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Connectivity between the north Yeal wetlands and Perth's regional groundwater

Perth Shallow Groundwater Systems Investigation Number 10

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Department of Water and Environmental Regulation
Prime House, 8 Davidson Terrace
Joondalup Western Australia 6027
Locked Bag 10 Joondalup DC WA 6919

Phone: 08 6364 7000
Fax: 08 6364 7001

National Relay Service 13 36 77
dwer.wa.gov.au

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For more information about this report, contact:
Water Resource Science Branch, Department of Water and Environmental Regulation

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Preface

This report describes groundwater interactions at wetlands in the northern Yeal Nature Reserve, which was studied as part of the Perth shallow groundwater systems (SGS) investigation. The Perth SGS was a four-year (2007–10) investigation program undertaken by the Water Resource Science Branch of the Department of Water and Environmental Regulation (DWER). The program was funded by the Government of Western Australia and the federal government's 2007 Water Smart Australia initiative. The report was completed to support the DWER's four-year Perth Region Confined Aquifer Capacity Project and water allocation planning.

The Perth SGS investigation focused on many wetlands of the Gnangara and Jandakot groundwater mounds, which are the most significant sources of groundwater for the Perth metropolitan area. The groundwater mounds also sustain numerous ecosystems that depend on shallow groundwater. At present, many of these ecosystems are stressed by land use changes, increased groundwater abstraction and climate change, resulting in a general deterioration in their social, cultural and environmental values.

The Perth SGS investigation was formulated from the outcomes of a groundwater management area review conducted in 2006 (McHugh & Bourke 2007). This review summarised the monitoring status and the management issues facing selected wetlands on Gnangara and Jandakot mounds, and identified the information required to address these issues. The outcome was an investigation program incorporating 28 wetlands on the Swan coastal plain, prioritised by a combination of ecological significance, management issues and geomorphic setting.

The specific objectives of the Perth SGS investigation were to:

- redesign and upgrade the existing monitoring infrastructure and install new monitoring networks at ecologically important sites
- investigate the hydrogeology of selected lakes, wetlands and remnant wetlands to determine the interactions and connectivity of surface water bodies and groundwater
- investigate the paleoclimate of some selected wetlands to provide an appreciation of how lakes have functioned in the past and to enable us to place the current changes within this long-term context
- investigate the chemistry of wetlands and wetland sediments to give a detailed understanding of the ability of wetlands to alter lake and groundwater quality.

The outcomes of this investigation have been used to evaluate the potential impacts of changes in groundwater levels modelled by the Perth Regional Aquifer Modelling System (PRAMS) and guide water allocation planning.

Summary

This is the first investigation of groundwater-dependent ecosystems (GDEs) in an area of the Gnangara groundwater system where clays in the Superficial aquifer influence watertable connectivity with the regional Superficial aquifer. The Yeal Nature Reserve in the Gnangara system's north has wetlands with high regional ecological and cultural significance, including Yeal Lake, Quin Swamp and wetlands associated with upper Quin Brook. These wetlands form part of an important ecological corridor through the Yeal Nature Reserve, which is one of the largest unfragmented areas of remnant endangered Banksia bushland near Perth, containing a rich diversity of habitats for birds, reptiles and amphibians. Little was known how sensitivity these wetlands are to water levels in the Superficial aquifer in this area – where the Superficial aquifer is directly connected with the regional influences of both the Leederville and Yarragadee aquifers. This report describes local-scale hydrogeological investigations at the three wetlands in the upper reach of Quin Brook to establish the dependence of the wetland ecology on water levels in the regional Superficial aquifer.

The wetlands of this part of the Gnangara Mound are hydrologically unique with diverse interactions between surface water inflows and perched to semi-perched shallow groundwater. Recent changes in these interactions has led to the wetlands becoming increasingly dependent on groundwater. During the past two decades these wetlands have changed from seasonally inundated, local flow-through systems with recharge from upstream flows in Quin Brook, to groundwater-dependent damplands. Yeal Lake, however, is less dependent on groundwater. The lake acts as a sump: it fills with surface water inflows and then levels recede depending on evaporation and recharge to shallow perched groundwater. This means water levels at the lake are disconnected from the Superficial aquifer and not influenced by regional water level decline. In contrast, the upper Quin Brook wetlands and Quin Swamp interact with semi-perched groundwater that is connected with and influenced by regional water level decline.

Perching and semi-perching of the groundwater at the wetlands is a feature of their location near the western edge of the generally low permeability Guildford Formation. The formation is shallower, clayey and more extensive below Yeal Lake and Quin Swamp than the upper Quin Brook wetland, but the permeability at Quin Swamp is greater in parts than at Yeal Lake. The influence of the regional Superficial aquifer depends on proximity to the edge and the depth of the Guildford Formation (such as at the upper Quin Brook wetland) or vertical permeability through the formation caused by interfingering of sands (such as at Quin Swamp).

Groundwater inflow to the wetlands is from perched groundwater upgradient of the wetlands. This perched groundwater is disconnected from the underlying regional Superficial aquifer. Unlike the deeper regional Superficial aquifer, it is typically more saline, with different ionic composition and higher concentrations of dissolved organic carbon and total nitrogen. Hydrochemical patterns, water level responses to recharge and geophysical sensing using nuclear magnetic resonance (NMR) techniques,

indicates that some groundwater flows vertically through parts of the Guildford Formation at Quin Swamp, but this is spatially variable. Acidity and dissolved metals such as aluminium and iron were also present in semi-perched groundwater at Quin Swamp and the upper Quin Brook wetland and may have contributed to declines in plant health. At Quin Swamp, this acidity extends through the Guildford Formation to the underlying regional aquifer.

Groundwater outflow from the wetlands was mainly to the west where there was greater interaction with the regional Superficial aquifer. Greater vertical flow and connectivity in the aquifer west of the wetlands was evident in hydrochemical, water level patterns and geophysical sensing using NMR.

Declining groundwater levels in the regional Superficial aquifer have led to deteriorating ecological health at Quin Swamp and upper Quin Brook wetland, but not at Yeal Lake. Rainfall decline explains most of the historic decline in groundwater levels near the wetlands, with an emerging influence of drawdown in the confined aquifers starting after the mid to late 2000s. For this investigation, wetland vegetation monitoring transects at each wetland incorporated over-storey *Melaleuca rhaphiophylla* and *Eucalyptus rudis* ranging to *Baumea articulata* within the wetland basins. These were used to calculate environmental water requirements (EWRs) for vegetation that forms the ecological corridor and for the macroinvertebrate assemblages. Analysis indicated that the following minimum hydrological conditions at each wetland would maintain ecological health:

- 58.3 mAHD at Yeal Lake in the watertable measured at bore YLc and an annual wetland inundation period of three months for at least two out of three years
- 55.2 mAHD at upper Quin Brook wetland in the watertable measured at bore CYWc
- 54.2 mAHD at Quin Swamp in the watertable measured at bore QUNEc.

The levels that can be maintained, considering climate change and the ability to reduce groundwater abstraction, will be considered through regional groundwater allocation planning processes.

Managing pumping effects on water levels in the regional Superficial aquifer can help protect the ecological values at Quin Swamp and upper Quin Brook wetland and should consider the EWRs determined for these sites. The emerging effects of confined aquifer drawdown on the water levels in the Superficial aquifer are likely to be more immediate at the upper Quin Brook wetland than at Quin Swamp. In contrast, the ecological values of Yeal Lake are unlikely to be affected by pumping drawdown of the regional Superficial aquifer. This means the EWRs for Yeal Lake do not need to be considered in regional groundwater allocation planning. Instead, these EWRs should be used to assess any options for enhancing runoff from the east and surface water flows to Yeal Lake.

These findings also highlight that the watertable at other wetlands on the boundary of the Guildford Formation and Bassendean Sand can be sensitive to regional groundwater level decline. The extent of this sensitivity will be mainly influenced by the depth, permeability and distance to the edge of the underlying Guildford Formation. Water levels at wetlands nearer to the edge of the Guildford Formation, where the Bassendean Sand is thicker and transmissivity is higher, are more sensitive to downgradient regional water level decline (e.g. Quin Brook wetland). Similarly, the variability in the permeability of the Guildford Formation near the western extent can also result in regional water level decline propagating to the watertable at the wetlands.

Implementing the findings

The findings of the north Yeal wetlands study will be used to inform DWER's water licensing, groundwater allocation planning and water monitoring, as well as the department's advice on any proposed land use change.

Allocation planning

- EWRs for upper Quin Brook wetland and Quin Swamp need to be considered as part of the management of water levels at the wetlands.
- Accelerated water level decline at the wetlands due to drawdown in the Leederville and Yarragadee aquifers will amplify decline in ecological health. Any stabilisation or increase in water levels would help protect current ecological heath.
- Additional drawdown in water levels and rate of decline in the regional Superficial aquifer and confined aquifers need to be minimised to support ecological health at upper Quin Brook wetland and Quin Swamp.
- Yeal Lake water levels do not need to be managed as part of regional allocation planning because its ecological health is unlikely to be affected by water levels in the regional Superficial aquifer.
- Consider QUNWc, CYWc and YLc as new GDE watertable monitoring bores for ongoing monitoring.
- Consider retaining GB22, GC4 and NG9d for ongoing monitoring and modify the frequency to monthly (or use of water level loggers with hourly logging). Monitoring GC4 and NG9d will verify any effects on the shallow groundwater in the surface water catchment for Yeal Lake.

Licensing and land use planning

- Ensure any new drawpoints from the Superficial aquifer in the Deepwater Lagoon subarea are set back at distances of at least 1 km from the edge of the area of perching to avoid water level decline extending towards Quin Swamp and upper Quin Brook.
- Through the land use planning process, advise other decision-makers that regular surface inflows to Yeal Lake from the Quin Brook catchment could be maintained by:
  - retaining current land use as mostly non-perennial vegetated rural and semi-rural
  - maintaining existing surface water drains across freehold land between Lennard Brook at Brand Highway and Yeal Lake inflow, and
  - avoiding using drains that lower the average of seasonal levels before 2012.

Water resource assessment and investigation

- Include the new hydrogeological understanding of the Superficial aquifer in this report in future conceptualisation of the Guildford Formation in PRAMS by.

updating the distribution of low vertical hydraulic conductivity (reflecting low permeability) in the Superficial aquifer at or to the east of Yeal Lake.

- Prioritise GB16 for early replacement when the shallow bore replacement program begins.
- Carry out opportunistic occasional monitoring of YL_SG to record the recession in lake levels after filling events to verify that lake recession remains independent of the recession in GB22.
- Install a watertable and deep Superficial aquifer monitoring bore on the western edge of Yeal Lake at the junction with the existing powerline track within five years and monitor for 10 years to confirm the extent and permeability of the Guildford Formation and monitor the effects of regional watertable decline closer to the lake.
- Consider options for enhancing surface water flows to Yeal Lake as an option to mitigate watertable impacts in wetlands (such as Quin Swamp) downstream of the lake from pumping in the Yarragadee or Leederville aquifers.
- Explore whether regional airborne electromagnetic data contains sufficient early signal information that can be re-analysed to confirm the western extent of the low permeability layers in the Guilford Formation to determine the likely propagation of water level decline in the regional Superficial aquifer and associated wetlands.

1 Context and objectives

The wetlands associated with Quin Brook in the Yeal Nature Reserve are sensitive groundwater-dependent ecosystems (GDEs). These wetlands are located in an area with complex hydrogeology where the interaction between the hydrology of wetlands, the watertable and the regional Superficial aquifer has not been studied previously. The connectivity of the Superficial and Yarragadee aquifers in the area adds to the complexity (McHugh & Bourke 2007). The wetlands in the area are best represented by Yeal Lake, Quin Swamp and Quin Brook wetland which are listed as Conservation Category wetlands (DPaW 2016b) and contain near-pristine vegetation.

The hydrogeology of these wetlands is different from other wetlands on the Gnangara Mound. All are paleodrainage features (McHugh & Bourke 2007) that are morphologically different from other Gnangara Mound wetlands where wetland–groundwater interactions have been previously investigated (e.g. see Department of Water 2011a; Searle et al. 2011) and interact differently with shallow groundwater.

Some of the wetlands overlie a recharge window to the Yarragadee aquifer where abstraction from this aquifer for public supply to the south is likely to have greatest effects on groundwater levels in the Superficial aquifer compared with drying due to climate change (McHugh & Bourke 2007; De Silva 2009). Deep drilling investigations have greatly refined our understanding of the complex hydrogeology of the Leederville and Yarragadee aquifers and interactions with the Superficial aquifer (Pigois 2010). However, in the Yeal area there is uncertainty about the interaction between water levels in wetlands and the regional Superficial aquifer and the influence of this on the hydrology and ecological condition of the wetlands.

A review of the management of shallow groundwater systems on the Gnangara and Jandakot mounds (McHugh & Bourke 2007) recommended a joint hydrogeological and ecological investigation of the wetlands in the central Yeal area (referred to as the north Yeal wetlands in this report). These recommendations formed the basis of this study’s objectives, which are to:

- upgrade the groundwater monitoring network around the north Yeal wetlands
- improve understanding of shallow groundwater interaction with Yeal Lake, Quin Swamp and the upper Quin Brook wetlands
- determine where acid sulfate soils are distributed in and around the wetlands, and any effects on water chemistry
- develop conceptual models of the relationships between wetland hydrogeology, chemistry and ecosystem function to provide a basis for improved management strategies
- highlight the water and land use issues to be addressed in regional groundwater allocation planning
- provide a basis for interpreting impacts on GDEs associated with Quin Brook from PRAMS modelling.

2 Background

2.1 Location, site characteristics and climate

The north Yeal wetlands are located on the Swan coastal plain about 60 km north of Perth and 14 km south-west of Gingin, Western Australia (Figure 1). The wetlands are near the northern extent of the Gnangara groundwater system, fall within the Quin Brook catchment and are linked by large tracts of vegetation to a range of wetland ecosystems in the surrounding Yeal Nature Reserve. The main wetland features include Yeal Lake, seasonally inundated sumplands – of which Quin Swamp is one of the largest – and interconnect floodplain wetlands (Figure 1). The lake and floodplain wetlands are a fluvial feature that is rare in the Gnangara system.

Table 1 Summary attributes of the north Yeal wetlands (after Hill et al. 1996)

Wetland name (WIN)[1]	Location (centroid)[2]	Type and description	Suite	Ecological recognition[3]	Aboriginal heritage	Management
Yeal Lake (38749652539)	E:387703 N:6525479	Seasonally inundated lake	Mungala (B/P.2)	Conservation Category wetland	Site of specific interest (DIA). Part of a larger recognised area of significance (Wright 2007b)	Department of Biodiversity, Conservation and Attractions (DBCA)
Quin Swamp (38385652763)	E:384046 N:6527784	Seasonally inundated sumpland	Mungala (B/P.2)	Conservation Category wetland	As above	DBCA
Quin Brook wetlands (3845652772)	E:385924 N:6526109	Seasonally inundated floodplain flats	Mungala (B/P.2)	Conservation Category wetland	As above	DBCA

[1] WIN: corresponding wetland identification number (after Hill et al. 1996)
[2] GDA 94 easting and northing coordinates
[3] As summarised by Froend et al. 2004a, b

The area has a Mediterranean-type climate with hot, mostly dry summers and mild, wet winters. The annual rainfall recorded at the monitoring station nearest the lake, at Gingin (site 9018; Bureau of Meteorology 2013), shows a declining trend during the past 40 years of the 126-year period of the record. Annual average rainfall from 1889–2015 was 725 mm. This has decreased to an annual average of 606 mm from 2000–2016 (Figure 2).

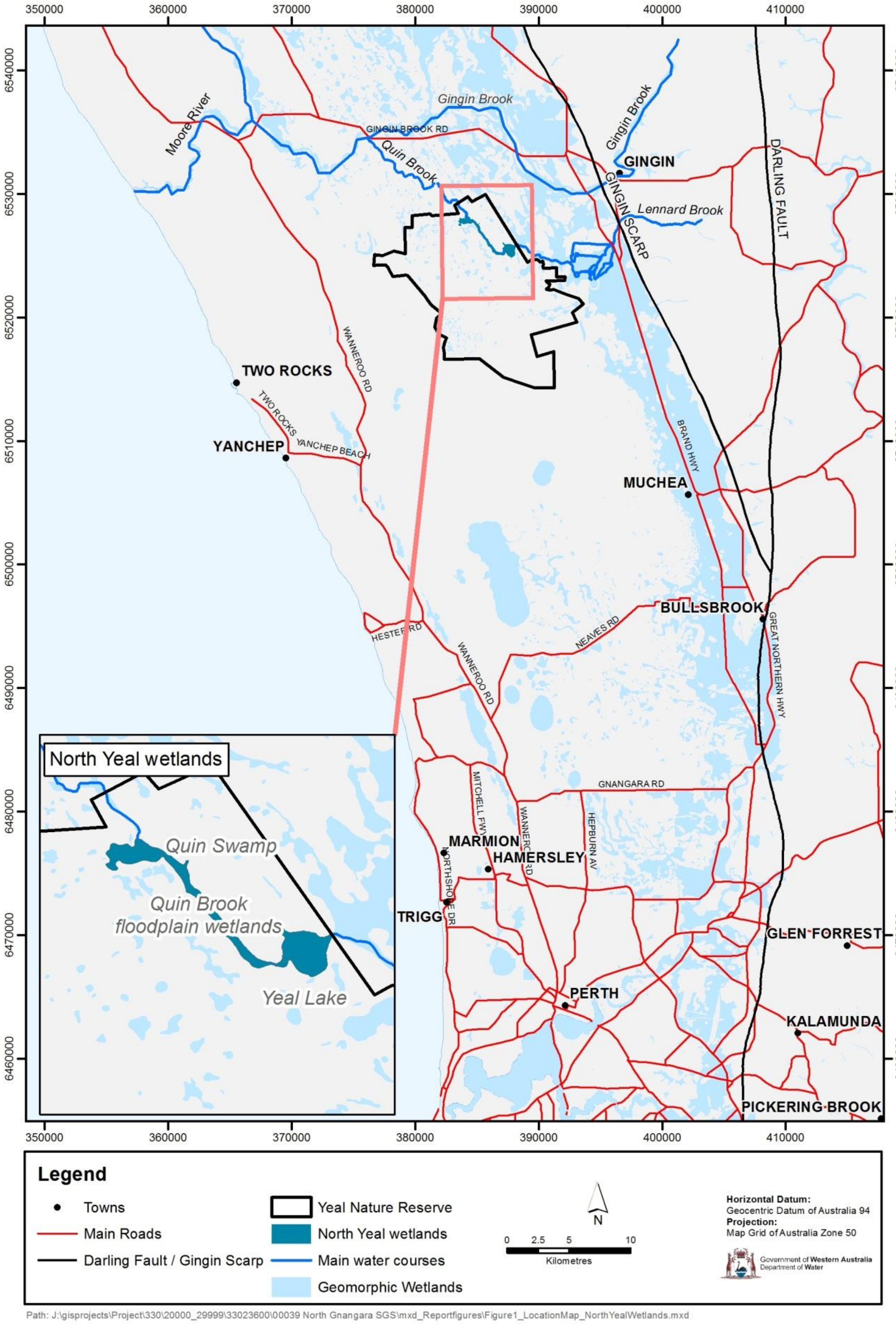

Figure 1 Location of the north Yeal wetlands and surrounding Yeal Nature Reserve

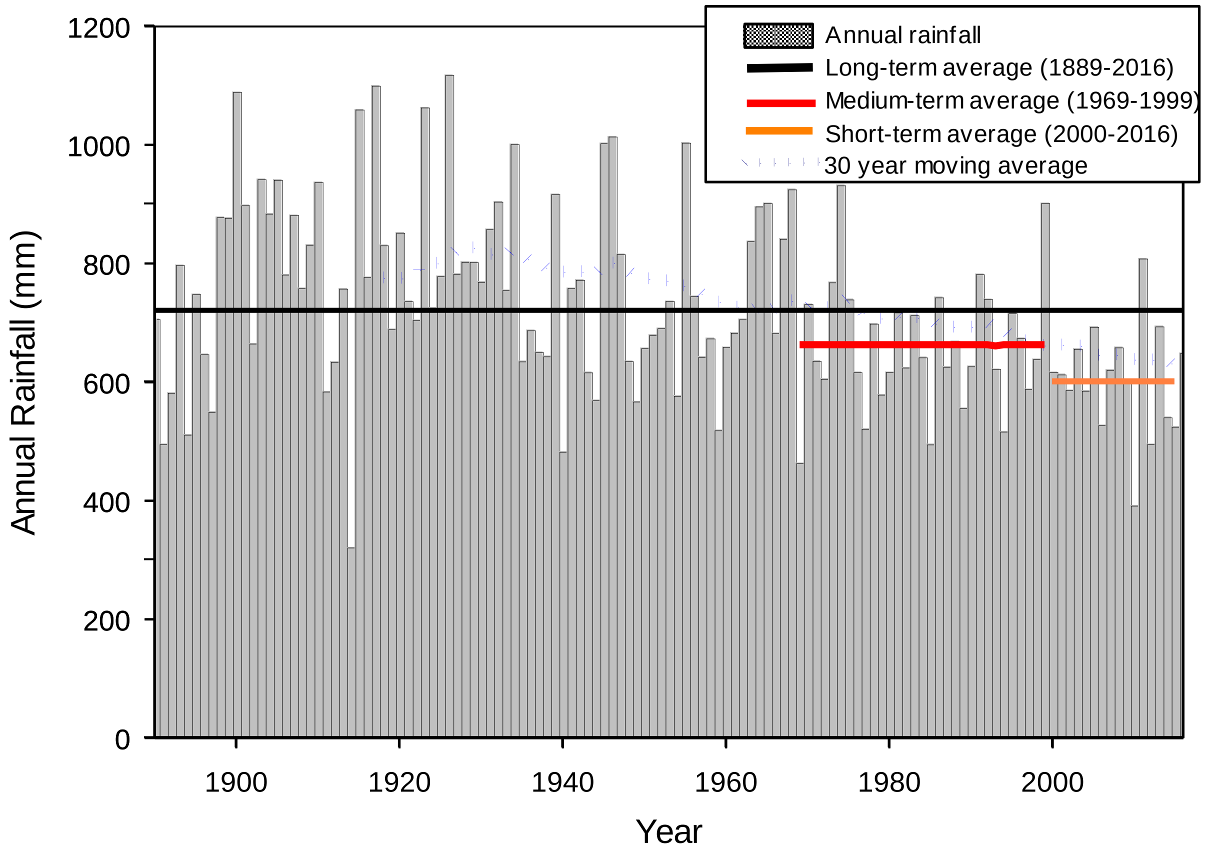

Figure 2 Annual rainfall at Gingin showing short- and mid-term averages relative to the long-term average

2.2 Geomorphology and geology

2.2.1 Regional geomorphology

The north Yeal wetlands are located on the northern Swan coastal plain at the eastern margin of the Bassendean Dune System abutting the Pinjarra Plain (Gozzard 2007a). The Swan coastal plain is the area of gently undulating north–south aligned dunes in the west, grading to broad plains in the east to the foot of the Darling and Gingin scarps. The superficial formations in the study area correspond with geomorphic units that trend sub-parallel to the present-day coastline (Gozzard 2007a). The main units in the area are the Pinjarra Plain, which consists of alluvial fans of the Guilford Formation abutting the Darling Scarp, and adjoining Bassendean Dune System. This is the oldest of a series of four dune systems extending to the coast (Gozzard 2007a).

The local geomorphology of the area around the north Yeal wetlands consists of mostly gently undulating dunes with occasional broad swales of the Bassendean Dune System. These dominate the surrounding Yeal Nature Reserve to the west and south-west of the wetlands, with the sumplands and damplands lying in the swales. The landscape to the east of the wetlands and nature reserve consists of flats of the Pinjarra Plain, with minor very gently undulating dunes and localised wetland depressions.

Yeal Lake, Quin Swamp and the connected floodplain wetlands are aligned along a paleodrainage feature of the Bassendean Dune System (McArthur & Bettenay 1960; Davidson 1995) corresponding with the surface outcrop of the Bassendean Sand (Figure 3 and Figure 4).

2.2.2 Regional geology

The study area is in the central part of the Perth Basin where there is more than 12 000 m of sediments – the shallowest ranging in age from Jurassic to Cainozoic (Playford et al. 1976; Table 2).

The Yarragadee Formation is of Jurassic age and is variously overlain by a range of strata (Figure 5) including the South Perth Shale, Gage Formation, Parmelia Group, Leederville Formation and superficial formations (Davidson & Yu 2006; Pigois 2010). In the study area, the Yarragadee Formation consists of mostly fine to gravelly sand interbedded with silts and clays (Table 2; Pigois 2009; Pigois 2010).

The Leederville Formation (Warnbro Group) and Parmelia Group in the study area overlie the Yarragadee Formation (Table 2). These generally subcrop the superficial formations. The Leederville Formation consists of mostly interbedded sand, silt and clay of the Wanneroo Member (Table 2). Minor finely interbedded clays of the Mariginiup Member are also present, along with the clay dominated South Perth Shale and Gage Formation (Table 2). The Parmelia Group underlies the superficial formations in the east and south-east of the Yeal Nature Reserve (Pigois 2012; Figure 5) and consists of mostly silt with minor sand and clay (Table 2). Members of this group have not been differentiated in previous investigations in this area (Pigois 2010) but in a regional interpretation were differentiated to include the Otorowiri and Carnac members (Davidson & Yu 2006).

The superficial formations consist of the basal Ascot Formation, overlaid by Gnangara Sand, Guildford Formation and Bassendean Sand (Table 2).

The Ascot Formation lies at the base of the superficial formations throughout most of the Yeal Nature Reserve, except in the central east where the Yarragadee subcrops the superficial formations (Figure 5). This formation is of estuarine origin and consists of calcarenite and fine to coarse glauconitic sand interbedded with minor clay and sandy clay (Table 2).

The Gnangara Sand is described as a discrete formation in this report because of the distinct appearance of its lithology. Previously, the formation has been interpreted as being part of the Bassendean Sand (Pigois 2010). However, the sands are clearly bimodal in particle distribution, with larger, more rounded quartz grains and more angular, finer sand grains in upward fining sequences as originally described by Davidson (1995). Both formations are fluvial and shallow-marine in origin (Gozzard 2007b) and are probably varying forms of the distal portions of alluvial fans.

The Guildford Formation or Bassendean Sand generally forms the upper part of the superficial formations in the study area (Table 2; Figure 5). The Bassendean Sand in the area has been described by Moncrieff and Tuckson (1989) and confirmed by

Pigois (2009) as light-grey to grey-brown quartzose sand, being fine to coarse grained in size. The sand is of fluvial and estuarine origin (Gozzard 2007b), consisting of typically well-sorted, subangular to subrounded mainly frosted grains (Moncrieff & Tuckson 1989). A layer of friable, limonite-cemented sand, colloquially called ‘coffee rock’, is present throughout most of the area near the watertable (Moncrieff & Tuckson 1989).

The Guildford Formation is often reported between 2 and 35 m thick in the eastern part of the Swan coastal plain (Davidson 1995), but in the Yeal Nature Reserve is typically less than 14 m thick (Table 2). The formation underlies the eastern extent of the reserve interfingering with the Bassendean Sand (Pigois 2010). There are both sandy and clay facies of the formation, with clays typically being various colours (black, light grey, brown, green and mauve) and variably sandy (Moncrieff & Tuckson 1989). The formation has previously been interpreted as mostly underlying the Bassendean Sand although it interfingers with the Bassendean and Gnangara sands to the west (Moncrieff & Tuckson 1989). Recent re-evaluation summarised that the Guildford, Bassendean Sand and Gnangara Sand formations are stratigraphic equivalents and represent the interaction of aggrading river systems near the Darling Scarp with fluvial and estuarine environments to the west (Gozzard 2007b). This re-evaluation has been significant for interpreting the stratigraphic succession of sediments around the Yeal Nature Reserve.

2.2.3 Acid sulfate soils

Lakes and wetlands on the Swan coastal plain are often associated with acid sulfate soil (ASS) materials that may become acidic if water levels decline to expose them. The soils are formed under permanently water-logged conditions and contain sulfidic minerals that are rich in iron sulfides such as pyrite (Sullivan et al. 2010). The soils also include those with sulfuric materials such as jarosite – if oxidised and no longer permanently water-logged (Sullivan et al. 2010). ASS materials oxidise when water levels are lowered, allowing air to reach the sulfidic materials. This triggers the release of sulfuric acid and iron that can leach other associated metals from soils into groundwater (Appleyard et al. 2006; Fältmarsch et al. 2008).

As many of the Gnangara Mound’s wetlands are progressively drying, there is an increasing likelihood that sediments containing ASS materials will be exposed, thus presenting a threat to their ecology (Sommer & Horwitz 2009). Broadscale mapping of ASS risk (Degens 2006) has indicated a high to moderate risk of shallow ASS (within 3 m of the ground surface) in the superficial formations beneath the north Yeal wetlands and many damplands in the Yeal Nature Reserve. The surrounding superficial formations have been mapped as moderate to low risk of shallow ASS (i.e. ASS risk increasing with depth).

Table 2 Stratigraphic sequence and hydrogeology in the area around the Yeal Nature Reserve (after Davidson 1995; Moncrieff & Tuckson 1989; Pigois 2010)

Age	Stratigraphy	Thickness (m)	Lithology	Aquifer
	Superficial formations			
Cainozoic (Quaternary – Late Tertiary)	Bassendean Sand	4 to 53	Light-grey to light grey-brown, fine- to medium-grained quartz sand with discontinuous ferruginised sand horizons	Superficial aquifer
	Guildford[1]	4 to 14	Light grey, buff, brown or grey-green sandy facies with black, light-grey to brown or green clayey facies that are variably sandy and exhibit occasional ferruginised horizons[1, 2]	Local aquitard
	Gnangara Sand		Pale-grey, fine to very coarse grained, bimodal, subrounded to rounded sand with abundant feldspar fragments[3]	Superficial aquifer
	Ascot Formation	10 to 29	Calcarenite and sand commonly containing glauconite and phosphatic nodules interbedded with clay and sandy clay	Superficial aquifer
			Unconformity	
	Warnbro Group – Leederville Formation			
Cretaceous	Wanneroo Member	77 to 175	Sand beds (up to 30 m thick) separated by clay horizons	Leederville aquifer
	Mariginiup Member	8 to 23	Finely interbedded clay, silt and sand layers	Local aquitard
	South Perth Shale	20[4]	Clay and silt with minor sand horizons	Confining bed
	Gauge Formation	26 to 74[4]	Sandy silt and clay	Confining bed
			Unconformity	
Cretaceous-Jurassic	Parmelia Group[2]	0 to > 55[3,4]	Silt with a minor sand and clay component	Yarragadee aquifer[2]
Jurassic	Yarragadee Formation[2]	> 2574	Sands interbedded with silts and clays	Yarragadee aquifer

1 Gozzard 2007b
2 Moncrieff & Tuckson 1989
3 Davidson 1995
4 After Pigois 2010

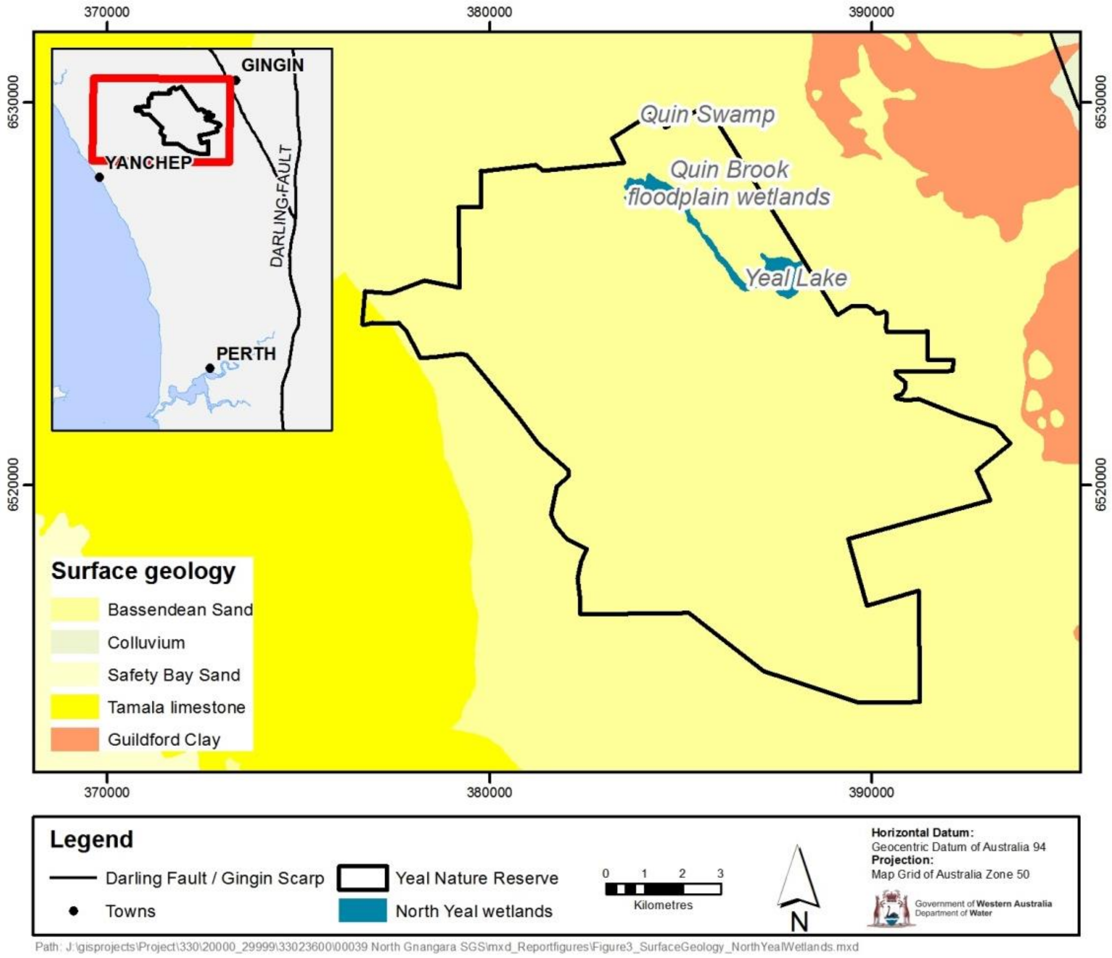

Figure 3 Generalised regional surface geology in the area around the Yeal Nature Reserve and north Yeal wetlands

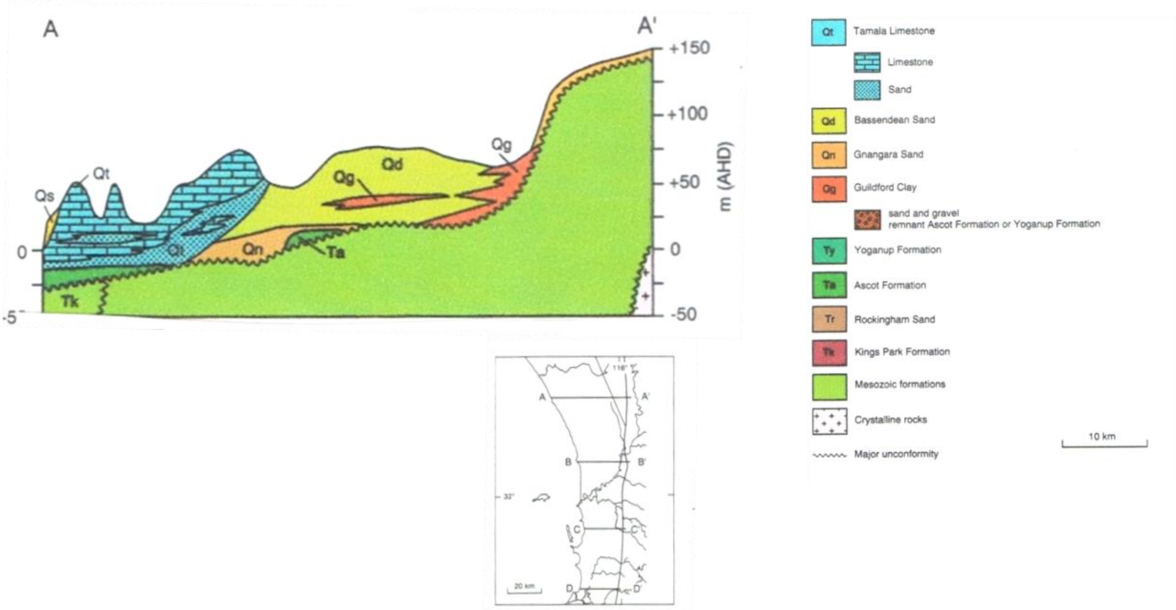

Figure 4 East–west geological cross-section through the superficial formations A-A' south of the north Yeal wetlands (from Davidson 1995)

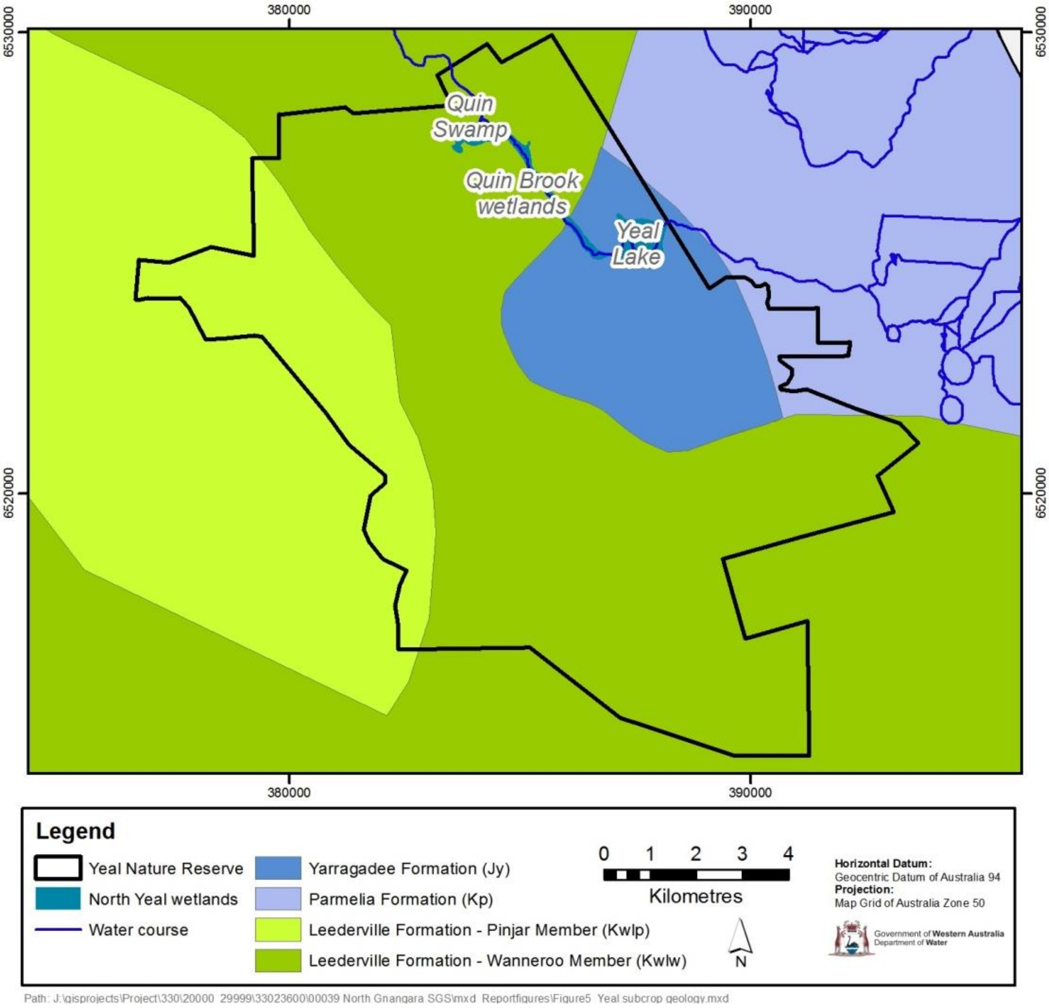

Figure 5 Formations subcropping the superficial formations in the north Yeal wetlands and surrounding Yeal Nature Reserve (after Pigois 2010)

2.3 Hydrogeology and hydrology

2.3.1 Regional hydrogeology

Groundwater resides in the superficial formations of the Swan coastal plain as well as in the deeper formations of the Perth Basin (Davidson 1995). There are six distinct aquifers that are generally separated by major confining layers, but which are locally in hydraulic connection (Davidson 1995). The Superficial aquifer is a regional unconfined aquifer comprising sediments of the superficial formations of the Swan coastal plain (Table 2).

