Groundwater – surface water interactions at Bool Lagoon, Lake Robe and Deadmans Swamp (Limestone Coast, SA)

Data review.

Taylor, AR, Lamontagne, S, Turnadge, CJ, Smith, SD, and Davies, P.

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Preface

The South East Regional Water Balance project is a collaboration between Flinders University, CSIRO and the Department of Environment, Water and Natural Resources (DEWNR), funded by the Goyder Institute for Water Research. The project commenced in September 2012, with the objective of developing a regional water balance model for the Lower Limestone Coast Prescribed Wells Area (LLC PWA). The project was initiated following conclusions from the South East Water Science Review (2011) that, due to a number of gaps in understanding of processes that affect the regional water balance, there is uncertainty about the amount of water that can be extracted sustainably from the Lower Limestone Coast region as a whole. The review also concluded that, because of the close link between groundwater and surface water resources in the region, surface water resources and ecosystems are particularly vulnerable to groundwater exploitation.

The South East Regional Water Balance project follows on from the report of Harrington et al. (2011), which recommended that a consistent framework of models is required to support water management in the South East, with the first step being a regional groundwater flow model to:

- bring together all existing knowledge
- address regional scale water balance questions
- provide boundary conditions for smaller scale models to address local scale questions, including those around "hotspot" areas and significant wetlands

Harrington et al. (2011) also identified the critical knowledge gaps that limit the outcomes from a regional scale model. These included but were not limited to:

- Spatial and temporal variability in groundwater recharge and evapotranspiration
- Interaquifer leakage and the influence of faults on groundwater flow
- The nature of wetland-groundwater interactions
- Understanding of processes occurring at the coastal boundary
- Surface water-groundwater interactions around the man-made drainage network
- The absence of information on historical land use and groundwater extraction

The South East Regional Water Balance project has included numerous tasks that have sought to improve the conceptualisation of the regional water balance, address some of the critical knowledge gaps, incorporate this and existing information into a regional groundwater flow model and understand how this improved understanding can be used in the management of wetland water levels.

An overview of the project and its output can be found in Harrington et al. 2015, *South East Regional Water Balance Project – Phase 2. Project Summary Report.* Goyder Institute Report 15/39.

Associated Reports and Research Papers

Technical Reports:

Harrington, N and Lamontagne, S (eds.), 2013*, Framework for a Regional Water Balance Model for the South Australian Limestone Coast Region.* Goyder Institute for Water Research Technical Report 13/14.

Morgan, LK, Harrington, N, Werner, AD, Hutson, JL, Woods, J and Knowling, M, 2015, *South East Regional Water Balance Project – Phase 2. Development of a Regional Groundwater Flow Model.* Goyder Institute for Water Research Technical Report 15/38.

Doble, R, Pickett, T, Crosbie, R, Morgan, L, 2015, *A new approach for modelling groundwater recharge in the South East of South Australia using MODFLOW,* Goyder Institute for Water Research Technical Report 15/26.

Smith, SD, Lamontagne, S, Taylor, AR and Cook, PG, 2015, *Evaluation of groundwater-surface water interactions at Bool Lagoon and Lake Robe using environmental tracers.* Goyder Institute for Water Research Technical Report 15/14.

Turnadge, CJ and Lamontagne, S, 2015, *A MODFLOW-based approach to simulating wetland – groundwater interactions in the Lower Limestone Coast Prescribed Wells Area.* Goyder Institute for Water Research Technical Report 15/12.

Barnett, S, Lawson, J, Li, C, Morgan, L, Wright, S, Skewes, M, Harrington, N, Woods, J, Werner, A and Plush, B, 2015, *A Hydrostratigraphic Model for the Shallow Aquifer Systems of the Gambier Basin and South Western Murray Basin.* Goyder Institute for Water Research Technical Report 15/15.

Harrington, N and Li, C, 2015, *Development of a Groundwater Extraction Dataset for the South East of South Australia: 1970-2013.* Goyder Institute for Water Research Technical Report 15/17.

Harrington, N, Millington, A, Sodahlan, ME and Phillips, D, 2015, *Development of Preliminary 1969 and 1983 Land Use Maps for the South East of SA*. Goyder Institute for Water Research Technical Report 15/16.

Harrington, N, Lamontagne, S, Crosbie, R, Morgan, LM and Doble, R, 2015, *South East Regional Water Balance Project: Project Summary Report.* Goyder Institute for Water Research Technical Report 15/39.

Research Papers:

Crosbie R, Davies P, Harrington N and Lamontagne S (2014) *Ground truthing groundwater-recharge estimates derived from remotely sensed evapotranspiration: a case in South Australia.* Hydrogeology Journal, 1-16. DOI: 10.1007/s10040-014-1200-7

Lamontagne S, Taylor A, Herpich D and Hancock G (2015) *Submarine groundwater discharge from the South Australian Limestone Coast region estimated using radium and salinity.* Journal of Environmental Radioactivity 140, 30-41.

Executive Summary

One of the objectives of the Goyder South East Water Balance Project is to develop a wetland – groundwater model to evaluate how future scenarios of change in climate, land-use and water allocation policy will impact on wetland water level regimes in the Lower Limestone Coast Prescribed Wells Area (LLC PWA). To help with the development of this model, a data review (this report) and a field study using environmental tracers (Smith et al., 2015) were undertaken in 2014 -2015 to evaluate groundwater-surface water interactions at three wetlands along a regional hydrogeological gradient. These were Deadmans Swamp (regional recharge), Bool Lagoon (regional flow-through) and Lake Robe (regional discharge). The data review included a comparison of historical surface water level and piezometric surface trends, an evaluation of the morphometry of the wetlands using remote sensing, and a preliminary water balance for Bool Lagoon for the 1987-2011 period.

The groundwater – surface water connectivity at Deadmans Swamp could not be evaluated in detail because of limited historical monitoring for both surface water and groundwater. However, freshwater conditions in surface water and groundwater, a variable water table, and an ephemeral water level regime are all consistent with a wetland located in a regional groundwater recharge zone in a Mediterranean to Temperate climate. Since Deadmans Swamp is surrounded by aeolian dunes, the local connectivity may be more complex but could not be evaluated. At the other end of the spectrum, Lake Robe is a hypersaline perennial lake, consistent with its location in a regional groundwater discharge zone. However, despite being located below sea level (–2 m AHD), nearby Lake Eliza is the lowest point in the landscape (–4 m AHD) and the possible focus for regional groundwater discharge. Lake Robe appears primarily fed by a local groundwater system associated with coastal sand dunes – in other words it is a local discharge wetland set in a regional groundwater discharge zone.

Bool Lagoon had the most complex groundwater – surface water regime of all three wetlands in part because it receives significant surface water runoff (from Mosquito Creek), is larger, and comprises several sub-basins. Comparison of piezometric surfaces and wetland surface water levels during a dry (2009/10) and a wet period (2011/12) demonstrated that groundwater – surface water connectivity for Bool Lagoon was variable in space and in time, with gaining, flow-through and losing conditions all encountered. However, the water balance analysis suggested that there is substantially more groundwater entering than leaving the wetland. Thus, on a regional groundwater point of view, Bool Lagoon is primarily a discharge wetland but, during wet periods, it can be a local recharge feature due to surface runoff inputs. The Bool Lagoon wetland complex is probably an example of a Boinka – a Mediterranean to Temperate landscape shaped by being located in a major regional groundwater discharge zone. Regional topography and subsurface control of regional groundwater flow are hypothesised to have generated the Bool Lagoon Boinka.

Based on the data and literature review, six factors are hypothesised to control wetland – groundwater interactions in the region:

1) Landscape position (regional recharge, flow-through and discharge zones);
2) Topography (that is, the increased likelihood to generate local flow systems in hummocky terrain);
3) Subsurface control (faults, shallow bedrock, etc);
4) Presence or absence of surface water runoff;
5) Presence or absence of a clogging layer at the wetland-aquifer interface;
6) Wetland morphometry.

This assessment of groundwater – surface water connectivity was greatly complicated by the sparse (in space or in time) groundwater and especially surface water level monitoring for the wetlands. This should be addressed as a priority, especially if one of the longer-term goals for managers is to generate predictive groundwater – surface water interaction models for the wetlands. However, the data review and the environmental tracer study of Smith et al. (2015) were useful to refine the understanding of the groundwater – surface water connectivity at least for the wetlands studied here. LLC PWA wetlands have intricate connectivities with both local and regional flow systems which must be understood because management intervention at the wrong scale may not achieve the desired outcomes. This will be especially true for problems such as wetland salinity, which will evolve at very different time-scales depending on whether they are locally or regionally-driven.

1 Introduction

The Lower Limestone Coast Prescribed Wells Area (LLC PWA) contains over 14,000 wetlands, including many wetlands of national and international significance (Taylor, 2006). Figure 1.1, includes all those wetlands that have been assessed in the South Australian Wetland Inventory Database (SAWID) for a greater than moderate wetland significance. Whilst most of these wetlands are at least partially groundwater-dependent, how they interact with local and regional hydrogeological systems is not well understood. As a part of the Goyder South-East Water Balance Project, groundwater – surface water interactions were evaluated for three wetlands (Bool Lagoon, Lake Robe and Deadmans Swamp) located along a landscape gradient in the LLC PWA (Figure 1.1). The overall conceptual model proposed for the region is that the water regime of groundwater-dependent wetlands is a function of:

1. Position in the landscape (regional groundwater recharge, flow-through and discharge zones);
2. Topography;
3. Subsurface control;
4. Presence or absence of surface runoff;
5. Presence of a clogging layer at the wetland – aquifer interface;
6. Morphometry.

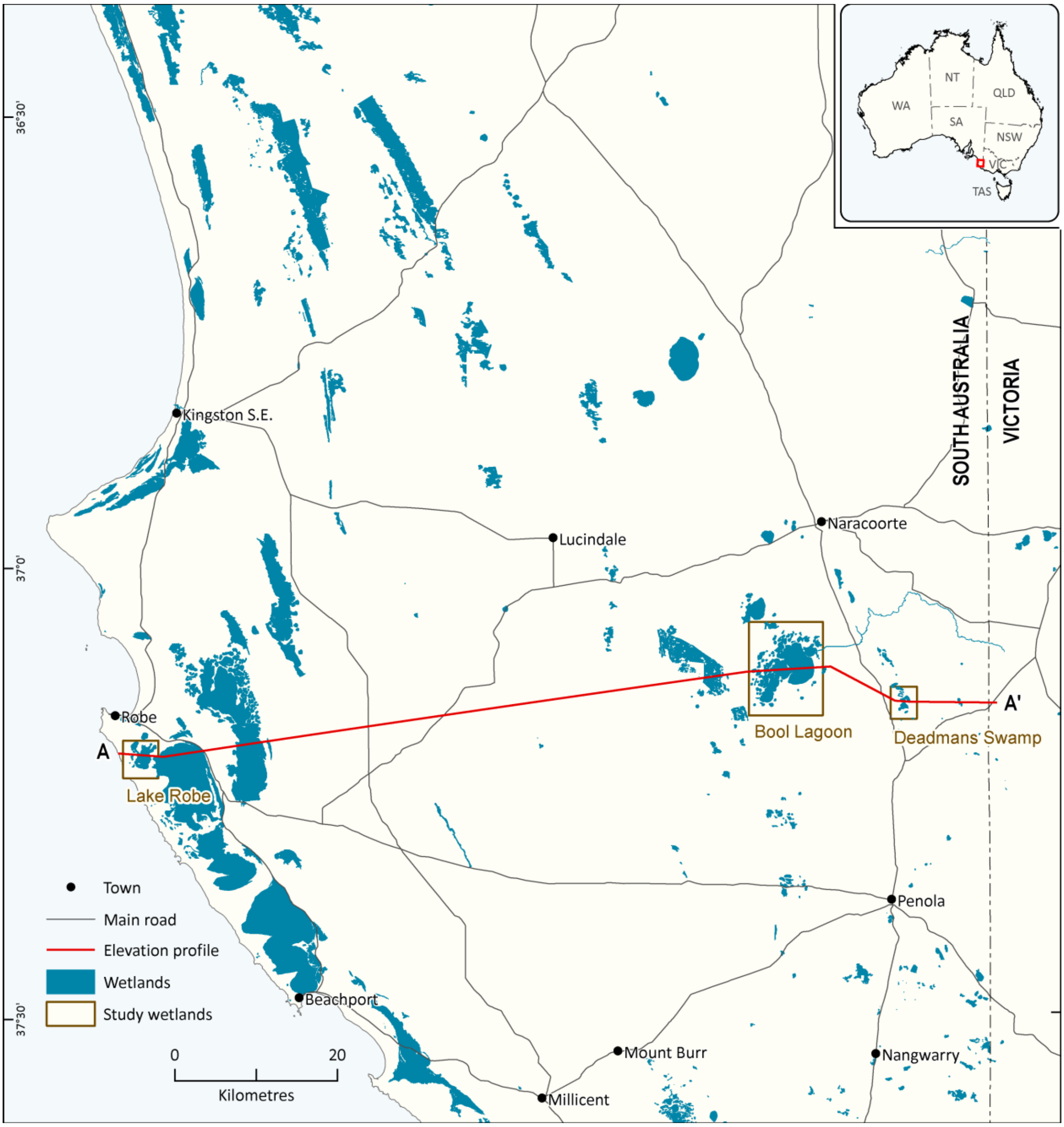


Figure 1.1 Location map highlighting the location of the three study wetlands in the South East and their relationship to elevation of the land surface.

Smith et al. (2015) summarise a field study to evaluate groundwater – surface water interactions at the three study wetlands using environmental tracers. In this report, historical water levels in surface water and groundwater are reviewed at the three wetlands for the same purpose. The wetlands were selected to evaluate the effect of landscape position on their water regime. Deadmans Swamp was thought to represent a regional groundwater recharge, Bool Lagoon a regional groundwater flow-through, and Lake Robe a regional discharge environment. In addition, to help the development of the Turnadge and Lamontagne (2015) wetland-groundwater model for the region, wetland morphometry was assessed using LIDAR and the hydraulic properties of shallow Bool Lagoon sediments (a suspected clogging layer) were measured. Finally, a preliminary water balance for Bool Lagoon was evaluated to provide further evidence for its groundwater dependency. The proposed conceptual model for wetland-groundwater interactions in the LLC PWA is further discussed.

2 Study area

2.1 Regional context

An overview of the study area and its hydrogeological systems is presented in Harrington and Lamontagne (2013). Briefly, the LLC PWA has a Mediterranean climate, with hot dry summers and cool wet winters. Daily maximum temperatures in the region range from up to 40°C in summer to 10 to 20°C during winter months. A significant north-south rainfall gradient exists, ranging from 450 mm/year in the north to 835 mm/year at higher elevations in the south. An approximate north-south evapotranspiration gradient also exists, with potential evapotranspiration ranging from approximately 1400 mm/year in the south (Mount Gambier) to approximately 1700mm/year in the north (Keith). Geologically, the LLC PWA encompasses the Gambier Basin of the Otway Basin and the south-western margin of the Murray Basin (Harrington and Lamontagne, 2013).

Two major aquifer systems occur in the area, the unconfined Tertiary Limestone Aquifer (TLA; also known as the Gambier Limestone) and the Tertiary Confined Sands Aquifer (TCSA; also known as the Dilwyn Sands). The two aquifers are separated by the Upper Tertiary Aquitard (UTA; or Ettrick Formation). Quaternary aeolian sediments cover the surface of the landscape and are most pronounced as a series of longitudinal dunes running parallel to the coastline, impeding surface water drainage.

The LLC PWA is a generally flat landscape, with the exception of the Naracoorte Ranges in the north-east and the longitudinal dune system. Along a transect intersecting the three study wetlands and east to the South Australian and Victorian border, elevation ranges from -5 to 125 mAHD (Figure 2.1). Deadmans Swamp is located within the regional topographic high, the Naracoorte Ranges. Bool Lagoon is located at the foot of the same range and Lake Robe is adjacent to a local dune system.

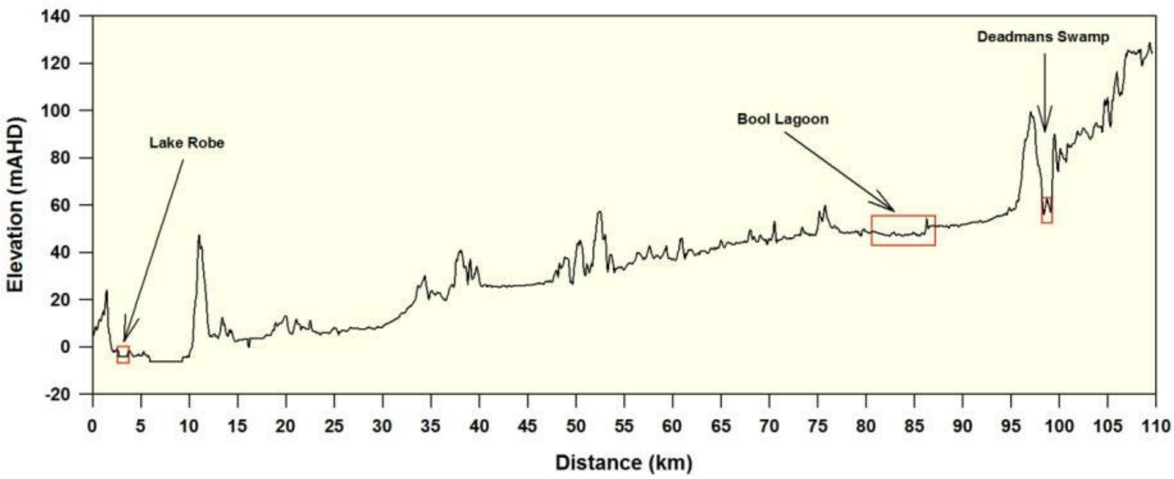


Figure 2.1 Regional elevation profile along a transect intersecting the three study wetlands (see Fig 1.1 for the transect location).

In the northern part of the study area, depths to bedrock are relatively shallower near the study wetlands (Figure 2.2) relative to areas further south; more detail in Harrington and Lamontagne (2013). Changes in basement topography at shallow depths provide the potential for bedrock control of regional groundwater flow and the development of local flow systems. Another important geological feature along the transect is the Kanawinka Fault, roughly located at the base of the Naracoorte Ranges (Figure 2.2). However, its role in controlling the hydrogeological systems is unclear (Harrington and Lamontagne, 2013).

Whilst Deadmans Swamp is located in a regional recharge zone, locally it is also surrounded by a local aeolian dune system. Bool Lagoon is located at the foot of the Naracoorte Ranges, in an area where the TLA thins and could be influenced by the Kanawinka Fault. Whilst located in a regional groundwater discharge area, Lake Robe is also at the foot of the Robe Range costal dune system.

