

Mapping phreatophytes on the Eyre Peninsula

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Foreword

The Department of Environment, Water and Natural Resources (DEWNR) is responsible for the management of the State's natural resources, ranging from policy leadership to on-ground delivery in consultation with government, industry and communities.

High-quality science and effective monitoring provides the foundation for the successful management of our environment and natural resources. This is achieved through undertaking appropriate research, investigations, assessments, monitoring and evaluation.

DEWNR's strong partnerships with educational and research institutions, industries, government agencies, Natural Resources Management Boards and the community ensures that there is continual capacity building across the sector, and that the best skills and expertise are used to inform decision making.

Allan Holmes
CHIEF EXECUTIVE
DEPARTMENT OF ENVIRONMENT, WATER AND NATURAL RESOURCES

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Context statement

Six South Australian Natural Resources Management (NRM) Boards entered into an agreement under the National Partnership Agreement on Coal Seam Gas and Large Coal Mining Development (<https://www.waterconnect.sa.gov.au/Industry-and-Mining/CSG-Coal-Mining/SitePages/Home.aspx>) to deliver a project (Stage 1) on the formation of a Water Asset Database. Water Assets were uniquely identified for each NRM region with the following water assets identified for the Eyre Peninsula from a regional expert workshop at Port Lincoln in 2012:

- Farm Dams
- SA Water Pipeline
- Tod Reservoir
- Watercourses
- Tod River
- Catchments
- Sub-catchments
- Wetlands (inland)
- Wetlands (estuarine)
- **Groundwater Dependent Ecosystems**
- Freshwater upwellings
- Sheeted catchments
- Prescribed Wells Area
- Monitoring Bores
- Aquifers
- Abandoned water schemes
- Southern Basin and Musgrave lenses
- Town water supply bores

Denny and Berens (2013) report on the spatial distribution of the above water assets across the Eyre Peninsula NRM Region as the outputs of Stage 1. The mapping of groundwater dependent ecosystems for the Water Asset Database utilised the Groundwater Dependent Ecosystem (GDE) Atlas which had the following two final layers (GDE Atlas, 2012):

- Ecosystems that rely on the surface expression of groundwater (rivers, wetlands, springs)
- Ecosystems that rely on the subsurface presence of groundwater (vegetation)

Denny and Berens (2013) utilised the GDE Atlas layer of 'surface expression of groundwater' to map the [Water Source] attribute of wetlands as groundwater dependent ecosystems on the Eyre Peninsula.

Stage 2 (reported here) mapped the 'subsurface expression of groundwater' on the Eyre Peninsula with the output mapping of phreatophytes being fed back into the Water Asset Database (Denny & Berens, 2013). The information reported within this document is broken into two sections:

- Section 1: reports on subsurface expression of groundwater ie. vegetation (herein called phreatophytes)
- Section 2: is a case study at Lake Hamp that reports on the linkage of wetlands (surface expression of groundwater) with vegetation zonation. This case study focuses on *Melaleuca halmaturorum* which has been identified as a phreatophyte (SKM, 2009).

The aim of this report is for the Water Asset Database (Stage 1) to be updated to include information on terrestrial vegetation likelihood of groundwater dependence. This information can also be used by the EP NRM Region for water planning purposes.

Stage 3 is reported in Deane and White (2014) and follows on from Stage 2 – Section 2 case study at Lake Hamp. Deane & White (2014) build on the knowledge of GDE function and their environmental water needs, and propose a monitoring approach for GDEs in the Prescribed Water Areas (PWAs) within the EP NRM Region.

Summary

As stated within the Context Statement, this report is broken into two sections that report on:

- subsurface expression of groundwater (phreatophytes)
- the linkage of wetlands (surface expression of groundwater) with vegetation zonation.

Specifically, Section 2 undertook a case study on *Melaleuca halmaturorum* which has been identified as a phreatophyte (SKM, 2009).

Section 1 provided the opportunity to pull together existing spatial data for further analysis to achieve a greater cohesive understanding of GDEs for water planning and management for the Eyre Peninsula Natural Resources Management Region. The aim of this study was to use the outputs of two previous bodies of work (SKM, 2009 and GDE Atlas, 2012) plus undertake remote sensing and ground-truthing to gain a regional perspective of groundwater interactions of phreatophytes on the Eyre Peninsula. Geographic Information System (GIS) rules were defined so that the outcomes of all three studies (NDVI vigour mapping, SKM (2009) and GDE Atlas (2012)) could be integrated to provide an overall likelihood of vegetation groundwater dependence. The outcome of the work was a more detailed map of groundwater dependence of phreatophytes on the Eyre Peninsula.

It was integral to this study that a ground-truthing component was undertaken, this allowed for the NDVI methodology to be checked against SKM (2009) and the GDE Atlas (2012) mapping. Five main field observations were identified which improved the knowledge and understanding of mapping phreatophytes on the Eyre Peninsula:

1. Patch size and density – a larger patch size may have been beneficial to this study for detecting vegetation vigour at a more comprehensive scale
2. Spatial variation – Mallee woodland dominated vegetation vigour in the drier more northern region whereas the southern region mapping aligned with SKM (2009) and GDE Atlas (2012) detection of Sugar Gum and Blue Gum vegetation associations.
3. Topographic occurrences – density of Mallee woodlands in sand dune country affected the output of vigour detection on swales, slopes and ridges. Also SKM (2009) classification of tussock grassland over deep watertables seemed unlikely to be groundwater dependent.
4. Groundwater processes – landscape detection of groundwater recharge and discharge points, and salinity in the landscape.
5. Effects of salinity – further investigation required of wetland salinity processes in regards to groundwater discharge and local rainfall perching (this was followed up with a case study in Section 2 of this report, and a further report of Deane & White (2014)).

Section 2 presents data from a case study undertaken on the water table and vegetation dynamics of Lake Hamp near Elliston in the Musgrave Prescribed Wells Area. This wetland was used as a case study to investigate a hypothesis that vegetation around saline wetlands may persist partly due to groundwater and the perching of rainfall. During field investigations it was considered that a shallow rainfall-derived freshwater layer may be perching above the denser saline groundwater table at some wetlands on the Eyre Peninsula. The aim of this study was to trial a method to link groundwater level data to existing vegetation by recording the elevation preference for key species. By linking the ground level where plants are found to water table dynamics data, an indication of the preferred water regime for those plant species can potentially be obtained. The results from the case study were not conclusive, but indicate that water table dynamics and vegetation zonation in relation to elevation align with each other. Even though the results of the case study were not conclusive, the tested methodology proved successful and gave reason for a follow-up field-trip. The follow-up field trip, described as Stage 3 in the Context Statement, is reported in Deane & White (2014) and proposes design and implementation principles for establishing a monitoring program for GDEs within at least the prescribed areas on the Eyre Peninsula.

1 Mapping phreatophytes

1.1 Introduction

Ecosystems depend upon water supply and in much of Australia groundwater is a vital water source for ecosystems. Increasingly much of Australia's extensive groundwater supplies are being extracted for agriculture, industry and potable water. Water managers are being challenged to balance the amount of groundwater used for human use with environmental water requirements. Groundwater management is required to preserve the flora and fauna that groundwater dependent ecosystems (GDEs) support.

GDEs are defined as ecosystems that require access to groundwater to meet all or some of their water requirements to maintain a community of plants and animals, ecological processes, and ecosystem services they provide. According to Eamus (2006) GDEs can generally be divided into the following three classes:

1. ecosystems residing within groundwater (aquifers and caves)
2. ecosystems dependent on surface expression of groundwater (springs, wetlands, rivers, estuaries, and near-shore marine ecosystems)
3. ecosystems dependent on subsurface expression of groundwater (terrestrial vegetation excluding aquatic, submerged and emergent vegetation).

This report focuses on the vegetation belonging to the third class, and specifically on phreatophytes, defined here as plants that have roots that can penetrate the capillary fringe and saturated zone. The report also considers groundwater processes on the Eyre Peninsula that support wetlands.

The three-stage assessment framework for determination of environmental water requirements (EWRs) of GDEs proposed by Richardson (2011) provides the basis to this study on the Eyre Peninsula. The focus is to gain understanding of where potential GDEs exist, conceptualisation of the hydrogeologic setting, the level of groundwater dependence that an ecosystem requires to maintain its ecological function, and understanding ecological responses to changes in groundwater levels. These processes in relation to phreatophytes are further discussed below.

1.1.1 Ecological consequences of changes in groundwater dynamics

Evidence is available within the scientific literature as to the likely impacts of reduced groundwater availability on GDEs (Stromberg *et al.* 1992; 1996; LeMaitre, 1999; Eamus, 2006). Impacts may depend on the following:

- nature of the ecosystem (surface or sub-surface expression of groundwater)
- timing of the disturbance relative to temporal reliance of biota on groundwater
- characteristics and severity of the impact (both in terms of magnitude and duration).

Ecosystems relying on the surface expression of groundwater may have highly complex dependence on water from different sources. This may include a combination of rainfall, channel flow, overbank flooding and groundwater. Within this context, impacts of a change in a single source (for example groundwater) may be difficult to predict. Vegetation associations with a phreatophytic component are relatively straightforward in terms of their reliance on groundwater and the resulting water balance. As a result of this, studies from other locations can be used to illustrate some general response patterns typically resulting from changes in groundwater availability. These are discussed in the following section after a brief review of some morphological characteristics of phreatophyte species.

1.1.2 Phreatophyte root structure and growth

In order to appreciate the types of impacts that may occur, understanding phreatophyte root structures is useful. A typical characteristic of phreatophyte species is a dimorphic root structure, with deep tap roots able to access groundwater and shallow lateral roots, which provide access to soil nutrients and rainfall (Le Maitre 1999, Eamus *et al.* 2006). Owing to elongate xylem vessels, tap roots exhibit greatly increased hydraulic conductivity (Pate *et al.* 1995; Dawson & Pate 1996) allowing water

from considerable depth to be accessed by the plant to meet their water requirements. These roots can reach surprising depths with 35 m recorded as accessing water tables (Stone and Kalisz 1991) and 68 m the deepest recorded (Canadell *et al.* 1996).

Phreatophytes respond to fluctuations in water tables through differential rates of root growth allowing tap roots to remain in contact with saturated layers (Le Maitre *et al.* 1999, Eamus *et al.* 2006). As a result phreatophytes are sensitive to sudden lowering of water tables where draw down rates exceed those of root extension (Rood & Mahoney 1990; Mahoney & Rood 1992; Stromberg 1992). Rapid root growth is commonly observed among phreatophytes, and both drought and fluctuating water tables have been correlated with increases in the growth rates of roots over those observed under static water tables (Amlin & Rood 2002). Experimental evidence has found drawdown rates exceeding 2 cm/d decreased the growth of roots and as a result the condition of two northern hemisphere phreatophyte genera *Populus* and *Salix*, evidence as a reduction in transpiration, leaf number and area (Mahoney & Rood 1992; Amlin & Rood 2002). In South Australia, Mensforth & Walker (1994) also observed plasticity in root growth for the wetland phreatophyte *Melaleuca halmaturorum*. In this instance growth was concentrated at different areas of the soil profile as water tables varied over the year. This observation was however at least in part attributed to the plant looking to exploit areas of lower soil water salinity rather than seeking to follow declining water levels.

Where groundwater is found at greater depths, more of the plants available energy may be directed to root growth (Mahoney & Rood 1992). This may lead to the characteristics of the observed phreatophyte community depending on the depth of groundwater. Stromberg *et al.* (1993) note that the growth form of *Prosopis velutina*, a northern hemisphere phreatophyte, changed as a function of the depth to groundwater. Where water tables were less than six metres below the surface *Prosopis* grew as a tree, while at depths of 12–15 m the species took the form of a shrub. Other vegetative characteristics, such as leaf number and area also changed.

An important ecological consequence of the dimorphic root structure is the benefits non-phreatophytes obtain as a result of hydraulic redistribution. This process occurs where root systems passively (that is, without any use or benefit being derived by the host plant) re-distribute water in three-dimensional space through the soil profile according to the relative dryness of the soil. A special case of redistribution is known as hydraulic lift (Caldwell *et al.* 1998; Le Maitre 1999; Orellana 2012), where phreatophytes in contact with the water table re-distribute water to shallow surface soils. This re-distribution means plant roots in shallow soils have access to water where nutrient concentrations are higher but uptake depends on shallow root competition and water becomes available for the use of all plants. Grasses and shrubs located close to phreatophytes have been reported to benefit from this process, performing better than more distant plants without access to the additional water source (Filella and Penuelas 2004; Ludwig *et al.* 2003). In other words, a loss of connection with groundwater may have implications for the vegetation association beyond that of any phreatophyte species themselves.

1.1.3 General impacts resulting from groundwater lowering

Predicting the results of a change to water table dynamics, as with all disturbances, will depend on the nature of the perturbation itself (Lake 2000). As the duration and magnitude of any perturbation increases impacts will become more likely and more evident. From the perspective of phreatophytic vegetation, a short term, pulse type disturbance to water table dynamics, or equally to water quality, will likely lead to a reduction in various measures of the performance of individuals. Impacts of extraction and drawdown from the aquifer may lead to changes in plant water potential, leaf size and/or number, canopy height, and the ratio of living to dead vegetation volume (Stromberg *et al.* 1992; 1996; Eamus 2006). Such impacts as these may not be immediately apparent to managers even where a typical vegetation monitoring program was in place. The shorter the duration of the pulse, the more likely this would only be apparent in variables such as canopy volume, leaf water potential or growth increments. Hence such early warning impacts are of a lower detection likelihood.

As the duration of a perturbation in groundwater supply continued, or its severity increased, a lack of recruitment success may be observed, especially in riparian systems (Le Maitre 1999). Younger trees are less able to extend root systems to reach, or keep pace with declining groundwater levels, hence the loss of this age class may occur early on. It should be noted that the process of recruitment is often opportunistic in nature and is also sensitive to land management, hence a lack of recruits within a red gum woodland size class distribution for example may not in itself indicate impacts on groundwater.

Continued groundwater draw-down would likely then result in the partial to complete mortality of older individuals unable to maintain demand to support their full canopy (Le Maitre 1999). Mid-age, actively growing trees will likely be most resistant to shorter-term disturbances with high root growth potential and smaller canopy demand to maintain. While all dependent

vegetation will suffer a decrease in performance with a disturbance to groundwater dynamics, mid-age trees at least may persist for several seasons. Ultimately, if the disturbance is not ameliorated, loss of all phreatophytes will likely occur with successional replacement by terrestrial species. Note that if the pre-impact water table is located at depth a level of hysteresis is highly likely to be observed. It is unknown if a return to phreatophytic vegetation would occur as a natural succession even if water table dynamics were restored once a shallow non-phreatophyte terrestrial plant community had established.

Concurrent with the loss of access to water provided via hydraulic lift from deep-rooted phreatophytes, it is reasonable to anticipate impacts on understorey species. Any understorey reliant upon hydraulic lift would be extirpated following the loss of phreatophyte connection with groundwater. Such a change in community structure and composition may be gradual and typical vegetation monitoring data will likely be a lag indicator of many impacts. The most easily detected early warning signals may well relate to simple groundwater monitoring data. Provided that pre-impact data are collected to indicate the range of variability in groundwater level and salinity, deviation from this can be taken as an indicator that phreatophyte communities may be under stress. This can be used to trigger more detailed investigations if considered necessary. Characterising both vegetation structure and density and observed water table variations while a groundwater dependent community is considered to be self-sustaining is a good natural resource management approach to establishing a baseline. Such information can be used as a benchmark guide to avoiding impact under multiple development scenarios.

As suggested above, phreatophyte root systems need to be able to maintain contact with the water table or capillary fringe, hence along with annual minima and maxima, seasonal rates of water table decline are critical variables to estimate under pre-impact conditions.

Eamus *et al.* (2006) present a conceptual model of the manner in which impacts become apparent along a gradient of increasing severity or duration. It is reproduced here to underline some of the concepts discussed above (Figure 1).

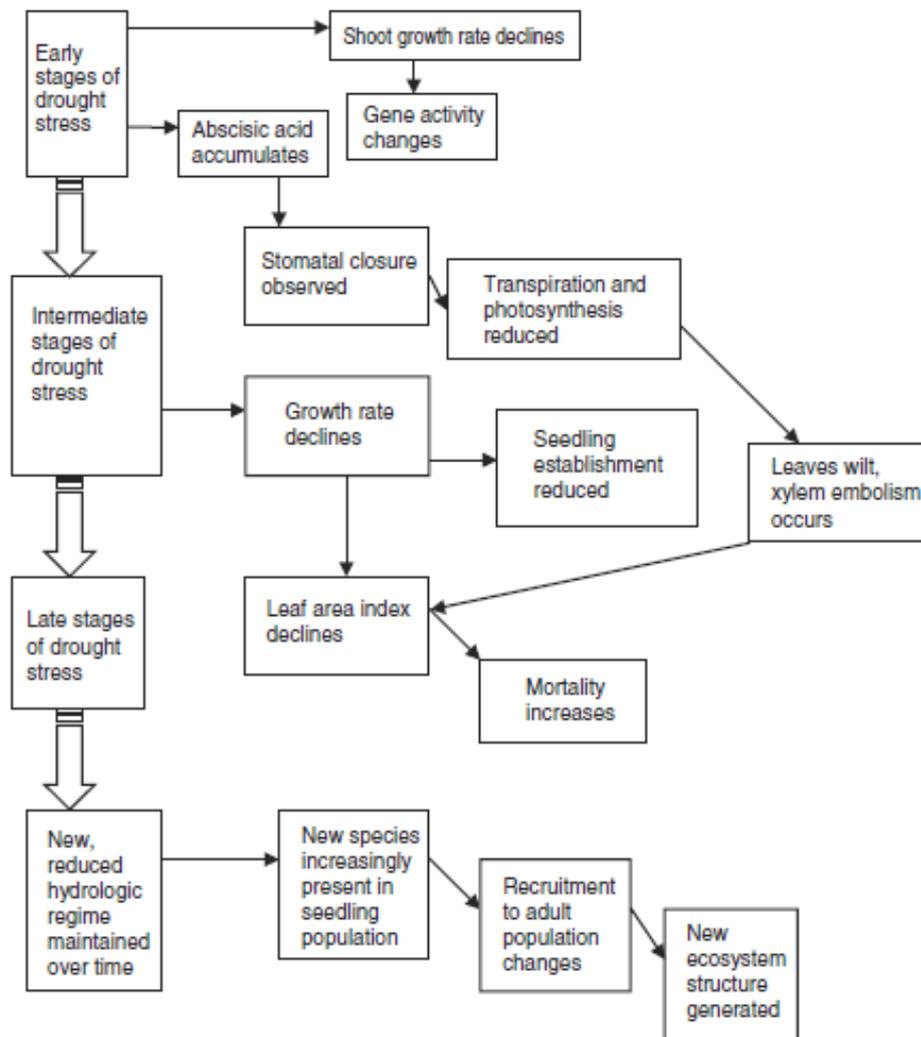


Fig. 1. A conceptual model of short-, medium- and longer-term changes in ecosystem function that can be monitored at a range of spatial scales and levels of biological organisation.