Many lakes and wetlands of the coastal plain are located where the watertable permanently or seasonally intersects the land surface. This is often in interdunal swales in the Spearwood and Bassendean dunes, and at the contact between different geomorphic units. Rockwater (2003) classed wetlands on the Pinjarra Plain and Bassendean dunes to be mainly flow-through lakes, while on the Spearwood dunes, cave systems can influence inflow and outflow. Surface water fluctuations in these lakes are related to changes in groundwater levels.

The north Yeal wetlands lie on a part of the Swan coastal plain where regional groundwater in the Superficial aquifer flows from the Gingin Scarp in a westerly direction (Figure 6). The wetlands lie within a zone of moderate hydraulic gradient with groundwater levels falling from > 60 mAHD to the east of the site to < 55 mAHD to the west.

The Superficial aquifer in the north Yeal area is hydraulically connected to both the Leederville and Yarragadee aquifers. The Leederville aquifer underlies the Superficial aquifer across most of the area and is unconfined (Table 2; Figure 5). The Yarragadee aquifer (Table 2) underlies and is in hydraulic connection with the Superficial aquifer (Pigois 2010) in the central and eastern extent of the Yeal Nature Reserve, including Yeal Lake (Figure 5). This is the only location in the Gnangara Mound groundwater management area where there is shallow connectivity between the Yarragadee and Superficial aquifers.

The Superficial aquifer in the north Yeal area mainly consists of the Bassendean Sand in the west, interfingering with the locally semi-confining Guildford Formation to the east. Groundwater interaction with Yeal Lake, Quin Brook and Quin Swamp is likely controlled by the variable presence of the Guildford Formation.

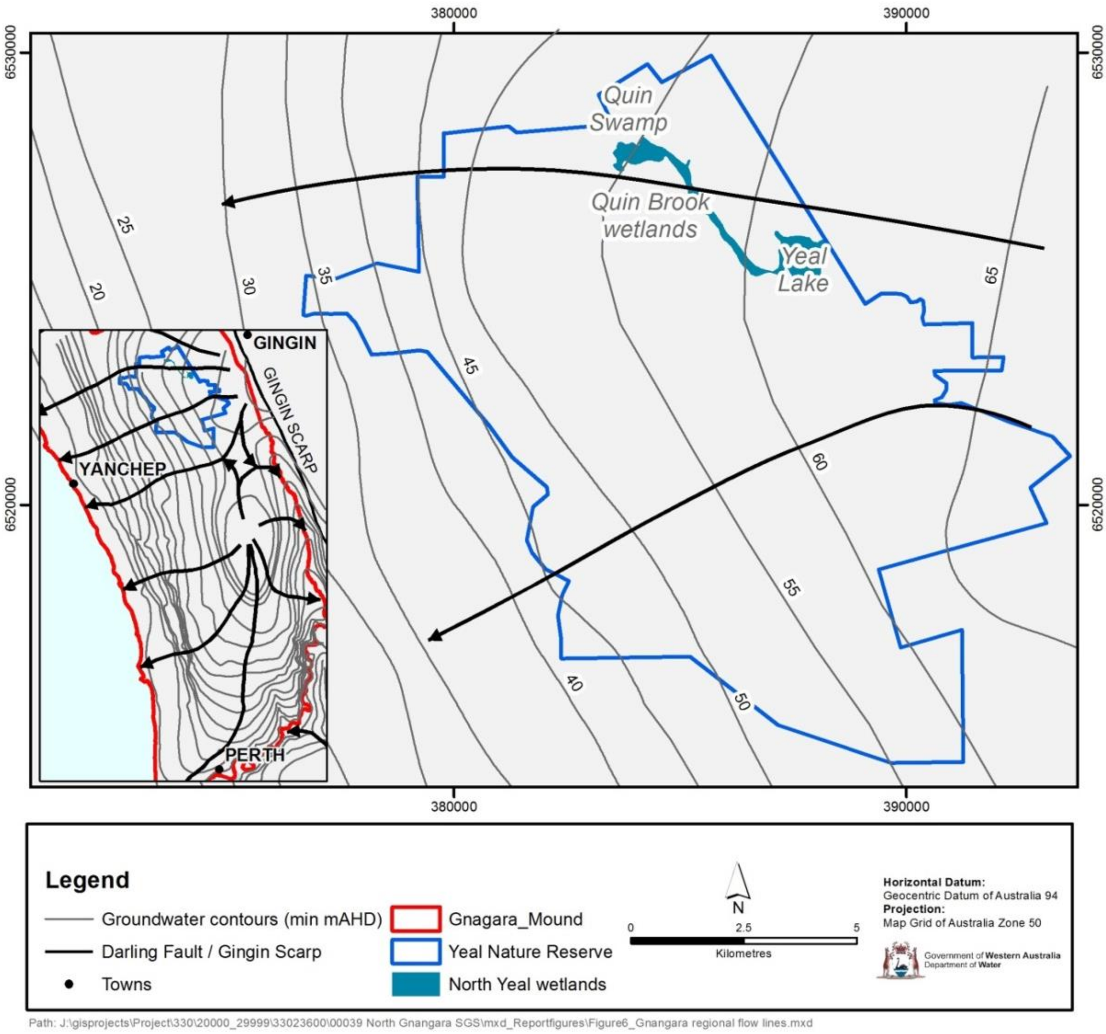

Figure 6 Regional groundwater flow lines (2004) in the Yeal Nature Reserve

Before this investigation, there was little recorded information on trends in water levels at the north Yeal wetlands. However, aerial photography between 1999 and 2011 indicates the wetlands were frequently wetter up until around 2006 and frequently drier in summer/autumn toward the end of this period (Appendix A). Analyses of hydrographs for bores in the Superficial aquifer closest to the wetlands found that water levels have been slowly decreasing during the past two decades (1979–2005; Yesertener 2008). Water levels decreased by more than 1.5 m from 1979–2005 at GB22 0.8 km to the south-west of Yeal Lake, but there was a smaller decrease of < 0.7 m at GB19 1.4 km north of Yeal Lake over the same period. The trends in GB22 reflect trends in bores further west and south-west, whereas those in GB19 reflect trends in bores further east – with the declines attributed to decreasing annual rainfall (Yesertener 2008). The range of water level trends may be due to localised perching of groundwater in the Superficial aquifer across the area. This perching is due to the presence of the low permeability Guildford Formation.

Predictions of future regional watertable changes are consistent with local water level trends. Modelling of regional water balance for the Gnangara Mound has indicated that groundwater levels in the Superficial aquifer in the northern Yeal area can be expected to decline by 1.0 to 2.0 m between 2008 and 2031, even with a stable rainfall pattern (De Silva 2009).

2.3.2 Local surface water hydrology

The north Yeal wetlands are in the upper Quin Brook catchment that discharges north-west into Gingin Brook. The landscape receives drainage from the Lennard Brook catchment to the east and drains to the north to Gingin Brook. Lennard Brook mainly drains from the Gingin Scarp and terminates at Lake Bambun, although there is evidence of water directly flowing to the Quin Brook catchment (Boniecka 2015).

The surface water hydrology of the wetlands is dominated by flows from the east to Yeal Lake, then north-west in an interdunal swale of the Bassendean Sand in which the Quin Brook channel has formed (Figure 7). Snapshot monitoring indicates that flows in Quin Brook are seasonal (Appendix B), although Lennard Brook to the east of this has perennial flow (Boniecka 2015). Lennard Brook has perennial flow at the edge of the Gingin Scarp (measured at the flow gauging station; Figure 7) with recent snapshot monitoring showing this extends to at least the Brand Highway (Appendix B).

There is some uncertainty about the eastern boundary of the Quin Brook catchment that discharges to Yeal Lake, but seasonally it includes the lower Lennard Brook catchment. East of Yeal Lake, the Quin Brook catchment is about 3000 ha of mostly flats and very gently undulating dunes (Figure 7). Winter flows (2011) were continuous to east of Sullivan Road, indicating that the lower Lennard Brook catchment contributes flows to upper Quin Brook (Appendix B). Furthermore, aerial photography and high-resolution land elevation data (LiDAR elevation) indicate shallow drainage channels connect the lower Lennard Brook at the Brand Highway through to Sullivan Road (Site B03; Figure 7 and Appendix B). Two flow paths are evident – a small channel to the north-east (via site B03) and a more defined channel to the south-east (via site B06) linking several basin wetlands to the overflow from Bambun Lake (Boniecka 2015). LiDAR elevation data for this drainage also indicates a gentle gradient on the base of the drain from the east to the west with no obvious constrictions. Surface water at Sullivan Road (Appendix B) flows via both channels during winter and after long periods of very little rainfall (e.g. August 2012).

There are two constructed channels draining into Yeal Lake and a narrow outflow channel to the west. The smaller of the inflow channels (northern channel in Figure 7) most likely drains the small area to the north-east bounded by Strickland Road. A larger inflow channel, to the south of the smaller channel, consists of a leveed bypass drain where a bund diverts discharge downstream of Sullivan Road around the southern side of the low-lying flats (bypass drainage channel in Figure 7). There would be significant recharge to groundwater when water flows via this channel because it is unlined, has a sand base and an invert that is mostly > 1 m above that of the adjoining flats and the regional groundwater.

The outflow channel from Yeal Lake is an excavation into the natural outflow depression, is 1.5–2 m wide and extends about 500 m east of the lake. This channel has reduced the maximum filling depth of the lake by about 0.5 m and was probably constructed to stop flooding of the farmland east of the lake when it was full.

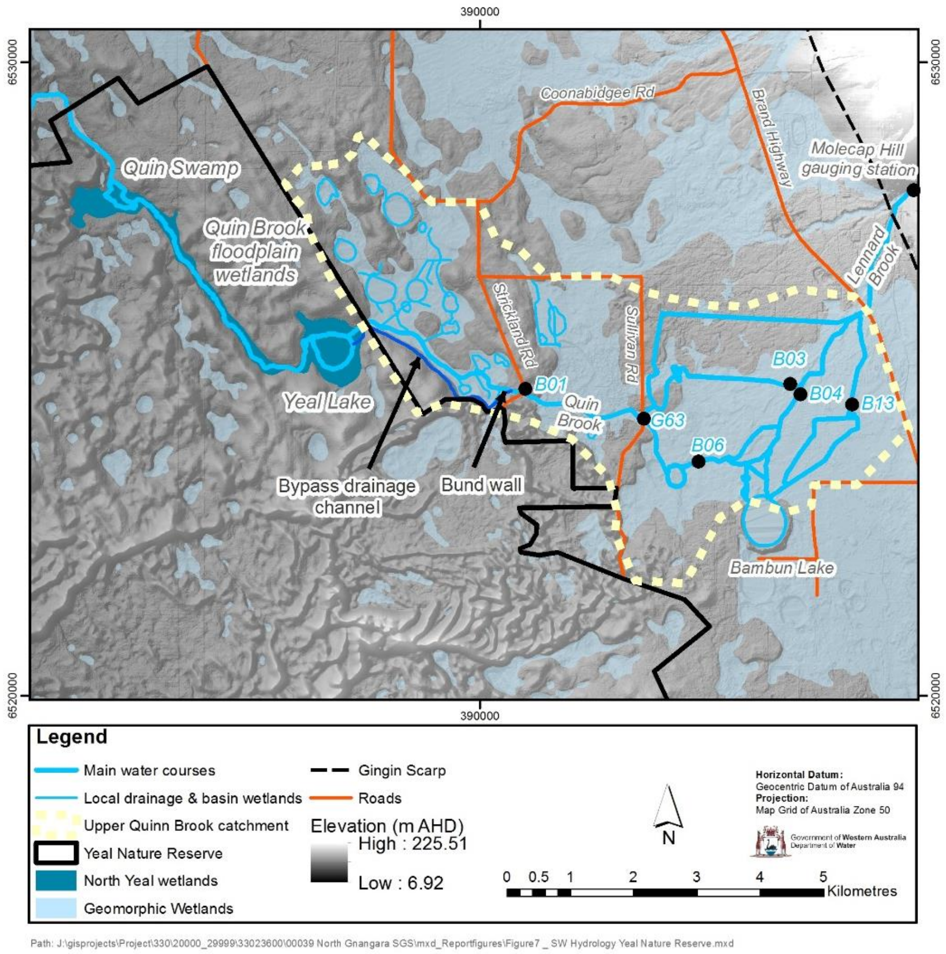

Figure 7 Local surface water hydrology of the north Yeal wetlands with sampling sites

2.4 Ecology

Yeal Lake, Quin Brook wetlands and Quin Swamp are located in the Yeal Nature Reserve, an 11 269 ha class A and C crown reserve for the conservation of flora, fauna and water (DPaW 2016a). The nature reserve is one of the largest unfragmented remaining habitats of its type on the Swan coastal plain. It is internationally recognised as a Strict Nature Reserve (Category 1a) in the International Union for Conservation of Nature (IUCN) protected area categories (DPaW 2016a).

The reserve has high conservation value because it:

- is an excellent example of the range of soil and vegetation types associated with the Bassendean Dune System, which is becoming increasingly uncommon on the Swan coastal plain (Department of the Environment 1995)
- has a significant area of remnant Banksia woodland with a rich diversity of habitats for birds, reptiles and amphibians (Department of the Environment 1995).

The Banksia woodlands in the reserve, of which the wetlands are part, are nationally recognised as endangered ecological communities (Commonwealth of Australia 2016).

The north Yeal wetlands are part of the linear chain along Quin Brook that links the permanent water habitats of the lower perennial Lennard Brook with those of the lower perennial reaches of Gingin Brook. Corridors formed by wetlands are critical to allow movement of species between these perennial systems, as has been reported for reptiles elsewhere in temporally variable wetlands (Roe & Georges 2007). The wetlands also support the range of habitats required for ecological functioning of the surrounding woodland community, including the provision of seasonal feeding grounds for fauna in the reserve.

2.5 Cultural significance

Wetlands across the Swan coastal plain are spiritually significant to Indigenous groups (Nyungar people) and were used extensively before European settlement (Wright 2007a). Many lakes and swamps were used as hunting and gathering areas for flora and fauna (McDonald et al. 2005).

An anthropologist was contracted to undertake an ethnographic survey of the north Yeal wetland region before drilling works began. This established the Indigenous heritage values of the wetland area in line with the *Aboriginal Heritage Act 1972* (WA) and the *Native Title Act 1993* (Clth).

The wetlands were surveyed using a team of traditional owners with an anthropologist and two archaeologists. The technique included making use of the traditional owners to widen the scope of the archaeological surveys (Wright 2007a). This area falls under the Yued people native title area, which abuts the Whadjuk people native title area to the south.

The survey found there were no areas of ethnographic cultural significance that would prevent drilling. The Yued native title claimants felt the proactive nature of the project would be beneficial to the environmental values associated with the groundwater systems (Wright 2007b).

Site works and disturbance were kept to a minimum by using smaller footprint direct-push drilling methods where possible and new infrastructure was installed within the existing disturbed areas.

2.6 Land and water management

The *Gnangara* groundwater areas allocation plan (Department of Water 2009b) sets out the approach for the allocation and licensing of all water users of the Gnangara groundwater system. DWER determines the volume and spatial distribution of water abstracted from the system by assessing potential impacts on groundwater resources, GDEs and existing users.

For allocation purposes, the Gnangara groundwater system is divided into groundwater areas and subareas. The north Yeal wetlands are located in the proclaimed Gingin Groundwater Area and within this, the Deepwater Lagoon South Subarea (Superficial; Figure 8) and the SA 3 South Confined Subarea (all of the area north of Deepwater Lagoon boundary, see Figure 8). These subareas are bordered to the south by the Reserve Subarea (Superficial) and the Gnangara Confined Subarea in the Gnangara Groundwater Area. For administrative purposes, allocation limits are divided into components (Table 3) for:

- water that is available for licensing:
  - general (or private) licensing
  - public water supply (PWS) licensing
- water that is exempt from licensing
- water that is reserved for future public water supply (PWS reserve).

The allocation status of the subareas described above is shown in Table 3. Licensed groundwater use from the Superficial aquifer in the Deepwater Lagoon South Subarea is nearing the allocation limit with limited water still available for licensing (Table 3). There is also limited water available for licensing from the Superficial aquifer in the Reserve Subarea and the Leederville aquifer in the Gnangara Confined Subarea. In the SA 3 South Confined Subarea the Leederville aquifer is over-allocated. The Yarragadee aquifer is also over-allocated in the Gnangara Confined Subarea.

The Yeal Nature Reserve is a crown reserve managed for conservation purposes by the Department of Biodiversity, Conservation and Attractions (Figure 8). The land use to the north and east of the nature reserve consists of partly cleared freehold land used mostly for grazing agriculture and lifestyle activities. There is some irrigated horticulture to the north. Land to the west and south of the reserve is mostly unallocated crown land used for plantation pine production, with some uncleared Banksia woodland to the south.

The area to the north of the north Yeal wetlands is subject to some private groundwater abstraction, with bores in a 2 km radius of Quin Swamp licensed to abstract up to 600 ML/yr from the Superficial aquifer and 16 ML/yr from the Leederville aquifer. Most abstraction within 5 km of the wetlands is from the Superficial aquifer via 22 mostly small entitlements (< 0.1 ML/yr) to the north and north-east of the wetlands (Figure 8). There are only two entitlements from the Leederville aquifer within 5 km of the wetlands, both being to the north of Quin Swamp. Demand for further groundwater from the Superficial aquifer is not anticipated to increase in the foreseeable future based on projected land development, however the potential for increased abstraction from the Yarragadee aquifers for public water supply at more than 25 km south of the wetlands was considered as part of the Perth Regional Aquifer Capacity Project.

Table 3 Allocation limits, licensed entitlements and water availability for new licences by aquifer for the groundwater subareas in the Yeal area (2013)

Subarea	Resource	Allocation limit components as at 2013 (GL/yr)[1]				Water available for further general licensing (GL/yr)	Water available for further PWS licensing (GL/yr)
		Licensable		Not Licensable	Reserved		
		General	PWS	Exempt	PWS reserve		
Deepwater Lagoon South	Superficial aquifer	3.49	-	0.01	-	0.11	-
SA 3 South Confined	Leederville aquifer	2.47	0.13	-	-	-0.42	-0.43
	Yarragadee aquifer	0	0	-	-	0	0
Reserve	Superficial aquifer	1.53	2.8	-	4.50	0.11	2.15
Gnangara Confined	Leederville aquifer	-	13.1	-	2.00	-	1.95
	Yarragadee aquifer	-	5.15	-	-	-	-5.90

[1] *Allocation limit components and water availability data are from WRL reports run on 2 May 2014.*

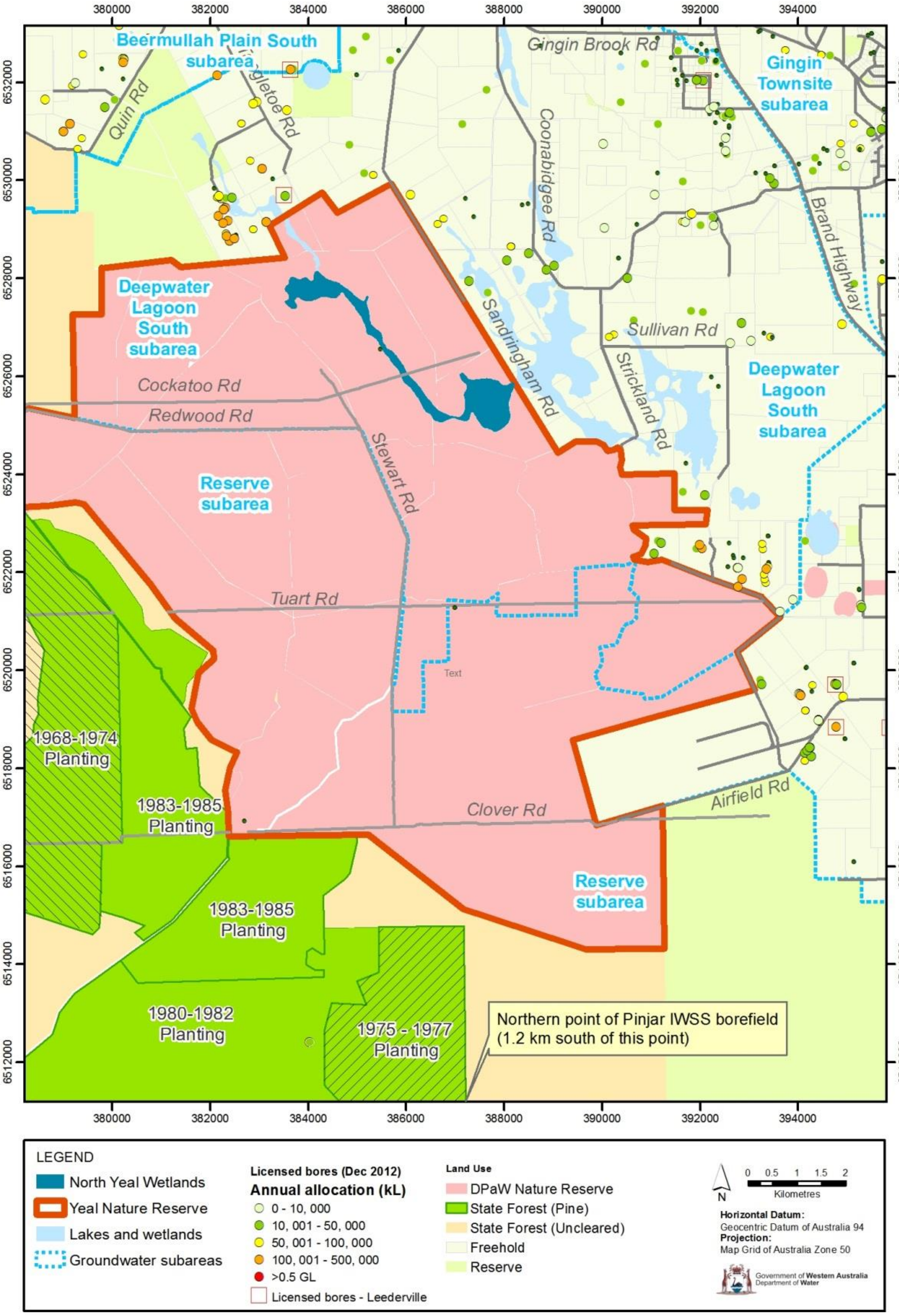

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Figure 8 Land use and annual licence allocations around the Yeal Nature Reserve (as at December 2012)

3 Investigation program

Shallow groundwater interactions at Yeal Lake, wetlands along Quin Brook, and Quin Swamp were studied in combined hydrogeological and ecological investigations. The hydrogeological investigations comprised drilling and construction of lithological cross-sections using data from drilling of previous monitoring bores, with hydraulic interactions interpreted from spatial and temporal trends in water level hydrographs. This was linked with ecological monitoring at the wetlands used to determine ecological water requirements (EWRs).

3.1 Bore construction

Groundwater monitoring bores were installed in clusters at each wetland to intercept both the perched and Superficial aquifers thought to be present in the area and allow measurement of groundwater flows. Two clusters were installed at Quin Swamp with one up-hydraulic-gradient of the swamp (east of the swamp) and a second down-hydraulic-gradient (west of the swamp; Figure 9). A single cluster was installed up-hydraulic-gradient at the upper Quin Brook wetland site (east of the wetland; Figure 9). A single shallow bore was installed up-hydraulic-gradient at Yeal Lake (east of the lake) to complement the nearby cluster of bores (NG15a and NG15b) installed previously to the lake's north-east (Figure 9).

Clustered bores installed at the upper Quin Swamp and Quin Brook wetland sites were screened at three depths representing different zones of the Superficial aquifer (Table 4). The drilling techniques, lithology and construction details of all the bores are reported in Searle (2009a, 2009b) with specific details reproduced in Appendix C. Infill and augering of the Yeal Lake and Quin Swamp beds (Figure 9) was later carried out using an AMS hand auger.

3.2 Acid sulfate soils analysis

Sediment samples were tested to determine the distribution and characteristics of sulfidic sediments and the potential to affect groundwater quality if exposed and oxidised by a declining watertable.

Field tests were conducted on sediment recovered by direct-push core extraction for the shallow investigation bores (QUNEc, QUNWc, CYWc and YLc) and hand auger sites. Field assessment of acid sulfate soils was carried out using field pH (to measure pH_F) and peroxide oxidation (to measure pH_{FOX}) methods, as detailed in previous shallow groundwater systems investigations (Degens et al. 2012). Details of field testing, laboratory analysis and assessment criteria are given in Appendix D.

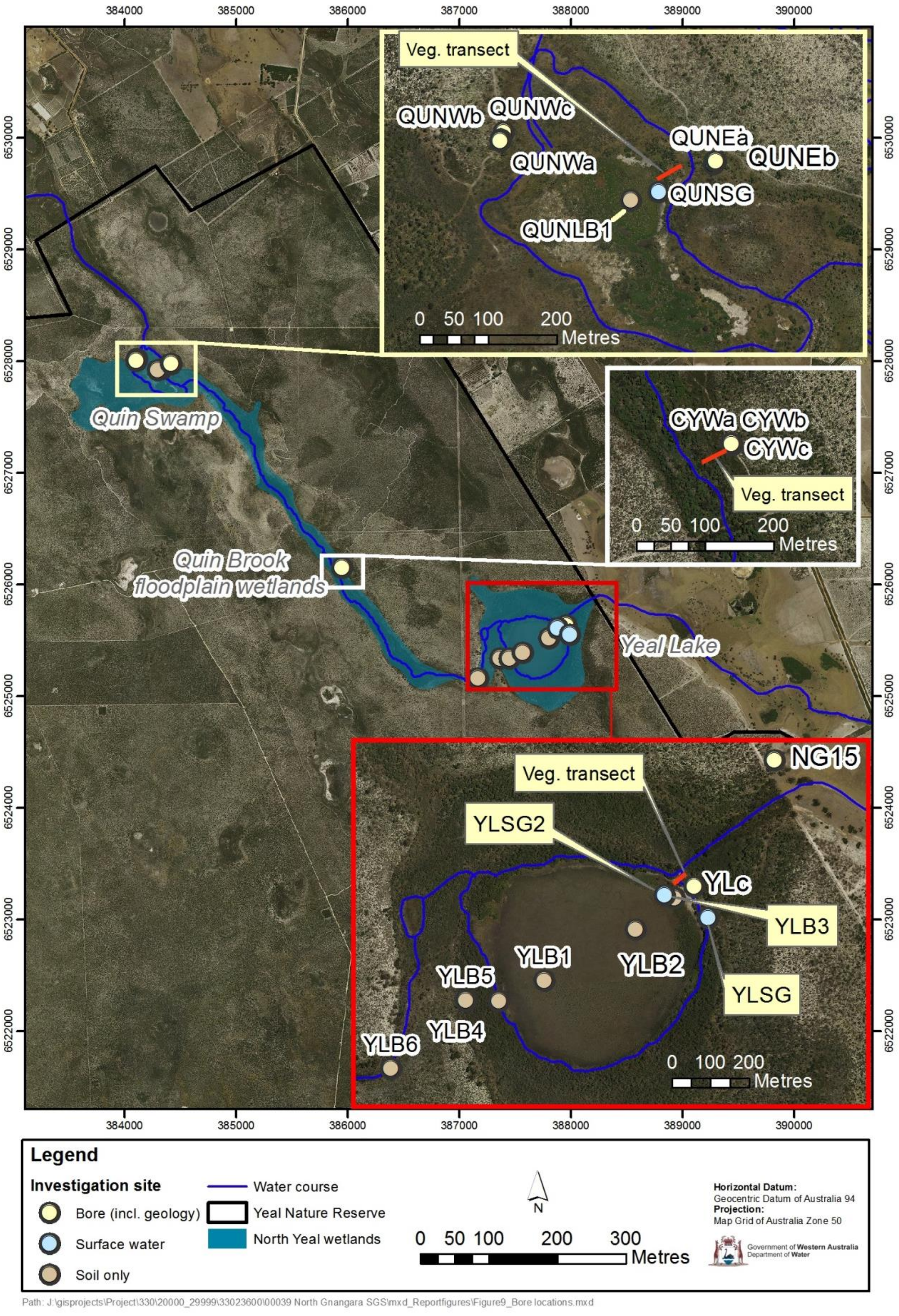


Figure 9 Location of groundwater bores, surface water gauges and vegetation monitoring transects and soil investigation sites

Table 4 Investigation bores installed at Yeal Lake, Quin Brook wetland (central Yeal) and Quin Swamp

Site	Bore ID (AWRC name)	AWRC number	Depth	Drilled depth (mbgl)	Screen interval (mAHD)	Formation
Yeal Lake	YLc	61710494	Shallow	4.8	59.84 – 56.84	Bassendean Sand
Quin Brook wetland (central Yeal)	CYWa	61710478	Deep	42	20.76 – 18.76	Gnangara Sand
	CYWb	61710479	Intermediate	24	41.08 – 39.08	Gnangara Sand
	CYWc	61710480	Shallow	9.5	57.87 – 51.87	Bassendean Sand
Quin Swamp (east)	QUNEa	61710590	Deep	39	24.27 – 22.27	Gnangara Sand
	QUNEb	61710591	Intermediate	21	36.85 – 34.85	Bassendean Sand
	QUNEc	61710592	Shallow	5	54.66 – 50.66	Bassendean Sand
Quin Swamp (west)	QUNWa	61710496	Deep	42	20.2 – 18.2	Gnangara Sand
	QUNWb	61710588	Intermediate	21.6	36.89 – 34.89	Bassendean Sand
	QUNWc	61710589	Shallow	5.6	55.27 – 51.27	Bassendean Sand

3.3 Water monitoring and sampling program

Lake water and groundwater level monitoring, sampling and analysis was undertaken to determine the aquifer's hydrochemical characteristics and groundwater and surface water relationship. Groundwater was sampled from the bores installed for the project (Figure 9; Table 4) and lake water samples were collected near the staff gauges in Quin Swamp and Yeal Lake (Figure 9).

Water samples from bores were collected using low-flow pumping methods and grab sampling. These were analysed using the same methods as previous investigations (Degens et al. 2012). Major ions, metals and nutrients were measured for all water samples (Table 5). Replicate samples for water quality were periodically taken from bores to assess the accuracy of analyses, with the laboratory undertaking repeat analyses to control precision errors. Samples were taken for analysis of pesticides from groundwater bores twice at Quin Swamp (June 2009 and January 2010), three times at the upper Quin Brook wetland (July 2008 and January and June 2009) and once at Yeal Lake (June 2009). A single sample of surface water was collected for analysis of pesticides from Yeal Lake in January 2010.

Table 5 *Summary water sample analysis suite*

Description	Element/compounds
Total metals	Hg, Al, As, Cd, Cr, Fe, Mn, Ni, Se, Zn
Dissolved metals (0.45µm filtered)	Ca, Mg, Na, K, B, Fe, Al
Nutrients	NH_3-N, TN, TP, NOx, SRP
Other inorganic constituents	EC, TSS, TDS, HCO_3, CO_3, Cl, F, SiO_2, SO_4, pH, Acidity, Alkalinity, DOC, DON
Pesticides	Aldrin, Atrazine, Azinphos-ethyl, Azinphos-methyl, Bromophos-ethyl, Chlordane, Chlorfenvinfos, Chlorpyrifos (tot), Chlorpyrifos-methy (tot), DDD-p,p, DDE-p,p, DDT-p,p, Diazinon, Dimethoate, Dieldrin, Diuron, Endosulf sulfate, Endosulf-a, Endosulf-b, Endrin aldehyde, Endrin ketone, Enthion, Fenchlorphos, Fenitrothion, Fenthion, HCH (BHC) a,b,d, HCH (BHC), Heptachlor, Heptachlor epoxide, Hexachlorobenzine, Hexazinone, Linuron, Malathion, Methoxychlor, Metolachlor, Mevinphos, Molinate, Oxychlordane, Oxyfluorofen, Parathion {Ethyl par.}, Parathion-methyl, Pendimethalin, Pirimiphos-ethyl, Pirimiphos-methyl, Simazine, Tetrachlorvinphos, Trifluralin

3.4 Ecological monitoring and ecohydrology

An ecological monitoring program was established to align with the hydrogeological investigation. Wetland vegetation was monitored at all three wetlands, along with macroinvertebrates at Yeal Lake and Quin Brook.

In 2009 vegetation transects were established that extended perpendicular from the waterline to at least 40 m, traversing near the monitoring bores (Figure 9). Baseline surveys were undertaken to describe the wetland vegetation communities and initial condition, with the sites being monitored annually for vegetation and macroinvertebrates.

The transect at Yeal Lake was established on the lake's north-eastern side (Figure 9), running in a west to east direction. At Quin Brook wetland the vegetation transect runs west to east, starting at the edge of the brook and ending at the CYW bores (Figure 9). Similarly, the transect at Quin Swamp was established on the swamp's eastern side from the edge of the wetland basin.