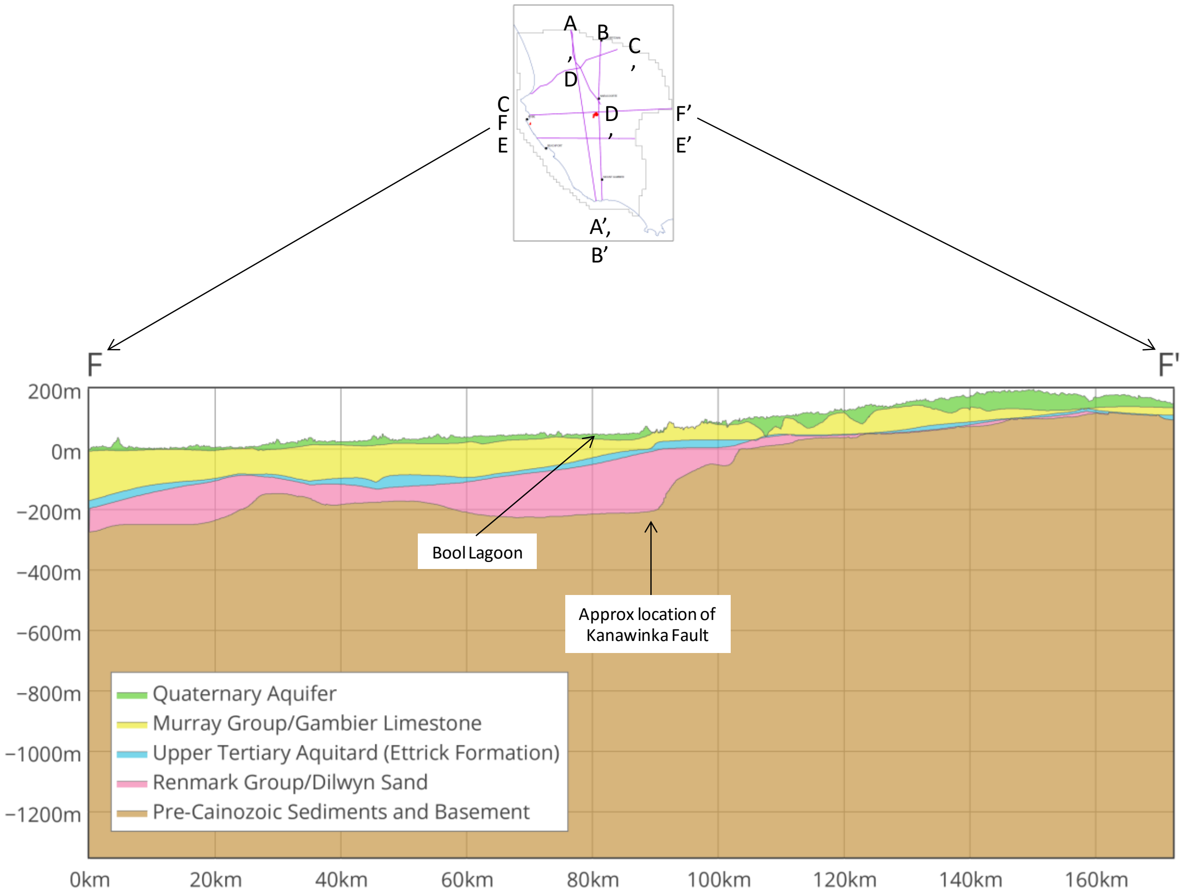


Figure 2.2 Hydrostratigraphic cross section (F – F') trending from the coast due east across the LLC PWA and into Victoria (see Harrington and Lamontagne (2013) for a description of the other transects inset).

2.2 Bool Lagoon

Bool Lagoon is a Ramsar-listed wetland complex of international significance. The lagoon complex (Figure 2.3) is ~20 km south to south-west from Naracoorte (at the base of the Kanawinka Scarp) and covers an area of ~30 km^2. The lagoon complex is situated on an interdunal flat and comprises of a series of circular shallow deflation basins with associated lunettes, including one of the largest in South Australia (Department for Environment and Heritage, 2006). The lagoon complex receives water from a combination of surface water and groundwater. Surface water is supplied from the discharge of Mosquito Creek, an ephemeral creek which drains a catchment of ~100,000 ha (Department for Water, 2011). Mosquito Creek first discharges into Hacks Lagoon, and subsequently by regulated releases into Bool Lagoon (SKM, 2010). The main lagoon is largely a terminal lake with limited surface outflow (Herpich and Butcher, 2010). However, when the wetland water volume exceeds 20 GL, excess water is released downstream via Drain M as part of the Park Management and Ramsar Plan (Department for Water, 2011). Bool Lagoon is thought to receive groundwater from the TLA. Bool Lagoon was selected for this study because it was thought to be located in a regional groundwater flow-through zone.

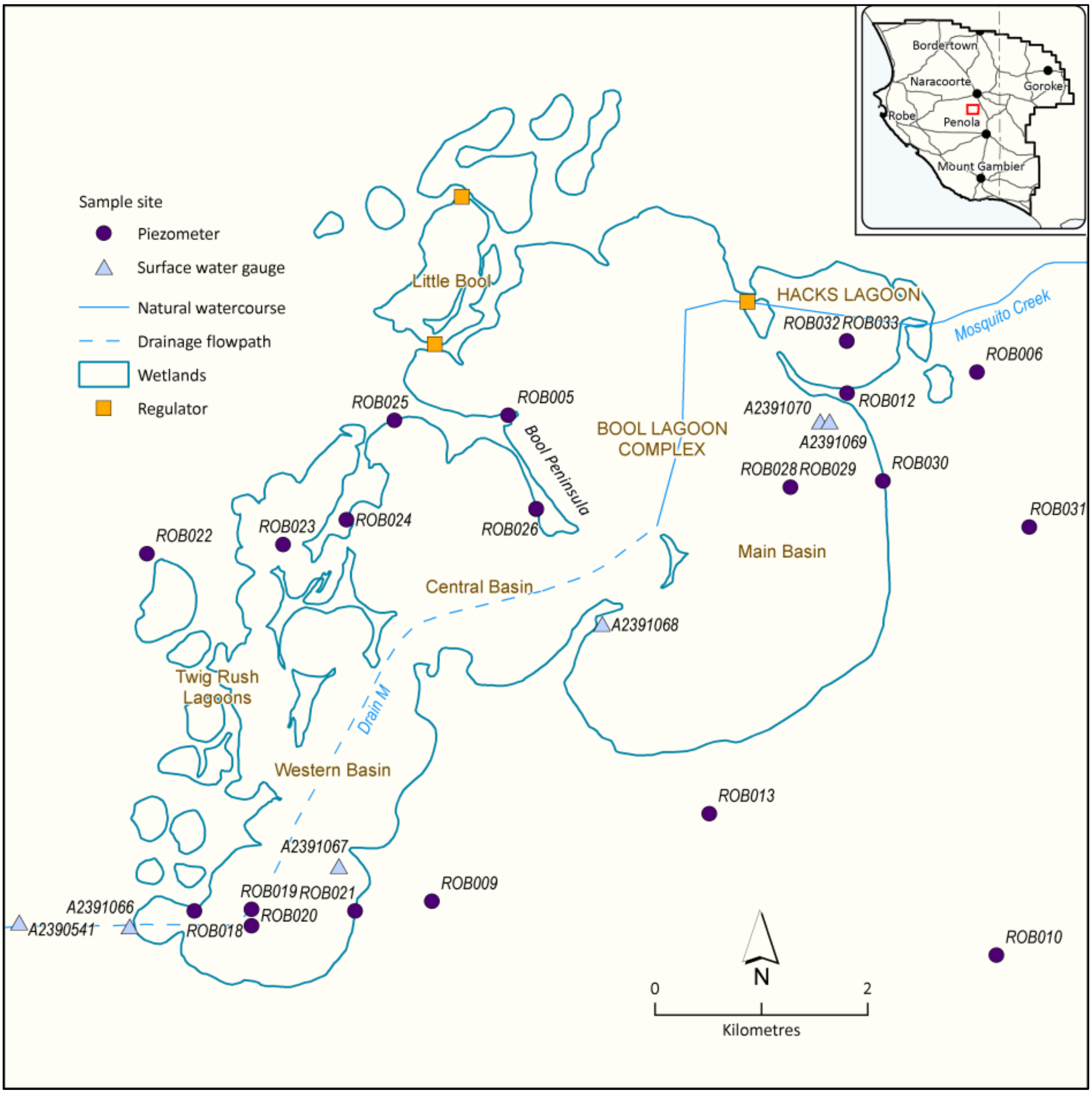


Figure 2.3 Site map of Bool Lagoon

2.3 Lake Robe

Lake Robe is a perennial hypersaline coastal lake situated 7 km south of the town of Robe (Figure 2.4). Lake Robe is one in a series of saline coastal lakes in the area, including lakes Eliza, St Claire and George. These sit in an interdunal hollow flanked by the coastal dune system of the Robe Range on the western side and Woakwine Range on the eastern side (Burne and Ferguson, 1983). The lakes were historically subjected to marine flooding (Bayly and Williams, 1966) and reportedly formed as marine lagoons isolated from the sea during the formation of an emerging coastline (Department for Environment Heritage and Aboriginal Affairs, 1999). Presently, Lake Robe is thought to receive inputs from various groundwater systems, including potentially from the sea because it is located below mean sea level (Burne et al. 1980). Lake Robe was used in this study because it was thought to be representative of a wetland within a regional groundwater discharge area.

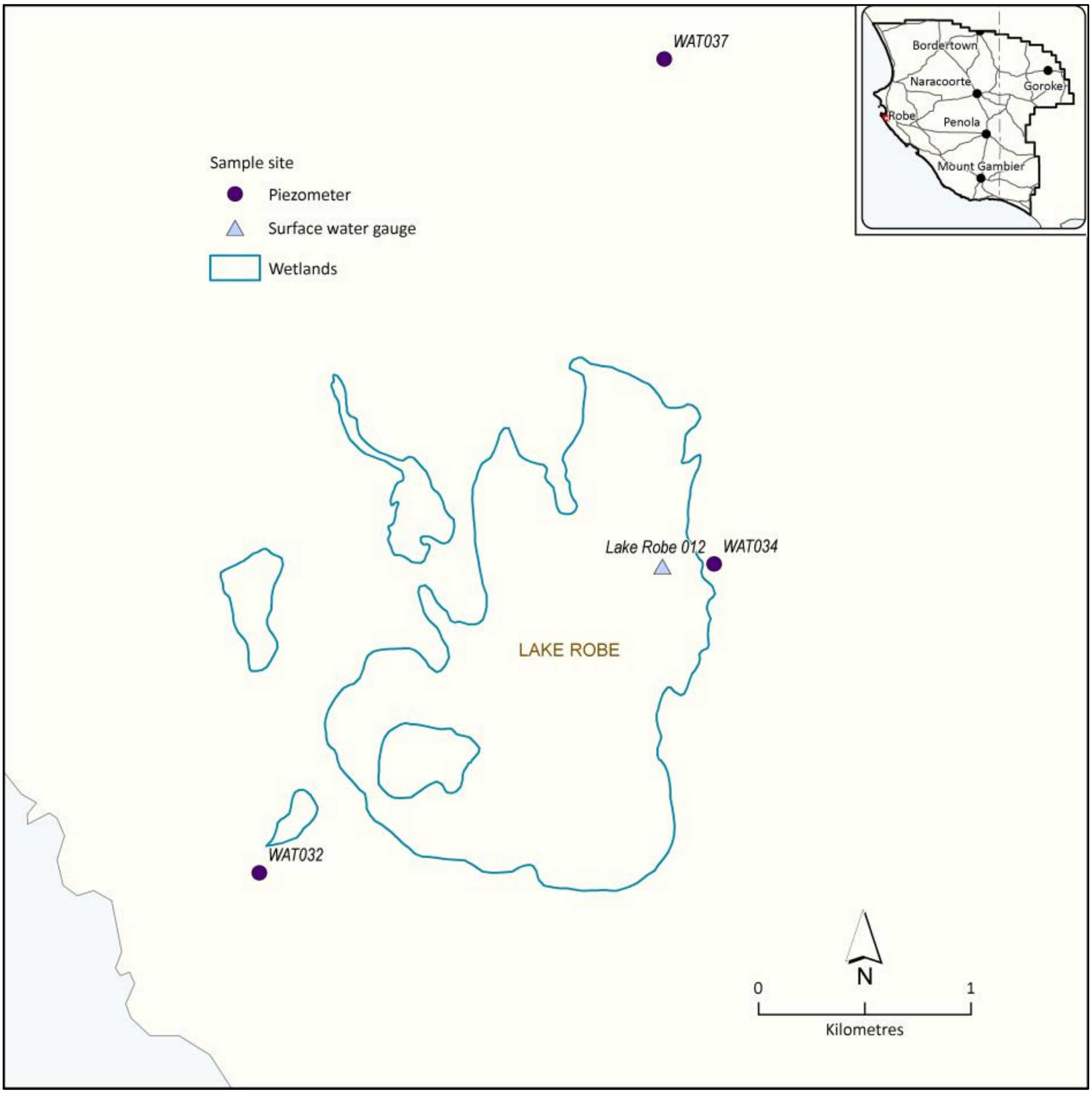


Figure 2.4 Site map of Lake Robe

2.4 Deadmans Swamp

Deadmans Swamp is a nationally significant ephemeral wetland complex located 24 km south of the town of Naracoorte, on the Naracoorte Plateau (Figure 2.5). The swamp is situated in a Native Forest Reserve (NFR) that comprises 5 km^2 of native vegetation managed by ForestrySA. Adjacent to the forest reserve is Glenroy Conservation Park, Wombat Flat Native Forest Reserve and an area of privately owned native vegetation that together generate a total connected area of 15 km^2 (ForestrySA, 2004). The wetland complex at Deadmans Swamp is approximately 1.2 km^2 in size and comprises two large and several small irregularly shaped ephemeral wetlands that may be associated with karst features (ForestrySA, 2004). Deadmans Swamp is located in a regional recharge area, but whether the wetland itself is a local recharge, flow-through or discharge feature is not clear.

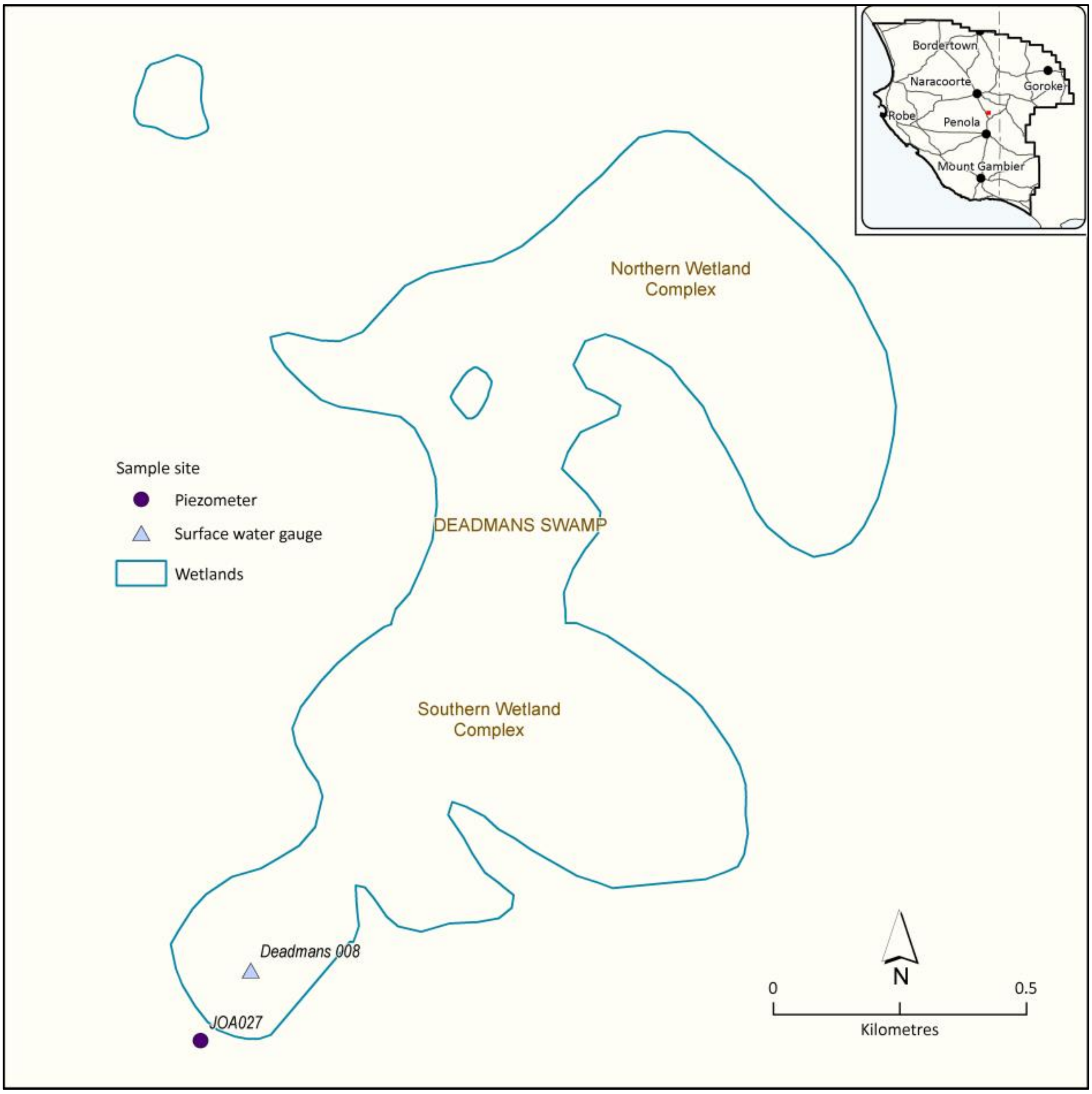


Figure 2.5 Site map of Deadmans Swamp

3 Data sources

3.1 Data collection and collation

3.1.1 METEOROLOGICAL DATA

Rainfall data specific to the study area was obtained from the Bureau of Meteorology (BOM) Climate Data Online (CDO) database (BOM, 2015). Evaporation (Class A pan evaporation) and evapotranspiration (ET) data was collated from the interpolated Scientific Information for Land Owners (SILO) datasets (DSITIA, 2015). SILO data is made available through the Science Delivery Division of the Department of Science, Information Technology, Innovation and the Arts (DSITIA). Data obtained from BOM and DSITIA are made available under a Creative Commons Attribution 3.0 Australia License.

3.1.2 SURFACE WATER DATA

Surface water levels, discharge volumes, EC, and the geographic location of surface water measurement gauges were obtained through WaterConnect, the Government of South Australia's water information portal (DEWNR, 2015a). The data obtained from WaterConnect is available and licensed under a Creative Commons Attribution 3.0 Australia License. Digitally logged and manual measurements of surface water levels and the location of surface water gauge boards within the three wetlands were obtained through the Department of Environment, Water and Natural Resources (DEWNR) South East Water Conservation and Drainage Board in Millicent.

3.1.3 GROUNDWATER DATA

Groundwater observation data including groundwater level, electrical conductivity (EC), location of groundwater infrastructure and elevation of the land surface was sourced from DEWNR. Quarterly observations of groundwater level referenced to depth below the ground surface were obtained from WaterConnect (DEWNR, 2015b). In addition, the geographic location of groundwater level observation points or groundwater infrastructure was also sourced from WaterConnect. High resolution (hourly/daily) groundwater level observation data was obtained from DEWNR's regional offices of Science Monitoring & Knowledge in Naracoorte and Mount Gambier.

3.2 Data summary

3.2.1 BOOL LAGOON

Data collated for Bool Lagoon comprises data associated with 27 groundwater sites that include 9 stock wells on the eastern and western fringes of the lagoon complex and 18 dedicated monitoring wells within and on the shoreline of the lagoons. Surface water observation infrastructure includes 2 electronic surface water gauges and 5 manual observation gauge boards. All of the data relevant to Bool Lagoon is summarised in Table 3.1.

