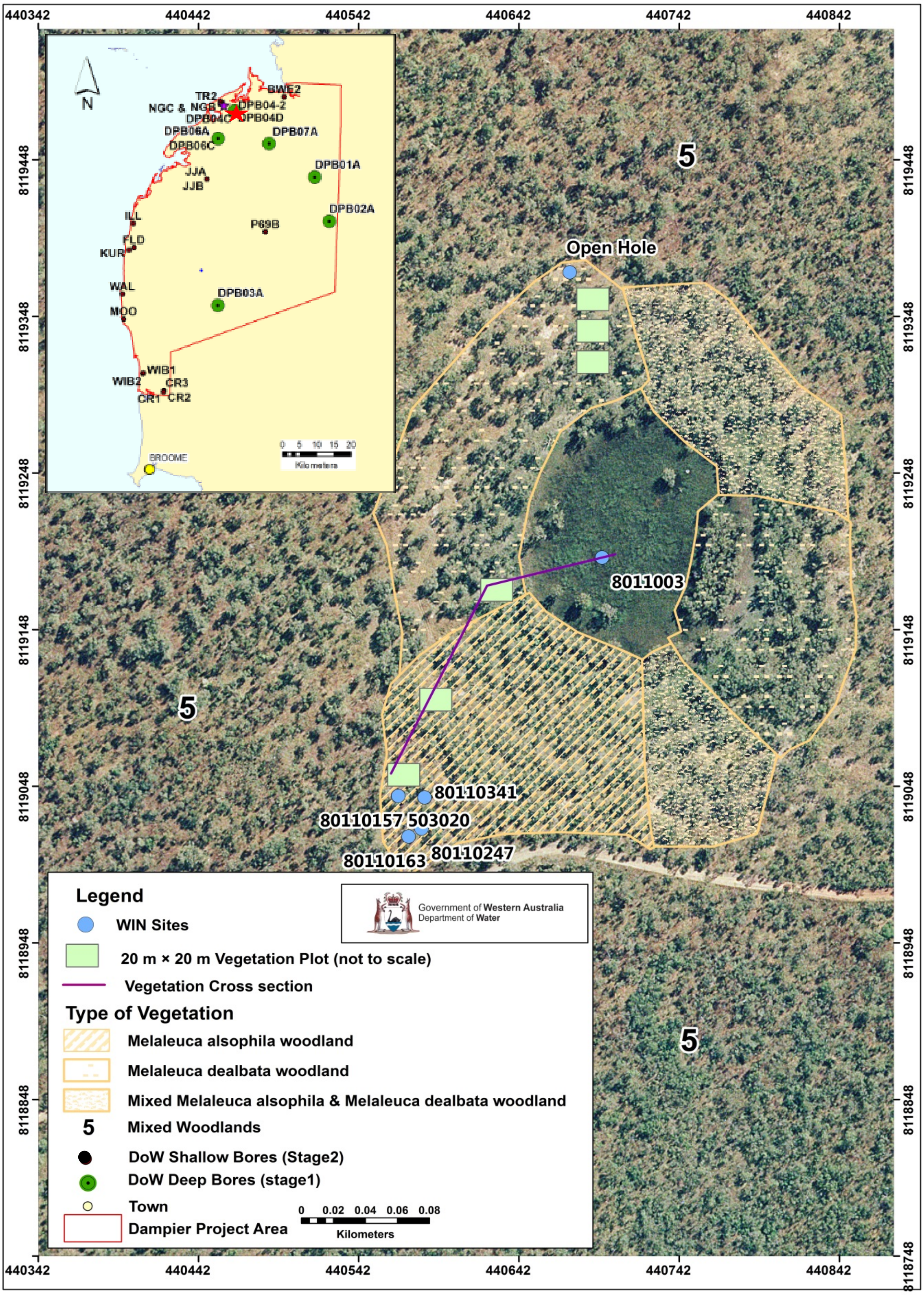


Figure 22 Oval wetland (DPB04) location, bores, vegetation and survey plots

DPB04-1

The transect here comprised three non-contiguous 20 x 20 m plots (Figure 22). It was set up in June 2014 to capture the transition from saltwater to freshwater species. At this time a shallow piezometer was hand augered to the watertable (DPB04D, 80110157).

In September 2013 a water supply bore (DPB04B, 80110164) and a deep bore (DPB04A, 80110163) were installed near the wetland's south-west corner. A shallow bore was installed in the same area in November 2014 (DPB04C, 80110247). A sonic rig was used to enable intact soil cores to be sampled for soil moisture and isotope analysis. A soil moisture probe (DPB04E, 80110341) and rain collector were also set up. Rain, surface water and twig samples were collected for isotope analysis.

DPB04-2

A second transect comprising three 20 x 20 m plots was established in April 2015 north of the wetland to capture the broader range of freshwater species (Figure 22). Two shallow piezometers were hand-augered to the watertable.

Results

DPB04-1

Depth to groundwater at bore DPB04C ranged from 2.4 mbgl in May 2014 to 4.06 mbgl in October 2014.

Drilling showed a very thin aquifer in the top few metres above a low permeability clay layer at 5.5 m. Beneath this was 5 m of saturated sand and clayey sands separated from the regional watertable by a very hard sandstone bed (Searle & Degens 2017). The four bores constructed at the site represent shallow groundwater (DPB04D), near-surface groundwater below the shallow clay layer (DPB04C) and the top (DPB04B) and bottom (DPB04A) of the deeper regional aquifer. Generally it appears that salt water overlies deeper fresh water.

Figure 23 shows the conceptual distribution of key species across an elevational gradient from the staff gauge to bore DPB04C. The three vegetation plots occur between 80 and 230 m on the transect.

Water levels experienced by the three overstorey species were lowest in December 2014 and highest in January 2015. *C. bella* levels ranged from 4.03 to 0.5 mbgl, *M. alsophila* from 2.6 to 0.15 mbgl and *M. dealbata* from 3.95 mbgl to inundated by 0.84 m (Figure 12).

The canopy condition of the *M. dealbata, M. alsophila* and *C. bella* of the DPB04-1 vegetation transect was rated as good to very good (Figure 10). Four *M. dealbata* seedlings and one sapling were recorded in plot A. The canopy of plot A was very open, possibly due to it being inundated for up to six months of the year. Plots B and C were denser, yet still classed as open. There was some increase in canopy density in all plots at the end of the dry (Figure 11), suggesting trees maintained access to water. Shoot water potentials were lower at the end of the wet season in all sampled species (Figure 12). However, *M. dealbata* and *C. bella* were well hydrated at the end of the dry.

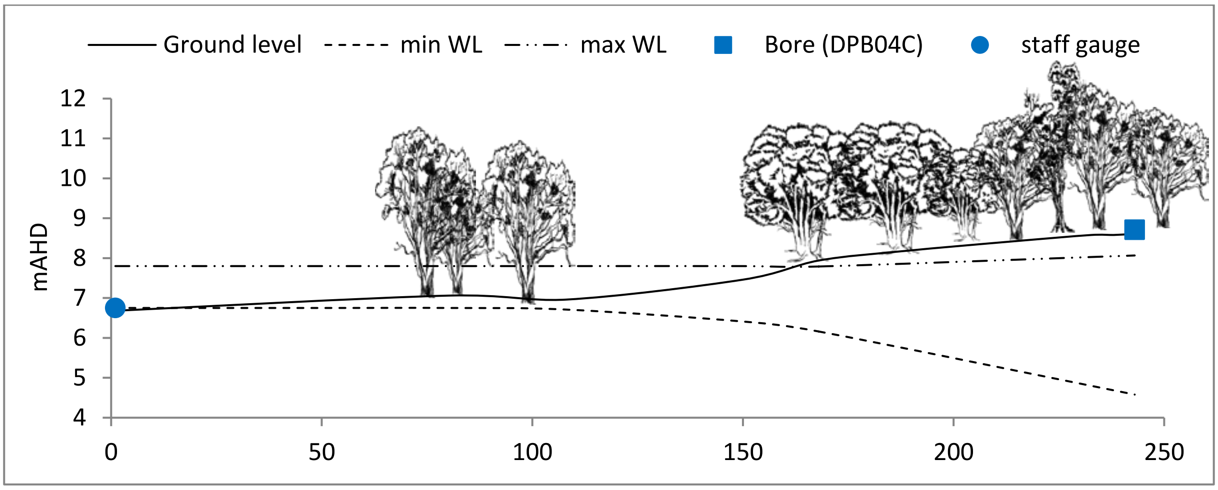


Figure 23 Water levels and vegetation distribution at the DPB04-1 site

The soil moisture probe set up near the bores showed a watertable near 2.0 mbgl and dry soil at 1.5 mbgl (Figure 24). Soil moisture at 0.3 and 1.2 mbgl responded to rainfall from November/December 2014 onwards (see rainfall graph in Appendix F), with deeper soils not responding until a major rainfall event in early January. At this time the watertable appears to rise to around 0.3 mbgl and stays high until late March, when it starts to fall to around 2.1 mbgl. The response in the watertable shown by the moisture probe is supported by a similar response in groundwater levels logged in bore DPB04C (Figure 24).

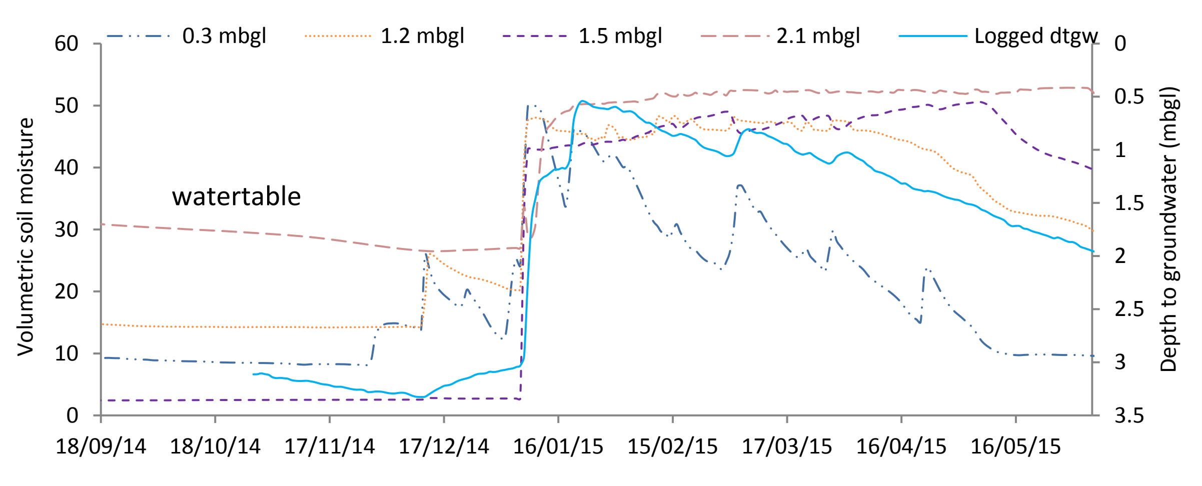


Figure 24 DPB04-1 soil moisture probe and groundwater logger results

Isotopic and soil moisture data from bore DBP04C suggest the *M. dealbata* and *C. bella* sampled furthest from the wetland but closest to the bore (Md-3, 4 and Cb-1), were most likely accessing groundwater from 4.0 mbgl (figures 25 and 26).

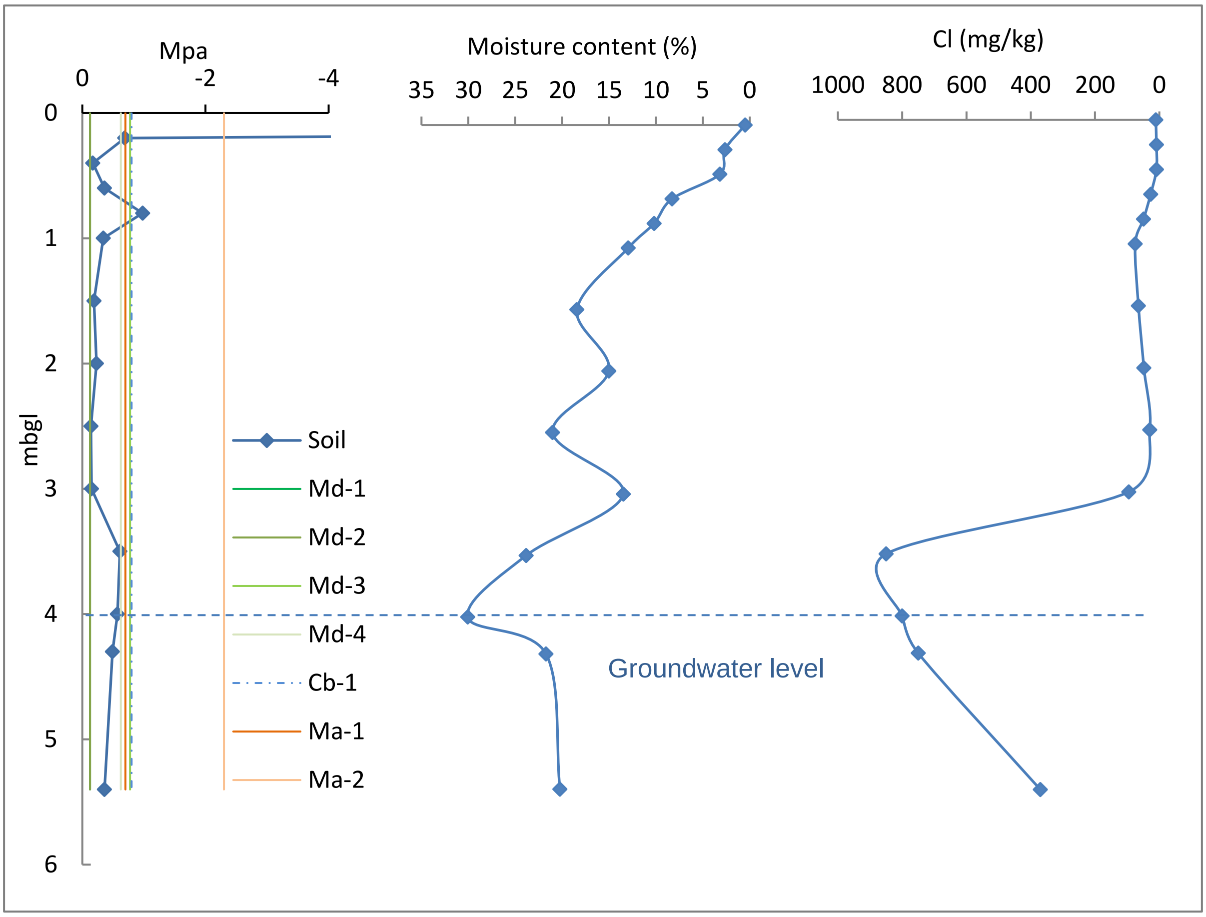


Figure 25 DPB04-1 – soil and shoot water potential, soil moisture content and soil chloride with depth

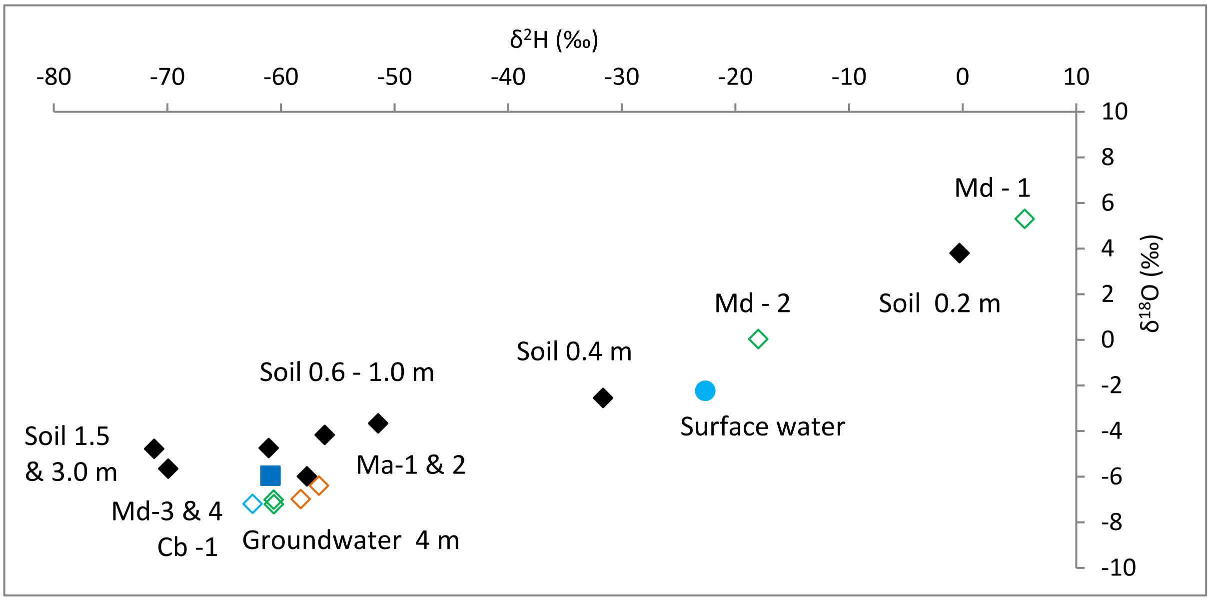


Figure 26 DPB04-1 – Deuterium and Oxygen-18 isotope signatures of trees and potential water sources

The two large *M. alsophila* on the wetland fringe (Ma-1, 2) were possibly accessing marginal quality water from the capillary fringe at 3.5 mbgl and/or groundwater. These individuals were also both less hydrated than others at the site (i.e. lowest shoot water potentials).

The *M. dealbata* in the wetland basin (Md-1, 2) appeared to be accessing very shallow groundwater or soil water (0.2 and 0.4 mbgl) that was isotopically very similar to the surface water still present in the wetland.

DPB04-2

Depths in DPB04-2 in April 2015 were 0.94 and 1.10 m at bores 1 and 2 respectively and the start of the transect was inundated to a depth of 0.5 m at the time of sampling.

Figure 27 shows the conceptual distribution of key species across an elevational gradient at DPB04-2. The vegetation plots occur between 40 and 80 m on the transect. Water levels experienced by the two overstorey species in May 2015 ranged from 3.0 mbgl to 0.25 m inundation for *M. dealbata* and 3.32 to 1.3 mbgl for *C. bella*.

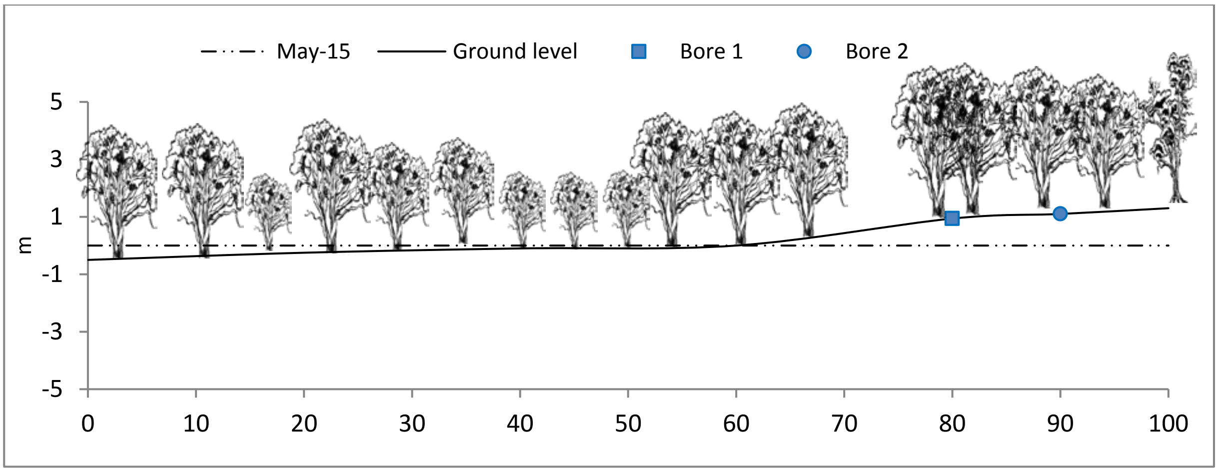


Figure 27 Water levels and vegetation distribution at the DPB04-2 site

The health of *M. dealbata* in all plots and a single *C. bella* in plot C was very good (Figure 10). The canopy of plots A and C were both open yet denser than plot B (Figure 11). However, there were 35 *M. dealbata* seedlings and one sapling recorded across plot B. Shoot water potential in May 2015 showed trees were well hydrated (Figure 13).

Is Oval wetland a groundwater-dependent ecosystem?

Results of the ecological investigation determined that the vegetation surrounding Oval wetland is dependent on groundwater, as well as surface water and soil moisture, depending on distance from the wetland basin.

Hydrographs from the wetland's western side (near DPB04-1) show similarities in the water levels of the two shallow bores (DPB04C and D), their responses to rainfall events and their seasonal fluctuations (Searle & Degens 2017). This contrasts with the response patterns of the two deeper bores (DPB04A and B). The salinities of the shallow bores are also similar and much more saline than the bores in the deeper aquifer. This suggests perching of the upper aquifer on the wetland’s western side – the area dominated by salt-tolerant *M. alsophila*.

As discussed earlier, large *M. dealbata* occur to the north and east of the wetland (DPB04-2), suggesting the availability of fresh, shallow groundwater. The AEM showed a layer of higher conductivity (saturated clay and/or increased salinity), extending under the wetland from the west and ‘pinching out’ to the east. This suggests the regional aquifer (Broome) is unconfined east of the wetland, and may be the source of water for the freshwater vegetation. The regional aquifer may also discharge into the wetland from the east, maintaining the small pool of relatively fresh water throughout the year (70–650 mg/L TDS) despite evaporation.

The unconfined area to the south and south-east (shown in the AEM as an area of low conductivity) corresponds to a poorly defined wash area. It is possible that overland flow is captured in the wetland, recharging the regional aquifer in this unconfined area. It is also possible that upward movement of fresher groundwater from the regional aquifer is occurring through the clay beds and into a shallow groundwater system. Further drilling on the wetland’s eastern side would be required to determine which of these alternatives is most likely.

In summary, Oval wetland’s western and northern sides are likely disconnected from the regional (Broome) aquifer with vegetation accessing shallow saline to brackish groundwater. However, there is a possible connection between shallow local groundwater and the Broome aquifer on the wetland’s eastern side (DPB04-2). Here, woodland of mature *M. dealbata/C. bella* occurs over fresher groundwater in sandier soils.

6.5 Flow Dam

Site description and methods

Flow Dam (Appendix F, Figure F4) is a constructed wetland. It was excavated decades ago to provide a permanent water source for livestock on Waterbank Station. The state government purchased the station in 1996 and largely de-stocked it, although feral cattle and horses still drink at the dam. As the name suggests, the wetland is associated with a drainage line, which drains surface water from higher areas in the east towards the coast, where water ponds at the base of steep sand dunes.

The vegetation in the lowest areas of the wetland is predominantly low woodland of *Melaleuca alsophila* (Figure 28). However, many of the mature individuals are in poor health, possibly from increasing periods of inundation. In higher areas there are open-woodlands of *M. dealbata* and *Lophostemon grandiflorus* (freshwater mangrove), consisting of individuals of varying ages. Away from the wetland edge *M. nervosa* is also common. The sedge *Schoenoplectus subulatus* was also noted.

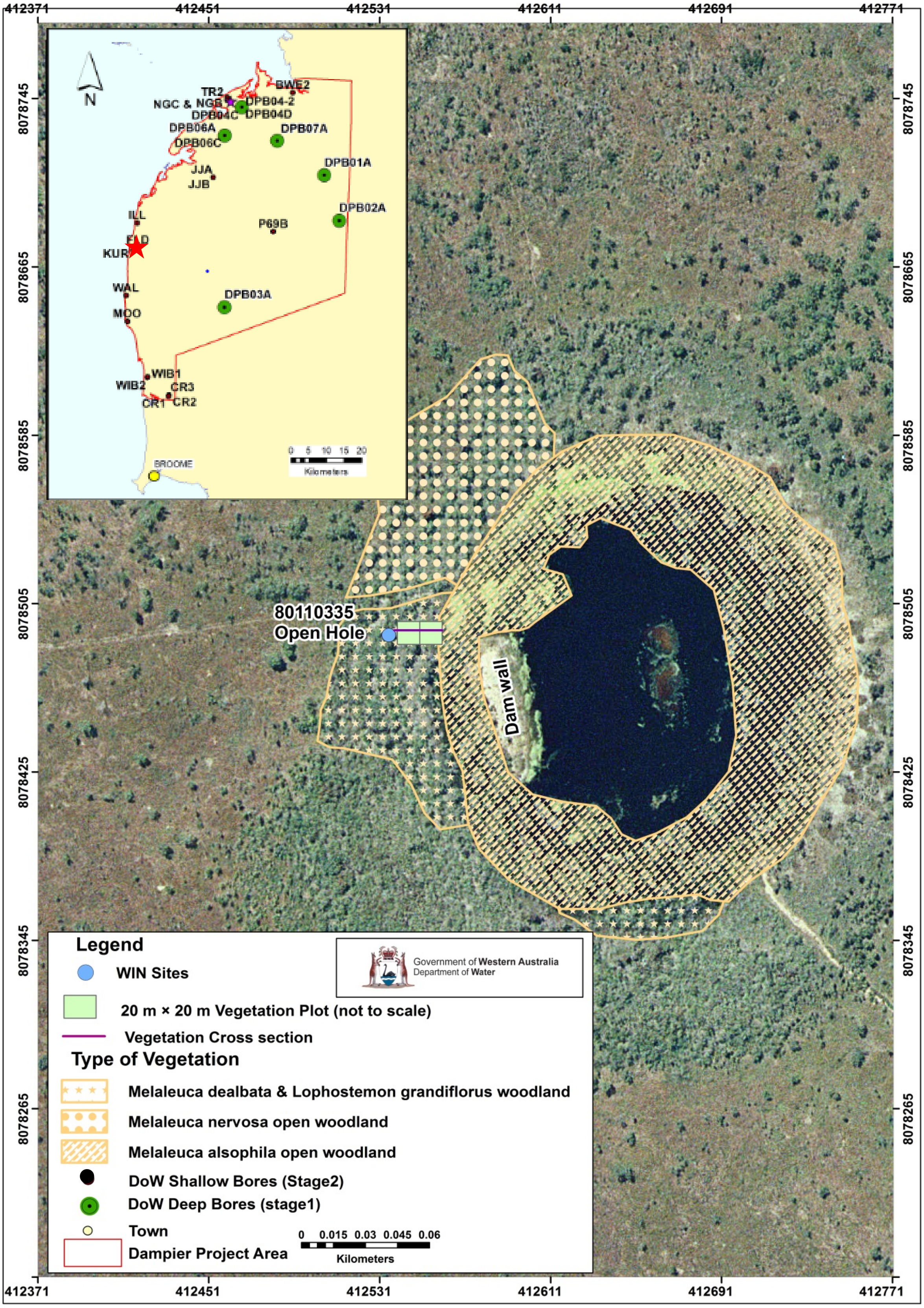


Figure 28 Flow Dam location, bores, vegetation and survey plot

The wetland itself supports various aquatic plants including *Nymphaea violacea* (water lily) and *Vallisneria nana* (narrow ribbonweed). Black swans, pelicans and various duck species were observed on the wetland and large fish, possibly *Chanos chanos* (milkfish), were seen jumping from the water.

A transect comprising two 20 x 20 m plots was set up in May 2014 on the wetland's western side to capture the transition from saltwater to freshwater species (Figure 28). A shallow piezometer was hand-augered to the watertable at this time (bore 1) and another in October 2014 (bore 2: 80110335) to collect samples for soil moisture and isotope analysis (Figure 28). We also sampled twigs, groundwater and surface water.

Results

Sandy clays were logged to 2.5 mbgl during hand augering, with hard lateritic nodules noted from 1.2 mbgl. This suggested wetting and drying in the soil profile for a long period of time. Groundwater was 1.2 mbgl in May 2014 and 2.2 mbgl in October 2014.

AEM results clearly show a shallow, 20 to 40 m thick, highly conductive (confining) layer in the area (Searle & Degens 2017). Flow Dam sits in a depression directly over an outcropping of this layer. It is possible that this represents the area that was excavated to capture water from the flow line. Subsurface flow follows a similar path with shallow groundwater occurring along the flow line. The confining layer runs further west to the Kurrukurugun riparian vegetation site (see Section **Error! Reference source not found.**) and also to the east. It is probably part of the regional confining layer newly described by Searle and Degens (2017), which extends to the north of the project area.

Figure 29 shows the conceptual distribution of key species across an elevational gradient. The vegetation plots occur between 10 and 50 m on the transect. Water levels for *L. grandiflorus* ranged from 3.5 mbgl (October 2014) to 0.65 mbgl (May 2014); *M. alsophila* from 3.85 mbgl to 0.3 m inundation; and *M. dealbata* from 4.44 to 0.45 mbgl (Figure 12). These were amongst the greatest depths to groundwater experienced by these species across the study area.

The canopy condition of the *M. dealbata, M. alsophila* and *L. grandiflorus* of the Flow Dam vegetation transect was rated as very good (Figure 10). There were eight *M. dealbata* seedlings and two saplings recorded in plot B with one *M. alsophila* and three *L. grandiflorus* saplings. The canopy of both plots was open, possibly due to being inundated for part of the year. There was a slight increase in canopy density at the end of the dry (Figure 11). However, there was a significant decline in shoot water potential – the lowest recorded for all three sampled species – suggesting trees were becoming water stressed (Figure 13).

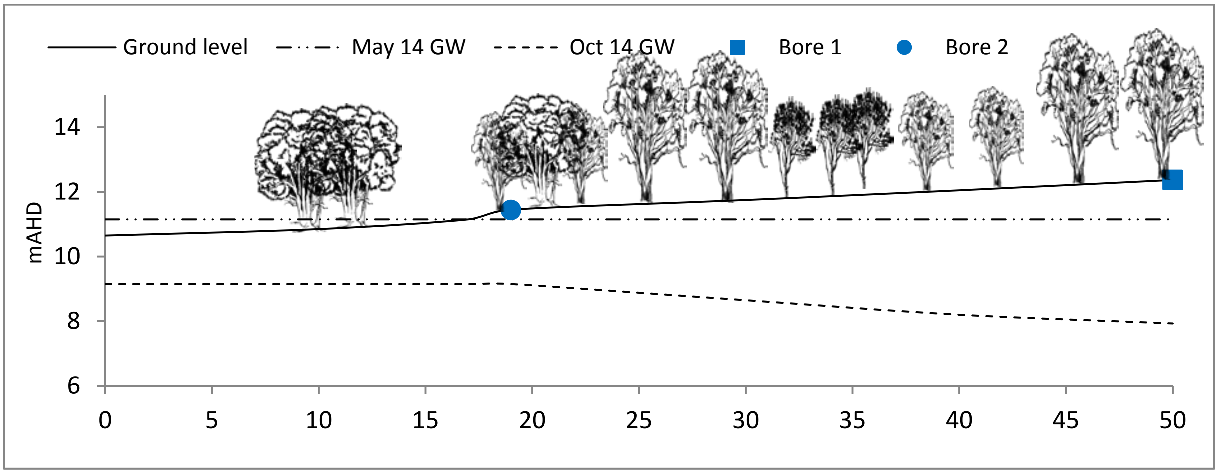


Figure 29 Water levels and vegetation distribution at the Flow Dam site

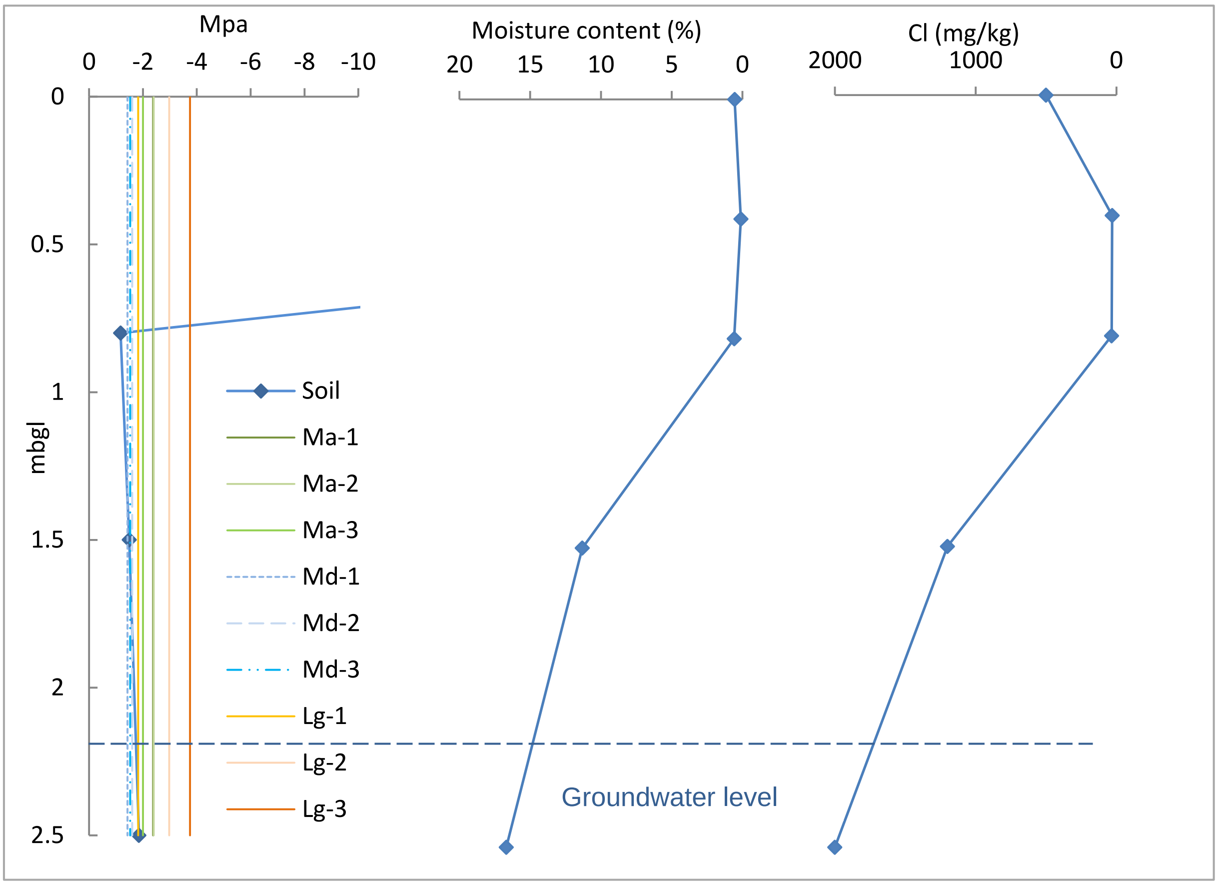


Figure 30 Flow Dam – soil and shoot water potential, soil moisture content and soil chloride with depth

Although canopies of *L. grandiflorus* were in good condition at the end of the wet (Figure 10), by the end of the dry soil moisture data show soils less than 1 mbgl were too dry for trees to access (Figure 30). Shoot and soil water potentials (Lg-1, 2, 3) suggest they were water stressed and probably had little if any access to water. Isotope data support this by showing tree signatures very different to water sources (Figure 31). Although the *M. alsophila* (Ma-1, 2, 3) are very close to the edge of the wetland they seem to use shallow groundwater in preference to surface water. The *M. dealbata* (Md-1, 2, 3) are likely to be using deeper groundwater.

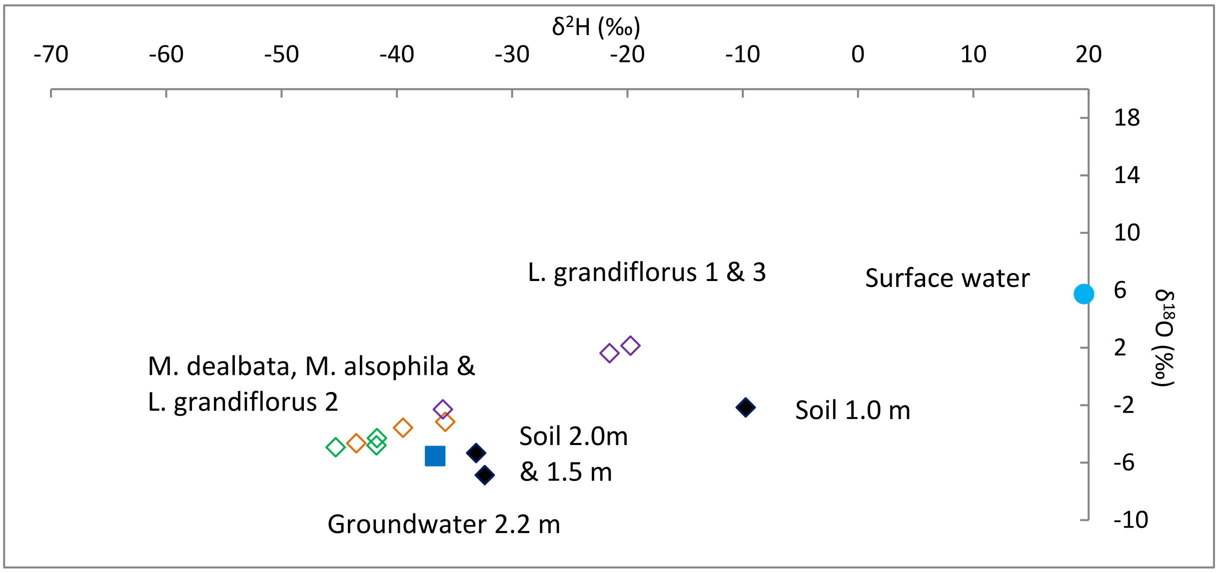


Figure 31 Flow Dam – Deuterium and Oxygen-18 isotope signatures of trees and potential water sources

Is Flow Dam a groundwater-dependent ecosystem?

Results of the ecological investigation showed that although trees sampled on Flow Dam's western side were using groundwater, they were becoming water stressed by the end of the dry season. This suggests there may be a limited supply of accessible water – possibly a shallow, localised watertable.

It is possible that the ponded water leaks under or through the dam and flows westward over the confining clay layer, creating a shallow local aquifer and supporting the wetland vegetation. It is unclear if there is further upward movement into the regional watertable and/or whether upward leakage is occurring, which would suggest connectivity with the Broome aquifer.

Wetland vegetation on Flow Dam's western side is accessing the limited water held up by the confining layer. It is not known if there is any connection with the underlying Broome aquifer.

6.6 Wibbijagun

Site description and methods

This large, shallow claypan (Appendix F, Figure F5) makes up the northern section of the Willie Creek wetlands, a DIWA listed system (Environment Australia 2001). A PEC-listed grassland occurs in the area. Wibbijagun is semi-permanent: filling during the wet and drying gradually. However, there is a small area in the centre of the wetland that appears to remain damp throughout the year.