EWRs for wetland vegetation were based on the mean water depths of common wetland species, as presented in Table 6. These are maximum depths after which the species will suffer stress (Froend et al. 2004a). For each species found at each wetland, the mean minimum water depth (m) was subtracted from the minimum elevation (mAHD) at which that species was found at the wetland. For example, the mean minimum water depth of *Melaleuca rhaphiophylla* is 2.14 mbgl and at Yeal Lake it was found at elevations of 59.83 to 61.08 mAHD. Following the appropriate calculation (59.83 - 2.14), the minimum water level required to maintain *M. rhaphiophylla* at Yeal Lake is 57.69 mAHD. If required, a maximum water level can be determined by adding the mean maximum water (m) of a species to its maximum elevation (mAHD) at a wetland.

EWRs were also determined for macroinvertebrates at Yeal Lake and Quin Brook based on maintaining sufficient surface water to ensure egg and seedbank survival. These were at least 0.5 m inundation for four to five months to ensure the survival of most spring and summer species (Strehlow et al. 2013) and calculated as the level above the deepest point of each wetland.

Table 6 *Common wetland species and minimum water depth requirement.*

Species	Mean range of groundwater depth (metres relative to ground level)[1]
Baumea articulata	0.28 to –1.22
Baumea juncea	0.28 to –2.65
Eucalyptus rudis	–0.7 to –3.26
Melaleuca rhaphiophylla	0 to –2.14
Melaleuca preissiana	–0.54 to –2.62

[1] *After Froend et al. 2004b*

3.5 Data processing and analysis

The charge balance for all water samples was verified by the laboratory before reporting and before use in analyses. This also applied to data included from previous groundwater investigations (Yesertener 2010; Pigois 2010). Deviations of more than 5% were investigated and excluded where there was no satisfactory cause. Values below laboratory reporting limits were deemed half this value for plotting and calculations.

Cation excess (or anion deficit) was typically attributed to under-estimation of HCO_3 for some samples, with low pH and high dissolved iron and organic acids where there were high concentrations of dissolved organic C (> 200 mg/L). Excess anions were found in low pH samples due to charge contribution from dissolved Al and Fe (assuming present as Al^{3+} and Fe^{2+} respectively). Rounding errors for analysis of Cl and SO_4 in samples with very low salinity also explained other deviations of up to 9%.

Only onsite measurements of pH, temperature, DO and ORP were used, with ORP converted to *Eh* (relative to the standard hydrogen electrode). Net acidity for water samples was calculated from alkalinity, pH and dissolved Fe, Al and Mn concentrations in groundwater as per Kirby and Cravotta (2005) and Degens (2013).

Rainfall reference values for major ion composition were obtained from Hingston and Gailitis (1976) for Yanchep and Perth. These were used to calculate concentrations of major ions with conservative evapo-concentration for use as reference points for analysis of major ions in surface water and groundwater. Hingston and Gailitis (1976) represents the best analysis of average major ion composition for a whole rainfall year relevant to Gnangara, given recent sampling was restricted to individual rainfall events spanning 2003 to 2008 (Yesertener 2010).

General characteristics, nutrients, trace elements and pesticides of lake and shallow groundwater were assessed against guideline values for south-west wetlands and aquatic ecosystems (ANZECC & ARMCANZ 2000). All groundwater results were compared with drinking water guideline values (NHMRC & NRMMC 2004) representing the highest-value use. These guideline values are more conservative but appropriate for groundwater in an area recharging deeper confined aquifers used for drinking water supply.

3.6 Collation and analysis of regional data

The hydrogeology of the wetlands was determined by analysing data from this investigation alongside other data from previous drilling and long-term groundwater level and quality monitoring in the area (Figure 10). This provided the subregional hydrogeological context for the hydrogeological interaction at the wetlands.

3.6.1 Collation and sourcing of data

Lithological and hydrochemical information was compiled from bore completion reports (e.g. Pigois 2009; Searle 2009a; Searle 2009b), verified records of lithology in the WIN database and scans of original lithology recorded during drilling (for shallow monitoring bores in the GA, GB, GC and GD series).

Hydrographs used for watertable trend analyses came mostly from watertable bores (Figure 10; Appendix E). Where available, data was used from bores where reasonable records of water levels existed (at least from 1977 until 2010) and the construction depth could be verified from either drilling records or recent site records. However, in some areas there were very few bores meeting these criteria and it was necessary to consider data from some bores with part records or uncertain construction (only total depth known). Data was excluded where water levels were below the extent of the dip tape or where blockages were apparent. Summary construction (where known) of all existing bores used in the investigation are presented in Appendix E.

Rainfall and evaporation data were obtained from the SILO data drill (Department of Environment and Resource Management 2012). This data is interpolated from actual records in the area. Rainfall was extracted for analysis of trends in water levels at site –31.45º latitude, 115.80º longitude (31 º 27' S, 115 º 48' E) corresponding with the approximate centre of the Yeal Nature Reserve. For assessing Yeal Lake’s water balance, daily rainfall and evaporation data was obtained for –31.40º latitude, 115.80º longitude (31º 24' S, 115º 48' E) corresponding with the nearest SILO data interpolation point to the centre of Yeal Lake.

3.6.2 Analysis of spatial patterns in water level trends

Watertable levels for bores screened across or within 2 m of the watertable in the Superficial aquifer were analysed to identify major temporal and spatial patterns in watertable trends across the investigation area. These were identified by graphical analysis and plotted spatially in ArcGIS by contouring historic watertable levels and contrasting these with contouring of more recent watertable levels (a four-year annual average covering 2009–12). Maximum and minimum levels were not analysed because the accuracy of these varied (as a result of the mix of monthly, quarterly and biennial level records for the bores in the area). Contouring was carried out by kriging water levels using the ArcGIS geostatistical spatial analysis tool.

3.6.3 Hydrograph analysis

The contribution of changing rainfall patterns to trends in watertable levels were evaluated for representative bores using linear multiple regression. HARTT (Hydrograph Analysis: Rainfall and Time Trends) software was used to statistically separate the effects of anomalous rainfall from other impacts such as land use change or groundwater pumping on temporal groundwater levels (Ferdowsian et al. 2001; Kelsey 2014). Rainfall trends were represented by cumulative deviation from mean rainfall (CDFM; Yesertener 2002) calculated as annual average residual rainfall (AARR), since this provided best representation of within-year fluctuations. The approach is outlined below – see Appendix F for details.

HARTT was used to statistically determine the best time-lag between rainfall and water level responses (rain-only model), then determine the rainfall time series for bores of interest using a set of ‘control’ bores. This approach follows that of Kelsey (2014) where the best start date (or origin) of the rainfall time series was first determined using ‘control’ bores GB21 and GC12 in similar geology (see Appendix F for details). ‘Control’ bores were those where the influence of land and water use is stable over the monitoring record; hence water level variation in bores must be mostly explained by variation in rainfall patterns.

Several bores across the nature reserve were selected for analysis to represent trends across the reserve (GA10, GB22, GB23, GC11, and GC19). These bores were screened across the watertable and had a record spanning at least 30 years (to 2012). Other nearby bores were considered but not analysed because of limited or inconsistent records, no suitable control bore, or were exhibiting a large influence from surface water flows (see Appendix F).

For the analysed bores, rainfall trend effects were determined through an iterative process of analysis to achieve the regression model with best fit. HARTT was initially applied to water level data using only rainfall data with a 1945 origin to determine the best lag period for the effects of rainfall (Ferdowsian et al. 2001; Kelsey 2014). As well as verifying the statistical fit (correlation coefficient and fit of variables), the modelled water levels were visually compared with the actual data to determine if most of the temporal patterns were reproduced throughout the period analysed. After

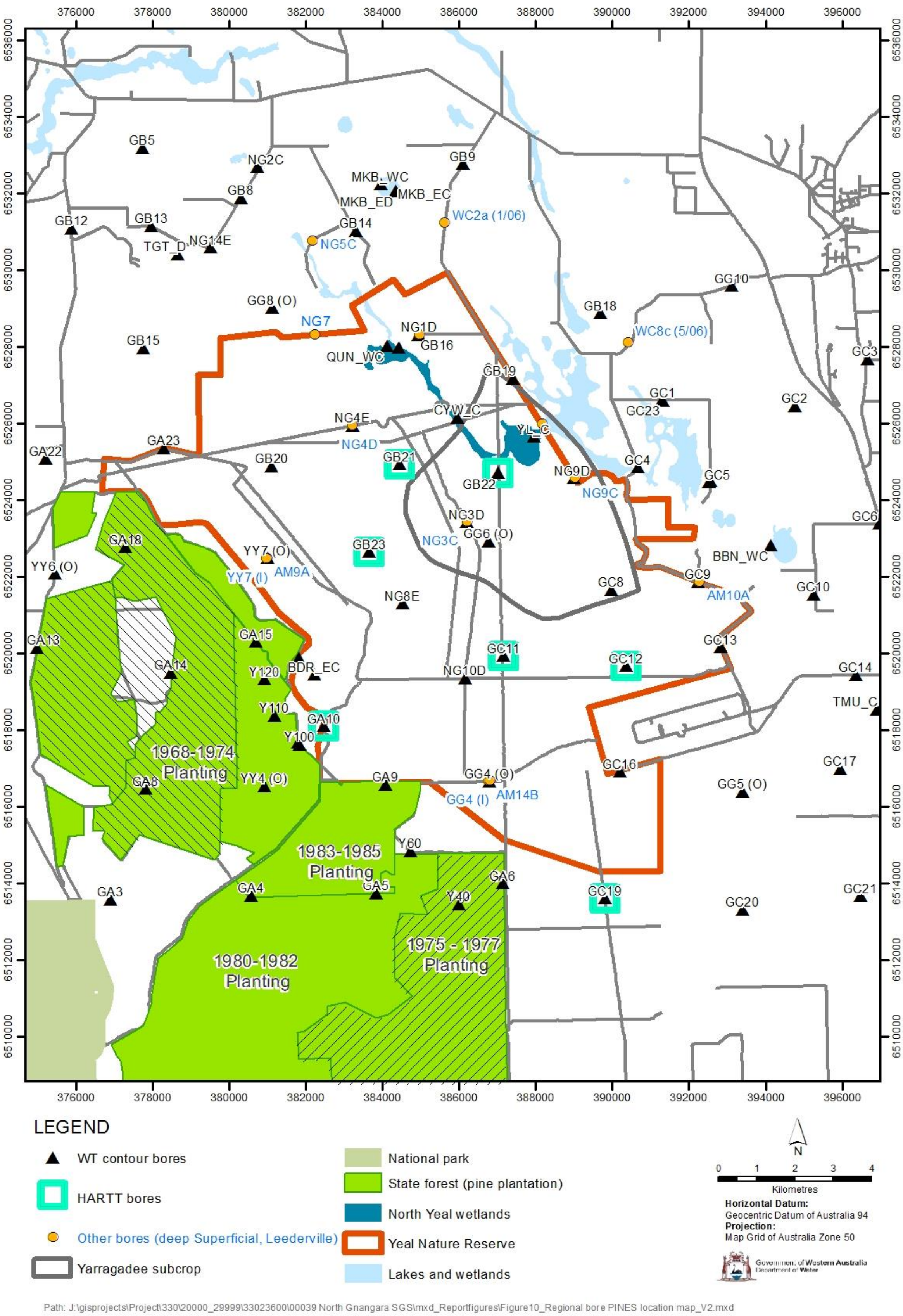


Figure 10 Monitoring bores where data on water levels or lithology were used in this investigation

this, extra variables were added stepwise to the models to correspond with when the rain-only model deviated from the actual water levels (see Appendix F). This was done to maximise r^2 values and reproduction of the majority of temporal patterns. These variables were only included where there was *a priori* evidence of land use change, surface water flooding, pumping or water level drawdown in the deeper aquifer corresponding in time with water level changes. Spatial fire history from DBCA (Department of Environment and Conservation 2012) was used to assess when fires were likely to influence water levels. For most models, stepwise application of the regression, applying rainfall then the effects of pine plantations, found that this could explain most variation without the need to consider any additional effects of drawdown of the Leederville aquifer toward the end of the analysis period.

4 Geology

4.1 Superficial and Mesozoic formations

Drilling found the superficial formations at the north Yeal wetlands to be at least 42 m thick (Table 7), comprising Bassendean Sand interfingering with the thinning western edge of the Guildford Formation and overlying the Gnangara Sand and Ascot Formation (Figure 11; Figure 12; Figure 13). These comprised the Superficial aquifer in the investigation area.

The Bassendean Sand clearly interfingered with the Guildford Formation at the upper Quin Swamp (QUN bores) and Quin Brook (CWY) wetland sites (Figure 12; Figure 13). Interfingering was not as distinct at Yeal Lake due to limited borehole data. However, the extension of the Guildford Formation beneath the lake is likely based on its presence to the east of the lake (NG15), shallow lithology in the lake bed (Appendix D) and an unsaturated zone identified from NMR logging at WC8c (Figure 11; Appendix G). Bassendean Sand was 2 to 13 m thick, present as grey to brown fine- to medium-grained quartz sands that were mostly well sorted.

The Guildford Formation was present as upward fining sequences of sands and clays. The sands were mostly light brown, medium to coarse grained and well sorted, commonly including silt. Clayey sands and sandy clays were typical towards the top of the sequence, being mostly grey-brown to dark brown. These corresponded with peaks in gamma log and/or induction profiles for the boreholes for some of the clay and sandy clay lenses at Quin Brook (CYWa) and Quin Swamp, although the gamma profile was weaker at QUNWa. NMR logging of the deep bores also confirmed the formation beneath the wetlands was of low permeability but saturated (Appendix G).

Lakebed sediments of Yeal Lake and Quin Swamp consisted of 0.2 to 0.8 m of organic silts underlain by thin sequences of mostly dark greyish-brown to greenish-grey sandy clays and sands (Appendix D). These appeared to be fluvial deposits and were interpreted to be contemporary with the Guildford Formation (after Gozzard 2007b), which also supported the reasoning for interpreting the Guildford Formation to extend beneath Yeal Lake (Figure 11).

The Guildford Formation was interpreted at NG1 and NG15 from the lithology of chip tray samples. Analysis of NG1 suggests the Guildford Formation from 6 to 23 mbgl. Gamma logging was not used at NG1a because the signal was attenuated by the steel used to case the drill holes through the Superficial formations. The formation was evident as upward fining sequences of sands (15–22 mgbl) overlaid by sandy clays (6–15 mbgl) and a thin reworked bed. Similarly, a sandier facies of the formation was interpreted at NG15 from 7 to 21 mbgl, containing minor clay beds and short upward fining sequences. This also linked with contemporary deposits in nearby Yeal Lake (Figure 11).

Gnangara Sand was interpreted as 9 to 29 m thick at a depth of > 21 m (< 41 mAHD) and unconformably overlaid the Ascot Formation (Figure 11). The formation was typically evident below the Guildford Formation and Bassendean Sand as a facies change to upward fining sequences of generally bimodal and poorly sorted, medium to very fine sands containing lithic fragments (mostly feldspars). Larger grains were rounded and smaller grains subangular, conforming with the Gnangara Sand description (Davidson 1995; Davidson & Yu 2006). Furthermore, greater feldspars with depth corresponded with an increase in the gamma radiation counts towards the base of the drilled holes in the downhole geophysical logs at Quin Swamp and Quin Brook. Upward fining sequences in the formation were interpreted to reflect a fluvial source pattern similar to the aggrading rivers depositing the similar aged Guildford Formation (Gozzard 2007b). In this case, the decreasing energy of fluvial transport to the nearshore or estuarine environment in which the Gnangara Sands were deposited may have resulted in a similar upward fining evident in the Guildford Formation.

Table 7 Stratigraphy and lithology for the deep bores drilled at Quin Swamp (QUNEa, QUNWa) and Quin Brook wetland (CYWa)

Bore	From	To	Dominant lithology	Formation	Code
QUNEa	0	2	Sand	Bassendean Sand	Qd
	2	24	Sand, silty sand, sandy clay	Guildford	Qg
	24	35	Silty sand and bimodal sand; upward fining	Gnangara Sand	Qn
	35	39	Calcarenite and sandstone	Ascot	Ta
QUNWa	0	1	Sand	Bassendean Sand	Qd
	1	18	Sand, silty sand, clayey sand and sandy clay; short upward fining sequences	Guildford	Qg
	18	25	Sand	Bassendean Sand	Qd
	25	26	Clayey sand	Guildford	Qg
	26	42	Silt sand and bimodal sand; upward fining	Gnangara Sand	Qn
CYWa	0	13	Silty sand, cemented sandstone	Bassendean Sand	Qd
	13	17	Sandy clay	Guildford	Qg
	17	25	Silty sand and sand	Bassendean Sand	Qd
	25	40	Silty sand and bimodal sand; upward fining	Gnangara Sand	Qn
	> 40		Siltstone and fine sandstone; glauconitic	Ascot	Ta

Drilling intersected 29 m of the Gnangara Sand at NG15 towards the bottom of the hole and in thinner intervals at NG1, NG3, NG4 and NG7 (Figure 11; Figure 12;

Figure 13). At NG15, this was identified during re-examination of chip samples as upward fining sequences containing bimodal non-calcareous sands and feldspar grains from 21 m (41.6 mAHD) to 50 m (12.6 mAHD). Similar facies indicated the formation at 23 to 30 m depth at NG1, 39 to 50 m depth at NG3 and 37 to 43 m depth at NG4. At NG7, a distal part of the formation was interpreted to be at 31 to 41 m depth. The lithological interpretation at NG1, NG3 and NG4 also corresponded with increased gamma counts in geophysical logging compared with the overlying Bassendean Sand. Gnangara Sand was not present at site WC8 based on the lithological log for bore WC8c (05/06) and comparison of gamma logging for adjacent bore WC8b (05/07).

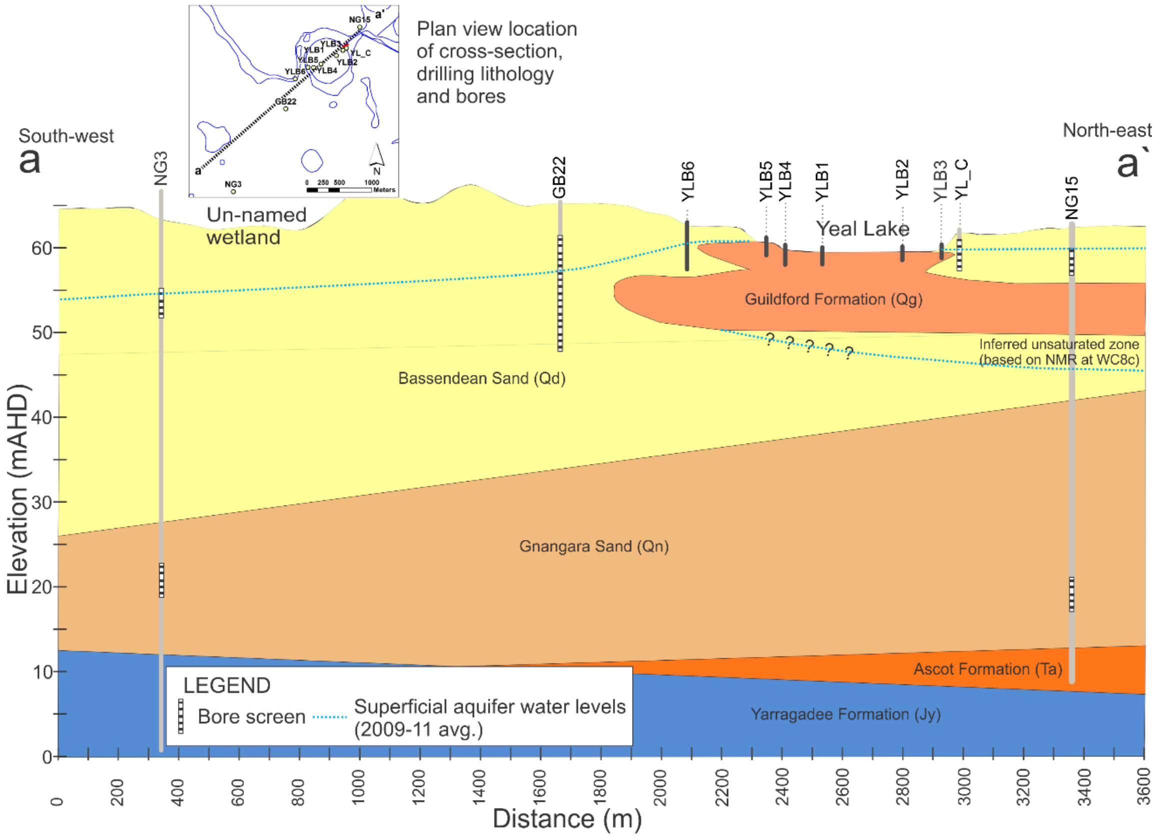


Figure 11 Interpreted local geology and hydrogeology cross-section including monitoring bores for Yeal Lake

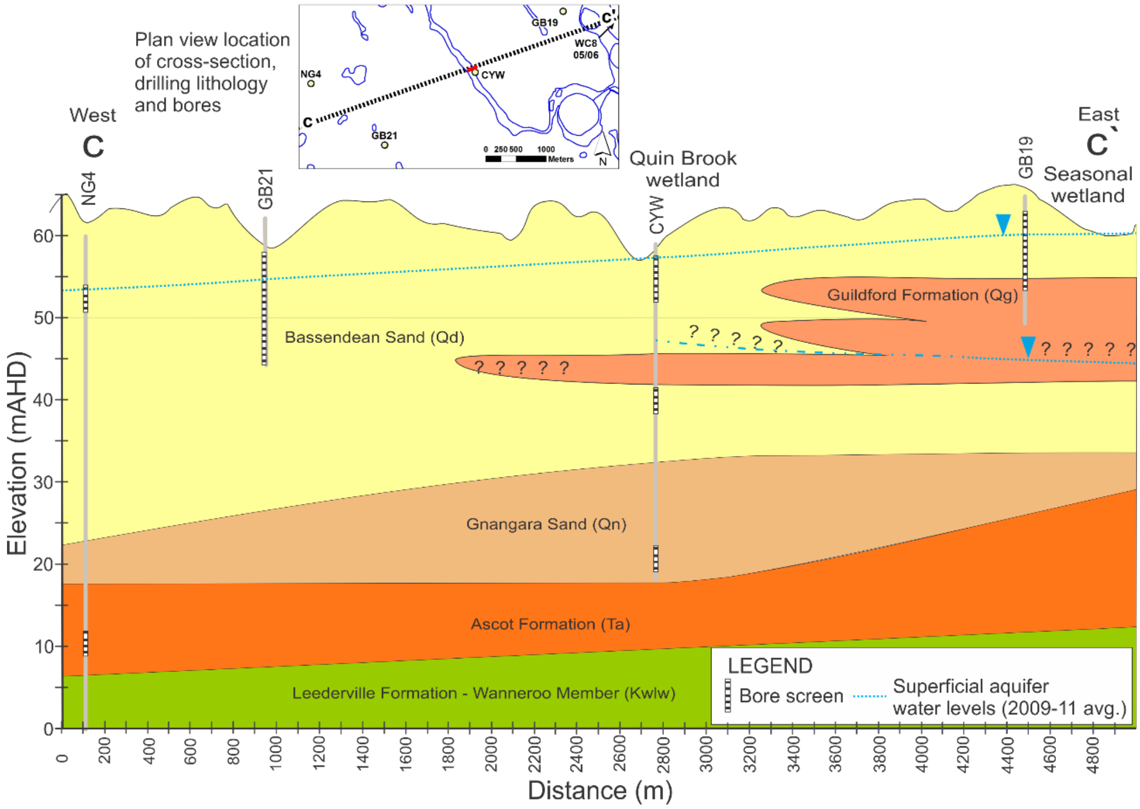


Figure 12 Interpreted local geology and hydrogeology cross-section including monitoring bores for the upper Quin Brook wetland

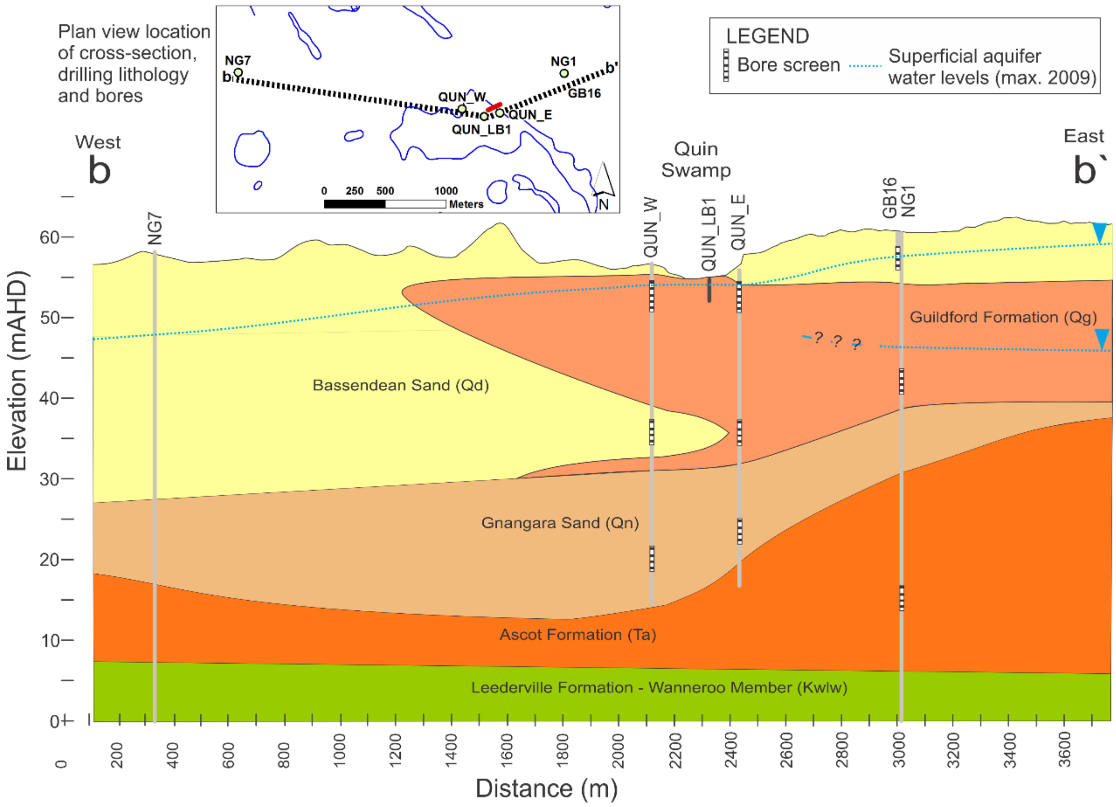


Figure 13 Interpreted local geology and hydrogeology cross-section including monitoring bores for Quin Swamp

The top of the Ascot Formation was intersected at > 35 mbgl at the Quin Swamp and Quin Brook wetland sites. The formation consisted of hard calcarenite (confirmed in acid testing of chip samples) cementing fine subangular sand containing minor glauconite and heavy minerals. The full thickness of the Ascot Formation was not drilled during the investigations, however was 4 to 24 m thickness at nearby sites (NG1, NG4, NG7 and NG15a). The Ascot Formation was interpreted to lie unconformably on the Leederville Formation (Warnbro Group) based on previous investigations at NG1, NG7 and NG15 (Pigois 2009; Pigois 2010). The top of the Leederville Formation was initially interpreted at > 36 m (< 19 mAHD) at Quin Swamp from lithology (Searle 2009a, b), but was not verified with geophysical data and palynological evidence illustrating the unconformity. Later examination of the lithology found the presence of calcarenite and glauconite consistent with the Ascot Formation.

4.2 Acid sulfate soil assessment

There were actual and potential acid sulfate soils (ASS) at all wetland sites and shallow actual ASS in Quin Swamp with no inherent neutralising materials. Potential ASS materials were found at Quin Swamp and Yeal Lake below the minimum watertable, but not detected at Quin Brook wetland. There was a general pattern of acidification in and around the wetlands. Shallow actual ASS was found in Quin Swamp and Yeal Lake and the soils around Quin Brook wetland and Quin Swamp had oxidised and acidified at up to 2 m thickness around the depth of the watertable. Further acidification of the wetlands and shallow aquifer is likely should the watertable decline, but there is minimal risk of harmful concentrations of trace metal mobilising from the soils.

ASS materials were in the aquifer in and around the bed of Yeal Lake with no neutralising materials such as carbonates. Around the lake, the shallow superficial sediments were generally non-acidified with pH being > 6 and contained minor levels of potential ASS from 2.4 (< 0.3 m below the watertable) to at least 4.5 m depth (Figure 14; Appendix D). In the lake bed, potential ASS materials were found in near-surface silt and peaty silt beds on eastern side (at YLB3) and at > 1 m depth in half of the cores (Figure 14; Appendix D). Most lake bed sediments were around neutral pH to more than 1.5 m, but on the lake's western side (YLB1 and YLB4) there was a thin acidic (pH < 4) lens at > 0.5 m depth (Figure 14; Appendix D). This was found in sand, clayey sand and sandy clay lenses that were below the watertable at the time of sampling and underlain by circum-neutral sands and sandy clays with PASS that containing up to 20 moles H^+/tonne (Appendix D).

The shallow superficial formations at the Quin Brook wetland was generally acidic (pH < 4) in a 1 m zone above and below the watertable at the time of sampling (2008), but less acidic with depth (Figure 14). Analyses indicated that the actual acidity (TAA; Appendix D) was generally low and did not exceed existing DEC (now DWER) guideline limits, indicating low risk to the environment. Acidification was attributed to ASS oxidation, but no PASS materials were indicated in field testing or detected in subsequent laboratory analyses.

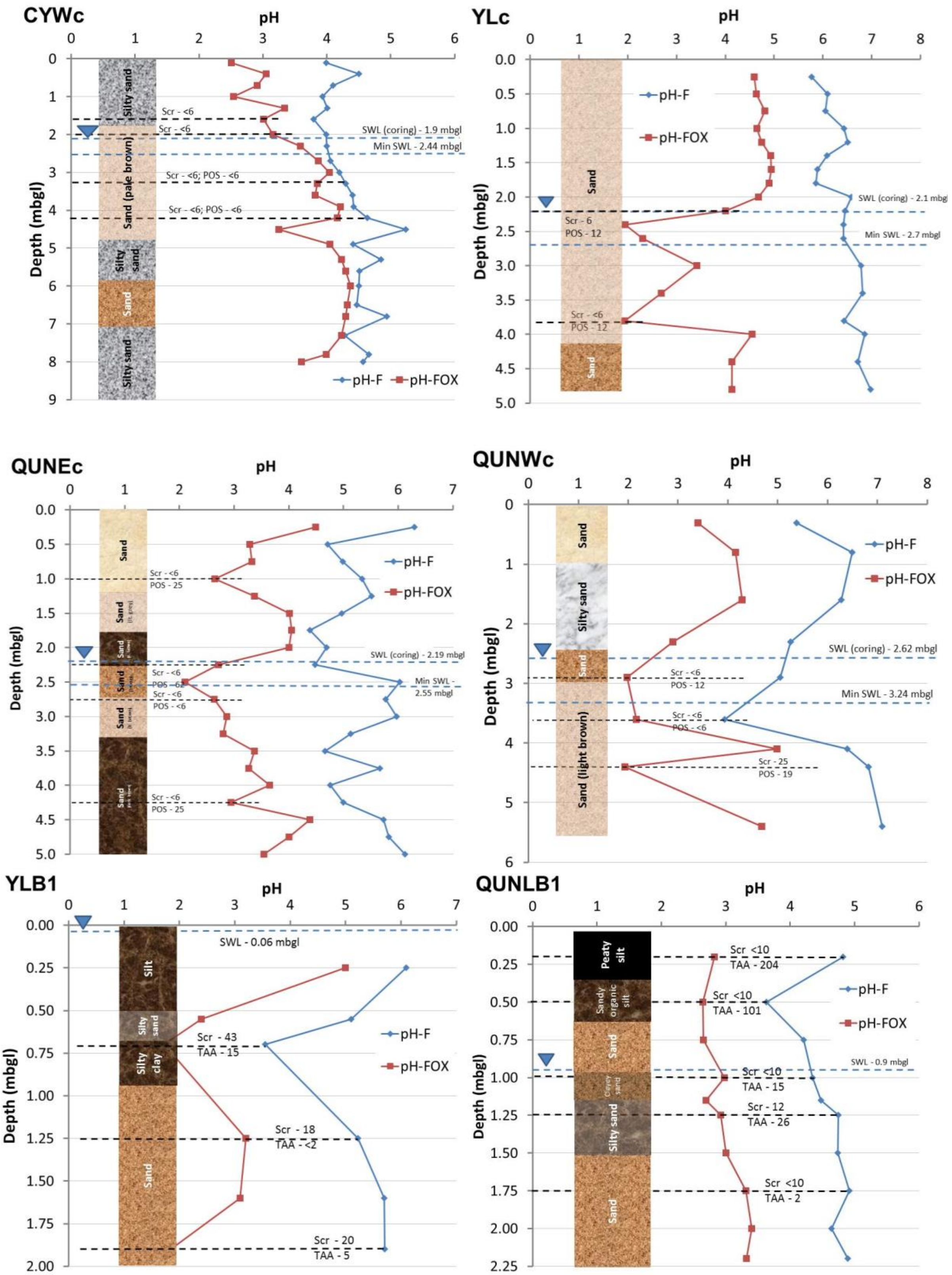


Figure 14 Field (F) and peroxide (FOX) oxidised pH, summary lithology and potential acidity analyses (moles H^+/tonne) for superficial formations and selected lake beds at three north Yeal wetlands

At Quin Swamp, the shallow superficial formations had a pattern of tending to be acidic (pH < 5) within 1 m of the watertable in the swamp bed and on the swamp's east and west side, but generally tended to be trending to circum-neutral with depth (Figure 14). On the swamp's west side, sediment pH was less than 4 at 3.6 m depth with was no significant actual acidity (Appendix D). In contrast, sediment pH was 4.4 to 4.7 near the watertable on the swamp's east side but at 2.25 m actual acidity (TAA) was four times DWER action criteria at 76 moles H^+/tonne (Appendix D). Field tests indicated potential acidity beneath the watertable on both sides of the swamp but laboratory analyses showed low-level PASS materials. The range of potential acidity was from less than 6 moles H^+/tonne to 62 moles H^+/tonne. The often more reliable S_{Cr} analysis method (Ahern et al. 2004) generally did not detect potential acidity. This is probably because losses of the low concentrations of ASS materials occurred during sample preparation and analysis.

In general, the potential acidity of the deeper sediments at the Quin Swamp sites exceeded most of the shallow sediments and all sites exceeded DWER guideline limits where sulfide acidity risks are deemed to pose a risk to the environment if unmanaged.

Organic rich sediments in the bed of Quin Swamp were found to be very acidic (pH_F < 4) and underlain with clayey sands and sands where the pH increased from 4.2 to 4.9 with depth. The acidic sediments (0.35–0.6 m) were above the watertable and contained significant available acidity (TAA) of up to 204 moles H^+/tonne but no residual potential acidity (Figure 14). Minor potential acidity remained below the watertable.

Low concentrations of potential acidity were not detected by laboratory analyses of many of the sands in and around the wetlands because of oxidation during sample preparation. This has previously been found for sands during sampling preparation for analysis (Ahern et al. 2004) – despite the use of rapid oven drying – and is evident from pH_{KCl} results on samples after drying and grinding being more than half a unit less than field pH to more than 1 unit greater in some samples.

Concentrations of metals and metalloids in the sediments indicated no risk to the environment, should these acidify by ASS oxidation. All were below the DWER sediment ecological investigation limit action criteria or with Cd, Se and As commonly being below detection (Appendix D).

5 Hydrogeology

Localised, shallow, semi-perched to perched groundwater within Bassendean sands was present above the Guildford Formation at the wetlands which, depending on the location, interacted with the regional Superficial aquifer beneath and to the west of the wetlands. The following section presents evidence in local water level responses and hydrochemical patterns of the spatial variation in connectivity between the wetlands, the semi-perched groundwater and the regional Superficial aquifer. Water levels for the bores and staff gauges constructed for the investigation were analysed in conjunction with levels recorded for bores in the area surrounding the wetlands.

5.1 Groundwater flow

Contouring of regional groundwater levels indicate flow in the Superficial aquifer is west-north-westerly around Quin Swamp, tending to south-westerly near Yeal Lake. Flow is also in a south-westerly direction in the broader Yeal Nature Reserve south of Yeal Lake. A localised radial flow pattern exists to the reserve's east which, in the decade to 2012, weakened in the north-east (see Section 6.2). Groundwater gradients are generally flatter in the reserve's east and central part (including around the north Yeal wetlands) and steepen downgradient of the reserve's western edge.