Table 3.1 Summary of data collated for Bool Lagoon

DATA TYPE	DATASET(S)	LOCATION	SOURCE	TIME PERIOD	COMMENTS
Groundwater level	ROB004	West of wetland	WaterConnect	1970-2014 (*n*=142)	EC 1971-2013 (*n*=78)
	ROB005	In Bool Lagoon	WaterConnect	1970-2014 (*n*=47)	EC 1967-2012 (*n*=9); hi-res levels 2007-2013
	ROB006	East of Bool Lagoon	WaterConnect	1970-2014 (*n*=150)	EC 1952-1977 (*n*=5)
	ROB007	East of Bool Lagoon	WaterConnect	1970-1978 (*n*=16)	EC 1977 (*n*=1)
	ROB008	South west of Bool Lagoon	WaterConnect	1970-2014 (*n*=117)	EC 1972-1977 (*n*=4)
	ROB009	South of Bool Lagoon	WaterConnect	1970-2014 (*n*=110)	EC 1977-1981 (*n*=2)
	ROB010	South east of Bool Lagoon	WaterConnect	1970-2014 (*n*=103)	EC 1975-1977 (*n*=2)
	ROB012	Adjacent to Hacks Lagoon	WaterConnect	1969 (*n*=1)	EC 1969 (*n*=1)
	ROB013	South of Bool Lagoon	WaterConnect	1980 (*n*=1)	EC 1993-2009 (*n*=63)
	ROB018	In Bool Lagoon	WaterConnect	2009-2014 (*n*=17)	EC 2010 (*n*=1)
	ROB019	In Bool Lagoon	WaterConnect	2009-2010 (*n*=3)	
	ROB020	In Bool Lagoon	WaterConnect	2009-2010 (*n*=3)	
	ROB021	On edge of Bool Lagoon	WaterConnect	2009-2014 (*n*=17)	EC 2010 (*n*=1)
	ROB022	West of Bool Lagoon	WaterConnect	2009-2014 (*n*=19)	EC 2011-2012 (*n*=3); hi-res levels 2009-2013
	ROB023	In Bool Lagoon	WaterConnect	2009-2014 (*n*=14)	
	ROB024	In Bool Lagoon	WaterConnect	2009-2014 (*n*=18)	EC 2010-2012 (*n*=4); hi-res levels 2009-2013
	ROB025	In Bool Lagoon	WaterConnect	2009-2014 (*n*=16)	
	ROB026	In Bool Lagoon	WaterConnect	2009-2014 (*n*=18)	EC 2011-2012 (*n*=3); hi-res levels 2009-2013
	ROB027	In Bool Lagoon	WaterConnect	2009-2013 (*n*=12)	EC 2012 (*n*=1)
	ROB028	In Bool Lagoon	WaterConnect	2009 (*n*=1)	
	ROB029	In Bool Lagoon	WaterConnect	2009 (*n*=1)	
	ROB030	In Bool Lagoon	WaterConnect	2009-2013 (*n*=15)	EC 2010-2012 (*n*=2)

DATA TYPE	DATASET(S)	LOCATION	SOURCE	TIME PERIOD	COMMENTS
	ROB031	East of Bool Lagoon	WaterConnect	2009-2013 (*n*=13)	
	ROB032	In Hacks Lagoon	WaterConnect	2009 (*n*=1)	
	ROB033	In Hacks Lagoon	WaterConnect	2009 (*n*=1)	
	ROB034	South of Bool Lagoon	WaterConnect	2009 (*n*=1)	
Surface water level	A2390519	Mosquito Creek (automated)	DEWNR	1971-2012 (*n*=15106)	Level, flux; EC 2006-2010 (*n*=609)
	A2390541	Drain M (automated)	DEWNR	1985-2012 (*n*=9976)	Level, flux
	A2391066	Regulator (Bool Lagoon)	DEWNR	1986-2013 (*n*=649)	
	A2391067	Yards (Bool Lagoon)	DEWNR	1986-2013 (*n*=598)	
	A2391068	Big Hill (Bool Lagoon)	DEWNR	1986-2013 (*n*=616)	
	A2391069	Office (Bool Lagoon)	DEWNR	1986-2013 (*n*=625)	
	A2391070	Hacks (Hacks Lagoon)	DEWNR	1986-2013 (*n*=640)	
Meteorological	Locksley Farm	South of wetland	BOM	2001-2014 (*n*=4807)	Observed precipitation – station 026103
	Struan	East of wetland	SILO	1900-2014 (*n*=41735)	Observed precipitation, evaporation, PET
	Bool Lagoon	In wetland	SILO	1900-2014 (*n*=41735)	Interpolated precipitation, evaporation, PET
	Wrattonbully	East of wetland	BOM	1967-2014 (*n=17456*)	Observed precipitation – station 026075
LiDAR	Bool Lagoon		DEWNR	25-31 July 2007	

3.2.2 LAKE ROBE

Data collated for Lake Robe comprises data associated with three groundwater observations wells and one surface water gauge board, the data is summarised in Table 3.2.

Table 3.2 Summary of data collated for Lake Robe

	DATASET	LOCATION	SOURCE	TIME PERIOD	COMMENTS
Groundwater level	WAT032	South west of Lake Robe in the coastal dune system	WaterConnect	2009-2013 (*n=7*)	Hi-res levels 2009-2011
	WAT034	On the eastern side of Lake Robe ~50 m from the shoreline	WaterConnect	2009-2013 (*n=8*)	Hi-res levels 2009-2011
	WAT037	Approximately 2 km to the north/north east of Lake Robe	WaterConnect	2010-2014 (*n=9*)	
Surface water level	Lake Robe_012	In the north eastern part of the lake	DEWNR		Limited data
Meteorological	Robe	North of Lake Robe	BOM	1915-2014 (*n=36195*)	Observed precipitation – station 026026
	Lake Robe	Adjacent to the lake	SILO	1970-2014 (*n=16436*)	Interpolated evaporation

3.2.3 DEADMANS SWAMP

Data collated for Deadmans Swamp comprises data associated with one groundwater observation well and one surface water gauge board, the data is summarised in Table 3.3

Table 3.3 Summary of data collated for Deadmans Swamp

	DATASET	LOCATION	SOURCE	TIME PERIOD	COMMENTS
Groundwater level	JOA027	South western edge/corner of Deadmans Swamp	WaterConnect	2009-2014 (*n=24*)	Hi-res levels 2009-2013
Surface water level	Deadmans_008	In the south western basin	DEWNR	2010-2011 (*n=648*)	Limited data

3.2.4 ADDITIONAL UNCONFINED GROUNDWATER

In addition to site (wetland) specific data, data was also collated from a number of groundwater wells in areas in the near vicinity (within 10 km) of the wetlands to gain an understanding of groundwater level variations and geochemistry for the unconfined Tertiary Limestone Aquifer (TLA). The data is summarised in Table 3.4.

Table 3.4 Summary of additional data collated from the unconfined groundwater system

	DATASET	LOCATION	SOURCE	TIME PERIOD	COMMENTS
Groundwater level	JOA001	East of Struan	WaterConnect	1971-1993 (*n=39*)	
	JOA008	East of Bool Lagoon	WaterConnect	1970-2010 (*n=117*)	
	JOA026	East of Bool Lagoon	WaterConnect	2009-2014 (*n=30*)	
	JOA028	East of Bool Lagoon	WaterConnect	2011-2013 (*n=24*)	
	JOA029	East of Bool Lagoon	WaterConnect	2011-2014 (*n=28*)	
	JOA030	East of Bool Lagoon	WaterConnect	2011-2014 (*n=26*)	
	JOA031	East of Bool Lagoon	WaterConnect	2011-2014 (*n=26*)	
	ROB007	East of Bool Lagoon	WaterConnect	1970-1978 (*n=16*)	

4 Methods

4.1 Clogging layer

4.1.1 WETLAND BED SEDIMENT DATA

At various locations in Bool Lagoon sediment pits were dug (Figure 4.1) to assess the spatial variability in the physical properties of the bed sediments, the variability in the depth to groundwater and the variability in groundwater salinity. At each location the depth to groundwater below bed level was measured, the EC of the pit water was measured using a hand held submersible probe and three undisturbed sediment samples were taken. Undisturbed sediment samples were taken from the face of a pit walls (Figure 4.2) using an Eijkelkamp sample ring kit. Sediment samples were carefully trimmed in the laboratory to the defined extent of the sample rings and placed in a shallow water bath to saturate. Saturation was carefully conducted by capillarity in the initial stages (days) before further water was added to the bath to immerse the samples up to 90% of their height where they remained for several weeks. Following saturation samples from each location were measured for water retention and saturated hydraulic conductivity (K_s). Water retention measurements were conducted using the pressure plate or porous plate method (Richards, 1948). K_s was determined using an Eijkelkamp soil water permeameter following the international standard 'Determination Of Hydraulic Conductivity Of Saturated Porous Materials Using A Rigid Wall Permeameter; ISO/FDIS 17312'.

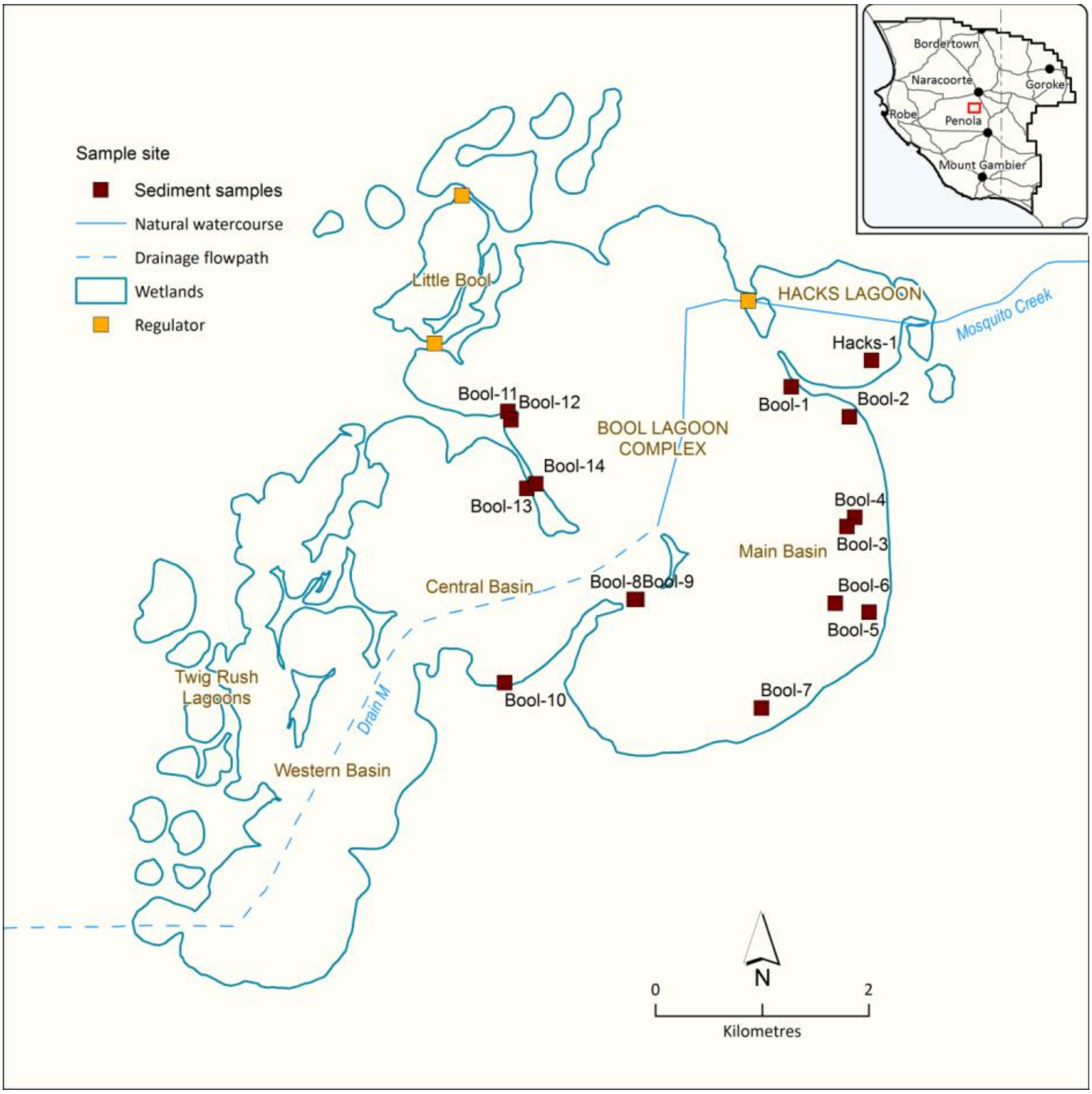


Figure 4.1 Location of 15 sediment pits at Bool Lagoon

Figure 4.2 Collection of undisturbed sediment samples from the bed of Bool Lagoon showing three sample rings in a pit wall

4.1.2 CLOGGING LAYER ASSESSMENT– BOOL LAGOON

A clogging layer can be any geological or biological porous media at the interface between a wetland and an aquifer with a lower hydraulic conductivity than the underlying aquifer. The presence of a clogging layer is a necessary condition to develop perched (or losing-disconnected) wetlands (Brunner et al. 2009) when water tables drop below bed level. The potential for the generation of perched wetlands can be evaluated from Brunner et al. (2009) :

$$K_c/K_a \leq h_c/(d + h_c) \quad (1)$$

where K_c and K_a is the hydraulic conductivity of the bed sediments and TLA respectively, h_c the thickness of the clogging layer, and d the wetland stage height. K_a was derived from the Turnadge and Lamontagne (2015) wetland model, h_c from lithology data and d from surface water level data. K_c was derived from the 15 K_s measurements made at Bool Lagoon and were used here to estimate its potential to become perched.

4.2 Land surface and wetland morphometry

In addition to the elevation data at point locations specific to groundwater and surface water observations, a regional spatial dataset of land surface elevation and wetland morphometry was obtained from DEWNR's South East Resource Information Centre in Mount Gambier. Spatial elevation data was collected by DEWNR using a fixed wing aircraft fitted with an airborne laser scanning (ALS) light detection and ranging (LiDAR) sensor coupled with ground support via a Global Positioning System (GPS) base station recording accurate geographic locations. The dataset was obtained from aircraft flown during the period 25/07/07 to 31/07/07. Since LiDAR imaging is unable to penetrate water, the existence of water bodies can result in inaccurate topographic results. In order to check whether this may have occurred during the LiDAR survey, a composite Landsat 7 image taken on 26/07/07 was obtained. This image confirmed that Deadmans Swamp and Bool Lagoon were dry during the survey but Lake Robe was not. LiDAR data was coupled with surface water levels to calculate the total area of inundation and the corresponding estimate in volume of water for a given set of water levels at Bool Lagoon.

4.3 Piezometric cross sections – Bool Lagoon

Of the three wetlands, Bool Lagoon was the only one where the density of piezometers and frequency of measurements enabled a more detailed comparison of variations in the piezometric surface surrounding the wetland over time. In other words, whether the wetland was a groundwater recharge, flow-through or discharge feature could be evaluated. However, even for Bool Lagoon the infrequent nature of surface water monitoring only allowed a comparison of wet years versus dry years and not seasonality in a given year. Furthermore, not all piezometers had been surveyed. For consistency, all surface water level gauges and piezometers in or around Bool Lagoon were standardised for elevation using a LiDAR-derived high-resolution digital elevation map. This was possible for the surface gauges because LiDAR was flown during a period when the wetland was dry. Three transects trending east to west across the lagoon complex were defined to produce piezometric cross sections. The Northern Transect was at the junction with Hacks Lagoon, the Middle Transect through the centre of the wetland, and the Southern Transect near the outlet (Figure 4.3).

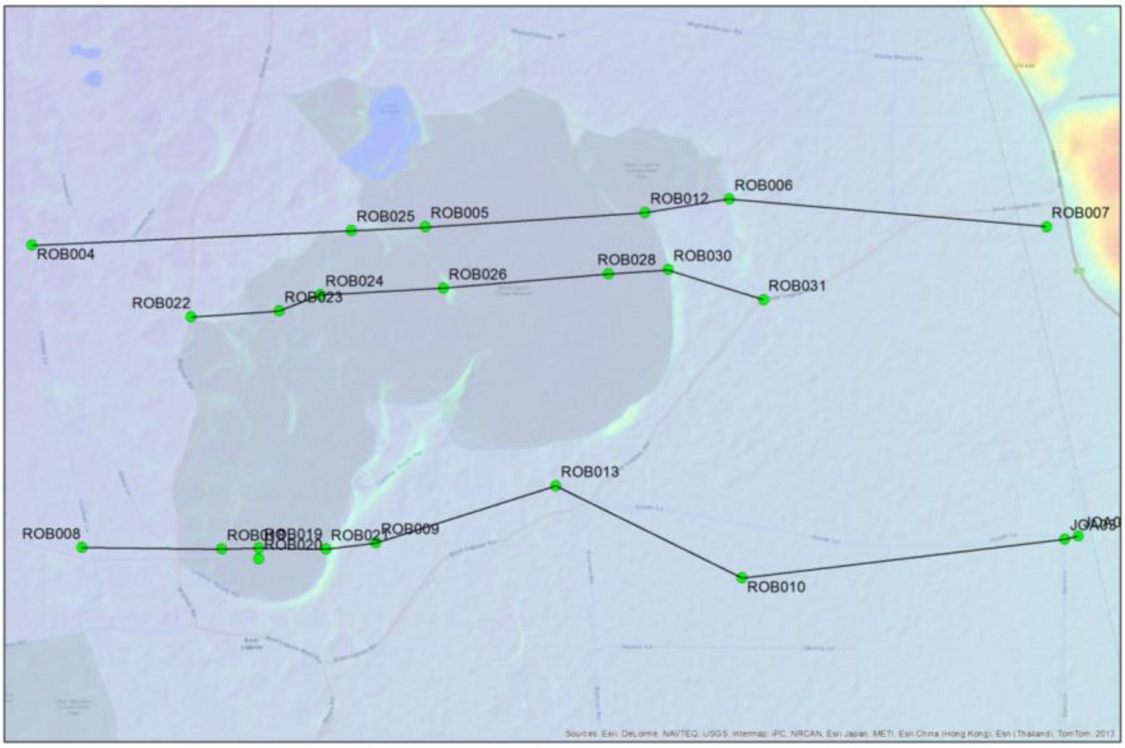


Figure 4.3 Location of three piezometric cross sections trending from east to west across Bool Lagoon, overlaying the spatial LiDAR coverage for the wetland complex and surrounding land.