Figure 1. From Eamus *et al.* (2006) A conceptual model of impact on phreatophyte community from groundwater drawdown

1.1.4 Degree of reliance on groundwater

Once an ecosystem has been identified as being dependent upon groundwater, attention is often directed towards establishing whether the nature of this use is facultative or obligate. This division can be usefully assigned to different species, such that the presence of an obligate in the landscape can be taken to be a definite indicator that groundwater is being used. The presence of a facultative species warrants further investigations to determine whether groundwater is contributing to the water balance of the association. Hence it is a useful tool at the level of mapping GDEs as discussed above and employed in this and other studies.

It is suggested however that for a mapped GDE this question is of little actual value to managers. Definitions of the terms 'obligate' and 'facultative' are confusing and contradictory; Eamus *et al.* (2006) cite Hatton & Evans (1997) with the origin of the terms, yet neither term appears in the document in currently available versions. While equating the proportion of the annual water budget being met by groundwater to the level of dependence to meet their objectives, those authors in fact state (Hatton & Evans 1997, p 11):

'Thus it is unlikely that there are ecosystems in Australia that exist in the presence of groundwater that have no dependence upon it, and were groundwater to be made less available, would not suffer. Were it to be shown that a woodland derived only 10% of its annual transpiration from groundwater, it may be unsafe to assume that denial of this resource would have only a trivial impact.'

Eamus *et al.* (2006), citing O'Grady *et al.* (2006) adopt the following definition:

'Facultative dependency occurs when groundwater is used when it is available but its absence does not cause the loss of this vegetation element from that site.'

In the direct absence of empirical evidence this may be of limited value and examples given by Eamus *et al.* (2006) potentially misleading. O'Grady *et al.* (2006) does not use the term 'facultative' but does suggest that some tree species use groundwater opportunistically over a five month study, while others were more obligate in their use of the resource. Few, if any, ecologists would be comfortable equating the term 'opportunistic' with the phrase 'ecologically unimportant'. Indeed, many critical ecological processes are highly opportunistic, yet nonetheless essential for population viability. Flood-based recruitment of floodplain trees or dispersal events are good examples.

A theme within Eamus *et al.* (2006) is the difficulty in establishing a level of dependency. Eamus *et al.* (2006) indicate that groundwater may become critical at irregular intervals for the maintenance of a given population. An example is given that a six month requirement for groundwater every 10-20 years is an obligate usage. The implication is that a short-term study would be extremely fortunate to observe one of these irregular events that define an obligate level of dependence. The argument that groundwater use can be both critically important and highly irregular and a conclusion of 'facultative' use by a vegetation association after a single year of study are incompatible; groundwater may periodically become obligate (only rely on groundwater) under circumstances outside those times not observed during the period of a short term study. Logically, only studies spanning several cohorts could reliably indicate a 'facultative' use.

Clifton *et al.* (2007) provides a different definition of a facultative GDE as:

'Facultative GDEs require access to groundwater in some landscapes, but in other landscapes can utilise alternate sources of water to maintain ecosystem function, i.e. the presence or absence of groundwater is not critical in determining ecosystem occurrence.'

This definition mixes a species level and habitat level designation. Note that this is not the same as saying that removal of groundwater access at the site in question will not impact the ecosystem. Yet researchers regularly conclude the opposite: that where groundwater is present, it will be used by the ecosystem to maintain structure and function (Hatton and Evans 1997; Le Maitre 1999; Murray *et al.* 2003). The fact is that whether in some locations a given vegetation association is found where groundwater is not present; the structure of both the facultative phreatophytes and any reliant understorey species would be fundamentally different if no groundwater were present. Indeed, Canham *et al.* (2009) identified a degree of plasticity in traits related to water stress resistance, with a facultative species of *Banksia* from a site where groundwater was available not differing from that of an obligate *Banksia*. If facultative users develop a comparable series of traits to those of obligate plants when groundwater is available, then loss of groundwater could be predicted to have similar consequences at a site, whether the species is a facultative user or not.

The presumed implication in delineating a facultative from an obligate GDE is that the loss of this ecosystem is of lesser importance because in places it is found where groundwater does not occur. Determining the exact features of ecosystem structure and function that are reliant upon groundwater is a costly and uncertain business. George *et al.* (2005) presents a good example, where riparian tree species are facultative users of groundwater, with other sources preferred, with the exception of long periods of drought, where the entire ecosystem relies entirely on groundwater to persist. Put another way, to classify an ecosystem as facultative implies some (anthropocentric) element of choice on behalf of the organism.

It is arguable that any dependence on groundwater should be viewed as essential to maintain the current characteristics of the ecosystem. Moreover observed facultative use may speak as much to the ability of scientists to identify all uses of groundwater as much as the ability of the ecosystem to do without. At ecosystem level the question of 'obligate' vs 'facultative' loses relevance and as such, management should focus on the values and risks to the systems they have and how groundwater supply figures in these. In other words, where groundwater dependence is recognised, there are more fruitful questions to focus on than the temporal usage pattern. Some suggested actions are provided for GDE managers in Section 2.

1.1 Study location

The Eyre Peninsula NRM region (Figure 2) covers a large proportion of South Australia (80 000 square km/8 million ha) and includes a diverse range of water dependent ecosystems that persist across the region, from coastal marine to inland arid areas. Much of Eyre Peninsula has limited surface water due to relatively low rainfall, high evaporation, permeable soils and flat landscapes, though it still supports a variety of wetlands that offer critical refugia in a largely fragmented agricultural landscape; wetlands may exist as lakes, swamps, streams, springs, rock holes, salt marshes, mangroves or estuaries.

Eyre Peninsula has a characteristic Mediterranean climate, with warm dry summers, and cool wet winters. Mean annual rainfall ranges from 250 mm in the north and northwest to more than 500 mm in the south of the region.

There are two main sedimentary sequences containing groundwater that overlie basement rocks on the Eyre Peninsula, being the Quaternary Limestone aquifer and the Tertiary Sands aquifer. More detailed information and conceptual understanding on the hydrogeology of the region can be found in the groundwater status reports (<https://www.waterconnect.sa.gov.au/Science-and-Research/Monitoring/SitePages/State%20and%20Condition%20Reports.aspx>).

In 2009, the Eyre Peninsula NRM region contracted Sinclair Knight Merz (SKM) to undertake a scoping study on groundwater dependent ecosystems on the Eyre Peninsula which aimed to classify 10 ecosystems; saline swamps, saline lakes, springs and underground water soaks, grasslands and sedgeland, hypogean, hyporheic and collapsed sinkhole ecosystems, phreatophytes, freshwater lakes, damp coastal and sub-coastal heaths (SKM, 2009) with the project delivering six of these classifications due to desktop data availability (Figure 3). The scoping study also investigated vegetation communities that could potentially access groundwater to meet some part of their environmental water requirements, these were considered to include; *Eucalyptus* forest and woodland, *Melaleuca* forest and woodland, *Melaleuca* shrubland >1 m, *Allocasuarina* forest and woodland, rushland/sedgeland, tussock grassland, and coastal shrubland.

Due to the SKM (2009) study being desktop based, this study built-on the existing knowledge base to undertake some field validation of phreatophyte mapping and to also undertake an initial assessment of wetland function in relation to understanding groundwater dependency on the Eyre Peninsula (Section 2) which was further investigated with a follow-up field trip and technical report (Deane and White, 2014).

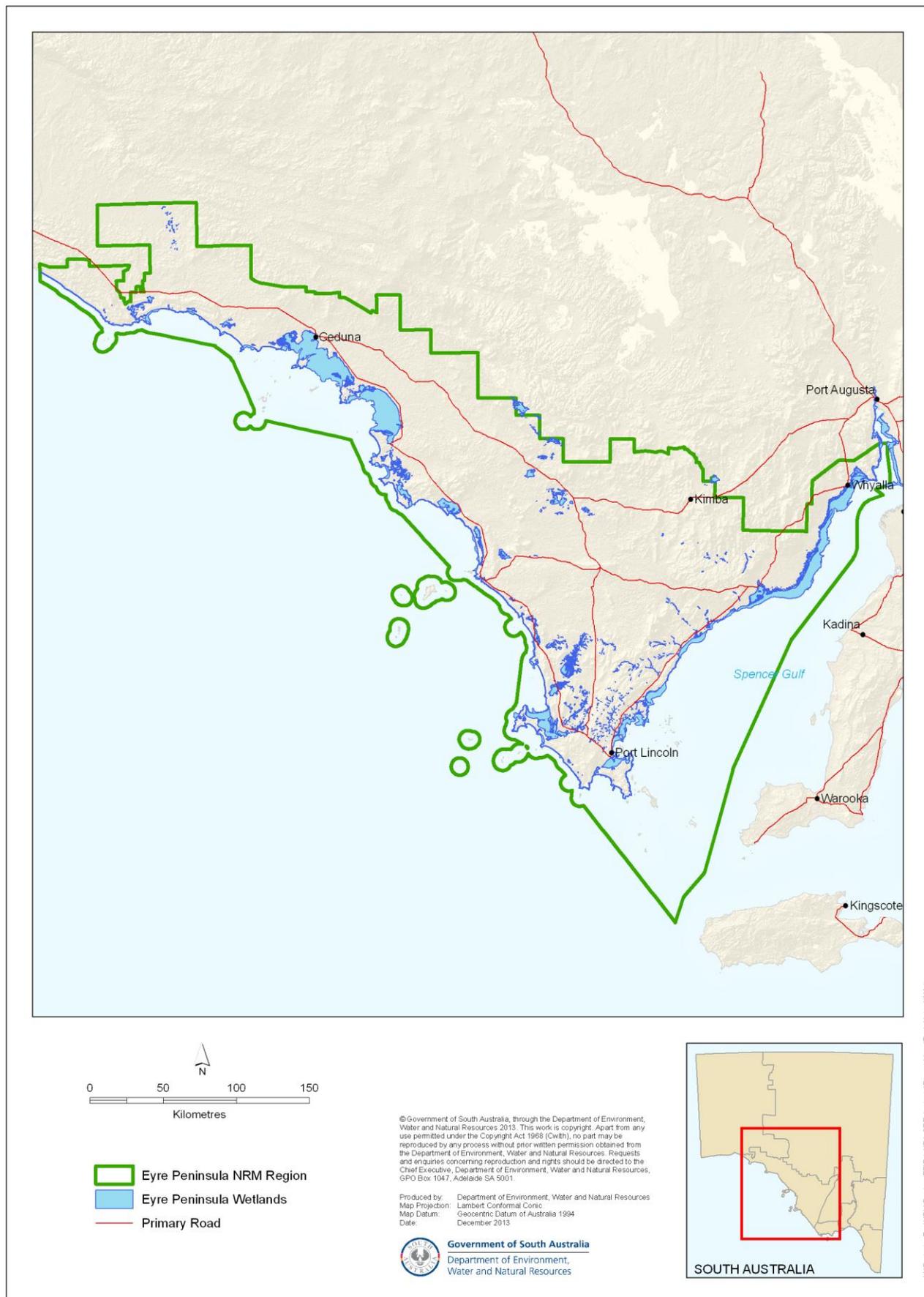


Figure 2. Eyre Peninsula NRM Region and locality of wetlands

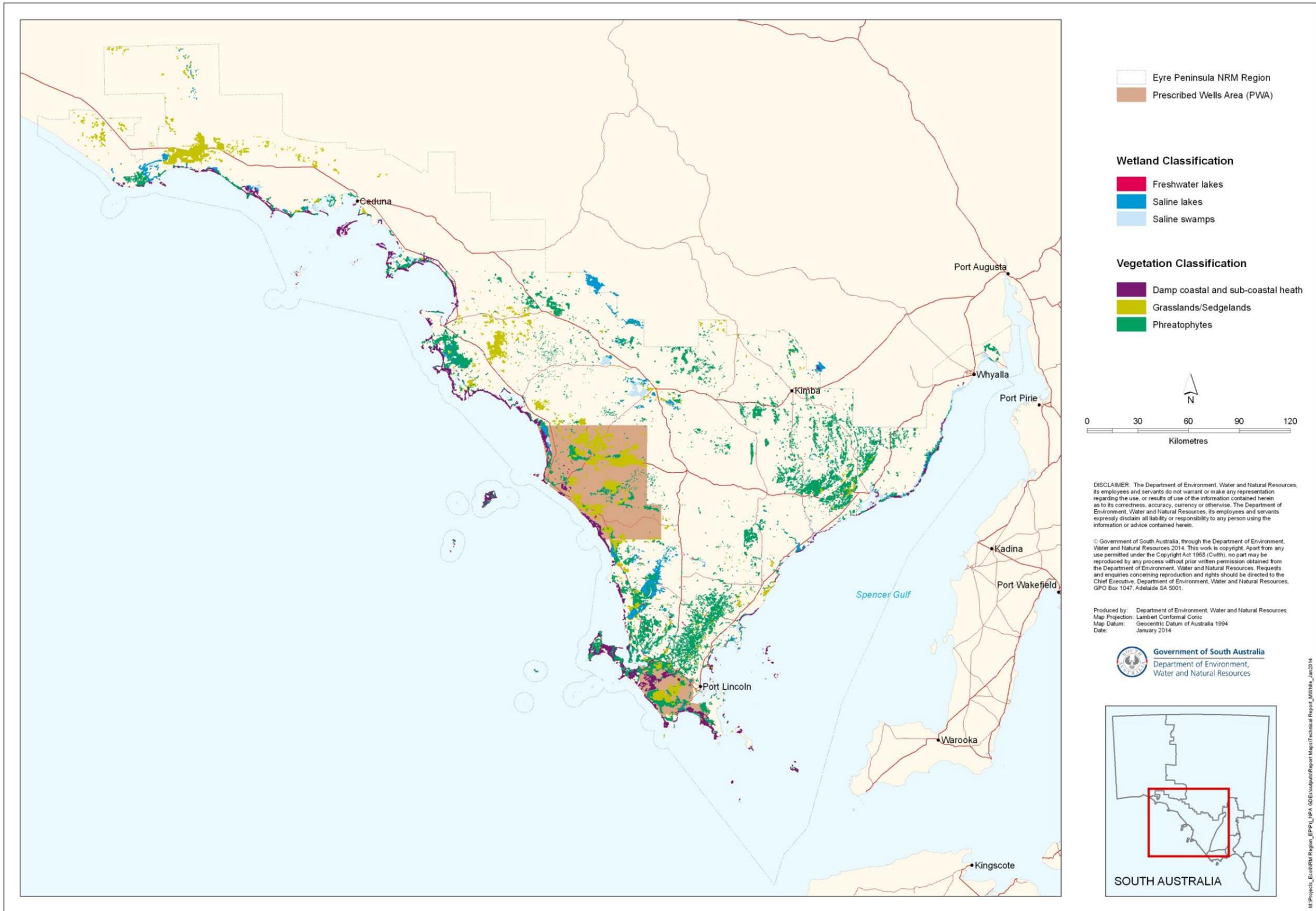


Figure 3. Classification of ecosystems on the Eyre Peninsula as reported by SKM (2009)

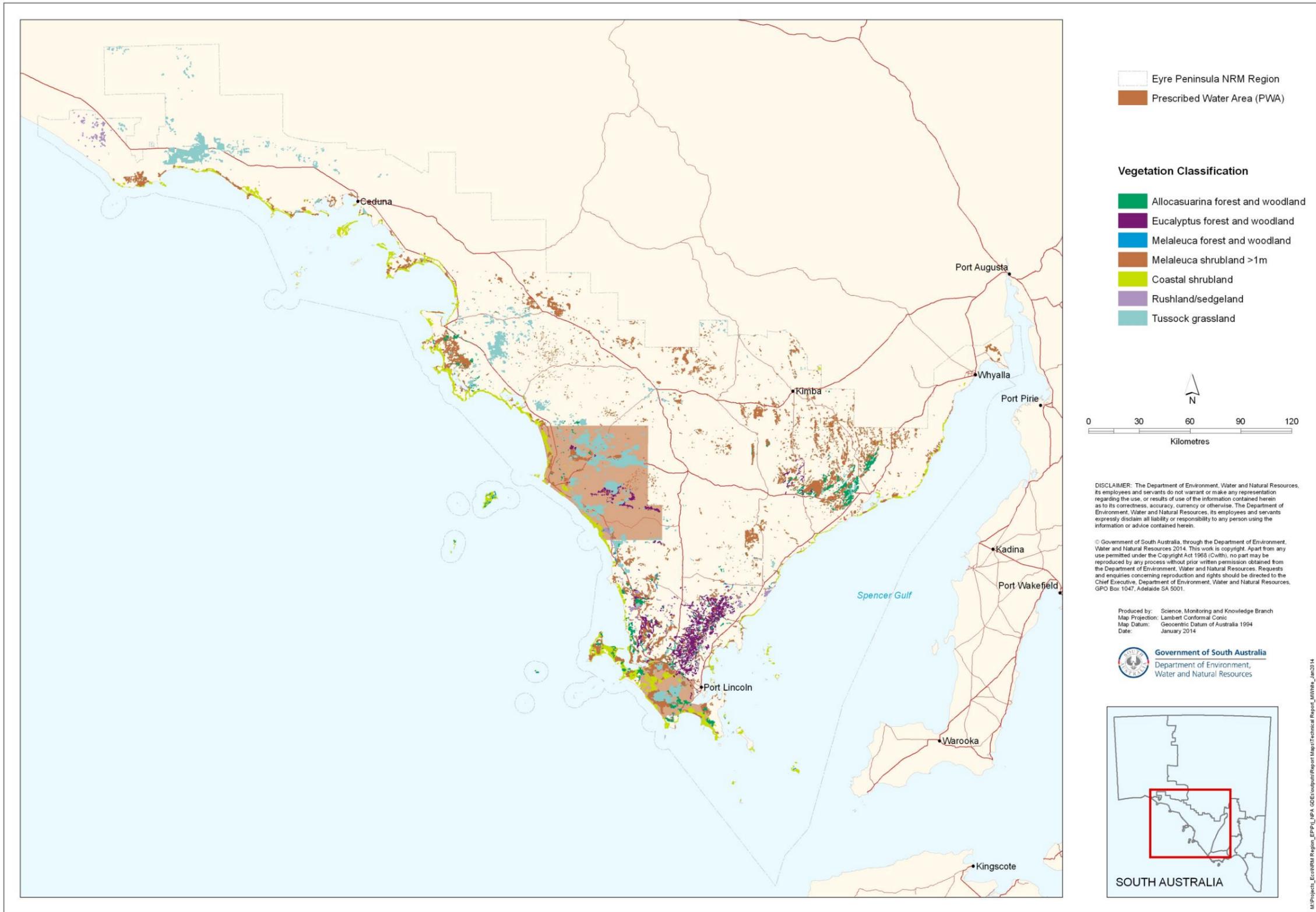


Figure 4. Vegetation communities that could potentially access groundwater to meet part of their environmental water requirements (SKM, 2009)

1.2 Methodology

1.2.1 Existing mapping

There have been two studies that have mapped potential GDEs on the Eyre Peninsula.