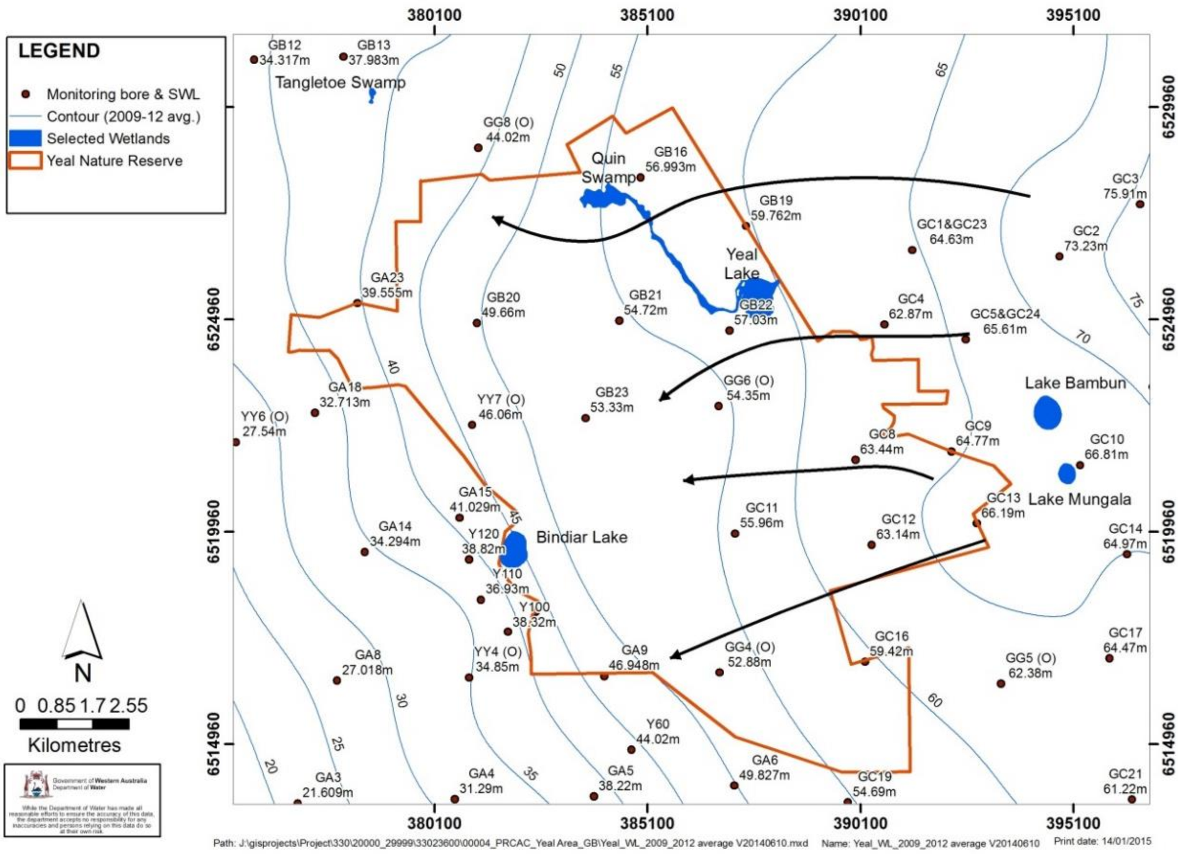


Figure 15 Average watertable contours in the Superficial aquifer 2009–2012 showing regional groundwater flow paths

5.2 Water levels in perched groundwater at Yeal Lake

Water level patterns indicate Yeal Lake fills with surface water inflows and seasonally interacts with a thin (1–6 m) perched groundwater system. The lake acts as a sump, with subsequent retention of water largely dependent on a high watertable around the lake. The downgradient regional watertable has limited influence.

5.2.1 Lake levels in relation to local groundwater levels

Levels at Yeal Lake varied significantly between dry and maximum filled states from 2008 to 2012. Lake levels exceeded 1.4 m depth (60.7 mAHD) in the 2008 and 2009 winters when water overflowed to Quin Brook for short periods of time and thereafter declined until the lake was dry. Levels also briefly increased to 0.36 m depth in 2011 before drying the following summer (Figure 16). Water levels typically rise in response to inflow initially from the small catchment to the lake's north-east (Figure 7), while major filling events in 2008 and 2009 were dominated by inflows via the larger channel draining from lower Lennard Brook (Figure 7).

The lake's water level patterns closely corresponded with groundwater levels at YLc and perched groundwater at NG15b, with no similar response deeper in the aquifer at NG15a (Figure 16). Water levels reached an annual maximum between early September to late October during the four-year monitoring period, with levels at NG15b tending to rise earlier and fall more slowly than at YLc and in the lake (Figure 16). There was a similar, but smaller amplitude seasonal response at GB22, 0.8 km south-west of the lake, with peak levels more than one month later (Figure 16). In contrast, no seasonal pattern was evident in the watertable at NG3c, 2.5 km south-west of the lake, or from the deep Superficial aquifer bore NG15a near the lake (Figure 16). The latter indicated little propagation of seasonal watertable responses or any effects of the lake filling to this depth in the aquifer. During inflow to the lake, groundwater levels at YLc tended to be greater than in the lake (up to 0.4 m), whereas during the drying phase were slightly below the lake (less than 0.05 m). When there was no surface water in the lake, groundwater levels at YLc were generally no more than 0.5 m below the lake bed, except in early 2011 when water levels fell to 0.75 m below the lake bed.

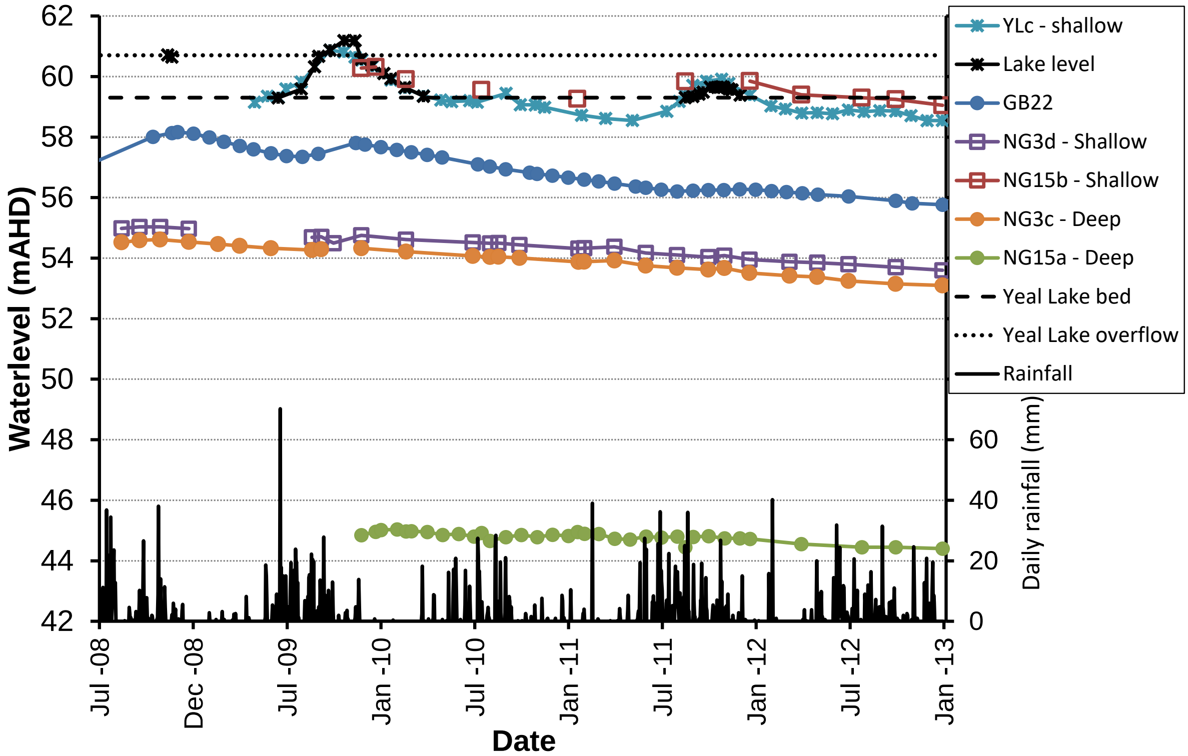


Figure 16 Hydrographs for Yeal Lake and nearby bores in the Superficial aquifer with rainfall at Gingin airport (9178)

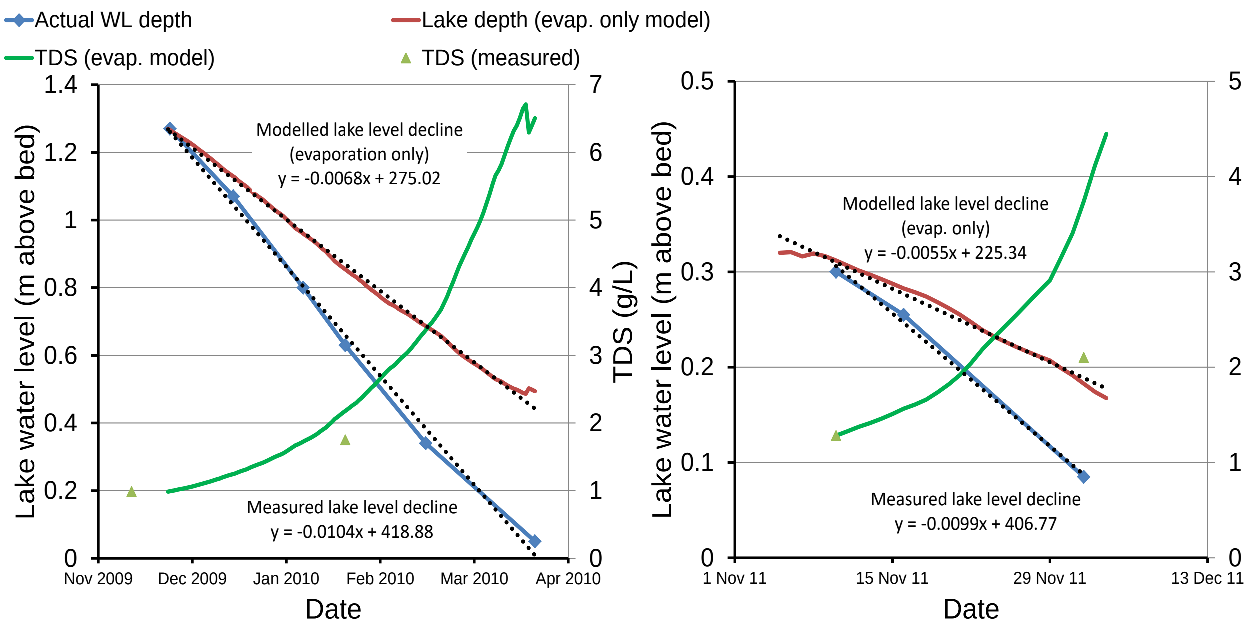


Figure 17 Measured and modelled evaporation only decline in water levels following cessation of surface inflow to Yeal Lake in 2009 and 2011

5.2.2 Interaction with groundwater indicated by recession in lake levels

Lake water levels receded by more than evaporation alone – indicating additional loss to shallow groundwater. The rate of decline in lake water levels after surface inflow ceased in 2009 and 2011 was 1.5 to 1.8 times greater than modelled evaporation (Figure 17). This indicates another pathway for loss that is most likely recharge to the shallow perched groundwater. Modelled decline in water levels due to net evaporation was estimated from daily SILO data as net evaporation (mm) = rainfall – 0.7 x pan evaporation (after Linacre 1993). The average rate of decline in excess of evaporation was estimated to be 3.6 to 4.4 mm/day (difference between linear regression slopes in Figure 17) representing more than 30% of water loss from the lake.

The fall in water levels faster than evaporation rates indicated the lake was losing to the shallow groundwater. When the lake contains water, leakage to groundwater is controlled more by the local mounding than downgradient water levels. The rate of lake level decline was greater than in groundwater (following peak recharge) west and north of the lake. Measured rates of decline of 10.4 to 9.9 mm/day in 2010 and 2011 (coefficient of regressions in Figure 17) were more than double that of groundwater at Quin Brook wetland (4.2–5.0 mm/day) and Quin Swamp (2.2–3.9 mm/day). These was also much greater lake level decline than watertable recession west of the wetland at GB22 (average 0.3–3.0 mm/day) or NG3d (1.1–1.6 mm/day). Transpiration by fringing vegetation might account for some but not the majority of the greater decline in water levels at Yeal Lake.

The rate that salinity increased in the lake during drying was less than evaporation, also indicating loss of lake water to groundwater. TDS modelled as evaporation from the lake surface (assuming the lake was a part-filled sphere) was greater than measured TDS by up to double. This was consistent with loss of water (and salts) as recharge to the thin perched groundwater around the lake, rather than conservative concentration of salts within the lake during drying. Some lake water may have discharged to the east with groundwater levels at YLc during the drying phases being slightly less than lake levels.

There is evidence that leakage is independent of the decline in groundwater levels downgradient. This is probably a function of the thin saturated thickness of the shallow aquifer, which limits lateral flows to the regional aquifer when the lake fills. The rate of lake recession in 2009 after filling (10.4 mm/day) was slightly less than that after filling in 2013 (11.9 mm/day), despite the downgradient water levels in the regional aquifer falling by more than 2 m in the same period. This indicated that the change in downgradient head levels had little effect on the rate of leakage from the lake. Further evidence of groundwater thickness limiting flows is indicated by the peak in groundwater at GB22 downgradient being more than one month later than peak levels in the lake. This is consistent with slow lateral propagation of groundwater levels arising from mounding at the lake or any overflow to the brook rather than a delayed recharge pulse, which is typically in October/November.

5.2.3 Local groundwater trends and gradients

Groundwater trends at the lake when it was dry corresponded more with upgradient than downgradient shallow groundwater. During dry periods across 2009–12, the minimum watertable at the shallow bore YLc decreased by an average of 0.15 m/yr. This was more similar to the long-term trend of 0.08 m/yr upgradient at GB19 than the 0.29 m/yr at GB22 downgradient (Appendix H). Declining trends at GB22 and NG3d east of the lake (Figure 16) were no greater than much further east at NG4d or GB21 (Figure 18). In contrast, groundwater levels in the deeper Superficial aquifer were declining at a slightly lesser rate of 0.11 m/yr near the lake at NG15a and a much greater rate of 0.33 m/yr to the west of the lake at NG3c.

There was a slight horizontal gradient at the watertable (< 0.15%) to the east of the lake when dry between NG15b and Ylc, indicating groundwater flow east to west beneath the wetland. When the lake filled in 2009 there was a slight local reversal in the perched watertable gradient. To the west, a steep watertable gradient of up to 0.5% forms when filled, as indicated by the difference in water levels between GB22 and the lake (Figure 16). When the lake is dry, however, the gradient falls to less than 0.4%. Measurement of water levels on the lake's western side during hand auger investigations in 2011 (Appendix D) indicated that a slight east to west gradient persisted across the lake when dry. Water levels in YLB6 (57.86 mAHD) were 1.68 m higher than 410 m further west at GB22 on the same day, indicating a gradient of 0.4% to the west of the lake.

In contrast with watertable gradients, water levels deeper in the aquifer were greater in the west at NG3c than at the wetland (indicated by NG15a), indicating likely groundwater flow from west to east (Figure 16). Similar watertable and deep aquifer water levels at NG3c also indicated a very slight downward gradient, whereas at NG15 a steep gradient was maintained with water levels in the deep aquifer – being consistently more than 14 m lower than the watertable.

5.2.4 Summary interpretation

Water level patterns indicate shallow groundwater is locally perched at Yeal Lake with a saturated thickness of more than 5.9 m thinning significantly to the west. This system contributes little direct groundwater discharge to the lake, but influences the retention of water in the lake, particularly on the eastern edge. Further east the shallow groundwater system is perched above a 2 m layer of clayey sands at 10 mbgl. Perching is based on an unsaturated zone indicated by mid-aquifer water levels being up to 5 m below the clayey sand layer and a dry zone at this depth reported during drilling at NG15a (JP Pigois pers. comm. 2013). The lack of a pressure response in the deeper aquifer (e.g. NG15a) when the lake is filled shows that this is disconnected from the shallow perched groundwater. The lake lies on interbedded shallow clay and clayey sand sediments that slow vertical recharge to groundwater, since some were dry and well cemented at depth (see YLB2 and YLB5, Appendix D). The low permeability layers likely extend at least to the lake's western edge, becoming shallower and constraining the saturated thickness of the perched groundwater. This pattern contributes to limiting the influence of declines in the regional Superficial aquifer on groundwater at the lake. When the lake contains water, this likely recharges groundwater on the western edge based on recession of lake levels and salinity during drying. When the lake is dry, trends in shallow groundwater levels are influenced more by trends upgradient than downgradient.

5.3 Water levels in semi-perched groundwater at upper Quin Brook wetland

Groundwater patterns indicate a thin, semi-perched groundwater system beneath upper Quin Brook wetland with limited local hydraulic connection to the regional Superficial aquifer but connection with this downgradient.

5.3.1 Patterns in local groundwater levels

The water levels in bores near Quin Brook wetland (CYW) displayed a typical seasonal pattern with greater amplitude in the shallower bores but almost none in deeper bores (Figure 19). Peak water levels in the shallow bore were generally reached between late September and late October, but were earlier in 2010, when rainfall was well below average (Figure 2; Figure 18). These peaks corresponded with some surface ponding in the wetland during 2008 and 2009. In contrast, water levels in the mid and deep aquifer bores peaked a month later in 2008 and 2009, but no peak was clear in the deeper bores in 2010 and 2011 (see also Appendix I). The seasonal amplitude of the shallow groundwater varied from 0.67 to 0.89 m. Despite a reduced monitoring frequency, the timing of seasonal peaks in water levels in the shallow bore GB19 was similar, but the amplitude of the seasonal variation was less than for the shallow bores at the Quin Brook wetland. In contrast, there was little seasonal variation in water levels in the watertable bore at NG4 west of the wetland, with slight peaks in November (Figure 18).

Hourly logging of water levels showed there was slow propagation of water pressure responses between the watertable and mid-aquifer at the wetland. This was clearest in 2008 and 2011 when mid-aquifer pressure responses were slow, being in the order of days to weeks after short-term watertable rises (Appendix I). NMR logging also indicated that the sandy clays lying between the shallow and deeper groundwater had low permeability. The clays contained high water content but this was generally present as capillary water and likely to have had low vertical hydraulic conductivity (Appendix G).

These results suggest impeded hydraulic connection between the shallower groundwater and the mid to deep groundwater in the Superficial aquifer immediately beneath Quin Brook wetland.

Shallow groundwater levels at the wetland varied between 0.5 m above to 0.9 m below the bed of the brook between 2008 and 2012 (Figure 18). These levels were consistently more than 10 m higher than in the mid-aquifer, which were less than 1.5 m greater than in the deep aquifer (Figure 18). This indicated a large downward gradient (up to 60%) between the semi-perched groundwater and the underlying Superficial aquifer, where the gradient was small (average 5%). There was a similar weak downward gradient (< 2%) in the Superficial aquifer east of the wetland with water levels at NG4 being less than 0.7 m different between the watertable and deep aquifer.

Groundwater flowed east to west beneath the wetland following a slight horizontal gradient at the watertable (0.14–0.15%) between the bores in the east (GB19) and west (NG4) of the wetland. Yet deeper in the aquifer water levels were greater in the west at NG4 than at the wetland, indicating likely flow from west to east (Figure 18).

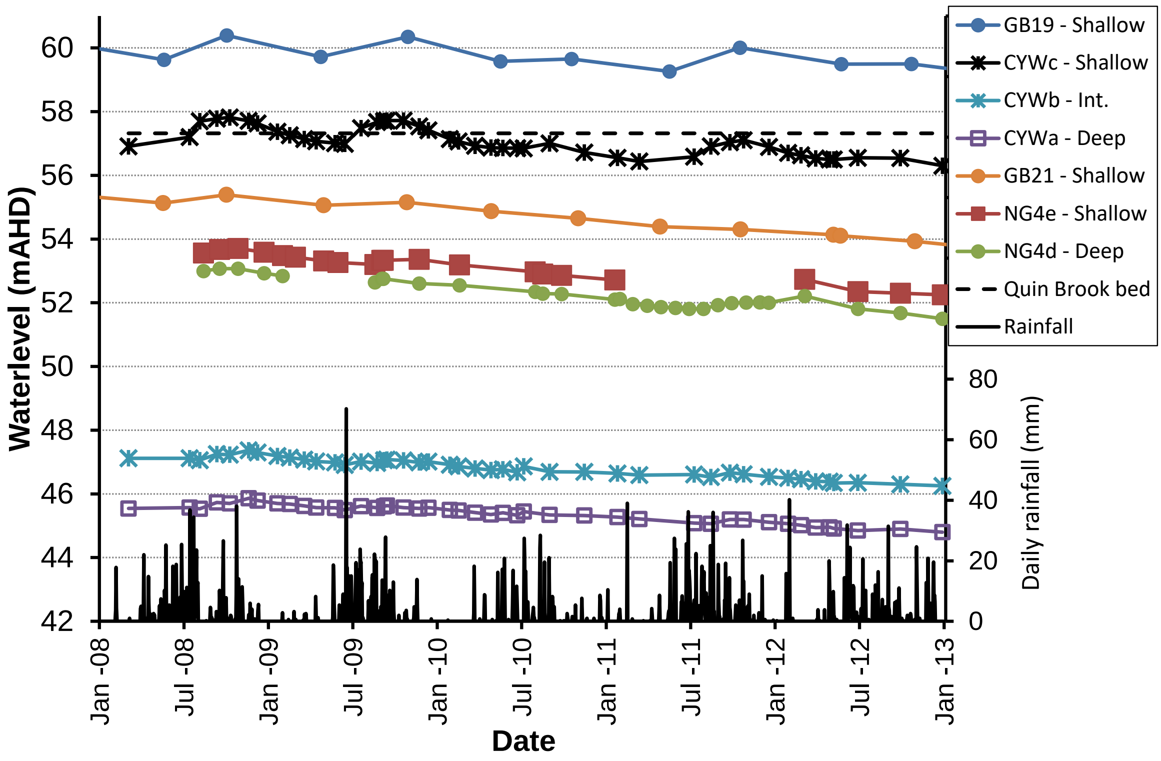


Figure 18 Hydrographs for bores in the Superficial aquifer at upper Quin Brook wetland (CYW) and nearby at NG4, GB21and GB19 with rainfall at Gingin airport (9178).

There were slight decreasing water level trends in all monitored bores around the wetland that were more similar to downgradient than upgradient bores. Watertable levels decreased at an average rate of 0.25 m/yr at Quin Brook wetland between 2008 and 2012. This was more than double the long-term trend of 0.09 m/yr at upgradient GB19 and more similar to the downgradient decline of 0.29 m/yr at GB21 (Appendix H) and 0.33 m/yr at NG4e. In contrast, mid and deep aquifer groundwater levels were declining at slightly slower rates of 0.18 to 0.22 m/yr.

5.3.2 Summary interpretation

Water level patterns indicated a local semi-perched shallow groundwater system beneath upper Quin Brook wetland with a saturated thickness of more than 10 m. This system is above a 4 m thick bed of low permeability sandy clay at 13 mbgl with poor hydraulic connection to the underlying Superficial aquifer. The shallow groundwater system is declining at a rate more consistent with regional decline to the west (outflow) than the east (inflow). The shallow groundwater system was not perched because of the absence of an unsaturated zone beneath the low permeability layers in NMR logging (Appendix G) and head pressures (water levels) in the mid depth of the Superficial aquifer maintaining water in contact with these. However, the aquifer is considered to be semi-perched (see Pederson 2000) on the basis of an interaction with the regional Superficial aquifer to the west.

Declining water levels in the regional Superficial aquifer at upper Quin Brook wetland indicate that this is likely to become disconnected from the shallow groundwater system, but not before 2032 at current rates of decline. During this time, water levels of the shallow groundwater system will be influenced by decline in the regional Superficial aquifer downgradient of the wetland more than beneath the wetland. NMR logging indicates that leakage through the low permeability beds is only likely to be by capillary flow. It is expected that the semi-perched groundwater will transition to a perched system if water levels continue to decline.

5.4 Water levels in semi-perched groundwater at Quin Swamp

Groundwater patterns indicate a thin (< 4 m) local semi-perched shallow groundwater system at Quin Swamp. This has a slight to weak hydraulic connection to the regional Superficial aquifer and is influenced more by water levels upgradient than downgradient.

5.4.1 Patterns in local groundwater levels

The water levels in bores near Quin Swamp (QUN series) displayed a typical seasonal pattern of fluctuations, being of greater amplitude in the shallow (watertable) bores than the deeper bores (Figure 19). Seasonal high water levels were generally between late September and early October at the watertable, although were earlier in 2010, when rainfall was well below average (Figure 2; Figure 19). A similar pattern was evident for the mid and deep aquifer but with the amplitude being less than a tenth that of the watertable. This is a typical dampening influence of the low permeability unit between the watertable and deep aquifer. The seasonal water level response at mid-aquifer was greater on the swamp's eastern than western side.

Hourly water level logging showed similar, slow propagation of rainfall recharge responses to the deep Superficial aquifer on both sides of the swamp. This is also consistent with a semi-perched shallow groundwater system overlying sediments with limited permeability (Appendix I). The pressure response pattern was best illustrated for recharge during the 2011 winter when rises in mid aquifer pressures east of the swamp were several weeks after short-term watertable rises (Appendix I). This indicated some hydraulic connection between the regional aquifer and the watertable east of the swamp. However, no connectivity was evident on the swamp's western edge, with mid aquifer water levels not reflecting changes in the shallower watertable.

Very limited propagation of seasonal recharge responses to the deep Superficial aquifer east of the swamp also indicated that shallow groundwater was semi-perched. Seasonal variation in the watertable was greater in bore GB16 than for the watertable bores at Quin Swamp, despite the reduced monitoring frequency at GB16 (Figure 19). The seasonal amplitude for the adjacent deep Superficial aquifer bores at NG1 were negligible and much less than in the deeper aquifer bores at Quin Swamp. This indicated seasonal pressure responses were more retarded than at Quin Swamp, which is typical of perched groundwater disconnected from an underlying regional aquifer (Pederson 2000).

Collectively these results suggest there is a semi-perched shallow groundwater system at Quin Swamp. There is weak hydraulic connection between the shallow and mid-aquifer on Quin Swamp’s eastern but not western edge and connection sharply decreases over the 700 m distance to NG1 east of the swamp.

A large vertical gradient (average > 26%) existed between the semi-perched shallow groundwater and the underlying regional aquifer. This was indicated by groundwater levels in shallow bores on both sides of Quin Swamp being consistently lower than the lake bed (by 0.3 to 1.6 m) and more than 4.2 m higher than in bores in the underlying regional aquifer (Figure 19). In comparison, water levels differed by less than 0.7 m between the deep and mid aquifer on both sides of the lake, indicating weak downward gradients (< 2%) in the underlying Superficial aquifer. A similar pattern was also evident east of the lake, where groundwater levels were more than 10 m greater in the shallow bore (GB16) than the deeper screened Superficial aquifer bores at NG1. Similar water levels for the two NG bores indicated there was no vertical gradient in the underlying regional Superficial aquifer.

There was no horizontal gradient across the lake (the shallow bores had similar levels), but a slight gradient existed in the underlying Superficial aquifer, indicating flow from the east to west (Figure 19). A large horizontal inflow gradient east of the swamp (average 0.2%) was indicated by watertable levels at GB16 being more than 1.5 m higher than the shallow QUNEc bore. In contrast, mid-aquifer water levels indicate flow eastwards with levels being typically 3.6 m lower in NG1C than QUNEb (Figure 19).

Slight decreasing water level trends at the watertable were evident in all monitored bores around the wetland and were more similar to upgradient than downgradient bores. From 2009 to 2012, the watertable decreased by an average of 0.1 m/yr at Quin Swamp, which was 10 times the long-term rate of decline at GB16 (0.01 m/yr) but similar to GB19 (0.09 m/yr) further upgradient (Appendix H). However, rates of decline were less than half of the rate of downgradient decline of 0.2 m/yr at GG8(O) or 0.33 m/yr at NG4e. In contrast, watertable levels in deeper bores below the low permeability layer were declining at about double that at the watertable and were more similar to the deep aquifer decline at NG4d downgradient.

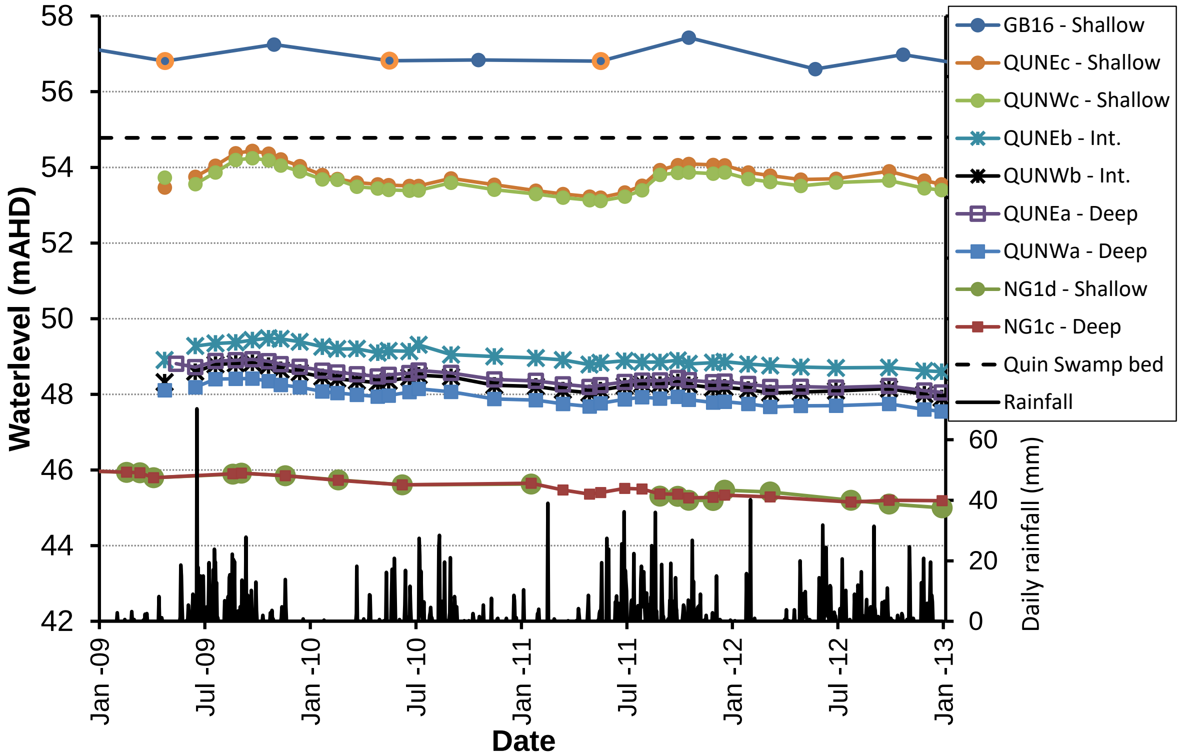


Figure 19 Hydrographs for bores in the Superficial aquifer at Quin Swamp and to the east (NG1 and GB16) with rainfall at Gingin airport (9178)

5.4.2 Summary interpretation

Water level patterns indicated a local semi-perched shallow groundwater system at Quin Swamp with a spatially varying saturated thickness of between 3 and 9 m. This system was above thin (< 1 m) discontinuous, low permeability beds of clayey sands and sandy clays at greater than 6 mbgl. The shallow aquifer was not considered truly perched at the swamp and was weakly hydraulically connected with the underlying Superficial aquifer at least on the eastern edge. This is consistent with being a semi-perched groundwater system (Pederson 2000). NMR sensing of pore water found no unsaturated zones beneath low permeability beds in the Guildford Formation and that the formation was more hydraulically conductive on the swamp's eastern than its western edge (Appendix G). This was also consistent with propagation of seasonal water level pressures east and west of the swamp indicating interaction of mid-aquifer groundwater with the shallow groundwater. The shallow groundwater becomes perched within 700 m east of the swamp, with evidence of hydraulic disconnection at NG1 and further east and north-east. At WC2A (north-east) and WC8C (east), the perched groundwater (0–6.5 mbgl) is separated by more than 10 m of unsaturated zone from the Superficial aquifer (Appendix G).

Declining water levels in the shallow groundwater at Quin Swamp indicate that this will gradually transition from a semi-perched to seasonally perched system. At current rates of decline, disconnection is calculated to be after 2025 on the swamp's eastern side and after 2035 on the western side. These times are based on when the water level will be beneath the low permeability beds either side of the wetland. Shallow groundwater levels are likely to continue declining after hydraulic disconnection from the regional aquifer. This will be spatially variable depending on the thickness and lithological composition of the low permeability beds, with NMR logging (Appendix G) indicating some capillary flow (leakage) through these is likely beneath the swamp.

5.5 Hydrochemistry

Vertical patterns in groundwater chemistry revealed differences in dominant hydrochemical facies reflecting the semi-perched groundwater at Quin Swamp and upper Quin Brook wetland, perched groundwater at Yeal Lake and variable influence of the Guildford Formation on interaction with the deeper regional aquifer.

5.5.1 General characteristics

Perched and semi-perched groundwater at each wetland had basic properties different from groundwater deeper in the aquifer and from surface water in Yeal Lake.

Water in Yeal Lake ranged from fresh after filling in winter to brackish during the final stages of drying in late summer and did not reflect the salinity of local groundwater (Table 8). Perched groundwater at the lake was often slightly more saline and varied less seasonally. In contrast, the salinity of semi-perched groundwater at Quin wetland (CYWc) and Quin Swamp (QUNEc) was, on average, half that at Yeal Lake but 1.5 times more saline to the west of Quin Swamp (Table 8). There was little seasonal variation in semi-perched groundwater salinity at Quin Brook wetland but at Quin Swamp maximum salinity (in early winter) was more than double that of minimum salinity. These patterns show that the groundwater salinity has little influence on wetland salinity and that plant transpiration is probably seasonally driving increased shallow groundwater salinity (through root uptake of water that leaves the salts behind in groundwater).

There was a mixed pattern of salinity with depth in the Superficial aquifer at each wetland, indicating significant spatial variation in recharge and flow paths beneath the wetlands. At Yeal Lake, groundwater at the base of the Superficial aquifer in NG15a was less than 250 mg/L TDS (Pigois 2009), contrasting with more than three times higher salinity in the shallow groundwater at YLc (Table 8) and GB22 (870 mg/L TDS, March 2014). Similarly, salinity decreased with depth in the aquifer east of Quin Swamp (Table 8). However, at Quin Brook wetland and to the west of Quin Swamp, salinity was greatest in the mid depth of the aquifer (Table 8).

Groundwater was generally mildly acidic at Yeal Lake, but at Quin Brook wetland and Quin Swamp a pattern of shallow groundwater acidification extended to mid aquifer. Surface water in Yeal Lake was within the range typical for south-west Australian wetlands with highly coloured waters (pH 4.5–6.5; ANZECC & ARMCANZ 2000). Shallow groundwater beneath the lake had slightly lower pH, but was above 5.7 (Table 9), whereas shallow groundwater in one-off sampling to the north at GB19 (March 2014) was an order of magnitude lower at pH 4.4. Acidic shallow groundwater at Quin Brook wetland and Quin Swamp was also reflected in acidic shallow groundwater east at GB19 (pH 4.4, March 2014) and west at GB22 (pH 5.0). The pH of groundwater increased with depth at both wetlands to average more than 5.5 at the base of the Superficial aquifer (Table 9).