4.4 Water balance – Bool Lagoon

A preliminary water balance for Bool Lagoon was estimated for the 1987 – 2011 period to help further understand its groundwater dependency. The water balance for the lagoon utilised data summarised in Table 3.1 and was defined as:

$$dV/dt = P + D_{in} + G_{in} - D_{out} - G_{out} - E \quad (2)$$

where dV/dt is the annual change in wetland volume (ML year^{-1}; using a 1 January – 31 December water year) and the loads (components) are (in ML year^{-1}) P precipitation, D_{in} drain input, G_{in} groundwater input, D_{out} drain outflow, G_{out} groundwater outflow, and E evaporation. There are five surface water gauge boards in the wetland and the average stage on a given date was used whenever possible. However, during the 1990s in particular, there were frequent breaks when stage was not measured at any station. Thus, dV/dt could not be estimated for many years so it had to be assumed it was ~0. This is a reasonable approximation because the wetland is either dry or nearly empty at the beginning of the water year on most years. Rearranging (2), the net groundwater load to the wetland (G_{net}) is:

$$G_{net} = G_{out} - G_{in} = P + D_{in} - D_{out} - E \quad (3)$$

Thus, it is not possible here to estimate G_{in} and G_{out}, just whether the wetland is a net source or a net sink for groundwater (G_{net}). Because of the semi-arid climate, E is likely to be the largest component of the water balance. However, because of a shallow water table and large variations in inundation area during the year, E is not simple to estimate. E will include evaporation from inundated areas and evapotranspiration (ET) from shallow water tables where sediment is exposed. As a first approximation, E was estimated as:

$$E = E_{pan} * k * A_{in} + ET_{sed} * (A_{tot} - A_{in}) \quad (4)$$

Where E_{pan} is the pan evaporation rate, k the pan coefficient 0.9 (McMahon et al. 2013), A_{in} the wetland area inundated, ET_{sed} the Penman-Monteith evapotranspiration rate and A_{tot} the total wetland area (corresponding to 49 m AHD). E was estimated daily and then summed to obtain yearly loads. Daily Class A evaporation rates and the Penman-Monteith FAO56 estimates of evapotranspiration (ET_{sed}) were estimated from the SILO database. Given very shallow water tables, often < 1 m, moderate salinities and heavy textured sediments, water table evaporation rates were assumed to be similar to ET. That is, variations in water potential, including osmotic and matric potential and associated unsaturated hydraulic conductivity for a shallow vadose zone, were assumed to not heavily inhibit diffuse discharge. This assumption is similar to findings outlined in Jolly et al. (1993); Thornburn et al. (1992) and Shah et al. (2007). A_{in} and A_{tot} are exclusive of Hacks Lagoon. When A_{in} was not known, the last measured stage was used as an approximation. P was estimated by multiplying daily rainfall by A_{tot} and summing over the year.

5 Results

5.1 Rainfall

5.1.1 BOOL LAGOON AND DEADMANS SWAMP

Observed rainfall data for Wrattonbully (BOM station 026075) east of Deadmans Swamp and Bool Lagoon spans 1967 to 2014. Fluctuations in annual rainfall range from 330 to 950 mm year^{-1} (Figure 5.1) with a mean annual rainfall for the area of approximately 640 mm year^{-1} (BOM, 2015). Missing annual totals correspond to years in which monitoring infrastructure required maintenance. The trend in long term annual rainfall is a slight reduction for the 48 year period. Interpolated annual evaporation for the area ranges from 1255 to 1578 mm year^{-1} over a 45 year period from 1970 to 2014. The mean annual evaporation is approximately 1440 mm year^{-1} (DSITIA, 2015).

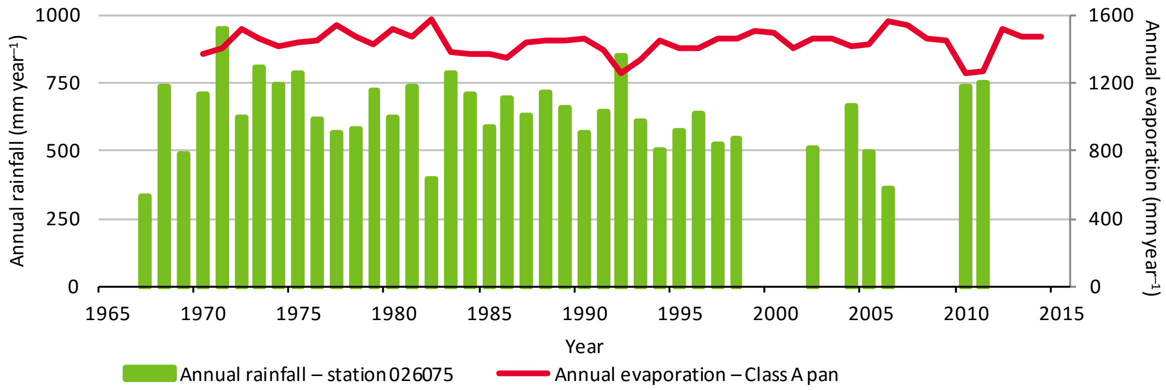


Figure 5.1 Annual rainfall and evaporation near Bool Lagoon and Deadmans Swamp

5.1.2 LAKE ROBE

Observed rainfall for the town of Robe (BOM station 026026) west of Lake Robe spans 1915 to 2014. Fluctuations in annual rainfall range from 360 to 870 mm year^{-1} (Figure 5.2) with a mean annual rainfall for the area of approximately 640 mm year^{-1} (BOM, 2015). The trend in long term annual rainfall is a very slight reduction for the 99 year period. Interpolated annual evaporation for the area ranges from 1174 to 1542 mm year^{-1} over a 45 year period from 1970 to 2014. The mean annual evaporation is approximately 1388 mm year^{-1} (DSITIA, 2015).

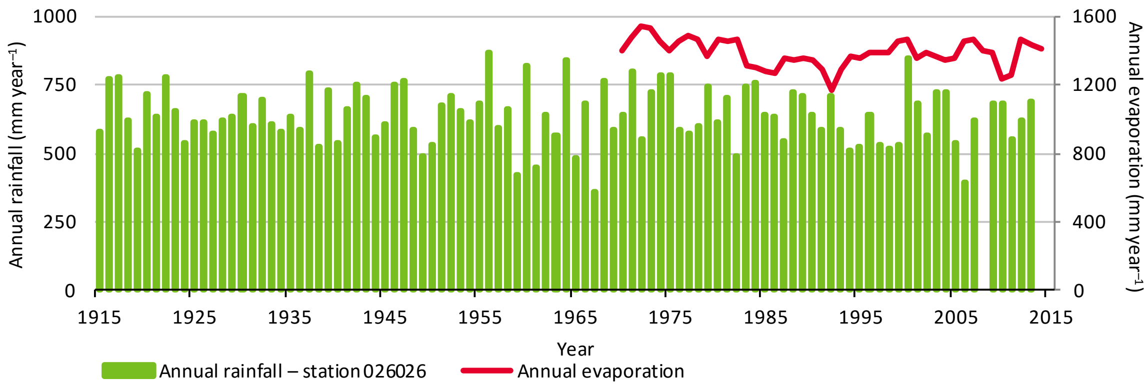


Figure 5.2 Annual rainfall and evaporation for Robe

5.2 Surface water

5.2.1 BOOL LAGOON

Mosquito Creek

Mean daily surface water levels and cumulative annual discharge for Mosquito Creek have been collated from gauging station A2390519 (MOSQUITO CREEK @ Struan) which is approximately 4 km upstream of Bool Lagoon, the data covers a 44 year period between 1971 to 2015. Variations in mean daily surface water levels range from 0 to 3.86 m (Figure 5.3). Cumulative annual discharge varies from no flow up to 68,000 ML. There are two distinct periods in the data, a wet period from 1971 to 1997 and a dry period from 1998 to 2015. Peak levels and discharge for Mosquito Creek within a given year usually occur during winter and spring when seasonal winter rainfall, soil moisture and runoff in the catchment area are highest. Years where cumulative annual discharge are low correspond to years of lower annual rainfall (Figure 5.1) in particular, low monthly winter rainfall, as occurred during the Millennium Drought (van Dijk et al. 2013).

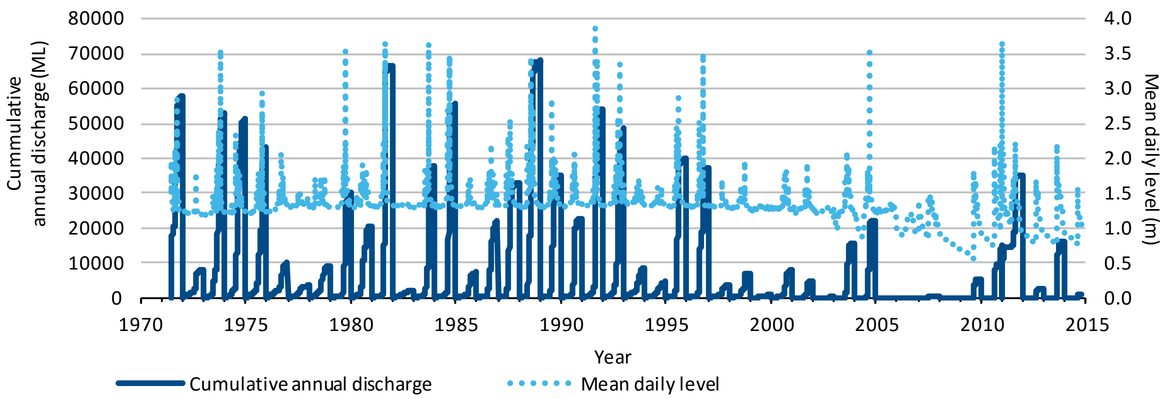


Figure 5.3 Cumulative annual discharge and mean daily surface water levels for Mosquito Creek

Drain M

In addition to surface water levels and discharge upstream of Bool Lagoon, observations of surface water levels and discharge were obtained for Drain M (Bool Lagoon outlet). Observations from gauging station A2390541 span a 29 year period from 1985 to 2014 (Figure 5.4). Cumulative discharge varies from no flow up to 68,000 ML/year. In comparison to mean cumulative discharge and levels for Mosquito Creek, flow to Drain M is regulated and reflects extensive periods of no flow. Under the requirements of the Park Management and Ramsar Plan for Bool Lagoon (Department for Water, 2011) water is usually only released to Drain M when the wetland volume exceeds 20 GL. For example, the period of minimal cumulative annual discharge from 1998 to 2015, corresponds to the same period where cumulative annual discharge in Mosquito Creek was lower (Figure 5.3).

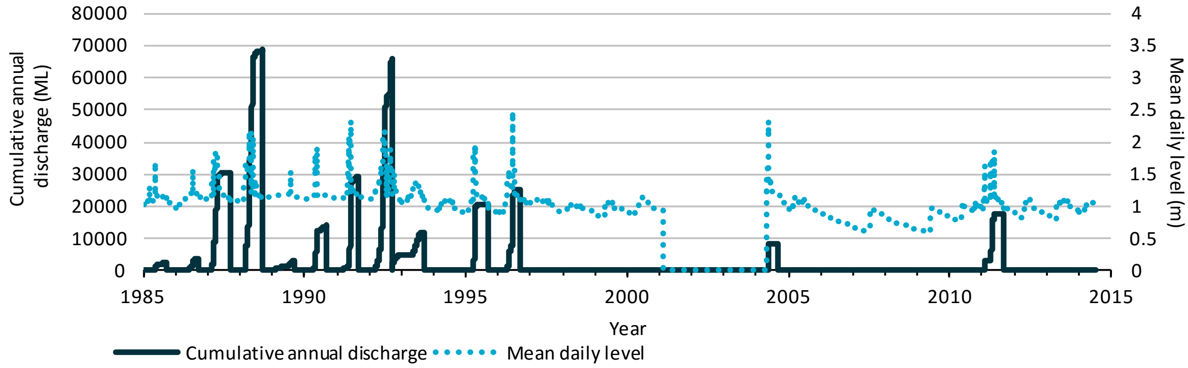


Figure 5.4 Cumulative annual discharge and mean daily surface water level for Drain M

Bool Lagoon

Surface water monitoring for Bool Lagoon is made manually at four different gauge boards in the wetland (Figure 2.3). Monitoring has been carried out by DEWNR for a 28 year period from 1986 to present. However, the data is sporadic especially from 1995 onward (Apx Figure 1). Variations in water level are fairly small. For example, at gauge A2391069, water level varied from 47.70 to 49.04 mAHD between 1986 and 2014 (Figure 5.5). The majority of monitoring within a given year occurs between June and December when winter flows from Mosquito Creek discharge into Hacks Lagoon and then by regulated release into Bool Lagoon. During the latter six months of the year, the water ponded in Bool Lagoon gradually evaporates reducing the area of inundation. The areas near gauge boards tend to dry out early on because the gauge boards are situated close to the outer perimeter (maximum area of inundation). However, following a number of visits to the site, it was observed that remnant pools tend to persist throughout the complex in small areas of low relief, in particular in the manmade channel created towards the southern outlet (Drain M) (Figure 5.6).

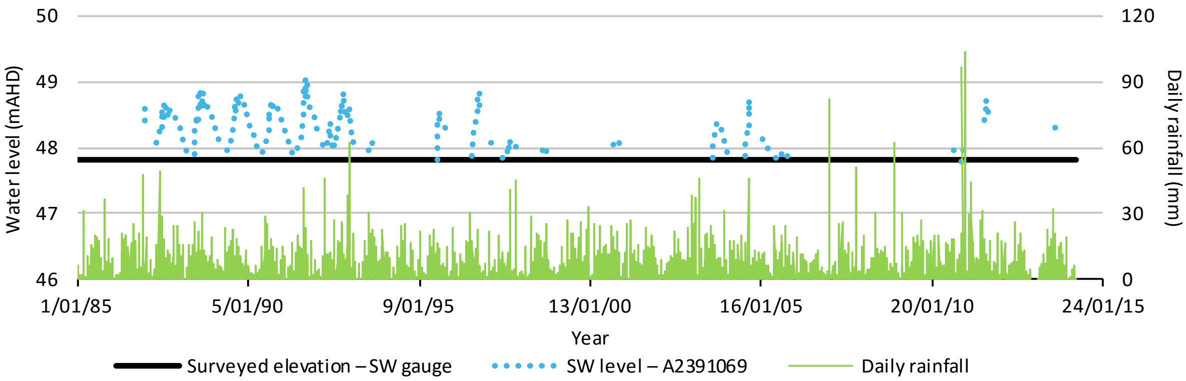


Figure 5.5 Surface water levels and daily rainfall observations for Bool Lagoon

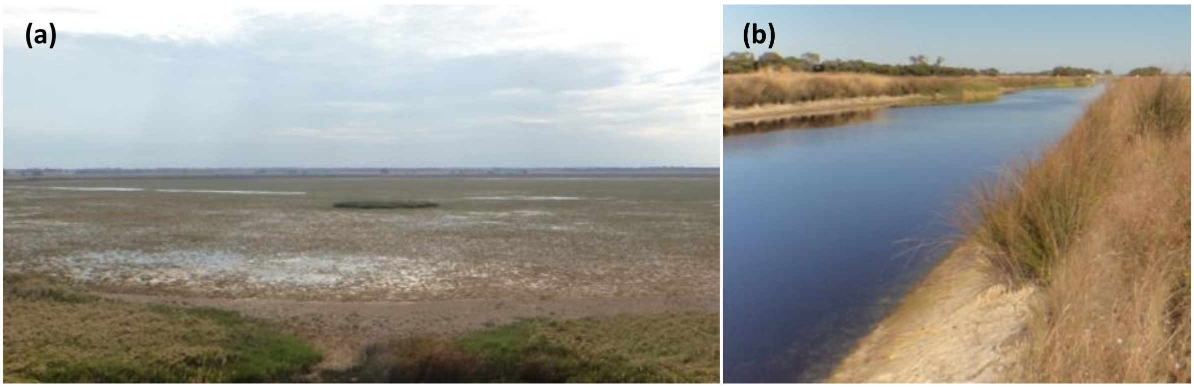


Figure 5.6 Bool Lagoon during March 2014, (a) looking west across the lagoon, (b) looking west up Drain M

5.2.2 LAKE ROBE

Surface water levels in 2010 to 2011 at Lake Robe are summarised in Figure 5.7. The period of monitoring only spans 12 months. Variations in water level range from -2.22 to -1.58 mAHD, or 0.90 m. Subtle temporary increases in the lake water level directly relate to increased rainfall (daily rainfall in excess of 20 mm as in December 2010, January 2011 and February 2011). However, there is a seasonal trend in water level of ~0.30 m. The highest levels tend to occur at the end of spring and the lowest levels at the end of summer (Figure 5.8) similar to the trends in the regional water table in the LLC PWA.

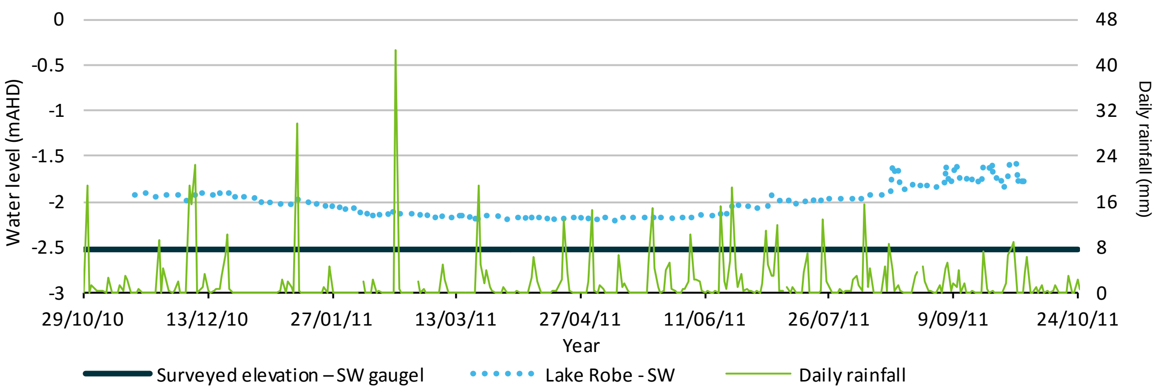


Figure 5.7 Surface water levels and daily rainfall observations for Lake Robe

Figure 5.8 Looking north across Lake Robe during late January 2014

5.2.3 DEADMANS SWAMP

Surface water levels at Deadmans Swamp for 2010 to 2011 are summarised in Figure 5.9. The period of monitoring only spans 12 months, similar to Lake Robe. Variations in water level range from 59.52 to 59.79 mAHD, or ~0.30 m. Small temporary increases in water levels result from increased rainfall (daily rainfall in excess of 90 mm in December 2010 and January 2011).

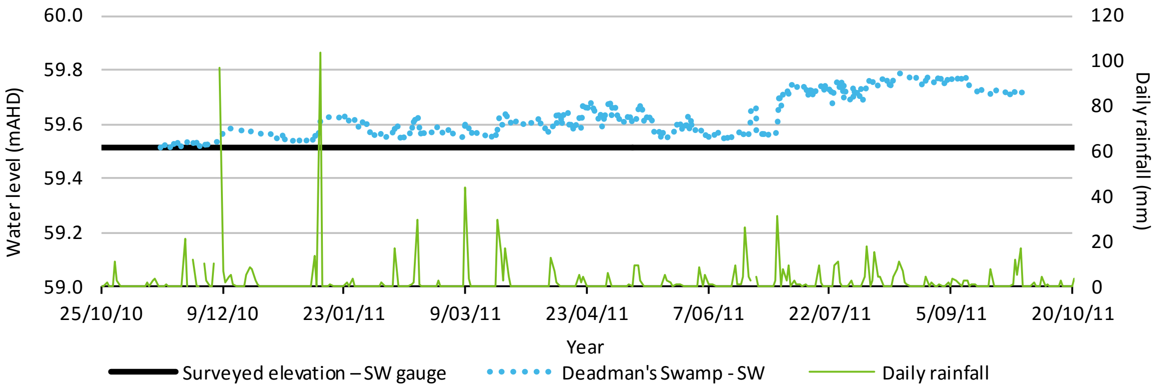


Figure 5.9 Surface water levels and daily rainfall observations at Deadmans Swamp

5.3 Groundwater

5.3.1 BOOL LAGOON – STOCK WELLS

Groundwater levels have been summarised for stock wells, ROB006 and ROB010, 1 and 2 km east of the lagoon and ROB004 and ROB008, 2 and 4 km to the west of the lagoon (Figure 2.3). All four stock wells are assumed to be tapping the unconfined aquifer (TLA) based on their purpose (stock water), depth, yield and chemical parameters (EC and pH), although no lithological data is available for them. All four wells have variations in levels of ~8.3 m, ranging from 42.80 to 51.09 mAHD (Figure 5.10). Site specific variations in levels range from 47.87 to 50.52, 48.50 to 51.09, 42.80 to 46.50 and from 44.87 to 48.54 mAHD for wells ROB006, ROB010, ROB004 and ROB008 respectively. Groundwater pumping at each site appears to induce a maximum drawdown and recovery in levels of up to 2 m, depending on the duration of pumping. The overall trend in groundwater levels for the last 44 years is, decreases of 2, 0.2, 2 and 1 m for ROB006, ROB010, ROB004 and ROB008 respectively.