As previously stated, SKM (2009) undertook a scoping study conceptualising, mapping and prioritising GDEs and their environmental water requirements, this study included surface expression of groundwater in wetlands and subsurface expression of groundwater as phreatophytes but did not include springs, soaks, sinkholes or caves where groundwater and their dependent ecosystems also exist.

In 2012, SKM and CSIRO undertook the GDE Atlas project that mapped surface and subsurface expression of groundwater at a National scale. The Atlas used pre-existing mapping, incorporated statewide data and knowledge, and used remote sensing and GIS to create an Inflow Dependent Ecosystem (IDE) layer to determine existence of potential ecosystems using groundwater across the Australian landscape (GDE Atlas, 2012). The GDE Atlas divided Australia into eight work package zones which were again divided into eco-hydrogeological zones. The Eyre Peninsula NRM Region is within one work package area but is spread across four eco-hydrogeological zones, which illustrates the climate and groundwater complexity of Eyre Peninsula.

1.2.2 Additional investigations

This study provided the opportunity to pull together existing data and provide further analysis to achieve a greater cohesive understanding of GDEs for water planning and management for the EPNRM Region that builds on work undertaken by DEWNR in 2012 (Doeg *et al.*, 2012). The aim of this study was to use the outputs of the two previous studies (SKM, 2009; GDE Atlas, 2012) plus undertake remote sensing and ground-truthing to gain a regional perspective of groundwater interactions of phreatophytes and wetlands on the Eyre Peninsula.

This study will follow a similar approach to that of Overton (2006) whereby four main questions from NCC (1999) were addressed. For this study these questions have been broken into the two methodologies that were undertaken.

Section 1: Mapping and understanding phreatophytes on the Eyre Peninsula:

- Is vegetation known to sustain growth through drought seasons?
- Does the vegetation remain lush throughout the year in an arid environment?

Section 2: Understanding wetland GDEs on the Eyre Peninsula through the presentation of a case study:

- Is the water table within the ecosystem root zone at any time in the natural cycle?
- Are there any indicator species which indicate groundwater dependency?

1.2.2.1 Normalised Difference Vegetation Index (NDVI)

The Normalised Difference Vegetation Index (NDVI) are derived from satellite data and a measure of the amount of live green vegetation. Live green vegetation absorbs visible light (solar radiation) as part of photosynthesis and at the same time plants scatter (reflect) solar energy in the near infrared. This difference in absorption is quite unique to live vegetation and provides a measure of the greenness of the vegetation. NDVI is an index which measures this difference, providing a measure of vegetation density and condition. NDVI is calculated from the red and near-infrared reflectances r_{Red} and r_{NIR} as:

$$NDVI = (r_{NIR} - r_{Red}) / (r_{NIR} + r_{Red})$$

Its value is always between -1 and +1. Vegetation NDVI in Australia typically ranges from 0.1 up to 0.7, with higher values associated with greater density and greenness of the plant canopy. NDVI decreases as leaves come under water stress, become diseased or die. Bare soil and snow values are close to zero, while water bodies have negative values.

The methodology for this study follows that of Overton (2006) whereby:

If vegetation remains lush during a dry period it could indicate that the vegetation has an alternate water supply which could be groundwater.

Using this as a hypothesis, this study used a dry time-series (epoch) approach as the landscape would be at its driest and therefore any vegetation that is using groundwater during these periods could be identified via NDVI. The constraints of the epochs for Eyre Peninsula were as follows:

- (1) Landsat acquisition post 1980
- (2) Annual rainfall below average
- (3) Image capture Autumn (February–April), the post-summer period when vegetation that is possibly using groundwater will have higher vigour than surrounding rainfall dependant vegetation
- (4) Also finding cloud-free periods across a 6–8 week period, as it usually took Landsat up to six weeks to cover the nine scenes required to cover the whole of the EPNRM Region
- (5) The two months prior to image capture also had to have average or below average rainfall, so the vegetation in the imagery will not be responding to a summer rainfall flush. The methods to determine the best low rainfall periods for Landsat image capture were:
 - (6) Rainfall station data was aligned with the stations that are used for the annual Groundwater Status Reports on the Eyre Peninsula (<http://www.waterconnect.sa.gov.au/GSR/>) this was deemed appropriate as the Musgrave PWA exists in the drier part of the peninsula, while the Southern Basins covers the higher rainfall area of the southern peninsula. The rainfall stations used were Elliston (18069) and Big Swamp (18017).
 - (7) Bureau of Meteorology (BOM) data was manually queried to find annual below average rainfall years with either average or below average rainfall over the two-month period late summer (Jan–Feb) for both the Elliston and Big Swamp stations.

Years matching the criteria were: 1991, 1993, 1994, 1998, 1999, 2008. These years were then shortlisted to best match cloud-free imagery and to also have below average rainfall two months prior to Landsat image capture; 1998, 2008 and 1994 best matched the criteria.

To determine if the above three dates were the best dates to undertake the analysis, we additionally looked at evapo-transpiration, cumulative deviation from annual rainfall and soil moisture trends on the Eyre Peninsula at Elliston and Big Swamp using SILO data; the general trend showed that a declining rainfall period occurred from 1992–2010 and evapo-transpiration increasing in response to declining rainfall especially from 2004-2010.

The NDVI analysis threshold was used for vegetative ecosystems known to support GDE's on the Eyre Peninsula i.e. vegetation surrounding groundwater dependent wetlands. The final mosaic was a dataset that intersected vigorous growth in all three dry years which gave a more conclusive dataset indicating where vegetation may have an alternate source of water other than rainfall.

1.2.3 Hydrogeology

1.2.3.1 *Wetland cross-sections*

As part of this project, additional desktop work was undertaken to provide further conceptual understanding of the hydrogeological setting and groundwater processes occurring around a number of wetlands.

Doeg *et al.* (2012) assessed the Environmental Water Requirements (EWRs) for wetlands on the Eyre Peninsula and selected representative wetlands where future monitoring should be targeted. The representative wetlands included Sleaford Mere, Lake Pillie, Round Lake, Lake Newland, Poelpena and the under-represented and rarely studied springs on the Eyre Peninsula.

Semeniuk and Semeniuk (2007a) previously installed piezometers around a number of these wetlands which have had some monitoring since 2005 though limited access to these data exists.

The hydrogeological desktop study targeted Lake Hamp, Lake Newland and Samphire Flat as depth to groundwater data have been collected since 2005 by Rob Coventry (DEWNR NRM Officer, Elliston) and was made available. Poelpena was also selected due to its proximity to the Polda groundwater lens. Hydrostratigraphic cross sections and a hydrogeological summary for these wetlands are provided in Section 3, Appendix. Aerial maps displaying recent groundwater data from nearby wells are also provided. With the exception of Poelpena, where groundwater data in the proximity of each wetland are generally sparse and predates 2000.

To construct the interpreted cross sections, information was collated from 1:50 000 surface geology mapping (Flint 1989; Flint & Rankin 1989; Rankin & Flint 1989), drillhole lithology data collected during historical drilling activities (SA Geodata, 2013), hydrostratigraphic 3D spatial layers (DEWNR, in prep.), wetland lithology and groundwater data (NRM Region monitoring piezometers; Semeniuk & Semeniuk, 2007a&b) and regional groundwater data (WaterConnect, 2013). Cross section construction was completed digitally using the GIS software package ArcMap™ and extension package Exacto V2.0©. A vertical exaggeration of 1:20 was used to aid display of information.

The hydrostratigraphic cross sections provide an indication of the likely water source for the specific wetlands studied using existing drillhole lithology and groundwater data. Whilst no hydrochemical sampling was undertaken as part of the current study, bores within each wetland's proximity were assessed for future inclusion into a sampling program.

1.2.3.2 Groundwater mapping

To support the NDVI analysis and subsequent field work, groundwater level and salinity maps were produced for the time periods 1994 to 2008, and 2010 to 2013 respectively. These maps are included in Appendix.

The interpolated groundwater level and salinity maps were constructed using the most recent groundwater level and salinity data collected during the specified time period, and archived in the state's groundwater information database (WaterConnect, 2013). The information was presented digitally using GIS software package ArcMap™ and the Inverse Distance Weighted (IDW) interpolation extension tool (cell size 50 m). As groundwater data from the EP NRM region are sporadic both spatially and temporally, it was necessary to increase the number of data points (and hence confidence in the interpolation method) by selecting for a date range rather than a specific year. Buffer distances were constructed around each data point to display confidence in the interpolation method: <2 km (high); 2–5 km (moderate); and >5 km (low).

1.2.4 Field ground-truthing

It was integral to this study that a ground-truthing component was undertaken, this allowed for the NDVI to be checked against SKM (2009) and the GDE Atlas (2012) mapping of GDEs on the Eyre Peninsula. The ground-truthing methodology included driving across various landscape and climatic regions of the Eyre Peninsula to get a good understanding of what vegetation, geology, elevation and groundwater processes may be occurring and how these vegetation patches matched against the desktop GDE mapping. It was recorded during the ground-truthing where the different methodologies matched or did not match.

During the field ground-truthing a case study looking at the interaction of water table dynamics and vegetation zonation was undertaken at Lake Hamp near Elliston. Depth to groundwater had been monitored monthly at Lake Hamp for the last five years, with Section 2 presenting the methods and results of this case study. The aim of this study was to trial a method to link groundwater level data to existing vegetation by recording the elevation preference for key species. By linking the ground level where plants are found to the water table dynamics data as an indication of the preferred water regime for those plant species can potentially be obtained.

1.2.5 Collating information

The aim of this study is to incorporate the outputs of the NDVI analysis with the GDE Atlas (2012) and SKM (2009) to gain a regional perspective of groundwater interactions with phreatophytes and wetlands on the Eyre Peninsula.

The NDVI analysis undertaken in this study used a dry time-series approach as the landscape would be at its driest based on inferred vigorous growth signatures. The final mosaic was a dataset that intersected vigorous growth in all three dry years which gave a more accurate indication of where vegetation may have an alternate source of water other than rainfall.

The GDE Atlas was produced by SKM and CSIRO in 2012 by processing remote sensing data to produce a gridded inflow dependence layer (IDE) using a rating system between 1–10 to determine the likelihood that vegetation utilises a source of water other than direct rainfall (ratings of 10 indicated landscapes that are highly likely to be accessing an additional source of water other than rainfall). The final assignment for potential groundwater interaction for any mapped ecosystem used a series of GIS processing rules based on existing spatial data and from the IDE layer to produce a classification of high/moderate/low potential for groundwater interaction. GDE Atlas (2012: pp. 44) note that more complex measures of reliability could have been developed, however, it was concluded that this would not have made the Atlas more useable and they state that:

“The Atlas is a management tool designed for use in the early stages of the planning process to indicate the location of potential GDEs”.

This context should be borne in mind when considering the reliability of the information and forms the reasoning behind using the remotely sensed IDE ratings for our analysis as opposed to the inferred high/moderate/low classification for potential groundwater interaction.

The Eyre Peninsula GDE Scoping Study (SKM, 2009) used the remote sensing technique NDVI to interpret whether each of the potentially groundwater dependent vegetation communities had access to groundwater based on inferred water stress signatures. NDVI was high where potential groundwater dependent vegetation (obligate and facultative) communities were mapped over shallow water tables suggesting that these vegetation communities have access to groundwater. Where facultative groundwater dependent vegetation communities occurred over deep water tables, NDVI was found to be low suggesting no access to groundwater and a low soil water store. Some inconsistencies were found, and it was suggested that vegetation health and density, and perched groundwater systems would be contributing factors needing to be considered.

1.2.6 Rules developed for assigning groundwater dependence

This section describes the methodology used to identify potential GDEs by integrating the spatial datasets within a GIS environment. The purpose of the GIS analysis was to intersect the different feature layers to present an ecosystem dataset layer with assigned groundwater dependence. The likelihood of groundwater dependence was assigned the categories of very high, high, moderate and unlikely, which was determined by attribute data within the three spatial datasets; NDVI analysis, GDE Atlas (SKM, 2012), and the Eyre Peninsula GDE Scoping Study (SKM, 2009). Figure 5 demonstrates the overlap in data from the three spatial datasets.

Within the GDE Atlas shapefile download an IDE value is given in the attribute table. The IDE value was determined from the gridded remote sensing layer with the values indicating a likelihood rating between 1 and 10. The higher likelihood rating (6 to 10) suggest that the landscape is more likely than not to be using an additional source of water, such as groundwater. Ratings of 10 indicate landscapes that are highly likely to be accessing an additional source of water.

The scoping study that SKM undertook (SKM, 2009) classified the vegetation mapping using the outputs from their NDVI analysis into four ecosystem types. These ecosystem types consist of obligate and facultative phreatophytes and unclassified systems.

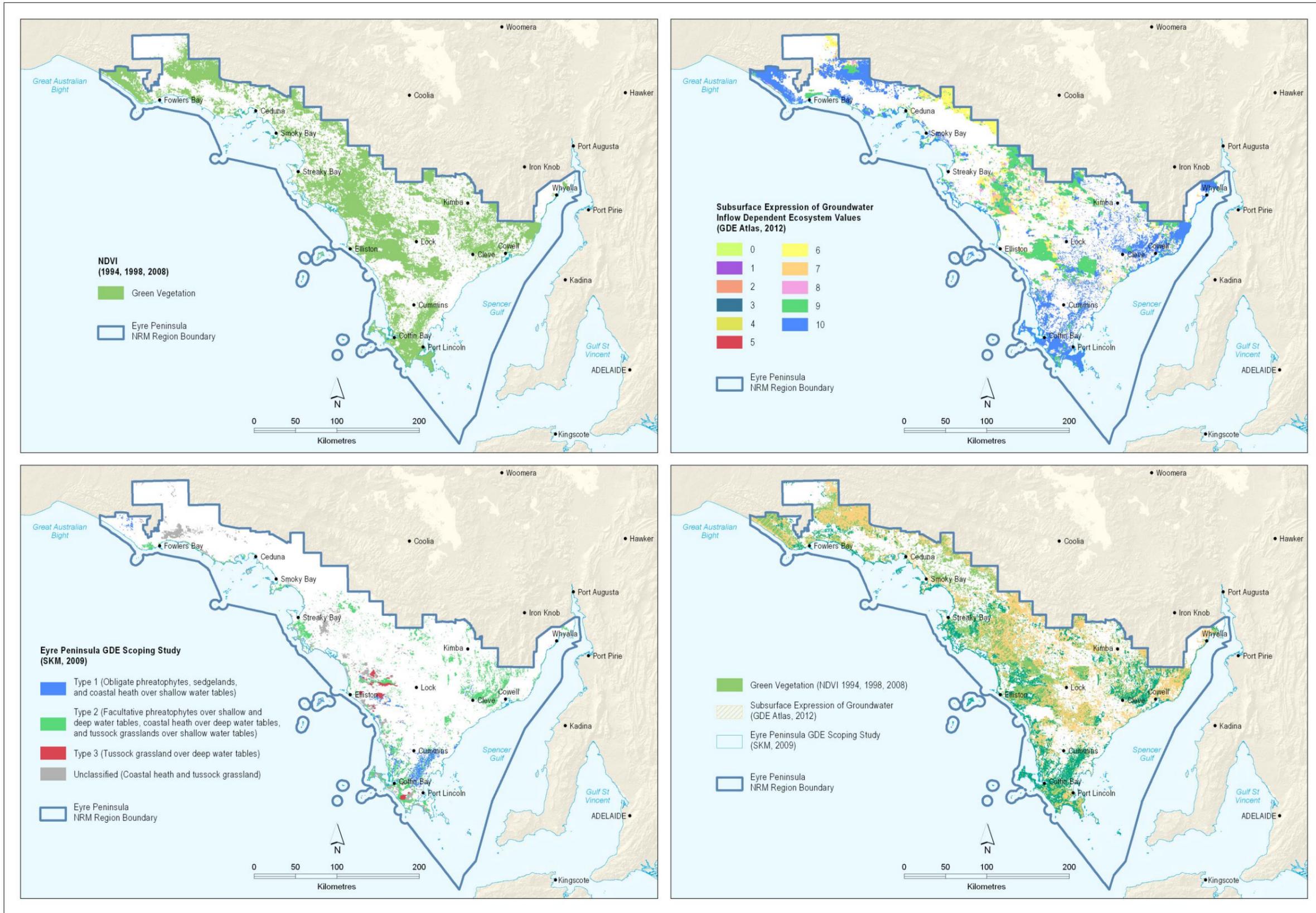


Figure 5. Incorporation of spatial data used for assigning rules for likelihood of groundwater dependence.

1.2.6.1 Very high likelihood of groundwater dependence

To determine a very high likelihood of groundwater dependence, ecosystems with an IDE value of 10 and were classified Type 1 (obligate phreatophytes, sedgeland, and coastal heath over shallow water tables), and also had NDVI from the dry-years mosaic occurring within the intersected patch were rated as very high (Figure 6).

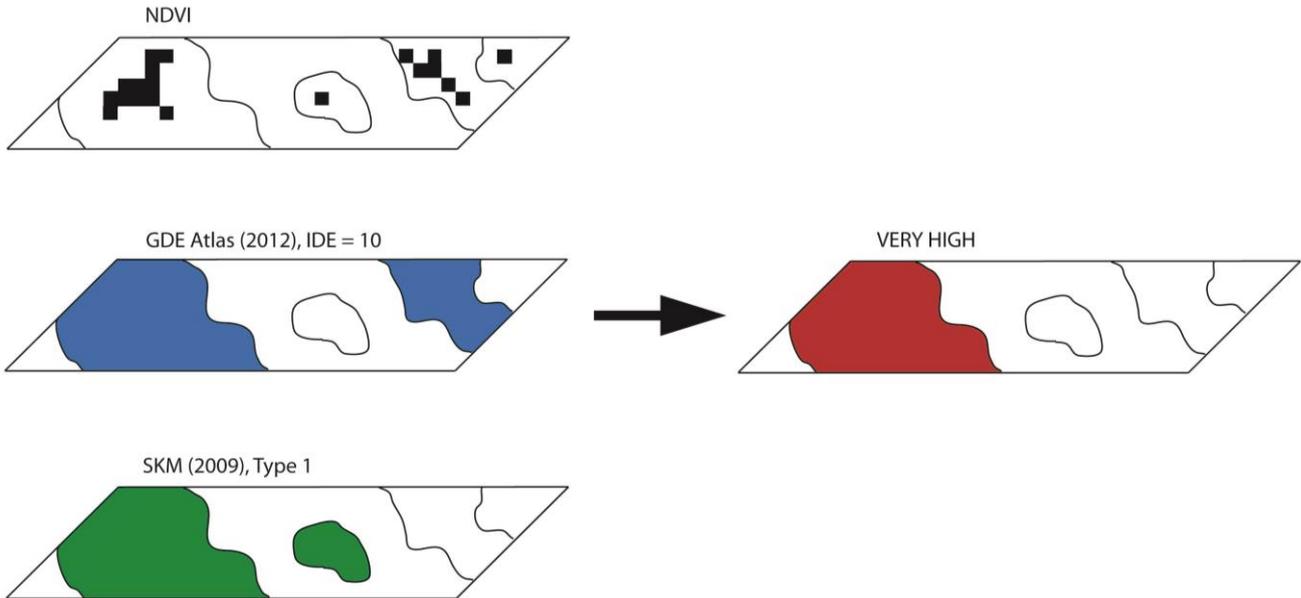


Figure 6. The 'intersect' approach used to determine very high likelihood of groundwater dependence

1.2.6.2 High likelihood of groundwater dependence

To determine a high likelihood of groundwater dependence, ecosystems with an IDE value of 6 to 9 and were classified Type 1 (obligate phreatophytes, sedgeland, and coastal heath over shallow water tables), and also had NDVI from the dry years mosaic occurring within the intersected patch were rated as high (Figure 7).