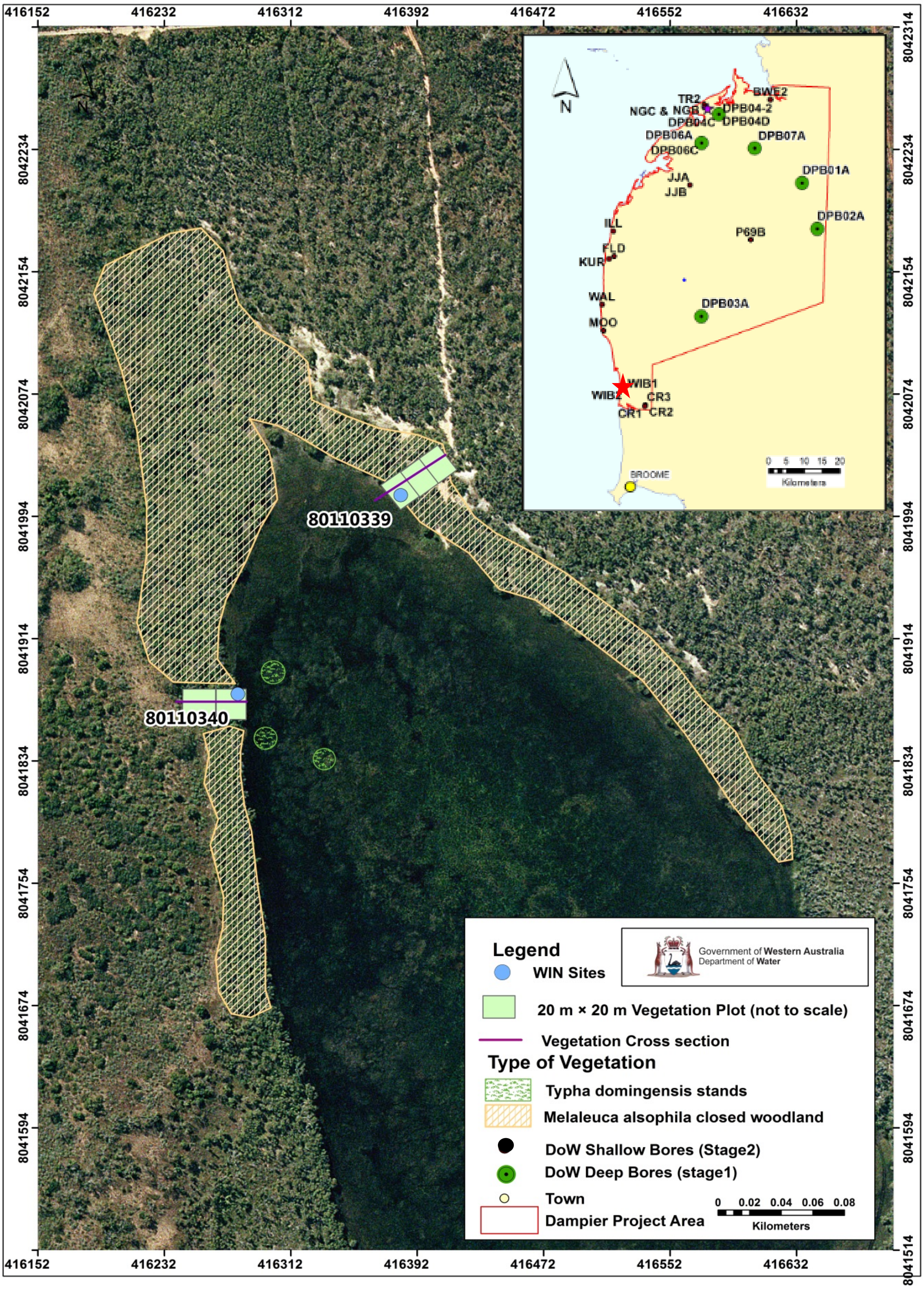


Figure 32 Wibbijagun location, bores, vegetation and survey plots

The dominant fringing vegetation is open forest of *Melaleuca alsophila,* which extends along most of the Willie Creek wetland system (Figure 32). However, there is an area of freshwater species forming mixed woodland of *M. dealbata* and *M. alsophila* with *Corymbia bella* on the north-west corner of Wibbijagun. There are also discrete patches of *Typha domingensis* in this area. The wetland basin itself supports dense *Schoenoplectus subulatus*, which does not occur across the broader Willie Creek system.

Two transects were set up at Wibbijagun, one on the lake's northern end and one on its north-western corner (Figure 32).

The northern transect, comprising three 20 x 20 m plots, was set up in May 2014 to capture the range of saltwater-tolerant *M. alsophila*. A shallow piezometer (80110339) was hand-augered to the watertable at this time and another in October 2014 to collect intact soil cores for soil moisture and isotope analysis. Twig samples were also collected.

A single 20 x 20 m plot was established in June 2014 in the north-west corner to capture the area of freshwater species. Some additional trees were also sampled beyond the plot (called plot B). A shallow piezometer (80110340) was hand-augered to the watertable in June 2014 and another in October 2014 to collect intact soil cores for soil moisture and isotope analysis. Twig samples were also collected.

A shallow bore (Don's: 80110237) about 3.8 km north of the site was sampled for a broad range of parameters during the hydrogeological investigation. This included CFCs and Carbon-14 (^{14}C) used to date groundwater and interpret recharge, and isotopes (Deuterium and Oxygen-18).

Results

At the northern site depth to groundwater ranged from 0.91 mbgl in May 2014 to 2.5 mbgl in October 2014. In the north-west depth ranged from 1.07 mbgl in June 2014 to 2.5 mbgl in October 2014 (Figure 12). Groundwater was fresh at both sites.

Figure 32 shows the conceptual distribution of key species across the wetland. The northern vegetation plots run from 0 and 60 m on the transect; the north-western plot from 200 to 220 m.

Wibbijagun north (WIB1)

In the north, water levels for *M. alsophila* ranged from 0.94 mbgl (May 2014) to 2.6 mbgl (October 2014) (Figure 12).

The canopy condition of *M. alsophila* ranged from good (plot A) to very good (plots B and C) (Figure 10). The canopy was very open in plot A, as the wetland half of the plot was open sedgeland. Plots B and C had an open canopy (Figure 11) however, 168 *M. alsophila* saplings were recorded across the two plots. Shoot water potential declined slightly over the dry season, but was very similar to values recorded for *M. alsophila* at other sites (Figure 13).

Soil moisture, chloride and water potential data show soils less than 1.5 mbgl were possibly too salty and too dry for trees to access on the northern plots (Ma-1, 2, 3 in

Figure 34). Isotopes suggest that ‘fresh’ soil moisture from around 2.4 mbgl was being used in preference to groundwater and shallower, saltier soils (Figure 35). However, regional groundwater was also similar in composition.

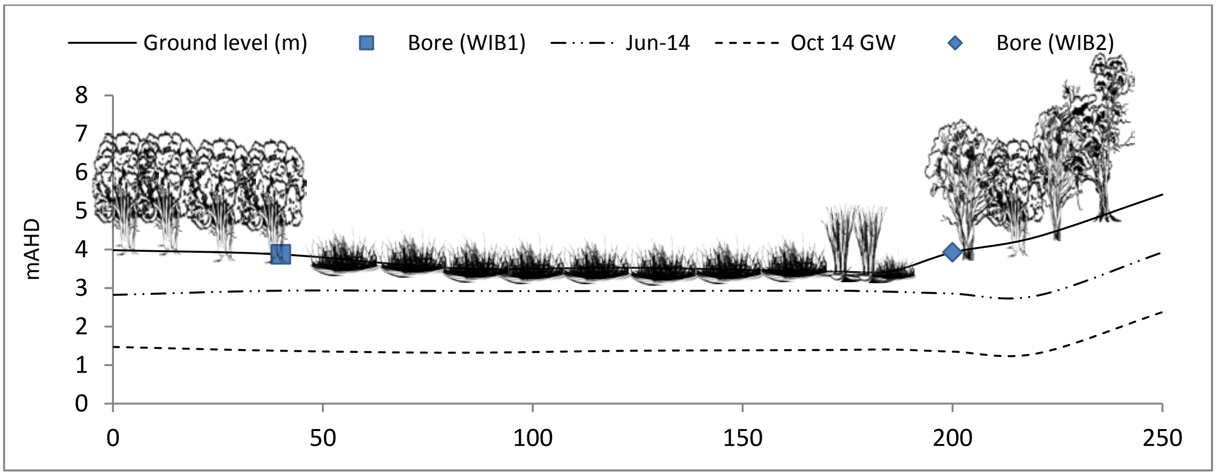


Figure 33 Water levels and vegetation distribution at Wibbijagun north (left) and west (right) and across the wetland basin

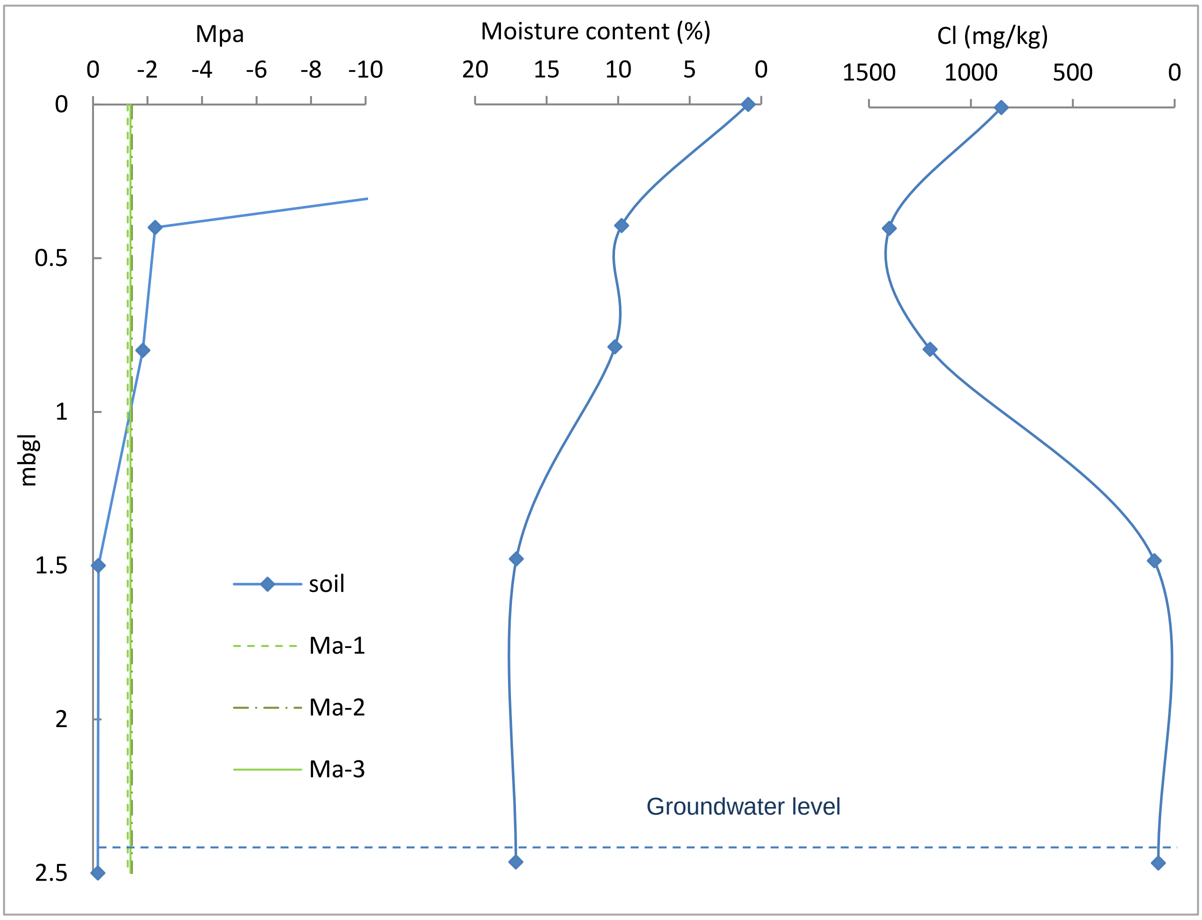


Figure 34 Wibbijagun north – soil and shoot water potential, soil moisture content and soil chloride with depth

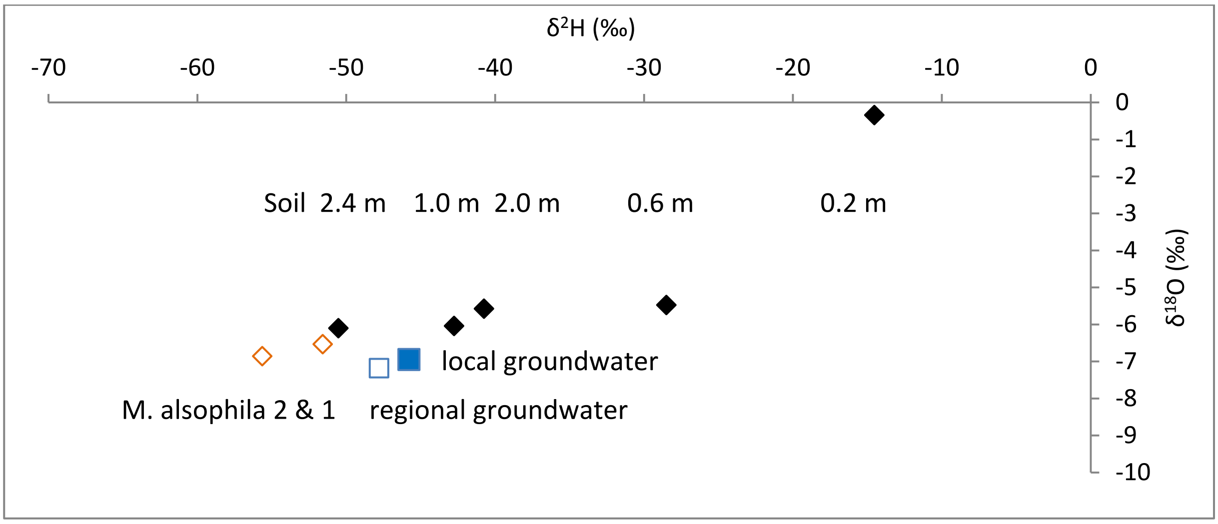


Figure 35 Wibbijagun north – Deuterium and Oxygen-18 isotope signatures of trees and potential water sources

Wibbijagun north-west (WIB2)

The canopy condition of the dominant overstorey species of the north-west transect was good (plot A) to very good (plot B) (Figure 10). Six *M. dealbata* and *C. bella* saplings and nine *M. alsophila* saplings were recorded. Only plot A was assessed for canopy density, with an increase recorded at the end of the dry (Figure 11). However, there was a small decline in shoot water potential across the same time period (Figure 13).

M. alsophila depths ranged from 3.0 mbgl (October 2014) to 1.07 mbgl (June 2014); *C. bella* from 3.05 to 1.5 mbgl; and *M. dealbata* from 3.05 to 1.07 mbgl (Figure 12).

Soil moisture, soil chloride, water potential and isotope data for the north-west plot clearly suggest *M. dealbata* (Md-1, 2, 3) are accessing soil moisture from 1.0 mbgl (figures 36 and 37). It is less clear from where the *M. alsophila* and *C. bella* are accessing water. Isotope data suggest *M. alsophila* (Ma-1, 2) are using soil water from 2.4 mbgl and/or groundwater. As these sources are less fresh, this may explain why these trees are slightly water stressed. *C. bella* (Cb-1, 2) may be using deeper, regional groundwater as they are well hydrated and have different isotopic signatures to all sampled soil moisture and groundwater.

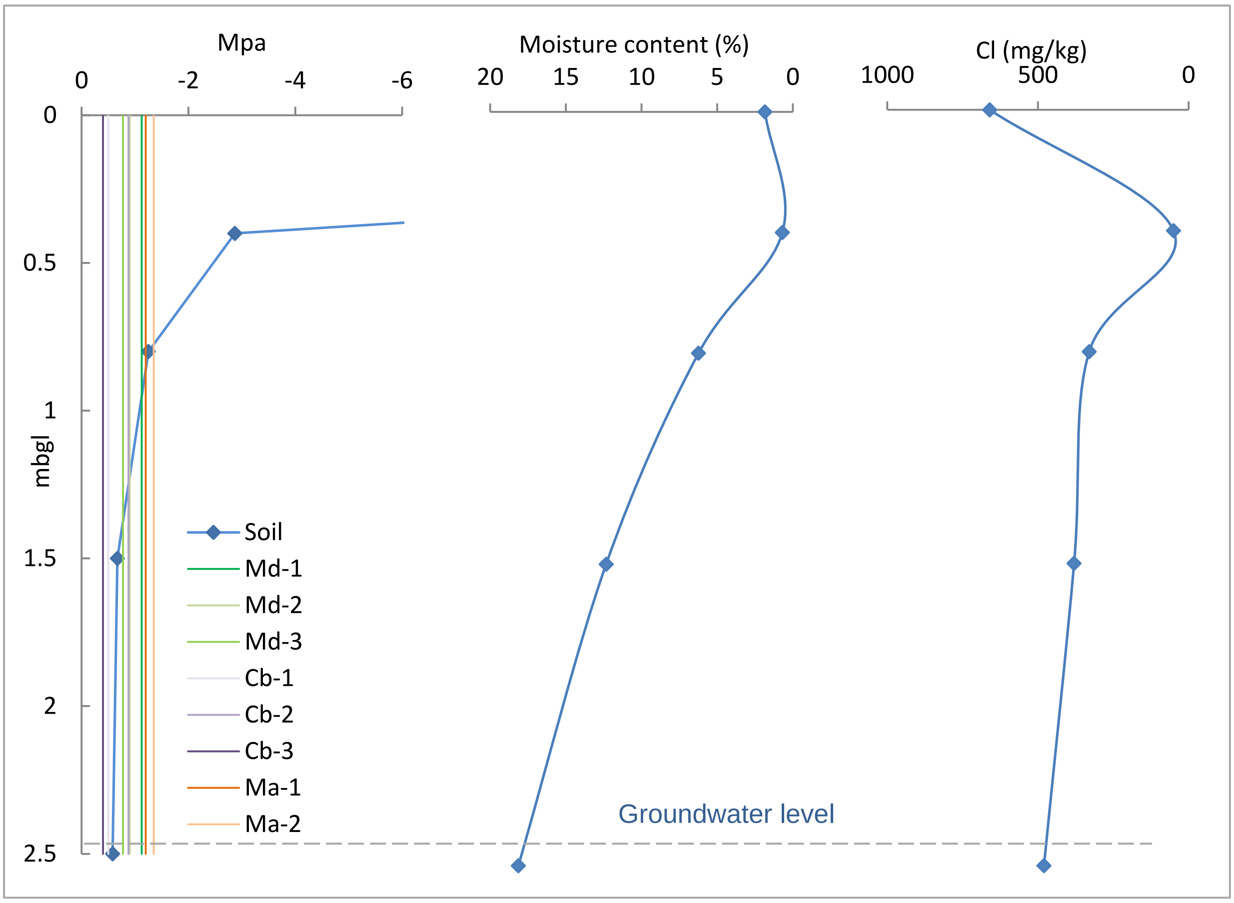


Figure 36 Wibbijagun north-west – soil and shoot water potential, soil moisture content and soil chloride with depth

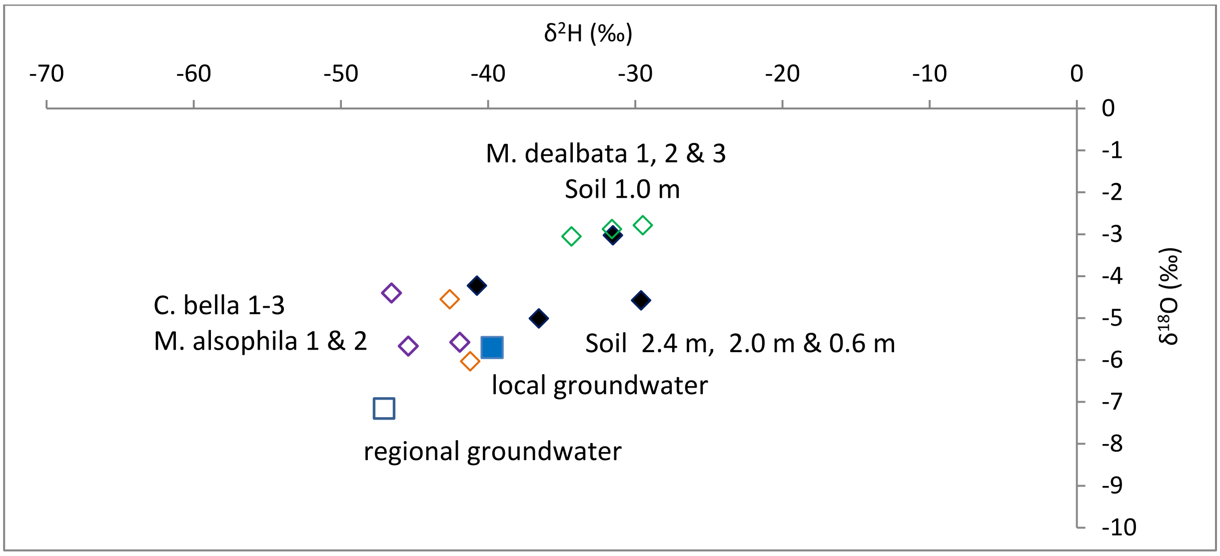


Figure 37 Wibbijagun north-west – Deuterium and Oxygen-18 isotope signatures of trees and potential water sources

The hydrogeological investigation showed that groundwater in nearby Don's bore did not contain detectable amounts of CFCs, so was recharged before the 1940s when CFCs were introduced. Chloride mass balance results support this. This means the groundwater is more than 70 years old and probably from the Broome Sandstone aquifer and not recent rainfall.

Is Wibbijagun a groundwater-dependent ecosystem?

Soil moisture, chloride and water potential data suggest most of the wetland trees are using fresh water sitting under a saltwater lens. Hydrogeological investigation results suggest it is likely that regional groundwater is interacting with the wetland (Searle & Degens 2017). This is described in more detail in Section 6.15.

6.7 Illelang (Spring Creek) and Watermelon Dam

Site description and methods

Illelang (Appendix F, Figure F6) is about 85 km north of Broome, partially within Coloumb Point Nature Reserve. It is a perennial system flowing 30 km from a series of springs at its headwaters to its mouth at Carnot Bay.

Watermelon Dam, which cannot be accessed by road, is one of the springs at the headwaters of the creek. Similar to Flow Dam (see Section 6.5), the spring was excavated to provide a permanent water source for livestock when Waterbank Station was still operating.

The lower reach of Illelang is tidal dominated and fringed by *Melaleuca alsophila.* Moving upstream the water freshens and large *M. dealbata, Corymbia bella* and *Pandanus spiralis* become dominant in the sandy alluvial soils. A shallow billabong about 800 m from the coast supports *Typha domingensis.* Further upstream the creek narrows and in places becomes deeply incised. Isolated *P. spiralis* and *M. viridiflora* and/or *M. nervosa* occur in sandy soils along the creek's upper reaches.

Watermelon Dam is fringed by a dense band of *Cyperus* sp. with an open forest of *M. dealbata* saplings (38 saplings and 29 seedlings recorded in plot A) (Appendix F Figure F6). The dam itself supports aquatic plants including *Triglochin* sp. Moving away from the water's edge, the size and age of the *M. dealbata* increases, until very large (up to 15 m tall), very old individuals occur between 60 and 80 m from the wetland. These are the largest trees of this species observed in the study area. Large *Pandanus* sp. and a single large *Terminalia* sp. also occur in this area.

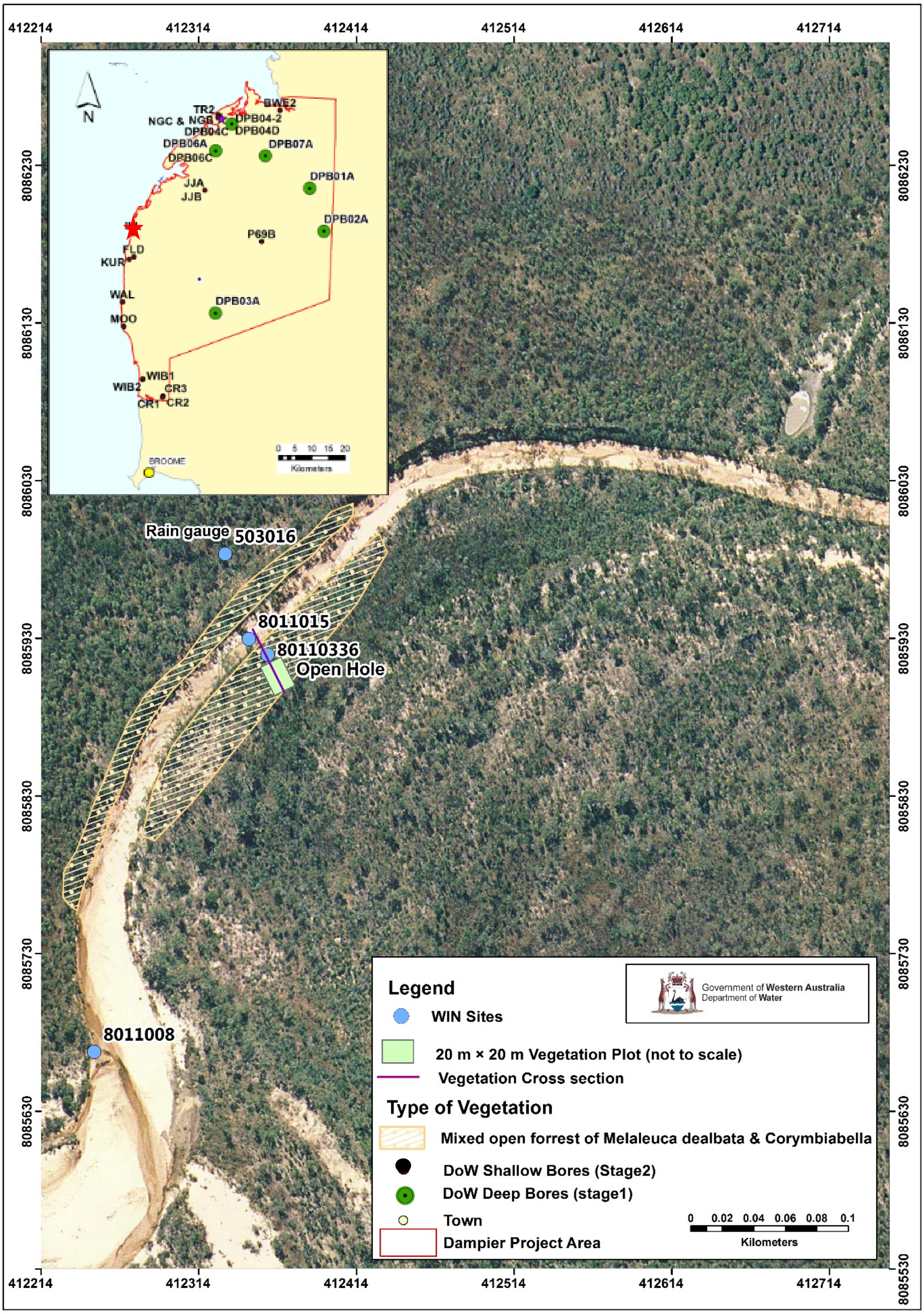


Figure 38 Illelang location, bores, vegetation and survey plots

A 30 x 30 m plot was established on Illelang about 1.2 km upstream from the coast in May 2014 in an area of freshwater vegetation (Figure 38). A shallow bore (80110336) was hand-augered on the riverbank in May 2014 to determine the depth to groundwater and another in October 2014 to collect intact soil cores for soil moisture and isotope analysis. Rainfall, river water and twig samples were also collected. A surface water logger (8011015) was installed in the creek in January 2014.

A transect was also established at Watermelon Dam in June 2014. The transect consisted of three 20 x 20 m plots and was set up on the wetland’s northern side to capture the range of freshwater species. We did not complete the full ecophysiological sampling or take soil and groundwater samples due to time constraints and the presence of a large feral bull. However, surface water samples were taken and a logger installed in the wetland.

In August 2015, multiple surface water samples (baseflow) were collected along the length of the Illelang from Watermelon Dam to the coast to identify where groundwater discharged into the creek and determine its likely source (Figure 39). No significant rainfall events had occurred since March 2015, suggesting any flow during the time of sampling was groundwater fed (Rothery 2016). Samples were analysed for ^{18}O and ^{2}H isotopes, Radon-222 and major ions, and some also for Carbon-14. Streamflow rates were also measured.

Results

Water-level loggers at either end of the stream show that Illelang is perennial and responds rapidly (within one day) to rainfall events across the catchment. Radon-222 activities analysed from baseflow samples taken along the creekline (Rothery 2016; Searle & Degens 2017) indicated the stream had groundwater inputs for at least 8 km (9–17 km downstream from Watermelon Dam) (Figure 39). Other environmental tracers and water quality data also demonstrated the influence of groundwater inflow.

Depth to groundwater near the Illelang piezometer became shallower over the dry season. This was possibly in response to groundwater that recharged higher in the catchment during the wet season moving towards the coast over time.

Depths ranged from 1.95 mbgl in May 2014 to 1.65 mbgl in October 2014. Water quality at Watermelon Dam was very fresh (90 mg/L) in June 2014. Logged water depths from June 2014 to August 2015 ranged from 1.18 m in December 2014 to 1.5 m in March 2015 (Figure 40). Although the response to rainfall events was fairly rapid, levels dropped quickly as water overflowed into the creek. Despite the overflow, the pool maintained water for the duration of the assessment at a depth of about 1.2 m.

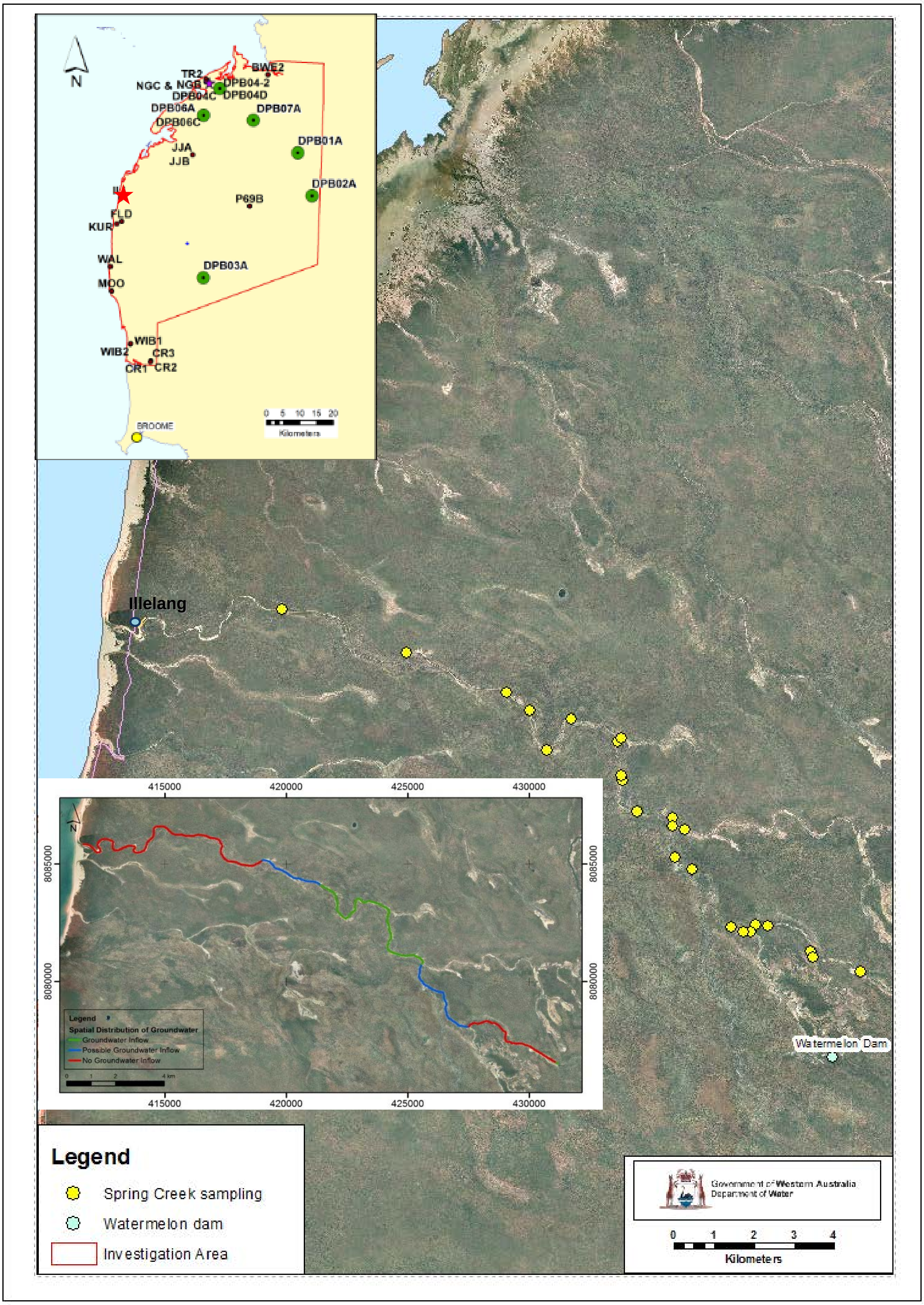


Figure 39 *Watermelon Dam to Illelang – ecological and longitudinal sampling sites and likelihood of groundwater inputs (insert)*

Dense *M. dealbata* of varying ages, including 76 saplings and two seedlings, fringed Illelang and dominated most of the plot, with a single *C. bella* and a small stand of *P. spiralis* upslope from the creek. The canopy condition of both tree species was considered very good (Figure 10). A fire in September resulted in a decrease in canopy cover from open to very open during the dry period (Figure 11). Although shoot water potential of *M. dealbata* also decreased over this time, the species remained among the most hydrated of all sampled trees at the end of the dry (Figure 13). The canopy condition in the three Watermelon Dam plots ranged from good in plot A to very good in plots B and C.

Figure 39 shows the conceptual distribution of key species at the Illelang site, moving upslope from the creekline. The plot runs from 10 to 40 m on the transect. Water levels for *M. dealbata* ranged from 3.52 mbgl (October 2014) to 0.8 mbgl (June 2014) and the single *C. bella* from 1.0 to 0.8 mbgl (Figure 12).

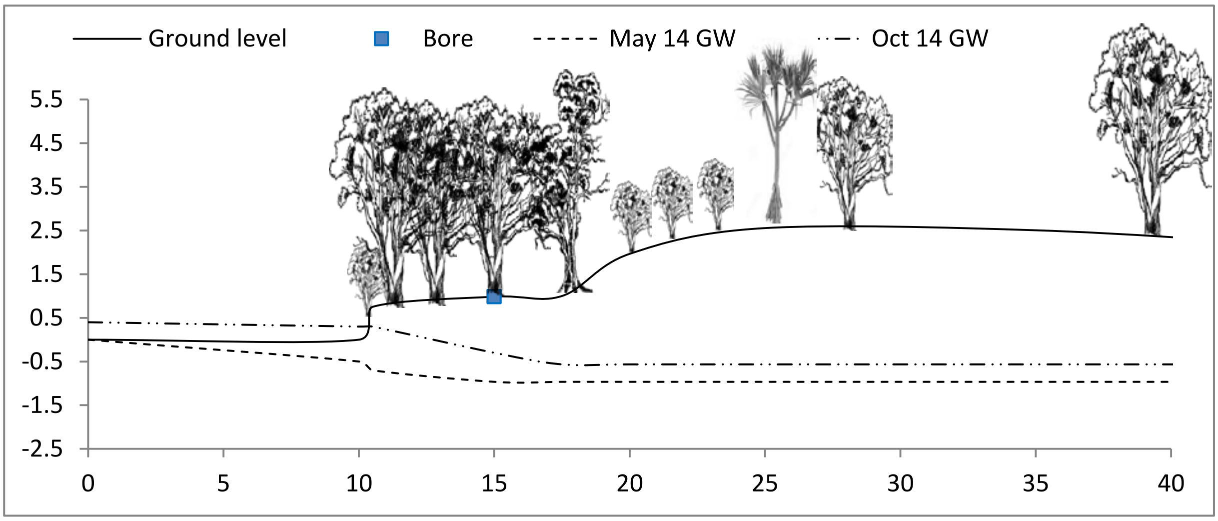


Figure 40 Water levels and vegetation distribution at the Illelang site

Soil chloride, soil moisture and isotopic data from the Illelang plot did not clearly indicate which water source the *M. dealbata* is accessing on the creekline (Md-1, 2) (figures 41 and 42). Nevertheless isotopic signatures of the groundwater-fed pools along Illelang (marked in green on map insert, Figure 39) were generally closer to those of the trees than local soils.

The isotopic signature of the *M. dealbata* sampled higher on the bank (Md-3) was very similar to surface water at Watermelon Dam (Figure 42). This suggests trees away from the creek may be using deeper groundwater, as the isotopic signatures are similar to the regional groundwater (expressing at the surface at Watermelon Dam). Further support for the trees' use of groundwater lies in the fact that they remain well hydrated throughout the year when soil moisture is lower.

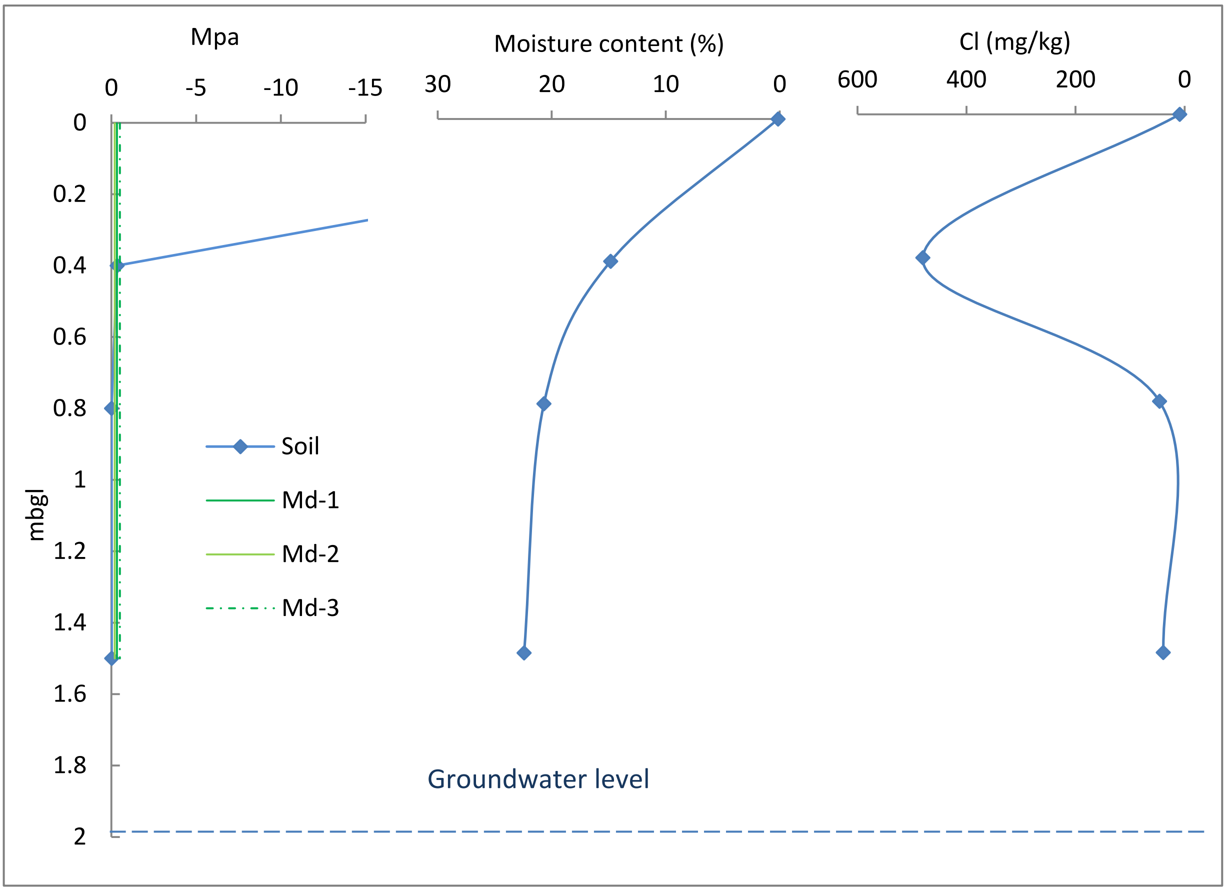


Figure 41 *Illelang – soil and shoot water potential, soil moisture content and soil chloride with depth*

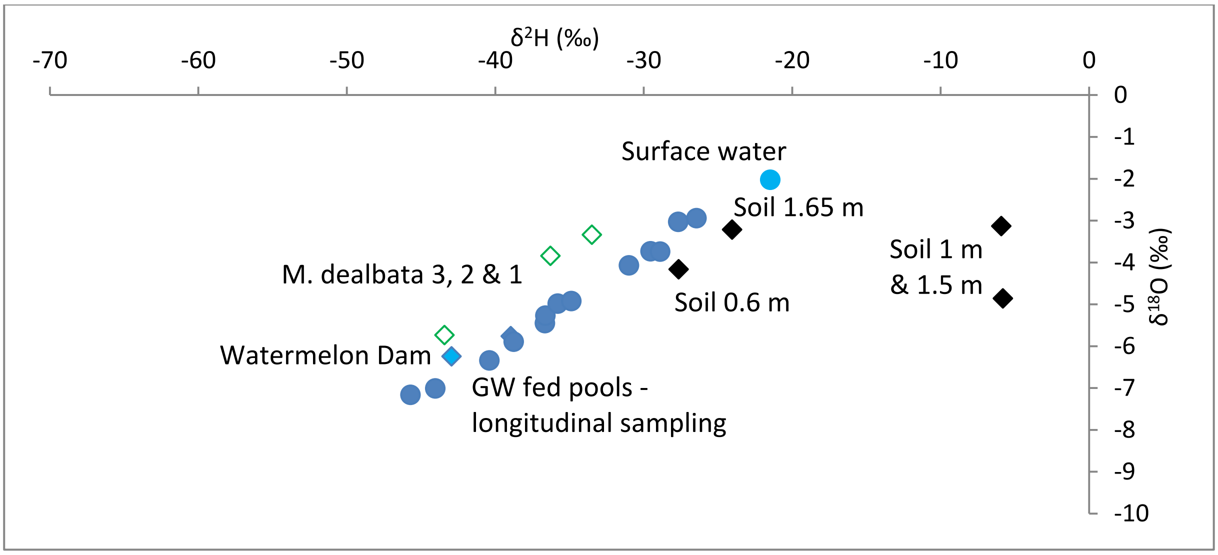


Figure 42 *Illelang – Deuterium and Oxygen-18 isotope signatures of trees and potential water sources (Illelang – Watermelon Dam)*

Are Illelang and Watermelon Dam groundwater-dependent ecosystems?