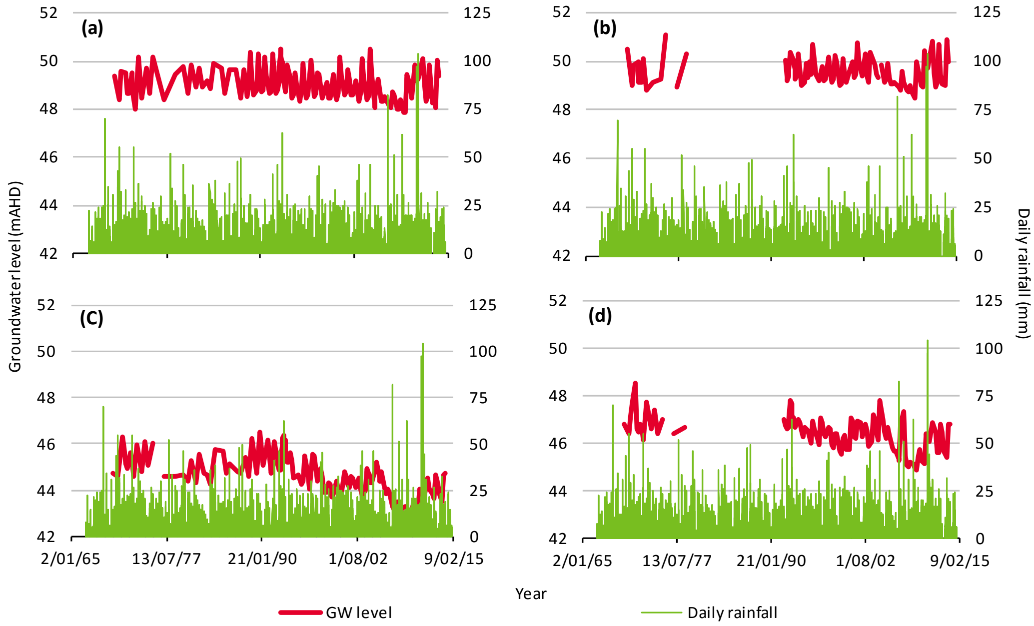


Figure 5.10 Groundwater levels and daily rainfall observations for stock wells ROB006(a) and ROB010(b) on the eastern side and wells ROB004(c) and ROB008(d) on the western side of Bool Lagoon

5.3.2 BOOL LAGOON – MONITORING PIEZOMETERS

Groundwater levels have been summarised for four piezometers on the shoreline of Bool Lagoon. ROB030 is on the eastern side of the main basin, ROB005 is on the western side of the main basin, ROB024 is on the western side of the central basin and ROB026 on the eastern side of the central basin (Figure 2.3). Collectively, all four piezometers have levels that vary between 44.60 to 49.00 mAHD. Site specific variations range from 45.88 to 48.46, 44.60 to 49.38, 46.05 to 48.39 and 46.18 to 48.47 mAHD for wells ROB030, ROB005, ROB024 and ROB026 respectively (Figure 5.11). Annual variations in the water table vary from 1 to 2 m. At the end of the Millennium Drought (van Dijk et al. 2013) the water table was down to 3 m below bed level at some piezometers but, raised in all piezometers to above bed level by the end of 2011 when drought breaking rain occurred. Post 2011, the water table was either slightly above bed level or down to 1 m below. Because of the heavy textured sediments the wetland can still be a groundwater discharge environment when the sediments are saturated due to inundation or when groundwater levels are 1 to 2 m below the bed surface (see Discussion).

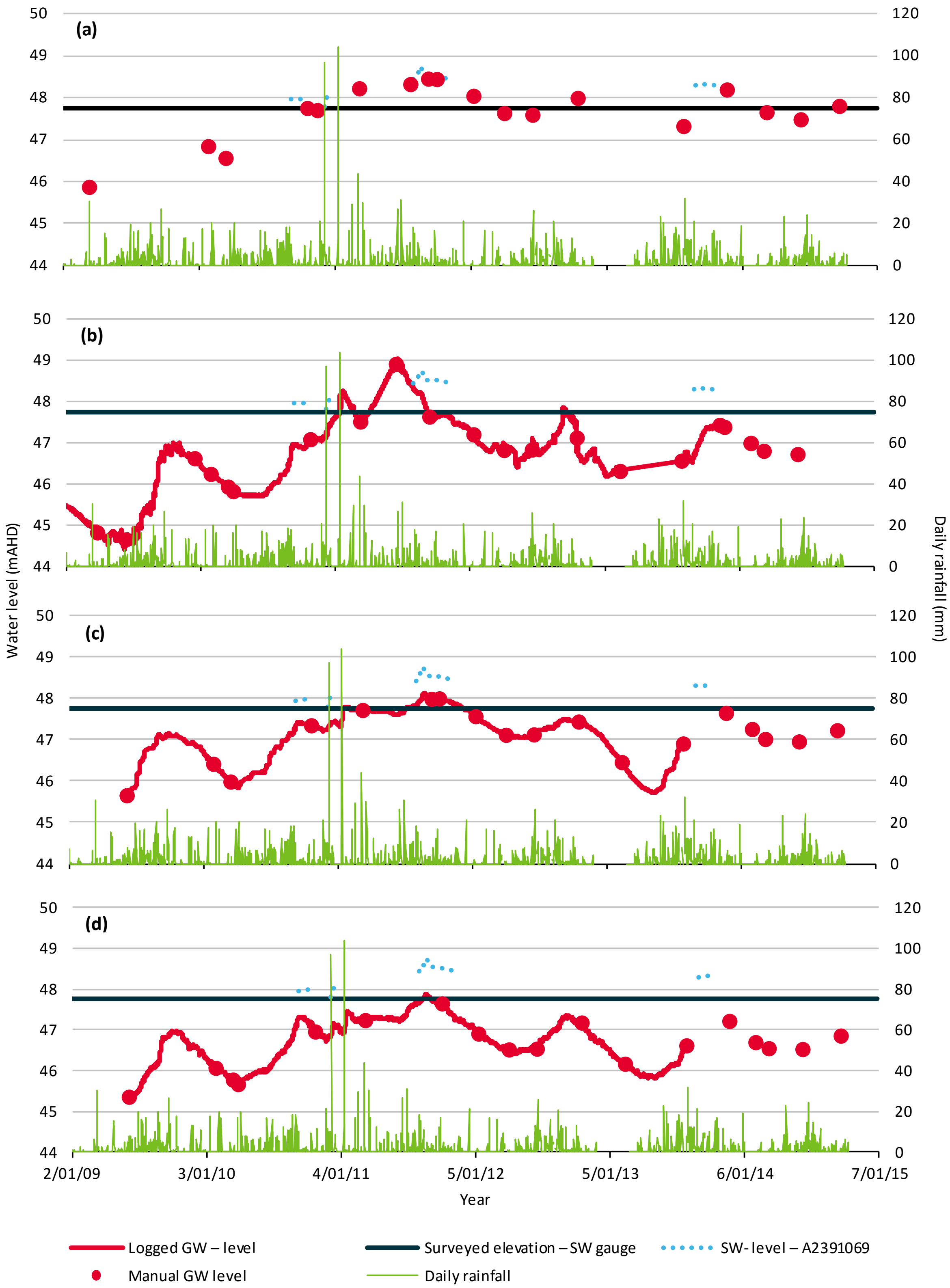


Figure 5.11 Groundwater levels, surface water levels and daily rainfall observations for piezometers (a)ROB030 (east), (b) ROB024 (east), (c)ROB026 (west) and (d)ROB024 within the lagoon complex

5.3.3 LAKE ROBE

Groundwater levels at Lake Robe are summarised in Figure 5.12. The data are from two piezometers, WAT032 in the Robe Range dune system to the west of the lake and WAT034 in the shallow sand aquifer to the east of the lake. Variations in levels for both piezometers range between -2.17 to 0.21 m AHD. Site specific variations for each well range between -0.16 to 0.21 and -2.17 to -1.30 mAHD for WAT032 and WAT034 respectively (Figure 5.12). Thus, in both cases, the lake is gaining groundwater. For example, at WAT032 in the dunes, groundwater levels are predominantly 2 m above surface water levels and in the case of WAT034, groundwater levels are ~0.5 m above lake water levels. One complication when comparing hydraulic heads between the lake and the surrounding groundwater is the much higher salinity in the lake. For example, groundwater salinity in the dune system to the west (WAT032) is fresh ~1.8 dS m^{-1}, whereas groundwater in the sand aquifer to the east (WAT034) is saline ~16 dS m^{-1} and the lake is hypersaline (~100 dS m^{-1}). However, correcting hydraulic heads for density effects (Post et al. 2007) does not alter the trend for Lake Robe being a groundwater discharge environment. The seasonal variations in the water table closely match the variations in the surface water level (Figure 5.12). This suggests Lake Robe is an expression of the water table above the land surface.

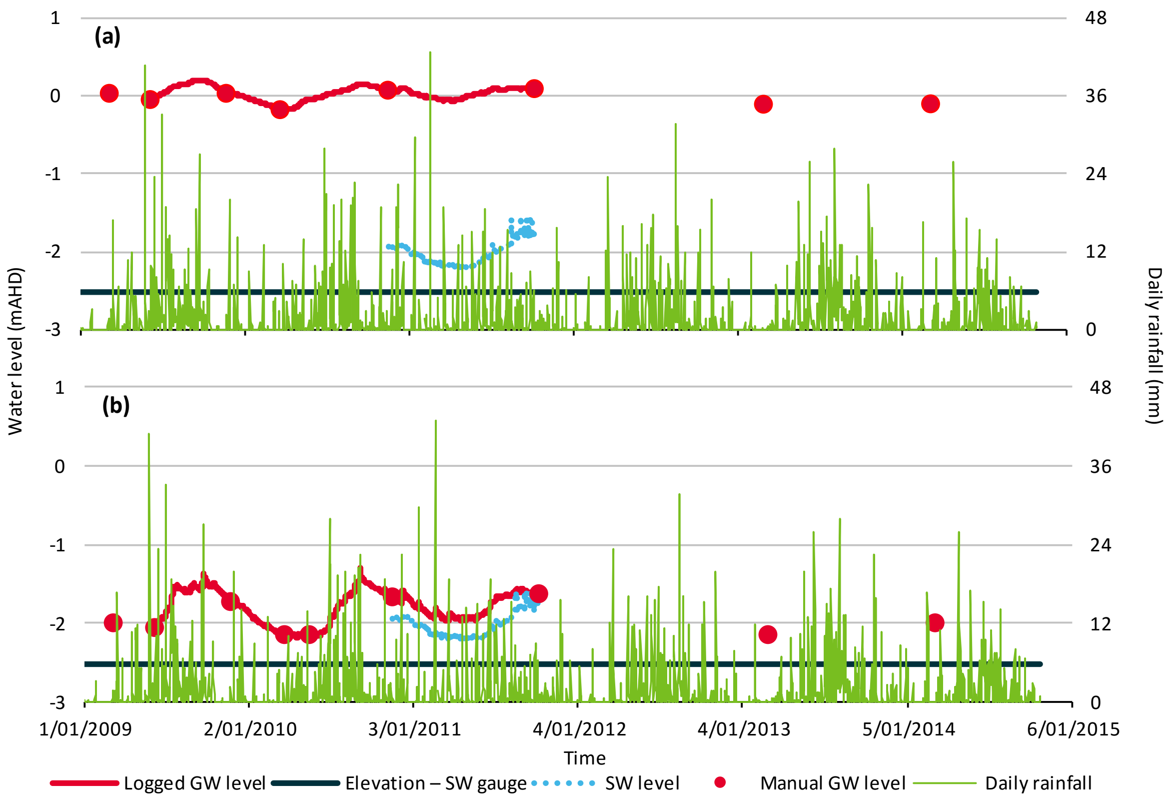


Figure 5.12 Groundwater levels, surface water levels and daily rainfall observations for wells WAT032(a) and WAT034(b) at Lake Robe

5.3.4 DEADMANS SWAMP

Groundwater levels for Deadmans Swamp are summarised in Figure 5.13. Only one piezometer for groundwater observations and lithology exists at the swamp (Figure 2.5). Variations in level range between 57.45 to 59.87 mAHD (Figure 5.13). Unfortunately, there is only 12 months of surface water monitoring at the site but, as part of this study the site was also observed to be dry during several visits in summer and spring in 2014 (Figure 5.14). Because only one piezometer exists at the site, it is not clear if the wetland is predominantly a groundwater recharge or a groundwater flow-through system. However, for a few weeks in 2011, the groundwater level was elevated compared to the surface water level in the swamp.

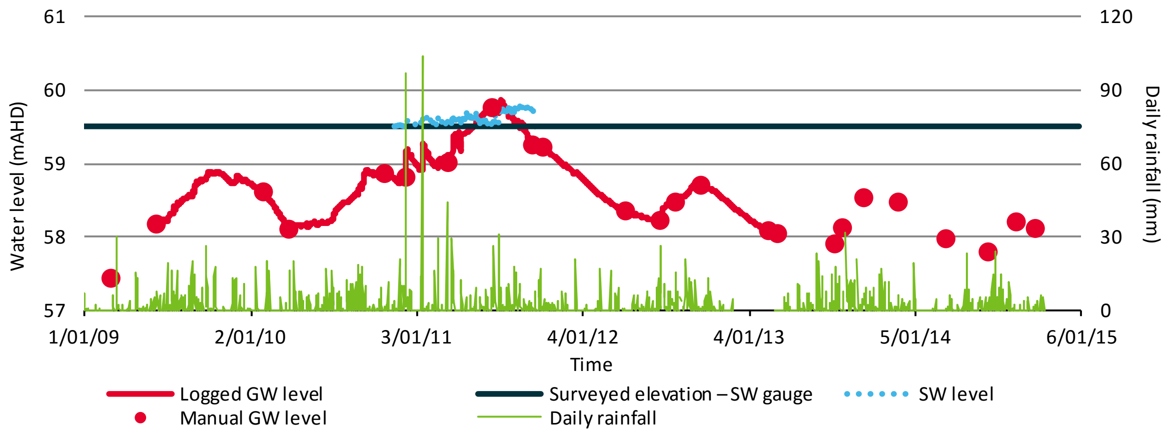


Figure 5.13 Groundwater levels, surface water levels and daily rainfall observations for well JOA027 at Deadmans Swamp

Figure 5.14 Looking north east across Deadmans Swamp during January 2014

5.4 Hydraulic properties of Bool Lagoon bed sediments

5.4.1 HYDRAULIC CONDUCTIVITY

The saturated hydraulic conductivity (K_s) of 15 sediment samples extracted from the bed of Bool Lagoon vary by two orders of magnitude, from $4{\cdot}10^{-8}$ to $9{\cdot}10^{-6}$ m s^{-1} (Figure 5.15;

Apx Table 1). Four of the five samples with the lowest log values for K_s ($\leq 10^{-7}$ m s^{-1}) were extracted from the northeast and central parts of the wetland bed (Figure 4.1) where lithological logs nearby indicate the clay layer is most prominent. The rest of the samples were extracted from the southern parts of the wetland where lithological logs nearby indicate the clay layer is thinner and intermittently changes with depth between clay, marl and limestone. Whilst a silt matrix was present at all sites, coarser material (roots, snail shells, etc) was also present in most cores.

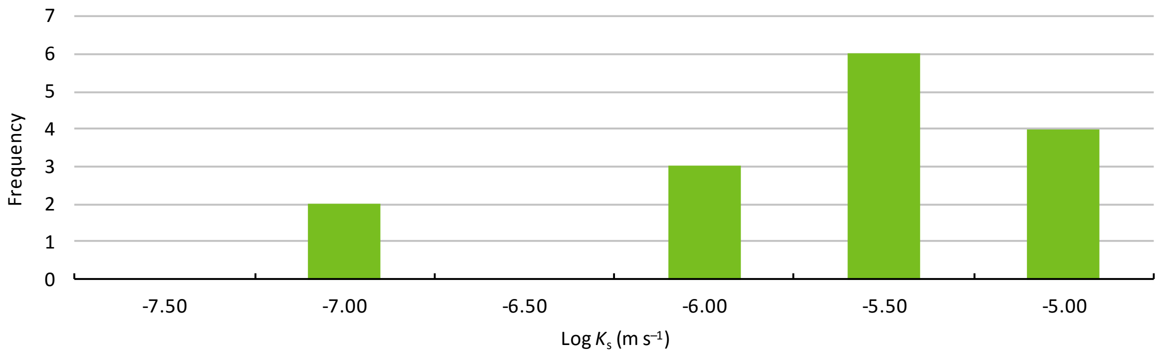


Figure 5.15 Histogram of K_s for sediment samples from the bed of Bool Lagoon

5.4.2 LIKELIHOOD FOR DISCONNECTION AT BOOL LAGOON

Using the criterion from Brunner et al. (2009) and the K_s values measured for Bool Lagoon sediments, the likelihood for disconnection was evaluated using Eq.1. Assuming $K_c(K_s)$ ~10^{-6} m s^{-1}, K_a = 10^{-5} m s^{-1}, h_c = 8 m and d = 1 m, 0.1 ≤ 0.9. While at face value this suggests disconnection is possible, this result is ambiguous considering the large spatial variability in K_c, K_a and h_c at Bool Lagoon. K_c measured here varies from $4{\cdot}10^{-8}$ to $9{\cdot}10^{-6}$ m s^{-1}, K_a values reported in Mustafa and Lawson (2002) and Stadter and Yan (2000) ranges between $9{\cdot}10^{-6}$ to $9{\cdot}10^{-3}$ m s^{-1}, h_c from lithological logs ranges between 4 to 11 m. Nevertheless, the lagoon probably has a low likelihood for disconnection overall, but subsections with finer sediments could maintain remnant pools when the water table drops below ground level.

5.4.3 WATER RETENTION CURVES

Water retention curves were measured for 15 Bool Lagoon sediments because this information is required to inform groundwater models including unsaturated zone processes. The water retention data for each core sample is summarised in Figure 5.16 and

Apx Table 2, the location of each sample is in Figure 4.1. This analysis of volumetric water content versus matric potential, provides a clear indication of the ability of different core samples to retain water over a given range in suctions (matric potentials). These differences directly relate to the clay content and structure within a core sample in particular, the pore size distribution. In other words, the ratio of pores that drain versus the pores that retain water at a given matric potential. In general, the samples with higher volumetric water contents (≥ 0.75) correspond to the samples with lower K_s (Figure 5.15). Overall, the data reflects similar spatial pattern to the K_s data, relating directly to the geographical presence of clay throughout the lagoon complex.