Table 8 Summary statistics for measurements of electrical conductivity (EC) and total dissolved salts (TDS) in Yeal Lake and north Yeal groundwater

Bore/site	EC (µS/cm @ 25ºC)			TDS (mg/L)		
	Min.	**Max.**	**Avg.**	**Min.**	**Max.**	**Avg.**
Yeal Lake *	1550	2940	2135	970	1870	1305
YLc (perched)	2070	2640	2246	1240	1710	1404
CYWa (deep)	220	240	229	170	280	213
CYWb (mid)	1380	1490	1449	830	950	926
CYWc (semi-perched)	740	1070	877	710	910	771
QUNEa (deep)	1430	1640	1554	790	950	881
QUNEb (mid)	1050	1140	1095	640	1021	761
QUNEc (semi-perched)	450	1060	750	480	920	704
QUNWa (deep)	600	750	629	330	420	366
QUNWb (mid)	1140	3170	2083	660	1910	1249
QUNWc (semi-perched)	2000	4450	3089	1440	2980	2028

* *data for July 2000 to January 2010*

Table 9 Summary statistics for measurements of pH, dissolved oxygen (DO) and redox potential (Eh) in Yeal Lake and north Yeal groundwater

Bore/site	pH			DO (mg/L)			*Eh* (mV)		
	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.
Yeal Lake *	6.4	7.1	6.7	4.5	8.4	6.5	N/A	N/A	N/A
YLc	5.7	5.8	5.8	0.1	0.5	0.3	-230	-81	-137
CYWa	5.6	6.0	5.7	0.3	2.3	0.8	-70	81	30
CYWb	4.5	5.0	4.7	0.2	1.9	0.7	-53	136	69
CYWc	3.3	3.8	3.5	0.3	3.1	1.1	25	212	149
QUNEa	6.4	6.9	6.6	0.2	0.6	0.3	-127	8	-43
QUNEb	5.1	5.5	5.2	0.1	0.4	0.2	-52	63	16
QUNEc	3.4	3.8	3.6	0.4	2.2	0.9	17	295	163
QUNWa	5.3	5.8	5.5	0.4	1.0	0.6	-123	-18	-63
QUNWb	4.7	5.6	5.3	0.1	0.5	0.3	-124	145	-13
QUNWc	3.3	3.6	3.5	0.1	0.9	0.3	-46	212	82

* *data for July 2000 to January 2010; N/A = measurement not applicable in surface waters*

Yeal Lake contained varying but moderate oxygen concentrations, with lower concentrations reflecting the influence of lake bed sediments when wetland levels were low (Table 9). Concentrations were less than the 90% saturation level recommended for south-west Australian wetlands (ANZECC & ARMCANZ 2000), indicating a risk of diurnal oxygen depletion if there was a significant algal bloom.

There was a general trend of chemical conditions becoming increasingly reducing with depth. Semi-perched groundwater at Quin Swamp and Quin Brook wetland was highly oxidised and had large seasonal variation. In contrast, groundwater at mid and bottom depths in the aquifer had consistently low redox potentials. This was consistent with classification of redox conditions (Jurgens et al. 2009) as ranging from generally mixed oxic at shallow depths to mostly anoxic deeper in the aquifer, with likely iron and sulfate reduction. DO and relative nitrate (assuming all NOx was nitrate), Mn and Fe concentrations (assuming dissolved species were Mn^{2+} and Fe^{2+} respectively) were used for this classification.

5.5.2 Ionic composition

Groundwater ionic composition changed with depth in the Superficial aquifer around Yeal Lake, Quin Swamp and Quin Brook wetland, reflecting the influence of the geological formations on ionic composition. The similarity between rainfall at Yanchep, Yeal Lake water and perched and semi-perched groundwater (YLc, NG15b, CYWc) reflected minimal change during runoff and recharge (Figure 20). This similarity extended towards GB22 downgradient of Yeal Lake, suggesting an influence of recharge from the lake. Within the aquifer, the composition ranged from Na-Cl type in the perched and mid-Superficial aquifer towards more Na-HCO_3-Cl type water deep in the aquifer (Figure 20; Figure 21). This was largely due to variation in anion composition HCO_3 and Cl and to a lesser extent SO_4.

Vertical differences in ionic composition were clear at Yeal Lake. Groundwater in the perched Guildford Formation was significantly different from that of the deeper Bassendean Sand and Gnangara Sand formations. There were larger differences between the composition of perched and underlying groundwater at NG15 east of the lake where the Guildford Formation was present, than south at NG9 and west at NG3 where this was absent. This also corresponded with the perched groundwater at NG15 being more saline (> 6 times) compared with shallow groundwater being only slightly more saline than deep groundwater at NG9 and NG3.

Vertical differences between semi-perched and underlying regional groundwater were less consistent at Quin Swamp and Quin Brook wetland given the spatial variation in the Guildford Formation’s thickness and composition. Semi-perched and underlying regional groundwater were different west of Quin Swamp (Figure 21) where the formation was thin, but similar east of the swamp where the formation was present throughout these depths. In contrast, the Guildford Formation at Quin Brook wetland had less influence on semi-perched groundwater chemistry than at Yeal Lake or Quin Swamp. Semi-perched and underlying regional groundwater was similar at Quin Brook wetland (Figure 21) despite the formation lying between these depths, suggesting that groundwater does not flow through the formation in this area.

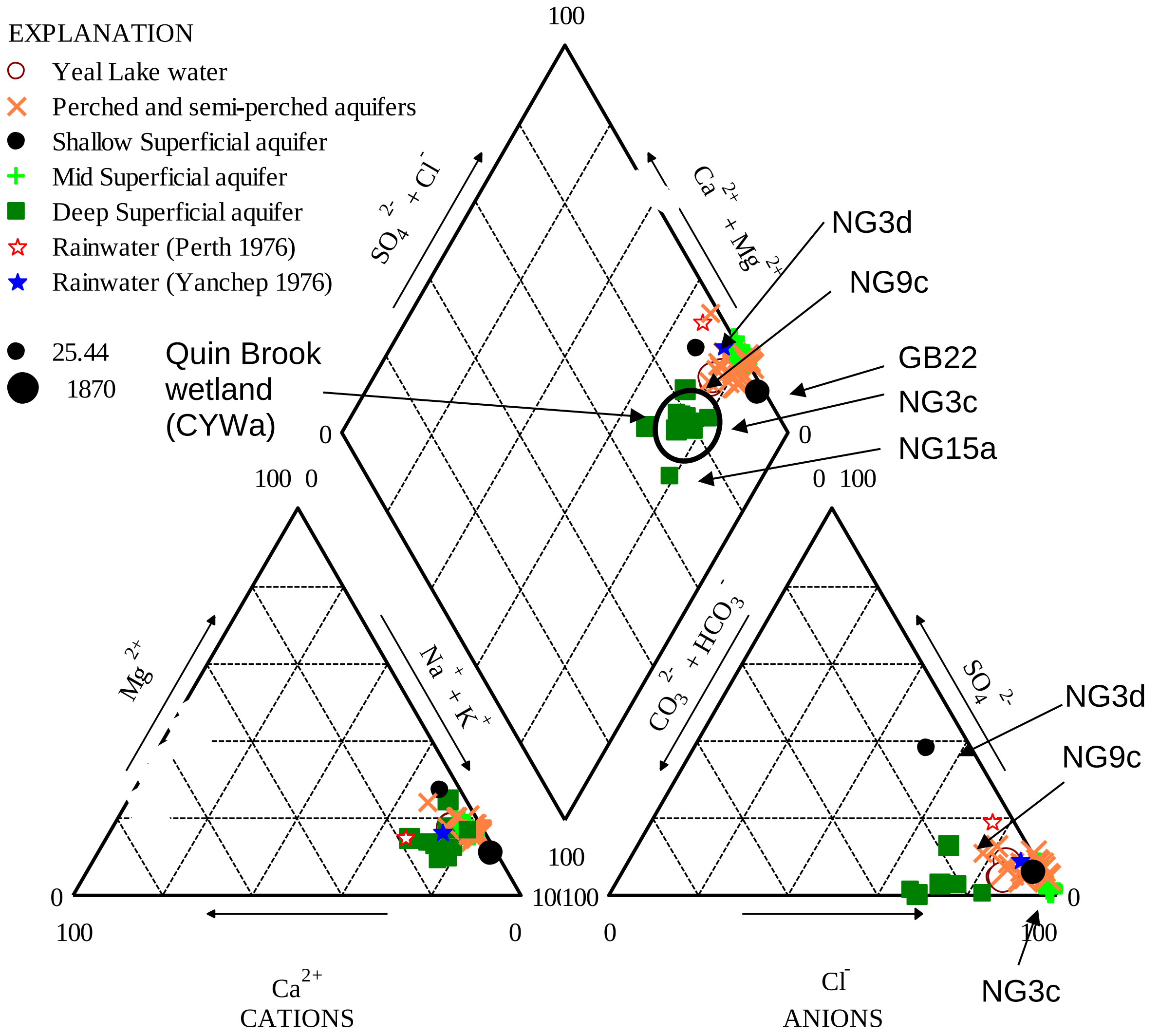


Figure 20 Ternary plot of major cations and anions in Yeal Lake and the aquifers around the lake including Quin Brook wetland (symbol size corresponds with salinity, multiple symbols = multiple samples for each bore)

At Quin Swamp and Quin Brook wetland, the nearby Ascot Formation influenced the ionic composition of the deep regional groundwater (Figure 21). Deep groundwater at NG1 east of Quin Swamp and at NG4 west of Quin Brook wetland were found to be the Ca-HCO_3 type waters typical of the Ascot Formation (Yesertener 2010). While deep bores at the wetlands were in Gnangara Sand and not the Ascot Formation, there was some influence of groundwater flow from the Ascot Formation – indicated by the divergence of ionic composition towards Ca-HCO_3 waters in deep groundwater at these wetlands.

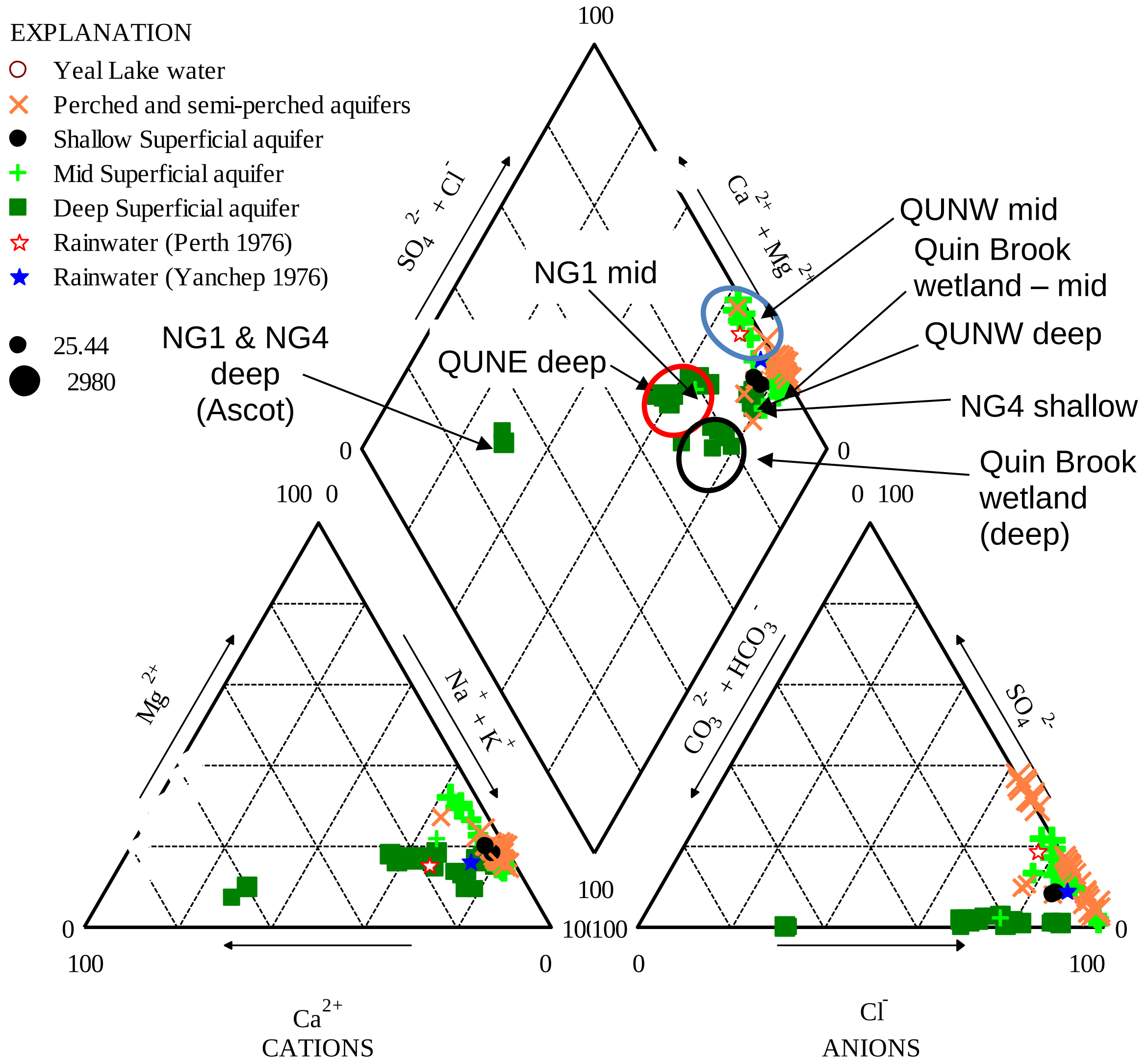


Figure 21 Ternary plot of major cations and anions in aquifers around Quin Swamp (QUN) and Quin Brook wetland (symbol size corresponds with salinity, multiple symbols = multiple samples for each bore)

5.5.3 Major cation ratios

Concentrations of major cations (Ca, Mg, K, Na) indicated few differences between groundwater at similar depths. However, for specific cations such as K and Ca there were patterns reflecting connectivity of the semi-perched and underlying regional Superficial aquifers. Most variation in concentrations, particularly of Na and Mg, were due to conservative evapo-concentration of the waters shown by concentrations of most cations varying linearly with chloride (Figure 22).

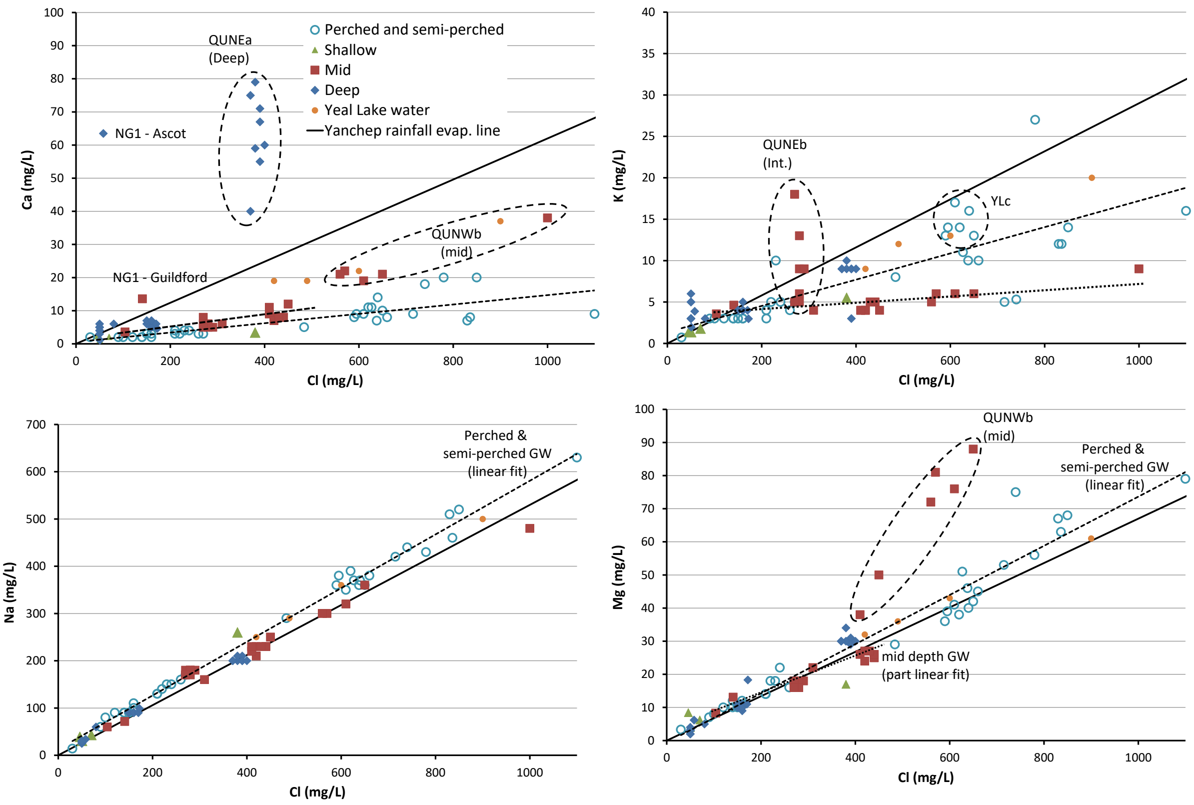


Figure 22 Ca, K, Na and Mg concentrations in relation to Cl in surface water and groundwater with Yanchep rainfall evaporation as a reference

Most potassium and calcium concentrations in the semi-perched/perched and underlying regional groundwater were depleted relative to rainfall, although to different extents that reflect interaction with the geology. Depletion of the cations indicated absorption during recharge, which is greater for potassium at some mid-depths than perched or semi-perched groundwater – indicating continued adsorption during flow into the aquifer (Figure 22). The exception was east of Quin Swamp where acidification may be causing weathering of clay minerals in the Guildford Formation. Adsorption of calcium does not continue with depth in the aquifer, although desorption is evident where there is acidification in the semi-perched and regional groundwater at Quin Swamp. Calcium-enriched groundwater was found deeper in the aquifer where groundwater was in or discharging from the Ascot Formation, where the water interacts with carbonate minerals (e.g. QUNEa, NG1c, NG1d and CYWa; Figure 36). The exception was deep groundwater west of Quin Swamp (QUNWa) and at NG9d, where no influence from the Ascot Formation occurs.

Yeal Lake water had cation patterns reflecting a groundwater origin, probably from shallow throughflow in the source catchment. The waters were slightly depleted in calcium and potassium (and sulfate – see below) relative to evapo-concentrated rainfall (Figure 22), indicating some influence of sediment interaction processes modifying ionic composition. This would be minimal for water with a surface runoff origin. The extent of this interaction is also evident in shallow groundwater at Yeal Lake where variation in K:Cl suggests mixing with surface waters, possibly due to recharge from the nearby Quin Brook.

5.5.4 Alkalinity, acidity and sulfate

Lake and groundwater at Yeal Lake contained moderate levels of alkalinity, whereas acidification dominated semi-perched groundwater at the other wetlands. The alkalinity of Yeal Lake varied from 70 mg $CaCO_3$/L after filling to more than 140 mg $CaCO_3$/L in the late stage of drying (Figure 23). This reflects the influence of evaporation and lake sediment geochemical processes. Perched groundwater at the lake (in YLc) contained lower and less variable levels of alkalinity that increased to the east (at NG15b).

Semi-perched groundwater at upper Quin Brook wetland and Quin Swamp contained no alkalinity and high concentrations of net acidity, consistent with the low pH in the oxidising ASS and groundwater (see sections 4.2 and 5.5.1). Net acidity in the semi-perched groundwater was an average of 335 mg $CaCO_3$/L on Quin Swamp's western side, but was an order of magnitude less at Quin Brook wetland and on Quin Swamp's eastern side (averages of 21 to 22 mg $CaCO_3$/L respectively). These values exceeded the guideline value of a maximum of 10 mg $CaCO_3$/L for aquatic organisms in saline surface water in Western Australia (Degens 2013) that also applies to fresh water.

The acidification extended to the underlying Superficial aquifer more than 15 m below the watertable at Quin Swamp and upper Quin Brook wetland. This reflected recharge of the semi-perched acidic groundwater to the underlying Superficial aquifer. Groundwater alkalinity in the mid Superficial aquifer at these sites was low, averaging less than 3 mg $CaCO_3$/L at Quin Brook wetland and 15 to 21 mg $CaCO_3$/L at Quin Swamp (Figure 23). This corresponded with the groundwater also containing average net acidity ranging from 4 to 21 mg $CaCO_3$/L. Deeper groundwater contained only marginally greater alkalinity (average 22 to 25 mg $CaCO_3$/L) than shallower groundwater, except on Quin Swamp's eastern side. Here, alkalinity was an average of 174 mg $CaCO_3$/L, which was consistent with the higher pH and closer proximity to the carbonate-rich Ascot Formation.

Other data indicates shallow groundwater acidification from oxidising ASS extends across the Yeal Nature Reserve. Water quality from clusters of nested bores at Bindiar on the reserve's south-western edge showed a similar pattern of pH, alkalinity and net acidity with depth as at Quin Swamp and Quin Brook wetland. Shallow groundwater at Bindiar contained some of the highest net acidity in the Gnangara groundwater system, with concentrations reaching 500 mg $CaCO_3$/L on the lake's eastern side. Data collated from sampling in the mid to late 2000s indicated that groundwater at the watertable was also acidic at GB19 and GB16 in the east and GB21, GB23 and NG4 in the west. This extended to the mid-aquifer at NG9, south of Yeal Lake. At the time of sampling, groundwater at all these sites had pH less than 5 and/or alkalinity less than 5 mg $CaCO_3$/L.

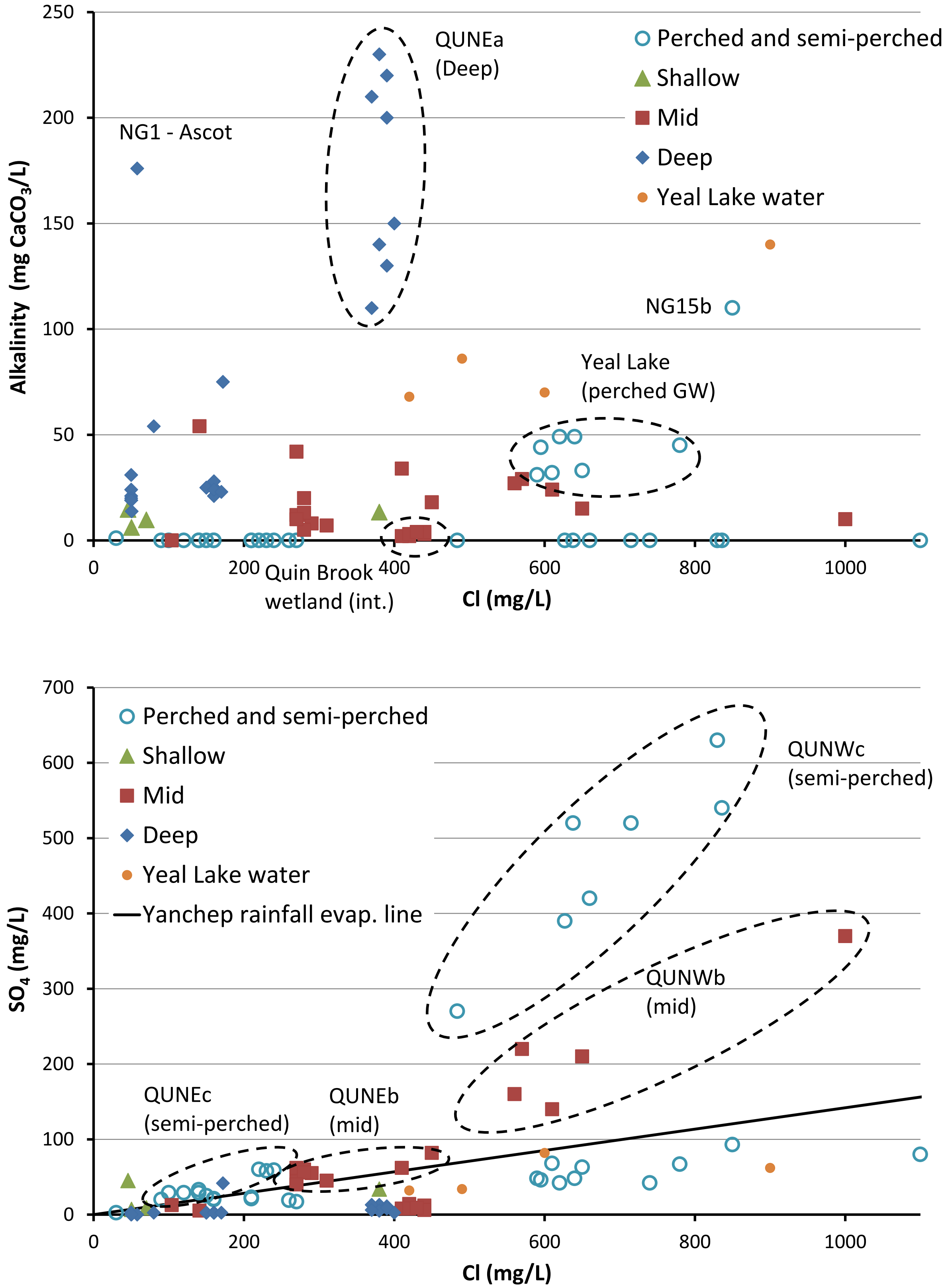


Figure 23 Total alkalinity and sulfate concentrations in relation to Cl in groundwater around the NW Yeal wetlands and Yeal Lake water with Yanchep rainfall evaporation as a reference (for SO_4^{+})

Patterns of sulfate concentrations also indicated the influence of ASS oxidation at Quin Swamp with sulfate reduction deeper in the aquifer. There were high concentrations of sulfate in the semi-perched and underlying regional groundwater west of Quin Swamp that were consistent with oxidation of ASS. Sulfate concentrations were greatly enriched (elevated) relative to that explained by evaporation of salts in rainfall. This was also mirrored to a lesser extent in the aquifer east of Quin Swamp. These patterns of sulfate enrichment corresponded with evidence of the low soil pH above and below the watertable, some residual sulfides below the watertable (see Section 4.2) and net acidity within the semi-perched groundwater.

Sulfate concentrations at other wetlands reflected evaporation of rainfall salt inputs, with sulfate removal by reduction resulting in reduced concentrations with depth in the aquifer. As with other major ions, evapo-concentration explains much of the spatial variation in semi-perched and perched groundwater sulfate concentrations. Depletion of sulfate with depth is most likely due to sulfate reduction as indicated by the redox status in the aquifer (see Section 5.5.1). This process can potentially contribute alkalinity to groundwater and buffer the extent that shallow acidification may propagate into an aquifer with recharge. However, in most perched and semi-perched groundwater, sulfate depletion by sulfate reduction is probably a transient process given the lack of evidence of consistently low redox conditions (see redox characteristics in Section 5.5.1).

5.5.5 Nutrients and dissolved organic carbon

Nutrients were present in groundwater and Yeal Lake water in generally moderate concentrations and that decreased with depth in the Superficial aquifer. Yeal Lake had organic nitrogen and nitrate concentrations similar to perched groundwater (in bore YLc; Table 10). In contrast, concentrations of phosphorus in the lake water were approximately double that of the perched groundwater (Table 10).

Nitrogen in groundwater was mostly present in organic forms with the highest concentrations recorded in perched and semi-perched groundwater (‘c’ bores in Table 10). There were moderately high concentrations of total nitrogen (TN) in most semi-perched and underlying regional groundwater (average exceeding 1.7 mg/L) extending to deep groundwater west of Quin Swamp (QUNWa). Even though these concentrations exceed guideline values for south-west wetlands, they are likely to be natural. Ammonium increasingly dominated TN with aquifer depth to more than half of TN. While exceeding drinking and aquatic water guidelines (Table 10), the concentrations were attributed to anaerobic microbial decomposition of dissolved organic matter under the generally anoxic conditions of the aquifer (see Section 5.5.1). There was little nitrate in groundwater with the exception of nitrate up to 0.96 mg/L to the west of Quin Swamp (at QUNWc). This was attributed to acidification of the groundwater inhibiting denitrification.

Total and soluble phosphorus in Yeal Lake water and perched or semi-perched groundwater at the wetlands frequently exceeded guideline levels for south-west Australian wetlands (Table 11). Concentrations of soluble phosphorus generally decreased with depth, except on the eastern side of Quin Swamp and at Quin Brook wetland. This was attributed to the confounding effects of particulate iron being dislodged from the screens during sampling, which also resulted in TP being anomalously high deeper in the aquifer. Total iron concentrations were up to an order of magnitude greater than soluble iron in deep bore samples (data not shown), indicating that iron precipitates were present, which can adsorb and concentrate phosphate and result in spurious total and soluble phosphorus concentrations.

Table 10 Summary statistics for nitrogen species in Yeal Lake and north Yeal groundwater bores

Site/bore	TN (mg/L)			Dissolved organic N (mg/L)			Ammonium-N (mg/L)			Nitrate-N (mg/L)		
	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean
Yeal Lake	**2.1**	**3.7**	**2.9**	2.0	3.3	2.7	0.04	**0.08**	**0.06**	< 0.01	**0.22**	**0.10**
YLc	**2.9**	**3.7**	**3.3**	2.0	3.5	2.7	**0.18**	**0.73**	**0.43**	0.02	**0.10**	0.05
CYWa	0.2	2.0	0.8	0.1	1.5	0.3	0.23	0.33	0.28	< 0.01	0.02	0.01
CYWb	0.3	2.0	1.7	0.2	1.3	1.0	0.07	0.68	0.55	< 0.01	0.03	0.02
CYWc	**4.3**	**5.2**	**4.6**	3.3	4.3	3.7	**0.44**	**0.66**	**0.53**	0.04	0.07	0.05
QUNEa	1.5	2.1	1.7	0.2	0.6	0.4	0.92	1.20	1.00	< 0.01	**0.10**	0.02
QUNEb	2.2	6.7	3.3	1.2	3.7	1.9	0.52	1.30	0.76	< 0.01	0.08	0.05
QUNEc	**3.7**	**5.1**	**4.4**	3.2	4.4	4.8	**0.35**	**0.43**	**0.39**	0.04	**0.10**	0.06
QUNWa	1.6	2.6	2.0	0.3	0.8	0.5	0.66	0.98	0.75	< 0.01	0.03	0.01
QUNWb	1.8	2.9	2.2	0.7	1.2	0.9	0.82	1.20	1.07	< 0.01	0.02	0.01
QUNWc	**3.7**	**6.0**	**4.9**	2.1	2.1	2.6	**0.53**	**0.77**	**0.64**	< 0.01	**0.96**	**0.31**
Aquatic guideline[1]		1.5			N/A			0.04			0.1 (NOx)	
DW guideline[2]		N/A			N/A			0.4*			50	

[1] *Aquatic ecosystem guideline value for south-west Australian wetlands (ANZECC & ARMCANZ 2000); exceedances in lake water and shallow groundwater only are underlined and in bold text.*

[2] *Drinking water guideline maximum concentrations from NHMRC & NRMMC (2004); exceedances of guideline values for all bores in red except where not available (N/A).*

Table 11 Summary statistics for total (Total P) and soluble phosphate (FRP) and dissolved organic carbon (DOC) in Yeal Lake and north Yeal groundwater bores

Site/bore	Total P (mg/L)			FRP (mg/L)			DOC (mg/L)		
	Min.	**Max.**	**Mean**	**Min.**	**Max.**	**Mean**	**Min.**	**Max.**	**Mean**
Yeal Lake	**0.37**	**1.10**	**0.82**	**0.260**	**0.790**	**0.515**	41	79	59
YLc (perched)	**0.21**	**0.82**	**0.40**	**0.160**	**0.550**	**0.299**	79	100	91
CYWa (deep)	0.07	0.52	0.34	0.009	0.046	0.027	5	7	6
CYWb (int.)	0.01	0.04	0.02	< 0.005	0.027	0.012	51	74	59
CYWc (semi-per.)	0.02	**0.10**	0.03	0.010	0.020	0.016	210	260	227
QUNEa (deep)	0.15	0.93	0.30	< 0.005	0.019	0.008	18	25	21
QUNEb (int.)	0.03	0.22	0.07	0.008	0.091	0.033	72	200	104
QUNEc (semi-per.)	0.03	**0.08**	**0.06**	0.008	**0.052**	**0.034**	120	240	200
QUNWa (deep)	0.05	0.55	0.16	< 0.005	0.020	0.009	21	31	25
QUNWb (int.)	0.01	0.04	0.02	< 0.005	0.026	0.006	35	45	40
QUNWc (semi-per.)	0.02	**0.14**	0.05	0.011	0.025	0.018	76	150	110
Guideline value[1]		0.06			0.03			N/A	

[1] *Aquatic ecosystem guidance value for south-west Australian wetlands (ANZECC & ARMCANZ 2000); exceedances in lake water and upgradient bores are underlined and in bold. Drinking water guideline maximum concentrations from NHMRC & NRMMC (2004).*

N/A – not applicable

Dissolved organic carbon (DOC) was present in high concentrations: often exceeding 100 mg/L in perched and semi-perched groundwater and diminishing with depth in the regional aquifer (Table 11). High concentrations were closely correlated with similarly high total nitrogen. While concentrations were almost 10 times greater than previously reported in surface waters draining Bassendean sands (Petrone et al. 2008), these were similar to perched groundwater at Lake Muckenburra to the north-east (Degens et al. 2012). Similar high concentrations were also found in perched groundwater east of Quin Swamp at GB16 (640 mg/L in March 2014) and west of Yeal Lake at GB22 (99 mg/L in March 2014).

Concentrations of DOC in Yeal Lake were less than 60% of that in perched groundwater at the lake (YLc) and semi-perched groundwater further along Quin Brook (at CYWc, QUNEc and QUNWc; Table 11). This suggests that the higher concentrations in perched groundwater were dominated by local root zone input through the soil rather than as recharge from the lake, wetlands or flows along Quin Brook (overflowing from Yeal Lake).

Locally high DOC concentrations below the semi-perched groundwater east of Quin Swamp indicated a local vertical leakage of semi-perched groundwater to the underlying Superficial aquifer. DOC concentrations in the mid-Superficial aquifer exceeded 35 mg/L and were typically half that of semi-perched groundwater at both

Quin Swamp and Quin Brook wetland (Table 11). Yet to the east of the Quin Swamp concentrations of up to 200 mg/L were still evident mid-aquifer. This was consistent with greater groundwater leakage from the semi-perched shallow groundwater to the underlying Superficial aquifer at this site. Generally higher DOC concentrations were also found in the shallow and mid-aquifer at NG9 south of Yeal Lake (up to 61 mg/L), but not east of the wetlands at NG3 and NG4 (less than 33 mg/L).

DOC concentrations diminished to less than 25 mg/L towards the base of the Superficial aquifer. These were similar to the less than 15 mg/L found toward the base of the aquifer at NG1, NG4 and NG3 (unpublished data, Jan 2013). Such concentrations are typical of the concentrations (10–20 mg/L) found elsewhere in the Superficial aquifer of the Gnangara groundwater system (Cargeeg et al. 1987; Martin & Harris 1982).

5.5.6 Minor, trace elements and pesticides

Concentrations of most minor and trace elements in Yeal Lake (for the four sampling events) were below aquatic ecosystem guideline values except for iron and aluminium (Table 12). Sampling for pesticides in Yeal Lake on one occasion did not detect anything above analytical reporting limits, all of which are were below health and environmental guideline limits (NHMRC & NRMMC 2004 and Department of Environment & Conservation 2010 respectively).

Very high concentrations of aluminium and trace metals (such as zinc and nickel) were found in the semi-perched groundwater at Quin Swamp and Quin Brook wetland: these exceeded guideline values for aquatic ecosystem protection (Table 12). Such concentrations can be attributed to acidification by ASS oxidation increasing mobilisation of metals in the shallow groundwater (see earlier ASS assessment in Section 4.2 and general characteristics in Section 5.5.1). The metal concentrations generally posed no risk for drinking water uses, except for nickel.

The effects of acidification were also evident in the underlying regional aquifer (Table 12), consistent with other hydrochemical evidence earlier in this section. Aluminium concentrations exceeded 1000 µg/L and iron concentrations were in the order of 1000’s µg/L in the regional aquifer’s mid-part but not deeper (Table 12). These concentrations most likely reflect leakage of acidic, iron and aluminium rich groundwater from the semi-perched groundwater system.

Table 12 Summary statistics for trace elements in Yeal Lake and north Yeal groundwater bores

Site/bore	Al (soluble; µg/L)			As (total; µg/L)			B (total; µg/L)			Cd (total; µg/L)			Cr (total; µg/L)		
	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.
Yeal Lake	**180**	**210**	**193**	1	3	2	74	140	106	< 0.1	< 0.1	< 0.1	<0.1	2	1
YLc (perched)	**1000**	**1600**	**1329**	1	4	2	77	190	130	< 0.1	< 0.1	< 0.1	2	4	3
CYWa (deep)	130	1000	333	1	30	16	< 0.01	36	134	< 0.1	0.5	0.2	29	1100	463
CYWb (int.)	980	1300	1169	1	3	2	19	39	26	< 0.1	< 0.1	< 0.1	2	5	4
CYWc (semi-per.)	**740**	**1200**	**970**	1	3	1	17	31	23	< 0.1	0.1	< 0.1	**4**	**7**	**5**
QUNEa (deep)	29	810	251	16	69	37	< 0.01	91	21	< 0.1	0.2	0.8	13	80	46
QUNEb (int.)	1200	4200	2650	18	27	23	< 0.01	62	21	< 0.1	< 0.1	< 0.1	11	160	43
QUNEc (semi-per.)	**1200**	**2400**	**1638**	1	2	1	< 0.01	66	27	< 0.1	< 0.1	< 0.1	**2**	**7**	**4**
QUNWa (deep)	77	1900	727	21	160	53	< 0.01	33	14	0.1	8.1	2.6	31	240	103
QUNWb (int.)	120	1400	558	2	10	6	< 0.01	29	13	< 0.1	< 0.1	< 0.1	7	73	22
QUNWc (semi-per.)	**8200**	**53000**	**25775**	3	8	6	< 0.01	64	48	< 0.1	0.1	< 0.1	**9**	**30**	**20**
Aquatic ecosyst. guideline value*		55			13 (for As(V))			370			0.2			1 (for Cr(VI))	
DW Guideline[$]		200***			7			400			2			50 (for Cr(VI))	

* *Aquatic ecosystem guideline values are for a high species protection level (95% confidence) suitable for most high value freshwater aquatic ecosystems (ANZECC & ARMCANZ (2000). Exceedances are underlined in **bold** for lake water and the shallow groundwater likely to interact with the surface environment.*

[$] *Drinking water guideline maximum concentrations from NHMRC & NRMMC (2004) applied to groundwater analyses with exceedance highlighted as red text.*

**** Guideline value is for aesthetic rather than health reasons.*

Table 12 (cont.)