At the time of sampling, Illelang was dependent on groundwater discharge to maintain streamflow and support its ecosystems. Environmental tracers showed groundwater inflow at the headwaters of Illelang into Watermelon Dam and into an 8 km section of the stream (Rothery 2016).

Although the Illelang vegetation plot was downstream of the inflow zone, the permanent flows recorded throughout the study and the condition of the vegetation indicates water is being derived from groundwater inputs upstream.

The location of Watermelon Dam at the head of Illelang, known to be spring-fed (Rothery 2016), combined with the permanence of the pool and the age and condition of the fringing riparian trees, suggest that the spring and surrounding vegetation are groundwater fed.

Rothery (2016) considered the groundwater component of Illelang is most likely from the underlying unconfined Broome aquifer. This was inferred by the geological interpretation and the regional geophysical AEM survey (Searle & Degens 2017).

6.8 Bindingangun (Yellow River)

Site description and methods

Bindingangun (Appendix F, Figure F7) is located about 3 km south of Illelang in the Coloumb Point Nature Reserve. The river has a main channel of 15 to 25 km in length, draining the area between the coast and the inland part of the Illelang catchment. The non-Aboriginal name derives from yellow soils formed by the merging of pindan and yellow muddy soils, most likely formed from iron oxidisation (Cedat & Duprat 2007).

Bindingangun seems to function the same as Illelang, originating as a series of springs some kilometres upstream. The lower reach of the river is tidal dominated and is fringed by dense stands of *Melaleuca alsophila.* Moving upstream the river narrows to a creek and the water freshens. *M. dealbata, Corymbia bella* and *Pandanus spiralis* with *Xyris complanata* (sedge) become increasingly dominant with distance from the sea.

A 25 x 30 m plot was established approximately 1 km from the coast in June 2014 to capture the transition from salt to freshwater vegetation species (Figure 43). A shallow piezometer (80110337) was hand-augered on the riverbank in June 2014 to determine the depth to groundwater and another in October 2014 to collect intact soil cores for soil moisture and isotope analysis. Groundwater, river water and twig samples were also collected.

A surface water logger (801102) was installed in the river in December 2014 and surface water sampled on two occasions.

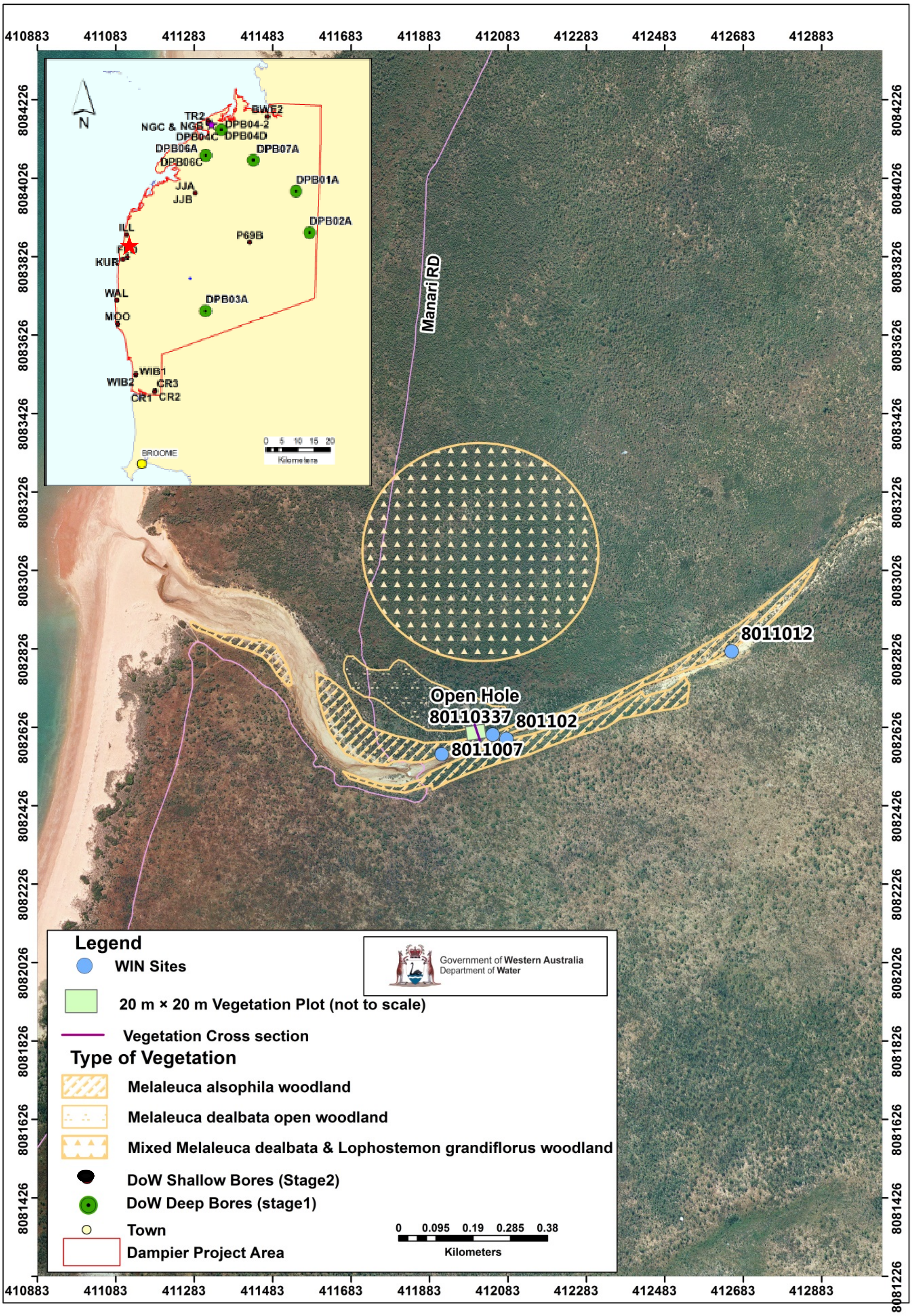


Figure 43 Bindingangun location, bores, vegetation and survey plot

Results

The surface water logger showed discharge to the coast was intermittent during the study period and often ceased early in the dry season. On one of the two occasions the river water was sampled, Bindingangun was five times more saline than Illelang (Searle & Degens 2017).

M. alsophila fringes the creekline and dominates the lower-lying area of the plot, with a small number of *M. dealbata* of various ages occurring upslope. The canopy condition of both species was considered very good (Figure 10). There was some increase in canopy cover during the dry period, although the canopy was still considered open (Figure 11). The *M. dealbata* in the plot remained well hydrated throughout the year (Figure 13). Twenty-five *M. alsophila* and 12 *M. dealbata* saplings were recorded on the plot.

Depth to groundwater at the piezometer (bore 1) was 1.4 mbgl in June 2014 and 2.20 mbgl in October. Figure 44 shows the conceptual distribution and water-level ranges of key species running upslope from the creekline. The vegetation plot runs from 10 to 40 m on the transect. Water levels for *M. alsophila* ranged from 3.25 mbgl (October 2014) to 1.4 mbgl (June 2014) and *M. dealbata* from 3.25 to 2.20 mbgl (Figure 12).

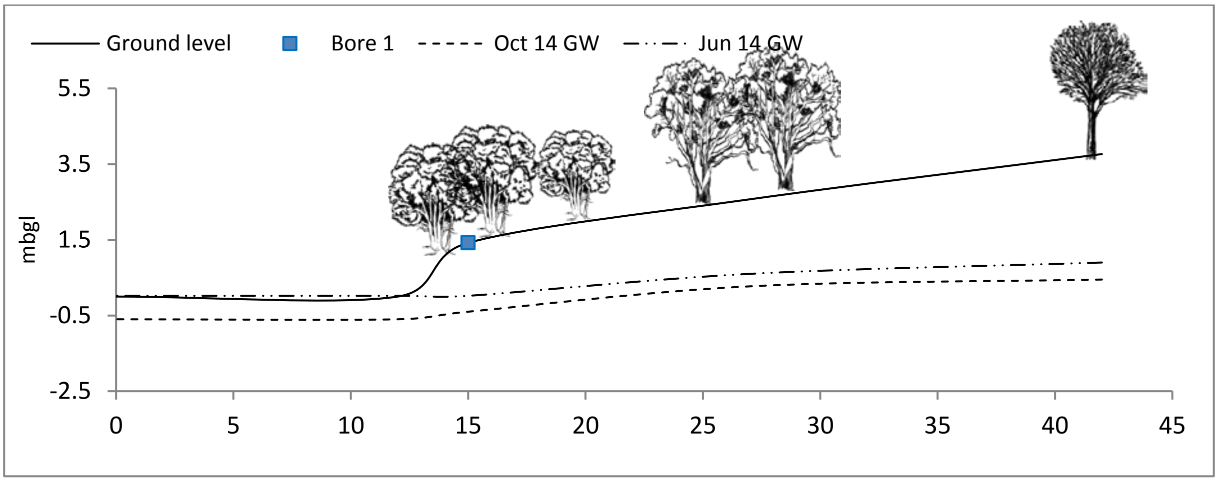


Figure 44 Water levels and vegetation distribution at the Bindingangun site

Soils less than 1 m below the surface were dry (Figure 45) and the isotopic signatures of soil from 2.0 m mbgl and surface water were dissimilar to that of the trees (Figure 46). However, the isotopic signatures of the *M. dealbata* (Md-3) upslope of the creek were similar to those of the regional groundwater, suggesting they were accessing deeper groundwater.

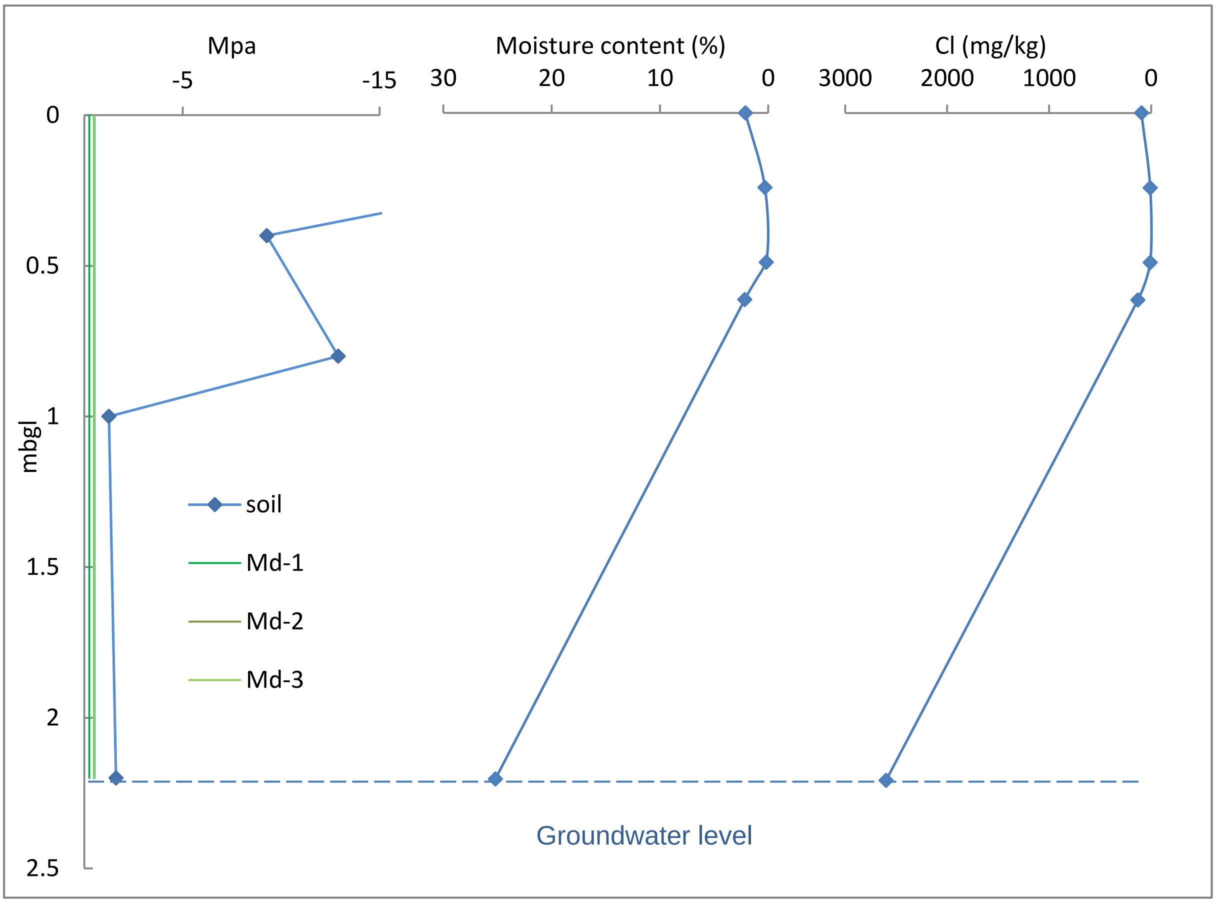


Figure 45 *Bindingangun – soil and shoot water potential, soil moisture content and soil chloride with depth*

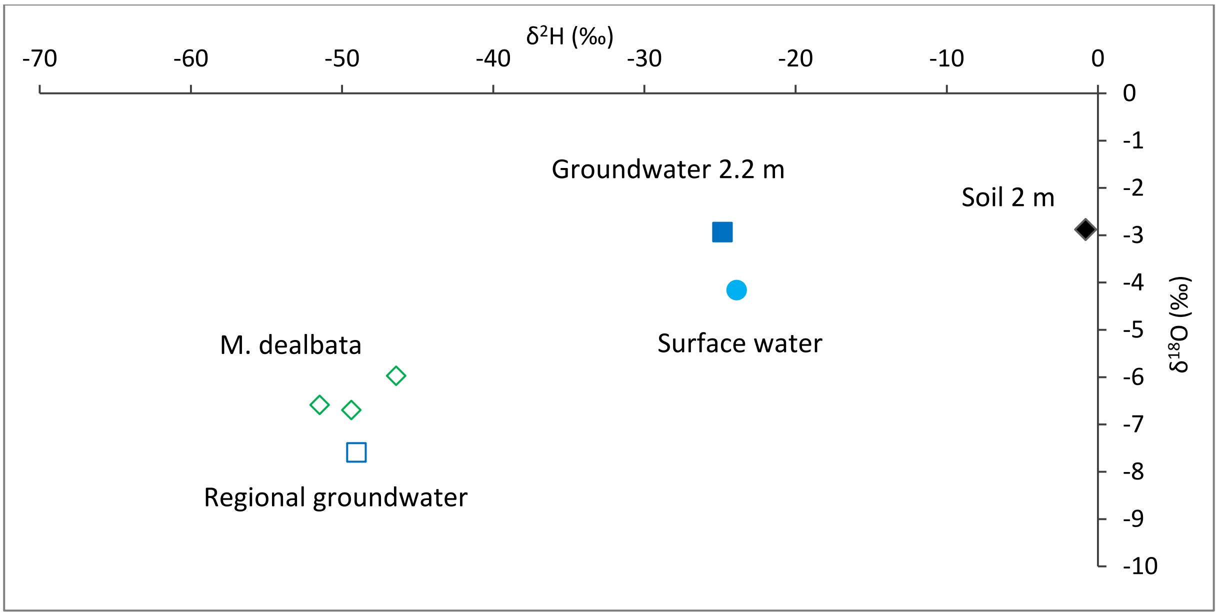


Figure 46 *Bindingangun – Deuterium and Oxygen-18 isotope signatures of trees and potential water sources*

Is Bindingangun a groundwater-dependent ecosystem?

The good health and level of hydration of the sampled *M. dealbata* supports their use of groundwater. Although the study site supported a limited number of *M. dealbata*, their increasing density and presence of other freshwater species (*P. spiralis* and *C. bella*) with distance along the river suggests increased groundwater input upstream.

It is likely that groundwater discharge to Bindingangun occurs some distance inland of the mouth and probably occurs in a distinct zone near the head of the main channel. Notably, this zone is less than 2 km west of the main discharge zone in Illelang (Searle & Degens 2017).

Bindingangun and associated vegetation are therefore considered dependent on groundwater from the regional Broome Sandstone aquifer.

6.9 Jabirr Jabirr

Site description and methods

Jabirr Jabirr (Appendix F, Figure F8) is an Aboriginal community located south-east of Carnot Bay, 85 km north of Broome and 40 km south-west of Beagle Bay. The community sits adjacent to a permanent, incised creek that is likely to be spring fed in much the same way as Bindingangun and Illelang. Within 100 m of the community is a permanent pool, which supports a population of unidentified native fish. Permanent yet less defined drainage lines occur upstream of the pool.

The narrow band of vegetation fringing the creek is generally dominated by *Melaleuca alsophila*, although closer to the pool *M. nervosa* become dominant with *Pandanus spiralis* (Figure 47). *M. nervosa* also make up the open overstorey of the drainage lines.

We did not establish a transect at Jabirr Jabirr; however, shoot water potential and isotope sampling was undertaken on the fringing *M. alsophila* and *M. nervosa*.

A shallow bore (JJB, 80110244) was installed on the creek’s south side in October 2014. A sonic rig was used so intact soil cores could be sampled for stable isotopes. Dew and twig samples were also collected for isotope analysis. Surface water was sampled on numerous occasions for isotopes, Radon-222 and other parameters.

Results

During the life of the project water levels at the bore ranged from 0.99 mbgl in April 2015 to 1.76 mbgl in April 2016.

Drilling showed a thin aquifer about 12 m thick with a low-permeability clay layer below extending to the maximum depth of the drill rig (41 m). The AEM data shows this clay layer is a continuation of a previously unidentified confining layer that extends across much of the central west of the study area (Searle & Degens 2017).

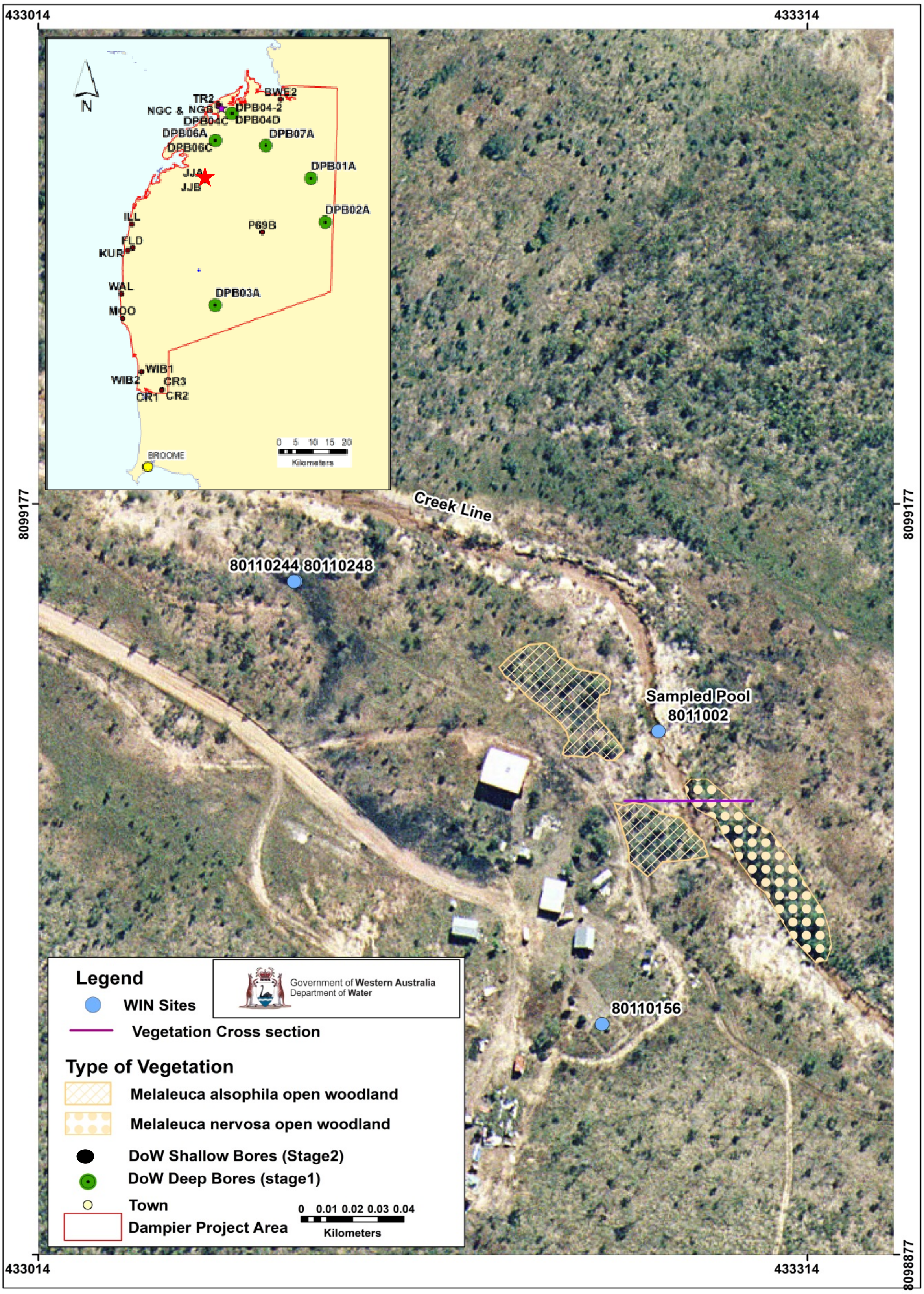


Figure 47 Jabirr Jabirr location, bores, vegetation and survey site

Radon-222 activities in the creek were the highest of all measured surface waters in the study area, indicating significant groundwater input throughout the dry season (Searle & Degens 2017). It is noteworthy that the creek was still flowing into the pool in May 2016, following one of the driest wet seasons in many years (rainfall of 240 mm compared with the long-term average of 480 mm).

Figure 48 shows the conceptual distribution of key species across the creekline. Water levels for *M. alsophila* ranged from 1.62 mbgl (December 2014) to 0.49 mbgl (May 2015) and *M. nervosa* from 1.54 to 0.49 mbgl (Figure 12).

The canopy condition of both tree species fringing the pool was considered very good (Figure 10). Although shoot water potential of both decreased during the dry season, trees remained relatively well hydrated (Figure 13). No seedlings or saplings were recorded in the area.

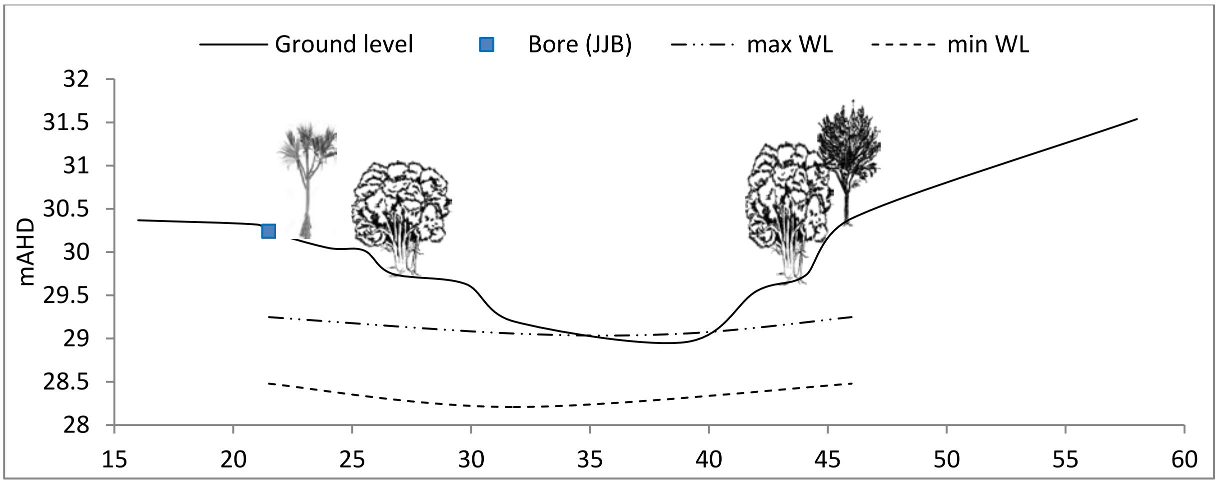


Figure 48 Water levels and vegetation distribution at the Jabirr Jabirr site

Water potential, soil chloride and soil moisture data (Figure 49) suggest the *M. nervosa* on the creekline (Mn-1,2,3) may be accessing soil water between 1.0 and 1.5 mbgl, as higher in the profile it is too dry. It is unclear where the *M. alsophila* (Ma-1,2) individuals are accessing water as their shoot water potentials remain much lower than soil water potential throughout the sampled profile.

Soil samples were not analysed for isotopes; however, groundwater and creek water samples were very similar in composition to each other and not dissimilar to all sampled trees (Figure 50). Dew was ruled out as a water source. Given their proximity to the creekline, it is possible the trees were using surface water and/or groundwater. This is supported by the relatively high level of hydration recorded at the end of the dry season.

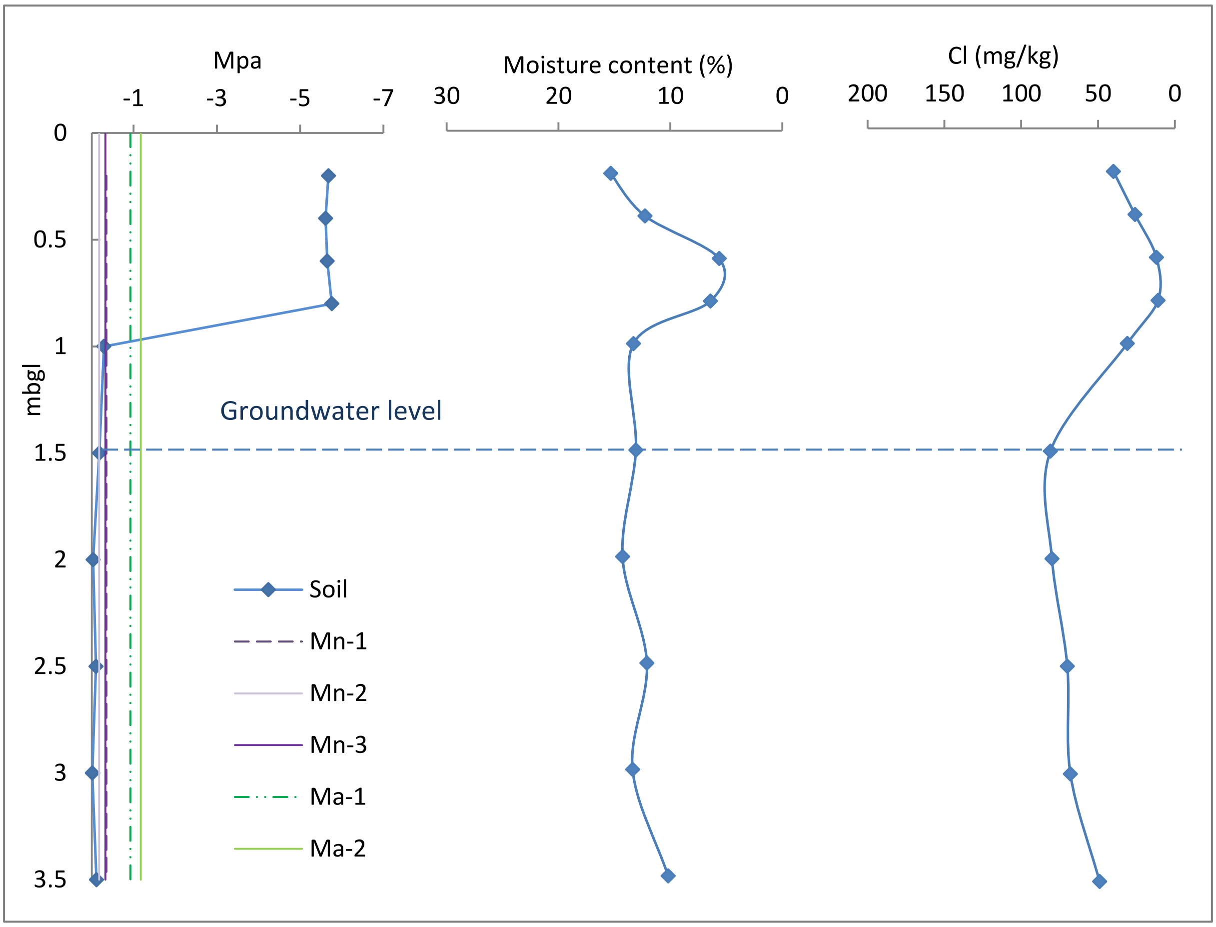


Figure 49 Jabirr Jabirr – soil and shoot water potential, soil moisture content and soil chloride with depth

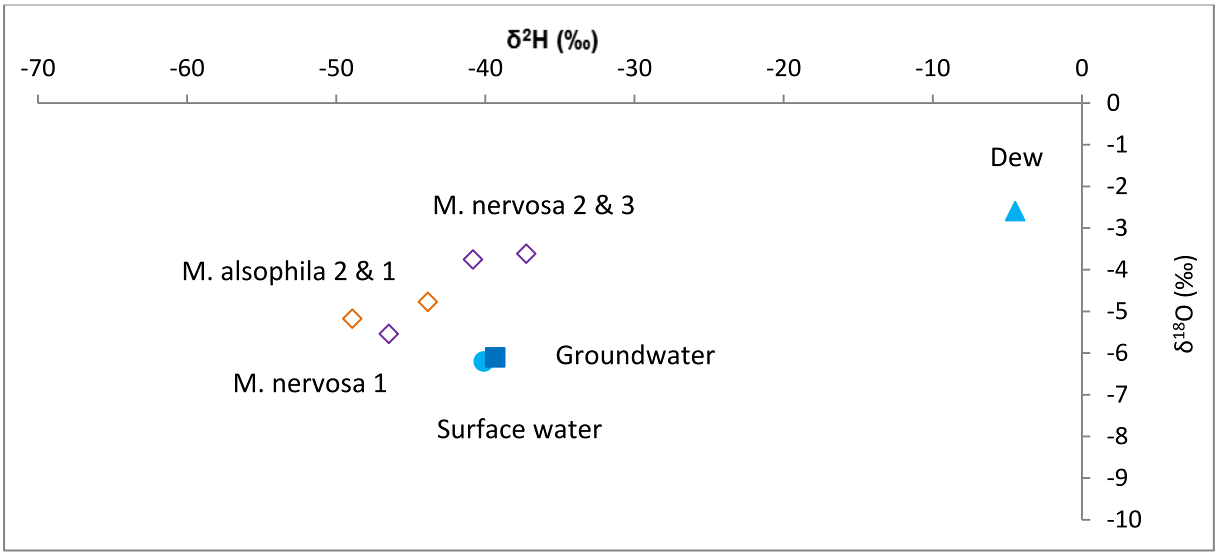


Figure 50 Jabirr Jabirr – Deuterium and Oxygen-18 isotope signatures of trees and potential water sources

Is Jabirr Jabirr a groundwater-dependent ecosystem?

Drilling, water sampling and the permanence of surface flow show there are continual groundwater inputs into the creek at Jabirr Jabirr. The health and hydration of trees along the creekline at the end of the dry supports their use of groundwater.

The creek, pool and associated vegetation at Jabirr Jabirr are supported by springs at the headwaters discharging throughout the year (Rothery 2016) – in much the same way as Illelang and Bindingangun. Geological information combined with a regional geophysical AEM survey identified the source of the groundwater as the unconfined Broome Sandstone aquifer (Searle & Degens 2017).

6.10 Banana Well (Burrguk)

Site description and methods

Burrguk (Banana Well) (Appendix F, Figure F9), meaning ‘high place or high ground’ in the Nyul Nyul language (Anon 2014), is on the southern side of Bobbis Creek about 8 km east of the Beagle Bay community.

A Nyul Nyul woman and her husband once had a market garden and banana plantation in the area – hence the European place name. The Burrguk Aboriginal Corporation, established in 1989, has a long-term lease on Banana Well Getaway, which now provides camping and accommodation for travellers (Anon 2014).

A spring at Banana Well provides the community with fresh water. Anecdotally, a hand-dug ‘well’ intercepted a very shallow, confined system and water has flowed freely ever since. This has created a small creek and pond that flows out onto the nearby salt flats.

There are also several very small springs on the salt flats. One such spring near Banana Well was observed to support the perennial sedge species *Schoenoplectus subulatus.*

The vegetation around the spring, creek and pond is dominated by *Melaleuca dealbata* and *Corymbia bella,* while *M. alsophila* becomes dominant closer to the salt flats (Figure 51). *Typha domingensis* occurs in the pond with *Nymphaea violacea* (water lily). The wider area has been largely cleared for the campground, but a small stand of very large *C. bella* and *M. dealbata* still exists. No saplings or seedlings were noted in the area.

We did not establish a transect or plot at this site due to the cultivated nature of the grasslands, although the ecophysiological work was undertaken in the stand of *C. bella* and *M. dealbata* described above.

Banana Well was also not investigated as part of the hydrogeological study. Other springs on Bobbis Creek were, however, studied as part of the national environmental research program (NERP) – carried out in conjuction with the Nyul Nyul rangers (Dobbs et al. 2015).

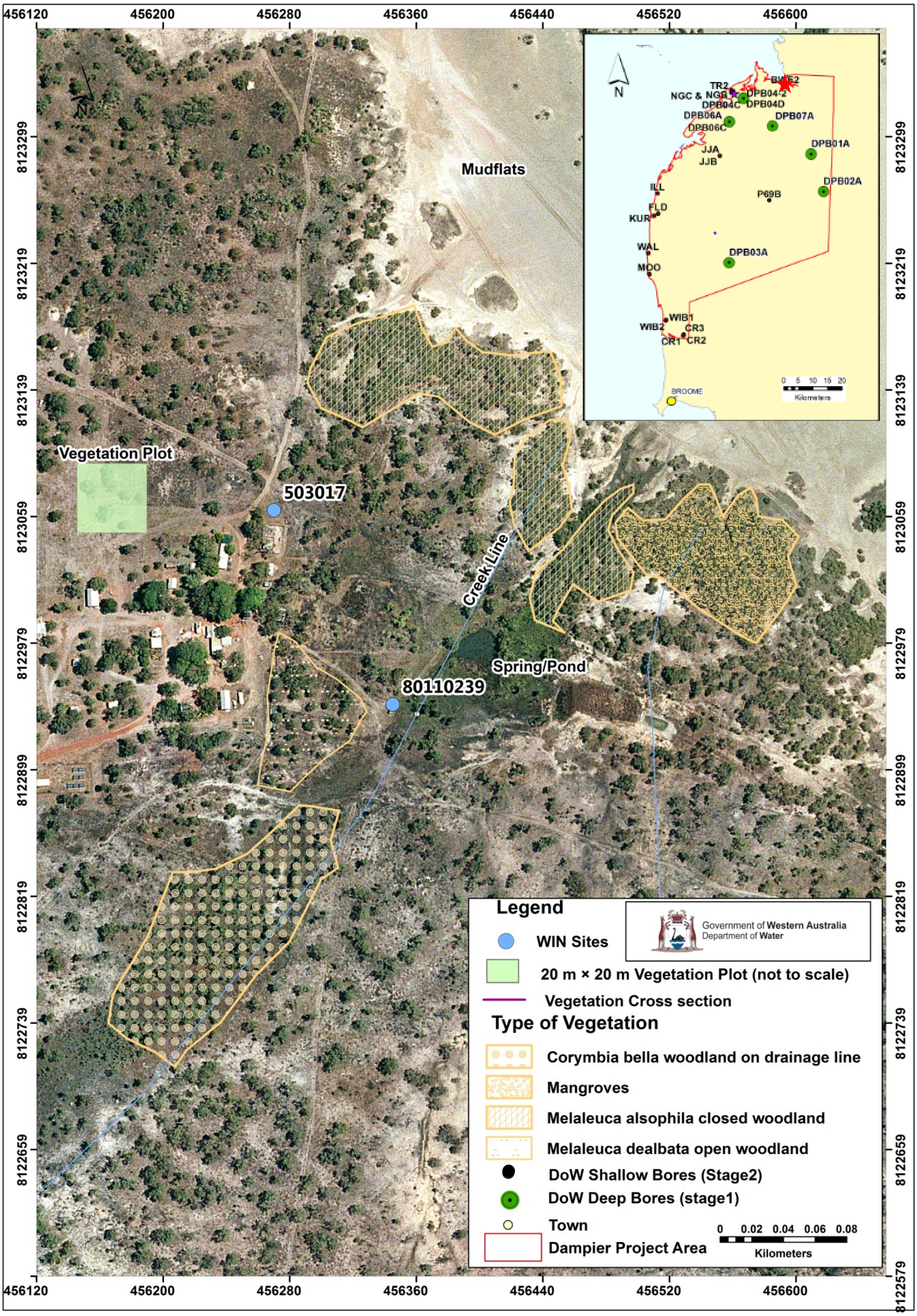


Figure 51 Banana Well location, WIN sites, vegetation and survey area

Results

The canopy condition of *C. bella* and *M. dealbata* was considered very good (Figure 10). Although the shoot water potential of both decreased during the dry season, the trees remained very well hydrated (Figure 13).

Along Bobbis Creek east of Banana Well, three springs were confirmed as dependent on groundwater, based on permanence and stable isotopes of water (^{18}O and Deuterium) (Dobbs et al. 2015). Rockwater (2004) also found local perched aquifers with artesian flow and associated mound springs south of Bobbis Creek.

Is Banana Well a groundwater-dependent ecosystem?

Characteristics including the spring’s permanence, the presence of freshwater vegetation and similarity to other known groundwater-fed springs nearby, suggest Banana Well is also groundwater dependent.

The locally confined aquifers within the Broome Sandstone are likely to be the source for Banana Well and nearby springs, although this cannot be confirmed without further hydrogeological work (Searle et al. 2016).

6.11 Mudoodon

Site description and methods

Mudoodon (Appendix F, Figure F10) is on the coast about 8 km south of James Price Point. Biota Environmental Services (2009) mapped the area as supporting both deciduous and evergreen monsoon vine thicket (MVT).