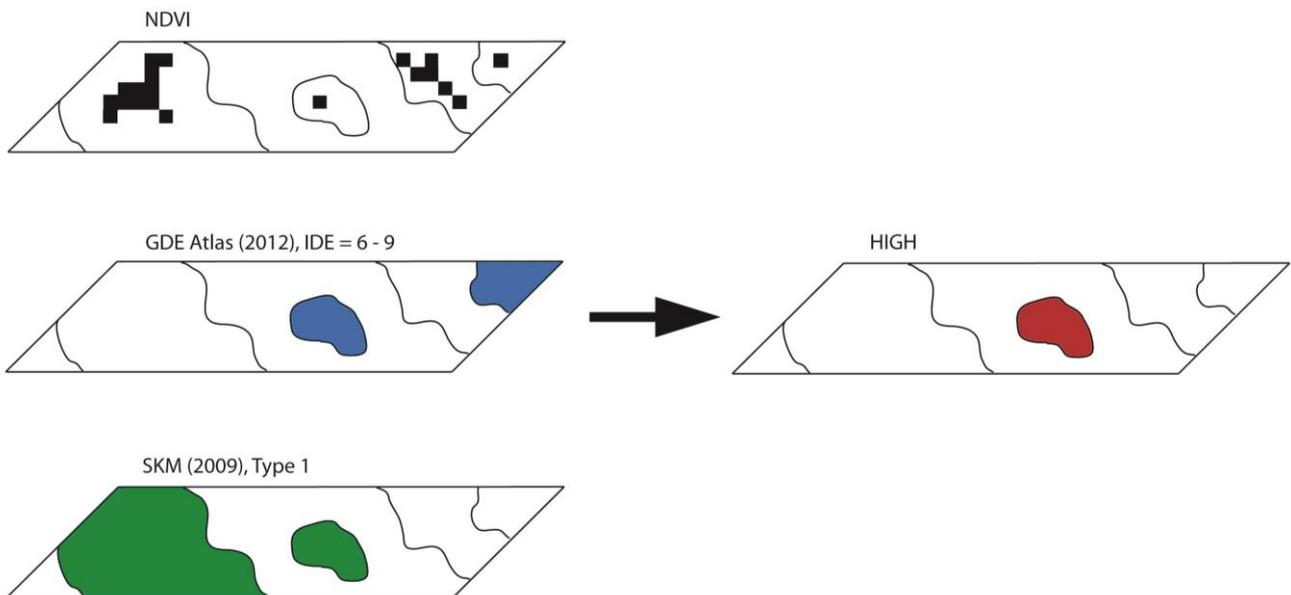


Figure 7. The 'intersect' approach used to determine high likelihood of groundwater dependence

1.2.6.3 Moderate likelihood of groundwater dependence

To determine a moderate likelihood of groundwater dependence, ecosystems with an IDE value of 6 to 10 and were classified Type 2 (facultative phreatophytes over shallow and deep water tables, coastal heath over deep water tables, and tussock grasslands over shallow water tables), and also had NDVI from the dry years mosaic occurring within the intersected patch were rated as moderate (Figure 8).

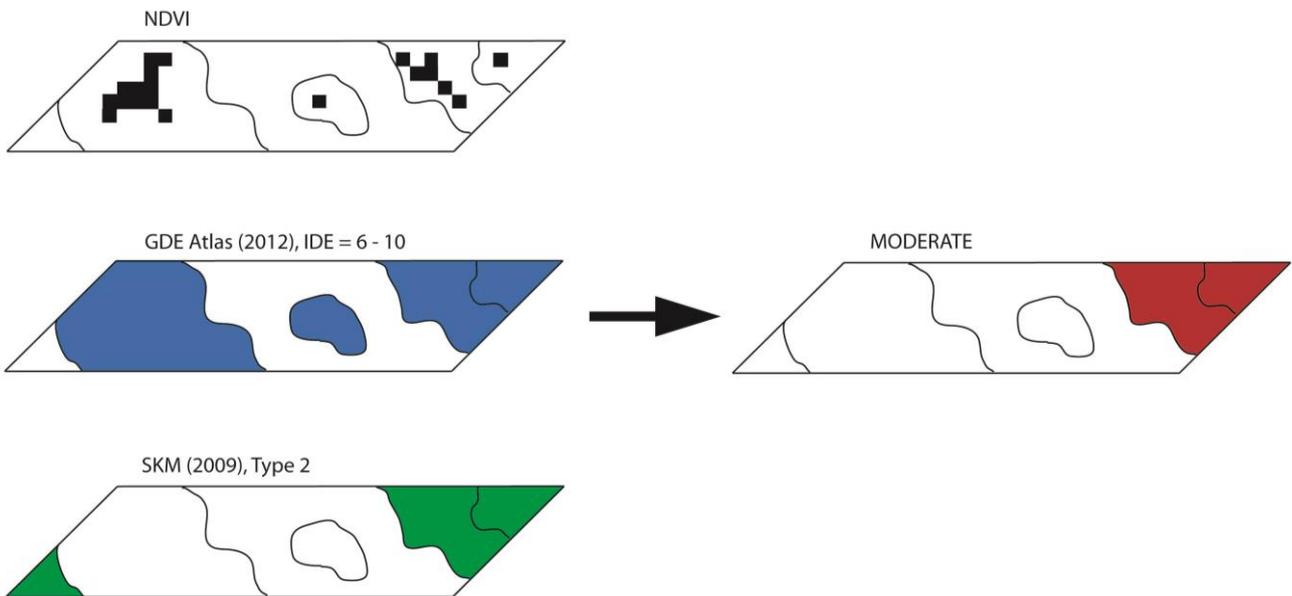


Figure 8. The 'intersect' approach used to determine moderate likelihood of groundwater dependence

1.2.6.4 Unlikely to be groundwater dependent

To determine if an ecosystem is unlikely to be groundwater dependent, ecosystems with an IDE value of 1 to 5 or ecosystems classified Type 3 (tussock grassland over deep water tables) were determined to unlikely to be groundwater dependent (Figure 9).

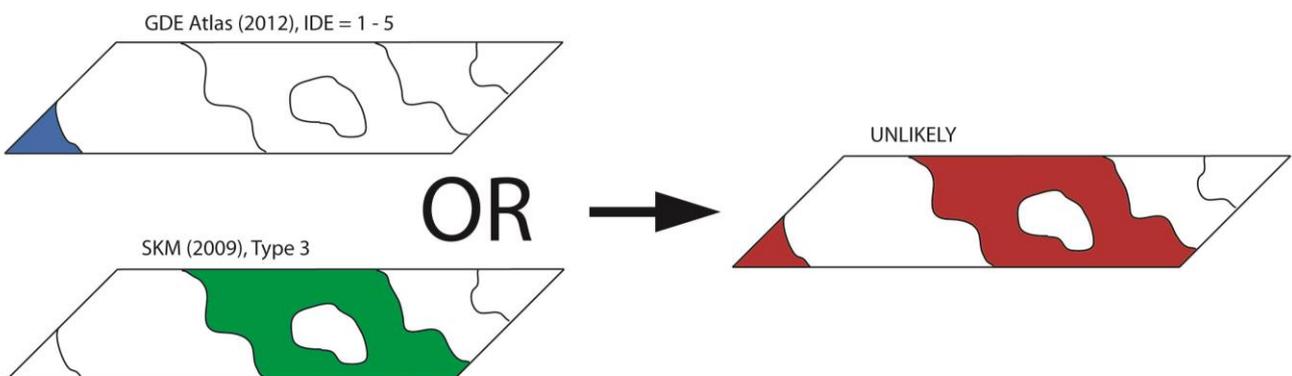


Figure 9. The 'intersect' approach used to low likelihood (therefore unlikely) of groundwater dependence.

1.3 Results and discussion

1.3.1 Hydrogeology

The hydrogeological setting on the Eyre Peninsula has been described in detail in Berens *et al.* (2011). The hydrogeological desktop study for the current investigation targeted Lake Hamp, Lake Newland, Samphire Flat and Poelpena. The results are presented in Appendix A and include hydrostratigraphic cross sections and interpretations, aerial maps displaying recent groundwater data near each wetland, and depth to water and salinity mapping for the broader EP NRM region to support the NDVI analysis and subsequent ground-truthing.

The hydrostratigraphic cross sections are essentially non-quantitative conceptual models that provide an initial assessment of source water, and may be applied to other sites of interest, e.g. other representative wetlands as identified by Doeg *et al.* (2012); stands of phreatophyte vegetation (red gums); or other wetlands in the potential zone of influence of proposed mine sites.

The current study did not include hydrochemical sampling for age or source water indicators, which would provide another line of evidence of source water for each wetland. However existing bores were assessed for potential inclusion in a future sampling program. Groundwater data in the Non-Prescribed areas of the EP NRM region are spatially and temporally sporadic. Where data are available, it usually predates 2000 and often only depth to water readings are reliable as bore construction details are insufficient or unavailable. In the vicinity of Samphire Flat and Lake Hamp, there is generally a paucity of nearby existing wells that are screened in one aquifer and are suitable for reliable hydrochemistry sampling .

The wetland monitoring piezometers installed Semeniuk & Semeniuk (2007a) near the majority of representative wetlands (as listed in Hydrogeology section 1.2.3) are potentially suitable for future hydrochemical sampling. It is recommended that these piezometers be surveyed to allow for comparison of levels against a datum, their current condition (eg. casing) needs to be assessed for future monitoring potential, and monitoring data be collated and stored in the state's groundwater database (SAGeodata) to allow for inclusion in future resource assessments and modelling.

1.3.2 Spatial distribution of phreatophytes

(8) Patch size and density

- a. For the NDVI processing the Landsat imagery pixel size of 25 m was maintained. We did not investigate if the pixel size affected the NDVI output for patch vegetation vigour but it was considered that an artefact of the NDVI processing was reduced patch size of vegetation vigour to what we saw while ground-truthing. It was considered that if a 25 m patch was dominated by vegetation without vigour but had vigorous vegetation occurring on the pixel boundary, then the NDVI would not detect this vegetative vigour. Due to the natural patchiness of vegetation (e.g. paddock trees) on the Eyre Peninsula a larger patch size (e.g. 50–100 m) may have been beneficial to this study for detecting vegetation vigour at a more comprehensive spatial scale.
- b. The density of the vegetation influenced if NDVI was detected. Sparse vegetation cover of a plant community was often missed during the NDVI processing, for example sparse coverage of red gums (*Eucalyptus camaldulensis*) in paddocks and open Mallee woodlands (*Eucalyptus* spp.) were not fully detected in the NDVI processing.

(9) Spatial variation

- a. In the northern area of the Eyre Peninsula (specifically Streaky Bay, Bairds Bay, Venus Bay, Wudinna, Elliston and Sheringa) the vegetation vigour was dominated by Mallee species, this cover matched the outputs of the GDE Atlas. Red gum stands east of Elliston were mapped as maintaining vigour in the NDVI analysis, they were also mapped as potential GDEs in the GDE Atlas and SKM (2009) outputs, as did the coastal shrubland community of *Olearia axillaris* along the western coast of the Eyre Peninsula.
- b. Approximately south of Lake Greenly, towards Port Lincoln, there was a noticeable shift in vegetation communities and their corresponding NDVI detection. Mallee continued to maintain vigour in this area but other species such as *Melaleuca* spp., *Allocasuarina* spp. and *Gahina* spp. were also detected during

the NDVI processing. Those species not found on the more northern section of the west coast, such as sugar gum (*Eucalyptus cladocalyx*) and blue gum (*Eucalyptus petiolaris*), were also detected as maintaining vigour. These findings aligned with the GDE Atlas and SKM (2009)

(10) Topographic occurrences

- a. Mallee communities characterised by rolling sand-dune landforms tended to detect vegetation vigour just in the swales, but in some instances vigour was detected across the whole landform i.e. swale, slope and ridge especially in instances when there was dense vegetation cover across the whole landform.
- b. During the ground-truthing it was considered that it was unlikely that Type 3 (SKM, 2009) (tussock grassland over deep watertables) was unlikely to be accessing groundwater as these occurrences were seen to be on top of rolling hills (Figure 10). This unlikeliness is also stated within SKM, 2009 (pg. 30). Neither the GDE Atlas nor the NDVI detected these areas to potentially be using an alternate source of water and it was therefore assigned 'unlikely' groundwater dependence during the GIS analysis (Figure 9).

(11) Groundwater processes

- a. Linking surface water flow to groundwater recharge and discharge points on the Eyre Peninsula landscape links the vegetation and their dependent ecosystem processes. It was observed that different vegetation communities align with these distinct recharge and discharge points. For example red gum woodlands east of Elliston occur at depressions in the landscape often over a limestone geology which could be groundwater recharge areas. Whereas, freshwater springs at Lake Newland are discharge points as are saline wetlands; though the two support different vegetation communities due to the salinity levels of the source aquifer.
- b. The Landsat imagery used for the NDVI processing was from 1994, 1998 and 2008, the results of the interpolation of water level depth below surface from 1994–2008 (Figure 11) and from recent data 2010–13 (Figure 12) shows that there are some broad differences in water level depths, this understanding in depth to groundwater and changes in groundwater level and salinity indicates that when mapping GDEs the ecosystem are in constant change and should be managed appropriately as described in the Conclusions and recommendations Section 1.4.

(12) Effects of salinity

- a. In Point 2a and 2b (spatial variation), a difference in northern and southern vegetation community composition with vegetation vigour was observed. A further observation was that this distinction may be linked to salinity being a limiting factor in the northern areas which would limit the duration that species like *Melaleuca* spp. and *Gahina* spp. can access groundwater. It is possible that these wetland species are able to access non-saline water seasonally in winter when the fresh rainwater is available and perches over the wetland clay layer. Whereas in summer the fresh water is no longer available and the vegetation does not use the saline water, therefore these communities did not show vegetative vigour from the NDVI mosaic, due to them not accessing groundwater from saline wetlands during dry periods. These groundwater processes are further discussed from the case study at Lake Hamp in Section 2 and in the follow-up report of Deane & White (2014)

The incorporation of the three datasets (NDVI, GDE Atlas and SKM, 2009) was described in Section 1.2.6. The outputs of the different combinations of these data into very high, high, moderate and unlikely likelihoods of groundwater dependence shows some core areas for potential terrestrial vegetation to be dependent on groundwater for water planning purposes (Figure 13).

A brief description of the rules assigned to the resulting layers for (Figure 13) are provided below or see Section 1.2.6 for a more detailed description:

- very high likelihood of groundwater dependence:
 - Intersection of NDVI, GDE Atlas IDE = 10 and SKM (2009) Type 1 (Obligate phreatophytes, sedgelands, and coastal heath over shallow water tables)
- high likelihood of groundwater dependence:
 - Intersection of NDVI, GDE Atlas IDE = 6–9 and SKM (2009) Type 1
- moderate likelihood of groundwater dependence:
 - Intersection of NDVI, GDE Atlas IDE = 6–9 and SKM (2009) Type 2 (Facultative phreatophytes over shallow and deep water tables, coastal heath over deep water tables, and tussock grasslands over shallow water tables)
- unlikely to be accessing groundwater:
 - Either GDE Atlas IDE = 1–5 Or, SKM (2009) Type 3 (tussock grassland over deep watertable).



Figure 10. Example of classification of Type 3 GDE (tussock grassland over deep watertable) (SKM, 2009) in this case being *Austrostipa* sp. grassland

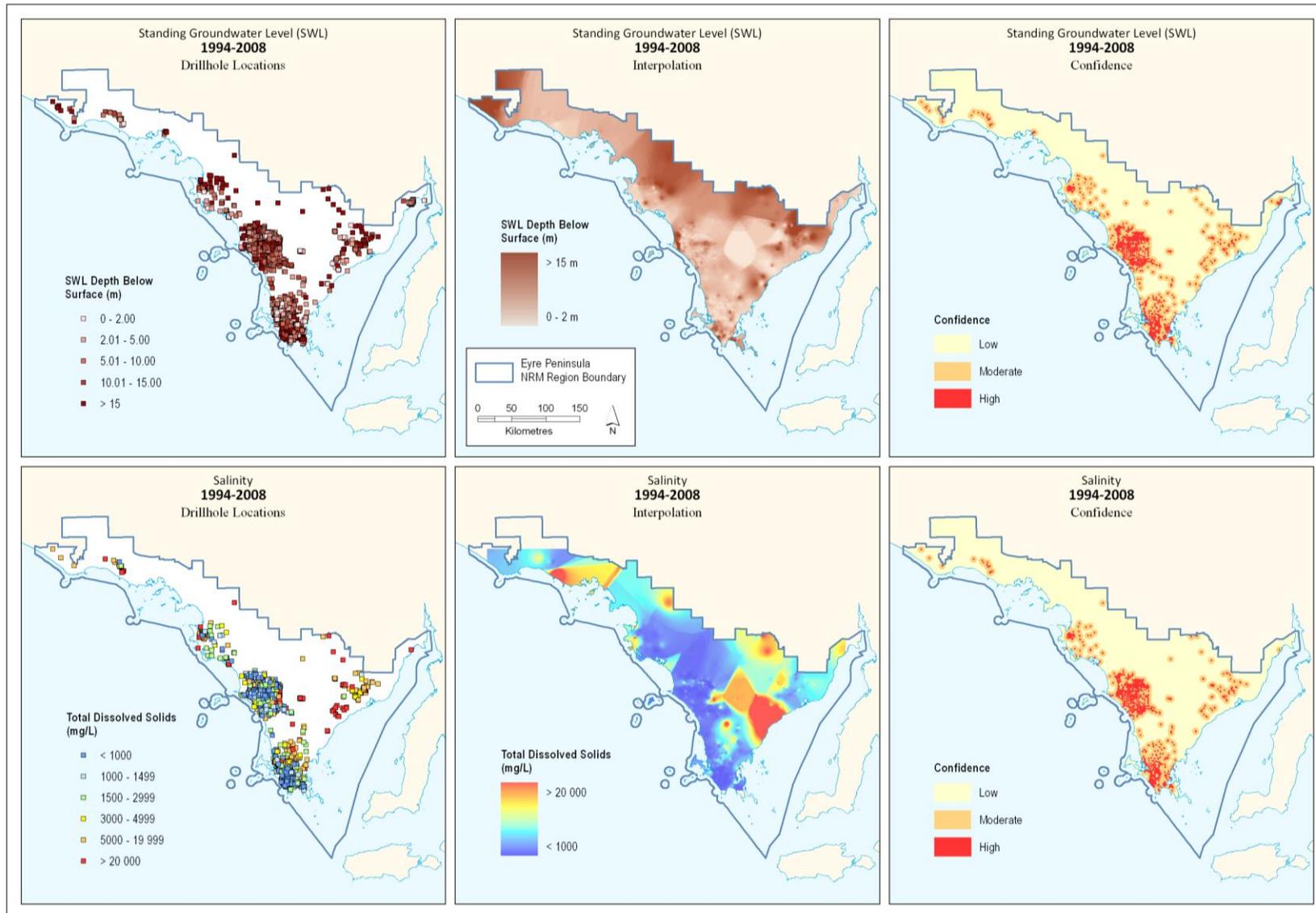


Figure 11. Interpolated groundwater and salinity trends during the Landsat imagery capture period 1994–2008