Site/bore	Fe (sol; µg/L)			Mn (total; µ/L)**			Ni (total; µg/L)			Zn (total; µg/L)		
	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.
Yeal Lake	200	**440**	**313**	3	8	6	< 0.1	0.2	0.1	< 0.1	3	1
YLc (perched)	230	**3300**	**1101**	2	12	6	7	**23**	**15**	**12**	**33**	**22**
CYWa (deep)	2000	3600	2629	9	23	14	3	170	77	4	99	42
CYWb (int.)	6700	9600	7700	10	12	11	2	11	5	2	110	27
CYWc (semi-per.)	**560**	**670**	**641**	4	65	18	1	**11**	4	5	**160**	**55**
QUNEa (deep)	220	2600	1765	62	170	107	9	29	19	14	150	64
QUNEb (int.)	7500	15000	11963	6	19	9	16	66	40	18	40	28
QUNEc (semi-per.)	**760**	**1800**	**1153**	1	14	5	**13**	**38**	**26**	5	**100**	**68**
QUNWa (deep)	920	1300	1084	20	55	29	18	77	36	52	250	104
QUNWb (int.)	7400	19000	12000	17	45	31	6	21	56	17	67	36
QUNWc (semi-per.)	**75000**	**160000**	**99000**	7	12	9	**59**	**200**	**113**	**72**	**150**	**94**
Aquatic ecosystem. guideline value*		300			1900			11			8	
DW Guideline$		300***			500 (100 for aesthetics)			20			3000***	

* *Aquatic ecosystem guideline values are for a high species protection level (95 % confidence) suitable for most high value freshwater aquatic ecosystems (ANZECC & ARMCANZ 2000). Exceedances in lake water and the shallow groundwater are underlined in **bold**. NB: Guidance value for Fe recommended by Department of Environment & Conservation (2010).*

**** Guideline value is for aesthetic rather than health reasons.*

$ *Drinking water guideline maximum concentrations from NHMRC & NRMMC (2004) applied to groundwater analyses with exceedance highlighted as red text.*

There was no mobilisation of arsenic within the semi-perched groundwater resulting from ASS oxidation, however arsenic and chromium are naturally present at greater depths in the aquifer (Table 12). Similar concentrations of arsenic in the regional Superficial aquifer have been identified nearby at Lake Muckenburra (Degens et al. 2012) and Tangletoe Swamp (Department of Water 2011b). These concentrations are more than an order of magnitude greater than those in a regional survey of the Superficial aquifer (generally < 5 µg/L in the Bassendean Sand; Yesertener 2010). The source of arsenic is most likely trace amounts of arsenic associated with iron oxyhydroxide minerals in the Bassendean Sand mobilised into solution as these undergo reductive dissolution under generally mildly anoxic to anoxic conditions.

The high concentrations of soluble aluminium and iron in Yeal Lake and perched groundwater in the absence of acidification are typical of other wetlands in the area (e.g. Lake Muckenburra – Degens et al. 2012) and elsewhere in south-west Western Australia (Kilminster et al. 2011). The potential toxicity of the aluminium in Yeal Lake is likely limited but would require further investigation to confirm. At the near-neutral pH of the lake water (see Section 5.5.1), the metal is generally not soluble as free aluminium ions (Nordstrom & Ball 1986). Concentrations of iron in the aquifer at the wetlands are also typical of anoxic groundwater present in Bassendean Sands (Davidson 1995; Yesertener 2010) with the dominant pattern of decreasing with depth (Davidson 1995).

Concentrations of boron, cadmium, manganese and zinc throughout the Superficial aquifer near the north Yeal wetlands were within drinking water and ecosystem guideline limits (Table 12). However, there are potential health risks posed by arsenic and chromium that need to be assessed further should the water be consumed untreated. DWER discourages direct consumption of groundwater without treatment.

The tendency for high chromium, arsenic and zinc in deep groundwater is probably in part due to contamination of samples, with metals adsorbed to particulate iron dislodged from the bore screens. Particulate iron in the samples is evident as total iron being an order of magnitude greater than soluble iron (data not shown). At the bore screens, the particulate iron can concentrate dissolved metals flowing through the screens and contribute to higher total metal concentrations in samples than are present as soluble metals in the aquifer.

5.6 Conceptualisation of wetland groundwater interaction

Most of the north Yeal wetlands along upper Quin Brook currently interact with perched to semi-perched groundwater systems with inflow from perched groundwater and outflow to the regional Superficial aquifer. The exception is Yeal Lake, which fills with surface water and acts as a sump interacting with perched groundwater. Overflow from the lake can affect wetlands downstream of Yeal Lake, but such flows are now rare. This conceptualisation is summarised below as a series of hydrogeological cross-sections incorporating interpreted flows consistent with spatial hydrochemical patterns (Figure 24; Figure 25; Figure 26).

The perched and semi-perched groundwater hydrogeology is controlled by the variable thinning and interbedding of the Guildford Formation where this meets the Bassendean Sand. The formation is sufficiently impermeable beneath Yeal Lake to form a perched groundwater system (Figure 24) whereas at upper Quin Brook wetland and Quin Swamp, the formation is deeper or more spatially permeable, respectively (Figure 25; Figure 26).

Yeal Lake interacts with a perched groundwater system where there is no hydraulic influence from the downgradient or underlying Superficial aquifer. Periodic surface inflow to the lake is more hydrologically important than the groundwater interaction, with the wetland transitioning from a recharge feature when surface water is present to a dampland with groundwater seepage in the dry state (Figure 24). Water levels in Yeal Lake directly depend on surface inflows from the Quin Brook catchment to the east of the lake and retention of water in the lake depends on perched groundwater levels around the lake. High watertable levels to the east of the lake are likely to generate runoff flows to the east of the lake. Water in the lake has a hydrochemistry slightly different from the local perched groundwater. This is consistent with the mixing of soil throughflow and surface water flow in the catchment east of the lake.

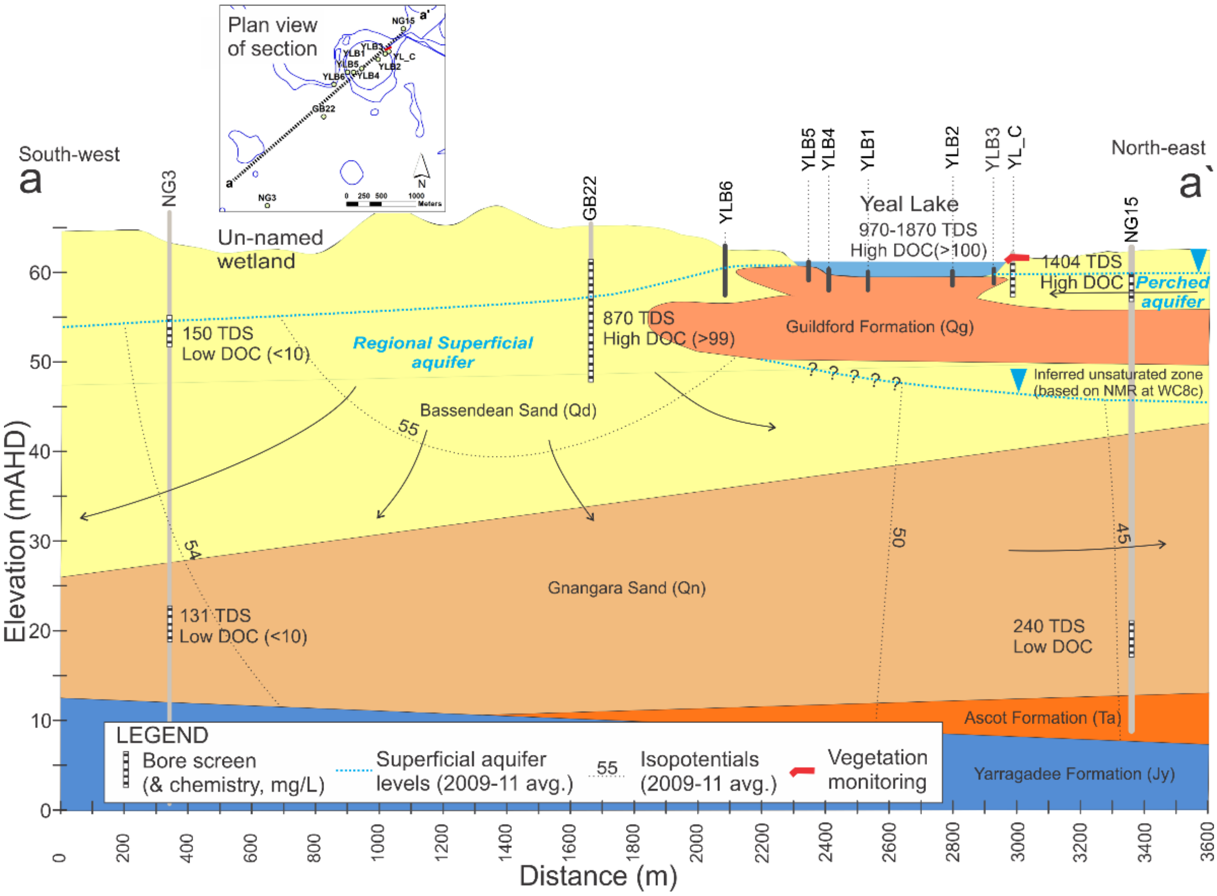


Figure 24 Cross-section of the local hydrogeology of Yeal Lake with interpreted groundwater flow paths

Filling of the lake results in local mounding of water levels with more than 30% of the lake volume recharging to the perched groundwater system. The effect of downgradient regional aquifer levels on retention of water in the lake appears minimal with no increase in leakage rates detected between 2009 and 2013 despite downgradient decline of more than 2 m.

Upper Quin Brook wetland and Quin Swamp interact with semi-perched groundwater that is hydraulically influenced either vertically or laterally by water levels in the regional Superficial aquifer. In the past these wetlands may have interacted with surface water flows as happens at Yeal Lake, but now interact with groundwater as recharge features (Figure 25; Figure 26).

Perching of groundwater and leakage through the Guildford Formation results in distinct patterns in the water chemistry. Perched and semi-perched groundwater at the wetlands was generally more saline, sometimes ionically distinct and with higher concentrations of DOC and total nitrogen than the underlying Superficial aquifer, indicating limited vertical connectivity. This was most evident immediately east of Yeal Lake and generally at Quin Swamp and upper Quin Brook wetland. At these wetlands, there were much larger differences between some semi-perched groundwater than mid-aquifer groundwater, which was similar to deep-aquifer groundwater. Downgradient (west) of the wetlands, however, the vertical difference in the composition of groundwater diminished.

Inflow to the semi-perched groundwater at Quin Swamp and upper Quin Brook wetland is from the east in the perched groundwater in and above the Guildford Formation (Figure 25; Figure 26). Flow of groundwater away from the wetlands is influenced by water levels in the regional Superficial aquifer where downward hydraulic pressures were evident at all wetland sites. The downgradient influence is greater at upper Quin Brook wetland than at Quin Swamp (see Figure 25 and Figure 26), but restricted at Yeal Lake by the thinness of the perched groundwater (Figure 24). The regional Superficial aquifer is slowly disconnecting from the semi-perched groundwater at all the wetlands, although complete perching will not be until after 2025 at pre-2012 rates of water level decline.

Groundwater pressures and quality beneath the wetlands show a complex pattern of groundwater flow from the perched system east of the wetlands to the regional Superficial aquifer west of these. This flow is attributed to the variable patterns of vertical leakage through the thin interbedded layers in what are the distal parts of the Guildford Formation. Although the formation locally forms a thin aquitard beneath the wetlands, this is not extensive or well developed and is often highly spatially variable.

Mid-aquifer head pressure gradients beneath Quin Swamp indicate groundwater recharges through the Guildford Formation from the semi-perched groundwater (Figure 26). Greater water levels in the mid-aquifer on the wetland’s eastern rather than western side reflect more interaction of the semi-perched groundwater through the formation. Leakage from semi-perched groundwater also influences the composition (major ions, DOC, dissolved metals) of the mid-Superficial aquifer water at Quin Swamp and to a lesser extent, upper Quin Brook wetland. Semi-perched groundwater > 4 m depth at these wetlands is also acidic, with high concentrations of some metals and evidence of this influencing mid-aquifer water chemistry to > 15 m depth below the watertable, particularly on Quin Swamp's eastern side.

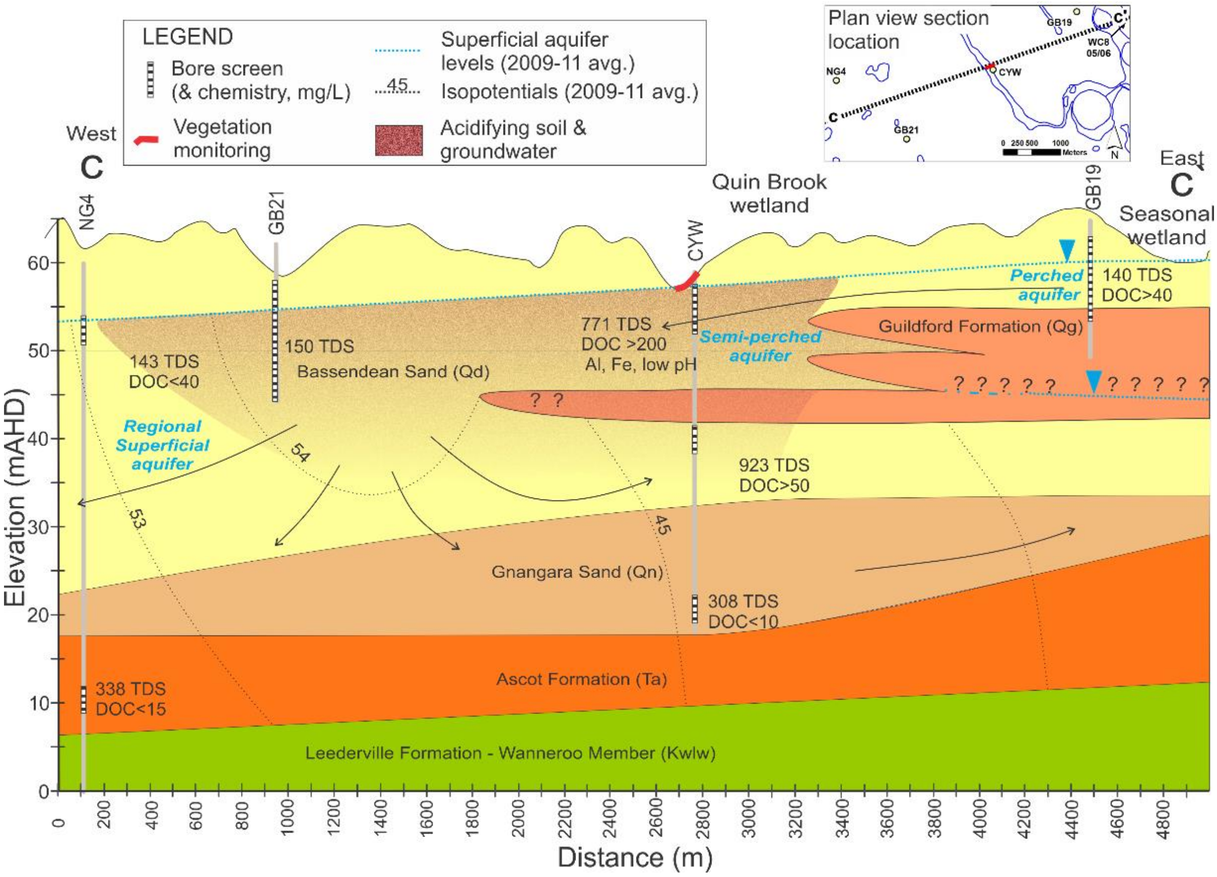


Figure 25 Cross-section of the local hydrogeology of upper Quin Brook wetland with interpreted groundwater flow paths

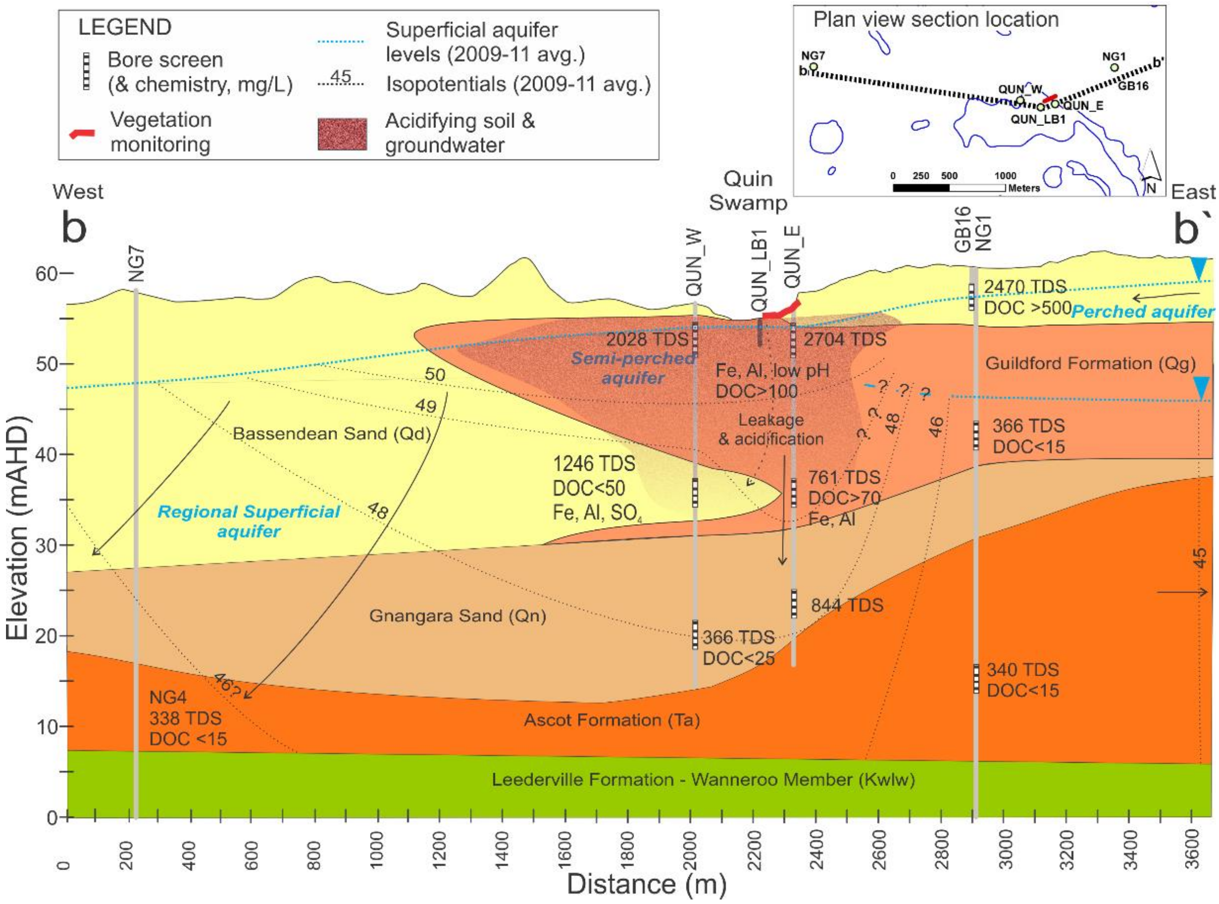


Figure 26 Cross-section of the local hydrogeology of Quin Swamp with interpreted groundwater flow paths

West of the wetlands there was a slight downward flow of groundwater in most parts of the mid to deep Superficial aquifer indicated by small downward pressure gradients (Figure 24; Figure 25).

Groundwater levels in the Superficial aquifer indicate some flow to the east beneath the low permeability layers causing perching. However, this would be variable with depth because flow is constrained immediately beneath the wetlands by the likely lower hydraulic conductivity (K) of the aquifer beneath the Guildford Formation. This was evident in the lower K estimated from NMR towards the base of the bores at upper Quin Brook wetland and Quin Swamp, and to a lesser extent in NG9 (see NMR summary in Appendix G).

6 Trends in groundwater interaction

6.1 Trends in watertable interaction with upper Quin Brook

Water level patterns indicate upper Quin Brook's hydrology and that of associated wetlands has been changing since the late 1980s. Increasing disconnection with the watertable started at Quin Swamp and progressively extended upstream to Yeal Lake.

Graphical analysis of selected bores near the wetlands (Figure 10) showed a consistent pattern of decreasing water levels from 1977 for all bores. This was more subdued to the east of the wetlands at GC4 and GC1 and GC24 than to the west of the wetlands at GB22 and GB21 (Figure 27; Figure 28). Trends in water levels in bore GB19 are between these and appear to be similar to maximum groundwater levels in GB16, where minima were not measured because of bore silting.

The rate of water level decline to the west of the wetlands at GB21 and GB22 appears to increase with time, particularly after the late 1990s. This is indicated by a better statistical fit of non-linear quadratic trends (r2 > 0.75) than fitting a linear trend (r2 < 0.6). A similar pattern is evident east at GB19 and GB16, although the onset is later in the early 2000s (Figure 27). Further east, water levels appear to decline at a steady rate from 1977 to 2012, with a slight linear but not significant trend (r2 < 0.04; P > 0.05; Figure 28).

Seasonal interaction of groundwater with Quin Brook upstream of Yeal Lake has become less frequent in the decade to 2012, likely hindering generation of surface runoff to the lake. Groundwater levels in bore GC4 indicate that groundwater seasonally interacted with the headwaters of Quin Brook before 1999. Levels increased to at least 20 cm above the bed of the brook in winter/spring and declined to more than 1 m below each summer/autumn (Figure 28). After 1999, the groundwater levels generally remain below the base of the brook, although the biannual monitoring may have missed periodic rises. Similar evidence is also clear in the frequency of filling of Yeal Lake after 1999 (see Appendix A). This section of Quin Brook has historically been mostly a losing reach – where water recharges to groundwater in early winter/spring until the watertable intersects drainage channels and wetlands. Lower groundwater levels in this area would reduce the conveyance and duration of surface water flows into Yeal Lake.

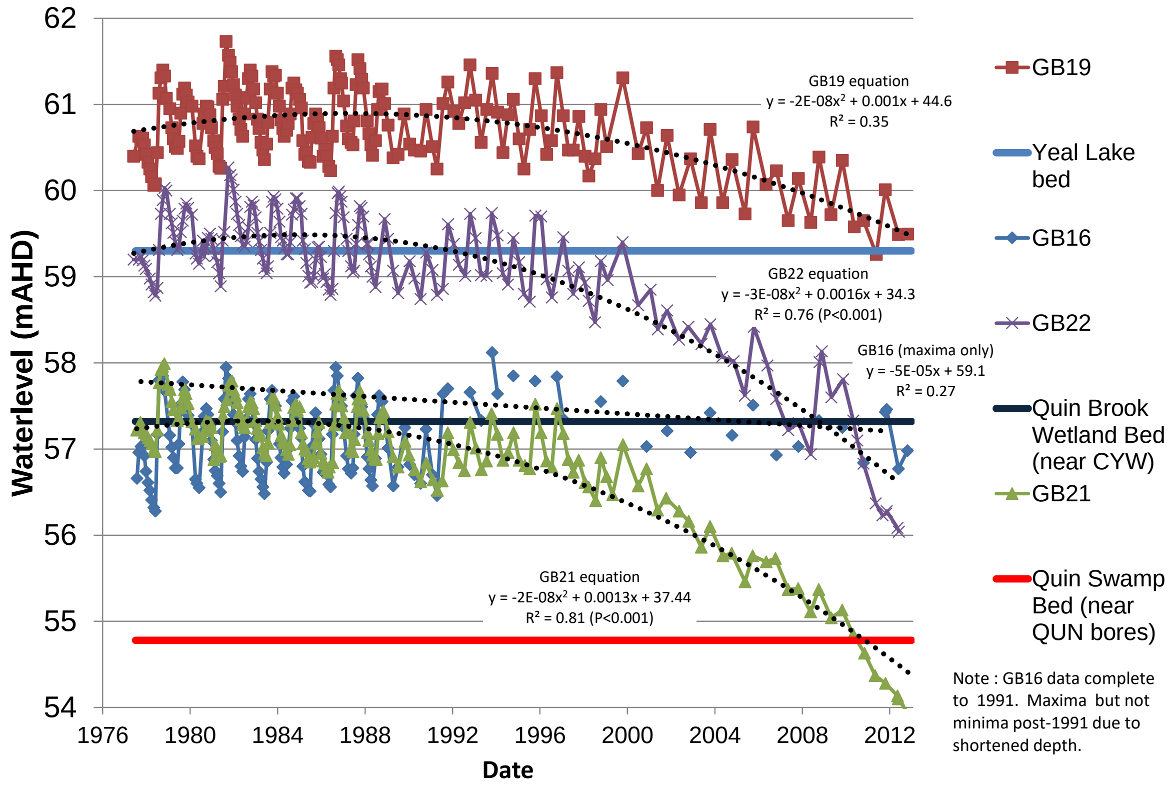


Figure 27 Long-term hydrographs for bores adjacent the north Yeal wetlands

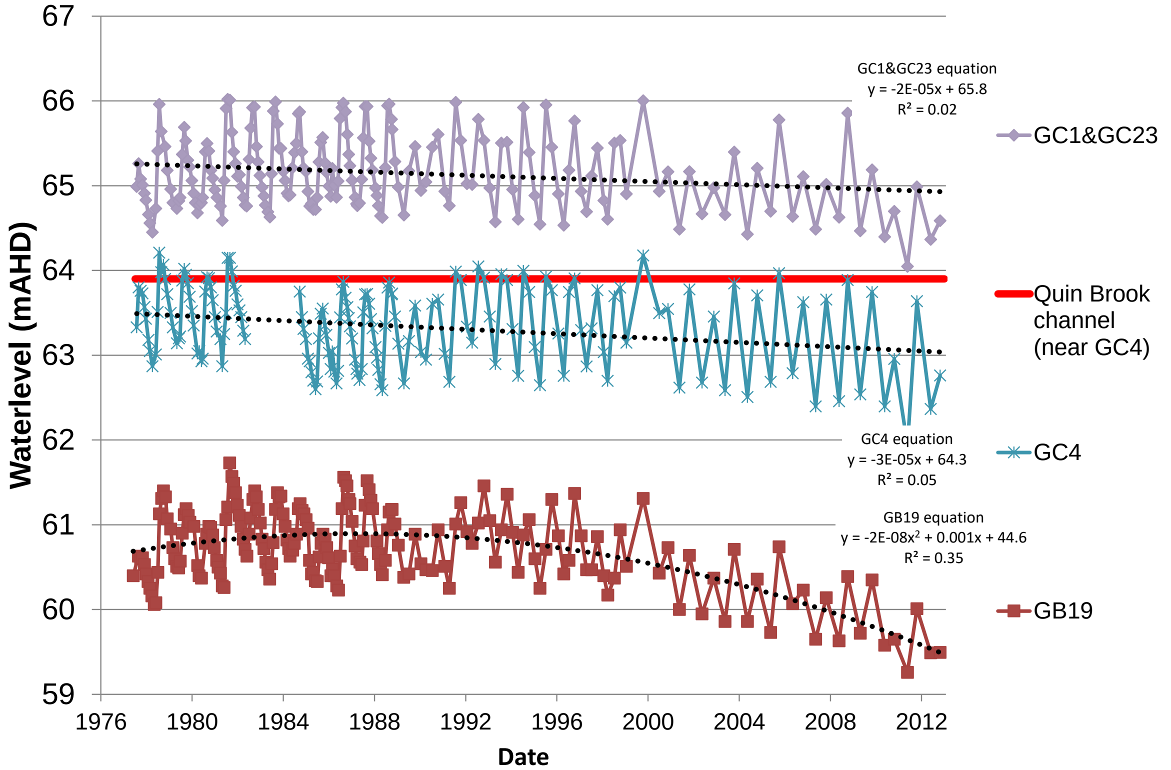


Figure 28 Long-term hydrographs for bores to the east of the north Yeal wetlands

Groundwater levels indicate that near-permanent interaction with upper Quin Brook between Yeal Lake and Quin Brook wetland happened before 1995, but this has since become more intermittent. The watertable at nearby bore GB22 was above the base of this reach of the brook for most of the period between 1977 and 1995 (Figure 27). From 1995 to 2008, groundwater levels at GB22 declined – indicating that discharge to the book became increasingly seasonally intermittent, starting near Yeal Lake and extending downstream (Figure 27). After 2008, it was unlikely there was any groundwater interaction along the reach, which is also consistent with evidence in aerial photography (see Appendix A). This analysis indicates that annual duration of ponded water and flows in upper Quin Brook have declined and that the brook is becoming dependent on overflows from Yeal Lake, rather than interaction with regional groundwater discharge.

Historic groundwater interaction from Quin Brook wetland to Quin Swamp is less certain, but the reach has changed from being mainly discharging to mainly recharging groundwater. Only broad extrapolation is possible based on trends in water levels at bore GB21 (Figure 27), which reflected the trend in water levels along the brook better than bores to the east, which are influenced by perching. Before 1989, water levels at GB21 indicated that groundwater was seasonally to almost permanently above the base of the channel and associated wetlands (Figure 27). Following this, groundwater was likely to have been at least seasonally in contact with this section of the brook and ceased before monitoring of the QUN series bores in 2009. This may have been in the early 2000s if the recent rate of decline of 0.1 m/yr in shallow groundwater at Quin Swamp (see Section 5.2) is extrapolated back a few years. Groundwater levels at GB16 indicate perennial interaction between groundwater and the bed of Quin Swamp. However, levels in the QUN series bores since 2009 indicate this does not happen (see Section 5.4).

6.2 Trends in groundwater flow patterns

The direction of groundwater flow in the reserve’s northern part around the upper Quin Brook wetlands has changed slightly in recent decades. Before the late 1990s, groundwater generally flowed from east-north-east to west-south-west in the reserve’s southern part and to the west-north-west in the northern part (Figure 29). Recent watertable contours indicate a shift in flow direction along upper Quin Brook to a more west-south-westerly flow direction (Figure 30), when this was previously more north-westerly. This reflects the reduced interaction of groundwater with upper Quin Brook (see Section 6.1 above).

Watertable decline has been evident across the Yeal Nature Reserve during the past 30 years and is greatest in the south-west. The trend is characterised as an increasing rate of water level decline generally after the late 1990s that has been more amplified at bores in the south and south-east (Figure 31). These patterns are clearest when water levels are normalised as a difference relative to average water levels in 1977 and 1998 (Figure 31). The start of the decline varies spatially and is earlier in the reserve’s south-west than west (Figure 31). Similarly, there is an east-west pattern where the decline is evident earlier in the west and is later with distance towards Yeal Lake (e.g. GA14-GA15 to YY7 (O) to GB23).

It is clear in many hydrographs in the west, south-west and south-east that seasonal fluctuation in water levels are generally absent after the late 1990s (Figure 31). There are only a few years for bores in these areas (e.g. GC20, GC11, GB23 and GA10) when groundwater seasonally rises against the dominant trend of declining water levels. Lack of a seasonal fluctuation reflects the high rate of groundwater decline, an absence of recharge or both.