A substantial number of overstorey species may occur in a MVT and these form part of the diagnostic characteristics for the community type. At Mudoodon *Diospyros humilis* (Birimbiri, ebony wood) is dominant with *Bauhinia cunninghamii* (Jigal), *Grewia breviflora* (Goolm, coffee tree), *Mimusops elengi* (Mamajen), *Terminalia petiolaris* (Marool, blackberry tree) and *Exocarpos latifolius* (Jarnba, mistletoe tree). In addition there is an area of freshwater tree species – *Melaleuca dealbata, Lophostemon grandiflorus* and *Pandanus spiralis* – mapped as a drainage basin associated with Murtjal Creek (Biota Environmental Service 2009).

A transect comprising two 20 x 20 m plots was set up in May 2014 to capture the transition from MVT to the dune (Figure 52). A shallow hole (80110333) was hand-augered to the watertable at this time to determine depth. A second hole was hand-augered in the same location in October 2014 to sample soil and groundwater for isotopes. Twig samples were also collected at this time.

A shallow water supply bore (80119857) about 800 m north of the site was also sampled for a broad range of parameters during the hydrogeological investigation. This included CFCs and Carbon-14 (^{14}C) used to date groundwater and interpret recharge, and isotopes (Deuterium and Oxygen-18).

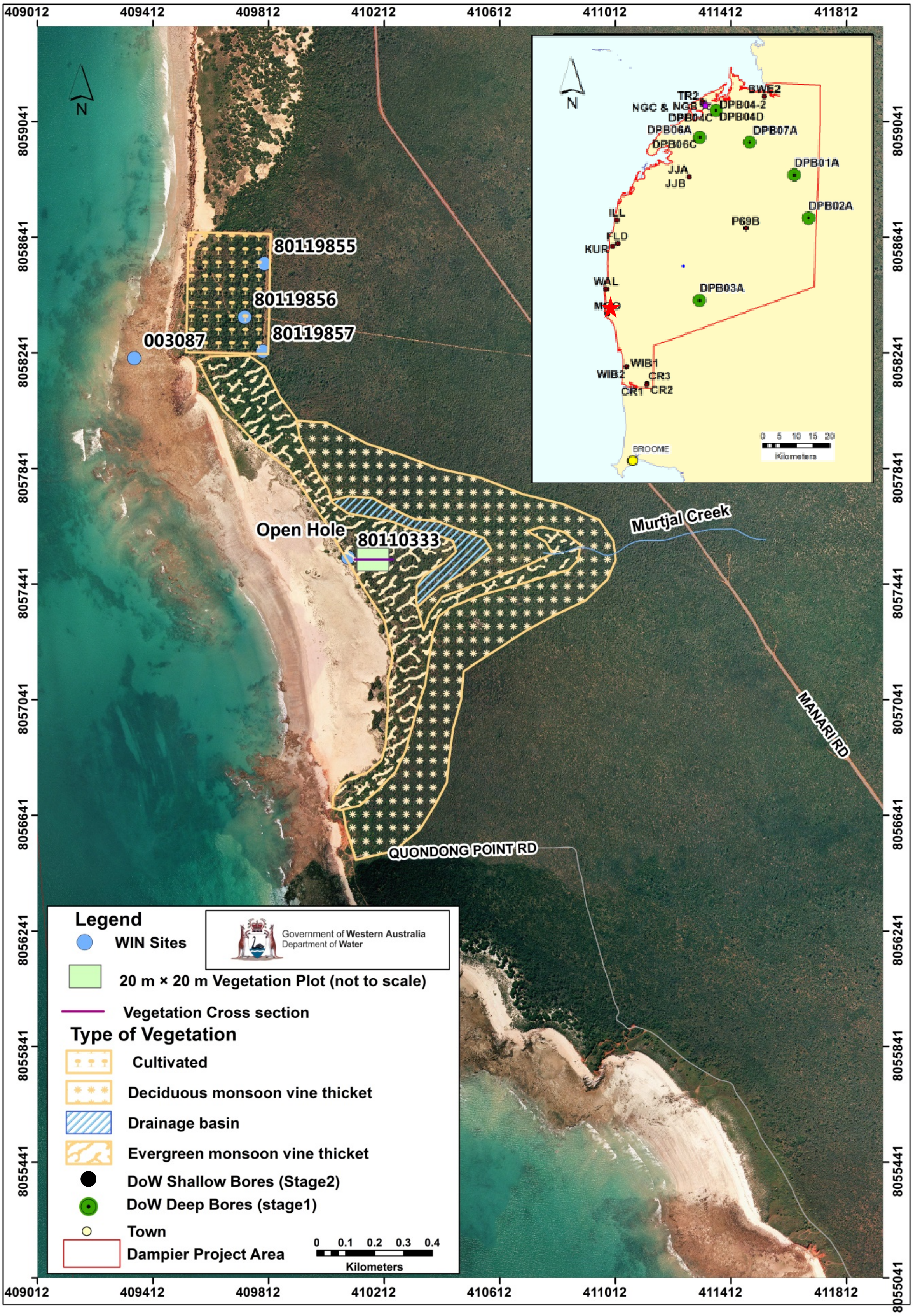


Figure 52 Mudoodon location, bores, vegetation and survey plots

Results

Depth to fresh groundwater at the bore ranged from 2.4 mbgl in May 2014 to 2.9 mbgl in October 2014.

Figure 52 shows the conceptual distribution of key species moving across the transect from the base of the sand dune. The plot runs from 5 to 45 m on the transect. Water levels for *M. dealbata* ranged from 3.9 mbgl (October 2014) to 3.4 mbgl (June 2014), *L. grandiflorus* from 4.05 to 3.4 mbgl and *D. humilis* from 3.4 to 3.9 mbgl (Figure 12).

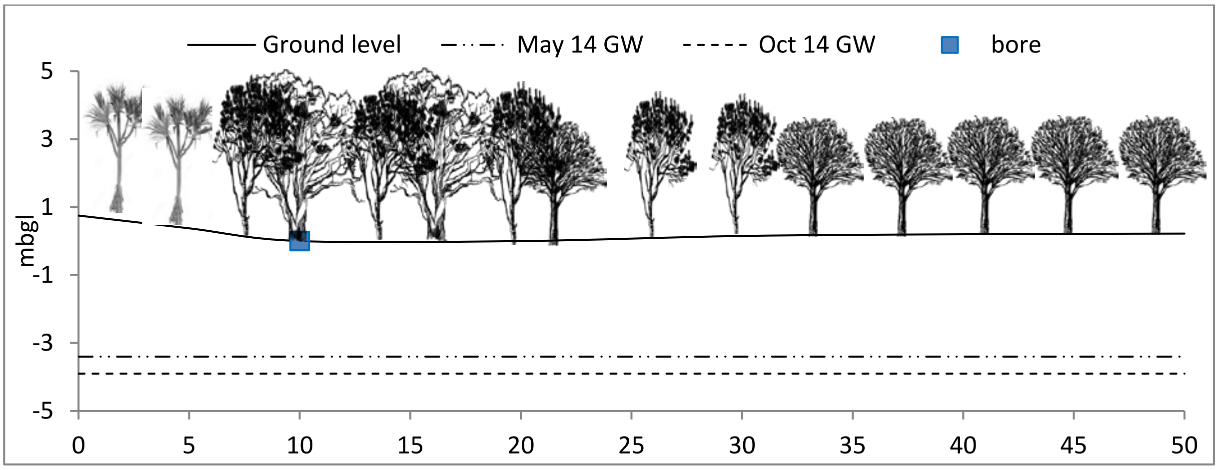


Figure 53 Water levels and vegetation distribution at the Mudoodon site

Diospyros humilis and *M. dealbata* at Mudoodon were in very good condition, with *L. grandiflorus* in good condition and a sapling of this species recorded in the plot (Figure 10). Although canopy cover decreased during the dry it remained moderate in plot A (Figure 11). Shoot water potentials were only measured at the end of the wet (May 2014) and as expected, the three species sampled were relatively well hydrated (Figure 13). Soil and shoot water potentials were not compared as no end-of-dry results were available.

The limited isotope samples taken at Mudoodon suggest trees were accessing shallow groundwater from the regional aquifer, given the results were similar to those from nearby bore (Figure 54).

Both the CFCs and Carbon-14 found during the hydrogeological investigation suggest the groundwater is a mix of older and younger waters: about 50 years old from the CFC results, and less than 600 years old from the ^{14}C method (Searle & Degens 2017). The age of the groundwater shows it is neither derived from recent rainfall nor from old, deep groundwater. Hence it is likely to originate from the regional Broome Sandstone aquifer.

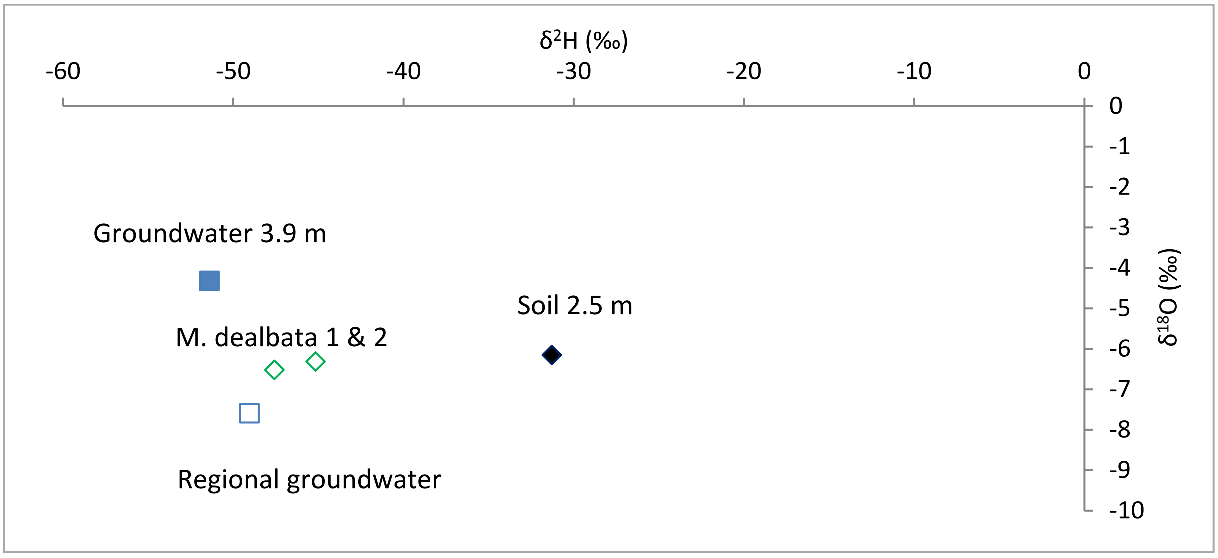


Figure 54 Mudoodon – Deuterium and Oxygen-18 isotope signatures of trees and potential water sources

Is Mudoodon a groundwater-dependent ecosystem?

The health and hydration level of the sampled vegetation suggests the site is groundwater-dependent. Despite a drainage line being nearby, we determined trees were accessing deeper groundwater in preference to local shallow groundwater that may have banked up behind the sand dunes.

Based on age dating of groundwater from MUD3, the broader area of MVT at Mudoodon sits over a shallow watertable in a regional groundwater discharge zone. Here, water from the Broome Sandstone is forced upwards over the saltwater interface, the presence of which was confirmed by the AEM (Searle & Degens 2017).

The MVT at Mudoodon is therefore considered dependent on groundwater from the regional Broome Sandstone aquifer.

6.12 Walmadan

Site description and methods

The Walmadan monsoon vine thicket (MVT) site (Appendix F, Figure F11) is located on the coast about 50 km north of Broome and 1 km south of James Price Point. Biota Environmental Sciences (2009) mapped the area as evergreen MVT. As with all MVT on the Dampier Peninsula, it occurs as a discrete pocket of dense vegetation on the leeward side of the sand dunes (English 2010).

The MVT here is characterised by many of the same species as recorded at Mudoodon. However, *Diospyros humilis* and *Corymbia bella* were dominant. This area also supports a very open woodland of *C. bella* over *Fluegga virosa* (snowball bush) and exotic grasses. A Priority 4 species, *Pittosporum moluccanum* has also been recorded at the site (Biota Environmental Service 2009).

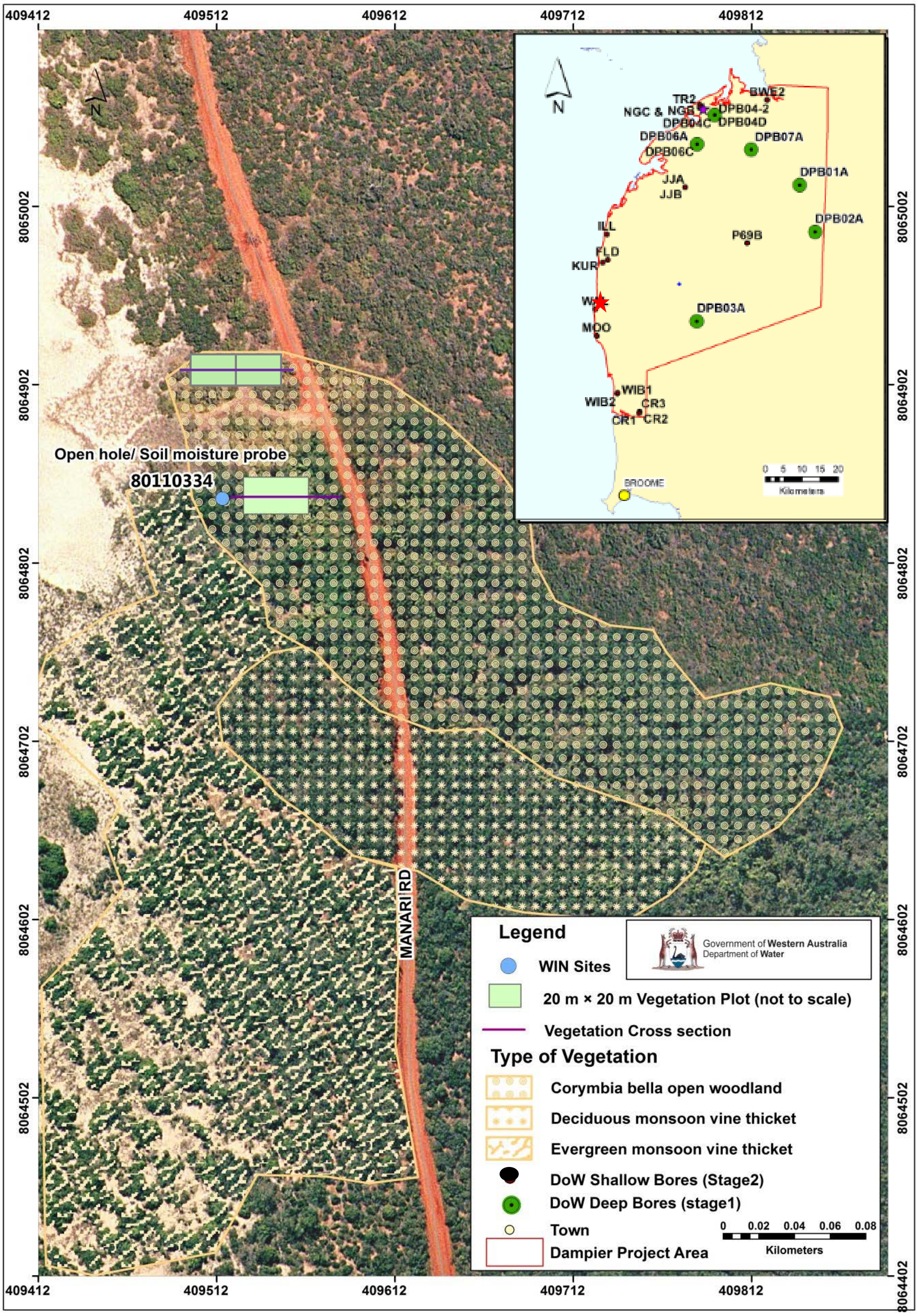


Figure 55 Walmadan location, bore, vegetation and survey plots

Two 20 x 20 m plots (A and B) were set up in May 2014 to capture the range of dominant species moving upslope towards the dunes (Figure 55). In November 2014 a third 20 x 20 m plot (C) was set up 100 m to the south to capture the broader distribution of *C. bella.*

Canopy condition, leaf area index and shoot water potential were measured across all three plots (figures 10, 11 and 12). A shallow piezometer was hand-augered to the watertable at plot C (80110334) in November 2014 and again in May 2015 to determine depth. During the November sampling we also measured key water quality parameters, sampled soil and groundwater for isotopes and soil moisture, and installed a soil moisture probe.

A monitoring bore (JP bore: 80110236) 1.4 km north of Walmadan was sampled for isotopes and water quality during the hydrogeological investigation program (Searle & Degens 2017).

Results

Depth to groundwater was 3.07 mbgl in November 2014 and 2.57 mbgl in May 2015.

Carbon-14 dating for the hydrogeological investigation showed that groundwater in JP bore (80110236), 1.4 km to the north, was roughly 1300 to 2200 years old (Searle & Degens 2017). Samples from this bore did not contain detectable amounts of CFCs, indicating recharge before 1940 when CFCs were introduced. This supports the Carbon-14 results (Searle & Degens 2017). The age of the groundwater shows it is not derived from recent rainfall and is likely to be old, deep groundwater being pushed up over the seawater interface from the regional Broome Sandstone aquifer.

Figure 55 shows the conceptual distribution of key species moving across the transect. Water levels for *C. bella* ranged from 2.69 mbgl (November 2014) to 2.02 mbgl (May 2015) (Figure 12). Ranges for *D. humilis* ranged from 2.80 to 2.12 mbgl.

The *D. humilis* and *C. bella* in plots A and B were in very good condition (Figure 10). Canopy cover was moderate in plot A, thinning out to very open in plot B (Figure 11). Although shoot water potential was only measured at the end of the wet, *C. bella* were very well hydrated and *D. humilis* moderately hydrated (Figure 13).

The condition of the *C. bella* in the overstorey in plot C was good, although the canopy itself was quite open. Canopy density changed very little over the dry season. As shoot water potential was only measured at the end of the wet – when trees were found to be well hydrated – it is not possible to comment on any changes over this time (Figure 13). Two *C. bella* saplings were recorded in the plot.

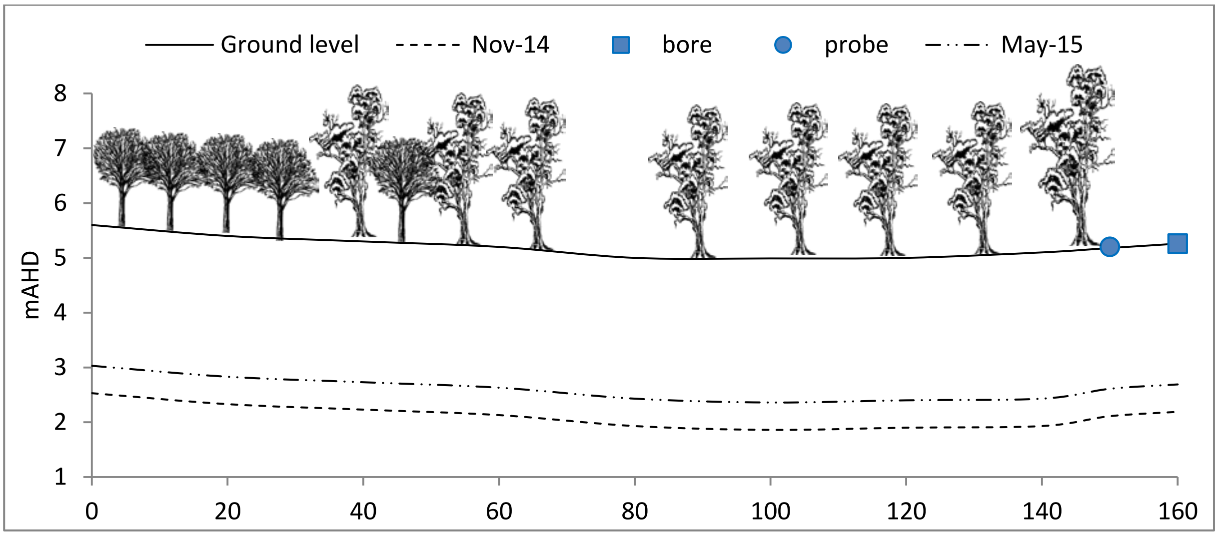


Figure 56 Water levels and vegetation distribution at the Walmadan MVT site

The soil moisture probe tracked rain moving through the soil profile but was too shallow to record an increase in groundwater level (Figure 57). There was no evidence of a confining layer or any clay layers that may have retained moisture at depth. Soil moisture at Walmadan was consistently the lowest of the four sites where moisture probes were installed.

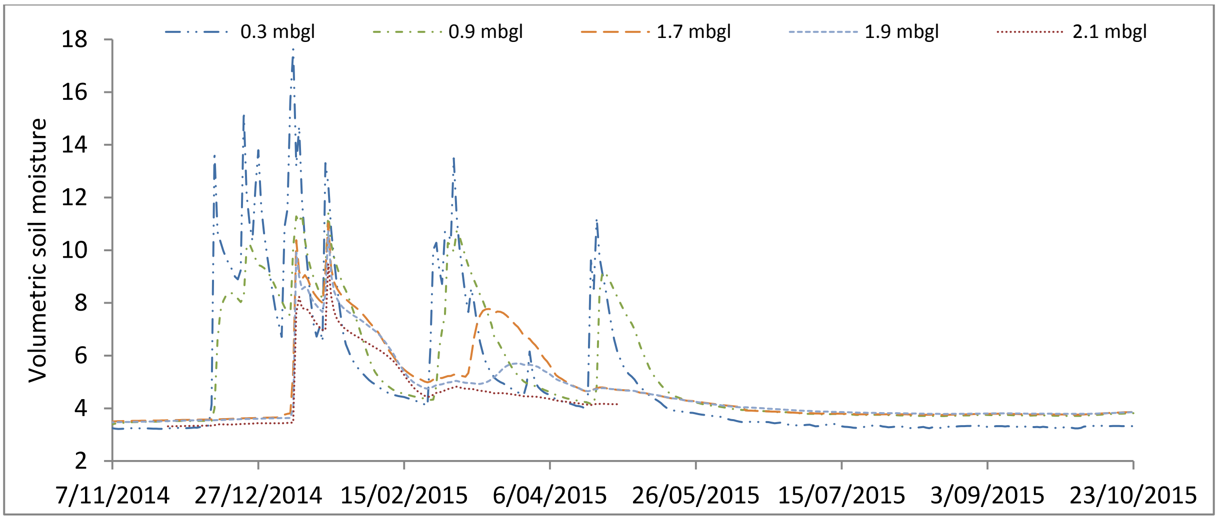


Figure 57 Walmadan – soil moisture probe results

Although soil moisture and chloride results show fresh soil water occurred at 1.5 mbgl, water potentials, the soil moisture probe and isotope results show this was not the water being used by trees (figures 57, 58 and 59). It is more likely they were using groundwater from 3.1 mbgl or regional groundwater (JP bore) as the isotopic signatures were similar to two of the *C. bella* (CB2, CB3 in Figure 59).

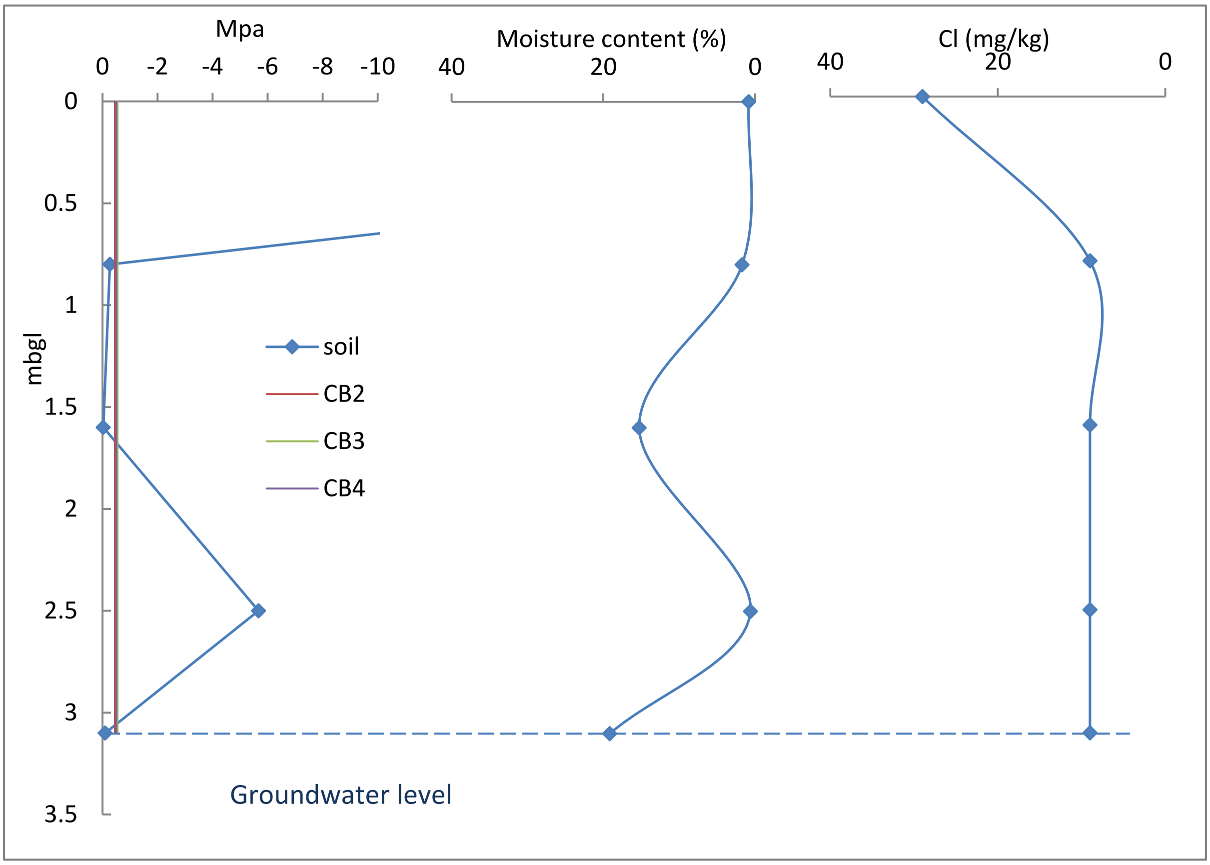


Figure 58 Walmadan – soil and shoot water potential, soil moisture content and soil chloride with depth

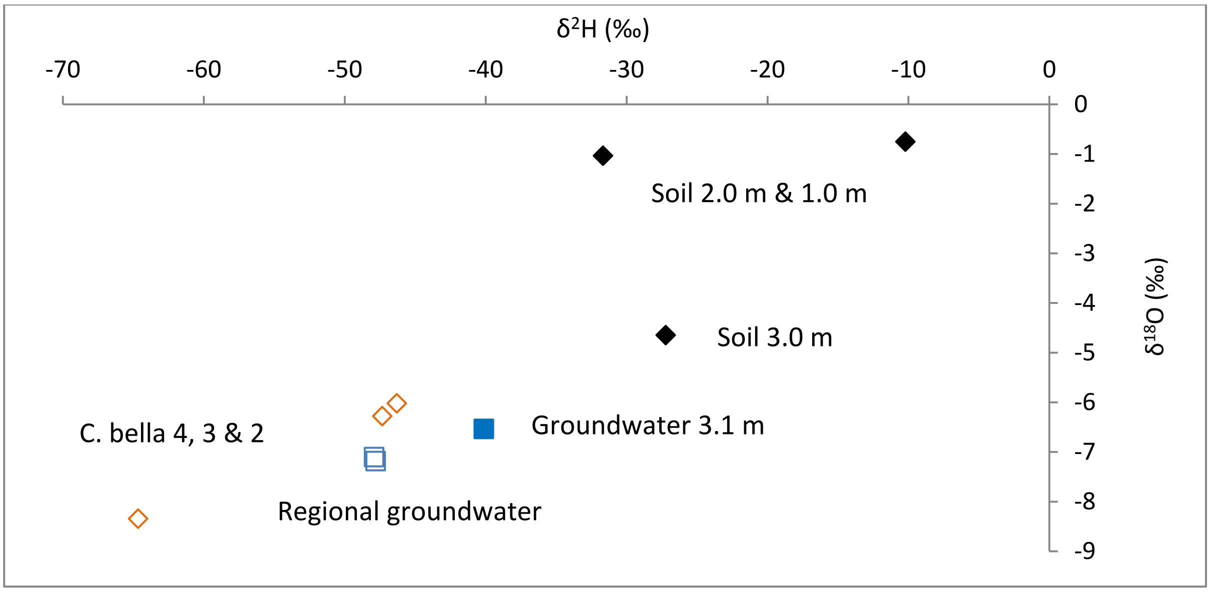


Figure 59 Walmadan – Deuterium and Oxygen-18 isotope signatures of trees and potential water sources

Is Walmadan a groundwater-dependent ecosystem?

Groundwater aging of the nearby JP bore show the area is sitting on a shallow watertable in a regional groundwater discharge zone (Searle & Degens 2017). Here, deeper older water from the regional aquifer is forced upwards over the saltwater interface, the presence of which was confirmed by the AEM.

Results of the ecological and hydrogeological investigations suggest the MVT at Walmadan is most likely dependent on groundwater from the regional Broome Sandstone aquifer.

6.13 Kurrukurugun

Site description and methods

This site is off Manari Road, about 65 km north of Broome. Kurrukurugun (Appendix F, Figure F12) is a flow line that drains from around Flow Dam towards the coast. After the wet season water can pond at the base of steep sand dunes and shallow groundwater is found along the flow line throughout the year.

Large *Melaleuca dealbata* run the length of the drainage line with *Lophostemon grandiflorus* of varying ages fringing both sides of the 'valley' (Figure 60). The understorey is dominated by grasses and native shrubs. Cattle graze at the site.

A transect comprising two 20 x 20 m plots was set up in May 2014 to capture the range of both dominant species. A shallow hole (80110338) was hand-augered to the watertable at this time to determine depth and key water quality parameters. A second hole was hand-augered in the same location in October 2014 to sample soil and groundwater for isotopes and soil moisture. Twig samples were also collected. A soil moisture probe (80110338) was installed in September 2014.

Results

Depth to fresh groundwater at the bore ranged from 0.65 mbgl in May 2014 to 3.0 mbgl in November 2014.

Figure 60 shows the conceptual distribution of key species moving across the transect. Water levels for *M. dealbata* ranged from 3.64 mbgl (November 2014) to 0.65 mbgl (May 2014) and *L. grandiflorus* from 4.24 to 0.70 mbgl (Figure 12).

Canopy condition of *M. dealbata* and *L. grandiflorus* was good and very good respectively (Figure 10). Canopy cover in plot A decreased during the dry season – most likely due to a fire in the month before sampling (Figure 11). Although shoot water potential in *M. dealbata* declined by the end of the dry, all individuals remained well hydrated, suggesting permanent access to water (Figure 13). Despite conditions seemingly suitable for recruitment of *L. grandiflorus* (two seedlings and three saplings recorded), the larger individuals were among the least hydrated of all species at any site.

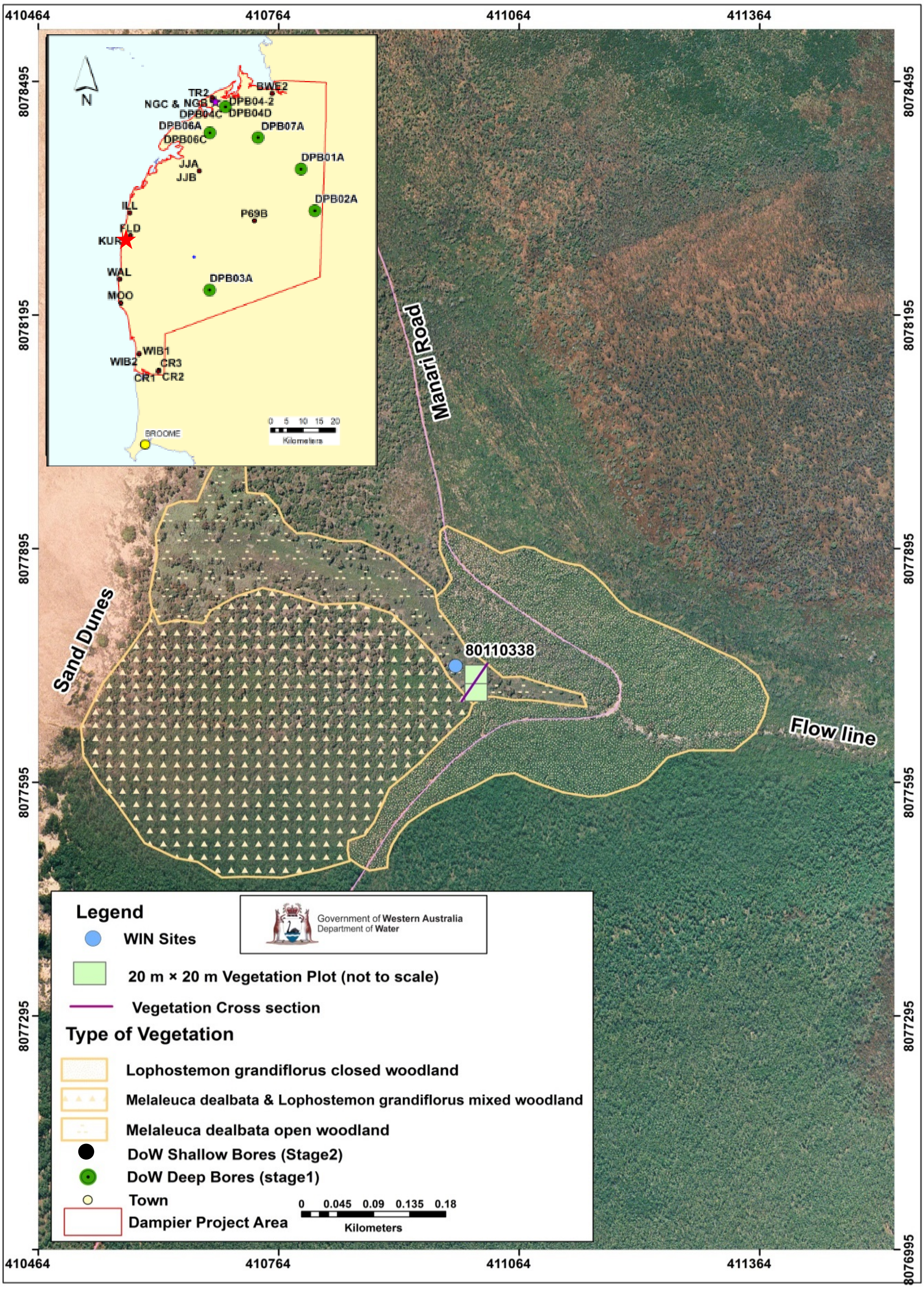


Figure 60 Kurrukurugun location, bores, vegetation and survey plots

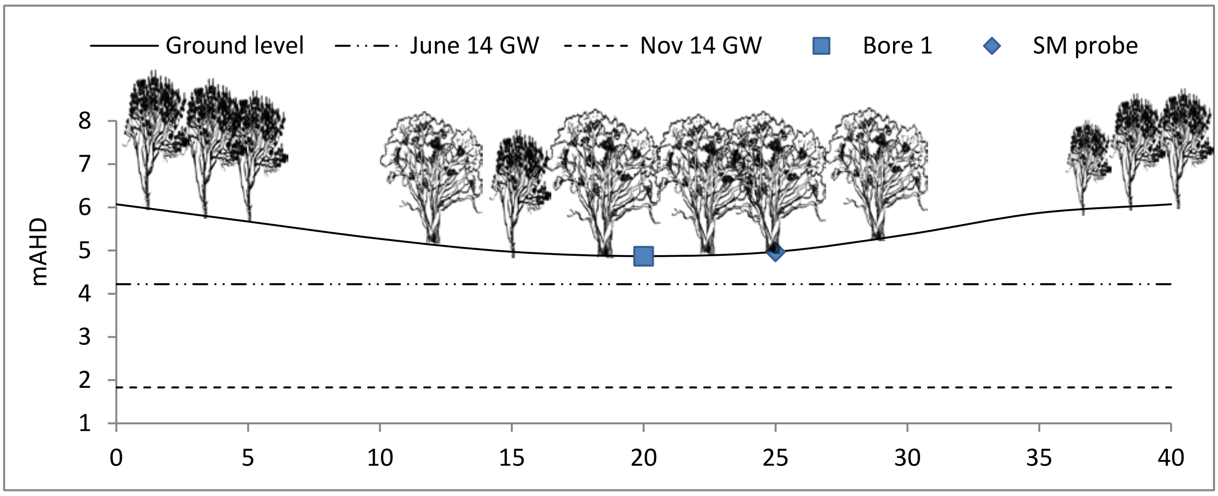


Figure 61 Water levels and vegetation distribution at the Kurrukurugun site

Results from the soil moisture probe identified subsurface flows. This was illustrated by increases in soil moisture/groundwater level at depths independent of increases in shallower profiles. In Figure 61, soil moisture at 0.3 mbgl shows some response to rainfall from early December 2014 onwards (see rainfall graph in Appendix G), yet this does not reach 0.9 mbgl or deeper soils. In contrast, soils at depths of 1.4 and 1.8 mbgl are already wetter than 0.9 mbgl and become quite wet from mid-January with the 1.8 m profile remaining so until the end of the dataset. This suggests lateral movement of subsurface flow mirroring the drainage line from Flow Dam, rather than surface flow or rainfall. The dryness of the soil at 0.9 mbgl suggests a confining layer.

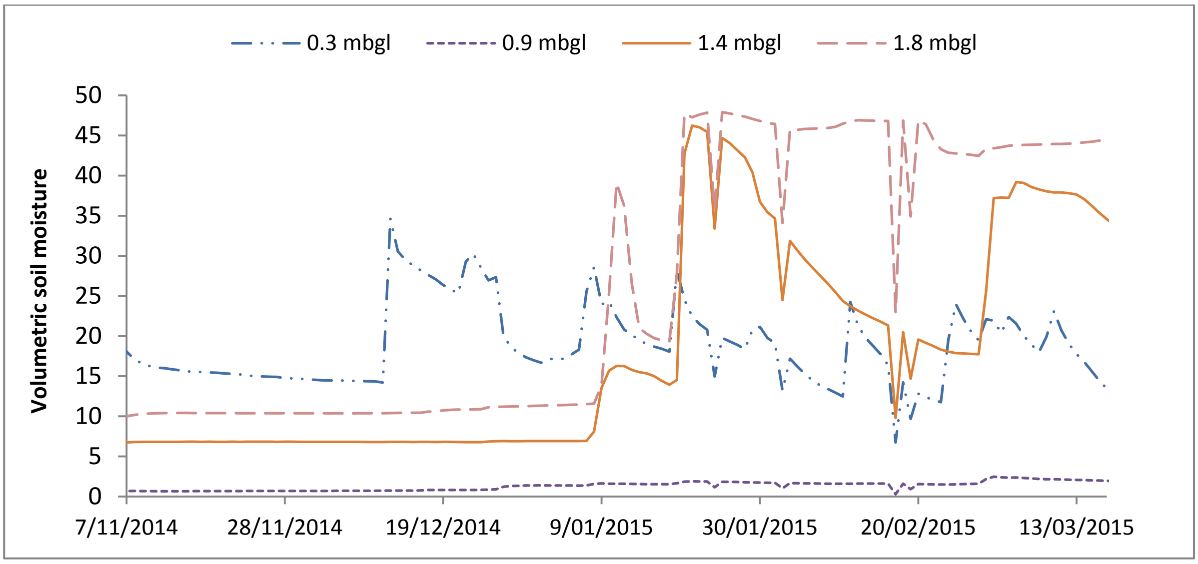


Figure 62 Kurrukurugun – soil moisture probe results

Soil moisture and chloride (salts) data support the assumption of a confining layer at 1.0 mbgl, as soil was wetter and less fresh immediately above, very dry at 1.0 mbgl and wetter again beneath (Figure 63). Groundwater at 3.0 mbgl was very fresh.