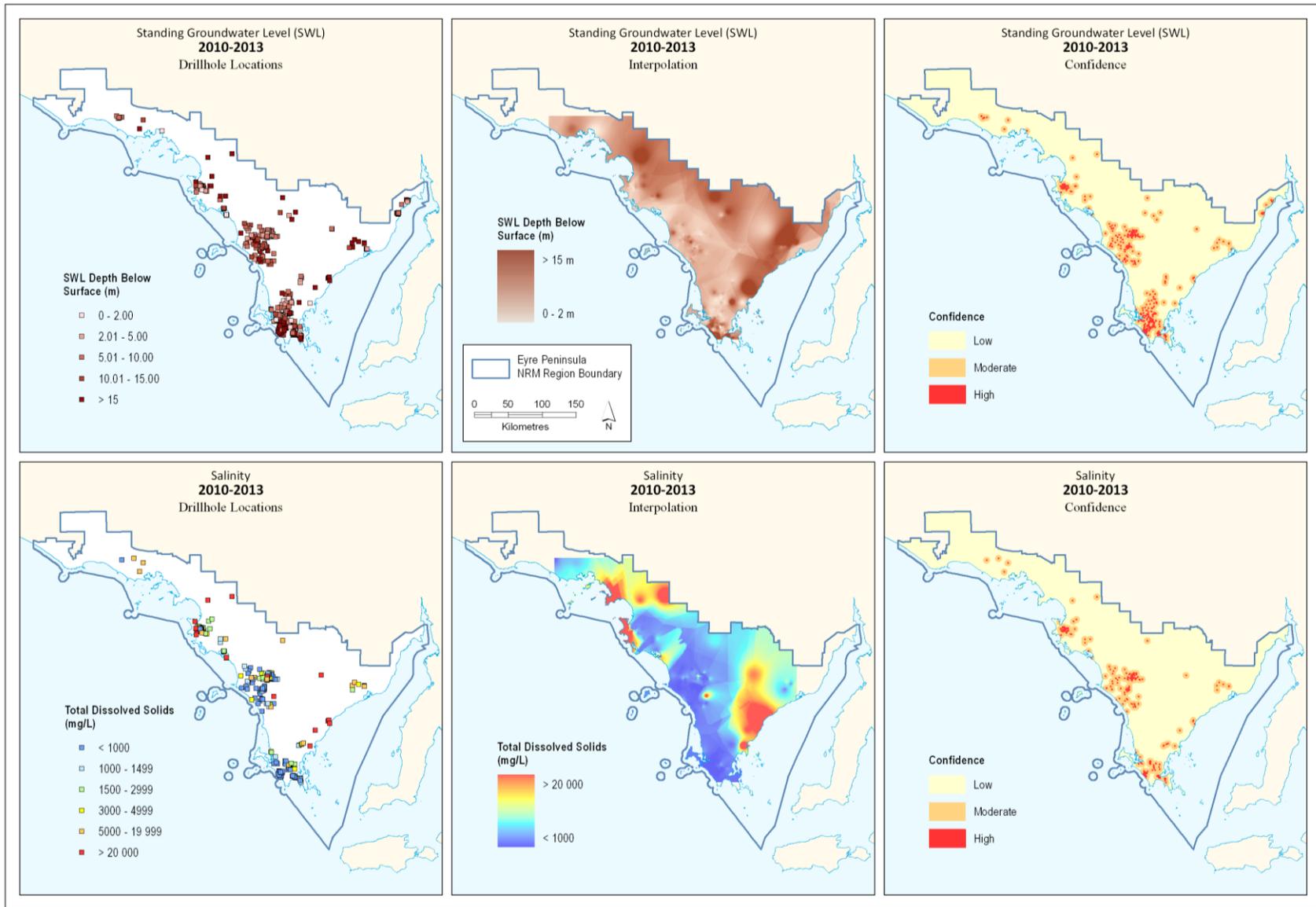


Figure 12. A current perspective of interpolated groundwater and salinity levels 2010–13

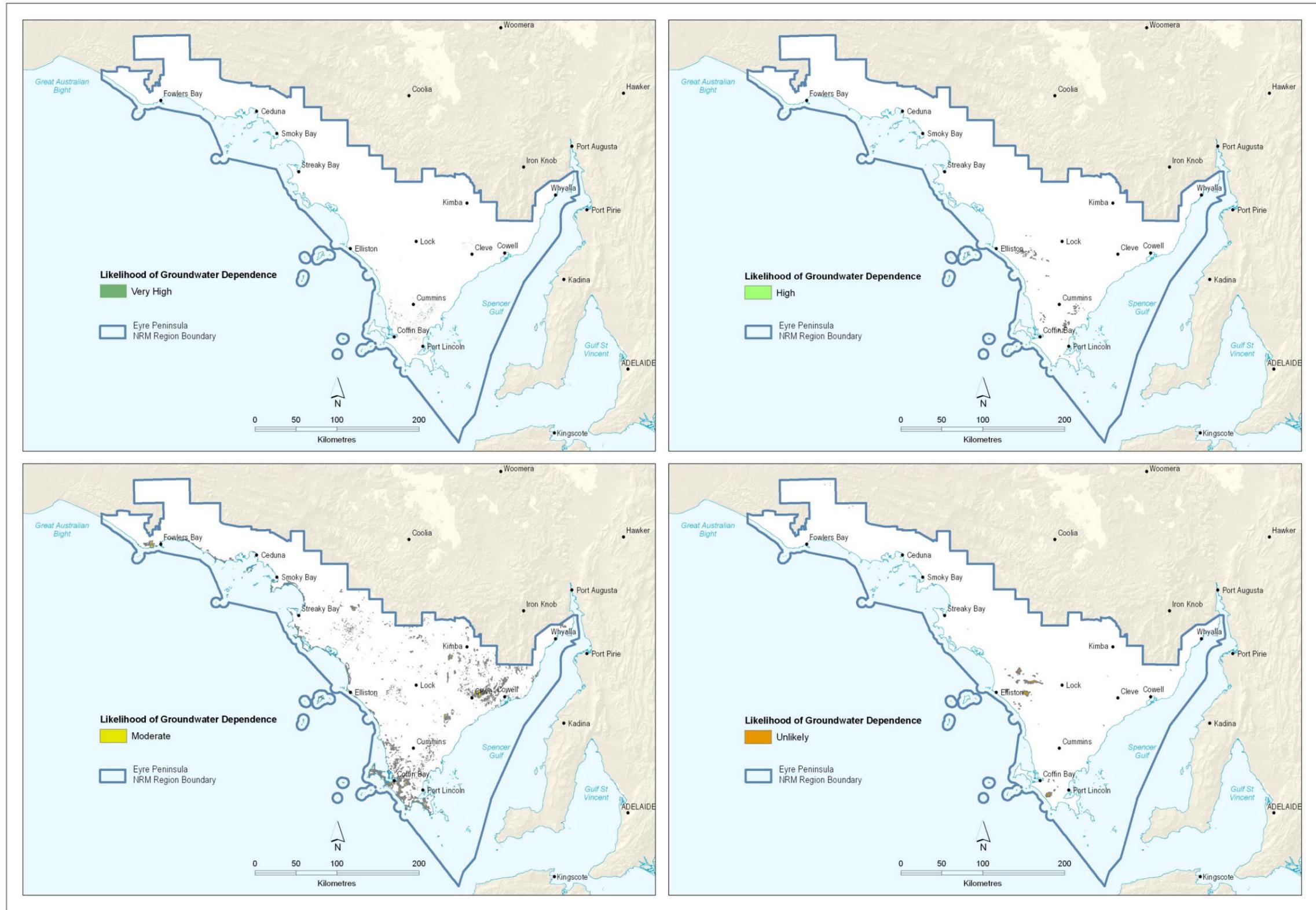


Figure 13. Output of the four different types of groundwater dependence from attribute data from NDVI, GDE Atlas (2012) and SKM (2009) using the developed GIS data rules

1.4 Conclusion and recommendations

1.4.1 Management of GDEs and phreatophytes

Given the uncertainty of determining whether a GDE is facultative, the following guidelines are suggested:

- (1) Assume that all potential GDEs are obligate in the first instance
- (2) Work to understand the distribution of groundwater flow systems. GDEs located within local, intermediate or regional scale flow systems have different risks, values and management options. It is important to determine their recharge and discharge points (including phreatophytic vegetation) and all GDEs which may rely on the water from recharge to discharge.
- (3) Identify which aquifer systems may be vulnerable to accelerated anthropogenic change. Local systems may be totally beyond management intervention, while regional scale systems may require multiple approaches. Recharge areas may be subject to planting; aquifers may be de-watered for mining, or pumped for agriculture.
- (4) Characterise the water table dynamics within each of the major flow systems supporting different GDE types recognising more than one GDE may rely on the same groundwater flow system. This provides a baseline for assessment of development proposals to determine an appropriate level of impact.
- (5) Do not allow a prior designation of the title 'facultative' to permit a loss of groundwater availability – whether facultative or obligate, the ecosystem will likely change as a result of its loss (Hatton & Evans 1997; Murray *et al.* 2003; Eamus *et al.* 2006).

1.4.2 Monitoring

Many of the indicators that may provide an early warning of stress such as water potentials require specialist equipment and training. There is also a need to establish the natural range in values of such indicators over a number of years in order that deviations of concern will be able to be identified.

1.4.2.1 Site selection for future studies of Environmental Water Requirements (EWRs)

Careful consideration should be given to site selection to ensure the full range of water availability can be sampled. The aim is to determine the variations in groundwater dynamics that lead to differences in vegetation from obligate wetland species through to those which are purely terrestrial. Hence an ideal site needs a largely undisturbed vegetation cover across an elevation gradient that exhibits such a turnover in vegetation types. Such sites may be difficult to locate on the Eyre Peninsula owing to the limited topographic variation and the high rates of historical land clearance. At the Lake Hamp (Section 2 case study) for instance, there is a limit to the information that can be gained, because the upper limit to the wetland extent has been obscured by the presence of roads and agricultural land. These peripheral areas are often heavily cleared, because they are also suitable for cultivation, but are important for understanding of aquatic plant communities as they represent the driest areas where wetland plants can survive.

In wetland systems on the Eyre Peninsula, salinity appears to be the major driver at the bottom end of the gradient, the point where water depth does not seem to determine zonation. A freshwater wetland would not have such limitations and the method could easily be directly employed in wetlands of depth up to one metre. Recommendations for future sites are constrained by the availability of water table data, but ideal sites would have the following characteristics:

- At least 3–5 years of water table data recorded at least quarterly, preferably monthly.
- A number of observation wells placed at the lowest point and at higher points along the dominant elevation gradient (note the range of water table variations observed should overlap – that is, when a higher gradient position well is dry the next lowest observation wells should be within its measurement range).
- Adjacent to the observation wells vegetation should grade naturally from terrestrial to wetland species – this need not be pristine native vegetation at the terrestrial end, it can be agricultural plants.
- A range of sites across the salinity gradient is ideal, but owing to their rarity and relative diversity freshwater wetlands are of very high value.

- A range of wetland functional groups and life forms (tree, shrub, groundcovers) should be available. Pest plants are no disadvantage (unless a monocover) and gathering information of the water tolerance of these species can provide valuable insights for those seeking some level of control via the maintenance of optimal water table dynamics.

This project also undertook a case study on the interaction of water table dynamics and vegetation zonation, which can be found in Section 2. On a second field trip this assessment of wetland groundwater and vegetation dynamics was continued and these findings have been reported with a more detailed methodology for undertaking a monitoring program on the Eyre Peninsula in relation to wetlands and phreatopyhtes (Deane & White 2014).

2 Case study: The interaction of water table dynamics and vegetation zonation at Lake Hamp

2.1 Summary

Data were collected on vegetation-elevation relationships at Lake Hamp (near Elliston – See Section 3 maps) where a five year period of monthly depth to water table data were available. Lake Hamp littoral vegetation shows a limited degree of zonation within the narrow fringing vegetation band, owing to the small topographic (and therefore water availability) variations over the surveyed area. The elevation range of the dominant canopy species *Melaleuca halmaturorum* supports a water regime within that previously described as constraining the species at the low ('too deep') end of the water availability gradient. Complete interpretation of the zonation observed at the site requires additional information on trends in salinity in addition to water level. Variations in salinity over the root zone appear to interact with water availability to limit the establishment of non-halophyte vegetation within the Lake bed itself. The site proved unsuitable for the estimation of upper ('too dry') limits owing to the low variation in elevation relief. The presence of a boundary road and land cleared for agriculture truncated the gradient masking natural zonation patterns. The methods employed are straightforward and well established in the scientific literature. These are thought to be applicable to the development of defined hydrological niche dimensions for water dependent vegetation in the region provided a site with an intact gradient from terrestrial to aquatic/amphibious vegetation can be identified.

2.2 Introduction

Water regime is well established as exerting a key control over wetland and groundwater dependent vegetation. The concept of the hydrological niche (Silvertown *et al.* 1999) holds that a major driver of wetland plant diversity is the variation in the range of water availability. The more variable the range of conditions at a given site, the broader the niche space, allowing species with diverse adaptation to co-exist without competitive elimination (Silvertown *et al.* 1999).

The grouping of aquatic plants into those with a similar tolerance for different depth-duration combinations is an approach that aids interpretation of functional relationships and different classification systems exist. The currently predominant classification in southern Australia is attributable to Brock & Casanova (1997) and known as 'plant functional groups' (Casanova & Brock 2000; Casanova 2011). This classification includes both recruitment and maintenance requirements and well adapted for use in natural resource management research questions.

If managers are to maintain the diversity of vegetation communities of water dependent ecosystems, the maintenance of water regimes to support the extant range of functional groups is essential. The aim of this pilot study was to trial a method to link groundwater level data to existing vegetation by recording the elevation preference for key species. By linking the ground level where plants are found to the water table dynamics data, an indication of the preferred water regime can be obtained.

2.3 Methodology

Vegetation on the north and south bank of Lake Hamp were surveyed with a differential global positioning system (dGPS – Trimble R8) employing real time kinematic survey (RTK). Indicative accuracy of the instrument in the vertical is between 10 and 20 mm. A 100 m baseline was established along the northern bank of Lake Hamp, adjacent to the location of two monitoring wells. Ten transects were randomly positioned along the baseline (spaced for a minimum distance of 5 m, to attain a level of independence based on the typical canopy width of the dominant cover *Melaleuca halmaturorum*). Elevation data points were recorded at spacing to limit any potential spatial correlation (notionally 5 linear metres or 0.2 m elevation increments) along transects and vegetation rooted within 0.5m either side of the data point at the same elevation was recorded. Raw data

collected are presence/absence of vegetation for a given observed elevation. Summary statistics were generated for the range of elevations where each species was recorded. For the dominant species (*M. halmaturorum*) adequate data points were available to fit a quadratic logistic regression that enables probabilistic distribution of elevation preference to be estimated. The summary elevation distribution data for *M. halmaturorum* were converted to water table variation and compared with published water requirements. Key characteristics of the water table were also determined from the time series.

To relate vegetation to water table dynamics as cumulative frequency distribution was plotted for groundwater level. This is analogous to a flow duration curve for streamflow and provides an indication of the percentage of time the depth to water exceeds a given value. By adjusting this curve by the observed elevation of groundwater dependent plants relative to the water table, the curve becomes a graph of the water requirement depth-duration domain.

2.4 Results

2.4.1 Water table dynamics

The Lake Hamp water table exhibits broad seasonal climatic variation, with annual maxima observed in Winter (Figure 14). Comparison with climate data, while desirable, was out of scope for this pilot study, but the water table shows signs of short term aseasonal responses most likely attributable to storm events. Four out of the six years of record saw the water table above ground level, meaning the Lake held surface water. The lowest level of the water table was observed in the summer immediately prior to the study at -1.4 (Figure 14).

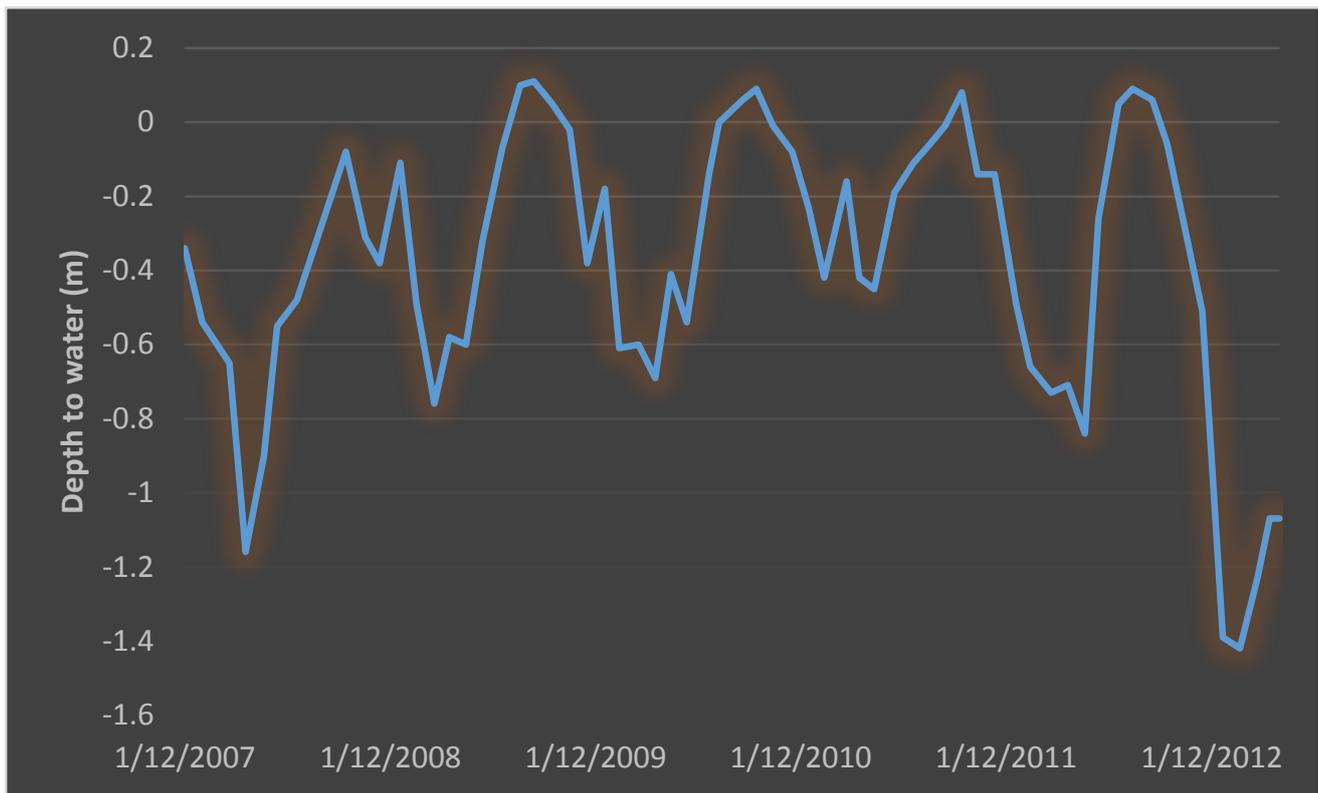


Figure 14. Monthly depth to water (m) relative to lake surface (Piezo A, Lake Hamp north shore)

The mean and standard deviation in water depth indicate that July to September the water table is at or near the surface and that these months are also the least variable (Figure 15). On average, 47 days per year the water table is above the lake bed, and the estimated longest continual inundation over the period of record was 89 days during winter-spring of 2009. Water tables remain near the surface for much of the time and more than 50% of the monitoring period water tables were within

0.3 m of the ground at the observation well (obswell). Estimates are based on monthly data, and as suggested by Figure 15 underestimate both values as a result.