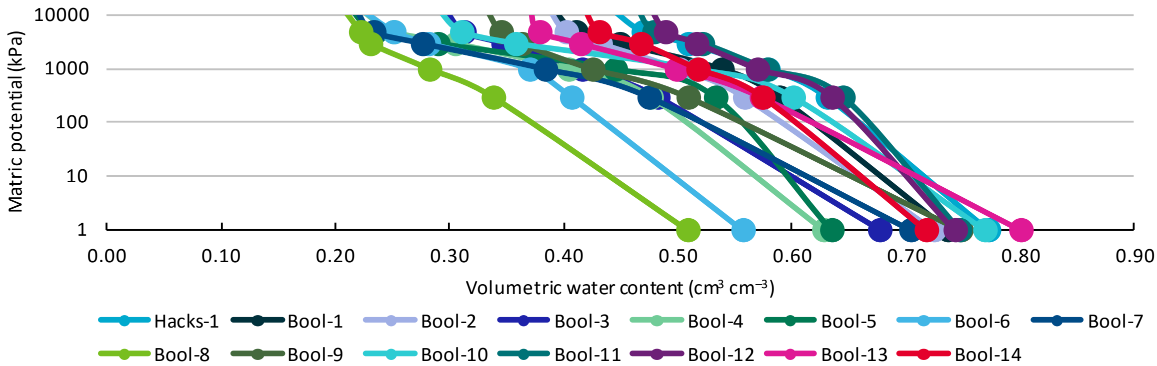


Figure 5.16 Water retention curves for sediment samples from the bed of Bool Lagoon

5.5 Piezometric cross sections – Bool Lagoon

Reconstructing piezometric surfaces around Bool Lagoon proved difficult because of limited overlap in monitoring data between piezometers in the wetland, stock wells around the wetland and the sparse surface water level record. Thus, the evaluation of connectivity focused on one dry year (2009/10) and one wet year (2011/12) where more detailed surface water and groundwater data was available. Piezometric surfaces were constructed for three transects spanning the wetland from north to south (Figure 4.3). It should be stressed that piezometric surfaces do not exactly reflect the true position of the water table. The piezometric surface will tend to be above the water table in discharge areas and below the water table in recharge areas. This is because Bool Lagoon is primarily instrumented with piezometers, which have narrow screens and measure pressure at a specific point in the aquifer. To more precisely measure the position of the free water table requires shallow water level wells, which have wider screens. Ideally, nests of piezometers tapping different sections of the aquifer combined with shallow water table wells should be used to evaluate vertical hydraulic gradients near wetlands (Freeze and Cheery, 1979).

5.5.1 NORTHERN TRANSECT

The Northern transect (Figure 4.3) is a comparison of changes in the piezometric surface ~5 km either side and below Bool Lagoon for a dry year (2009/10) and a wet year (2011/12). This transect (Figure 5.17) extends from the west at ROB004 through ~ 2 km of the main basin of the wetland and further to the east at ROB006. In both cases (dry and wet) the piezometric surface at the transect scale (~10 km) slopes from east to west indicative of the direction of groundwater flow. Furthermore, the two surfaces intersect the bed of the wetland in the east and gently slope just below (dry year) or to the level of the bed (wet year) at the western boundary of the lagoon (ROB025). Further to the west the surface is several metres below bed level at ROB004. Overall, based on the piezometric surfaces, the wetland at the Northern Transect is a *groundwater discharge* zone during dry periods. Whilst the overall slope of the piezometric surface suggests that the wetland could have been a flow-through system, the wetland was dry in 2009/10 so the discharging groundwater along the eastern margin was probably evapotranspired rather than recharged along the western margin. In contrast, the comparison of the surface water elevation and the piezometric surface in 2011/12 shows that the wetland was a *local recharge feature* during the wet period.

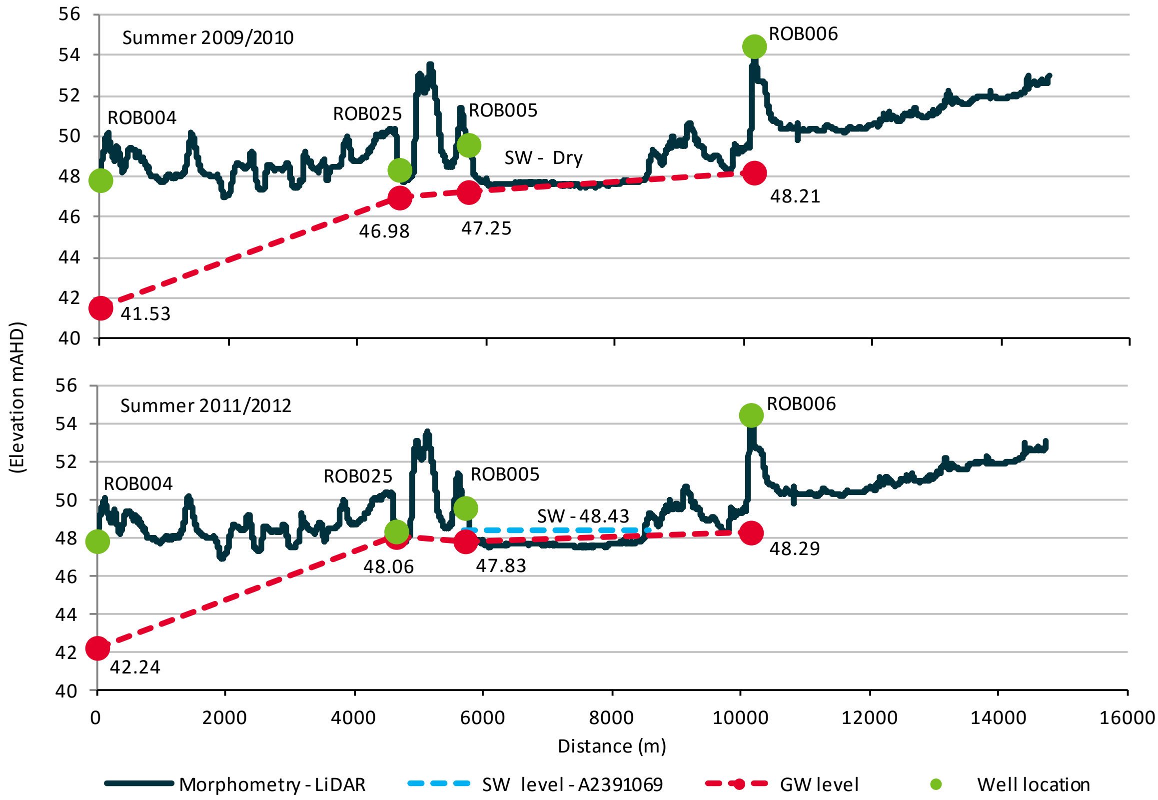


Figure 5.17 Piezometric cross sections for the Northern Transect ROB006 to ROB004.

5.5.2 MIDDLE TRANSECT

Figure 5.18 is a comparison of changes in the piezometric surface for 2009/10 (dry) and 2011/12 (wet) at the Middle Transect (Figure 4.3). This transect extends from the west at ROB022 through ~ 6 km of the central and main basins of the wetland and extends east to ROB031. In 2009/2010 when the wetland was dry, the surface at transect scale (~9 km) was generally sloping from east to west. However, variations in the surface and in hydraulic gradients were less pronounced and more subtle than for the Northern Transect. For example, the surface was 1 m higher than the bed of the wetland in the east (ROB031) and ~2 m below bed level in the west (ROB022). The slope of the piezometric surface at the transect scale was east to west but the piezometric surface was ~1 m below bed level in the dry year and at or just below bed level in the wet year. Overall, the wetland at the Middle Transect was probably a *groundwater discharge* during the dry year but a groundwater *flow-through* in the wet year. Note that, in heavy textured soils and in a semi-arid climate, significant evaporation from the water table is possible even when the water table is 2 -3 m below the ground surface.

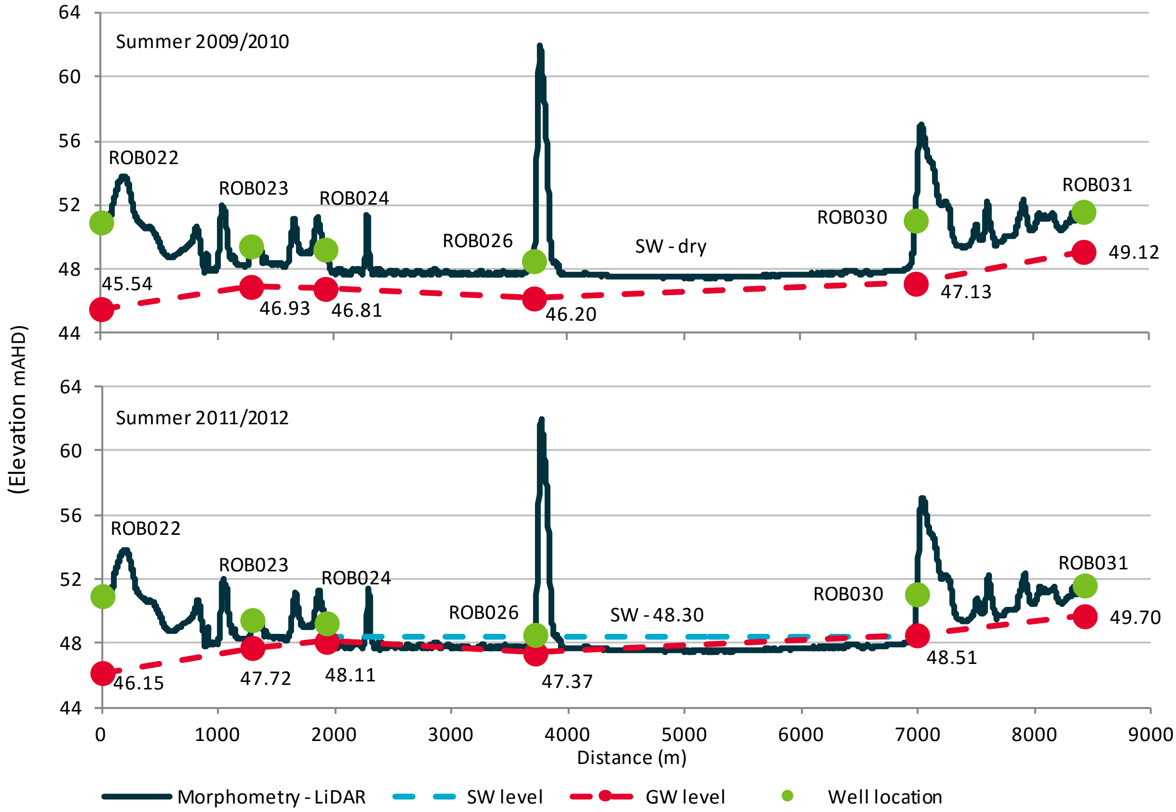


Figure 5.18 Piezometric cross section for the Middle Transect ROB031 to ROB022.southern transect

5.5.3 SOUTHERN TRANSECT

Figure 5.19 is a comparison of changes in the piezometric surface for 2009/10 (dry) and 2011/12 (wet) at the Southern Transect. This transect extends from ROB008 in the west through ~2 km of the western basin of the wetland to JOA026 ~12 km east of the wetland. The piezometric surface in both 2009/10 (dry) and 2010/11 (wet) slopes from east to west and has a groundwater mound below the western basin of the wetland. Thus, in the vicinity of Drain M the wetland is a *local recharge feature* but, further away in the floodplain, may be a groundwater *discharge zone* (either by plant transpiration or water table evaporation).

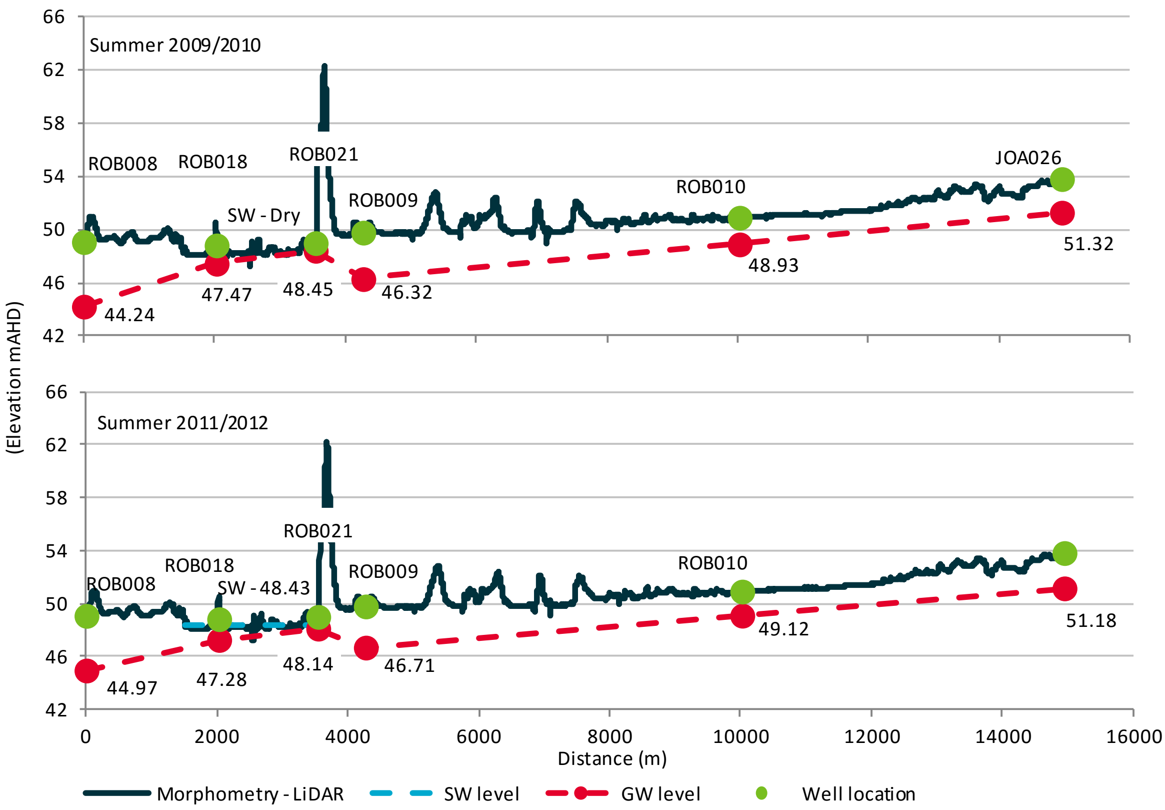


Figure 5.19 Piezometric cross section for the Southern Transect JOA026 to ROB008

5.6 Water balance

5.6.1 STAGE – SURFACE AREA RELATIONSHIPS

LiDAR data were used to develop estimates of inundation and volume for a given range of wetland stage heights. From analysis of gauge board data, it was found that the wetland stage heights at Bool Lagoon typically varied between 47 and 49 m AHD. Spatial analysis methods were used to identify the inundated area and volume of the Bool Lagoon wetland complex at 0.1 metre intervals, a subset of those results are shown in Figure 5.20.

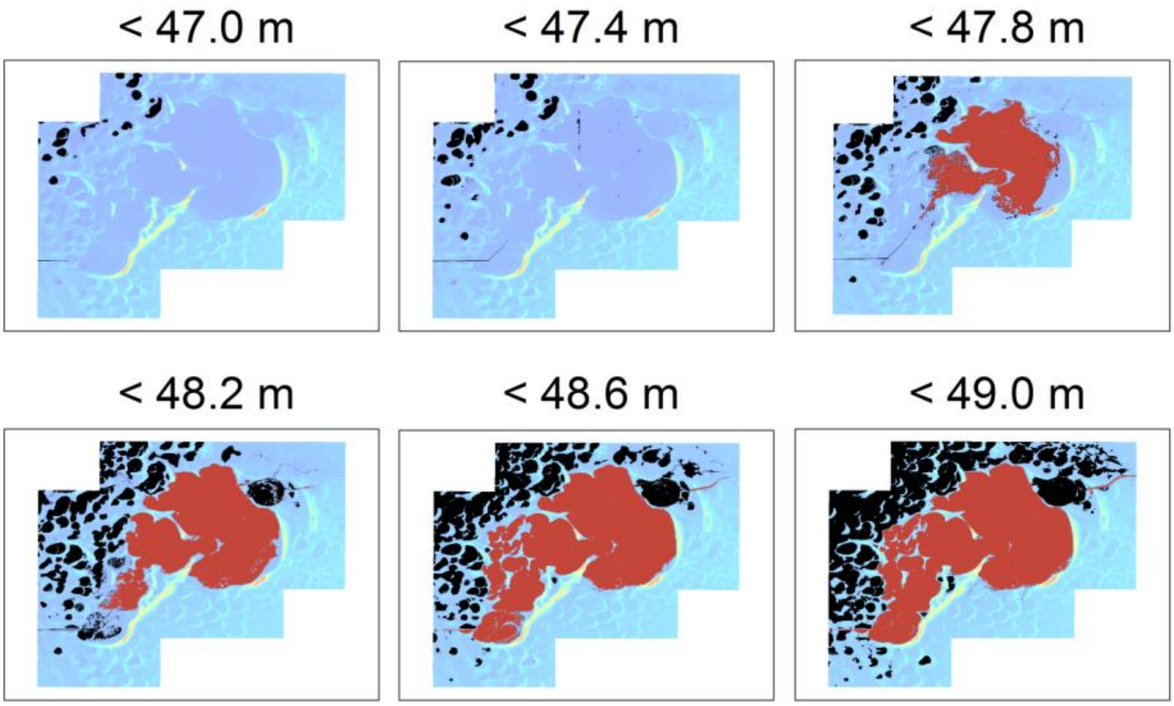


Figure 5.20 Spatial analysis highlighting changes to the area of inundation (red) for a subset of different wetland stage heights in Bool Lagoon, surrounding wetlands (black) were excluded.

Relationships were derived between wetland stage height and both the volume and area of Bool Lagoon (Figure 5.21).

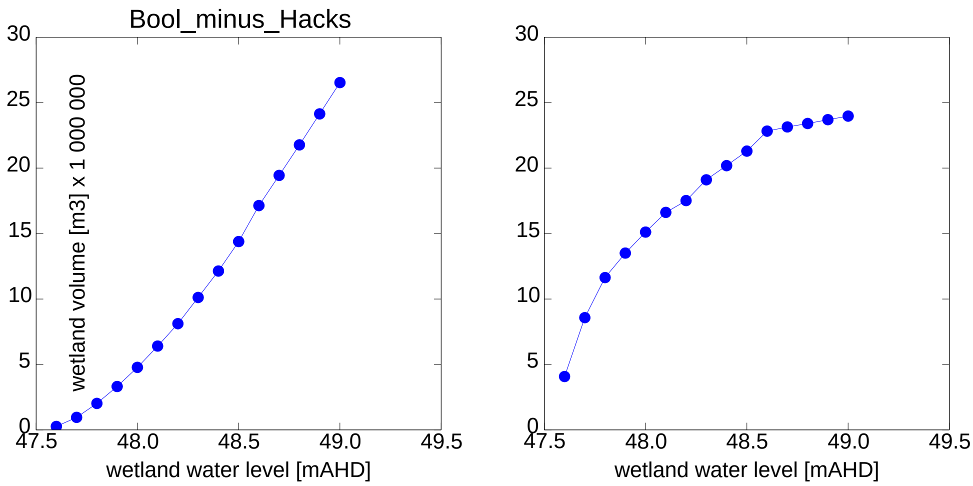


Figure 5.21 Estimated inundated area and volume of Bool Lagoon for stage heights 47-49 m AHD, as based on LiDAR data

5.6.2 MORPHOMETRY

LiDAR imagery was used to evaluate the cross-sections for the wetlands (Figure 5.22). Note that the four Lake Robe profiles feature significant interpolation between data points; this is due to the presence of surface water during LiDAR acquisition, preventing the accurate surveying of wetland morphometry. The areal extent of both Deadmans Swamp and Lake Robe is generally 1-2 km, whereas Bool Lagoon is approximately 5 km wide and approximately 9 km in length (north east–south west). The maximum depth of both Bool Lagoon and Lake Robe is approximately 1–3 m, whereas Deadmans Swamp is up to eight metres deep (assuming it were fully inundated) however, currently it is generally dry. Overall, the three wetlands are flat and shallow but can be steep-sided due to the presence of lunettes and sand dunes along their margins.