The isotopic signature of two of the *L. grandiflorus* (Lg-1,2) and a large *M. dealbata* (Md-1) are closest to that of soil at 0.8 mbgl, suggesting that these individuals are accessing water from this depth (Figure 64). The lower level of hydration found in the *L. grandiflorus* (Figure 13) may indicate they are relying on the subsurface flow only. However, the *M. dealbata* were well hydrated and are likely to be preferentially using groundwater from below the shallow confining layer. The remaining *M. dealbata* (Md-2,3) are also likely to be accessing water from greater depths, possibly 3.0 mbgl (Figure 63). The deeper groundwater below the shallow confining layer may be the regional aquifer (Figure 64).

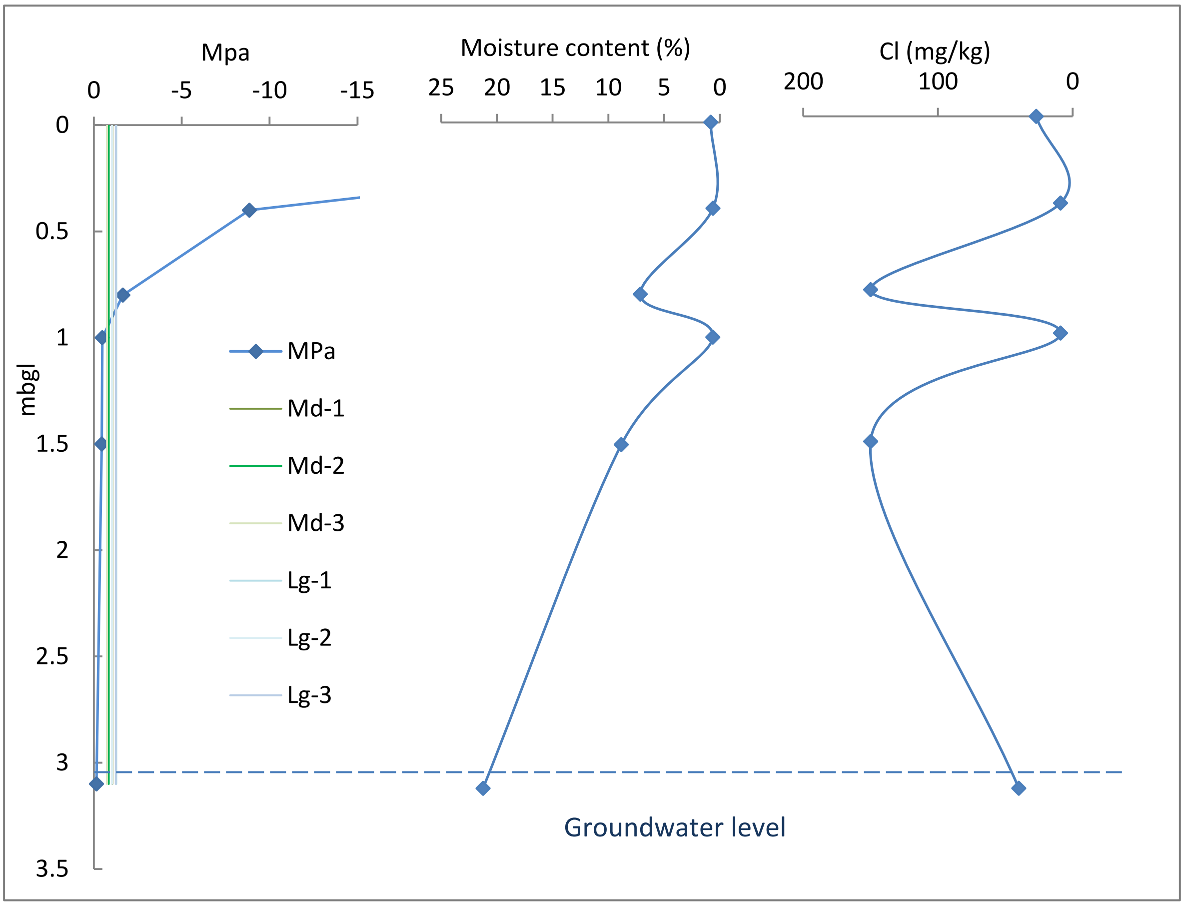


Figure 63 Kurrukurugun – soil and shoot water potential, soil moisture content and soil chloride with depth

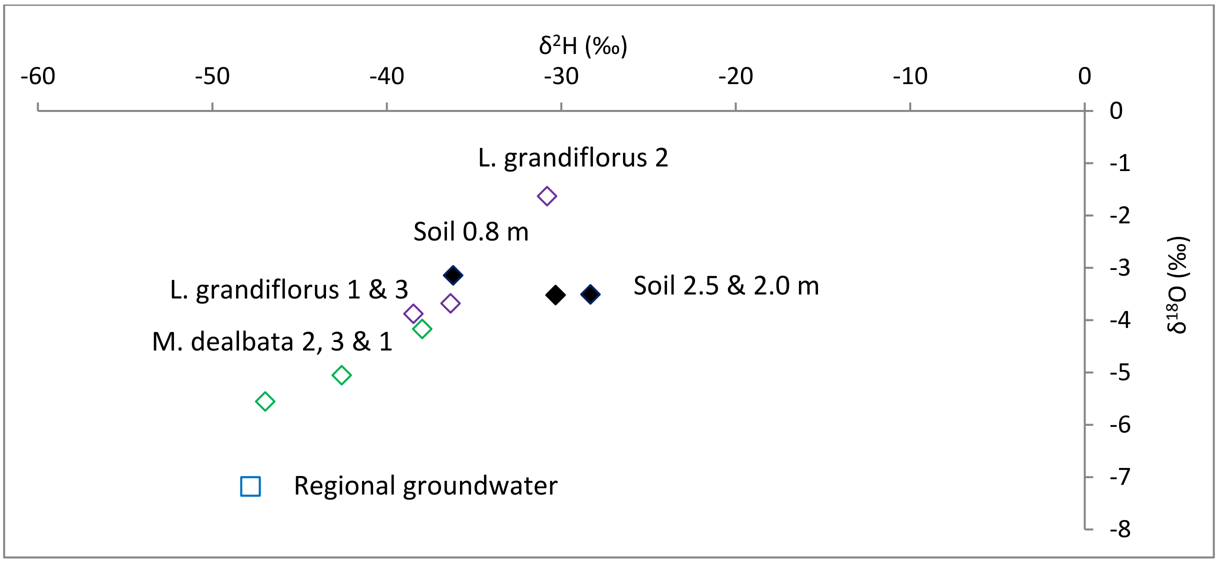


Figure 64 Kurrukurugun – Deuterium and Oxygen-18 isotope signatures of trees and potential water sources

Is Kurrukurugun a groundwater-dependent ecosystem?

Kurrukurugun receives subsurface, lateral flows from the Flow Dam area to the east. Although the associated shallow confining layer helps retain some soil moisture and supports *L. grandiflorus*, the continued level of hydration recorded in *M. dealbata* suggests a more permanent water source. It is likely these trees are accessing deeper groundwater as it is both fresher and more available. It is unclear if this is a local, shallow aquifer held up behind the extensive sand dunes or regional groundwater being forced upwards over the saltwater interface.

The terrestrial phreatophytic vegetation at Kurrukurugun may therefore be dependent on groundwater from either a small local aquifer or the regional Broome Sandstone aquifer (or both). Further hydrogeological work is required to verify this.

6.14 DPB06

Site description and methods

DPB06 (Appendix F, Figure F13) is on the Carnot Bay access track about 22 km east of the Cape Leveque Road. The site is within a very extensive area of pindan vegetation. It was chosen as a reference site as its position in the landscape suggested groundwater would be too deep for vegetation to access and it did not support any known phreatophytic species.

Low open woodland of *Corymbia greeniana* (Dampier’s bloodwood) and *Eucalyptus tectifica* (Darwin box) over mixed shrubs and grasses dominate the area (Figure 65).

A 20 x 20 m plot was established on the southern side of the access track in June 2014. Unfortunately the site was burnt not long after and had to be relocated to the other side of the track.

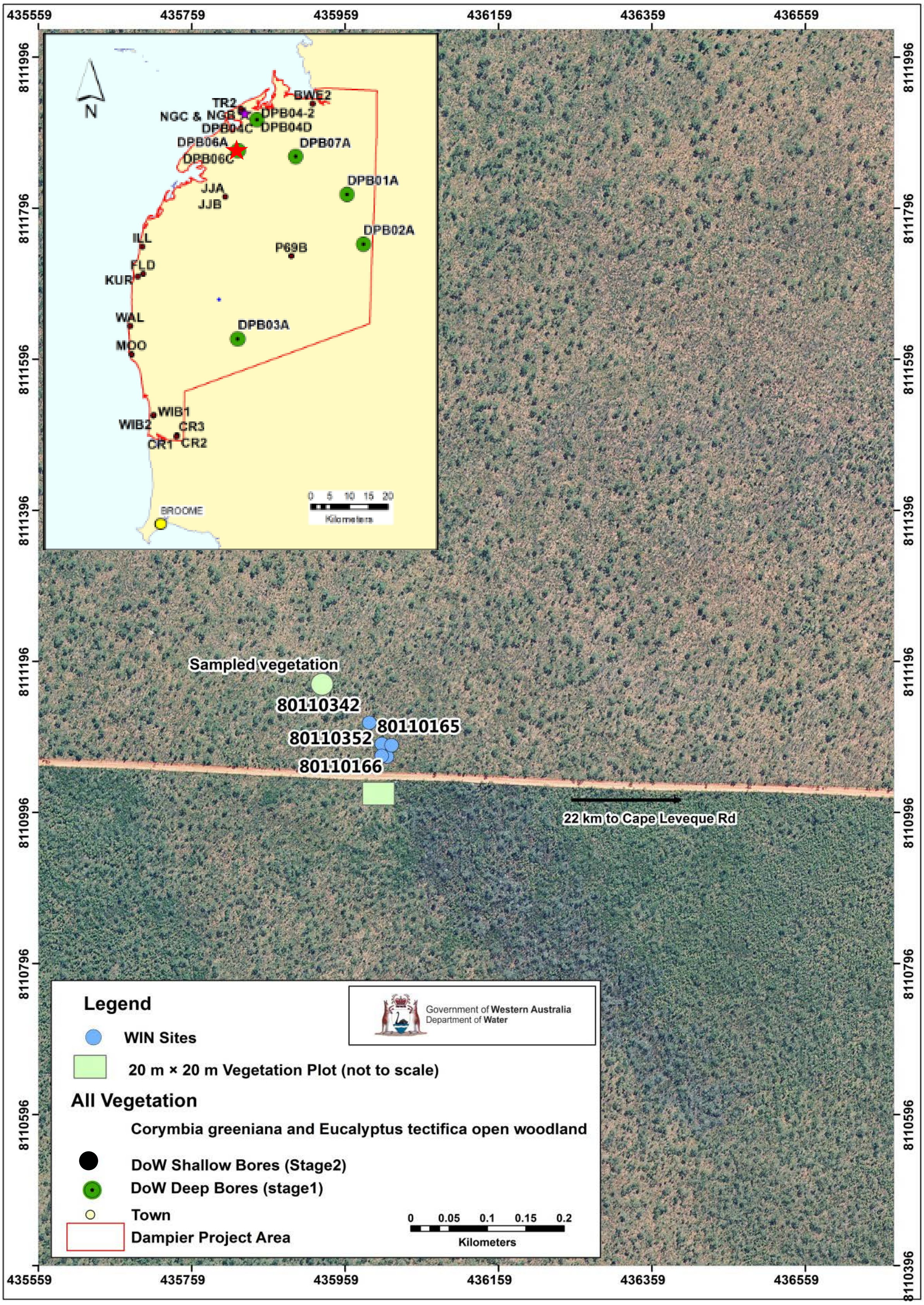


Figure 65 DPB06 location, bores, vegetation and survey plots

A water supply bore (DPB06B: 80110166), screened above the regional confining layer, and a deep monitoring bore (DPB06A: 80110165) screened in the confined aquifer, were installed on the northern side of the track in October 2013. The deep bore was sampled for a range of groundwater parameters.

In October 2014 a sonic rig was used to install a shallow bore (DPB04C: 80110352) and sample intact soil cores for soil moisture and isotope analysis. Twig samples were also collected for isotopes. A soil moisture probe was set up in September 2014 (80110342).

Results

The condition of the tree canopies on both sides of the road was regarded as good (Figure 10). Although canopy density was not measured in the replacement plot, the original plot was quite open (Figure 11). The shoot water potential of *C. greeniana* in the replacement plot remained relatively high over the dry season (Figure 11).

At the time of installation, depth to groundwater at the shallower bores (DPB06B, C) was about 32 m and 8 m at the deep bore (DPB06A). The shallowness of groundwater at DPB06A results from upward pressure (subartesian) exerted by the water being held under a confining layer. The presence of the confining layer first identified by AEM and confirmed by drilling, revealed a confined aquifer that is unlikely to be part of the Broome aquifer. The presence of the confining layer, which spans more than 930 km^2 across the Dampier Peninsula, along with the associated confined aquifer, was a new finding for the area.

The soil moisture probe was installed in deep pindan soils. As would be expected, soil moisture at 0.3 mbgl, and 0.6 mbgl to a lesser extent, wet and dried quickly after rainfall in November/December 2014 (see rainfall graph in Appendix G). Deeper soils did not respond until a major rainfall event in early January. Figure 66 shows wetting fronts moving through the soil profile and then drying.

Although the probe tracked the progress of wetting fronts, soil moisture and isotope data showed soil water was not available for use by vegetation at less than 2.0 mbgl (figures 66 and 67). The isotopic signature of the sampled trees was closest to soils deeper than 5.5 mbgl. The soil was relatively moist and soil water fresh at these depths.

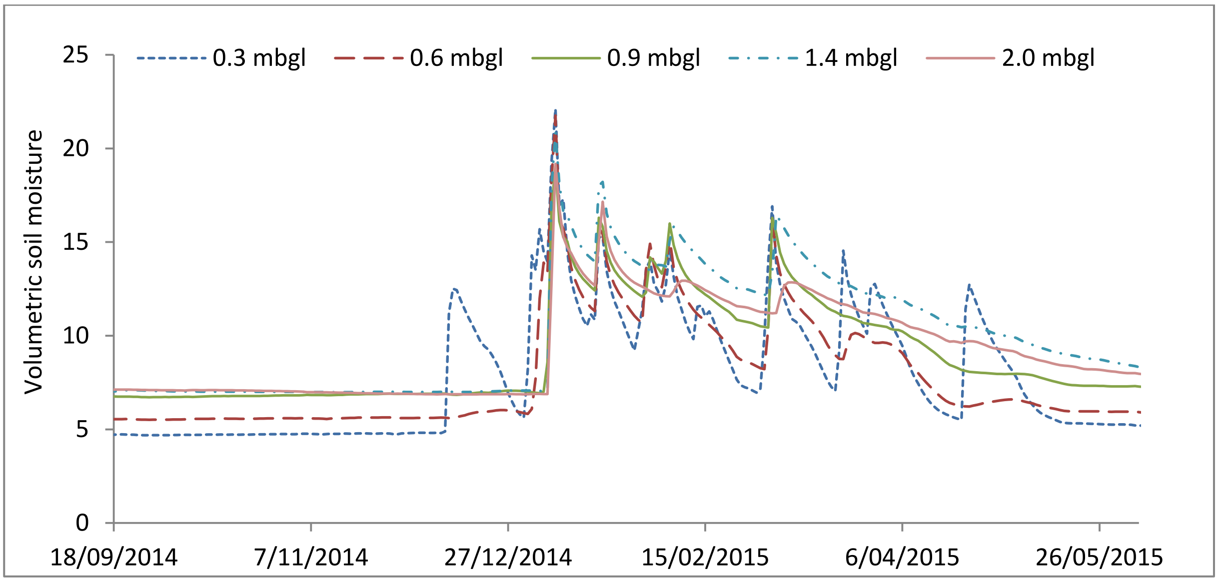


Figure 66 DPB06 soil moisture probe results

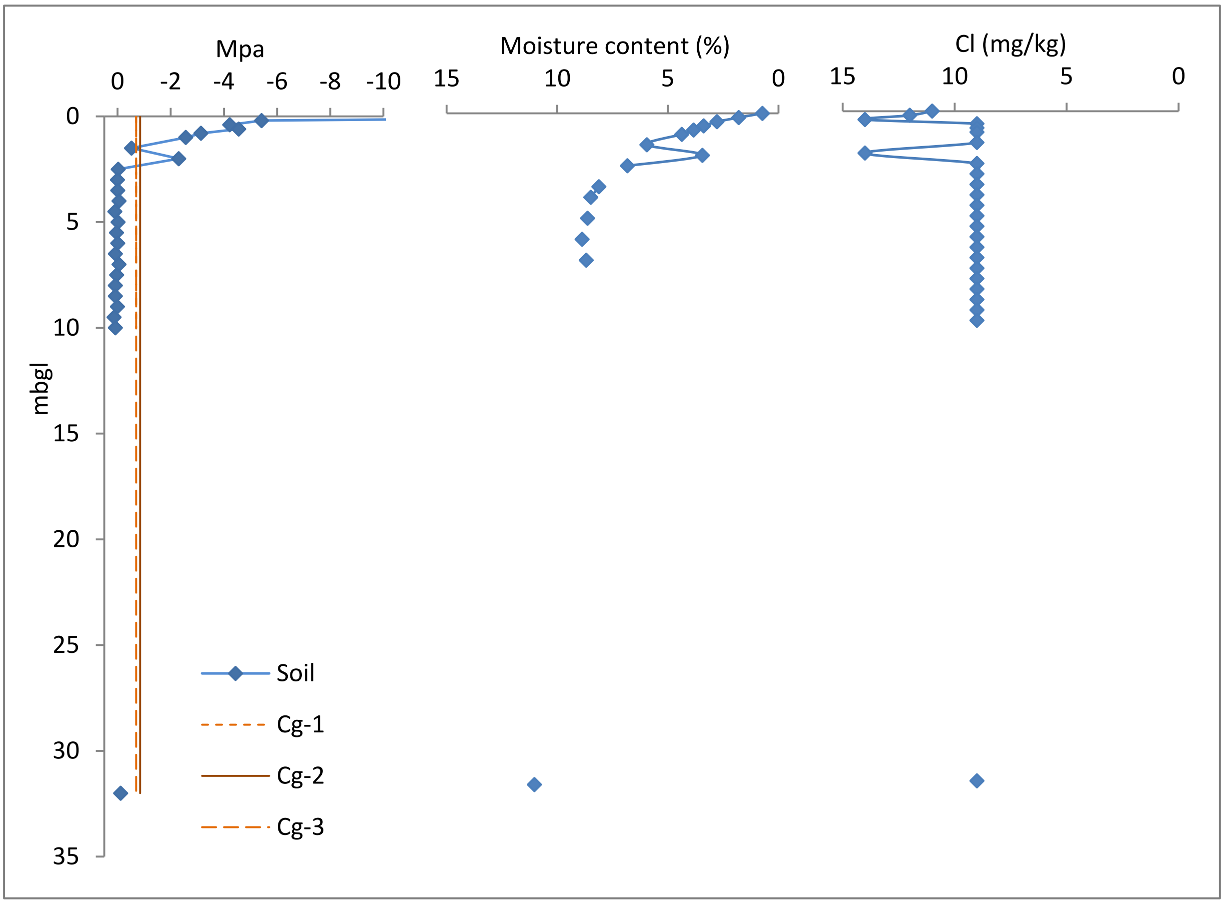


Figure 67 DPB06 – soil and shoot water potential, soil moisture content and soil chloride with depth

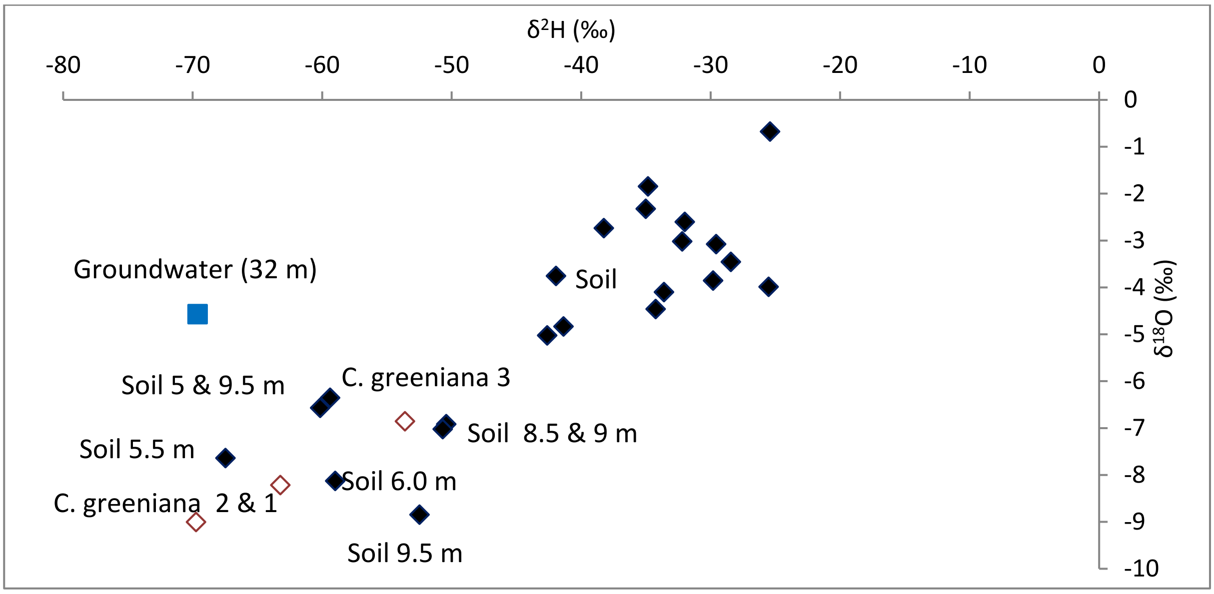


Figure 68 DPB06 – Deuterium and Oxygen-18 isotope signatures of trees and potential water sources

Is DPB06 a groundwater-dependent ecosystem?

The level of tree hydration recorded at the end of the dry season was not expected from the reference site as the watertable was considered too deep for tree roots to access. However, pindan soil appears to retain sufficient soil moisture to meet the requirements of *C. greeniana* in the absence of groundwater and rain. This is likely to apply equally to the trees in the replacement plot and the *E. tectifica* and *C. greeniana* from the original plot and the pindan soils across the broader area. These results suggest vegetation at DPB06 is not groundwater-dependent.

6.15 Summary

In this section we briefly describe which of our study sites are groundwater-dependent, summarise why we think so (evidence) and indicate which groundwater (aquifer) – if any – they are likely to be accessing (Table 2).

Triangle wetland in the study area's north was determined to be dependent on localised, shallow groundwater systems not in direct connection with the regional Broome Sandstone aquifer (Table 2). The western and northern sides of Oval wetland are also likely to be disconnected from the regional aquifer. These areas were characterised by low permeability clay layers and brackish to saline groundwater and were dominated by *Melaleuca alsophila* woodlands.

There is a possible connection between shallow local groundwater and the Broome aquifer on Oval wetland's eastern side (DPB04-2). Here woodland of mature *M. dealbata/Corymbia bella* occurs over fresher groundwater in sandier soils.

Also in the north, Ngadalargin wetland has a perched aquifer overlying a deeper aquifer which may be connected to the Broome aquifer.

Flow Dam and Kurrukurugun (Table 2) most likely rely on a local, shallow, perched groundwater system. This system is thought to develop where surface flow and local rainfall are held up by the dam wall before infiltrating into the underlying sediments. Water then flows laterally towards the coast along a shallow clay layer before ponding against the sand dunes and forming a thin, shallow aquifer. Nevertheless, there may be inputs from the regional Broome aquifer. Soils become sandier and salinity declines moving west from the wetland itself, through Kurrukurugun to the dunes. This is reflected in a change in vegetation from *M. alsophila* woodland around the wetland to open *M. dealbata* woodland on the dam's west side through *M. nervosa* open woodland to Kurrukurugun, which is dominated by large *M. dealbata* in lower areas fringed by dense *Lophostemon grandiflorus* on higher ground.

The headwaters of Illelang, Bindingangun and Jabirr Jabirr are supported by the unconfined Broome aquifer. There are two conceptual models for these spring systems. The first option is that groundwater from the east flows up and over the confining layer, which then intersects with a change in topography forming a series of springs and seepages which feed the creeks. The second option is that the springs occur along the newly identified geological fault, which acts as a hydraulic conduit. Detailed investigations showed that groundwater also discharges at various locations along Illelang throughout the year. It is possible that both groundwater and rain-derived surface flow infiltrate sandy banks downstream of discharge points and form localised freshwater aquifers which support vegetation. However, moving closer to the coast, tidal influence increases. The vegetation again reflects the change in potential water sources. Fringing *M. alsophila* woodland dominates the lower reaches of the creeks, grading to *M. dealbata* and *C. bella* as freshwater inputs increase upstream. The groundwater discharge zones support some *M. dealbata, C. bella* and *Pandanus spiralis,* but *M. nervosa* is the most common species.

The monsoon vine thickets (MVT) at Mudoodon and Walmadan are supported by the unconfined regional Broome Sandstone aquifer. This coastal area is a regional groundwater discharge zone, with a mix of old and younger groundwater being pushed up over the saltwater interface, discharging in the intertidal zone. The vegetation at these sites is dominated by *Diospyros humilis, Bauhinia cunninghamii* and other species characteristic of MVT, with the addition of other freshwater species – *M. dealbata, C. bella* and/or *L. grandiflorus*.

Wibbijagun is thought to be connected to the regional Broome Sandstone aquifer in a similar way to the MVT sites. The vegetation fringing the vast majority of the wetland, where soils appear clayey and have a higher salt content, is closed *M. alsophila* woodland. The small areas of *M. dealbata* and *C. bella* with *Typha domingensis* on the western edge seem to occur on sandier soils.

Banana Well is likely to be supported by locally confined aquifers within the Broome Sandstone, but this cannot be confirmed without further study. Although *M. alsophila* occurs where the spring flows out onto the salt flats, vegetation at the spring and over shallow groundwater in the area is dominated by *M. dealbata* and *C. bella.*

DPB06 is not groundwater-dependent. The vegetation here is dominated by *C. greeniana* and *E. tectifica* which are accessing moisture held in the pindan soils.

Table 2 Groundwater-dependent ecosystems – summary of 'evidence'

GDE type	Name	GDE	Aquifer	Hydrogeological evidence (Searle & Degens 2017)	Ecological evidence
Wetland	Ngadalargin	Yes	Local & Broome	AEM, drilling, GW & SW (levels, chloride, isotopes), recharge rates	Low SWP[1], vegetation composition & condition, isotopes,
	Triangle	Yes	Local	AEM, drilling, GW & SW (levels, chloride, isotopes), recharge rates	Low SWP, isotopes, vegetation composition
	Oval	Yes	Local & Broome	AEM, drilling, GW & SW (levels, chloride, isotopes), recharge rates	SWP, vegetation composition & condition
	Flow Dam	Yes	Local	AEM, SW sampling (chloride, isotopes), GW depth	SWP, vegetation composition & condition, isotopes
	Wibbijagun	Yes	Broome	Groundwater (depth, chloride)	SWP, vegetation composition & condition, isotopes
Creek	Illelang	Yes	Broome[2]	AEM, SW (radon, chloride, isotopes), flow rate, GW depth	SWP, vegetation composition & condition, isotopes
	Bindingangun	Yes	Broome[2]	AEM, SW (radon, chloride, isotopes), GW depth	SWP, vegetation composition & condition
	Jabirr Jabirr	Yes	Broome	AEM, drilling, GW & SW (levels, radon, chloride, isotopes)	SWP, vegetation composition & condition, isotopes
Spring	Banana Well	Yes	Broome		SWP, vegetation composition & condition
Monsoon Vine Thicket	Mudoodon	Yes	Broome	AEM, GW (depth, age dating, isotopes)	SWP, vegetation composition & condition
Phreatophytic vegetation	Kurrukurugun	Yes	Local & Broome	AEM, GW depth	SWP, vegetation composition & condition
	Walmadan	Yes	Broome	AEM, GW (depth, age dating, isotopes)	SWP, vegetation composition & condition
Reference	DPB06	No	n/a	AEM, drilling, GW (depth, isotopes)	SWP, vegetation composition & condition, isotopes

[1]Shoot water potential, [2]Groundwater inputs well upstream of vegetation sampling site

7 Additional groundwater-dependent ecosystems – results and discussion

A second group of potential groundwater-dependent ecosystems was identified during various field campaigns and ongoing consultation with traditional owner groups and other stakeholders (Table 3). In visiting these sites we applied the species and ecosystem knowledge gained during the detailed investigations to determine their likely groundwater dependence.

Assessment of these sites was generally restricted to simple vegetation community descriptions as it was impractical to do the full suite of investigations. However, more detailed work was undertaken at some sites, as shown in Appendix C.

We visited a small number of sites in June 2014 with researchers from the National Environmental Research Program (NERP) and the Nyul Nyul ranger group. These sites were sampled for aquatic fauna and/or basic water quality and isotopes (Oxygen-18 and Deuterium) as part of a three-year study of freshwater wetlands in Nyul Nyul country. Some data were published in a freshwater management plan developed for the Nyul Nyul people (Dobbs, Davies et al. 2015) and are also presented here.

In this section we describe each of the additional sites in terms of the type of groundwater-dependent ecosystem, its location and general site description. We also describe the distribution of dominant species and depth to groundwater, where possible. If basic work, tree canopy condition and/or water quality was done we summarise the key findings (figures 69 and 70). Shoot water potential was also measured at some sites (Figure 71). These data were added to the study-wide vegetation datasets and used to characterise and map groundwater-dependent ecosystems in Section 8.

At the end of Section 7.8 we briefly describe which of our additional sites are groundwater-dependent, why we think so (evidence) and which groundwater (aquifer) – if any – they are likely to be accessing (Table 4, Figure 69).

Table 3 Additional sites

GDE type	Name and abbreviation	Easting	Northing	Description
Wetland				
	Crescent Lake	421818	8034185	Permanent freshwater wetland
	Boolamon	446843	8123123	Seasonal wetland
	Bungarrduk (BUN)	471136	8122634	Seasonal wetland
	Lake Louisa (LKL)	486429	8114270	Seasonal wetland
Creek				
	Illelang	412001	8085150	Fed by inland springs/seepages
Spring				
	Town Spring*	464413	8122163	Freshwater spring
	Pandanus Spring*	463657	8122326	Freshwater spring
	Bunda Bunda	427742	8103506	Freshwater spring
	Bobbis Creek springs (Donkey and Bubble spring)	Various locations		Freshwater springs
Monsoon vine thicket				
	Kardilakin and Rurrjaman	410915 413458	8055880 8051908	Monsoon vine thickets (Listed TEC)
Phreatophytic vegetation				
	Banana Well west (BWE)	456182	8123046	Woodland fringing salt flats
	Moorak (MOOR)	409895	8063011	Woodland over shallow groundwater
	Bindingangun south (BIN)	411281	8082676	Woodland over shallow groundwater
	Black Tank	423559	8036733	Woodland over shallow groundwater
	Manari Rd north			Mixed woodland over shallow groundwater
	Minaringy	410464	8081056	Woodland over shallow groundwater
Pindan reference				
	Pump 69	450637	8084246	Woodland on deep pindan soils
	DPB03	437461	8062347	Woodland on deep pindan soils
	DPB07	450998	8110048	Woodland on deep pindan soils

*project names

Figure 69 Additional and intensive groundwater-dependent study sites

7.1 Vegetation datasets - additional sites

Canopy condition

As with the extensive study sites, canopy condition (tree health) was only assessed as part of site descriptions when sites were first established. This was generally at the end of the wet season (May/June) in 2015. As a result trees would have been well hydrated and most likely at their healthiest. This also means we could not compare condition between wet (high water availability) and dry (low water availability) seasons.

Average canopy condition was recorded across 10 vegetation plots (Figure 70). No canopies were classified as being in poor or average condition, three were in good condition (score of 12–17) and the remainder were considered to be in very good condition (score > 17).

Trees at Banana Well west plots A and B received the lowest scores (15.7 and 15.8). The highest scores were recorded for the four plots at Bindingangun west (all > 20).

Foliage cover

Although we aimed to assess foliage cover at the end of both the wet and dry to allow comparisons between seasons, only the Moorak plot was assessed in both seasons (Figure 71). All plots had open canopy covers. At Moorak canopy cover remained very similar across the dry season.

Shoot water potentials

Despite aiming to measure shoot water potentials of important overstorey species at the end of both the wet and dry to allow comparisons between seasons, only the Moorak site was assessed in both seasons (Figure 72).

Both *Melaleuca dealbata* and *C. bella* maintained high levels of hydration across the dry season even though there was a notable decline in shoot water potential (i.e. shoot water potentials were less negative). *Lophostemon grandiflorus* was only sampled at the end of the dry, but was very water stressed at that time (i.e. shoot water potentials were most negative). This is a similar result to the intensive sites where the *L. grandiflorus* were also relatively water stressed, suggesting they were not accessing groundwater.

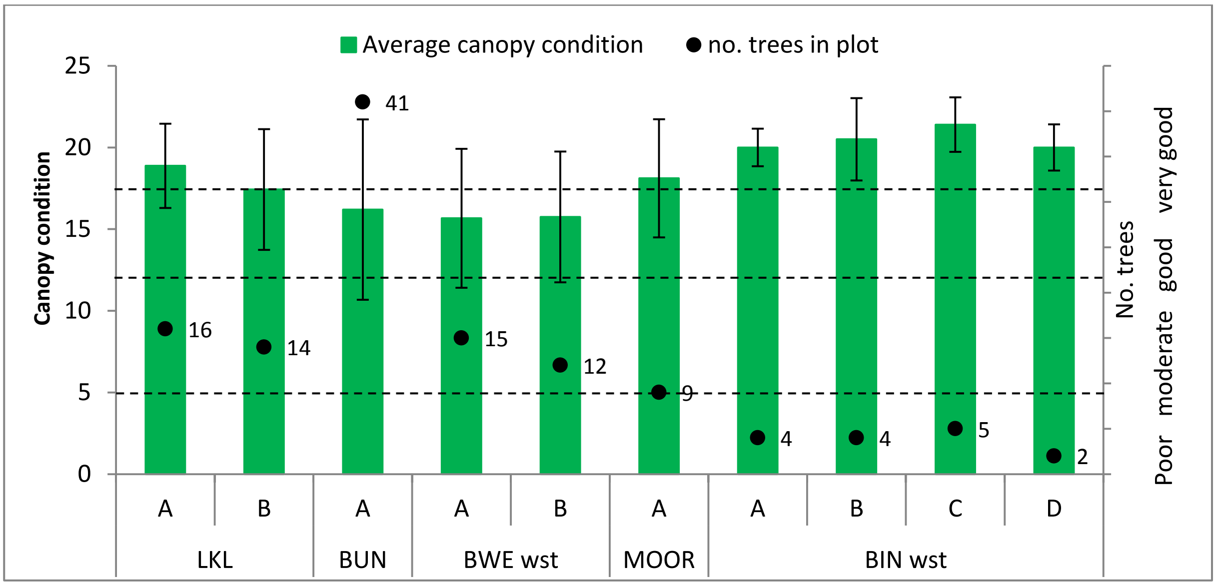


Figure 70 Average canopy condition by plot – additional sites

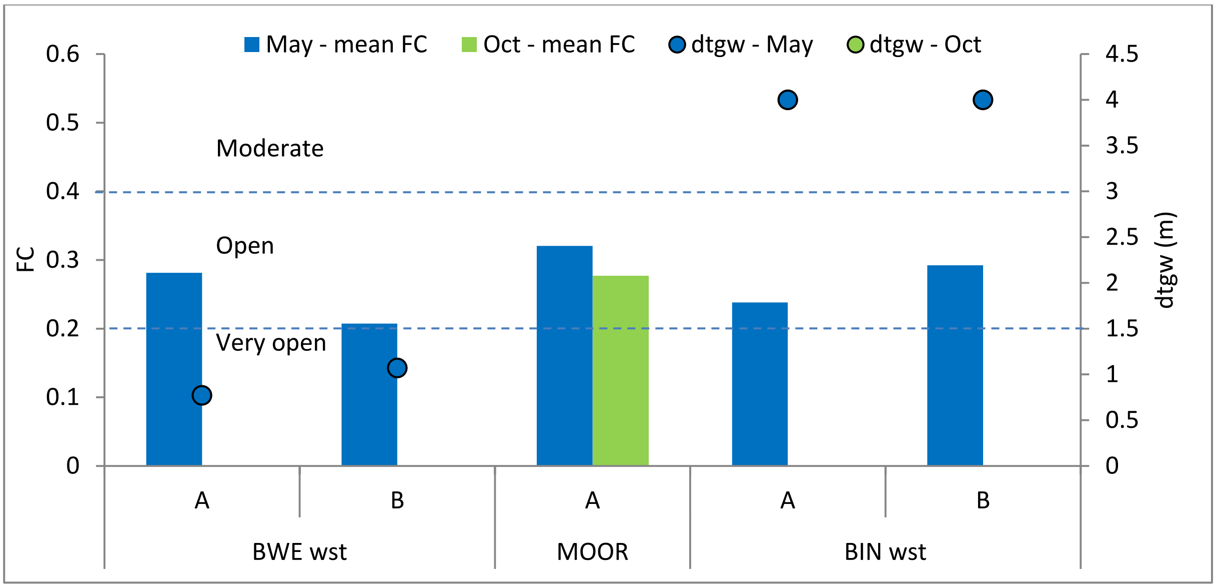


Figure 71 Average foliage cover (FC) and depth to groundwater – additional sites

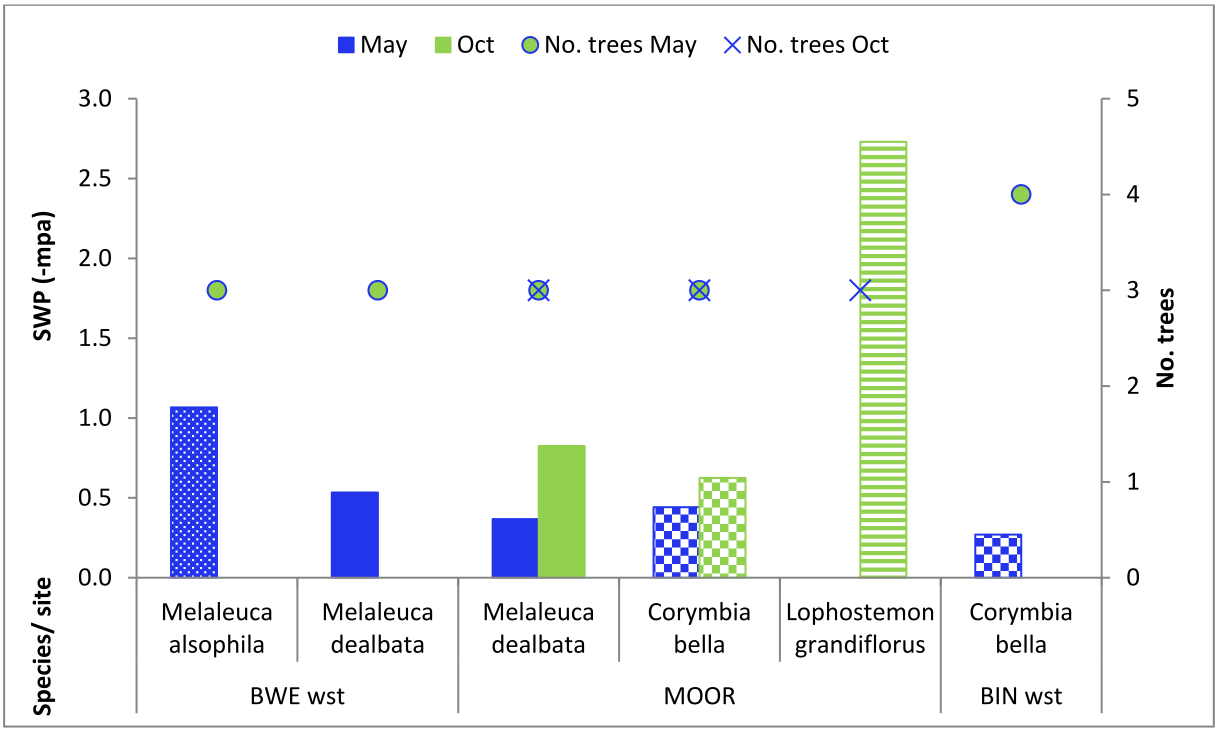


Figure 72 Shoot water potentials of key species – additional sites

7.2 Wetlands

Crescent Lake (Willie Creek wetlands)

Site description and methods

Crescent Lake, Nimalaica Swamp/Clay Pan (figures 68, F14, F15) and another unnamed wetland form part of the Willie Creek wetlands, a DIWA-listed system (Environment Australia 2001). The Nimalaica Clay Pan is listed as a PEC (Department of Parks and Wildlife 2016). These permanent, spring-fed freshwater wetlands fringe the eastern edge of the tidal-dominated Willie Creek system.