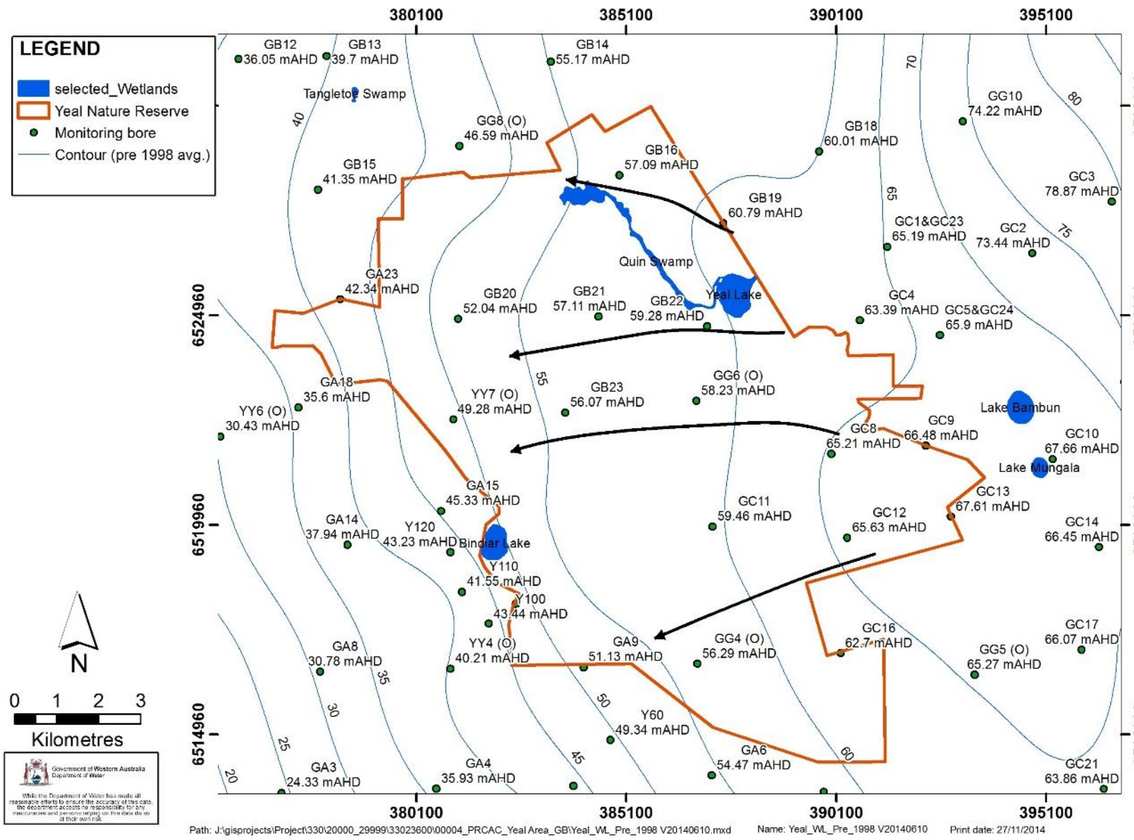


Figure 29 Average watertable contours in the Superficial aquifer 1977–1998 showing regional groundwater flow paths

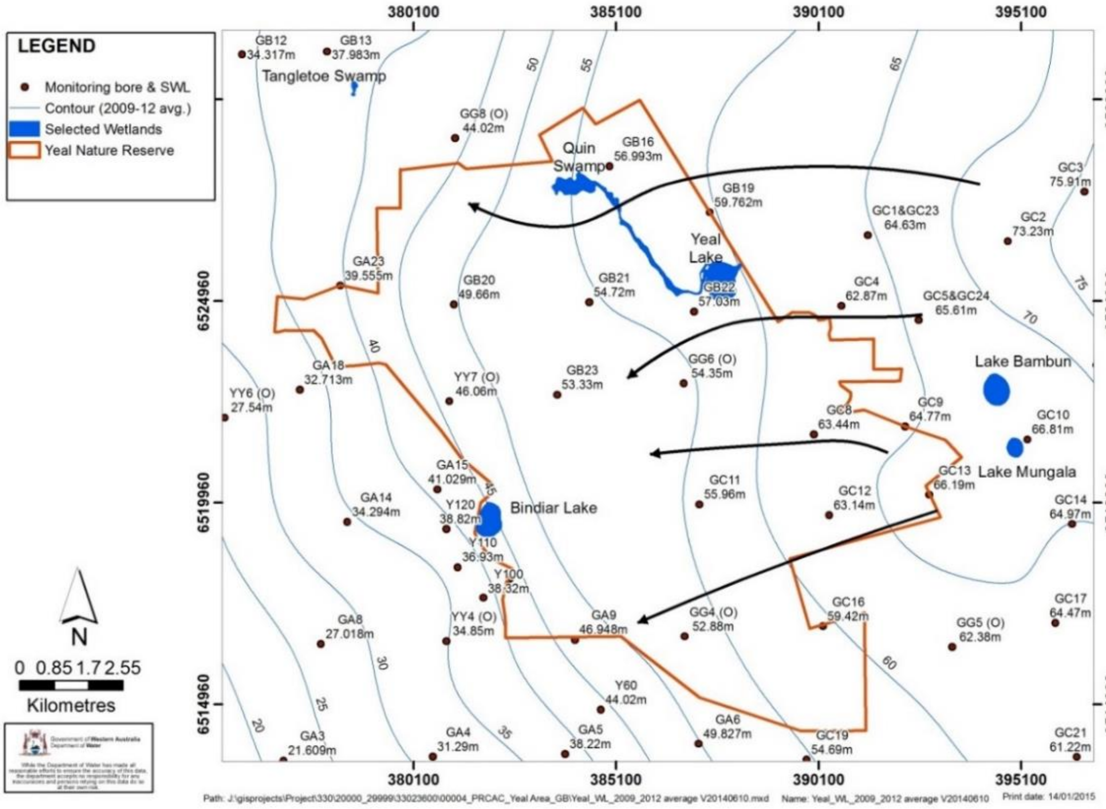


Figure 30 Average watertable contours in the Superficial aquifer 2009–2012 showing regional groundwater flow paths

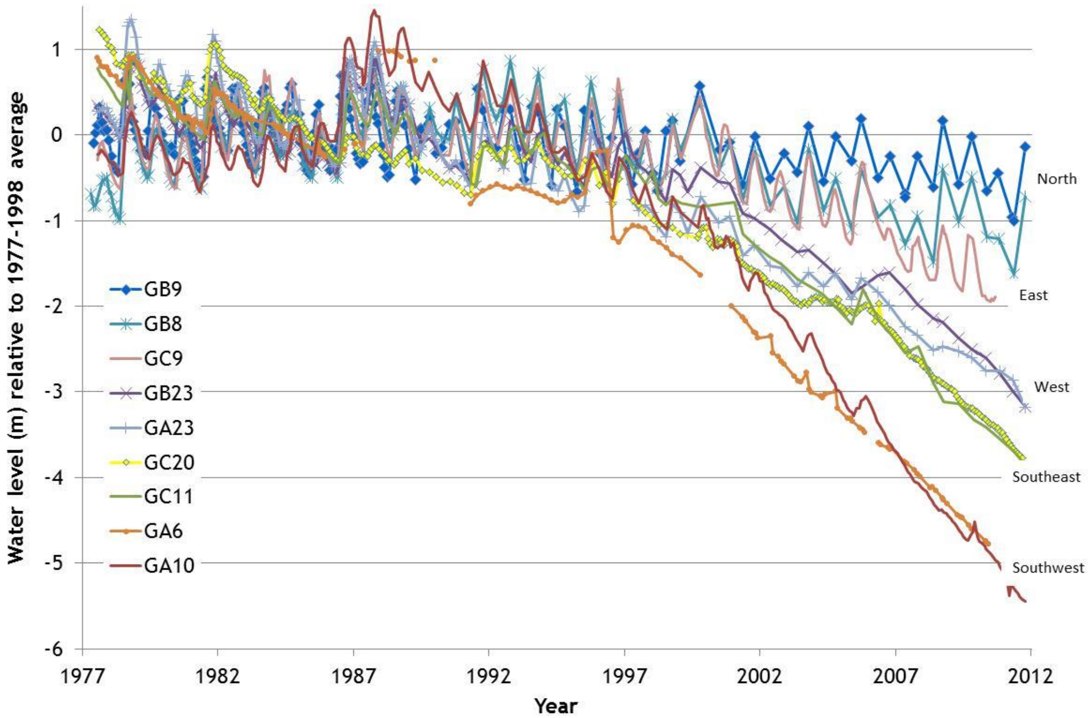


Figure 31 Long-term hydrographs for selected bores (normalised to 1977–1998 average) representing trend patterns across the Yeal Nature Reserve

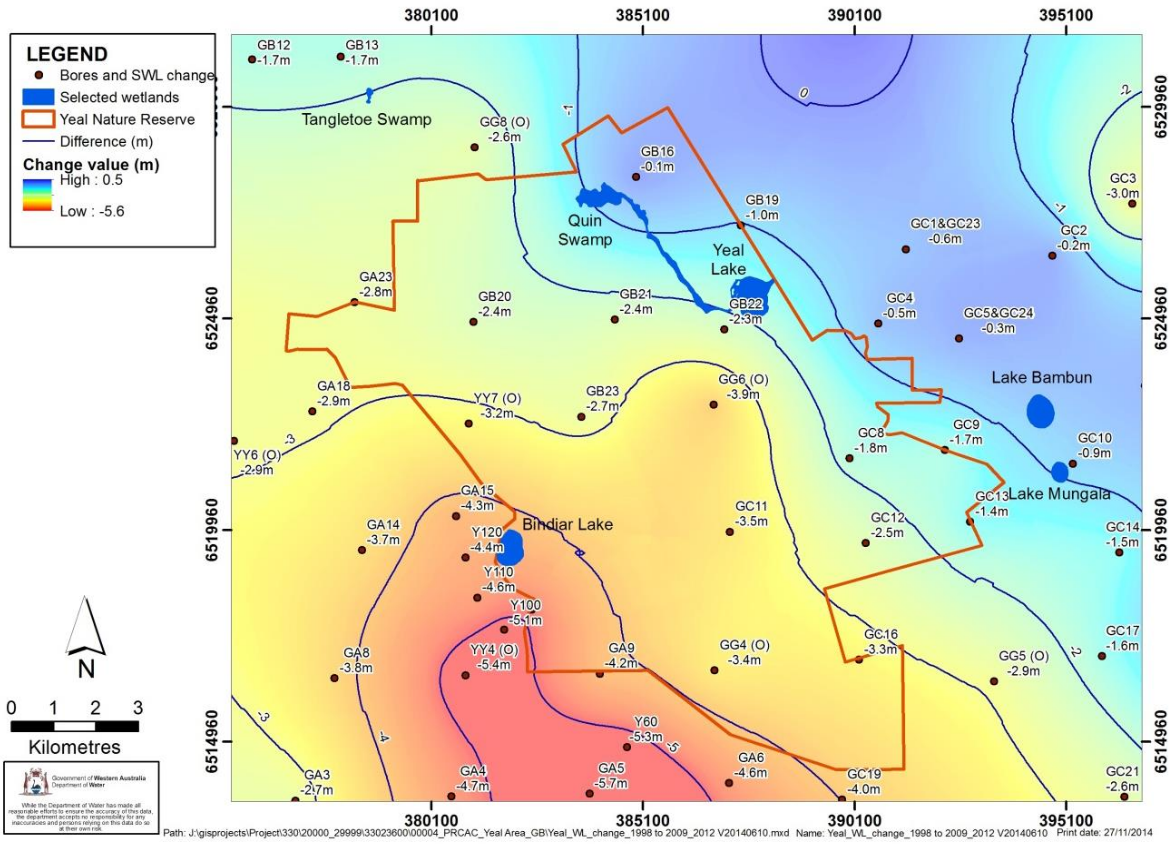


Figure 32 Contoured change in watertable between 1977–1998 and 2009–2012

Spatial mapping of watertable decline is illustrated as the change in water levels between the 1977–1998 average and that of 2009–2012 (Figure 32). Greater decline in the reserve's south-west corresponds with the timing of growth and maximum water use in the pine plantations (see Section 6.3).

6.3 Water level trend analysis

Regression analysis of selected bores using HARTT indicated that for most of the 30-year period up to 2012, rainfall decline explained most of declining watertable trends in the regional Superficial aquifer near the north Yeal wetlands (at GB22). However, from the late 2000s there was an emerging influence of confined aquifer drawdown in the reserve's south and centre, which is likely to continue affecting these wetlands in addition to rainfall decline. In the south of the wetlands in the central and southern parts of the Yeal Nature Reserve, a combination of rainfall decline, pine effects on recharge and confined aquifer drawdown explained watertable decline (at GC11, GA10 and GC19). In this area, clearing of vegetation and planting of pines downgradient of the bores had effects extending into the reserve's south and west (see results in Appendix F). Effects of confined aquifer drawdown were evident in the reserve's central and southern parts and tended to emerge after the mid-2000s. The main trends are summarised below (see Appendix F for details).

Watertable trends west of Yeal Lake (at GB22) in recent decades largely reflect the effect of declining rainfall offset by recharge from surface water flows in Quin Brook. The best-fitting model of water level trends consisted of rainfall trend with a variable increasing after 1991 and a second variable decreasing after 2008 (Figure 33;

The effect of Banksia woodland clearing and planting of pine trees on watertable trends at Yeal Nature Reserve's south-western edge is clearly illustrated at GA10. Rainfall trend combined with three additional variables achieved the best-fitting model (15, Appendix F). The variable with positive effect on water levels was interpreted to be recharge from Yeal Lake overflows to upper Quin Brook and was corroborated by the timing of overflow from the lake and peak water level recharge events (Appendix F). The late declining influence (after 2008) was introduced to reproduce the divergence between monitoring and the regression model toward the end of the period (2010 onwards). This represents the emerging influence of drawdown in the underlying confined aquifer (Yarragadee aquifer). Since the late 1970s, the approximately 4.1 m of water level decline at GB22 was mostly due to rainfall, with confined drawdown contributing about 0.6 m after 2008 (see also Table). Recharge from the flows in Quin Brook offset the decline by 0.6 m after 1991.

The additional variables independently represented positive and negative factors affecting water levels. There was a positive (recharge) effect from clearing of Banksia woodland west of the bore (1983–1985).

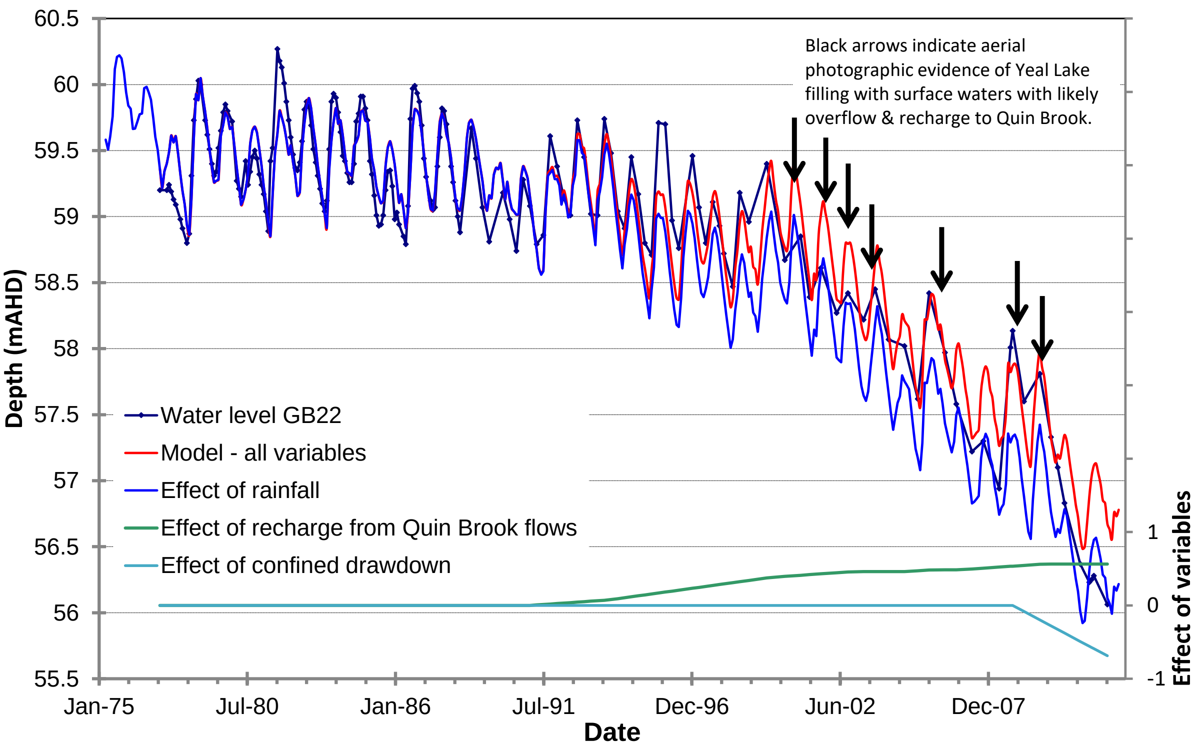


Figure 33 HARTT modelling of water level decline based on rainfall and other variables at GB22 west of Yeal Lake

This was followed by a two-part negative effect interpreted to be reduced recharge following planting of the pines, with the onset of confined aquifer pumping emerging after 2004. The effect of the pine growth was driven by increasing leaf area cover in the pine plantations, which generally reaches a maximum 14 years after planting (URS 2008). The effect of the timing of drawdown effects in the confined aquifer corresponded with the timing of impacts evident in water level monitoring (see Appendix F).

Since the late 1970s, overall water level decline at GA10 – due to rainfall, reduced recharge under the pine plantations and then drawdown in the confined aquifer – was about 5.3 m. Rainfall decline explained 2 m of this decline with the net effect of clearing and planting of the pines being about 2.3 m and confined pumping adding about 1 m after 2004 (see also Table). The rainfall effect was similar to a previous assessment at this bore up to 2004 (Yesertener 2008).

Watertable decline at GC11 and GB23 (see Appendix F) south of the wetlands also contained effects of upgradient propagation of water level decline at the pine plantations, as well as rainfall decline. Rainfall trend combined with an additional step-wise variable starting after 1997 achieved the best-fitting model for GC11 (Table A15, Appendix F) with good visual reproduction of water levels (Figure 34). This variable is best explained as the negative but sustained effect of reduced recharge after planting of the pines; the effect of which does not reach a maximum until at least 14 years after planting (i.e. 1999 at the latest). The effect would also take some time to propagate upgradient, hence the lag in the timing of influence of downgradient pine growth propagating to the bore. In contrast, any positive effect of clearing was short-term and therefore did not propagate the 5 km upgradient to the bore. There was also a slight, late influence of increasing of a third variable; that is, confined aquifer drawdown (leakage into the Leederville aquifer).

In summary, the approximate 4.5 m decline in water levels at GC11 from the late 1970s to 2012 consisted of 2.6 m caused by rainfall decline, with an additional net effect of clearing and planting of the pines of 1.7 m and then confined drawdown (after 2000) of about 0.05 m (see also Table). The rainfall effect was less than a previous assessment at this bore up to 2004 (Yesertener 2008), mostly because impacts of downgradient clearing of Banksia and pine growth were not previously considered.

Drawdown in the confined aquifer is an emerging factor after the mid to late 2000s in the centre and south of the Yeal Nature Reserve: it increasingly contributes to the decline in watertable levels. Regression analysis found the drawdown effect to be earlier in the south (after 2004 at GA10 and GC19) and later (mostly after 2008) in the reserve’s centre and west (GC11, GB22 and GB23). These analyses suggest a northward propagating effect of confined aquifer drawdown that may eventually affect water levels in the reserve’s north at the Yeal and Quinn brook wetlands. This is consistent with hydrographs in the reserve’s south (at AM14b) that indicate a steady increase in the effects of Leederville aquifer water-level decline on the deep Superficial aquifer, with the vertical gradient gradually increasing to a maximum in the late 2000s (Figure, Appendix F). This pattern indicates that the drawdown effect was likely to be initially small compared with the larger, shallower effects of the reduced recharge beneath in the plantations but increases with time (see discussion in Appendix F). In addition, the effect somewhat diminishes northwards, with the hydrographs at AM9a indicating a smaller drawdown and no change in vertical gradient in this area (Appendix F).

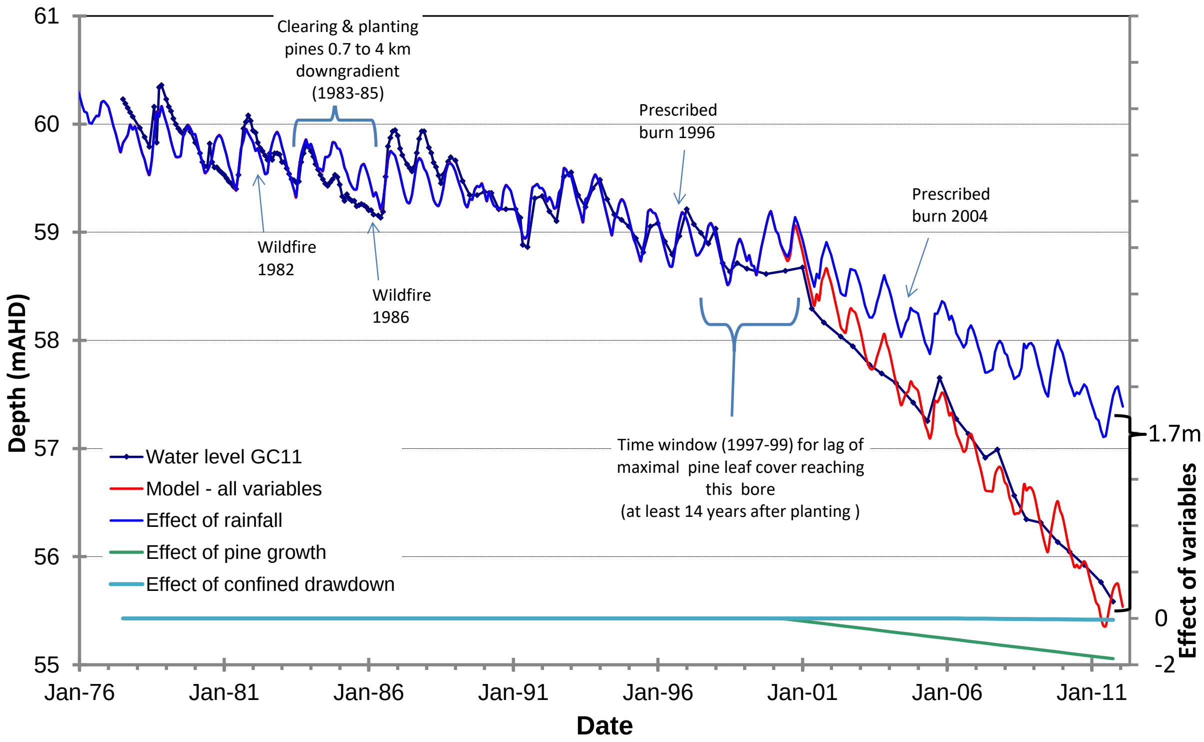


Figure 34 HARTT modelling of water level decline based on rainfall, land use and confined aquifer drawdown variables at GC11, central Yeal Nature Reserve

6.4 Summary

The main trends relevant to the north Yeal wetlands are:

- Inundation from surface flows in Quin Brook overflowing from Yeal Lake was frequent before the mid-2000s. Higher groundwater levels in the recent past would have enabled increased duration of flows in upper Quin Brook and greater periods of inundation in the wetlands after each flow event (between Yeal Lake and Quin Swamp).
- Reduced flows along upper Quin Brook overflowing from Yeal Lake have led to less local recharge to groundwater along the brook.
- Quin Swamp and upper Quin Brook wetland are now dependent on the balance between inflow from a perched groundwater system and outflow or leakage to the regional Superficial aquifer.
- The decrease in the watertable at the north Yeal wetlands over several decades (to 2012) is largely influenced by the effects of declining rainfall but

there is an emerging influence of confined drawdown in later years. Near the wetlands (at GB22), the watertable trends show the effect of fewer recharge events from surface water flows into Yeal Lake. The overall decline is not greater in the area recharging the Yarragadee aquifer (at bores GB22, NG3d) compared with further west outside of the area (bores GB21, NG4d).

- The 30-year pattern of watertable decline south of the wetlands (at GB23, GC11, and GC19) is only half explained by declining rainfall since the 1970s. The effects of downgradient pine plantation growth on recharge could explain most of the remaining decline, with the effects extending upgradient into the reserve to 2012. The effects of the pines ranges between 1.7 to 3 m depending on distance from the edge of the plantation.
- Accelerated drawdown in the confined aquifer was an additional significant factor emerging generally towards the late 2000s in the centre and south of the Yeal Nature Reserve. This factor explained between 0.05 m to 1.1 m of the watertable decline in these areas.

7 Ecology and ecohydrology

Ecological monitoring at the wetlands established a basis for calculating EWRs. The following describes the baseline surveys in 2009 and changes since then.

7.1 Vegetation

The vegetation monitoring transect established at Yeal Lake (Figure 9) traverses semi-submerged to terrestrial vegetation. It begins at a stand of *Baumea articulata* and continues upgradient to an overstorey of mature *Melaleuca rhaphiophylla* and an understorey of mixed sedges and M. teretifolia shrubs. At the time of transect establishment, an historic fire event was evident, with most trees still recovering (Wilson et al. 2009).

At the upper Quin Brook wetland the vegetation transect traversed more terrestrial vegetation, starting from the brook's edge and ending at the CYW bores (Figure 9). The overstorey consists mostly of M. rhaphiophylla, M. preissiana and Eucalyptus rudis, with the occasional large Nuytsia floribunda. The vegetation changes to open Banksia woodland at the transect's eastern end (Wilson et al. 2009).

The transect at Quin Swamp had a strong zonation of wetland vegetation in 2009. M. rhaphiophylla saplings covered the wetland basin with occasional M. teretifolia on the outer edge. The next band consisted of very large, multi-stemmed M. rhaphiophylla all with many fallen limbs. The third band of vegetation consisted of young M. rhaphiophylla recruits and beyond this band was mixed wetland and terrestrial vegetation (Wilson et al. 2009).

The baseline canopy assessment, which scored aspects of condition to rate mean tree health, rated all wetlands as 'good', with the upper Quin Brook wetland scoring the highest rating, followed by Quin Swamp and Yeal Lake. The baseline survey noted there had been recent fires at Quin Brook and Yeal Lake resulting in high regeneration at these sites, particularly at Quin Brook (Wilson et al. 2009). Quin Swamp was burnt in 2011 with only the M. rhaphiophylla saplings in the wetland basin surviving the fire.

Canopy condition has declined at all wetlands since 2009. The largest changes have been at Yeal Lake, with mean canopy condition in 2013 declining by 59% compared with 2009. There has also been increasing recruitment of *M. rhaphiophylla* saplings on the bed of the wetland since 2009, which is reducing the area of open water when filled. Exotic cover increased by 24% at the wetland in this period. In 2011 large numbers of *M. rhaphiophylla* trees on the lake's western side appeared to have died. In 2012 and 2013, the majority of these trees showed no recovery despite higher rainfall in 2012. During the 2013 assessment, vegetation along and adjacent to the transect had been considerably damaged by off-road vehicles (Wilson & Froend 2014). Changes in the vegetation were attributed to declining water levels and less frequent filling of the lake.

Though canopy condition has declined marginally at the upper Quin Brook wetland and Quin Swamp since the baseline year, some recovery was evident from 2012 to 2013. Exotic cover at Quin Brook has also reduced since 2009 and has remained relatively stable at Quin Swamp (Wilson & Froend 2014). This is despite the likelihood that groundwater levels have been declining near the wetlands since as far back as the late 1980s.

EWRs for vegetation at each of the wetlands were based on the vegetation with the least tolerance for minimum groundwater levels. These were calculated for the monitoring bores best representing the shallow groundwater at each wetland:

- Yeal Lake – water levels at YLc to be at least 58.3 mAHD based on the requirements for Baumea articulata.
- Upper Quin Brook wetland – water levels at CYWc to be at least 55.2 mAHD based on the requirement to maintain Melaleuca rhaphiophylla.
- Quin Swamp – water levels at QUNEc to be at least 54.2 mAHD based on the requirements for Baumea articulata.

7.2 Macroinvertebrates

Yeal Lake has been sampled for water quality and macroinvertebrates in four recent years (2008, 2009, 2011 and 2013) when it has held surface water. The monitoring has shown the lake is highly coloured, has near neutral pH waters and is nutrient enriched (Judd & Horwitz 2010). High macroinvertebrate family richness was recorded in 2008, 2009 and 2011. Three consecutive years of dry/very low lake levels may have contributed to the lower-than-average family richness recorded in 2013 (Sampey et al. 2014).

Sampling at the upper Quin Brook wetland was restricted to two events in spring and summer 2008 as the wetland has not been inundated since. The brook flows from Yeal Lake so unsurprisingly the monitoring found it was highly coloured and nutrient enriched. Moderate macroinvertebrate family richness was recorded in both the spring and summer sampling (Judd & Horwitz 2010). Sampling at the wetland was last attempted in September 2012 but no standing water could be located and sediments were dry.

To maintain macroinvertebrates, water levels must reach at least 0.5 m above the bed level of the wetlands. The calculated water level achieving the EWR for macroinvertebrates at each wetland was:

- Yeal Lake – 59.8 mAHD at YLc is maintained for at least four months based on the deepest point of the lake being 59.3 mAHD (Figure 16).
- Upper Quin Brook wetland – 57.8 mAHD in bore CYWc is required for at least four months based on the deepest point of the wetland depression being 57.3 mAHD (Figure 18).
- Quin Swamp – 55.3 mAHD in bore QUNEc is required for at least four months based on the deepest point of the wetland being 54.8 mAHD (Figure 19).

Though the north Yeal wetlands are known to support a range of waterbirds and other water-dependent vertebrates including frogs and turtles, limited vertebrate fauna monitoring has been conducted to date. However, the diversity and abundance of these communities are likely to be associated with the hydrologic regimes of the wetlands. Wading birds require access to shallow water in summer and early autumn for feeding, as well as higher winter water levels to maintain the distribution of open water and vegetated habitats (Froend et al. 2004b). Any changes to the hydrologic regime of the wetlands (timing, duration, frequency and extent of inundation) will impact waterbirds and other wetland-dependent vertebrates.

8 Processes and interactions between surface water and groundwater

This study has found that wetlands in the north Yeal Nature Reserve interact with perched and semi-perched groundwater that have varied levels of connectivity with the regional Superficial aquifer. Groundwater at Yeal Lake is perched and disconnected from the influence of water levels in the regional Superficial aquifer or drawdown from the underlying confined aquifers. Further downstream along the brook, groundwater beneath the wetlands is semi-perched and influenced by the water levels in the regional Superficial aquifer either vertically or laterally. The dominant hydrogeological and ecological interactions can be represented by simple conceptual models (Figure 35, Figure 36; Figure 37) and are summarised below.

The variable connectivity between groundwater at the wetlands and the regional Superficial aquifer is due to the variable permeability and proximity to the Guildford Formation's western edge. Groundwater ranges from perched to semi-perched at the wetlands above thin, interlayered clayey beds in the western extent of the Guildford Formation, which is of varying thickness around the wetlands with no continuous clay layers. This causes lateral variation in hydraulic connectivity between shallow groundwater and the regional Superficial aquifer, illustrated at Quin Swamp where connectivity is greater on the eastern side relative to the western side despite similar interlayered clayey beds (Figure 37). Such patterns of connectivity are typical of semi-perched groundwater systems (Pederson 2000). Hydrochemical patterns also show a difference between the semi-perched groundwater and the Superficial aquifer. This difference is greater where the semi-perched groundwater is less hydraulically connected. The watertable and the regional Superficial aquifer becomes completely connected within 1.5 km downgradient (west) of the wetlands (Figure 35; Figure 37; Figure 36). In contrast, to the east and north of the wetlands the watertable is perched and hydraulically disconnected from the regional Superficial aquifer by shallow clays in the Guildford Formation (as indicated by NMR, water levels and lithology). This understanding of connectivity has been included with other information that broadly indicates limited connectivity is mostly a feature of the northern part of the Yeal Nature Reserve (Appendix J).

Yeal Lake interacts with a perched groundwater system that discharges to the regional Superficial aquifer, but is not hydraulically influenced by this aquifer. This is due to the low permeability of the silty sandy and sandy clays (Guildford Formation) underlying the lake, as well as the limited saturated thickness of the perched aquifer that restricts the influence of the downgradient regional aquifer on water levels (

Figure 35). The limited saturated thickness constrains the transmissivity of the perched groundwater and the extent that any downgradient regional watertable decline will have on the lake. This is clearly shown by generally similar rates of lake level decline after filling that are independent of the downgradient watertable decline.

At Quin Swamp semi-perched groundwater has some connection with the regional aquifer, mostly through the Guildford Formation rather than laterally. Groundwater locally leaks through the formation probably because it is sandier in parts, which may accelerate if regional groundwater levels decline (Figure 37). However, watertable trends at Quin Swamp presently reflect more influence from the upgradient shallow groundwater than the downgradient regional aquifer. In contrast, downgradient regional water levels have a greater influence on the trends at Quin Brook wetland, with limited connectivity through the Guildford Formation beneath the wetland (Figure 36). The downgradient influence on water levels here is due to the greater saturated thickness of the semi-perched aquifer (> 10 m compared with 3–9 m at Quin Swamp) at a location close to the likely edge of the low permeability parts of the formation.

Shallow groundwater interaction with ecosystems at Yeal Lake, upper Quin Brook and Quin Swamp is gradually decreasing. Water levels at Quin Swamp and the upper Quin Brook wetland have become dependent on the balance between inflow from the perched groundwater system and outflow to the regional flow in the Superficial aquifer. Before the mid-2000s, high groundwater levels enabled frequent inundation at Quin Swamp and the upper Quin Brook wetland. Because of declining groundwater levels, inundation is now rare and only for short durations when Yeal Lake overflows to generate surface water flow in upper Quin Brook. Decline in water levels at the wetlands is driven by downgradient decline in groundwater levels at all wetlands except Yeal Lake. This will continue until the regional aquifer completely disconnects from the shallow groundwater system at each wetland. Disconnection is not expected until after 2025 at rates of watertable decline observed up until 2012. During disconnection, hydraulic interaction of the deep and semi-perched groundwater often continues until the deeper levels fall more than several metres below low permeability layers (Brunner et al. 2010). After disconnection, the groundwater system at each wetland will be either semi-perched or perched depending on the permeability of the underlying Guildford Formation.

Yeal Lake depends on surface inflows to fill and groundwater perched above the Guildford Formation to retain water (Figure 35). The lake fills with surface flows from the upper Quin Brook catchment to the lake’s east that rely on high watertables to generate and convey runoff to the lake. Lake water recharges the shallow groundwater after filling and influences how long water is retained in the lake. Leakage from the lake has been largely constant and is most likely restricted by the thinness of the perched groundwater system (limiting transmissivity). This has also limited the effect of large declines in groundwater levels downgradient of the lake.

Watertable decline has resulted in the exposure of ASS and acidification of shallow groundwater at the upper Quin Brook wetland and Quin Swamp (to > 4 m below the watertable). The influence of this extends to more than 10 m into the aquifer, probably assisted by recharge from Quin Brook. The lateral and vertical migration of the acidification front will continue into the Superficial aquifer, with intermittent recharge and continued watertable decline generating more acidity in the wetland ASS materials as these are exposed. Neutralisation of this may slow penetration of the acidity. The main mechanisms for neutralisation include recharge of higher alkalinity surface waters along Quin Brook (alkalinity in Yeal Lake exceeds 70 mg

$CaCO_3$/L) and potentially sulfate reduction deeper in the aquifer. Groundwater is also acidifying elsewhere in Yeal Nature Reserve at wetlands (Bindiar) and in shallow parts of the Superficial aquifer between these.

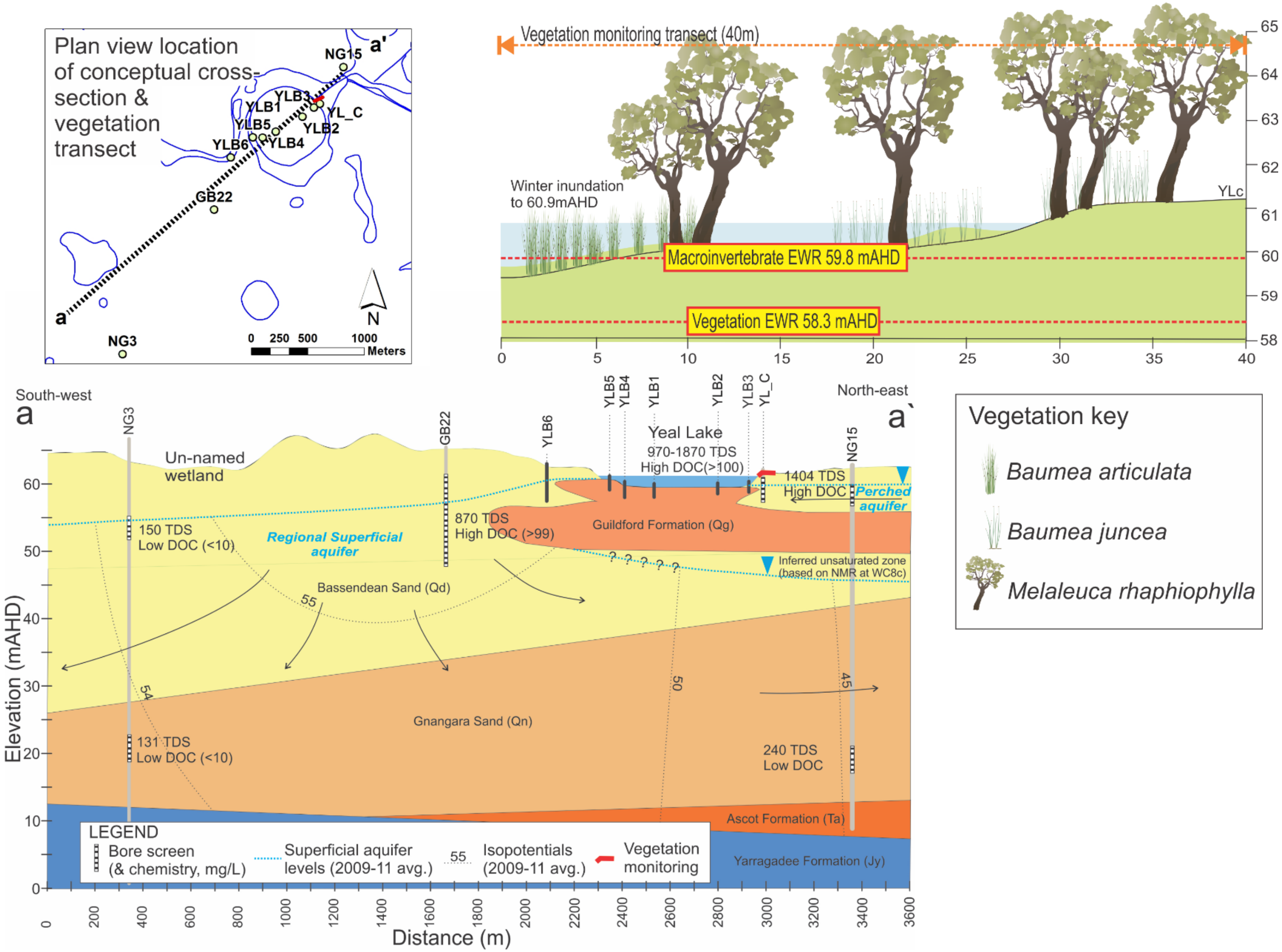


Figure 35 Conceptual model of groundwater–ecological interaction at Yeal Lake when inundated