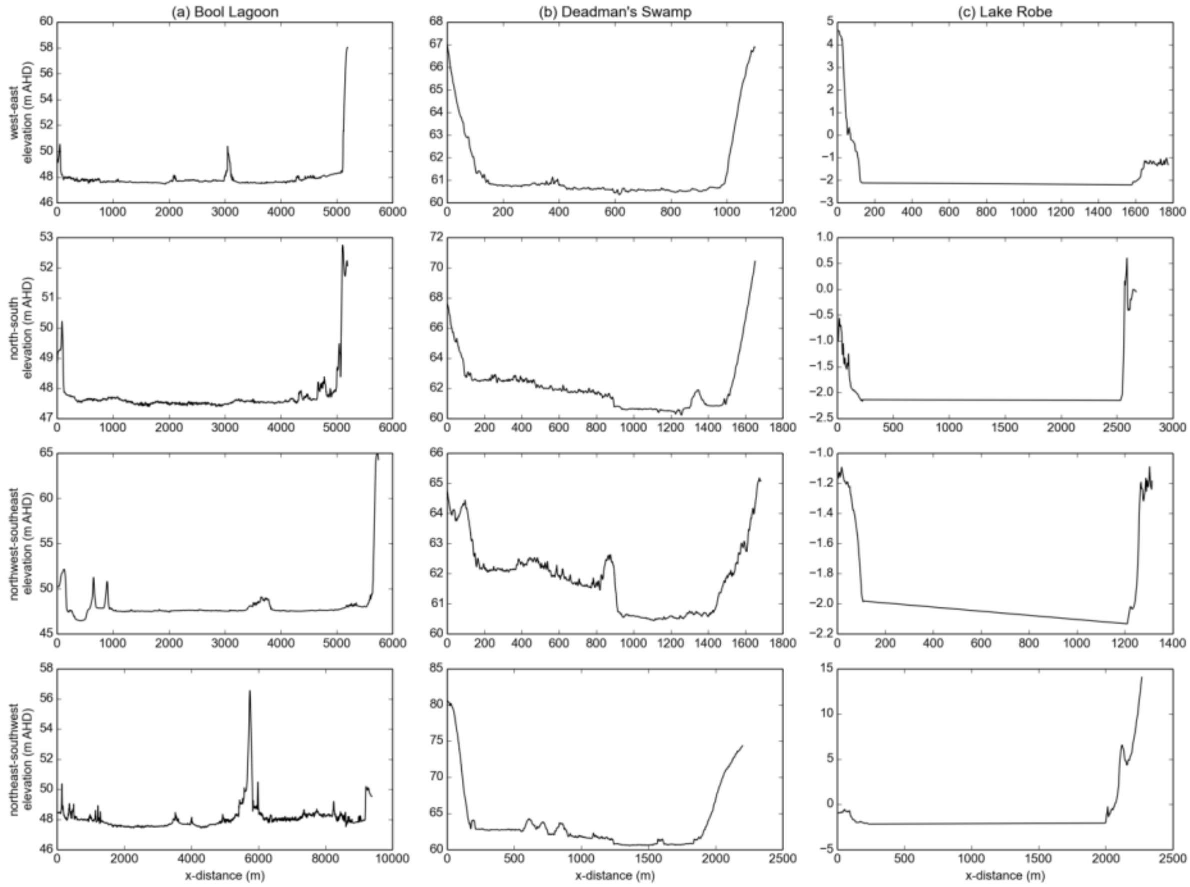


Figure 5.22 LiDAR-based morphometric cross sections for (a) Bool Lagoon, (b) Deadmans Swamp and (c) Lake Robe. Note that Lake Robe profiles feature significant interpolation between data points.

5.6.3 WATER BALANCE ANALYSIS – BOOL LAGOON

Two different periods were considered in the water balance for Bool Lagoon, where the drain components were vastly different. Firstly, from 1987 to 1996 (or 'wet' period) where there were large annual drain inflows (D_{in}) and drain outflows (D_{out}). During the wet period, D_{in} varied between 4500 and 67900 ML year^{-1}, whilst D_{out} varied between 0 (1994 only) and 68600 ML year^{-1} (Figure 5.23). Secondly, from 1997 to 2011 (or 'dry' period) where annual drain inflows were lower and drain outflows only occurred occasionally. During the dry period, D_{in} varied between 0 and 34900 ML year^{-1}, whilst D_{out} varied between 0 and 17400 ML year^{-1}, there were no outflows in 11 of the 15 years. A summary of the annual data for each component can be found in

Apx Table 3. Overall, during the wet period, $D_{in} > P$ and $D_{out} \geq E + ET_{sed}$, conversely, during the dry period, $P > D_{in}$ and $E + ET_{sed} > D_{out}$. G_{net} varied between negative (net groundwater inflow) to positive (net groundwater outflow) during both periods, but overall, G_{net} was ~ -7000 ML year^{-1} and ~ -9000 ML year^{-1} for the wet and dry periods, respectively. Whilst this water balance undoubtedly has a large uncertainty due to the assumptions used (especially to evaluate E), it suggests that Bool Lagoon is predominantly a groundwater discharge zone. This tendency was more pronounced between 1997 and 2011 because low drain inputs limited local recharge.

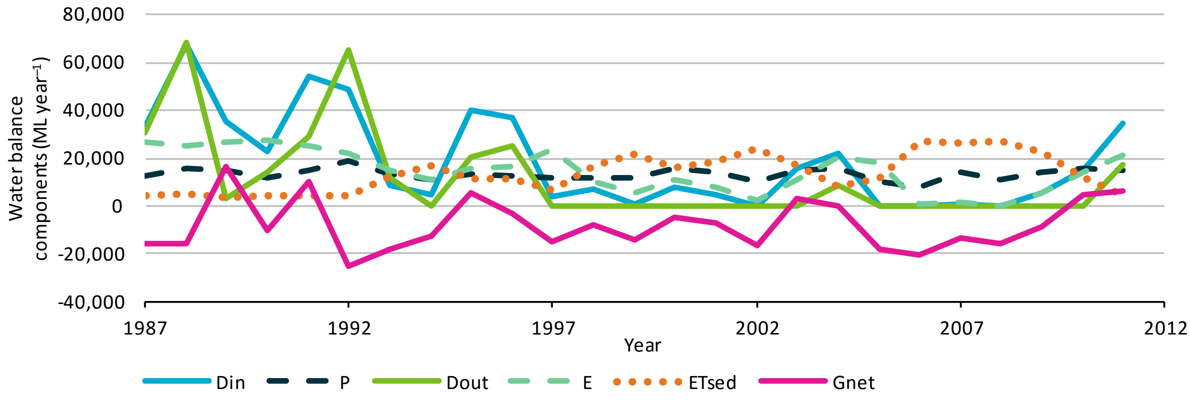


Figure 5.23 Summary of the components of the water balance for Bool Lagoon.

6 Discussion

6.1 Review of connectivity

The aim of this data review and companion environmental tracer field study (Smith et al., 2015) was to evaluate the groundwater – surface water connectivity for three South East wetlands. At the regional scale, the wetlands were located in hypothesized recharge (Deadmans Swamp), flow-through (Bool Lagoon) and discharge zones (Lake Robe). Combining all lines of evidence, it can be concluded that South East wetlands are part of both local and regional flow systems. The connectivity at Bool Lagoon was different than anticipated – this wetland is located in a major regional discharge rather than in a flow –through zone, as shown by the piezometric surface, water balance and environmental tracer analyses, and recent regional groundwater modelling (Figure 6.1). The Bool Lagoon complex is part of a discharge zone for a significant intermediate-scale groundwater flow system (Figure 6.1) but, during wet periods, is also a local recharge feature for the TLA. The Bool Lagoon wetland complex is probably an example of a Boinka – a semi-arid landscape shaped by being located in a major regional groundwater discharge zone (Macumber, 1991). Regional topography (toe of the Kanawinka Scarp) and subsurface control of regional groundwater flow (Kanawinka Fault?) are hypothesised to have generated the Bool Lagoon Boinka.

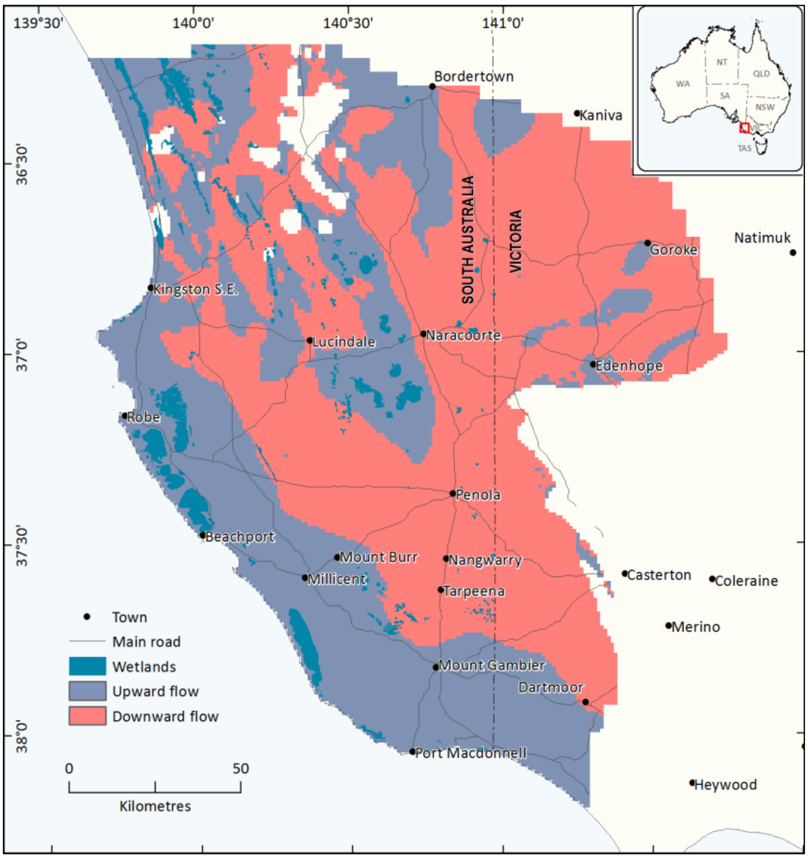


Figure 6.1 Estimated areas of upward (purple) and downward (red) groundwater flow, based on vertical velocity vectors derived from the steady state regional scale groundwater flow model (L. Morgan, unpublished data).

Groundwater – surface water connectivity at Lake Robe was also slightly different than anticipated. This wetland is a discharge feature but primarily for a local coastal sand dune aquifer. Thus, Lake Robe can be characterised as a local groundwater discharge wetland within a regional discharge zone. Further evaluation of connectivity at Deadmans Swamp will require the installation of a more comprehensive monitoring network. Based on the available evidence, the water table regime at Deadmans Swamp is consistent with a wetland located in a regional recharge environment. However, the local-scale connectivity could be different (flow-through, etc) than the regional one because Deadmans Swamp is surrounded by a significant aeolian dune system.

The scale(s) of connectivity for a groundwater-dependent wetland must be understood because management intervention at the wrong spatial scale may not yield the desired outcomes. This will be especially true for problems such as wetland salinity, which will evolve at very different time-scales whether they are locally or regionally-driven. This concept is widely used, for example, for River Murray floodplains impacted by salinity, where different management strategies are used to control local and regional sources of groundwater salinity (Jolly and Walker, 1996).

6.2 The six factors controlling groundwater – surface water connectivity in South East wetlands

Combining evidence from this study and other sources, we propose that a combination of six regional or local-scale factors determine the wetland-groundwater connectivity in South East wetlands. This scheme is aimed at small, shallow wetlands such as deflation basins rather than those associated with karst features in the region. However, wetlands associated with karst features should share many of the attributes of shallower wetlands, at least for factors operating at the regional scale. The three regional-scale factors are:

1) Landscape position (regional recharge, flow-through and discharge zones);
2) Topography (that is, the increased likelihood to generate local flow systems in hummocky terrain);
3) Subsurface control (faults, shallow bedrock, etc);

And the three local-scale factors are:

4) Presence or absence of surface water runoff;
5) Presence or absence of a clogging layer at the wetland-aquifer interface;
6) Wetland morphometry.

These are reviewed in more detail in the following.

6.2.1 LANDSCAPE POSITION

Groundwater-dependent wetlands in the South East can be classified according to their location in the landscape, that is, whether they are located in regional groundwater recharge, flow-through, or discharge zones (Webster et al., 1996); Figure 6.2). Regional recharge areas tend to have the more variable water tables at seasonal and longer time scales (Figure 6.3). As a consequence, wetlands in recharge areas will be more likely to be seasonally ephemeral and will be more susceptible to drying during drought periods (i.e. Deadmans Swamp). In a semi-arid climate, they will also tend to be among the freshest wetlands in the landscape. At the other end of the spectrum, the water table in regional groundwater discharge zones tends to be less variable than in recharge areas (Figure 6.3). As a consequence, wetlands will be more likely to be perennial and less likely to dry during droughts (i.e., Lake Robe). However, wetlands in discharge environments will tend to be the most saline.

Wetlands in regional flow-through zones are likely to be intermediate in water level regime variability and salinity between regional discharge and recharge environments. In the case of Bool Lagoon, the high variability in water levels and salinity are the result of surface runoff and the presence of a clogging layer. In the nearby southwest Murray Basin, one of the consequences of regional groundwater flow-through wetlands is a gradual increase in groundwater salinity downgradient (Macumber, 1991).

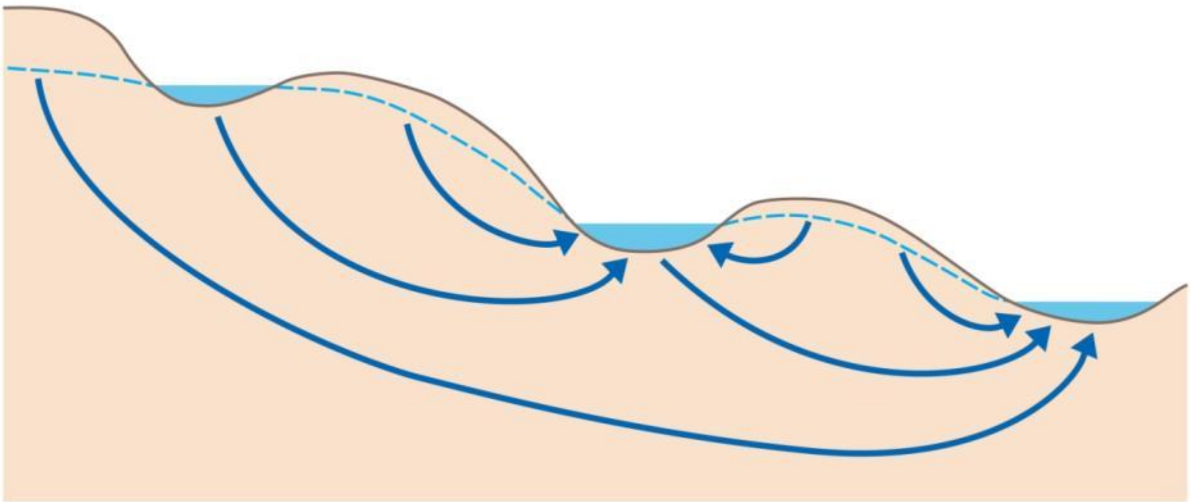


Figure 6.2 Conceptual representation of a regional groundwater flow system, showing the location of a wetland in a regional recharge (left), flow-through (middle) and discharge zone (right).

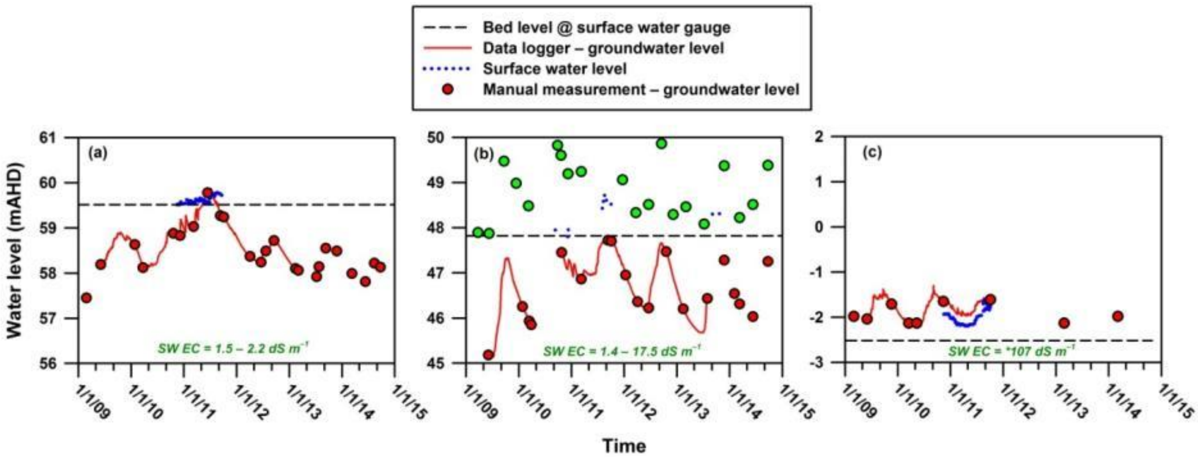


Figure 6.3 Seasonal water table variations and surface water salinity at (a) Deadmans Swamp, (b) Bool Lagoon and (c) Lake Robe

6.2.2 TOPOGRAPHY

The relative importance of regional and local groundwater flow systems in a landscape is strongly controlled by topography (Figure 6.4). Where the landscape slope is steep and the surface relief is 'smooth', regional flowpaths are more likely; when the landscape is flat and the relief is hummocky, local flow systems will be common (Freeze and Witherspoon, 1967). In the context of the LLC PWA, the low landscape slopes and the presence of extensive dune systems suggest that local flow systems will be significant. Breaks in slopes, such as at the foot of the Kanawinka Scarp, can also contribute to the formation of groundwater discharge areas.