Although *Melaleuca alsophila* is dominant around the system, both of these wetlands support large stands of *M. cajuputi* (or *M. dealbata*) open-forest with *Timonius timon* and *Pandanus spiralis* – all freshwater species. Spike rush (*Eleocharis dulcis*) sedgelands also occur along with patches of *Typha domingensis* and *Acrostichum speciosum* (mangrove fern). Many of the species found here are at their southern range limits or are disjunct populations (DPAW 2014).

As part of the hydrogeological investigations, three shallow piezometers (CR1: 80110349, CR2: 80110350, CR3: 80110351) were hand-augered to the watertable near the freshwater/saltwater species transition zone at Crescent Lake. The bores were sampled for a broad range of parameters including CFCs and Carbon-14 (^{14}C) used to date groundwater. Surface water samples were also taken.

Results

In April 2015 depth to groundwater of 1.07 m was measured at bore CR1 within the freshwater vegetation, and the water was considered fresh at 380 mg/L TDS. Depth to groundwater increased moving away from the wetland: 3.3 mbgl at CR2 and 3.74 at CR3.

Carbon-14 and CFC age dating suggest there is a mixture of young and older water, possibly due to mixing of deeper groundwater being forced up over the seawater interface and discharging along the coast and Willie Creek area (Searle & Degens 2017). Water closest to the wetland at CR1 is oldest, becoming progressively younger towards CR3 (1262 years old, 37 years old and ‘modern’ respectively). However, CFCs were also found in CR1 and CR2, suggesting mixture with water recharged during the past 70 years (after introduction of CFCs into the atmosphere in the 1940s).

Surface water samples taken at the end of dry season were not salty but brackish (1410 mg/L) – despite the proximity to tidal flats and influence of high tides – suggesting fresh groundwater input.

The wetlands dried out in late 2015, anecdotally a very rare event, leading to fish deaths. It was thought that this was a combination of low rainfall and increased groundwater abstraction from the recently extended Broome town water supply borefield immediately to the east. Despite a very poor 2015–16 wet season, water levels rose in April/May 2016. It was found that groundwater abstraction had declined over this period due to operational issues.

Is Crescent Lake a groundwater-dependent ecosystem?

The area is sitting on a shallow watertable in a regional groundwater discharge zone (Searle & Degens 2017). Discharge is probably the result of upward flow of deeper groundwater to the surface caused by the seawater interface beneath the wetland.

The historical permanence of the wetlands and their reported response to increased groundwater abstraction combined with the shallow watertable, groundwater age and presence of freshwater vegetation shows the wetlands depend on groundwater from the regional Broome aquifer.

Lake Louisa (Rubabunan)

Site description and methods

Rubabunan was sampled under the NERP program. The lake is a large, shallow, semi-permanent wetland near the inland extent of Bobbis Creek (Figure 69). It fills during the wet and dries in all but the wettest years (Dobbs, Davies et al. 2015).

This site is important as a hunting place for the Nyul Nyul people. They hunt for cattle, bush turkey, goanna, ducks and duck eggs and other birds (Dobbs, Davies et al. 2015).

The vegetation fringing Rubabunan is predominantly mixed woodland of *Eucalyptus camaldulensis* (river red gum) and *Melaleuca nervosa.* However, in lower-lying areas that are inundated for at least part of the year, *Lophostemon grandiflorus* forms low-open woodland (Appendix F, Figure AF16). The wetland itself supports numerous aquatic herbs including the priority species *Nymphoides beaglensis* (P3), *N. violacea* (water lily) and *Najas tenuifolia* (Dobbs, Davies et al. 2014).

Results

We assessed canopy condition across two transects: one parallel to the lake and the other moving upslope away from the lake. Overstorey species on both transects were found to be in good to very good condition (LKL on Figure 72).

Two native fish species were recorded during the NERP surveys: Jalabunan (ox-eye herring, *Megalops cyprinoides*) and Madjalk (milkfish, *Chanos chanos*) along with the introduced mosquito fish (*Gambusia holbrooki*). Both native species are estuarine or near-shore marine species that move into freshwater when wetlands are connected. As Rubabunan is 35 km from the coast, and dries most years, this shows a high degree of connectivity between the wetland and Bobbis Creek during the wet.

Macroinvertebrates recorded at Rubabunan included highly mobile beetles, mayflies and true-waterbugs along with snails and crustaceans.

Is Rubabunan groundwater-dependent?

NERP's water quality results suggest the lake has a high evaporation rate with little or no groundwater input to replace evaporated water over the dry season (Dobbs, Davies et al. 2015).

Bungaduk

Site description and methods

Bungaduk was sampled under the NERP program. It is a semi-permanent waterhole on Bobbis Creek (Figure 69). It fills during the wet and dries most years. Early in the dry season (May/June) the pool can be up to 40 m wide and 400 m long.

The wetland is part of a significant Song Cycle and migration route and these days is also an important local picnic and camping place (Dobbs, Davies et al. 2015).

There is a very narrow band of *Melaleuca alsophila* and *M. viridiflora* fringing the wetland (Appendix F, Figure AF17) with some *M. alsophila, Pandanus spiralis* and *Corymbia bella* upslope. Numerous aquatic species occur in the wetland itself including *Elocharis dulcis* (sedge) and *Nymphaea beaglensis* (P3)*, N. violacea* and *Najas tenuifolia*.

Results

Overstorey species fringing the waterhole were found to be in good condition (BUN in Figure 70).

Four native fish species were recorded during the NERP surveys. Jalabunan (ox-eye herring, *Megalops cyprinoides*), empire gudgeon (*Hypeseleotris compressa*), Garajj (barramundi, *Lates calcarifer*) and Barool (lesser salmon catfish, *Neoarius graeffei*) (Dobbs, Davies et al. 2015). However, the introduced mosquito fish was the most common. Fish species composition was found to change from year to year depending on how easily they could migrate from the coast during the wet season (Dobbs, Davies et al. 2015).

Water quality readings in October 2013 showed fresh, slightly acidic water (pH 6.1) with low turbidity (Dobbs, Davies et al. 2015). Shallow groundwater in the area was also found to be slightly acidic (Searle & Degens 2017).

Is Bungaduk groundwater-dependent?

The wetland is not considered highly groundwater dependent (Dobbs, Davies et al. 2015). However, the freshness of the spring water and its proximity to known springs means the possibility of groundwater input to Bungaduk cannot be discounted.

Boolamon

Site description and methods

Boolamon is north-east of Oval wetland within the Twin Lakes Cultural Park (Figure 69). The park is an Aboriginal business operated on land held by Manowan Aboriginal Corporation on behalf of Nyul Nyul families.

Boolamon Lake is semi-permanent and probably connected to the adjacent, tidally dominated Camp Inlet. It was sampled under both the NERP program and the hydrogeological investigation.

The wetland is fringed by low-forest of large, multi-stemmed *Melaleuca alsophila* with *Eleocharis* sp. and *Cynodon dactylis* (exotic grass) in the understorey (Appendix F, Figure F18). *Nymphaea violacea* (water lily) and *Najas tenuifolia* occur in the wetland itself.

In the mid dry season the lake is up to 250 m wide, 600 m long and 1.5 m deep. Lake water was considered brackish with low turbidity (Dobbs, Davies et al. 2015).

Results

NERP and the Nyul Nyul rangers recorded four native fish: Jalabunan (ox-eye herring, *Megalops cyprinoides*), Garajj (barramundi, *Lates calcarifer*), Madjalk (*Chanos chanos*) and Banjarr (banded scat, *Selenotoca multifasciata).* Significantly, no mosquito fish were recorded.

Numerous macroinvertebrates were noted, including mussels, worms, water mites, fly larvae, beetles, snails and dragonfly larvae. Wedgetail eagles and heron and seven other bird species were also recorded.

Is Boolamon groundwater-dependent?

Boolamon is not likely to have any groundwater inputs. Water levels and chemistry are strongly influenced by evaporation over the dry season (Dobbs, Davies et al. 2015).

Twin Lakes (Gunmamirrd and Goolyaroodk)

Site description

The Twin Lakes, south of Boolamon, are further from the coast but still within the Twin Lakes Cultural Park (Figure 69).

The lakes appear to be semi-permanent. Gunmamirrd is fringed by *Lophostemon grandiflorus* woodland with some *Melaleuca dealbata* and *Corymbia bella. Nymphaea violacea* occur in the wetland (Appendix F, Figure F19). *Nematolosa erebi* (bony bream) and *Anguilla bicolor* (freshwater eel) are known to inhabit the lake.

A water supply bore 500 m east of Gunmamirrd was sampled in June 2014. The depth to groundwater was approximately 5.5 m.

Are Twin Lakes groundwater-dependent?

There is insufficient information to determine if the wetlands are groundwater fed. However, the presence of *M. dealbata* and *C. bella* at Gunmamirrd and shallow groundwater nearby suggests there may be some groundwater input.

7.3 Creeks

Julyulkun

Site description

Julyulkun is south of Illelang (Figure 69) with headwaters about 7 km inland from the coast. They appear to originate from a line of springs in much the same way as Bindingangun and Illelang.

The vegetation fringing the lower reaches of the creek is mostly woodland of *Melaleuca alsophila.* Vegetation composition upstream is unknown, although woodland of *M. dealbata* fringes a drainage line running south-west from Illelang to Julyulkun, possibly the old course of Illelang.

Is Julyulkun groundwater-dependent?

As with Illelang and Bindingangun, the lower reaches of Julyulkun are tidally influenced. It is expected that the vegetation upstream is also similar to these larger creeks. It is therefore highly likely that this creek line is, in part at least, also maintained by groundwater-fed springs.

7.4 Springs

Bobbis Creek springs – Donkey Spring and Bubble Spring

Site descriptions and methods

Bobbis Creek discharges into Beagle Bay (Figure 69). The creek floods/flows in most wet seasons, but after very low rainfall in 2005 (and probably 2015–16) no flow was recorded. The location of 20 mound springs has been confirmed along the creek, including Lolly Well Springs – a priority 4 ecological community (Ecologia Environmental 2004b). Artesian flow from some community bores along the north of the study area has also been reported along with numerous small springs (Searle & Degens 2017).

The Nyul Nyul rangers and NERP sampled a number of springs on Bobbis Creek for water quality parameters and isotopes (Deuterium and Oxygen-18). The small, permanent wetlands of Donkey and Bubble springs were sampled on two occasions.

In June 2014 Bubble Spring was little more than a very shallow, muddy pool which had been trampled by donkeys and/or cattle (Appendix F, Figure AF20). However, the spring supports a small, yet dense stand of *Melaleuca viridiflora*, which is in stark contrast to the surrounding open grassland.

Donkey Spring is larger and deeper than Bubble Spring and supports a small number of *M. alsophila, M. viridiflora* and *Corymbia bella* (Appendix F, Figure AF21). A dense mat of the sedge species *Schoenoplectus mucronantus* has formed in the middle of the spring. At the time of the site visit in June 2014, there was evidence of recent fire and grazing by donkeys and/or cattle.

Results

The springs seemed to be driest at the end of the wet season and wettest in the mid dry season, suggesting groundwater input. Isotope data supported this – showing there was little enrichment from evaporation over the dry season.

Although the water in the springs was fresh, turbidity varied in response to the presence of donkeys and/or cattle (Dobbs, Davies et al. 2015).

Are the Bobbis Creek springs groundwater-dependent?

The permanence and freshness of these small springs along with the presence of freshwater vegetation suggests they are supported by groundwater inputs.

Beagle Bay springs – ‘Town Spring’ and ‘Pandanus Spring’

Site descriptions

There are several small springs in and around the Beagle Bay community where Bobbis Creek approaches the coast. We visited two of the springs in June 2015 with the Nyul Nyul rangers and took water quality readings at Pandanus Spring.

A very small (< 10 m wide) spring-fed pool sits on the side of the main road into the community (Town Spring) (Figure 69). It supports *Melaleuca dealbata, Corymbia bella, Pandanus spiralis* and *Typha domingensis.* At the time of the site visit, the Nyul Nyul rangers had just finished fencing the wetland to prevent impacts from donkeys and were in the process of a controlled burn.

A slightly larger (< 20 m wide) permanent spring-fed pool to the west of the community (Pandanus Spring) supports *M. nervosa, P. spiralis, Lygodium microphyllum* (climbing maidenhair fern), *Cyperus difformis* and an unidentified sedge species (Appendix F, Figure F22). Water quality measured in-situ showed it was very fresh (154 µs/cm or < 100 mg/L TDS).

Are the Beagle Bay springs groundwater-dependent?

Although these springs were not directly sampled during the NERP project, it was found that evaporated water is rapidly replaced by groundwater in other, similar springs around Beagle Bay (Dobbs, Davies et al. 2015). This, combined with the freshness of the water and the presence of freshwater vegetation at the springs, suggests the Beagle Bay springs are groundwater-dependent.

The locally confined aquifers within the Broome Sandstone are likely to be the source for the springs, however this cannot be confirmed without further study. The springs could also be related to a major fault that runs north-west close to the spring sites (Beagle Bay fault) (Searle & Degens 2017).

Bunda Bunda

Site description

Bunda Bunda mound springs is situated on the coast near the Carnot Springs Community in the Coloumb Point Nature Reserve (figures 69 and F23). It is listed in the DIWA as a freshwater spring of outstanding cultural significance and is also listed as a TEC (Environment Australia 2001).

The spring supports the only occurrence of ‘wet rainforest’ on the Dampier Peninsula. Vegetation includes the freshwater tree species *Timonius timon, Carallia brachiata*, *Sesbania formosa* and *Melaleuca cajuputi.* It also supports fern species including *Lygodium microphyllum* (climbing maidenhair)*, Cyclosorus interruptus* and *Acrostichum speciosum* (mangrove or swamp fern).

Is Bunda Bunda groundwater-dependent?

Although not sampled as part of the project, Bunda Bunda is considered to be groundwater-dependent. It is thought that the Broome Sandstone discharges from depth through the overlying alluvium to the surface.

7.5 Monsoon Vine Thickets

Kardilakin and Rurrjaman

Site description

The Kardilakin monsoon vine thicket (MVT) site is located at the northern end of the Quondong Point access track. The Rurrjaman MVT is to the south on Manari Road between the Quondong Point access track and Barred Creek (Figure 69).

Department of Parks and Wildlife (then DEC) mapped both areas as evergreen monsoon vine thicket (MVT).

A substantial number of overstorey species may occur in a MVT and these form part of the diagnostic characteristics for the community type. At both sites *Diospyros humilis* (Birimbiri, ebony wood) are dominant with *Bauhinia cunninghamii* (Jigal) and *Corymbia bella.*

The shallow water supply bore at Mudoodon (80119857) 2.7 km north of Quondong Point was sampled for isotopes and water quality during the hydrogeological investigation program.

Are MVT at Kardilakin and Rurrjaman groundwater-dependent ecosystems?

Samples from Mudoodon bore show the Kardilakin/Rurrjaman area is sitting on a shallow watertable in a regional groundwater discharge zone (Searle & Degens 2017). In this location, deep, old water is forced upwards over the saltwater interface, the presence of which was confirmed by the AEM.

The Kardilakin and Rurrjaman MVT are therefore considered dependent on groundwater from the regional Broome Sandstone aquifer.

7.6 Phreatophytic vegetation

Moorak

Site description and methods

The Moorak terrestrial vegetation site is on Manari Road, immediately west of the James Price Point industrial hub proposal area, about 50 km north of Broome (Figure 68). Biota Environmental Sciences (2009) mapped the area as a drainage basin.

An open mixed woodland of *Melaleuca dealbata, Corymbia bella* and *Lophostemon grandiflorus* over a weedy understorey is dominant along the road edge (Appendix F, Figure AF24).

A transect comprising two 20 x 20 m plots was set up in May 2014 to capture the range of dominant species. Canopy condition, leaf area index and shoot water potential were measured at this time.

No piezometers were installed or holes augered, although there is an old bore and windmill 200 m to the south and a series of bores drilled by Woodside within a kilometre to the east. Depth to groundwater measured at the closest Woodside bore – BH6X (80110304) 500 m to the south-west of the plot – was approximately 6 m.

Moorak also sits between JP (80110236) and Mudoodon (80119857), bores that were sampled for isotopes and water quality during the hydrogeological investigation program.

Results

Canopy condition in the three overstorey species was good to very good (MOOR in figures 70, 71 and 72). Canopy cover declined slightly across the dry season (Figure 71) and there was a corresponding decrease in shoot water potential over the same period. However, only *L. grandiflorus* showed indications of water stress (Figure 72).

As previously described, the hydrogeological investigation showed that groundwater in JP bore had a radiocarbon age of 1300 to 2200 years, and did not contain detectable amounts of CFCs, so was recharged before 1940 when CFCs were introduced (Searle & Degens 2017) and not by recent rainfall.

Is Moorak a groundwater-dependent ecosystem?

Based on groundwater aging, the hydrological investigation showed the broader area sits over a shallow watertable in a regional groundwater discharge zone. At this location, deep, old water is forced upwards over the saltwater interface, the presence of which was confirmed by the AEM (Searle & Degens 2017).

Combined with the shallow groundwater at the closest bore and the continued health of the overstorey, the above suggests the vegetation at Moorak is at least partially dependent on groundwater from the regional Broome Sandstone aquifer. However, it is possible that it also receives surface inputs from the drainage line.

Banana Well west

Site description and methods

Banana Well west terrestrial vegetation site (Appendix F, Figure F25) is less than 2 km north-west of the Banana Well spring on the edge of the expansive salt flats associated with the mouth of Bobbis Creek (Figure 69). Aerial photographs suggest there is a permanent wetland, possibly a spring, within 200 m of this site.

Open forest of *Melaleuca alsophila* fringes the salt flats grading into open woodland of *M. dealbata* and *Corymbia bella* moving upslope away from the tidal influence. *Pandanus spiralis* also occur at the higher elevations. There is a dense grassy understorey of *Pseudoraphis spinescens* (cutting grass) with some of the exotic *Passiflora edulis* (passionfruit vine).

A transect comprising two 20 x 20 m plots was set up in April 2015 to capture the range of the three dominant species. Shoot water potential, canopy condition and leaf area index were measured at this time and a shallow hole hand-augered to determine the depth to the watertable.

Results

Canopy condition, canopy cover and shoot water potential were only measured at the end of the wet (BWE west in figures 69, 70 and 71). Canopy condition in the three overstorey species was good although the canopy of both plots was considered relatively open. The *M. alsophila* at the edge of the salt flats were less hydrated than the *M. dealbata* further upslope. One *M. alsophila* sapling and one *M. dealbata* seedling were recorded at the site.

The depth to groundwater at the hand augered site in April 2015 was 1.07 m.

Is Banana Well west a groundwater-dependent ecosystem?

The spring at Banana Well is one of many springs in the area thought to be fed by groundwater from localised aquifers within the Broome Sandstone.

The shallow groundwater noted at the Banana Well west site, along with the presence of healthy freshwater species, suggests the same hydrogeological mechanism that supports the nearby springs also supports the vegetation. The terrestrial phreatophytic vegetation at this site is therefore considered dependent on groundwater from the regional Broome Sandstone aquifer.

Bindingangun west (Yellow River west)

Site description and methods

The terrestrial vegetation site at Bindingangun (Appendix F, Figure F26) is about 800 m west of the river/stream site (Figure 69). It is significantly higher in the landscape, sitting on the top of the terrace. The Goolarabooloo people describe this site as being on the old river flow line. A shallow community bore (YRA) is located in this area.

The site is dominated by open woodland of *Corymbia bella* with *Gyrocapus americanus, Bauhinia cunninghamii* and *Grevillea pyramidalis* over mixed shrubs and grasses.

A transect comprising four 20 x 20 m plots, running perpendicular to the river, was set up in April 2015 to capture the range of *C. bella,* although there was very little change in gradient. Shoot water potential, canopy condition and leaf area index were measured at this time.

The bore was sampled for a range of groundwater parameters to determine quality and age.

Results

The condition of the *C. bella* was very good, although the canopy was quite open (figures 69 and 70). Shoot water potentials showed trees were very well hydrated, as would be expected at the end of the wet season (Figure 72).

Groundwater was fresh (350 mg/L TDS). The shallow bore (YRA) is thought to be in a sand bed of the confining layer first described at DPB06, which based on AEM is a continuous layer. The groundwater has a radiocarbon age of about 17 600 years, and a weak upward head (upward pressure). Water was found to be significantly older at YRA than in DPB06 (Searle et al. 2016) – suggesting flow could be toward the coast (i.e. from DPB06 to YRA) with the aquifer recharged near the centre of the peninsula.

Is Bindingangun west a groundwater-dependent ecosystem?

The health and presence of *C. bella* over fresh, shallow groundwater suggests the individuals are groundwater-dependent. They are likely accessing a freshwater lens (local watertable) sitting within the confining layer. However, it is also possible that this local aquifer is connected to and supported by the regional aquifer.

Black Tank

This terrestrial vegetation site is located near an old Waterbank Station water supply bore, Black Tank (80119874). It is about 1.5 km east of Crescent Lake on the corner of Manari and Cape Leveque roads (Figure 69).

There is an isolated patch of *Melaleuca dealbata* and *Corymbia bella* over mixed grasses. The depth to groundwater at this site is less than 4.0 m.

Is Black Tank a groundwater-dependent ecosystem?

The site’s proximity to Crescent Lake, known to be dependent on groundwater from the regional Broome aquifer, along with the presence of freshwater species and shallow groundwater, suggests vegetation at Black Tank is groundwater-dependent.

Manari Road North (Flat Rock/Dugool to Illelang)

A strip of terrestrial vegetation along Manari Road between Illelang and Flat Rock (Figure 68), where drainage lines flow into coastal sand dunes, supports extensive yet discontinuous stands of freshwater tree species. Open woodlands of *Melaleuca dealbata, Lophostemon grandiflorus* and/or *Corymbia bella* with *Pandanus spiralis* are common (Appendix F, Figure F27).

Also within this area is a drainage line running south-west from Illelang to Julyulkun, possibly the old course of the creek. Woodland of *M. dealbata* fringe the drainage line.

No hydrological or ecological investigations were undertaken in the area. However, depth to groundwater was estimated as less than 10 m, based on topography and groundwater contours (Searle & Degens 2017).

Is Manari Road North a groundwater-dependent ecosystem?

The presence of known groundwater-dependent species over a shallow watertable suggests some areas of vegetation between Flat Rock and Julyulkun are groundwater-dependent. As with Mudoodon and Walmadan, also on the coast, it is possible that this is the regional Broome aquifer.

Minaringy (Pandanus palm cluster)

Site description

This site is about 100 m west of a saltwater creek (Minaringy) (Figure 69). Although not an MVT, this site occurs in the same position – on the leeward side of high coastal dunes – and supports *Pandanus spiralis* (Appendix F, Figure F27)*.* The creek itself is fringed with *Melaleuca alsophila* woodland.

No hydrological or ecological investigations were undertaken in the area.

Is Minaringy a groundwater-dependent ecosystem?

Pandanus spiralis is generally an indicator of fresh water. However, given the absence of other freshwater species and the site's location at the base of a sand dune, it is possible that a small localised freshwater aquifer has formed in the dunes and is supporting the 'palm cluster'. This is similar to the situation described previously for Triangle wetland.

7.7 Reference sites

We selected three additional reference sites over deep groundwater (greater than 30 mbgl) to further examine if non-groundwater-dependent vegetation communities differed in composition and condition to those with access to shallow groundwater.

DPB03

Site description and methods

DPB03A (80110162) is on the Cape Leveque Road about 50 km north-east of Broome (Figure 69). A deep bore was drilled here in October 2013 as part of the groundwater investigation program.

The area is dominated by pindan vegetation. It was chosen as a reference site because its position in the landscape suggested groundwater would be too deep for vegetation to access and it did not support any known phreatophytic species.

The vegetation community at the site was described as *Corymbia greeniana* scattered low trees to low open woodland (patchy) over *Acacia eriopoda* tall shrubland over *Dodonaea hispidula, Acacia hippuroides* scattered shrubs over *Sorghum plumosum*, *Chrysopogon fallax* and *Eriachne obtusa* tussock grassland.

Before the deep bore was installed, a plant survey was conducted by Outback Ecology (2013). This was to determine whether any species of conservation significance occurred within the area and if so, to locate an alternative site for the drill pad and associated track.

A logger was installed in the bore and it was sampled for a range of groundwater parameters.

Results

AEM and groundwater sampling results showed the area overlies the deep, unconfined Broome Sandstone aquifer. The depth to groundwater at DPB03 at the time of drilling was 135 m.

Only one conservation-significant species, the Priority 1 species *Glycine pindanica* was recorded during the survey. The vegetation association supporting this species appeared to be widespread and the locations of *G. pindanica* widely spaced, therefore it was considered quite feasible that a drilling program could be undertaken that would impact either none or very few of this species (Outback Ecology 2013).

Is DPB03 a groundwater-dependent ecosystem?

The absence of species previously determined to be groundwater-dependent, coupled with the deep groundwater at DBP03, indicates the vegetation at the site is not groundwater-dependent.

Pump 69 – reference site

Site description and methods

Pump 69 (80110214) is a Main Roads water supply bore, installed in 2013. It is in the centre of the study area on the Cape Leveque Road about 80 km north-east of Broome (Figure 69). It was also chosen as a reference site as its position in the landscape suggested groundwater would be too deep for vegetation to access and it did not support any known phreatophytic species.

Vegetation at the site is dominated by *Corymbia greeniana* and *Eucalyptus miniata* open woodland over *B. cunninghamii* (Jigal), *Acacia colei* (soap bush) and *Codonocarpus cotinifolius* (native poplar) over mixed grasses (Appendix F, Figure F28).

A logger was installed in the bore and it was sampled for a range of groundwater parameters. Although the bore appears to sit in a drainage line, the depth to groundwater is about 32 m.

Is Pump 69 a groundwater-dependent ecosystem?

The depth to groundwater, sampling results and AEM show Pump 69 is located on a deep unconfined aquifer, which indicates that vegetation at the site is not groundwater-dependent.

DPB07A

Site description and methods

DPB07A (80110167) (Appendix F, Figure F29) is on the privately owned Carnot Bay access track about 6.5 km west of the Cape Leveque Road and 15 km east of DPB06A (Figure 69). A deep bore was drilled here in November 2013 as part of the groundwater investigation program.

The site is within a very large area of pindan vegetation. It was chosen as a reference site as its position in the landscape suggested groundwater would be too deep for vegetation to access and it did not support any known phreatophytic species.

Low open woodland of *Corymbia greeniana* (Dampier's bloodwood) and *Eucalyptus tectifica* (Darwin box) over mixed shrubs and grasses dominate the area.

Depth to groundwater at the deep bore was about 86 m at the time of installation. A logger was installed in the bore and it was sampled for a range of groundwater parameters.

AEM and groundwater sampling results showed the area overlies the deep, unconfined Broome Sandstone aquifer.

Is DPB07 a groundwater-dependent ecosystem?

The depth to groundwater and AEM results, which show a deep unconfined aquifer, indicate that vegetation at DBP07 is not groundwater-dependent.

7.8 Summary

In this section we briefly describe which of our additional study sites are groundwater-dependent, summarise why we think so (evidence) and indicate which groundwater (aquifer) – if any – they are likely to be accessing (Table 4).

Crescent Lake, part of the Willie Creek wetlands, was determined to be dependent on the Broome Sandstone aquifer. Although much of Willie Creek is tidally influenced and dominated by *Melaleuca alsophila,* the wetlands at its inland fringe support stands of *M. cajuputi* and other freshwater species. This coastal area is a regional groundwater discharge zone, with a mix of old and younger groundwater being pushed up over the saltwater interface.

Monsoon vine thickets (MVT) at Kardilakin and Rurrjaman and the phreatophytic vegetation at Moorak and Black Tank also occur in the coastal discharge zone. These sites were therefore also considered dependent on groundwater from the Broome aquifer. Kardilakin and Rurrjaman support vegetation characteristic of MVT, while *M. dealbata* and *Corymbia bella* are dominant at Moorak and Black Tank. *Lophostemon grandiflorus* is also found at Moorak.

Further to the north, phreatophytic vegetation sites at Illelang and Bindingangun also occur in the coastal discharge zone, however the aquifer is much thinner due to the presence of a confining layer. *M. dealbata, Pandanus. spiralis* and/ or *C. bella* occur at these sites. Further upstream both creeks are supported by spring-derived flows from the east – also from the Broome Sandstone. Here *M. nervosa* and *P. spiralis* fringe the creeks.

Julyulkun itself is likely to be fed in part from the inland springs in the same way as Bindingangun, Illelang and Jabirr Jabirr.

The small stand of *P. spiralis* at Minaringy was not thought to be associated with the Broome Sandstone, as the area is tidally influenced and dominated by *M. alsophila.* It is possible that a localised, shallow aquifer has formed under the nearby dunes in much the same way as at Triangle wetland, and this supports the *P. spiralis*.

Phreatophytic vegetation running along the coast between Dugool (Flat Rock) and Julyulkun was determined to be groundwater-dependent. However, it is not clear if the source is the regional discharge zone or a localised aquifer formed by direct rainfall and/or creekflow banking up behind the dunes. This area supports *M. dealbata* and large stands of *L. grandiflorus*.

Phreatophytic vegetation at Banana Well west is likely to depend on the Broome Sandstone, where groundwater comes to the surface at the coast (Beagle Bay). There are a number of small, unnamed springs on the nearby coastal mudflats, which are also likely to be supported this way. Although the vegetation on the fringe of the mudflats is dominated by *M. alsophila, M. dealbata, C. bella* and *P. spiralis* occur slightly upgradient on sandy soils.

Bunda Bunda mound spring relies on groundwater from the Broome Sandstone discharging from depth through the overlying alluvium to the surface. *M. cajuputi* and *Sesbania formosa* are among the dominant species.

Donkey and Bubble springs on Bobbis Creek and Pandanus and Town springs near the Beagle Bay community were all determined to be groundwater-dependent. The locally confined aquifers within the Broome Sandstone are likely to be the source for the springs, however this cannot be confirmed without further study. The springs could also be related to a major fault running north-west close to the spring sites (Beagle Bay fault). All four springs are very small, have free-standing water and support stands of *M. viridiflora.*

It was unclear if the northern wetlands, Bungaduk and Twin Lake are groundwater-dependent as neither are permanent but still show some evidence of groundwater input. *M. alsophila* and *M. viridiflora* are dominant at Bungaduk and *L. grandiflorus* at Twin Lakes.

Boolamon and Rubabunan wetlands are not groundwater-dependent. Both are strongly influenced by evaporation and show no evidence of groundwater input. Boolamon is dominated by *M. alsophila* and Rubabunan by *L. grandiflorus*, although there are some fringing *Eucalyptus camaldulensis* and *M. nervosa*.

DPB03, DBP07 and Pump 69 are not groundwater-dependent. All three bores occur over the unconfined Broome Sandstone aquifer, which is too deep for vegetation to access. The vegetation is dominated by *C. greeniana* and *E. tectifica* accessing moisture held in the pindan soil.

Table 4 Additional sites – summary of 'evidence'

GDE type/name	GDE	Aquifer	Hydrogeological	Ecological
Wetland				
Crescent Lake	Yes	Broome	[1]GW & SW (isotopes, radon EC)	Veg composition & condition
Rubabunan	No	-	[1]GW & [2]SW (quality, isotopes)	–
Bungaduk	?	Broome	[1]GW & [2]SW (quality, isotopes)	Veg composition
Boolamon	No	-	[2]SW quality, isotopes	Veg composition
Twin Lakes	?	Broome	Depth to groundwater	Veg composition
Creek				
Julyulkun	Yes	Broome	Extrapolation (Illelang)	Extrapolation
Spring				
Donkey Spring	Yes	Broome	[2]SW quality, isotopes	Veg composition
Bubble Spring	Yes	Broome	[2]SW quality, isotopes	Veg composition
Town Spring	Yes	Broome	Extrapolation	Veg composition
Pandanus Spring	Yes	Broome	[1]SW quality	Veg composition
Bunda Bunda	Yes	Broome	Listed mound spring	Listed TEC
Monsoon Vine Thicket				
Kardilakin	Yes	Broome	Extrapolation (Mudoodon)	Listed TEC
Rurrjamam	Yes	Broome	Extrapolation (Mudoodon)	Listed TEC
Phreatophytic vegetation				
Moorak	Yes	Broome	Extrapolation (JP and Mudoodon bores)	Veg composition & condition, SWP
Banana Well west	Yes	Broome	Depth to groundwater	Veg composition & condition, SWP
Bindingangun west	Yes	Broome	[1]AEM, GW (radon, chloride, isotopes)	Veg composition & condition, SWP
Black Tank	Yes	Broome	Extrapolation (Crescent Lk)	Veg composition
Dugool – Julyulkun	?	?	Depth to groundwater	Veg composition
Illelang woods	Yes	Broome	Depth to groundwater	Veg composition
Minaringy	No	Local	Extrapolation (Triangle)	
Reference				
DPB03	No	-	[1]AEM, drilling, GW depth, radon, isotopes	Veg composition
Pump 69	No	-	[1]AEM, drilling, GW depth, radon, isotopes	Veg composition
DPB07	No	-	[1]AEM, drilling, GW depth, radon, isotopes	Veg composition

[1]Searle & Degens 2017; [2]Dobbs et al. 2014

8 Characterisation and mapping of groundwater-dependent ecosystems

Characterisation of groundwater-dependent ecosystems will support future groundwater-dependent ecosystem studies on the Dampier Peninsula and potentially the broader Kimberley region. Using vegetation composition and soil type, it will allow field officers to identify different types of potential groundwater-dependent ecosystems, even in the absence of depth to groundwater.

To characterise groundwater-dependent ecosystems into types, we identified and described the vegetation communities that were found to rely, or not rely, on groundwater.

Firstly we assessed species specific data to determine the likely level of dependence of key vegetation species (Section 8.1). We then characterised vegetation communities based on surface water, groundwater and soil conditions. The location of the vegetation in relation to landscape features, such as creeks, was also considered (Section 8.2). Using these data we then identified and characterised five types of groundwater-dependent ecosystem (Table 5).

In the project’s final phase we developed a groundwater-dependent ecosystem probability map which can be used as a predictive tool (Figure 75).

8.1 Groundwater-dependence of key vegetation species

In this section we summarise the results of the study-wide datasets to identify which of our key tree (overstorey) species are groundwater-dependent.

Shoot water potential

We analysed shoot water potential by species to see if there were differences in tree hydration between the end of the wet and end of the dry seasons (Figure 73). We sampled a much greater number of *Corymbia bella, Melaleuca dealbata* and *M. alsophila* than other species as they were more common at our study sites.

Results show there is no difference in shoot water potential between wet and dry seasons for *C. bella, M. alsophila* and *M. dealbata*. This supports our findings that these species are likely to be accessing shallow groundwater during the dry season to maintain their water potential during periods of low or no rainfall.

Although there is also no difference in *C. greeniana,* the small number of individuals sampled (three) had access to unexpectedly high soil moisture stored in pindan soils.

There is a difference in *Lophostemon grandiflorus* and *Diospyros humilis* – more negative in October – suggesting they may not have access to groundwater during the dry. However, as only two *D. humilis* were sampled in October, further work is required on this species. Although *M. nervosa* was less negative in October, only three individuals were sampled and these results need further verification.

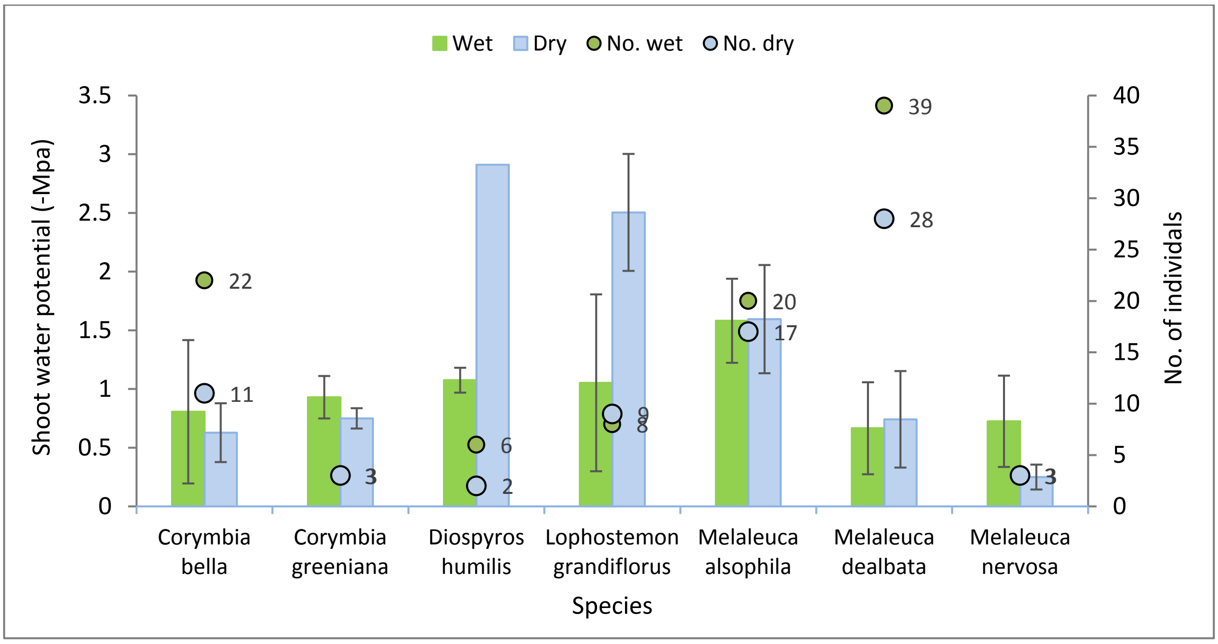


Figure 73 Average shoot water potentials of key species

Depth to groundwater

We found that all individuals of all the species we investigated occurred in areas where the depth to groundwater was less than 5 m from the land surface (Figure 74). This confirmed our choice of these sites, as we expected these species would be located in areas of shallow groundwater. Two species, *M. alsophila* and *M. dealbata,* were also inundated by shallow surface water. Although not recorded in the dataset, *L. grandiflorus* was inundated at two of the additional wetland sites.

The three melaleuca species and *Pandanus spiralis* had similar average depth ranges (x to y mbgl), although *M. nervosa* was only recorded at two sites. *C. bella* had a slightly deeper range. This supports findings in the literature that riparian melaleuca species are generally restricted to riversides, while *C. bella* is most often found on the top of levee banks (O'Grady, Eamus et al. 2005). *L. grandiflorus* and *D. humilis* occurred over the deepest average water levels – which is consistent with their low shoot water potentials (Figure 73). The large range in depths to groundwater experienced by *L. grandiflorus* suggest it is disconnected from groundwater during the dry.