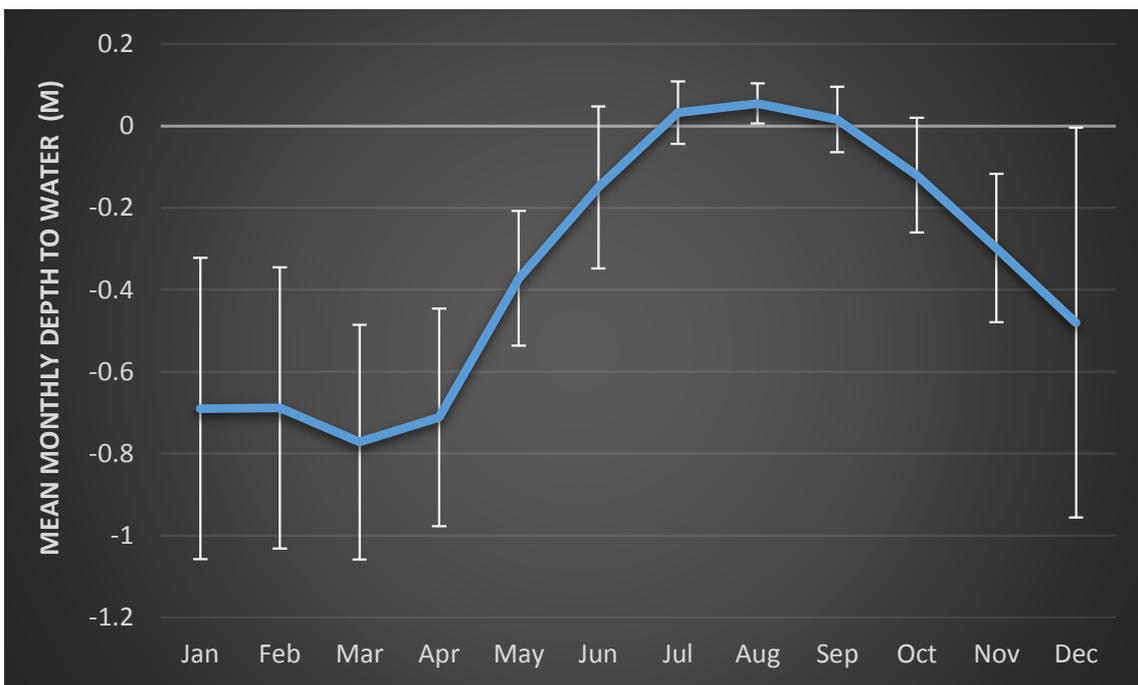


Figure 15. Mean monthly depth to water (m) and standard deviation in the mean

Seasonal rates of rise and fall are modest, with the maximum estimated rate of decline less than 1 cm/d during summer drawdown, though the same caveats owing to temporal resolution of data applying (Figure 16).

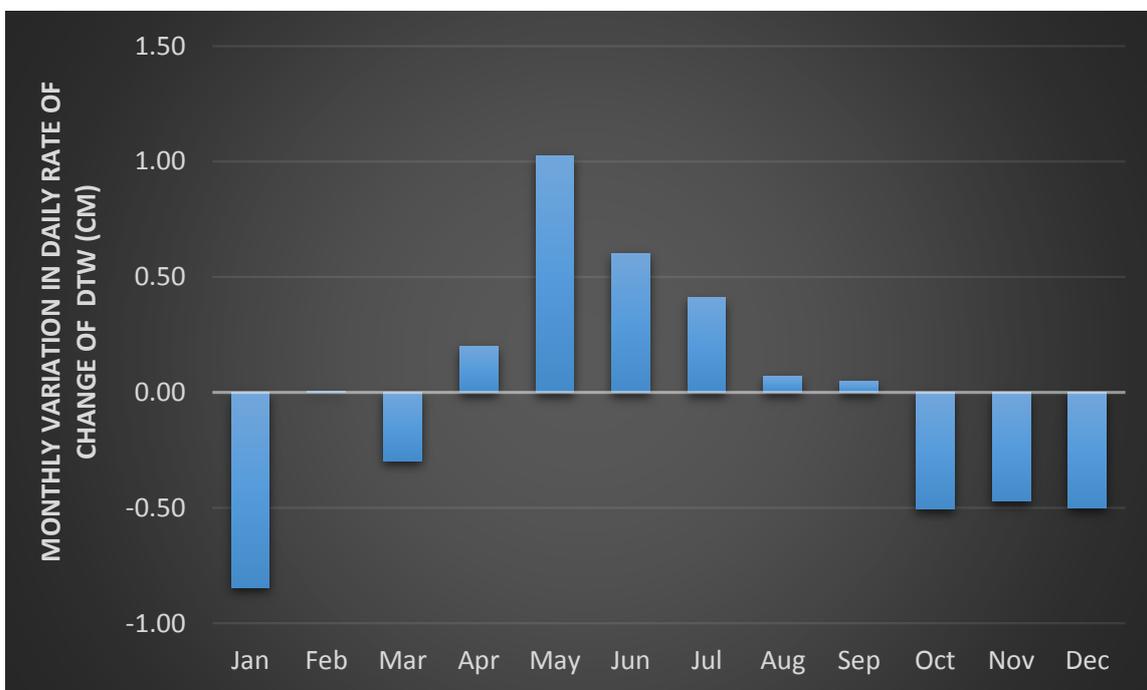
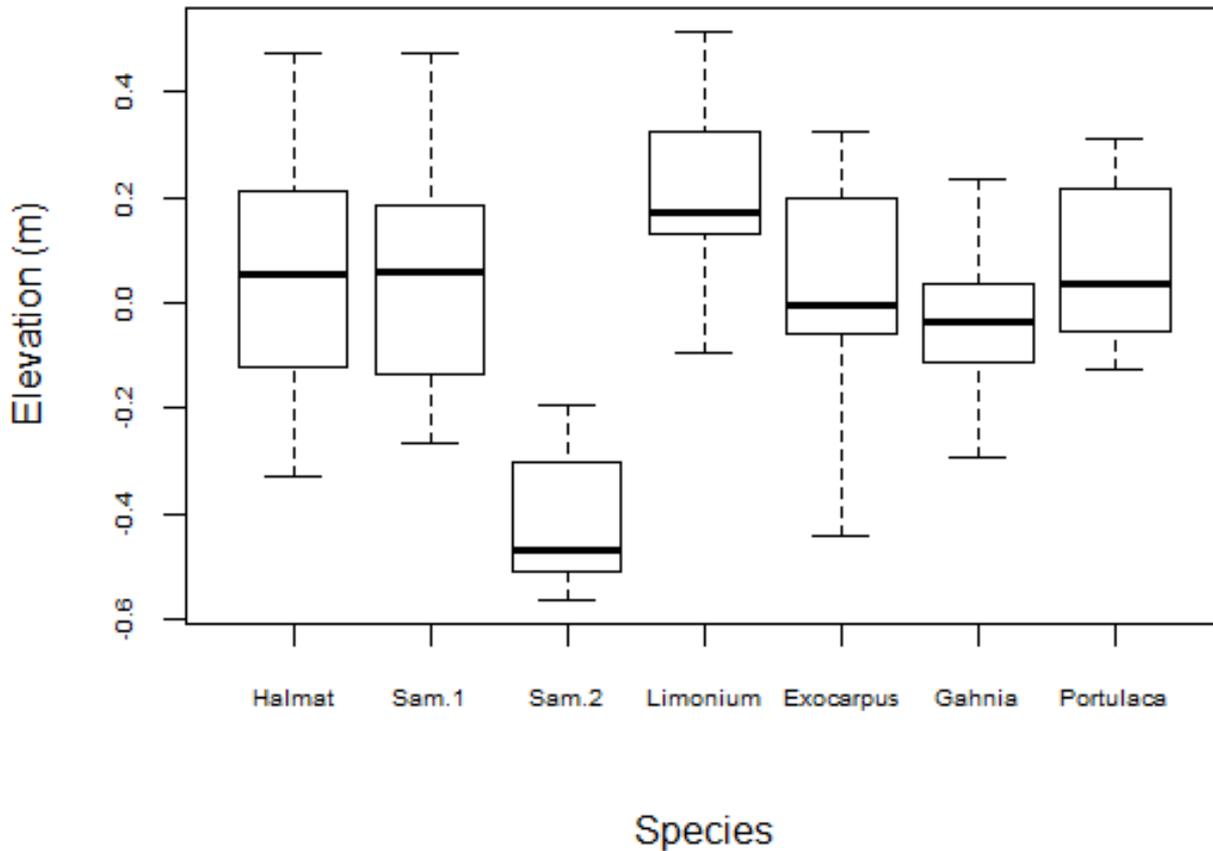


Figure 16. Estimated daily rates of rise and fall calculated by month over the whole period of record

2.4.2 Plant elevation relationships

A total of seven species had adequate data available to estimate a distribution



- (
- 3 Figure 17). There is considerable overlap in the observed elevation distributions, with only *Limonium* and samphire species 2 differentiated. Most species had a median elevation preference between 0 and 0.1m, relative to the observation well ground level datum. Samphire species 2 (shown as 'Sam.2') was largely observed within the Lake itself and was the only species present. This clearly tolerates lower positions on the elevation gradient and suggests salinity plays a major role in zonation. A total of seven species had adequate data available to estimate a distribution.

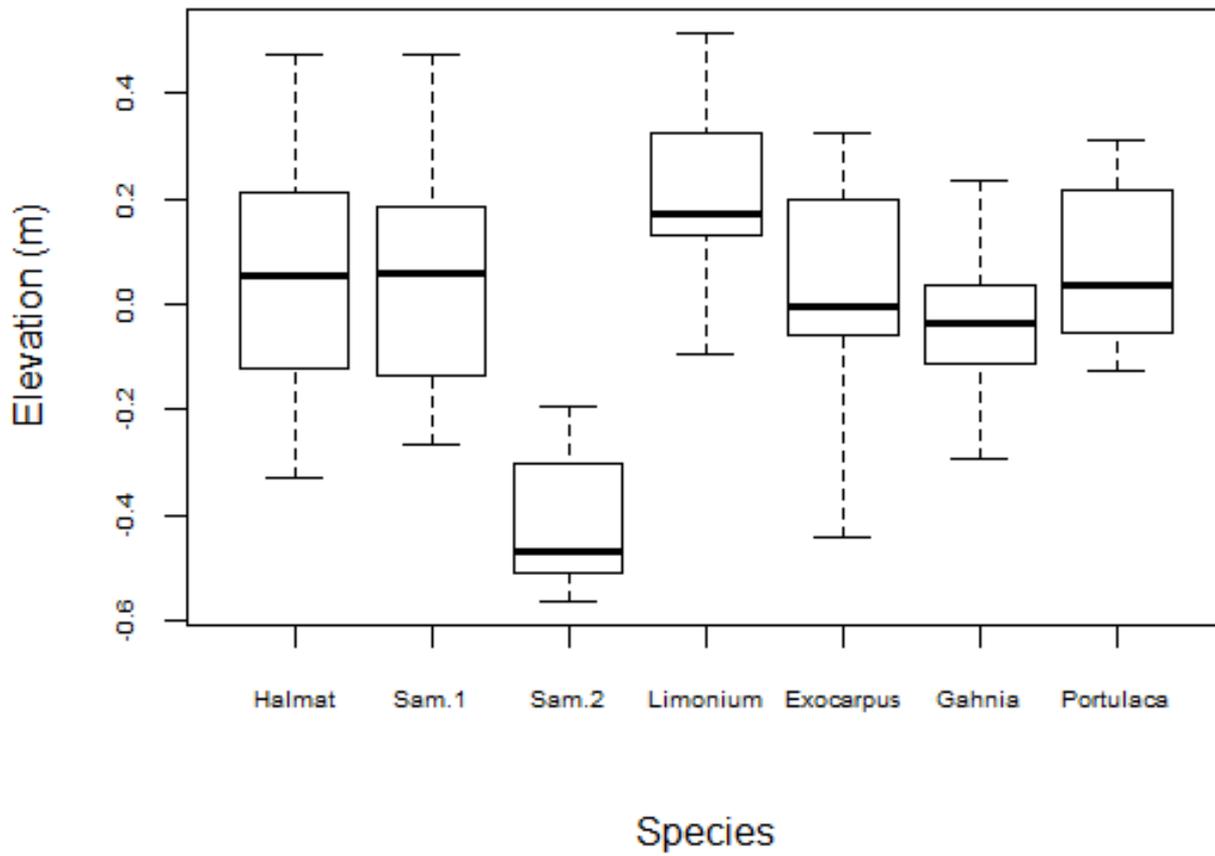


Figure 17. Boxplot of observed elevation where indicated species were recorded. An elevation of 0 is with respect to the observations well data ground datum.

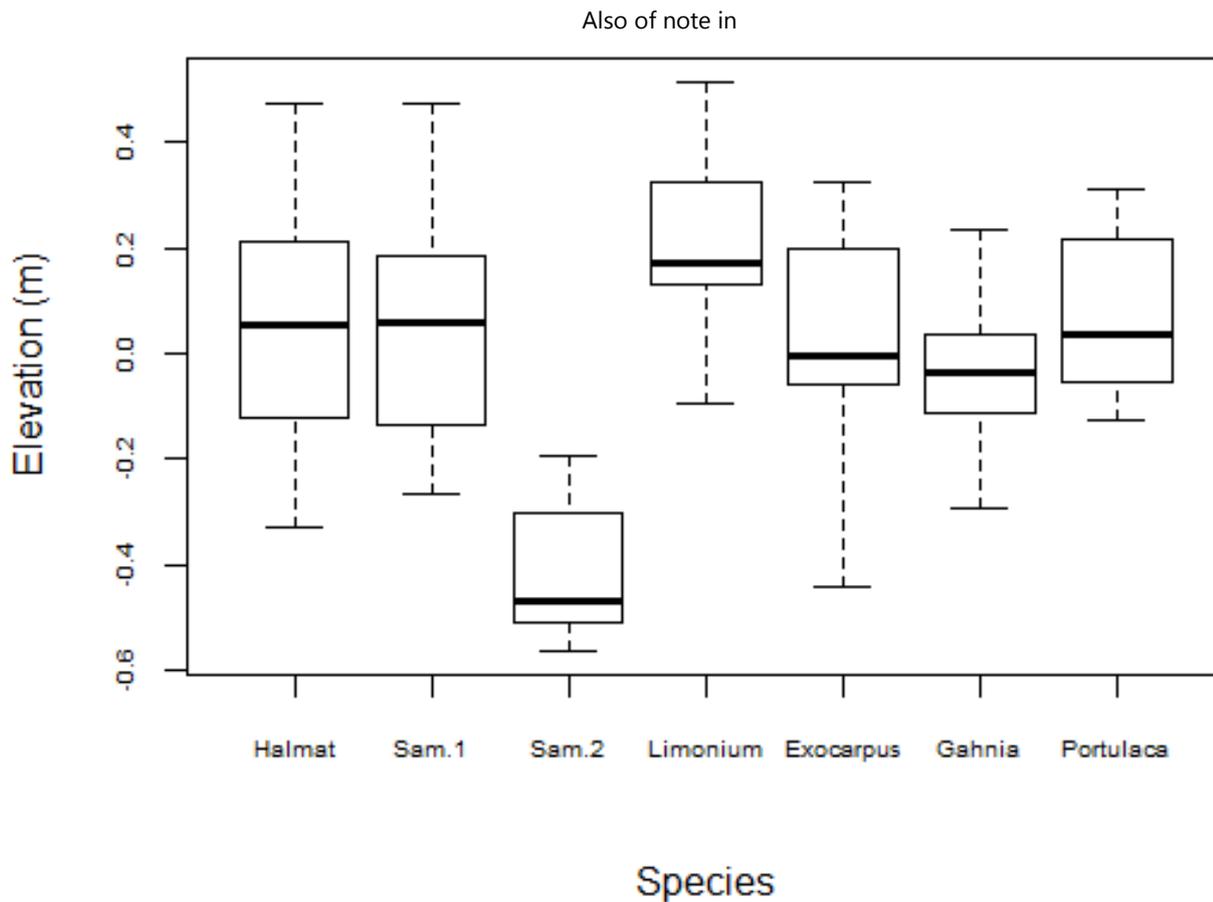


Figure 17 is the relatively narrow range of elevations where *Gahnia* was observed, although this was not a prominent component of the vegetation and this may not be a true reflection of the width of the depth-duration gradient which it can tolerate.

The best model describing the probability of observing *M. halmaturorum* was of a quadratic (rather than linear) form, suggesting an optimal level within the surveyed range. This is believed to be an artefact of the site itself, where higher elevations corresponded to a road levee and it was therefore impossible for any vegetation to establish. The optimal elevation (peak of the curve) predicted by logistic regression was 0.05m, close to the median from the sample distribution (0.04 m) (Figure 18).