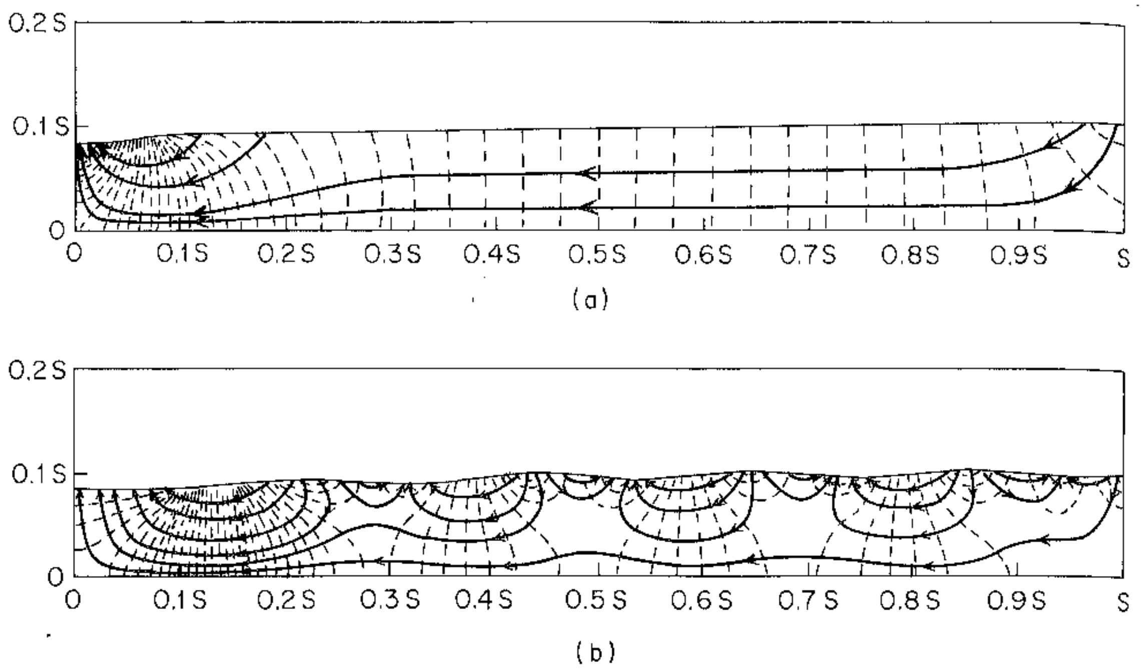


Figure 6.4 Effect of topography on the development of local and regional flow systems (from Freeze and Cherry 1979, based on Freeze and Whiterspoon 1967).

6.2.3 SUBSURFACE CONTROL

Depth to bedrock, faults and the saltwater wedge at the seawater/freshwater interface along coastlines can all affect the development of hydrogeological flow systems (Figure 6.5). In the South-East context, depth to bedrock is shallower in the north than the south of the LLC PWA, which will tend to favour the development of local flow systems in the north. The potential role of faults in the hydrogeology of the region is reviewed in Harrington and Lamontagne (2013). Briefly, it is generally thought that major faults in the region impede horizontal groundwater flow in the TLA (due to aquifer constriction). This could, in turn, generate groundwater discharge zones when horizontal flow impedance results in the development of a vertical groundwater flow component (Figure 6.5). Bedrock control of groundwater flow induced by the Kanawinka Fault may be a key factor that has concentred regional groundwater discharge in the vicinity of Bool Lagoon and led to the formation of the Bool Lagoon Boinka.

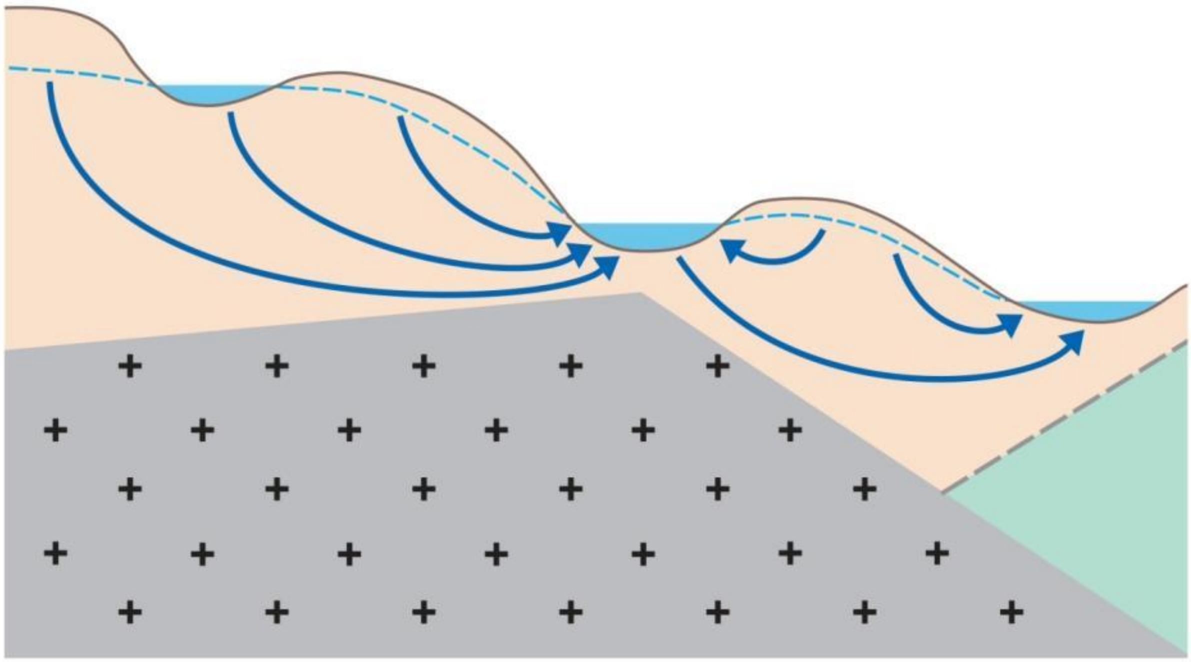


Figure 6.5 Conceptual representation of a regional flow system showing the potential impact of a bedrock intrusion (grey) or the saltwater wedge (green) on regional groundwater flow.

6.2.4 SURFACE RUNOFF

Many wetlands in the LLC PWA are part of significant, often man-made, surface water drainage systems (i.e. Bool Lagoon) and others are not (i.e. Lake Robe). The drainage system in the region is either designed to lower saline water tables (north) or to alleviate waterlogging (south), hence surface water drainage will vary in salinity. Surface runoff tends to be episodic, with much of the flow occurring in late winter and early spring. Wetlands receiving significant surface water runoff probably have the most variable water level regimes in the region for example, Bool Lagoon; (Figure 6.3). As many LLC PWA wetlands have regulated inlets and outlets, surface runoff is a key management lever for South East wetlands.

6.2.5 CLOGGING LAYER

Clogging layers can be any geological or biological (algal mats, etc) porous media with a lower hydraulic conductivity than the surrounding aquifer. In the South East context, clay layers in wetland sediments are probably the most common type of clogging layer. A clogging layer is a necessary condition for the development of 'perched' (or losing-disconnected) wetlands, when an inundated wetland sits above an unsaturated zone (Brunner et al. 2009). Without a clogging layer, the wetland simply dries out once the water table drops below bed level. For management purposes, knowing which wetland can become perched is necessary because, once perched, they will not respond to managed changes in the water table until the latter raises to bed level again. The presence and extent of clogging layers (and local geology in general) are not known for most LLC PWA wetlands. However, by collating data relating to the physical properties of the bed, local geology and underlying aquifer, as has been done here for Bool Lagoon, a simple assessment of connectivity can be made. Lamontagne et al. (2014) propose a simple field based approach using augered profiles through riverbeds and sediment pits on river banks, to assess disconnection in the field for semi-arid rivers, this type of approach could also be adapted to semi-arid wetlands.

6.2.6 WETLAND MORPHOMETRY

The shape of a wetland can have a significant influence on its groundwater – surface water connectivity. Most deflation basin and interdunal wetlands are relatively flat and shallow – meaning that small variations in water table elevation can result in large changes in surface area inundated. How incised the wetland is in the landscape has a strong impact on its water level regime. For example, in the Bool Lagoon Complex/Boinka, the main basins of Bool Lagoon have an ephemeral water level regime (wet in winter and spring, dry in summer). In contrast, nearby Little Bool Lagoon is perennial. The main difference between the two water bodies is that Little Bool lagoon is more incised (~2 m deeper) and intersects the water table throughout the year. Similarly, Lake Robe is located at the lower end of a regional elevation gradient and although it is only incised by a few metres, it is enough to intersect the water table year round.

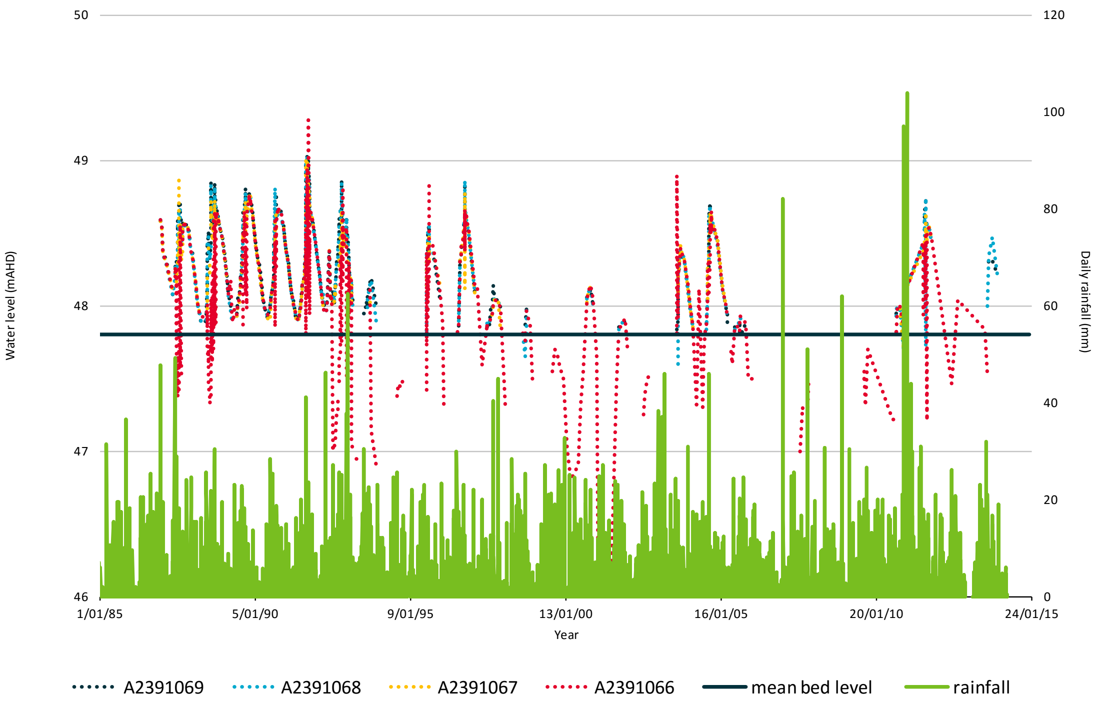
7 Conclusions

This study has provided a better understanding of groundwater – surface water connectivity for three LLC PWA wetlands. Among its findings, it proposes that the Bool Lagoon Complex is a Boinka – a system of wetlands that was created by the occurrence of a major groundwater discharge zone over a long period. The study also demonstrated why there are different scales of wetland – groundwater interaction in the region. These must be understood because management interventions aiming to preserve the ecological integrity of wetlands may not achieve their objectives if they are targeted at the wrong scale. Whilst it is not practical to study groundwater – surface water interactions in detail for the thousands of wetlands in the LLC PWA, hydrogeological subregions based on regional-scale factors (landscape position, topography and subsurface control) could be defined and assessments made at that scale (Turnadge and Lamontagne, 2015).

The main challenge in understanding groundwater – surface water interactions for LLC PWA wetlands is the sparse temporal monitoring for surface water and groundwater levels near a given wetland. Hence, the inability to generate water balance estimates and construct piezometric surfaces for Deadmans Swamp and Lake Robe. As preserving the ecological integrity of groundwater-dependent wetlands is one of the management objectives for sustainable use of groundwater resources in the region, temporal variations in wetland surface water levels must be monitoring continuously at selected locations in the future. Because of the likelihood for strong vertical hydraulic gradients near some wetlands, piezometer monitoring networks should be installed in nests (that is, with two or more piezometers at the same location but with screens at different depths) and include a shallow water well to measure the position of the water table (Freeze and Cheery, 1979).

In the short-term, the lack of historical surface water level monitoring for South East wetlands could be addressed with an analysis of remote sensing data, which can go as far back as the 1970s. Deane et al. (2015) provide an example for how remote sensing can be used to evaluate variation in inundation for South East wetlands.

Appendix A



Apx Figure 1 Surface water levels from all gauge boards and daily rainfall observations for Bool Lagoon.

Apx Table 1 Hydraulic conductivity data for Bool Lagoon bed sediments

SAMPLE ID	BULK DENSITY ($g\ cm^{3-1}$)	FIELD VOLUMETRIC WATER CONTENT ($cm^3\ cm^{3-1}$)	Ksat ($m\ s^{-1}$)	GROUNDWATER SALINITY–SEDIMENT PIT ($dS\ m^{-1}$)
Hacks-1 - Ksat	0.72	0.75	2.6E-06	5.50
Bool-1 - Ksat	0.72	0.68	3.9E-08	7.25
Bool-2 - Ksat	0.80	0.72	2.6E-06	13.98
Bool-3 - Ksat	0.92	0.67	3.0E-06	17.52
Bool-4 - Ksat	1.07	0.61	5.2E-07	19.20
Bool-5 - Ksat	1.02	0.64	1.5E-06	8.65
Bool-6 - Ksat	1.10	0.60	8.8E-06	–
Bool-7 - Ksat	0.81	0.72	3.2E-06	20.34
Bool-8 - Ksat	1.47	0.50	7.3E-06	20.41
Bool-9 - Ksat	0.62	0.77	4.0E-06	10.73
Bool-10 - Ksat	0.59	0.80	4.3E-07	8.38
Bool-11 - Ksat	0.79	0.73	6.9E-07	5.90
Bool-12 - Ksat	0.76	0.74	7.9E-08	8.93
Bool-13 - Ksat	0.61	0.76	1.9E-06	8.05
Bool-14 - Ksat	0.84	0.69	2.7E-06	7.48

Apx Table 2 Water retention data for Bool Lagoon bed sediments

SAMPLE ID	BULK_DENSITY (g cm$^{3-1}$)	VOLUMETRIC WATER CONTENT - cm^3 cm$^{3-1}$					
		0 (kPa)	100 (kPa)	300 (kPa)	1000 (kPa)	3000 (kPa)	1500 (kPa)
Hacks-1 - Water Ret	0.68	0.772	0.631	0.579	0.509	0.470	0.440
Bool-1 - Water Ret	0.73	0.737	0.589	0.539	0.449	0.411	0.390
Bool-2 - Water Ret	0.77	0.725	0.559	0.501	0.432	0.402	0.386
Bool-3 - Water Ret	0.89	0.677	0.482	0.416	0.347	0.312	0.295
Bool-4 - Water Ret	1.02	0.628	0.476	0.404	0.305	0.251	0.218
Bool-5 - Water Ret	0.99	0.635	0.533	0.445	0.290	0.235	0.212
Bool-6 - Water Ret	1.10	0.557	0.407	0.370	0.281	0.251	0.218
Bool-7 - Water Ret	0.82	0.704	0.475	0.384	0.276	0.233	0.217
Bool-8 - Water Ret	1.49	0.509	0.338	0.282	0.231	0.222	0.205
Bool-9 - Water Ret	0.70	0.748	0.509	0.425	0.363	0.345	0.332
Bool-10 - Water Ret	0.68	0.769	0.601	0.516	0.358	0.311	0.288
Bool-11 - Water Ret	0.79	0.747	0.645	0.578	0.522	0.479	0.463
Bool-12 - Water Ret	0.76	0.743	0.635	0.570	0.516	0.489	0.475
Bool-13 - Water Ret	0.62	0.801	0.573	0.499	0.415	0.379	0.372
Bool-14 - Water Ret	0.81	0.718	0.574	0.518	0.467	0.431	0.417

Apx Table 3 Annual components of the water balance for Bool Lagoon

YEAR	INFLOW (ML YR^{-1})	PRECIPITATION (ML YR^{-1})	TOTAL INFLOW (ML YR^{-1})	OUTFLOW (ML YR^{-1})	EVAPORATION (ML YR^{-1})	PET (ML YR^{-1})	TOTAL OUT (ML YR^{-1})	NET (ML YR^{-1})
1987	33,039	12,348	45,387	30,694	26,672	4,165	61,531	-16,144
1988	67,918	15,868	83,786	68,615	25,364	5,426	99,404	-15,619
1989	35,375	14,974	50,349	2,928	27,072	3,749	33,749	16,600
1990	22,767	12,113	34,881	13,840	27,229	4,002	45,071	-10,190
1991	54,012	15,141	69,153	29,373	25,292	4,529	59,193	9,960
1992	48,554	18,915	67,470	65,748	22,099	4,683	92,531	-25,061
1993	8,680	13,005	21,685	11,817	15,092	12,595	39,505	-17,820
1994	4,528	10,821	15,349	0	10,873	17,014	27,886	-12,537
1995	40,032	13,405	53,437	20,637	15,979	11,538	48,155	5,283
1996	37,166	12,902	50,068	25,144	16,497	11,469	53,109	-3,041
1997	3,551	11,940	15,492	8	23,532	6,801	30,342	-14,850
1998	7,031	11,974	19,005	0	10,031	17,005	27,036	-8,031
1999	775	11,612	12,387	0	5,378	21,563	26,941	-14,554
2000	7,851	15,396	23,246	112	11,399	16,377	27,887	-4,640
2001	5,035	13,967	19,002	0	7,545	18,491	26,037	-7,035
2002	175	10,440	10,615	0	2,647	24,147	26,793	-16,179
2003	15,778	15,300	31,077	0	10,852	16,920	27,773	3,305
2004	22,084	15,405	37,489	8,314	20,745	8,167	37,226	263
2005	161	10,550	10,711	0	17,898	11,313	29,211	-18,500
2006	1	7,826	7,827	0	1,068	27,517	28,585	-20,758
2007	670	13,875	14,545	0	1,379	26,761	28,140	-13,595
2008	0	11,245	11,245	0	0	27,355	27,355	-16,110
2009	5,407	14,180	19,587	0	5,649	22,660	28,309	-8,722
2010	14,938	15,755	30,693	0	14,201	12,037	26,238	4,455
2011	34,926	15,180	50,106	17,414	21,521	4,537	43,472	6,634

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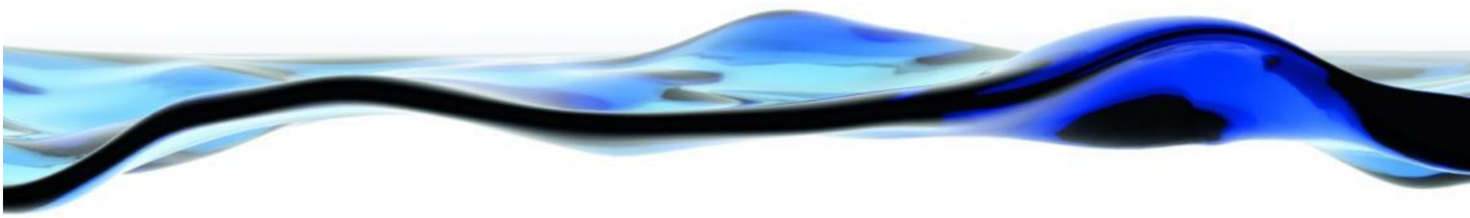

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