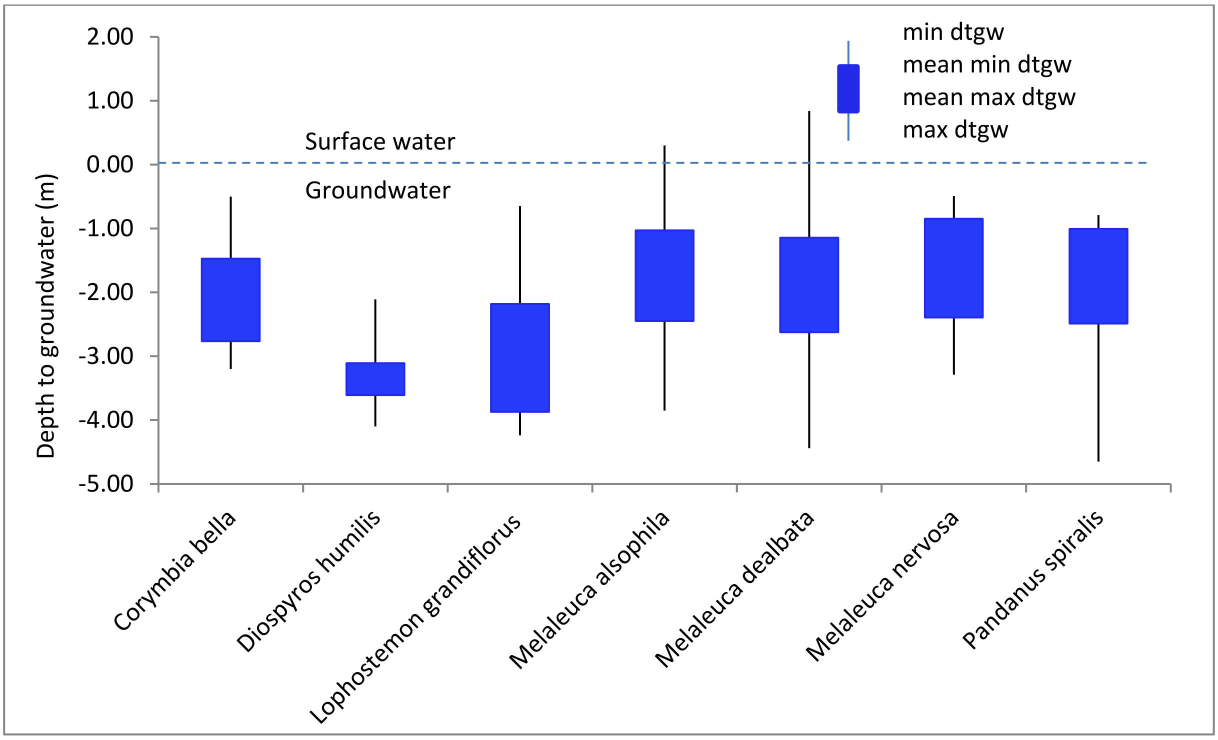


Figure 74 Water depth ranges of key species

8.2 Vegetation community characterisation

In this section we consider the outcomes of Section 8.1 and findings from the broader study to describe the dominant groundwater-dependent vegetation communities and the ecosystem types and water sources they are associated with.

Melaleuca alsophila

Melaleuca alsophila (salt water melaleuca) woodland on the Dampier Peninsula is generally associated with creeklines and wetlands with a significant surface water component, and is often flooded for part of the year. Surface water may come from ocean tides, surface flow (creeks) and/or rainfall runoff.

Although *M. alsophila* is also often associated with shallow groundwater (< 5 mbgl) and clayey soils, the key driver of its distribution appears to be the presence of brackish to saline surface water. Salts are derived from tides, evaporation and/or tree water use. However, *M. alsophila* is also found fringing some freshwater systems and can form mixed woodlands with *M. dealbata*.

The greatest densities of *M. alsophila* seedlings/saplings were recorded at Wibbijagun and Bindingangun where sandy clay soils had been seasonally inundated by freshwater, but became more saline with evaporation.

Melaleuca dealbata

Melaleuca dealbata (freshwater melaleuca) woodland is also associated with creeklines and wetlands and is tolerant of periods of flooding. However, as expected, it is strongly associated with freshwater systems and is rarely found in brackish conditions. *M. dealbata* is generally found in sandier soils than *M. alsophila.*

In addition to ecosystems with a significant surface water component, it is commonly associated with areas of shallow groundwater (< 10 mbgl) where it may also be found with *C. bella*.

The greatest densities of *M. dealbata* seedlings/saplings were recorded on the Illelang, Watermelon Dam and Oval wetland (DPB04-2) plots. These sites had sandy soils and had either been inundated by freshwater or sat on very shallow groundwater. On the Dampier Peninsula fresh, shallow groundwater is associated with the Broome Sandstone aquifer.

Corymbia bella

Corymbia bella most often occurs in mixed woodland with *M. dealbata*, although it can also form open woodland in areas with little to no flooding where depth to groundwater is < 10 mbgl. As with *M. dealbata* it seems to prefer sandy soils and fresh groundwater.

Melaleuca viridiflora and M. nervosa

Melaleuca viridiflora (broad leaf paperbark) open woodland is often associated with freshwater springs, where it can tolerate permanent but shallow inundation. It is also found fringing some spring-fed creeklines. When located slightly higher in the landscape and not subject to frequent flooding, it can be found with *P. spiralis.*

Melaleuca nervosa was not common in the study area – forming open woodland at two sites only. At both sites it was over shallow groundwater (< 5 mbgl) in sandy clay soils upgradient of a seasonal wetland.

Lophostemon grandiflorus

Lophostemon grandiflorus (freshwater mangrove) generally occurs in mixed woodland with *M. dealbata,* however it is also found in monospecific stands. Although it is not specifically groundwater-dependent it is associated with a range of conditions, from inundated seasonal wetlands to shallow groundwater on drainage lines and behind sand dunes.

Pandanus spiralis

Pandanus spiralis is found in small stands or as individuals fringing freshwater wetlands, creeks or springs and in areas of shallow groundwater. Other than at springs, it is rarely inundated and appears to prefer sandy soils. It is often associated with *M. dealbata* and *M. viridiflora.* It is a good indicator of both fresh surface water and shallow groundwater.

Other species

On the peninsula *Sesbania formosa* (white dragon tree) occurs in large stands fringing freshwater springs.

Diospyros humilis is most often associated with sandy soils and monsoon vine thickets. Although usually in areas of shallow groundwater it does not seem to be exclusively groundwater-dependent.

8.3 Groundwater-dependent ecosystem characterisation

The five types of groundwater-dependent ecosystems, as well as non-dependent ecosystems, are described below and summarised in Table 5.

Wetlands

Three vegetation communities were associated with wetlands in the study area:

- *M. alsophila* woodlands on clayey soils – supported by shallow (< 5 mbgl) local groundwater and runoff/overland flow
- *M. dealbata* woodlands on sandy soils – supported by shallow (< 5 mbgl) regional groundwater
- mixed *M. alsophila*/*M. dealbata* woodland on clayey sand soils – supported by shallow (< 5 mbgl) local aquifers and/or drainage lines.

Creeklines

Three vegetation communities were associated with creeklines in the study area:

- mixed *M. nervosa/M. viridiflora* open (fringing) woodland with *M. alsophila* on sandy alluvial soils – supported by spring flow from regional aquifer
- mixed *M. dealbata*/*C. bella* woodland on sandy alluvial soils – supported by shallow (< 5 mbgl) local and/or regional aquifers
- *M. viridiflora* very open woodland on sandy clays – supported by shallow (< 5 mbgl) local aquifer.

Springs

Two vegetation communities were associated with springs in the study area:

- *M. dealbata* woodland on sandy soils – supported by surface discharge from regional aquifer
- *M. viridiflora* with *P. spiralis* open (fringing) woodland on sandy soils – supported by surface discharge from regional aquifer.

Monsoon vine thickets

Monsoon vine thickets (MVT) in the study area have a number of overstorey species that from part of the diagnostic characteristics for the community type. The MVT in the study area are closed woodland of *Diospyros humilis* with a mix of *Bauhinia cunninghamii, Grewia breviflora*, *Mimusops elengi*, *Terminalia petiolaris* and *Exocarpos latifolius* on sandy soils*.* They are supported by shallow (< 10 mbgl) regional groundwater.

Phreatophytic vegetation

Two phreatophytic vegetation communities were described in the study area:

- *M. dealbata* woodland on sandy soils – supported by shallow (< 5 mbgl) regional groundwater
- *M. dealbata* and/or *C. bella* woodland on sandy soils – supported by shallow (< 10 mbgl) regional groundwater.

Non-groundwater-dependent ecosystems

A range of vegetation communities in the study area were found not to rely on groundwater. The most common were:

- *L. grandiflorus* woodland on sandy clays – associated with seasonal wetlands
- mixed *Eucalyptus tectifica/Corymbia greeniana* woodland on pindan soils

  M. alsophila woodland on sandy clays – associated with creeklines and seasonal wetlands.

Table 5 Groundwater-dependent ecosystem characterisation

GDE type	Dominant vegetation community	Soil type	Groundwater source and depth	Surface water source	Sites
Wetland	*M. alsophila* woodland	Clay to sandy clay	Local aquifer < 5 m	Rain and runoff	Ngadalargin, Oval west, Triangle, Boolamon, Wibbijagun north
	M. dealbata woodland	Sand to clayey sand	Regional aquifer < 5 m	Runoff and groundwater	Oval east, Wibbijagun north-west
	Mixed *M. dealbata/ M. alsophila* woodland	Clayey sand	Local aquifer < 5 m	Drainage line	Flow Dam, Ngadalargin east
Creek	Fringing *M. nervosa/ M. viridiflora* with *M. alsophila*	Sand (alluvium)	Regional aquifer 0 m	Spring	Illelang, Jabirr Jabirr
	M. dealbata/*C. bella* woodland	Sand (alluvium)	Regional aquifer < 5 m	Groundwater, drainage line	Illelang, Bindingangun
	M. viridiflora very open woodland	Sandy clay	Local aquifer < 5 m	Drainage line	Bobbis Crk
Spring	*M. dealbata* woodland	Sand	Regional aquifer 0 m	Spring	Banana Well
	Fringing *M. viridiflora* with *P. spiralis*	Sandy clay	Regional aquifer 0 m	Spring	Bobbis Crk springs, Pandanus, Town
Monsoon vine thicket	Characteristic MVT species	Sand to sandy clay	Regional aquifer < 10 m	n/a	Kardilakin, Rurrjaman, Mudoodon
Phreatophytic vegetation	*M. dealbata* woodland	Sand	Regional aquifer < 5 m	n/a	Illelang woodland, Kurrukurugun
	M. dealbata and/or *C. bella* woodland	Sand	Regional aquifer < 10 m	n/a	Banana Well west, Moorak, Black Tank, Bindingangun west

GDE type	Dominant vegetation community	Soil type	Groundwater source and depth	Surface water source	Sites
Non GDE	*L. grandiflorus* woodland	Sand to sandy clay	n/a	Rain and run off	Rubabunan, Kurrukurugun fringe
	E. tectifica/ *C. greeniana* woodland	Pindan	>30 m	n/a	DPB06, DPB03, DPB07, Pump 69
	M. alsophila woodland	Clayey sand	n/a	Tidal	Mouths of Bindingangun, Illelang, Julyulkun, Willie Crk

8.4 Groundwater-dependent ecosystem probability map

We mapped the probability – low to high – of other groundwater-dependent ecosystems occurring across the study area (i.e. those not identified in this study or in previous work).

A preliminary probability map (Appendix H) was developed by combining our intensive groundwater-dependent ecosystem study site locations and species distribution data with previous survey information and existing mapping of threatened and potentially threatened ecological communities. This was modelled against depth to groundwater defined in the hydrogeological investigations, NDVI (vegetation density) and distance from creeklines.

The preliminary model explained around 80 per cent of the variation in the presence of known groundwater-dependent species, with depth to groundwater and distance from creeks being important predicators and NDVI having little influence.

The relationship between the probability of a groundwater-dependent species occurring and groundwater depths predicted 50 per cent probability of groundwater-dependent ecosystems occurring where groundwater depth was less than 12.5 m.

The final map incorporated the preliminary model outcomes with the location of our additional groundwater-dependent study sites and the downstream reaches of the creeklines that we consider most likely be groundwater-fed (Figure 75).

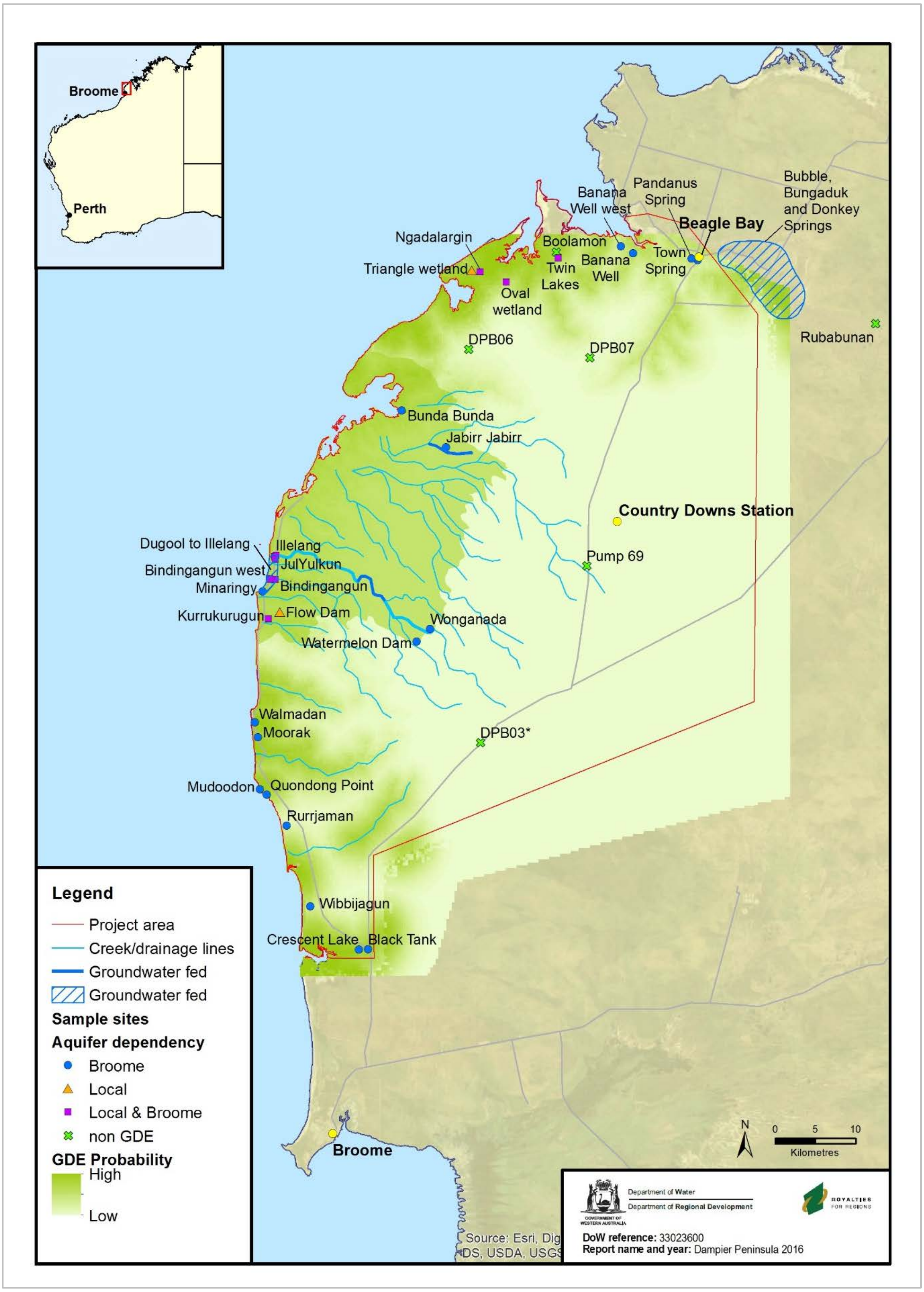


Figure 75 *Groundwater-dependent ecosystem study sites, aquifer dependency and groundwater-dependent ecosystem probability map*

9 Water opportunity map and management

The information provided in this report provides the most up-to-date understanding of groundwater-dependent ecosystems on the Dampier Peninsula. It will be a critical consideration for proponents exploring development opportunities on the peninsula and potentially applying for groundwater licenses. Groundwater-dependent ecosystems and their water requirements are also a major consideration in the water allocation planning process.

9.1 Water opportunity map

The water opportunity map summarises and communicates the findings of both the ecological and hydrogeological investigations in one visual product (Figure 76). It will help proponents identify where future abstraction may be able to progress relatively simply and where there will be extra management considerations.

Several spatial datasets, based on scientific attributes of the groundwater resource, dependent ecosystems and other users, were combined to produce the final map (Table 6). Once these layers were combined, the land was categorised as having high, medium, low or restricted opportunity for water development. In this context, water opportunity means how many or few constraints there are likely to be to groundwater development in a particular area, and does not guarantee or rule out a water license being granted.

Table 6 Spatial layers used to develop the water opportunity map

Layer	Comments
Groundwater-dependent ecosystems	A layer developed based on project study sites, creek systems with a 5 km buffer, NDVI greenness and depth to groundwater.
TEC and PECs	State and federal listed
Creek systems	Based on linear hydrography of the creeks determined to be groundwater-dependent, with a 1 km buffer zone
Existing users	Includes Aboriginal communities, Country Downs and Willie Creek pearl farm, with a 5 km buffer zone.
Saltwater interface	Determined from AEM survey and limited water quality information. The toe of the seawater wedge is the boundary.
Depth to groundwater	Determined from topography and groundwater contours.
Confined aquifer	Based on the large continuous conductive layer identified by the AEM survey and confirmed by the drilling.

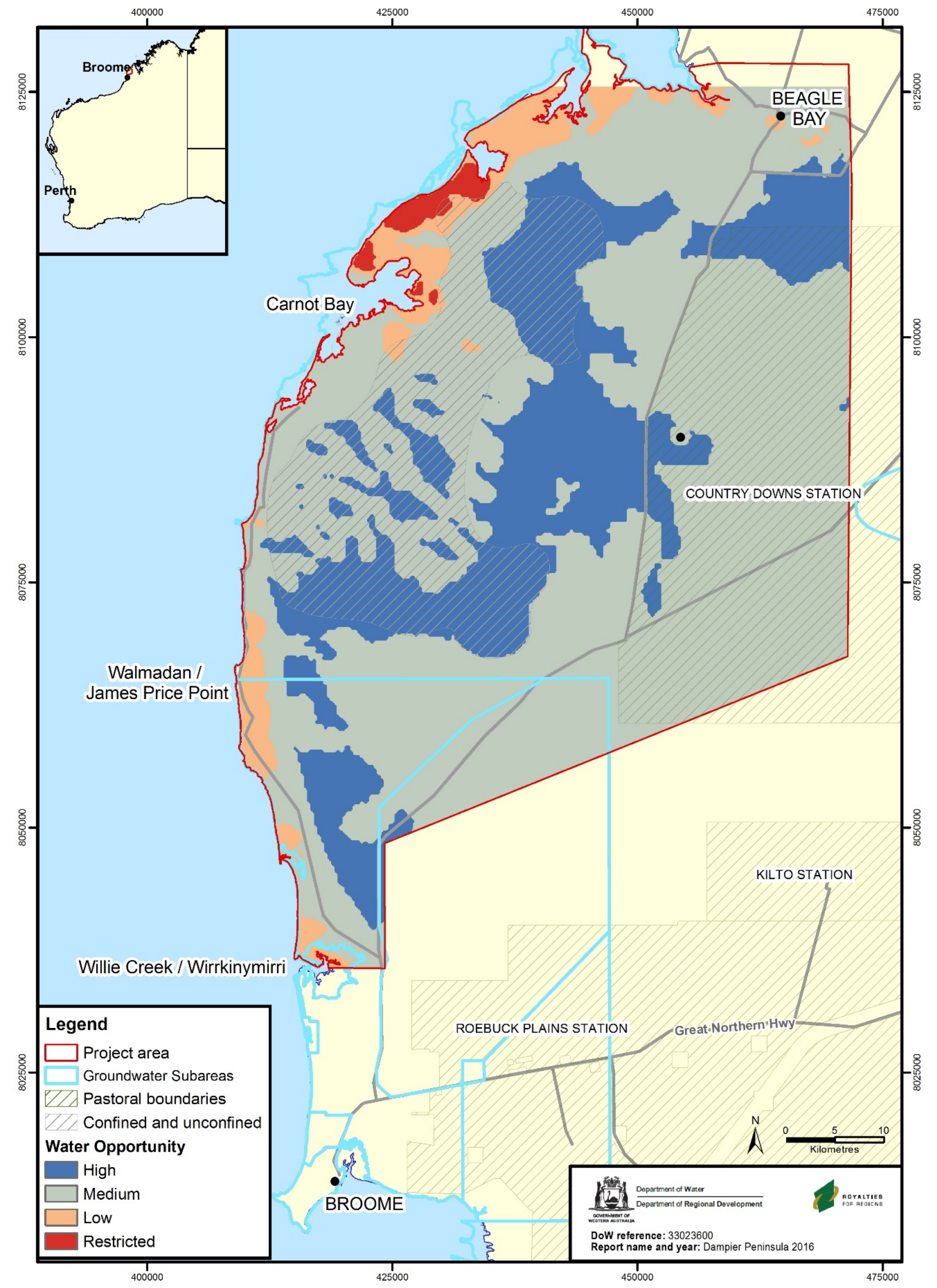


Figure 76 Water opportunity map

9.2 Water allocation planning and licensing

Water allocation planning in Western Australia: A guide to our process (Department of Water 2011) describes our approach to water planning in this state. Water allocation plans outline how much water can be sustainably taken from a surface or groundwater resource and the rules that apply to accessing and taking water. Allocation plans ensure individual use while protecting the resource as a whole for social, ecological and economic benefits.

An important part of the allocation planning and licence assessment process is understanding the relationship between ecosystems and groundwater. These relationship are known as ecological water requirements and we aim to maintain them at a low level of risk (Water and Rivers Commission 2000).

This report provides a solid foundation for future water planning in the region. As demand for water on the Dampier Peninsula is very low there is not an immediate need to develop an allocation plan. The Department will continue to monitor the level of water use.

9.3 Further work

Monitoring

The current groundwater monitoring program on the Dampier Peninsula is restricted due to the low level of demand and the high costs involved. As demand increases the program will be expanded as proponents undertake groundwater monitoring associated with their individual licences.

The following sites, representing each of the different ecosystem types on the peninsula, are a priority for an expanded monitoring program:

- wetlands – Oval waterhole (DPB04C: 80110247) and Crescent Lake (CR1: 80110349)
- creeks – Jabirr Jabirr (JJB: 80110244),
- springs – Bobbis Creek springs (TTM09: 80110228)
- monsoon vine thicket – James Price Point (JP bore: 80110236)
- phreatophytic vegetation – as no appropriate bores exist near project sites use bore in area of high potential for GDE (Dons bore: 80110237).

To better understand the regional groundwater resource, the following bores are a priority for an expanded monitoring program:

- HCL5 shallow (80119412)
- HCL6 (80119413)
- DPB03 (80110162)
- Pump 69 (80110214)
- DPB06A (80110165)

- DPB07 (80110167).

Understanding groundwater-dependence

Further investigation of shallow groundwater systems would verify the current understanding of how groundwater-dependent ecosystems are supported by the regional Broome aquifer. This kind of work would be carried out by a proponent who applied for a water licence to demonstrate that water can be taken sustainably.

At the springs near Beagle Bay (including Bobbis Creek) and the monsoon vine thickets (MVT) along the coast, further work would ideally involve the use of shallow core drilling to clearly characterise and sample the shallow geology.

Combined with intensive monitoring of seasonal water-level responses within the aquifer and use of environmental tracers to distinguish groundwater discharge pathways, the dependence of springs and MVT on regional groundwater could be determined.

At other coastal springs, including Bunda Bunda, environmental tracer and age dating sampling combined with continuous water-level monitoring could be used to determine whether these systems are dependent on discharge from the confined aquifer.

An expanded program of longitudinal sampling of the creek systems, including Bindingangun and Jabirr Jabirr, could improve the understanding of their interaction with regional groundwater. This could involve using an expanded range of tracers (such as tritium) combined with spear-point sampling of groundwater and springs along the creeks. This would allow expanded mapping of groundwater interaction with the creeks.

Appendices

Appendix A – spatial datasets considered

Ecological components	**Spatial layers and datasets**
Native vegetation and fauna	
Conservation reserves and land recommended for conservation reserves	DPAW Managed Lands and Waters System 1–5 and 7–12 Areas DEP 06/95
Listed WA threatened ecological community	Threatened Ecological Communities (buffers) – DPAW
Habitat for WA threatened fauna or flora	Threatened Fauna – DPAW Threatened and Priority Flora – DPAW
Nationally listed threatened ecological community	Protected matters search tool – DoE
Any native vegetation not associated with a wetland or watercourse	Native Vegetation Current Extent – DAFWA Aerial photography
Habitat for nationally threatened fauna (EPBC)	Protected matters search tool – DoE
Wetlands and watercourses	
Wetlands and watercourses to which an international agreement applies (e.g. Ramsar)	Protected matters search tool – DoE
Wetlands or watercourses where management category has not been assigned but may be of high conservation priority for any reason, including: • occurs within conservation reserves and land recommended for conservation reserves, TEC and buffers, habitat for threatened flora or fauna • provides a dry season refuge for aquatic or terrestrial fauna (e.g. river pools). • aquifers (supporting significant stygofauna). Support species or communities of listed or otherwise recognised high conservation significance.	Wetland features: • Rivers – DoW • Hydrography, linear • Aerial photography • GDE atlas – BOM • Water observations from space (persistence of waterbodies) – Geoscience Australia Conservation priority, the above, plus: • DPAW Managed Lands and Waters • System 1–5 and 7–12 conservation areas DEP 06/95 • Threatened Ecological Communities (buffers) – DPAW • Threatened Fauna – DPAW • Threatened and Priority Flora – DPAW • Wetlands – DIWA • GDE atlas – BOM
Matters of National Environmental Significance	
World heritage properties	EPBC Protected matters search tool – DoE

Ecological components	**Spatial layers and datasets**
National heritage places	
Wetlands of international importance (listed under the Ramsar Convention)	
Listed threatened species and ecological communities	
Habitat for migratory species protected under international agreements (JAMBA, CAMBA, ROKAMBA)	

Appendix B – Flora and fauna of conservation value

The following lists of flora and fauna were sourced from the former Department of Parks and Wildlife (2016) for the Dampier Peninsula study area.

Fauna

Conservation significance	**Relevant legislation**	**Species recorded or potentially occurring**
International	CAMBA, JAMBA, IUCN	Rainbow bee-eater *(Merops ornatus)* Gouldian finch *(Erythrura gouldiae)* Fork-tailed swift (*Apus pacifies)* Garganey duck *(Anas querquedul)* Common noddy *(Anous stolidus)* Eastern great egret *(Ardea modesta)* Eastern reef egret/heron *(Ardea sacra)* Ruddy turnstone *(Arenaria interpres)* Sharp-tailed sandpiper *(Calidris acuminata)* Sanderling *(Calidris alba)* Red knot *(Calidris canutus)* Pectoral sandpiper (*Calidris melanotos)* Red-necked stint *(Calidris ruficollis)* Long-toed stint (*Calidris subminuta)* Streaked shearwater *(Calonectris leucomelas)* Little ringed plover *(Charadrius dubius)* Greater sand plover *(Charadrius leschenaultii)* Greater sand plover (Mongolian) (*Charadrius leschenaultii* subsp. *leschenaultii)* Oriental plover *(Charadrius veredus)* Oriental cuckoo *(Cuculus saturatus)* Lesser frigatebird *(Fregata ariel)* Swinhoe’s snipe *(Gallinago megala)* Oriental pratincole *(Glareola maldivarum)* White-bellied sea-eagle *(Haliaeetus leucogaster)* Barn swallow *(Hirundo rustica)* Bar-tailed godwit *(Limosa lapponica)* Black-tailed godwit *(Limosa limosa)* Brown booby *(Sula leucogaster)* Wood sandpiper *(Tringa glareola)* Green turtle (*Chelonia mydas)* Flatback turtle (*Natator depressus)* Hawksbill turtle (*Eretmochelys imbricata*) Loggerhead turtle (*Caretta caretta)* Leatherback turtle (Dermochelys coriacea) Olive ridley turtle (*Lepidochelys olivacea*)

National	EPBC	Bilby (*Macrotis lagotis*) Northern quoll (*Dasyurus hallucatus*) Golden bandicoot (*Isoodon auratus auratus*) Curlew sandpiper (*Calidris ferruginea)* Great knot *(Calidris tenuirostris)* Lesser sand plover *(Charadrius mongolus)* Airlie Island ctenotus, Airlie Island skink (*Ctenotus angusticeps)* Dugong *(Dugong dugon)* Red goshawk *(Erythrotriorchis radiatus)* Bernier Is. variegated fairy-wren *(Malurus lamberti* subsp. *Bernieri)* Australian painted snipe *(Rostratula benghalensis subsp. Australis)*
State	WCA	Gouldian finch *(Erythrura gouldiae)* Bilby *(Macrotis lagotis)* Golden back tree rat (*Mesembriomys macrurus)* Peregrine falcon *(Falco peregrinus)* Australian peregrine falcon *(Falco peregrinus* subsp. *Macropus)* Little bittern *(Ixobrychus minutus)* Dampierland plain slider, skink *(Lerista separanda)* Dampierland burrowing snake *(Simoselaps minimus)* Australian white ibis *(Threskiornis molucca)*

Flora

Conservation significance	Relevant legislation	Level	Species name
National	EPBC	Critically endangered	*Keraudrenia exastia*
		Endangered	*Pandanus spiralis* var. *flammeus*
State		P1	*Glycine pindanica* *Nicotiana heterantha* *Aphyllodium parvifolium* *Acacia platycarpa* *Bonamia oblongifolia* *Corymbia polycarpa* *Cyperus haspan* subsp. *haspan* *Haemodorum capitatum* *Ipomoea* sp. *A Kimberley Flora* *Jacquemontia* sp. *Broome* *Polymeria* sp. *Broome (K.F. Kenneally 9759)* *Utricularia stellaris*
		P2	*Gomphrena pusilla*
		P3	*Nymphoides beaglensis* *Acacia monticola x tumida* var. *kulparn* *Aphyllodium glossocarpum* *Triodia acutispicula* *Stylidium costulatum* *Eriachne semiciliata* *Polymeria distigma* *Colocasia esculenta* var. *aquatilis* *Dendrophthoe odontocalyx* *Lophostemon grandiflorus* subsp. *grandiflorus* *Pterocaulon intermedium* *Scinaia tsinglanensis* *Stylidium costulatum* *Stylidium pindanicum* (pindan triggerplant) *Terminalia kumpaja* *Triodia caelestialis*
		P4	*Pittosporum moluccanum*

Appendix C – Project sampling and assessment at each GDE site

GDE site	Bore type[1]	Soil samples		Water samples[2]			Ecological					
		Isotopes	Moisture /Cl	Taken	Isotopes/ radon	EC	Canopy condition	LAI[3]	Size class	SWP[4]	Isotopes	Description
Intensive sites												
Ngadalargin	D, S	*	*	S, G	S, G	S, G	*	*	*	*	*	*
Triangle	D, S	*	*	S, G	S, G	S, G	*	*	*	*	*	*
DPB04 1	D, S, H, M	*	*	S, G, R	S, G, R	S, G, R	*	*	*	*	-	*
DPB04 2	O	-	-	S, G	S	-	*	*	*	*	*	*
Flow Dam	O	*	*	S, G	S, G	S, G	*	*	*	*	*	*
Wibbijagun north	O	*	*	S, G	S, G	S, G	*	*	*	*	*	*
Wibbijagun west	O	*	*	S, G	S, G	S	*	*	*	*	*	*
Illelang	O	*	*	S, G, R	S, G, R	S, G, R	*	*	*	*	*	*
Bindingangun east	O	*	*	S, G	S, G	S, G	*	*	*	*	*	*
Jabirr Jabirr	D, E	-	*	S, G	S, G	S, G	*	-	*	*	*	*
Banana Well	E	-	-	S, R	S, R	S	*	-	*	*	*	*
Walmadan	O, M	*	*	G	G	G	*	*	*	*	*	*
Mudoodon	O, E	*	*	G	G	G	*	*	*	*	*	*
Kurrukurugun	O, M	*	*	G	G	G	*	*	*	*	*	*
DPB06	D, S, M	*	*	G	G	G	*	*	*	*	*	*
Additional sites												
Crescent Lake	H	-	-	S, G	G	S, G	-	-	-	-	-	*
Lake Louisa	-	-	-	S	-	S	*	*	*	-	-	*
Bungaduk	-	-	-	S	-	S	*	*	*	-	-	*
Boolamon	E	-	-	S	-	-	-	-	-	-	-	*
Twin Lakes	-	-	-	-	-	-	-	-	-	-	-	*
Julyulkun	-	-	-	-	-	-	-	-	-	-	-	*

GDE site	Bore type[1]	Soil samples		Water samples[2]			Ecological					
		Isotopes	Moisture /Cl	Taken	Isotopes/ radon	EC	Canopy condition	LAI[3]	Size class	SWP[4]	Isotopes	Description
Watermelon Dam	-	-	-	S	S	S	*	*	*	-	-	*
Bubble Spring	-	-	-	S	-	-	-	-	-	-	-	*
Goonard Spring	-	-	-	S	-	-	-	-	-	-	-	*
Pandanus Spring	-	-	-	S	-	S	-	-	-	-	-	*
Town Spring	-	-	-	-	-	-	-	-	-	-	-	*
Bunda Bunda	-	-	-	-	-	-	-	-	-	-	-	*
Kardilakin	-	-	-	-	-	-	-	-	-	-	-	*
Rurrjaman	-	-	-	-	-	-	-	-	-	-	-	*
Moorak	-	-	-	-	-	-	*	*	*	*	-	*
Banana Well west	O	-	-	G	-	-	*	*	*	*	-	*
Bindingangun west	S, E	-	-	G	G	G	*	*	*	*	-	*
Black Tank	E	-	-	-	-	-	-	-	-	-	-	*
Manari Rd north	-	-	-	-	-	-	-	-	-	-	-	*
Minaringy wood	-	-	-	-	-	-	-	-	-	-	-	*
DPB03	D	-	-	G	G	G	-	-	-	-	-	*
Pump 69	E	-	-	G	G	G	-	-	-	-	-	*
DPB07	D	-	-	G	G	G	-	-	-	-	-	*

[1] D – deep, S – shallow, H – hand augered bore, O – hand augered open hole, E – existing, M – soil moisture probe

[2] S – surface water, G – groundwater, R – rain

[3] LAI – leaf area index (canopy photography)

[4] SWP – shoot water potential (pre-dawns)

Appendix D – Groundwater-dependent species of the Dampier Peninsula

Species descriptions from Paczkowska and Chapman (2000).

Riparian/wetland tree species

Corymbia bella

- 6–20 m tall; bark – smooth, white, shedding in thin scales, flowers – white, cream, Jul–Dec.
- usually on alluvial soils, along watercourses or floodplains
- found primarily along the top of river/creek banks (O'Grady, Eamus et al. 2002).

Melaleuca dealbata (freshwater paperbark)

- 6–15 m tall; flowers – cream, Aug–Nov
- sand or sandy soil, seasonally wet depressions, small watercourses
- found on lowest terraces and is generally only associated with permanent water sources, and is sensitive to changes in water regime (O'Grady, Eamus et al. 2002).

Melaleuca alsophila (saltwater paperbark)

- 2.5–15 m tall; flowers – white, cream, Sep–Oct
- sandy soils, often saline, along watercourses, swamps, floodplains, coastal flats.

Melaleuca nervosa

- 1.5–10 m; flowers – pale green cream, yellow, red, Mar–Sep
- alluvium, sandy soils, along watercourses, in damp depressions.

Melaleuca viridiflora (broadleaf paperbark)

- 2.5–20 m tall; flowers – green, white, cream, yellow, red, Jan–Aug
- sand, sandstone, sometimes clay, along watercourses, swamps, seasonally damp sites.

Lophostemon grandiflorus (Lardik)

- 3–15 m tall; flowers – cream to white, Jan–Dec
- damp habitats, sandstone gorges.

Sesbania formosa (white dragon tree)

- 2.5–13 m tall; flowers – white/cream, May–Sep
- alluvium, sand, along creeks and rivers, margins of swamps.

Other riparian/wetland species

Pandanus spiralis (Mangban)

- tree-like monocot to 10 m; fruits – orange-red
- sand, loan, clay, alluvium, creeks, rivers, valleys, beaches, coastal dunes.

Pandanus spiralis var. *convexus*

- tree-like monocots, 3–10 m; fruits – red
- sands, sandstone, creeks, beaches.

Schoenoplectus subulatus

- aquatic, perennial sedge, 0.6–2.8 m high; flower – pale brown, Oct–Feb
- alluvium, pools, swamps, streams.

Monsoon vine thicket – diagnostic species

The following overstorey species form part of the ‘key diagnostic characteristics’ for listing monsoon vine thickets as threatened ecological communities (Threatened Species Scientific Committee 2013).

Diospyros humilis (ebony wood)

- shrub or tree to 12 m tall; flower – cream, yellow, Oct–Nov
- sand, sandstone, coastal areas, rocky gorges.

Bauhinia cunninghamii (Jigal)

- tree or shrub, 1–12 m high; tessellated to fissured bark; flower – red, Apr–Oct
- variety of habitats often along drainage lines.

Exocarpos latifolius (Jarnba, mistletoe tree)

- small tree or shrub, 1.5–10 m tall; hemiparasitic on roots; flowers – green, cream, yellow, brown, orange, Mar–Nov
- sand, clay, sandstone gullies, sand dunes, river banks.

Grewia breviflora (Goolmi, coffee fruit)

- shrub or tree, 0.4–9 m tall, flower – orange, yellow, green, Nov–Feb
- sandy soils, basalt, often behind coastal dunes or edges of vine thickets.

Mimusops elengi (Mamajen)

- tree or shrub, 2–16 m tall; flower – white, Jan–Sep
- sandy soil, sandstone, basalt, coastal or near-coastal areas.

Sersalisia sericea (Mangarr)

- shrub or tree, 1–15 m high; flowers – cream–yellow, Jan–Dec.
- sandy soils over sandstone or basalt, along watercourses.

Terminalia ferdinandiana (Gubinge)

- slender, spreading shrub or tree, to 14 m high, bark mottled grey, green, cream, orange, yellow, fissured; flower – white, Oct–Dec or Feb
- red sand, sandy clay, black peat, sandstone, ironstone, granite. Sandplains behind beaches, dry creek beds, flood plains, cliff tops, ridges, coastal vine thickets, mangrove edges.

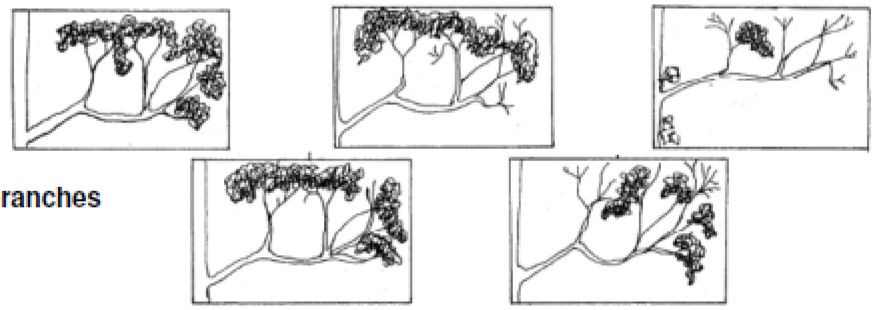
Terminalia petiolaris (Marool)

- deciduous tree, 4–14 m tall; flowers – cream, white, Feb–May/Dec
- sandy soils, sandstone, coastal areas, often in vine thickets.