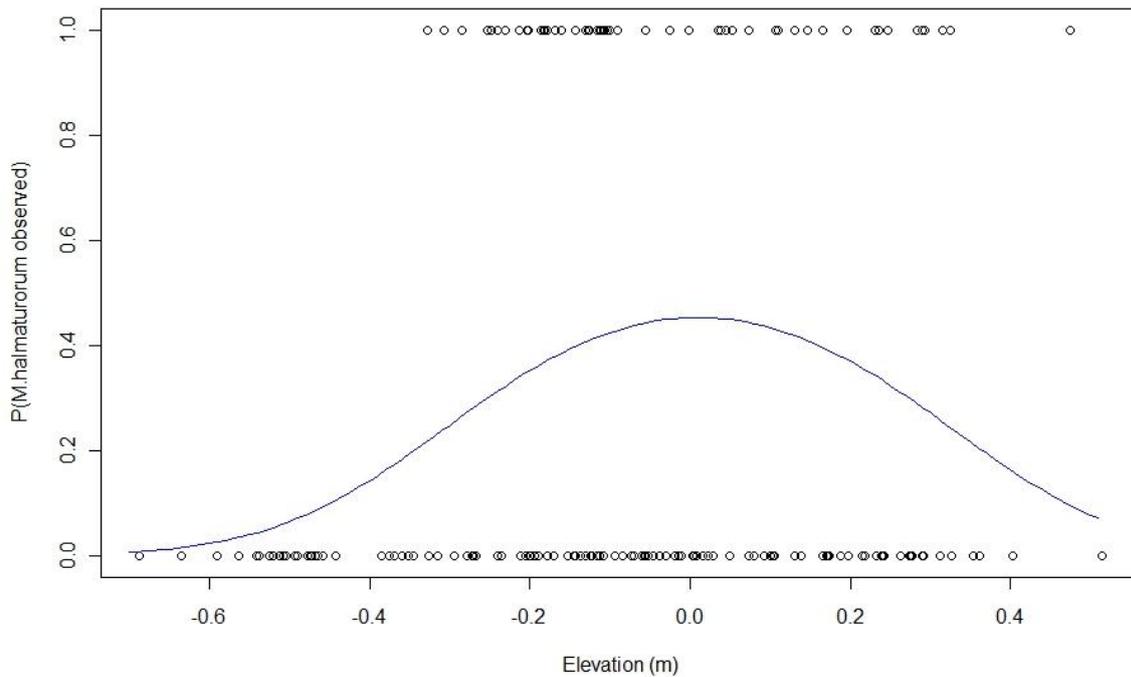


Figure 18. The probability that *Melaleuca halmaturorum* was observed as a function of elevation. Elevation here is relative to the zero (ground level) datum for water table fluctuations at the site.

Normalisation of the probability curve to create an elevation preference curve allows adoption of 0.5 as an indication of the upper and lower boundary at the site. This approach leads to values of -0.25 and 0.47. These values can be used to shift the observed depth to water duration curve and establish the preferred depth-duration domain for *M. halmaturorum* at the site (Figure 19). At the upper elevation, the maximum depth to groundwater over the period is 1.87 m and the water table never exceeds 0.11 m. This suggests the species can tolerate water being at least 0.37 m below the surface at all times and at a depth to water of more than 1 m annually for at least 30% of the time (Figure 19). The minimum elevation preference suggests the species at the site is able to tolerate surface saturation or deeper for around 50% of the time, a peak maximum depth of 0.36 m.

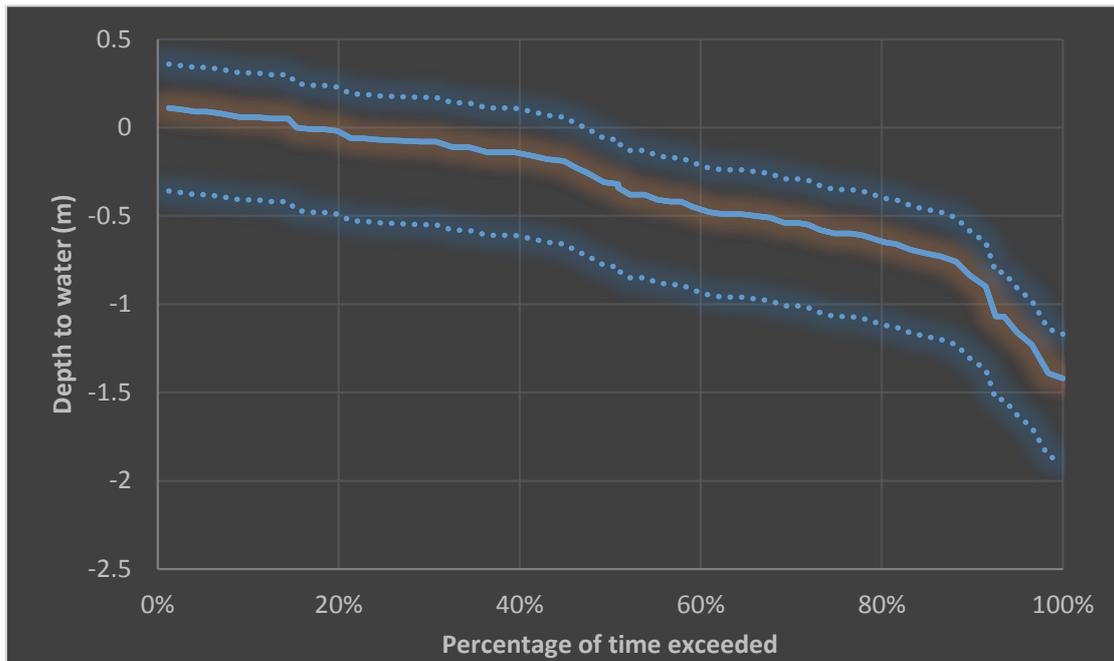


Figure 19. Depth-duration curve for Lake Hamp piezometer A 2007–12 (solid line) and the range of water table preference range for *Melaleuca halmaturorum* at the site (dashed line)

3.1 Discussion

Melaleuca halmaturorum is both salinity and water logging tolerant (Denton & Ganf 1994; Mensforth & Walker 1994), but is thought to have a narrow regeneration niche where saturation at ground surface level is preferred (Denton & Ganf 1994; Nicol & Ganf 2000). This narrow regeneration window will dictate the width of the observed zonation and is a function of the interaction of topographic variation and water table dynamics. In flatter topographic settings it may form wide zones, while in a steeply sided wetland profile it would be expected to form a sharp lower boundary centered around elevations where water regimes supporting optimal germination success were located, but may extend some distance above this level. Observed age class structure in a given population might be expected to reflect the regularity with which such conditions were present and the level of disturbance creating available sites. In terms of groundwater dynamics, the presence of the species has been reported to be favoured where water tables are less than 4 m below the surface (Marcar *et al.* 2003). Therefore it is unlikely that the species is limited at the upper end of the gradient by groundwater availability.

Juveniles of the species are considered intolerant of flooding (Denton & Ganf 1994) and this may limit the lower-range zonation at Lake Hamp, where the water table exceeds ground level on average more than 47 days per year. Once established however adults are more tolerant of flooding, so if juveniles were to establish during a drier period, depth of water would not be the major driver of zonation. It is most likely that salinity, rather than water-table dynamics structures the zonation at the low end of the elevation gradient. Mensforth & Walker (1994) observed *M. halmaturorum* overlying groundwater of salinities exceeding seawater (up to 71 dS/m) at a site in the South East region of South Australia. Those authors found that while the species accessed water from the shallow water table during summer, winter water use was largely from the unsaturated surface zone where rainfall diluted soil water salinity. In other words, *M. halmaturorum* around salt lake peripheries may well persist partly due to groundwater, but may persist only due to a shallow rainfall-derived freshwater layer perched above the denser, saline water table, or indeed low salinity unsaturated zone soil moisture as observed by Mensforth & Walker (1994).

The observed water-table preference domain at the site is constrained at the upper end by the topography and infrastructure which prevents any vegetation establishing at elevations much above around 0.3 m. Nonetheless, at the lower end the findings are consistent, and of course water tables – especially highly saline ones – can be equally detrimental to non-adapted vegetation as excessive drawdown to dependent species. Due to the limited nature of the site and the inability to sample other wetlands as a result of weather and lack of water table data, conclusions as to the tolerances should be seen as preliminary and indicative. The methods employed, while still under development, appear to offer some promise in the determination of

quantitative water requirements. Some considerations for further improvement are described below and in Deane & White (2014).

3.1.1 Issues for resolution and future development of methods

3.1.1.1 *Methodological issues*

While this method provides considerable insight into vegetation zonation as a function of water table dynamics, there are two major areas where development and verification are required: sampling protocols and metrics used to relate vegetation presence to water table dynamics.

3.1.1.2 *Technical sampling design*

The main questions here are how best to address trade-offs in data collection involving certainty that elevation relates to water table dynamics and the interspersed and independence of samples.

Obtaining adequate interspersed and independence of sample points across the site is necessary to ensure inference at site scale and statistical power needs are met. Independence of samples is a trade-off against replication, as the further sites are situated from one another, the greater the independence, but the longer time involved in data collection and the less clearly these relate to observation well data. Complicating this further is the need to estimate water table dynamics at each vegetation sampling point. There are two aspects to this, intra-sampling area variation and extrapolation (or for multiple wells, interpolation) of water table data across the landscape. For the current study, only a single observation well was available so sampling was clustered around this site. Sampling area was effectively 1 m laterally, and 0.1 m along the gradient, with only presence absence recorded. The assumption here is that across the gradient (for 1 m) the elevation is consistent. Equally a 1 x 1 m quadrat could be used, or many other dimensions. These technical design issues require further consideration via over-sampling and comparison at suitable locations. There is the potential for fine tuning from site to site depending on local topographic and micro-topographic variation but this will require additional work at multiple sites to establish the range of natural variations across the different regions.

The issue of relating elevation data to water tables relates to the proximity of observation wells to sampling sites. The further that vegetation samples are gathered from monitoring well data, the greater the chance that water tables vary from the measured relationship. Sample independence requires adequate spacing of data points, yet the larger the area sampled the greater the chance of microtopographic variation within the sampling area decreasing the precision of the sample as a function of elevation.

The most important thing to recognise is the need to collect water table data to allow observed vegetation zonation to be determined. Collection of water table data relevant to the condition of groundwater dependent ecosystems is of high value for planning purposes for natural resource management. The commitment the Region has made to date is acknowledged – it represents considerable foresight to begin this task at wetland sites. Such data are invaluable when preparing water allocation plans or development applications are to be prepared. Some advice on sighting of such infrastructure follows:

- While more is better, a minimum of three observation wells from the lowest to the highest point of the elevation gradient where wetland vegetation is present are recommended.
- Placing at least one data logger allows for continual collection of information at resolutions that are impossible from manually read wells. A single logger within a network of observation wells across the elevation gradient provides a means to interpolate small scale variations across the wetland.
- It is recommended that the non-logged wells should be read a minimum of quarterly, and preferably monthly for 2-5 years. Over time as relationships are established, a single well should prove adequate, provided the inter-relationships are time invariant.
- The elevation gradient along which the transect is established should also reflect the groundwater flow direction.

3.1.1.3 *Determining the best measure of water table variation*

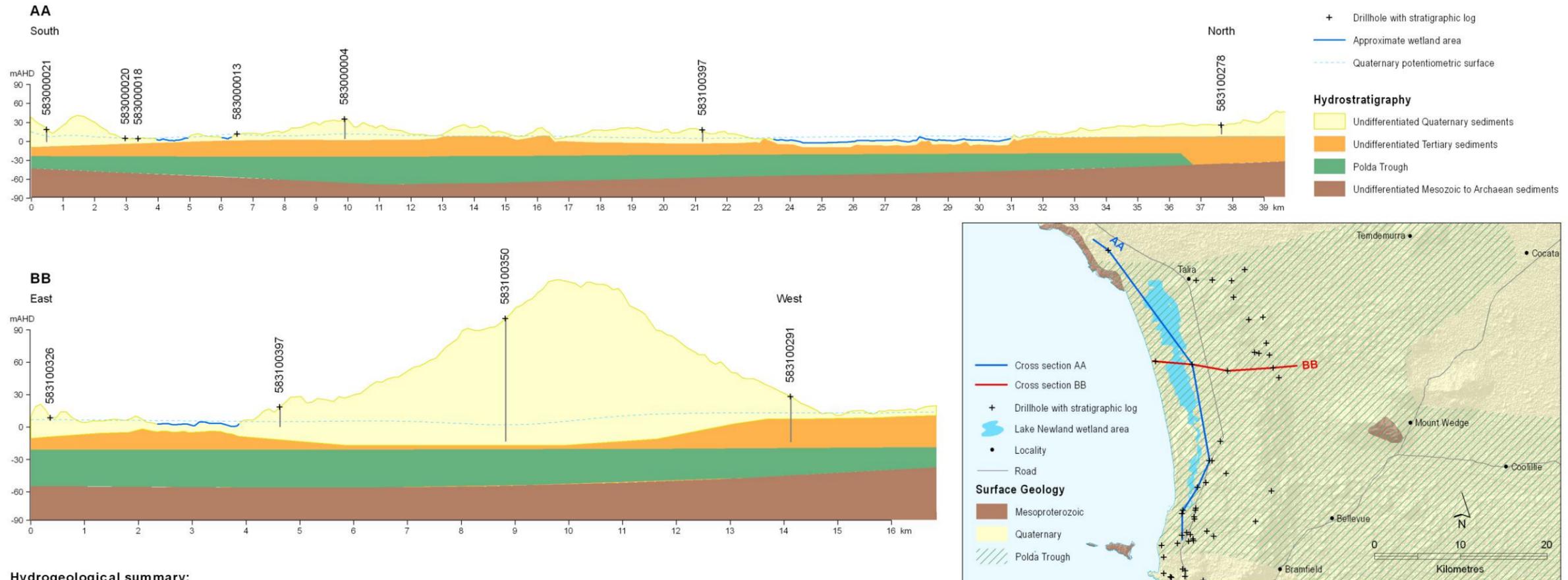
This is a technical problem that can be readily solved with adequate data. A number of measures have been successfully applied in the literature and various modelling techniques can be brought to bear to resolve this question, provided enough data are gathered at enough sites, and across enough species.

4 Appendix

A. Hydrogeological desktop study results

Hydrostratigraphic cross-sections and recent groundwater data

LAKE NEWLAND, EYRE PENINSULA Interpolated Simplified Geological Cross Sections



Hydrogeological summary:

Lake Newland is located in a karst landscape which is overlain by Holocene sand dunes, some of which flank the lake's western margin and form a barrier to the sea.

The sediments within the wetland consist of calcareous muds overlying a marine shelly limestone. Many sinkholes are evident on islands within and at the margins of the wetland (Semeniuk, 2007a).

The topography at the wetland margin is generally less than 5 mAHD, with the surrounding dunes rising to around 130 mAHD. The thickness of the Quaternary sediments in the area is quite variable, but is generally thin in the immediate vicinity of the wetland. The underlying Tertiary sediments are generally less than 30 m thick. The confined Jurassic Polda Formation also extends beneath this area with a thickness of around 40m. Underlying the sedimentary sequences, the Basement fractured rock aquifer is generally 40-60 m below the wetland surface. There is basement outcropping nearby to the north and east of the wetland.

Monitoring data within the wetland (Semeniuk, 2007a&b) indicates the springs on the eastern margin are fresh (TDS 900 – 1500 mg/L) to hypersaline (TDS 5000 – 7000 mg/L), and slightly alkaline (pH 8). The watertable beneath the wetland area generally displays seasonal fluctuations of approximately 0.5m. Water quality within the basins is driven by evapotranspiration and is generally hypersaline (TDS 38,000 - 118,000 mg/L) and neutral (pH 6.9 - 7.4).

Recent data (post 1990) from nearby wells is sparse. A well screened in the Quaternary aquifer 2 km to the south east indicates that the groundwater level in November 2010 was 6 mAHD (salinity 3680 mg/L TDS). This salinity data is consistent with that obtained in the wetland.

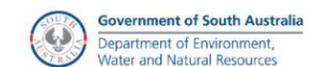
Regional groundwater flow is east to west. The regional model developed for the Eyre Peninsula (DEWNR, in prep.) indicates that the interpolated potentiometric surface for the Quaternary aquifer projects slightly above the wetland surface. The pressure head results in major springs and seeps along the wetland's eastern margin, discharging from the Quaternary limestone aquifer and sustaining permanent water in some of the basins (Semeniuk, 2007a). The interpolated potentiometric surface for the Tertiary aquifer suggests potential for upward leakage in the absence of a confining layer and thus potential contribution to the wetland – however this cannot be validated due to a lack of data points near the wetland. Targeted hydrochemical analysis and possibly additional drilling would be required before this could be confirmed. It is unlikely that the deeper fractured rock aquifers are a water source for the wetland owing to the occurrence of the Polda Trough.



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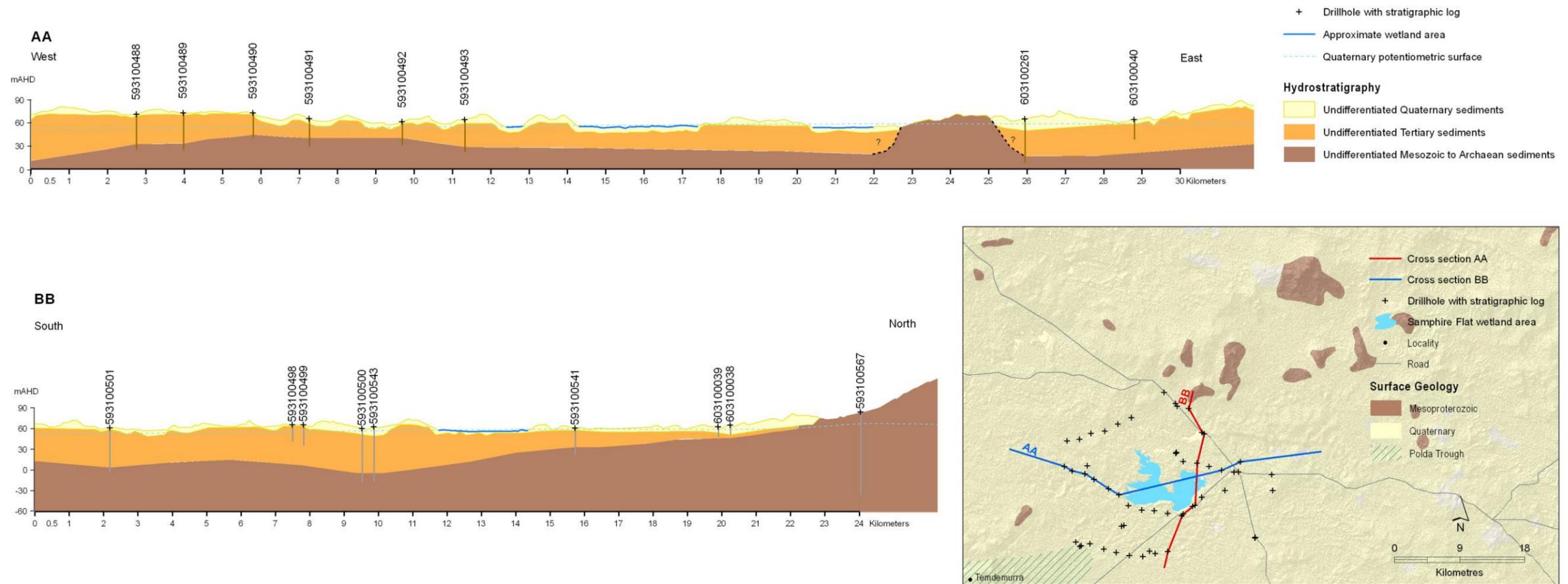
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Map Projection: Lambert Conformal Conic
Map Datum: Geocentric Datum of Australia 1994
Date: July 2013



References:

- DEWNR (in prep.) Phase 2 Prescribed Areas Groundwater Assessment, Simplified Hydrostratigraphic 3D Model for the Eyre Peninsula NRM Region.
- V&C Semeniuk Research Group (2007a) A Baseline Survey of the wetlands of Eyre Peninsula 2005-2007.
- V&C Semeniuk Research Group (2007b) Lake Newland Baseline Survey and Literature Review, Eyre Peninsula.
- SA Geodata (2013) Hydrogeological Database, administered by the Department of Environment, Water and Natural Resources.
- Groundwater level and salinity data is publicly available on the South Australian Government's Water Connect website (www.waterconnect.sa.gov.au/GD).