Appendix E – Tree canopy assessment scale

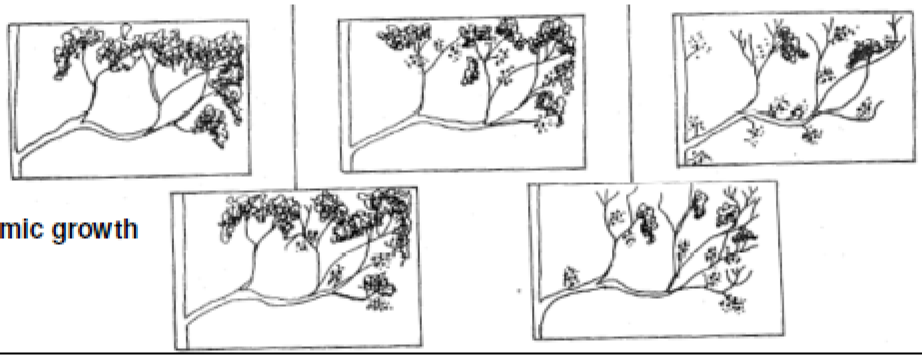
Dead branches

9	7	5	3	1
No visible dead branches or branchlets except thin twigs inside new leaf development and lowest branches	Dead branches evident on close inspection. Not all over crown	Small branches dead, not all over crown. Easily observed but nor seriously	Large and/or small braches dead over part of the crown. Serious	Large and small branches dead over most of the crown



Epicormic growth

5	4	3	2	1
No epicormic growth with normal foliar growth concentrated at the branch extremities	Slight in part of crown only	Moderate over most of crown	Severe on crown or stem	Severe on crown and stem



Crown density

9	7	5	3	1
Very dense leaf clumps evenly over crown. Very little light penetrating clumps	Dense leaf clumps unevenly over crown	Clumps of average density equally disturbed or dense clumps unevenly over crown	Clumps sparse and poorly spread	Very few leaves anywhere in crown

Appendix F – Study site photos

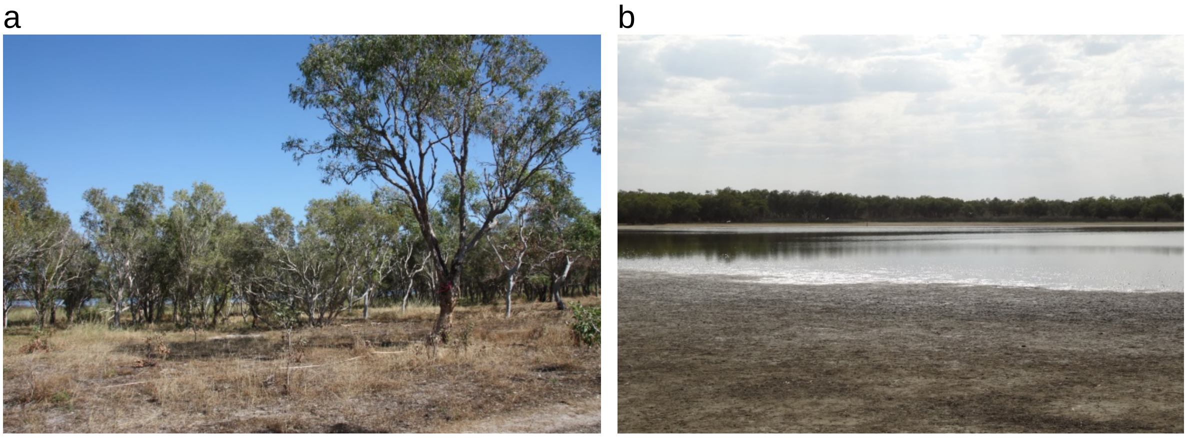


Figure F1 Ngadalargin waterhole (a) transect May 2014, (b) wetland October 2014

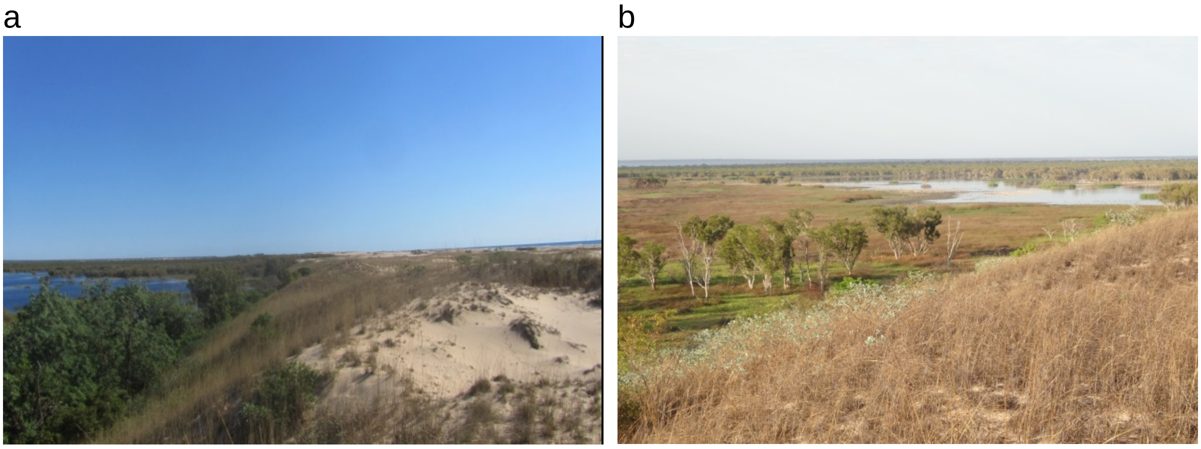


Figure F2 Triangle wetland from dunes (a) June 2014, (b) October 2014

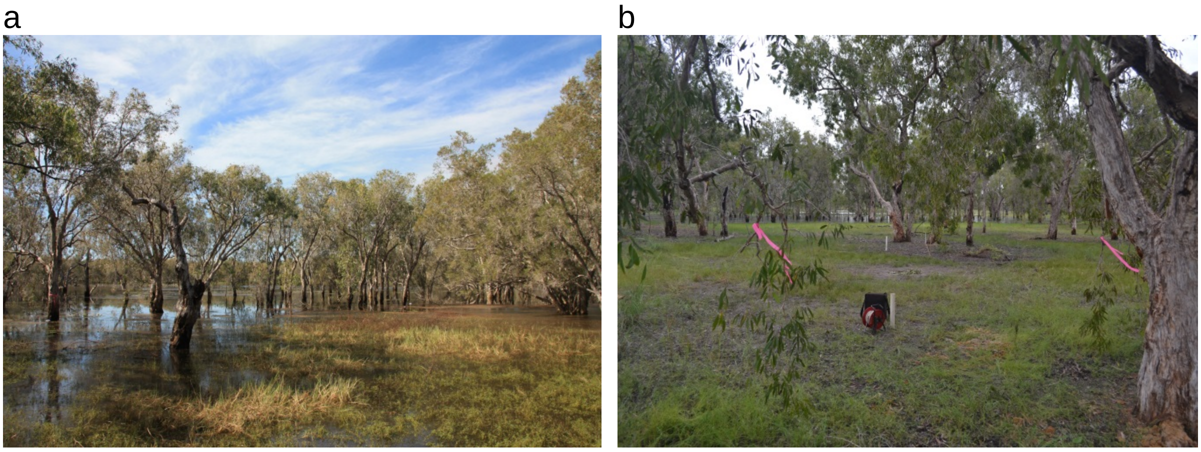


Figure F3 Oval waterhole (a) DPB04-1, May 2014, (b) DPB04-2, May 2015

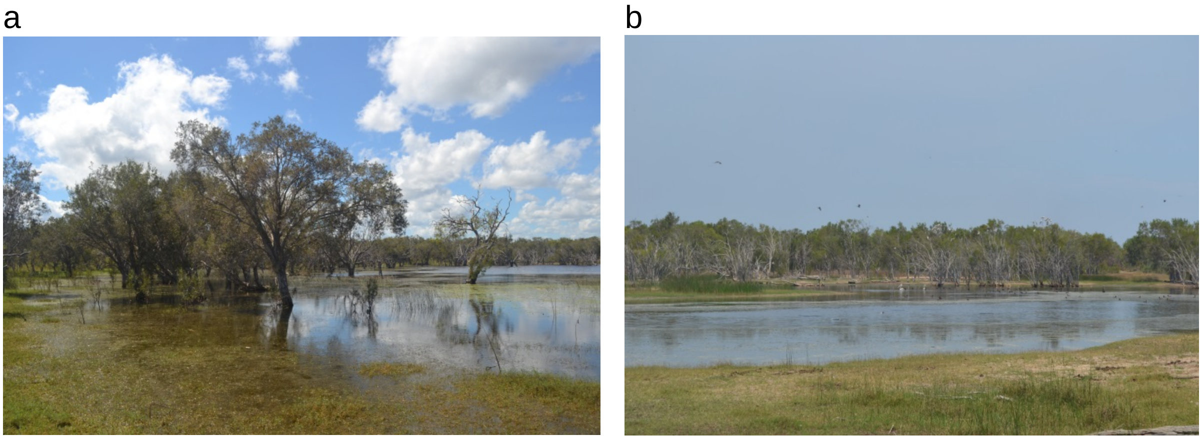


Figure F4 Flow Dam (a) May 2014, (b) October 2014

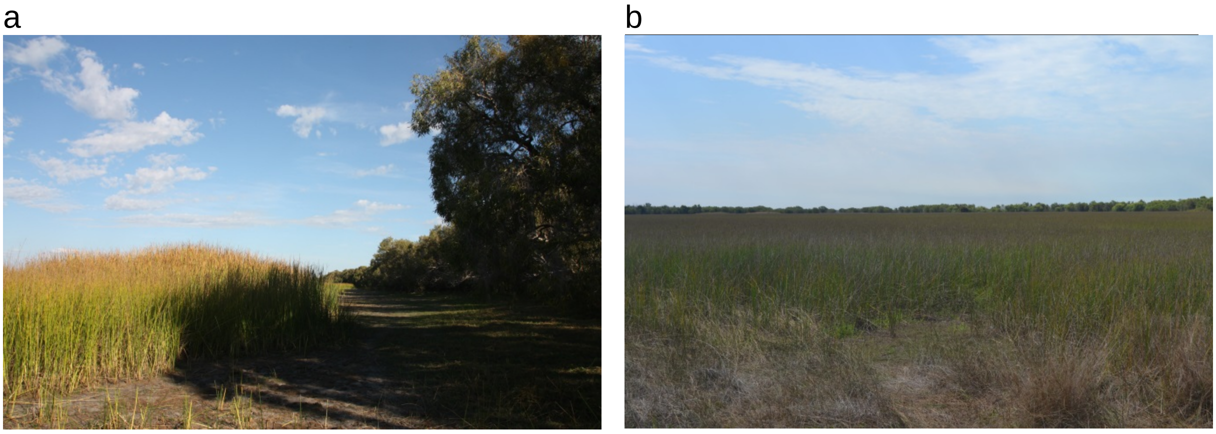
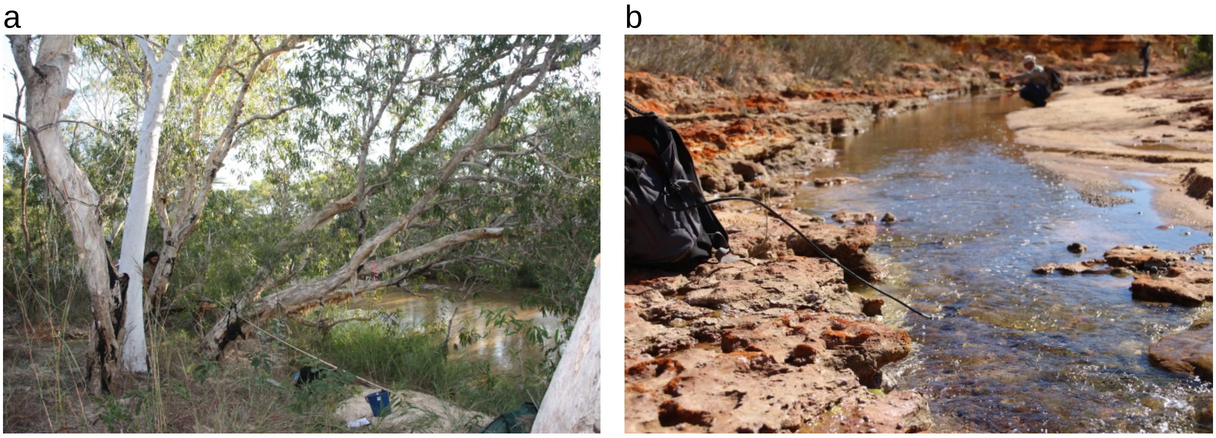


Figure F5 Wibbijagun west (a) May 2014, (b) October 2014



c

Figure F6 Illelang (a) transect May 2014, (b) longitudinal sampling August 2015, (c) Watermelon Dam

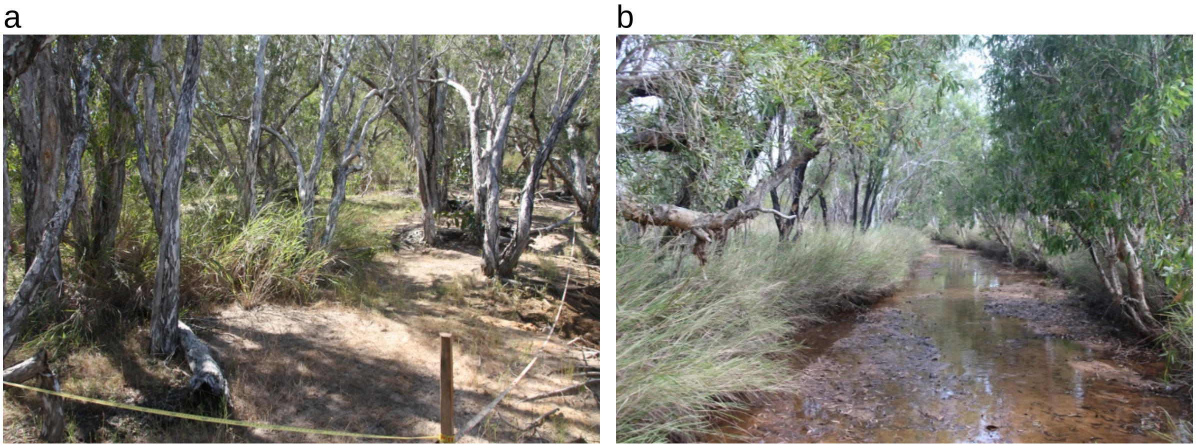


Figure F7 Bindingangun (a) transect May 2014, (b) upstream May 2014

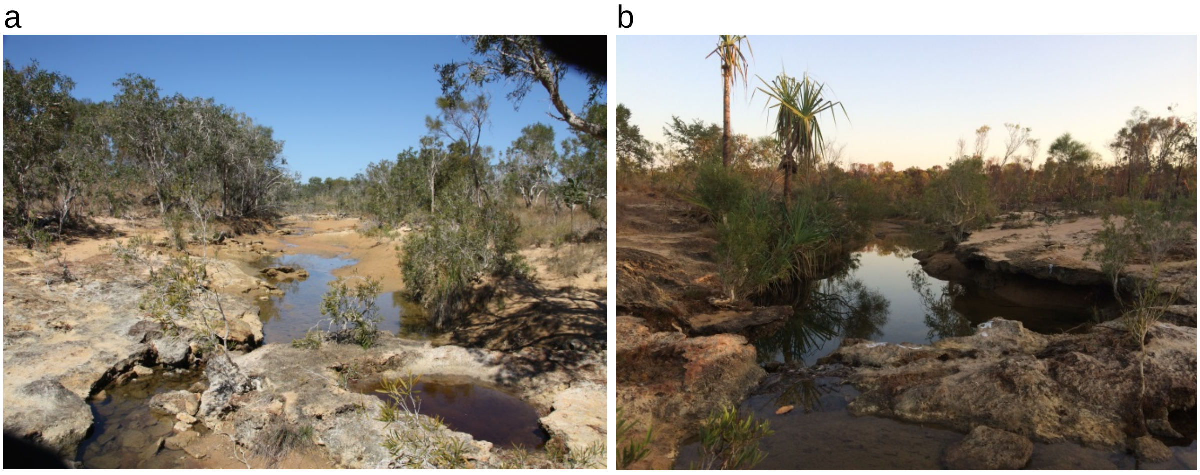


Figure F8 Jabirr Jabirr (a) creekline May 2014, (b) pool October 2014

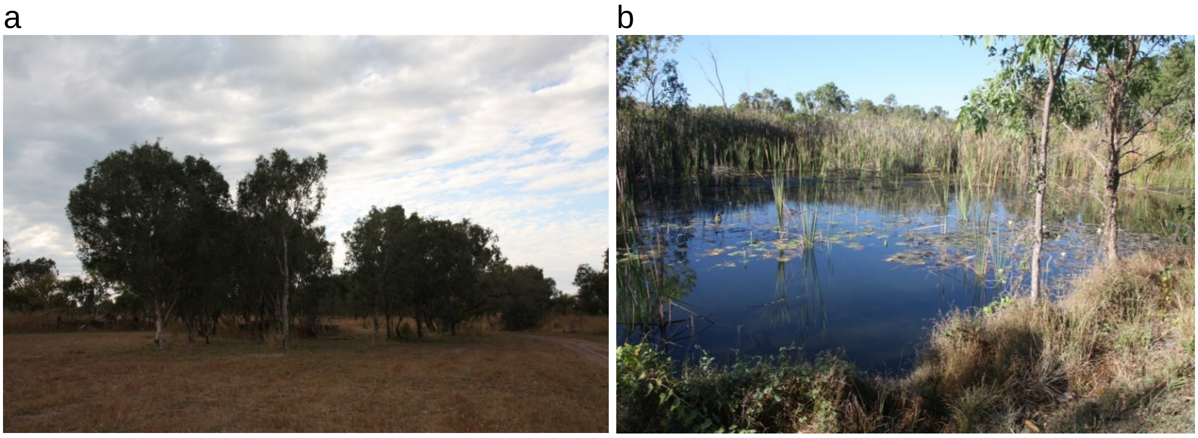


Figure F9 Banana Well (a) vegetation plot October 2014, (b) 'pond' October 2014

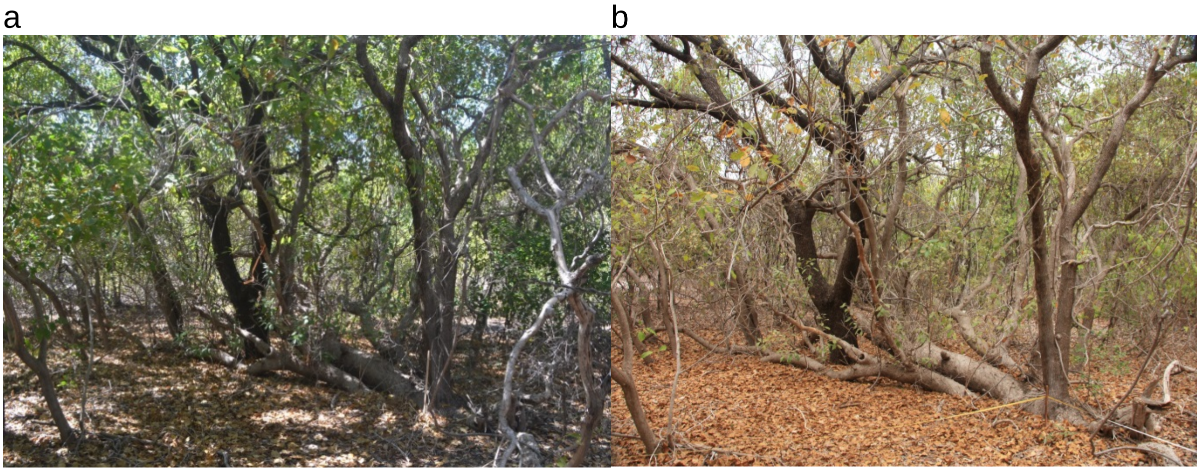


Figure F10 Mudoodon (a) transect May 2014, (b) October 2014

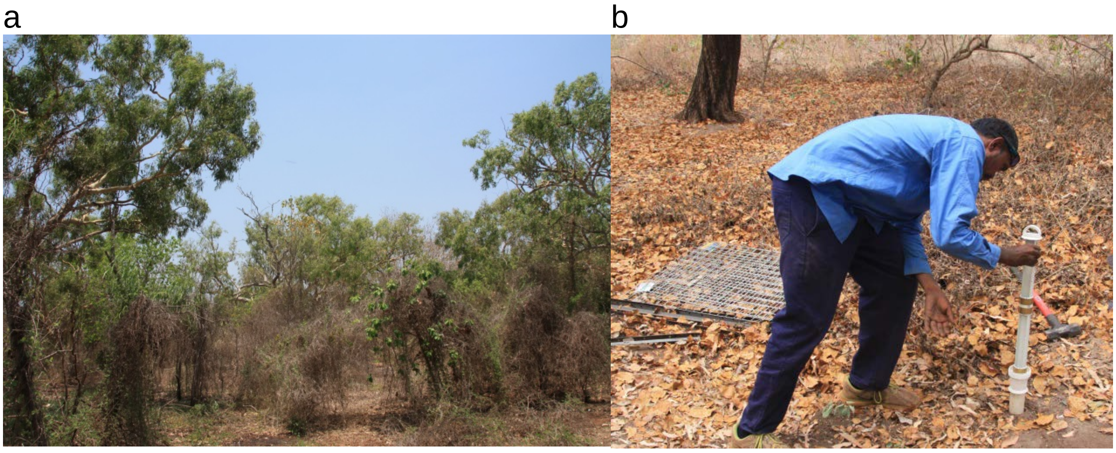


Figure F11 Walmadan (a) transect November 2014, (b) soil moisture probe

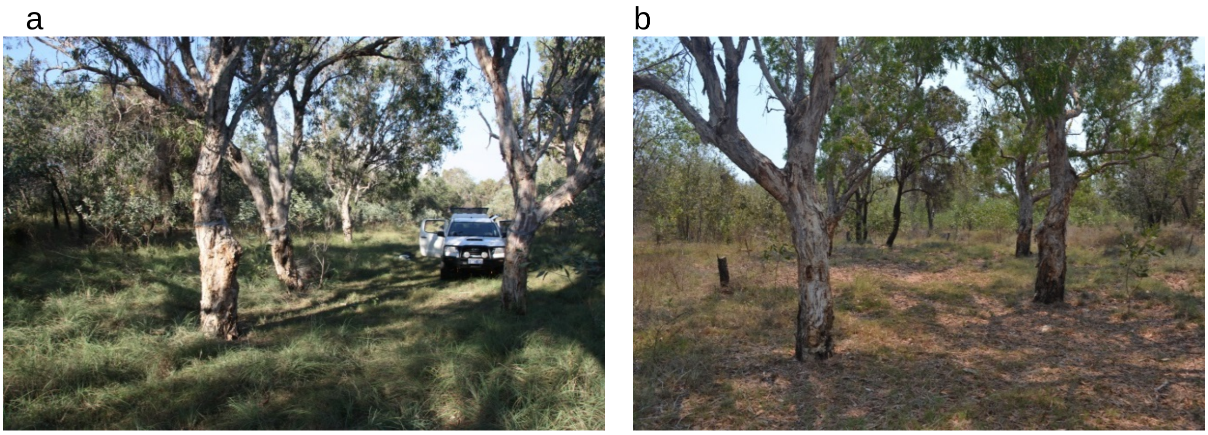


Figure F12 Kurrukurugun (a) transect May 2014, (b) October 2014

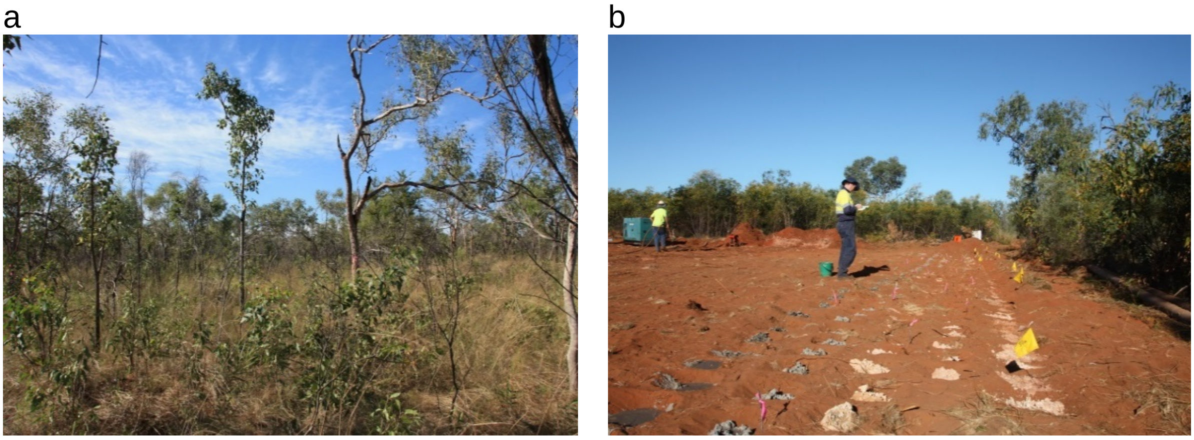


Figure F13 DPB06 pindan reference (a) transect, (b) drilling deep bore

Figure F14 Crescent Lake vegetation

Figure F15 Crescent Lake

Figure F16 Lake Louisa

Figure F17 Bungaduk

Figure F18 Boolamon

Figure F19 Twin Lakes

Figure F20 Bubble Spring

Figure F21 Donkey Spring

Figure F22 Pandanus Spring

Figure F23 Bunda Bunda

Figure F24 Moorak

Figure F25 Banana Well west

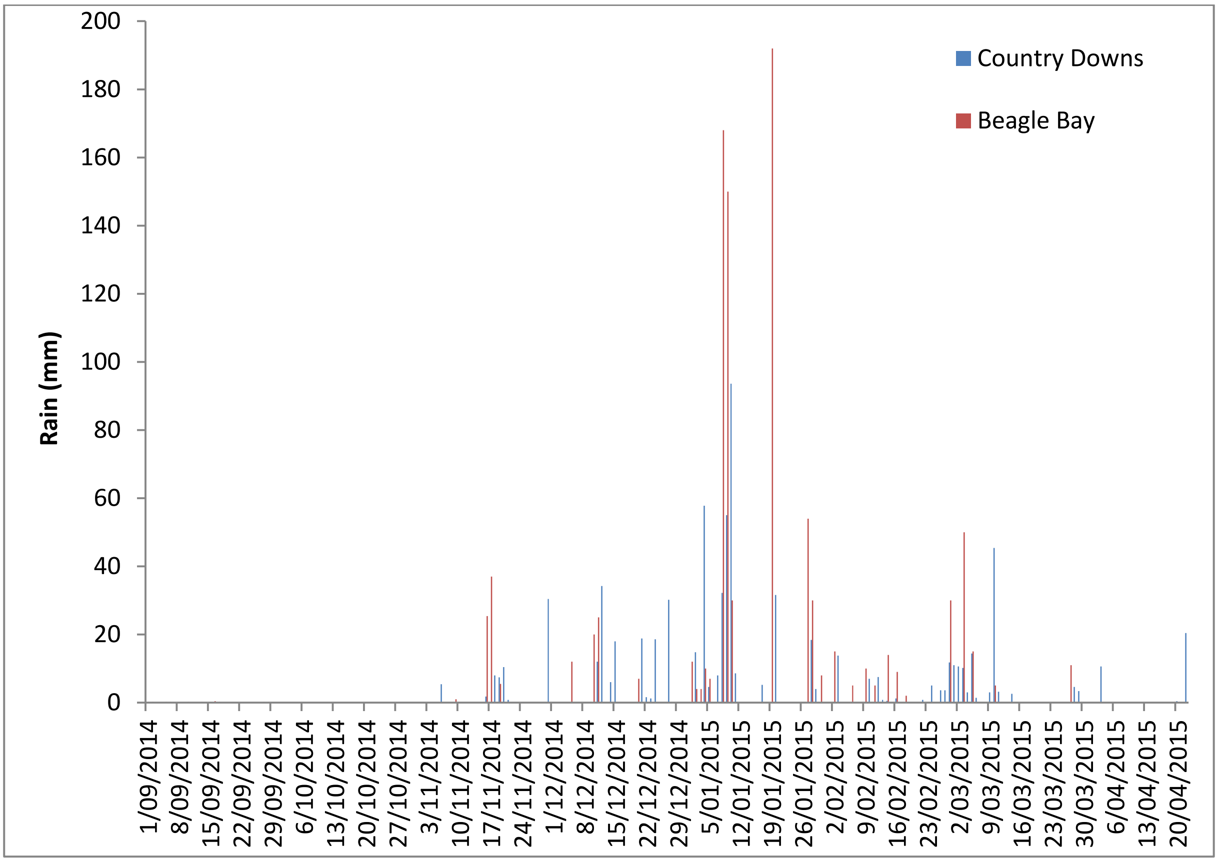
Figure F26 Bindingangun west

Figure F27 Minaringy

Figure F28 Pump 69

Figure F29 DPB07

Appendix G – Daily rainfall: Country Downs and Beagle Bay



Appendix H – Preliminary GDE distribution model

A preliminary distribution model of potential groundwater-dependent vegetation species was developed by Dr Jarrod Kath (previously from Water for Food) for the Dampier Peninsula project. The model combined multiple datasets from vegetation surveys on the Dampier Peninsula. This included datasets from Department of Water and Environmental Regulation investigations, consultant surveys undertaken as part of the James Price Point gas hub proposal, and threatened and priority ecological community mapping. The model was supplemented with several dummy variables of GDE absences based on the available vegetation mapping.

The probability of occurrence of a groundwater-dependent vegetation species was modelled as a function of groundwater levels (based on interpolations from monitored bores), NDVI images and the distance from the stream network.

The model explained around 80 per cent of the variation in the presence of groundwater-dependent species. However, this result should be regarded as preliminary as dummy absent sites (sites with no groundwater-dependent vegetation) were included in the model. The groundwater level and distance from the stream network were importance predictors, but NDVI was not.

The relationship between the probability of a groundwater-dependent species occurring and the groundwater level is shown in Figure H1. It is predicted that there is better than 50 per cent probability of groundwater-dependent vegetation occurring with groundwater levels of 12.5 m or less. The preliminary distribution of potential groundwater-dependent vegetation across the Dampier Peninsula study area is shown in Figure H2.

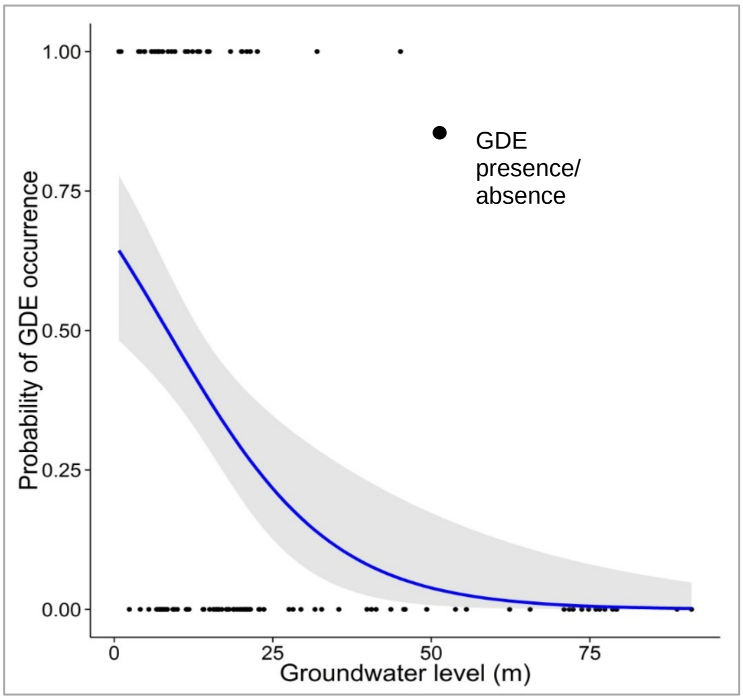


Figure H1 Occurrence probability of potential groundwater-dependent species in relation to depth to groundwater

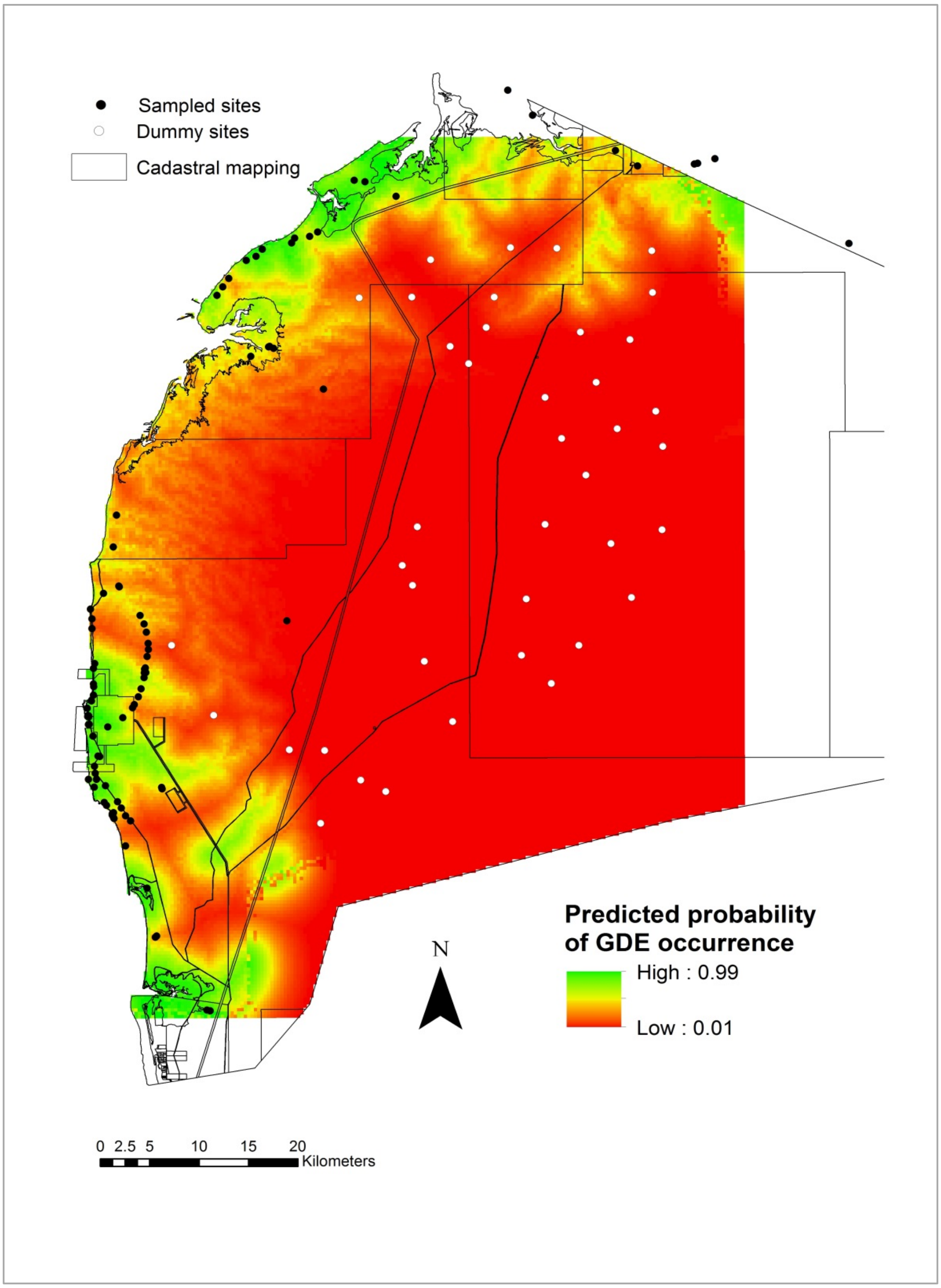


Figure H2 Predicted distribution of potential vegetation GDE species in the Dampier Peninsula study area

Shortened forms

AEM	Airborne electromagnetics
CAMBA	China-Australia Migratory Bird Agreement
CFC	Chlorofluorocarbons
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DBH	Diameter at breast height
DEC	Department of Environment and Conservation (now DPAW)
DPAW	Department of Parks and Wildlife
DIWA	Directory of Important Wetlands of Australia
DWER	Department of Water and Environmental Regulation
DRF	Declared rare flora
EC	Electrical conductivity
EPBC	*Environmental Protection and Biodiversity Conservation Act 1999* (Cth)
EWP	Environmental water provision
EWR	Environmental water requirement
FC	Foliage cover
GDE	Groundwater-dependent ecosystem
GW	Groundwater
JAMBA	Japan-Australia Migratory Bird Agreement
KLC	Kimberley Land Council
LAI	Leaf area index
mbgl	Meters below ground level
MPa	Megapascal
MVT	Monsoon vine thicket
n/a	Not applicable
NDVI	Normalised difference vegetation index
NERP	National Environmental Research Program
PEC	Priority Ecological Community
SAFA	State agency funding agreement
SW	Surface water
SWP	Shoot water potential
TDS	Total dissolved solids

TEC	Threatened Ecological Community
TO	Traditional owner
$\delta\,^{2}H$	Deuterium isotope (Hydrogen 2)
$\delta^{18}O$	Oxygen-18 isotope
^{14}C	Carbon-14 isotope

Glossary

Abstraction	The permanent or temporary withdrawal of water from any source of supply, so that it is no longer part of the resources of the locality.
Allocation limit	Annual volume of water set aside for use from a water resource.
Alluvium	Fragmented rock transported by a stream or river and deposited as the river floodplain.
Aquifer	A geological formation or group of formations able to receive, store and/or transmit large amounts of water.
Artesian aquifer	A confined aquifer in which the hydraulic pressure will cause water to rise in a bore or spring above the land surface. If the pressure is insufficient to cause the well to flow at the surface, it is called a sub-artesian aquifer.
Artesian head	The hydraulic pressure of water in a confined aquifer.
Bore	A narrow, normally vertical hole drilled in soil or rock to monitor or withdraw groundwater from an aquifer.
Confining layer	Sedimentary bed of very low hydraulic conductivity.
Ecosystem	A community or assemblage of organisms, interacting with one another and the specific environment in which they live and also interact.
Ecological water requirement	The water regime needed to maintain ecological values of a water-dependent ecosystem at a low level of risk.
Evapotranspiration	The combined loss of water by evaporation and transpiration. It includes water evaporated from the soil surface and water transpired by plants.
Habitat	The area or natural environment in which an organism or population normally lives.
Hydrogeology	The hydrological and geological science concerned with the occurrence, distribution, quality and movement of groundwater, especially relating to the distribution of aquifers, groundwater flow and groundwater quality.
Groundwater	Water which occupies the pores and crevices of rock or soil beneath the land surface.
Groundwater area	The boundaries that are proclaimed under the *Rights in Water and Irrigation Act 1914* (WA) and used for water allocation planning and management.
Groundwater-dependent ecosystem	An ecosystem that is dependent on groundwater, at least in part, for its existence and health.
Groundwater level	An imaginary surface representing the top of the watertable.

Groundwater subarea	Areas defined by the Department of Water and Environmental Regulation within a groundwater area, used for water allocation planning and management.
Isotope	Atoms with the same number of protons but different number of neutrons.
Licence	A formal permit which entitles the licence holder to ‘take’ water from a watercourse, wetland or underground source.
Phreatophyte	A plant (often relatively deep rooted) that obtains water from a permanent ground supply or from the watertable.
Recharge	Water that infiltrates into the soil to replenish an aquifer.
Riparian vegetation	Plant communities along the river margins and banks or the interface between land and a river or stream.
Salinity	A measure of the concentration of total dissolved solids in water.
Spring	A spring is where water naturally rises to and flows over the surface of land.
Stygofauna	Fauna – generally small aquatic invertebrates that live within groundwater systems, such as caves or aquifers.
Surface water	Water flowing or held in streams, rivers and other wetlands on the surface of the landscape.
Surficial	Pertaining to the surface. Surficial aquifer is the topmost, shallow aquifer.
Unconfined aquifer	Is the aquifer nearest the surface, having no overlying confining layer. The upper surface of the groundwater within the aquifer is called the watertable. An aquifer containing water with no upper non-porous material to limit its volume or to exert pressure.
Watertable	The saturated level of the unconfined groundwater. Wetlands in low-lying areas are often seasonal or permanent surface expressions of the watertable.

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