SAMPHIRE FLAT, EYRE PENINSULA Interpolated Simplified Geological Cross Sections



Hydrogeological summary:

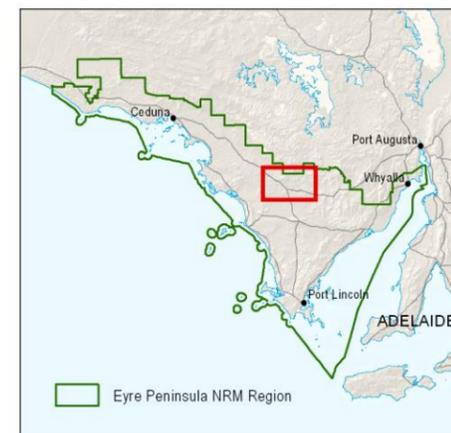
Samphire Flat wetland is located in the Tuckey dune field, which consists of north west to south east trending sand ridge plains. The sediments within the wetland are indicative of wetting/drying cycles, being clayey or quartz sands overlying semi-confining layers of calcrete or limestone (Semeniuk, 2007).

The topography at the wetland is approximately 60 mAHD, with the surrounding dunes rising to 120 mAHD in the north. In the vicinity of the wetland, the Quaternary sediments are generally less than 15 m thick with the underlying Tertiary sediments generally 30 m thick. The Tertiary Poelpena Formation (aquifer) occurs unconformably around the wetland, however the closest observation of the Peolpena Confining Bed is 10km to the south west. Underlying the sedimentary sequences, the Basement (fractured rock aquifers) are generally 40 m below the wetland surface. There is basement outcropping to the east, west and north of the wetland, including outcropping of highly weathered Archaean-Paleoproterozoic basement rocks on the wetland's north-east edge.

Monitoring data within the wetland (Semeniuk, 2007) indicates hypersaline (TDS 41,000 - 270,000 mg/L) and acidic (pH 3.5 - 7.1) conditions. The watertable displays little seasonal fluctuation (<0.15 m) despite discharge/recharge events. Seasonal inundation is generally less than 0.2 m.

Recent data (post 1990) from nearby wells is very sparse. A well screened in the Quaternary aquifer 7.5 km to the north indicates the groundwater level in April 2005 was 70 mAHD (no salinity observation), with another well 6.5 km to the south east recording 55 mAHD in October 2012 (no salinity observation). There are no wells completed in the Tertiary or Basement fractured rock aquifers within 20 km of the wetland area. The majority of groundwater level and quality data near the wetland predates 2000 or is unreliable.

Regional groundwater flow is generally from north east to south west. The water source for the wetland is likely to be direct rainfall inputs and seepage from the Quaternary aquifer (Semeniuk, 2007). Targeted hydrochemical analysis and possibly additional drilling would be required to determine if any contributions are made from the deeper aquifers.



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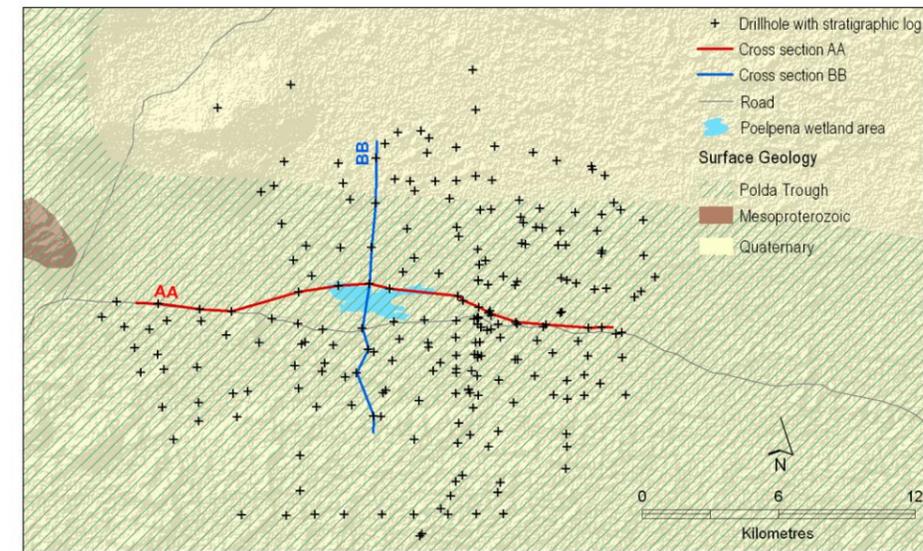
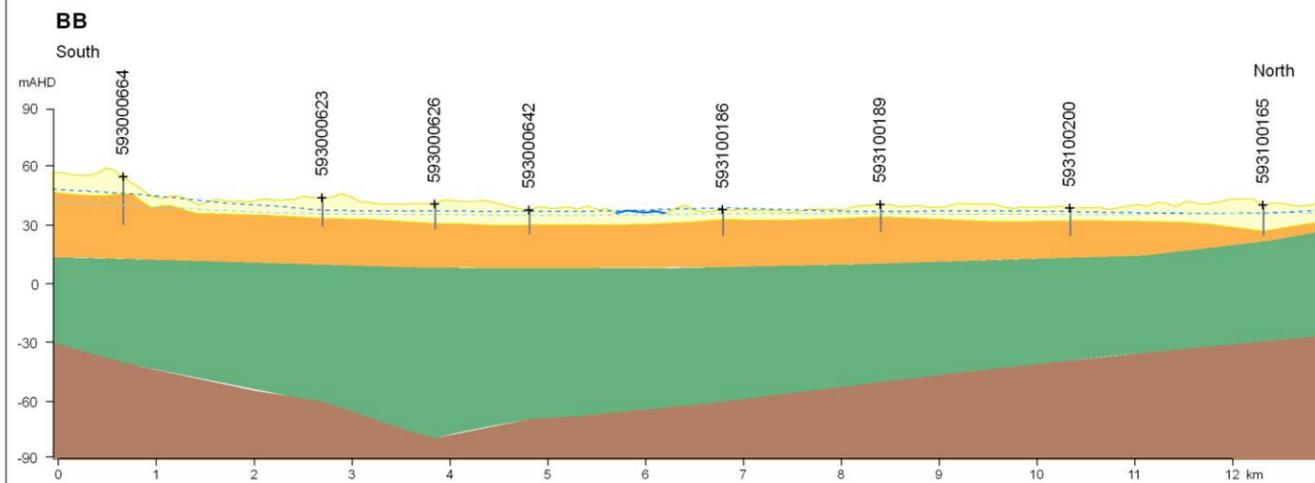
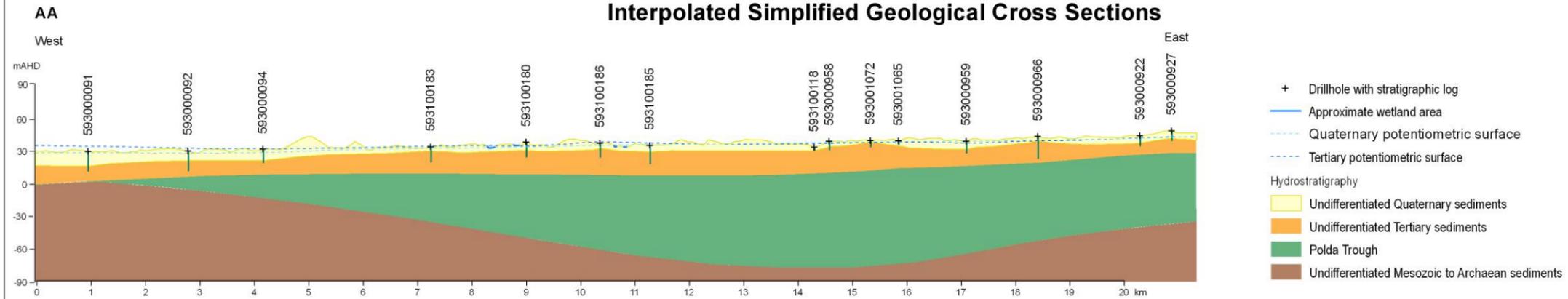
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POELPENA, EYRE PENINSULA Interpolated Simplified Geological Cross Sections

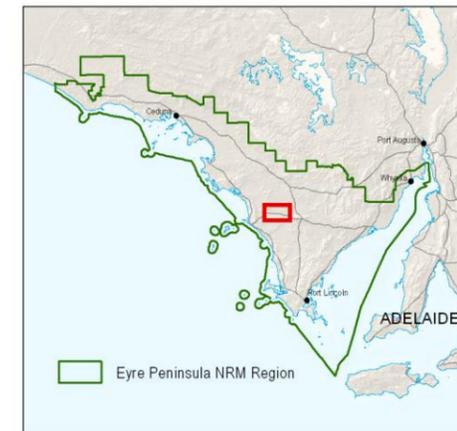


Hydrogeological summary:

Poelpena is located 40 km east of Elliston amidst low limestone hills. The sediments within the wetland consist of carbonate muds and calcareous sands (Semeniuk, 2007). The topography of the surrounding catchment ranges from 30 to 60 mAHd, with the surface of the wetland ranging from 40 mAHd at the eastern end to 32 mAHd at the western end where sediments are inundated. The thickness of the Quaternary sediments is variable and generally less than 20 m in the wetland area. Beneath the Quaternary sediments, the Tertiary Poelpena Formation (which forms a confined aquifer) is generally 20 m thick and the Jurassic Polda Formation is generally 80 m thick. Underlying the sedimentary sequences, the Basement fractured rock aquifer is generally more than 110 m below the wetland surface. There is basement outcropping nearby to the west of the wetland (Mount Wedge).

There is no monitoring data available within the wetland, however there is an extensive observation bore network adjacent to the wetland that provides current data for the Quaternary and Tertiary aquifers. Recent data from the Quaternary aquifer indicates that groundwater elevations generally decrease towards the west, from 25 to 39 mAHd. Time series data from a well screened in the Quaternary aquifer on the wetland's south east margin (which has been monitored on a regular basis since 1963) indicates water levels ranging from 30.1 to 34.7 mAHd. The water quality is variable but generally fresh to slightly brackish. Data from the Tertiary aquifer indicates variable groundwater levels ranging from 30 to 40 mAHd. Time series data from a well screened in the Tertiary aquifer on the wetland's north west margin (also monitored on a regular basis since 1963) indicates water levels ranging from 29.6 to 33.7 mAHd. The water quality is highly variable and generally brackish to saline. There is no data available for the Basement aquifer in the vicinity of the wetland.

Regional groundwater flow is generally from east to west. Monitoring data suggests there is potential for upward leakage from the Tertiary aquifer in the absence of a confining layer and thus a potential contribution to the wetland. It is likely that the water sources for the wetland include direct rainfall inputs and groundwater discharge predominantly from the Quaternary aquifer and possibly the Tertiary aquifer. It is unlikely that the deeper aquifers are a water source for the wetland owing to the presence of the overlying low permeability confining layers.



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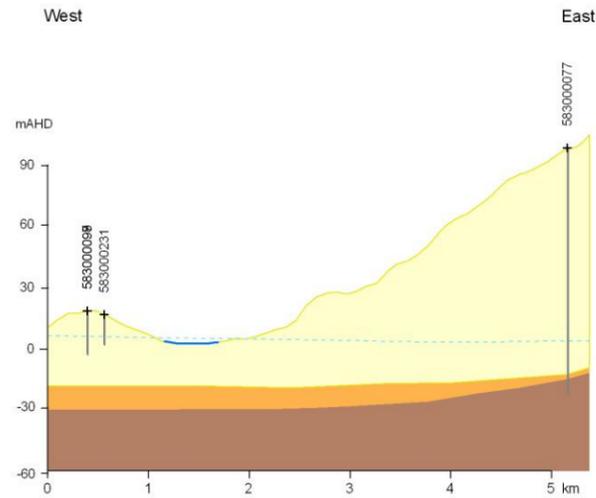
References:

- DEWNR (in prep.) Phase 2 Prescribed Areas Groundwater Assessment, Simplified Hydrostratigraphic 3D Model for the Eyre Peninsula NRM Region.
- V&C Semeniuk Research Group (2007a) A Baseline Survey of the wetlands of Eyre Peninsula 2005-2007.
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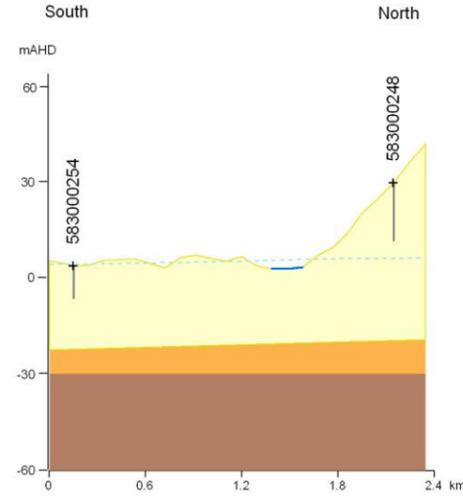
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LAKE HAMP, EYRE PENINSULA Interpolated Simplified Geological Cross Sections

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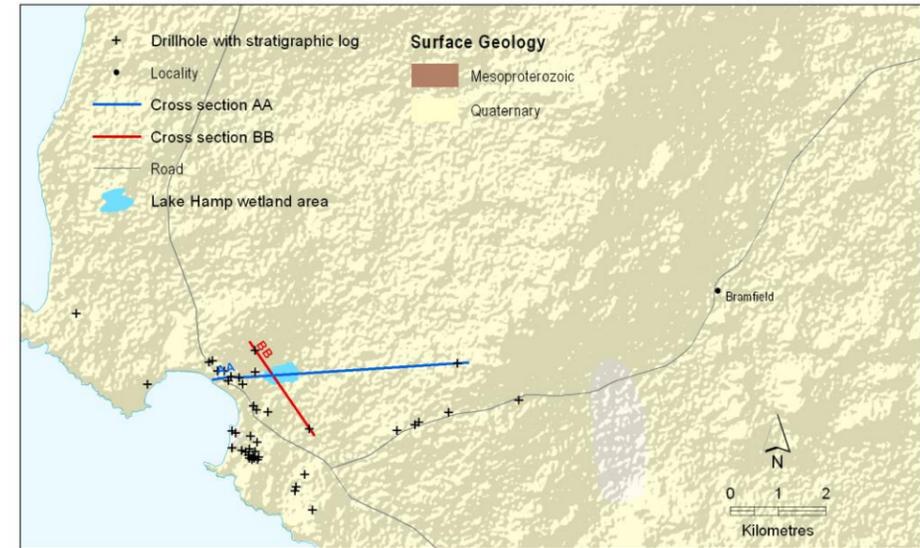
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- + Drillhole with stratigraphic log
- Approximate wetland area
- - - Quaternary potentiometric surface

Hydrostratigraphy

- Undifferentiated Quaternary sediments
- Undifferentiated Tertiary sediments
- Undifferentiated Mesozoic to Archaean sediments



Hydrogeological summary:

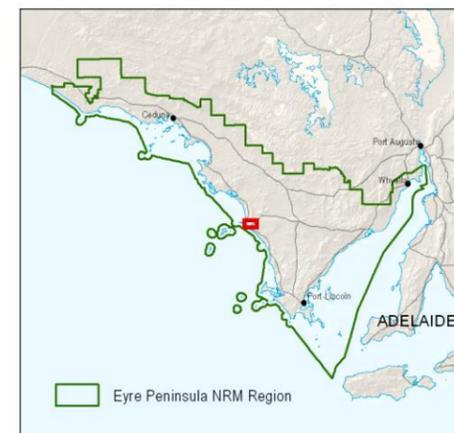
Lake Hamp is located in a karst landscape with a coastal dune ridge lying on its western margin. The sediments within the wetland consist generally of a white calcareous mud (2-3 m thick) underlain by limestone with surficial/subsurface layers of calcrete, which suggest the lake was once a sinkhole (Semeniuk, 2007).

The topography at the wetland margin is generally less than 5 mAHd, with the karst landscape rising to around 100 mAHd to the east. The thickness of the Quaternary sediments is quite variable, however in the immediate vicinity of the wetland is thought to be about 30 m. The underlying Tertiary sediments are generally thin, increasing in thickness to the north. Underlying the sedimentary sequences, the Basement fractured rock aquifer is generally 30-40 m below the wetland surface.

Monitoring data within the wetland (Semeniuk, 2007a) indicates that groundwater is hypersaline (TDS 96,000 – 150,000 mg/L) and acidic (pH 6 - 7). The watertable beneath the wetland area generally displays seasonal fluctuations of approximately 1.5 m causing periodic inundation and drying.

Recent data (post 1990) from nearby wells is very sparse. In the vicinity of the wetland, the data indicates groundwater levels ranging up to 7.2 mAHd of fresh to brackish quality. There are no wells completed in the Tertiary aquifer or Basement fractured rock aquifer in the vicinity of the wetland.

The water sources for the wetland are likely to be direct rainfall inputs and seepage from the Quaternary aquifer (Semeniuk, 2007a). Regional groundwater flow in this aquifer is generally from east to west. Significant contributions to the wetland from deeper aquifers are unlikely due to the presence of low permeability confining layers. Targeted hydrochemical analysis and possibly additional drilling would be required to confirm this.



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 Map Projection: Lambert Conformal Conic
 Map Datum: Geocentric Datum of Australia 1994
 Date: July 2013



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5 Units of measurement

1.1 Units of measurement commonly used (SI and non-SI Australian legal)

| Name of unit | Symbol | Definition in terms of other metric units | Quantity |
|--------------|---------------|---|---------------|
| day | d | 24 h | time interval |
| gigalitre | GL | 10^6 m^3 | volume |
| gram | g | 10^{-3} kg | mass |
| hectare | ha | 10^4 m^2 | area |
| hour | h | 60 min | time interval |
| kilogram | kg | base unit | mass |
| kilolitre | kL | 1 m^3 | volume |
| kilometre | km | 10^3 m | length |
| litre | L | 10^{-3} m^3 | volume |
| megalitre | ML | 10^3 m^3 | volume |
| metre | m | base unit | length |
| microgram | μg | 10^{-6} g | mass |
| microliter | μL | 10^{-9} m^3 | volume |
| milligram | mg | 10^{-3} g | mass |
| millilitre | mL | 10^{-6} m^3 | volume |
| millimetre | mm | 10^{-3} m | length |
| minute | min | 60 s | time interval |
| second | s | base unit | time interval |
| tonne | t | 1000 kg | mass |
| year | y | 365 or 366 days | time interval |

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