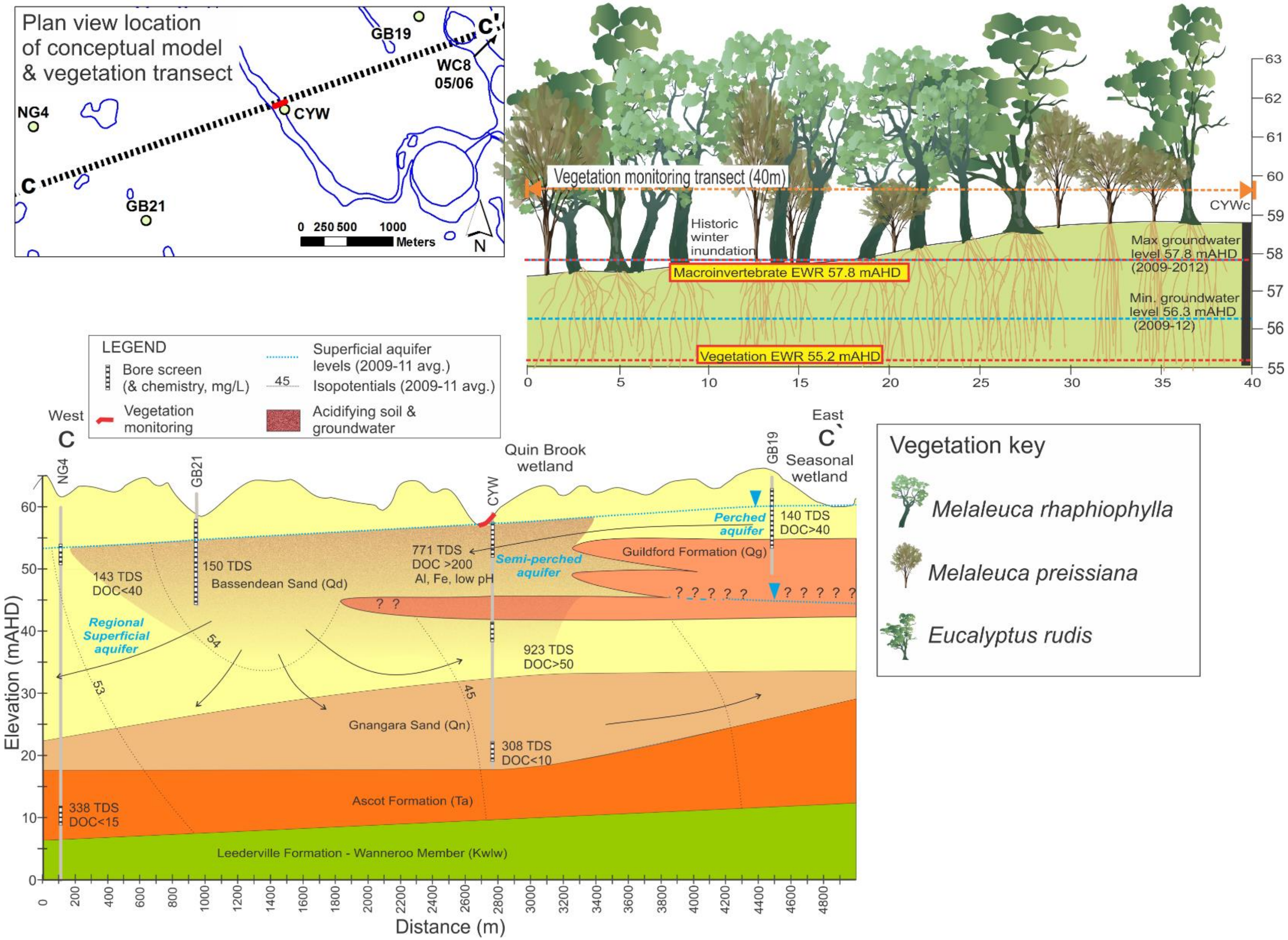


Figure 36 Conceptual model of groundwater–ecological interaction at the upper Quin Brook wetland

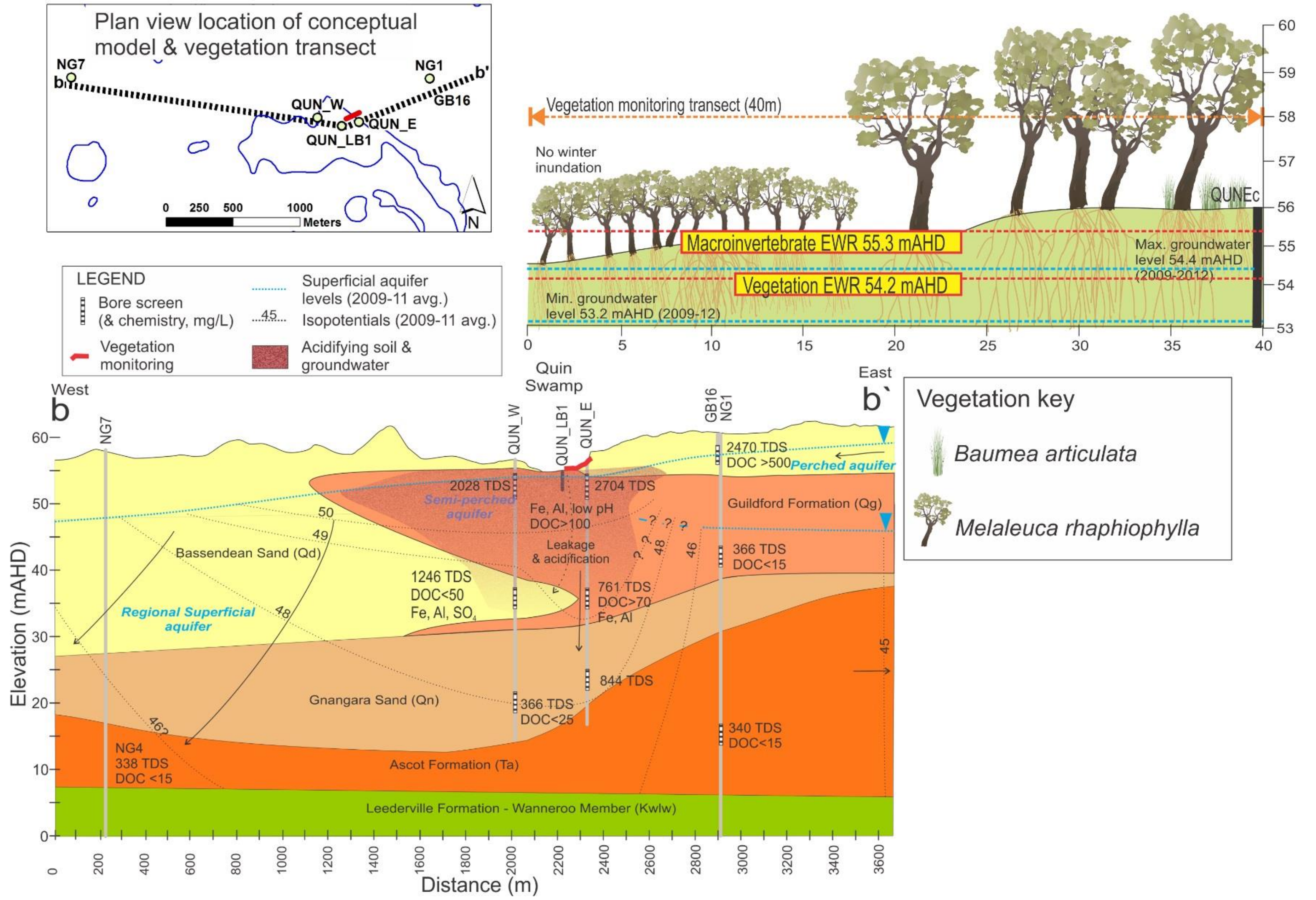


Figure 37 Conceptual model of groundwater–ecological interaction at Quin Swamp

9 Implications for ecological health and management

9.1 Ecological

Declining groundwater levels in the regional Superficial aquifer have had large effects on the ecology of Quin Swamp and the upper Quin Brook wetland, but not the ecology of Yeal Lake. This threatens the ecological function of these wetlands in the greater Banksia woodland and as a water habitat corridor between the permanent habitats of the lower Lennard Brook and lower Gingin Brook. Much of the water level decline until 2012 was due to declining rainfall, with an emerging influence from regional drawdown in the underlying confined aquifers (Leederville and Yarragadee) that threaten to increase the rate of decline. The regional drawdown in Superficial aquifer levels caused by abstraction from these aquifers needs to be minimised to protect the ecological health of Quin Brook and Quin Swamp.

EWRs determined at the upper Quin Brook wetland and Quin Swamp are recommended for the management of abstraction that affects regional water levels in the Superficial aquifer. The phreatophytic vegetation community at Quin Swamp and Quin Brook wetland is completely dependent on semi-perched groundwater that is connected with the regional Superficial aquifer. The groundwater level is declining and probably has been since the late 1980s. Any additional acceleration of water level decline by drawdown in the underlying confined aquifers will cause further impacts at these wetlands and the chain of wetlands downstream of these.

EWRs determined at Yeal Lake are suitable for local water level management and not the management of abstraction that impacts on regional water levels in the Superficial aquifer to the lake's west. In this context, the EWRs should be considered in the assessment of any options to increase runoff and surface water inflow from the east. The phreatophytic vegetation and macroinvertebrate communities at Yeal Lake depend on perched groundwater that is recharged when the lake is filled by surface inflows. The surface water inflows are largely independent of the decline of the regional Superficial aquifer, being from the catchment with perched groundwater east of the lake. Surface water flows to the wetland are becoming increasingly intermittent with declining rainfall trends – the main factor likely to be driving the decline in vegetation condition at the lake. This is because less recharge to the perched groundwater that supports the phreatophytic vegetation is occurring. Trends in the wetland's aquatic ecology are not yet clear but will become increasingly influenced by fewer overflows and reduced open area of water. The frequency of lake filling has decreased from annually before the early 2000s to every few years in the past decade (see Appendix A). This is likely to result in greater algal growth in the wetland, as well as greater retention of nutrients and potentially higher concentrations in the reduced surface inflows. Continued shrinking of the lake's open water area as *M. rhaphiophylla* saplings encroach from the edges will erode the lake's high value habitat for waterbirds and macroinvertebrate communities. This habitat is becoming increasingly regionally limited. Greater frequency of filling should minimise the loss of the open water habitat at this lake.

Water levels in the semi-perched groundwater system were sufficiently high to meet the EWRs of the wetland vegetation communities at Yeal Lake and Quin Brook wetland but not at Quin Swamp (Figure 35, Figure 36; Figure 37). In contrast, the EWRs of macroinvertebrate communities were not being met at Quin Brook wetland or Quin Swamp. These were last met in Quin Brook wetland in 2008 when levels at CYWc exceeded 57.8 mAHD for four months (Figure 18) and at Quin Swamp, levels have been below the lake bed since before 2008 (Figure 19).

The observed declines in vegetation condition and distribution at each wetland have been driven by the combined effects of previous water level decline and current poor water quality in the shallow groundwater systems. Groundwater was highly acidic with high concentrations of dissolved metals at Quin Swamp and the upper Quin Brook wetland as a result of ASS oxidation. Exposure of phreatophytic vegetation to acidic conditions can potentially damage and stunt root growth, mainly through damage to fine roots (Vanguelova et al. 2007). This could induce mineral deficiencies and increase susceptibility to plant pathogens such as *Phytophthora*.

The combination of acidity and aluminium toxicity is likely to have contributed to declines in plant health observed at Quin Swamp and the upper Quin Brook wetland through damage to plant roots and disruption of plant ionic balance. Both low pH (indicating concentrations of H^+) and aluminium can be toxic to roots (Vanguelova et al. 2007). Most plant species are tolerant to generally less than 1 mg Al/L, which was marginally less than the highest concentrations in shallow groundwater at Quin Swamp and the upper Quin Brook wetland. However, the sensitivity of plants to aluminium can be greater if the relative concentrations of calcium are low. The molar ratio of calcium:aluminium in soil pore water is an indicator of whether aluminium concentrations pose a risk to plant growth (Vanguelova et al. 2007) and can be applied to shallow groundwater in the root zone of the wetlands. Molar calcium:aluminium ratios in the shallow groundwaters ranged from an average of 0.3 on Quin Swamp’s western side to more than 1 on the eastern side and at the upper Quin Brook wetland. Where the ratio exceeds 0.2 there is a high risk of adverse impacts from aluminium concentrations on fine roots (Vanguelova et al. 2007).

The shallow acidity and high concentrations of metals is also likely to affect any aquatic life at Quin Swamp or in the depressions in the upper Quin Brook wetland should water levels rise to allow ponding. Aquatic organisms are typically more sensitive to acidification than plants (Driscoll et al. 2005), with high concentrations of aluminium and iron in the acidified groundwater magnifying the impact when this discharges to the surface. These metals are known to have direct and indirect toxic effects on aquatic organisms (Degens 2013; Fältmarsch et al. 2008). Minimising the exposure of ASS by limiting groundwater decline will lessen these the impacts in the long-term.

9.2 Land and water use

Abstraction from the Superficial and underlying regional confined aquifers is beginning to affect the north Yeal wetlands. While declining rainfall patterns have been previously responsible for most of the decline in water levels at the wetlands, the emerging effect of drawdown in the confined aquifers (Leederville and Yarragadee) poses an additional increasing stress on the ecological health of the wetlands, particularly at Quin Swamp and upper Quin Brook wetland. Management of these impacts will need to consider management of regional drawdown in the Leederville and Yarragadee aquifers due to pumping.

The connectivity between the regional Superficial aquifer and the watertable at the wetlands can be used to interpret the impacts of watertable changes modelled in PRAMS until the model is updated. The current version of PRAMS (version 3.5) under-represents the spatial extent of the Guildford Formation mapped in this study, and potentially over-predicts watertable drawdown at Yeal Lake. Despite this, the model should reasonably predict long-term drawdown at Quin Swamp or the upper Quin Brook wetland where the drawdown is driven by regional drawdown. Updating PRAMS could explicitly represent the Guildford Formation as a distinct layer within the Superficial aquifer by varying the hydraulic conductivity zones (Kv and Kh) of the three layers that currently represent the aquifer. Currently there is no variation in Kv or Kh in any of the 3 layers west of the Yeal Lake to the edge of the Gingin Scarp. The extent of the formation can be derived in regional mapping of watertable connectivity presented with this report (Appendix J).

Management and licensing of private use in the Deepwater Lagoon groundwater subarea to the east of the wetlands should consider conditions on licences that include avoiding impacts on the wetlands. Any increased pumping from the deeper Superficial aquifer to the east should avoid causing further water level declines in the aquifer immediately beneath the wetlands. This can be achieved through assessing licences to ensure that maximum drawdown cones do not extend to the western edge of the Guildford Formation. However, pumping from the perched and semi-perched groundwater in freehold areas east of the lake does not require particular management conditions. The limited saturated thickness of this groundwater at the wetlands and within several kilometres east naturally limits suitability for larger pumping from single abstraction points. This indicates limited effects of any smaller pumping (< 1 ML/yr) of groundwater exempt from licensing.

Maintenance of the existing land use in the cleared freehold land east of the wetlands will benefit water levels and the hydroperiod of Yeal Lake. Any change in land use that reduces runoff, such as extensive planting of non-irrigated perennial vegetation or modified shallow drainage, would reduce surface water volumes and frequency into Yeal Lake. Regional water level decline in the underlying Superficial aquifer will not affect watertable decline across most of the area because the shallow groundwater is perched on the Guildford Formation. However, upper Quin Brook flows to Yeal Lake cross an area where the Guildford Formation is thin (west of Bambun Lake) and water levels may be influenced by downgradient watertable decline in the regional Superficial aquifer (see Figure 32). The flow in this part of the brook is sensitive to groundwater levels where flows have decreased since 2000 because of increasing losses to shallow groundwater (Boniecka 2015).

Opportunities exist to increase flow of surface waters into Yeal Lake whereby overflows to the wetlands downstream could potentially mitigate any future decline in regional groundwater levels caused by pumping the confined aquifers. Surface water modelling indicates an average of 1.4 GL/yr flows to the lake for the period 2000 to 2013, with an average of 7.5 GL/yr lost to groundwater in conveyance to the lakes (Boniecka 2015) – most likely west of Lake Bambun. An increase in surface flows to Yeal Lake of about 2 GL/yr may be possible, assuming the 25% of flow lost to shallow groundwater is captured. Recharge of this would be sufficient to offset a 0.2 m/yr decline in watertable across an area of 32 km^2 in the Yeal Nature Reserve. This is similar to the area of the Yarragadee recharge window beneath the Superficial aquifer.

Options for increasing surface water flows east of Yeal Lake include upgrading and clay lining existing channels to reduce loss to shallow groundwater and constructing channels to increase recharge to existing wetlands. Widening and clay lining the existing northern channel from lower Lennard Brook through to Sullivan Road (see Figure 7) is likely to increase winter flows from Lennard Brook. Clay lining and widening channels between Sullivan Road and Strickland Road (see Figure 7) would reduce conveyance losses (recharge to shallow groundwater). With greater surface flows near Yeal Lake there are opportunities to increase recharge along Quin Brook downstream of the lake or to divert flows to existing adjacent wetlands. Two areas are immediately apparent south and west of Yeal Lake from assessment of LIDAR elevation (Figure 38):

- The first is wetland area A, similar in size to Yeal Lake, where water might be channelled from the existing bypass flow channel.
- The second is wetland area B south of Yeal Lake, where surface flows overflowing from Yeal Lake might be diverted to a smaller series of wetlands.

All wetlands would locally benefit from additional recharge to groundwater and in this location there would be direct recharge to the Yarragadee aquifer. Increased surface water inflows would be unlikely to result in increased loading of nutrients to Yeal Lake because flows are still less than historic flows. Any potential eutrophication effects of improving surface water flows would need to be compared with the effects of ongoing declines in the hydroperiod with no intervention.

Modified management of land within the reserve may benefit water levels at the wetlands in the long-term, although further investigation is required to establish the size of this benefit as climate change causes further drying. Manipulation of burning frequencies in the Banksia woodland has been proposed to increase recharge (Farrington et al. 1989), but this benefit may be limited given little recharge is evident in the hydrographs of the past decade that incorporate current burning practices. Furthermore, recent investigations indicate little recharge following fuel reduction burning in Banksia woodland (Silberstein et al. 2013).

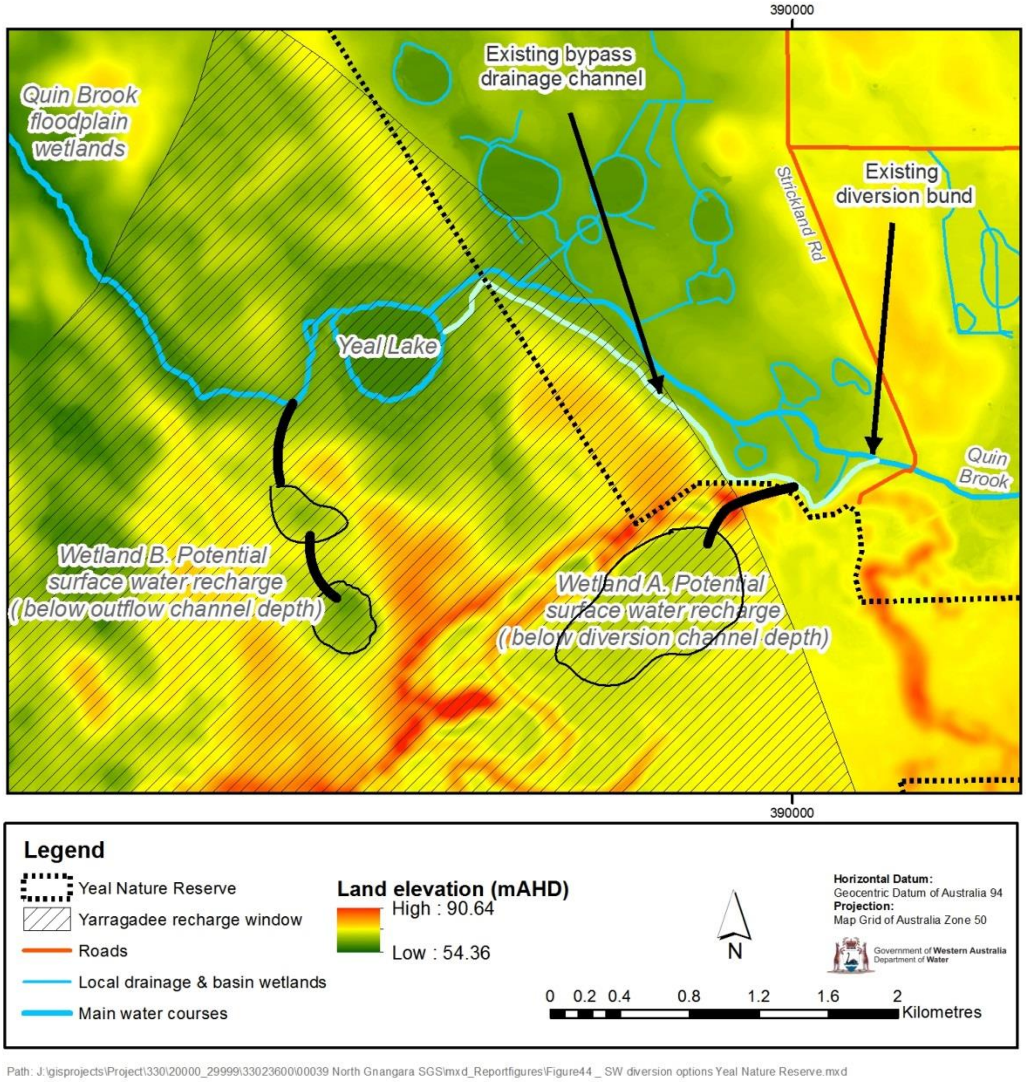


Figure 38 Potential options for enhanced surface water recharge from Quin Brook

Any land management practices aimed at increasing recharge are unlikely to prevent further degradation of the wetlands' ecological values because the vegetation will continue to be affected as long as shallow groundwater remains acidic. The effects of climate change on the Gnangara groundwater system are forecast to increase, with reduced rainfall driving declines in many shallow groundwater systems (CSIRO 2009; De Silva 2009). Consequently, implementing land management practices to increase recharge may not be enough to prevent future drying and rewetting of wetland sediments, leading to further acidification events. Slow neutralisation of the acidity could potentially be mediated by increased alkalinity in recharge water. The latter is likely through recharge of alkaline waters from Quin Brook, particularly if flows are increased. Acidic water migrating into the Superficial aquifer may also be neutralised by microbial sulfate reduction deeper in the aquifer with recharge of high DOC water, but this would depend on rates of recharge and acid flux from the drying, acidifying surface soils.

Thinning or removing the pine plantations to the reserve's west would provide significant benefits to water levels in the reserve's western part, but little benefit to water levels at the north Yeal wetlands. There is minimal recharge under the mature, high-density pine plantations on Gnangara (Crosbie et al 2010) and evidence that the effect of this on the watertable extends at least several kilometres east into the reserve.

10 Implementing the findings

The findings of the north Yeal wetlands study will be used to inform DWER's water licensing, groundwater allocation planning and water monitoring, as well as the department's advice on any proposed land use change.

Allocation planning

- EWRs for upper Quin Brook wetland and Quin Swamp need to be considered as part of the management of water levels at the wetlands.
- Accelerated water level decline at the wetlands due to drawdown in the Leederville and Yarragadee aquifers will amplify decline in ecological health. Any stabilisation or increase in water levels would help protect current ecological heath.
- Additional drawdown in water levels and rate of decline in the regional Superficial aquifer and confined aquifers need to be minimised to support ecological health at upper Quin Brook wetland and Quin Swamp.
- Yeal Lake water levels do not need to be managed as part of regional allocation planning because its ecological health is unlikely to be affected by water levels in the regional Superficial aquifer.
- Consider QUNWc, CYWc and YLc as new GDE watertable monitoring bores for ongoing monitoring.
- Consider retaining GB22, GC4 and NG9d for ongoing monitoring and modify frequency to monthly (or use of water level loggers with hourly logging). Monitoring of GC4 and NG9d will verify any effects on the shallow groundwater in the surface water catchment for Yeal Lake.

Licensing and land use planning

- Through the land use planning process, advise other decision-makers that that regular surface inflows to Yeal Lake from the Quin Brook catchment could be maintained by:
  - retaining current land use as mostly non-perennial vegetated rural and semi-rural
  - maintaining existing surface water drains across freehold land between Lennard Brook at Brand Highway and Yeal Lake inflow, and
  - avoiding using drains that lower the average of seasonal levels before 2012.
- Ensure any new drawpoints from the deep Superficial in the Deepwater Lagoon subarea are set back at distances of at least 1 km from the edge of the area of perching to avoid water level decline extending towards Quin Swamp and upper Quin Brook.

Water resource assessment and investigation

- Include the new hydrogeological understanding of the Superficial aquifer in this report in future conceptualisation of the Guildford Formation in PRAMS by updating the low vertical hydraulic conductivity (reflecting low permeability) in the Superficial aquifer at or to the east of Yeal Lake.
- Prioritise GB16 for early replacement when the shallow bore replacement program begins.
- Carry out opportunistic occasional monitoring of YL_SG to record the recession in lake levels after filling events to verify that lake recession remains independent of the recession in GB22.
- Install a watertable and deep Superficial aquifer monitoring bore on the western edge of Yeal Lake at the junction with the existing powerline track within five years and monitor for 10 years to confirm the extent and permeability of the Guildford Formation and monitor the effects of regional watertable decline closer to the lake.
- Consider options for enhancing surface water flows to Yeal Lake as an option to mitigate watertable impacts in wetlands (such as Quin Swamp) downstream of the lake from pumping in the Yarragadee or Leederville aquifers.
- Explore whether regional airborne electromagnetic data contains sufficient early signal information that can be re-analysed to confirm the western extent of the low permeability layers in the Guilford Formation to determine the likely propagation of water level decline in the regional Superficial aquifer and associated wetlands.

Appendices

Appendix A — Hydrological information extrapolated from aerial image analysis

Aerial image-based assessment of historic water level status for the north Yeal wetlands including wetlands in the upper Quin Brook upstream of Yeal Lake.

Year	Aerial image identification	Capture date	Annual rainfall relative to 1970–2011 average at Gingin (9018)	Rainfall in the six months before photo	Assessment of water level status				Yeal Lake full or filled during winter of year
					Yeal Lake	Quin Swamp	Wetlands and lakes in catchment NE of Yeal Lake	Wetlands and lakes in catchment SE of Yeal Lake	
1999	Perth North 120 cm	Nov 1999	249 mm above	594 mm	Full (overflowing)	Flooded	Full to north and south	NE Strickland full SE Sullivan full	Yes
2000	Gingin 50 cm	June 2000	35 mm below	266 mm	Full	Dry	Mostly dry	Lakes NE Strickland Rd full; Lakes SE Sullivan Rd full	Yes
2001	Swan Coastal Plain North 2002 40 cm	Dec 2001 – Feb 2002	40 mm below	380 mm	Full (overflowing)	Not in photo	Dry (except SE drain)	Lakes NE Strickland Rd partly wet; Lakes SE Sullivan Rd full	Yes
2002	No image	N/A	66 mm below	N/A					Yes based on 2003 image
2003	Swan coastal plain north 40 cm Ledge Point Gingin 50 cm	Jan 2003 Jun 2003	At average	285 mm	Full (overflowing) Mostly dry	Not in photo Dry	Not in photo Mostly dry	Not in photo Lakes NE Strickland Rd dry; Lakes SE Sullivan Rd partly wet	Likely
2004	No image	N/A	67 mm below	N/A					Uncertain
2005	No image	N/A	40 mm below	N/A					Yes based on 2006

Year	Aerial image identification	Capture date	Annual rainfall relative to 1970–2011 average at Gingin (9018)	Rainfall in the six months before photo	Assessment of water level status				Yeal Lake full or filled during winter of year
					Yeal Lake	Quin Swamp	Wetlands and lakes in catchment NE of Yeal Lake	Wetlands and lakes in catchment SE of Yeal Lake	
2006	Gingin 50 cm	Jan 2006	-125 mm below	> 500 mm	Full (including overbank)	Flooded	Some filled, dry to SE (except drain)	Lakes NE Strickland Rd near dry; Lakes SE Sullivan Rd part filled	Uncertain
2007	No image	N/A	-32 mm below	N/A					Uncertain
2008	Gingin 50 cm	July 2008	At average	282 mm	Full (including overbank)	Part flooded	All filled	NE Strickland full SE Sullivan full	Yes
2009	No image	N/A	50 mm below	N/A					Yes (from WL records)
2010	Swan coastal plain north 10 cm	Feb–May 2010	261 mm below	~ 290 mm	Drying	Dry	All dry	All dry	No
2011	Swan coastal plain north 15 cm	Feb–Mar 2011			Dry	Dry	All dry	All dry	No (only part filled from WL records)
2012	Gingin 50 cm	Feb–Mar 2012			Dry	Dry	All dry	All dry	No
2013	Plain north 15 cm	Jan 2013			Dry	Dry	All dry	All dry	Yes (from WL records) but no overflow

Assessment of Yeal Lake winter filling based on known water levels in Yeal Lake, aerial photographic analysis (above), annual rainfall and hydrograph of downgradient bore (GB22).

	Year												
	1999	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**
Max. water depth recorded in lake (m above bed)	N/A[1]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	> 1.4	1.9	< 0.1	0.3
Annual rainfall at Gingin Aero – 9718 (mm)	881	636	572	491	684	518	737	539	694	738	692	421	757
Lake filling evident from aerial images	Y	Y	Y	N/A	Y	N/A	Y	N/A	N/A	Y	Y	N	
Seasonal recharge peak evident in GB22[2]	Y	Y (delayed)	Y	Y (delayed)	Y	N	Y	N	N	Y	Y	N	N
Assessment of lake filling in winter	Y	Y	Y	Y	Y	N	Y	N	N (partial?)	Y	Y	N	N (partial)

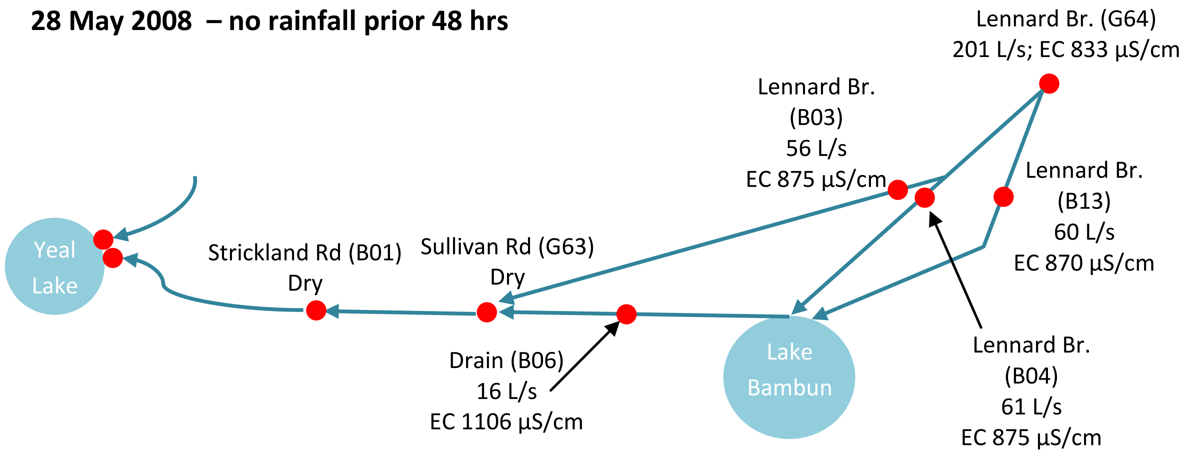
1 N/A – no records available for year (Note: no records of lake water levels before gauge board installed in November 2008).

2 Interpretation of likely historic lake filling and overflow where aerial image data was lacking based on seasonal water level responses at GB22 since 1999. Larger seasonal rise in water levels corresponded when Yeal Lake was known to be full and overflowed to Quin Brook (e.g. 2008, 2009) with much smaller rise during years when the lake was known to be dry with no overflow to Quin Brook (e.g. 2010 and 2011).

Appendix B — Summary surface water snapshot results - Quin Brook and Lower Lennard Brook

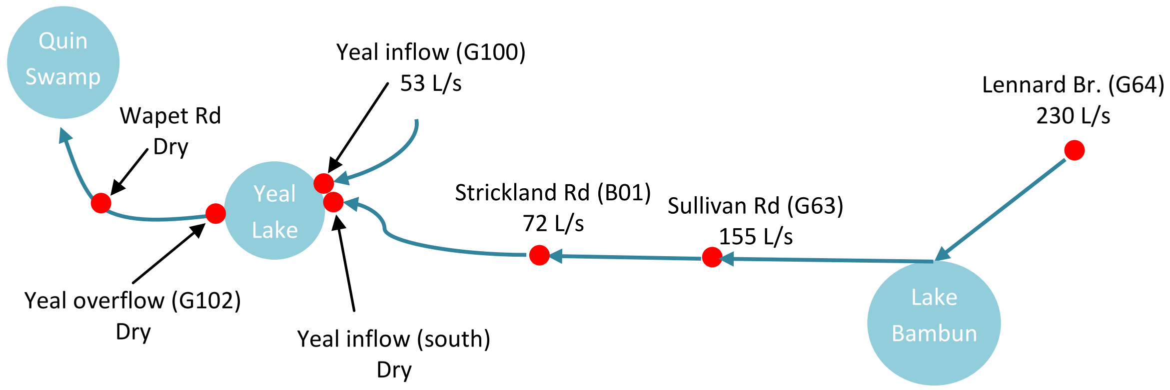
Autumn 2008 Bambun inflow surface water snapshot – schematic map

28 May 2008 – no rainfall prior 48 hrs

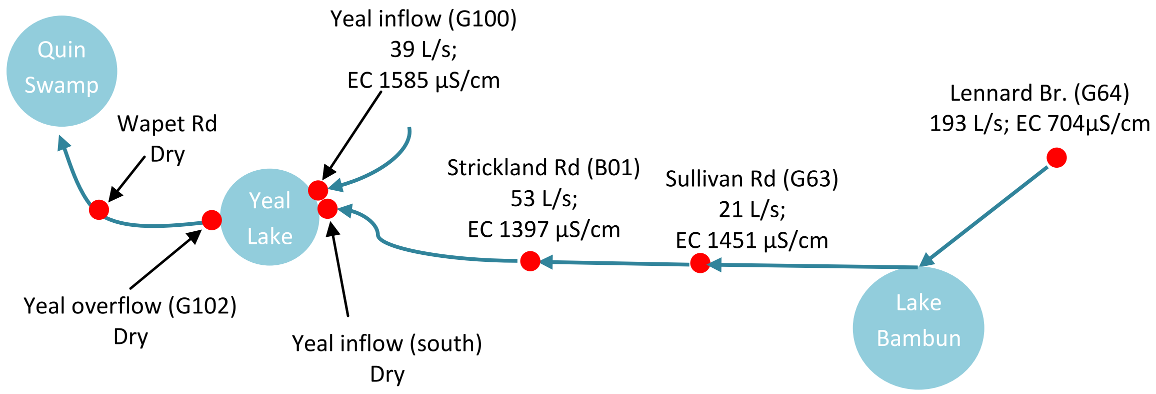


Spring 2011 surface water snapshot – schematic map

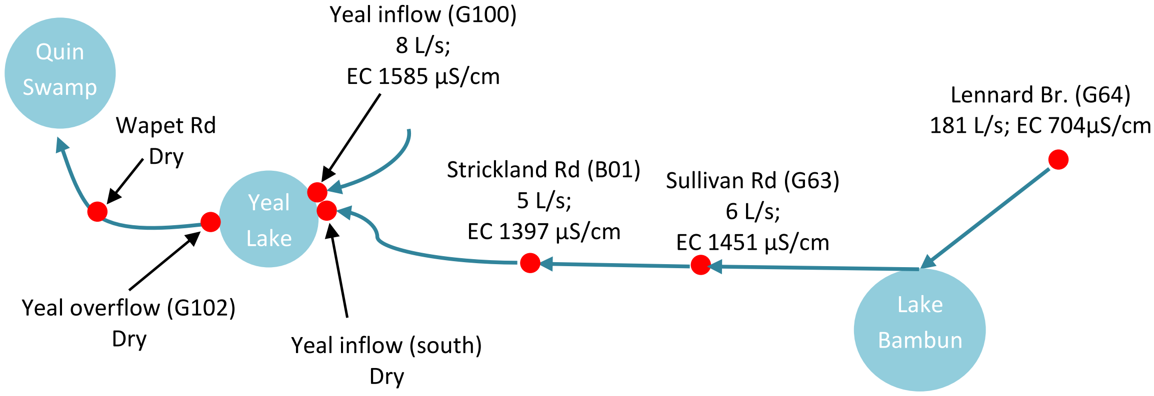
21 Sept 2011 – 1 mm rainfall prior 48 hrs



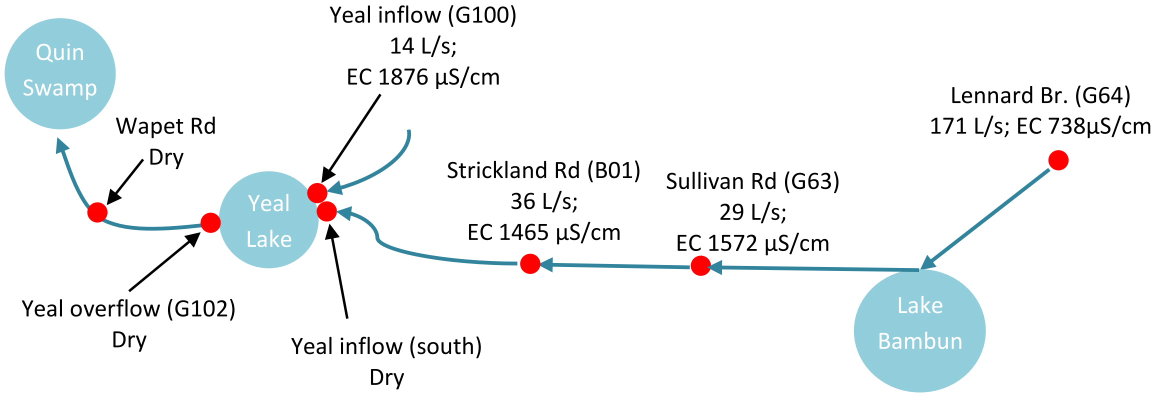
5 Oct 2011 – no rainfall prior 48 hr



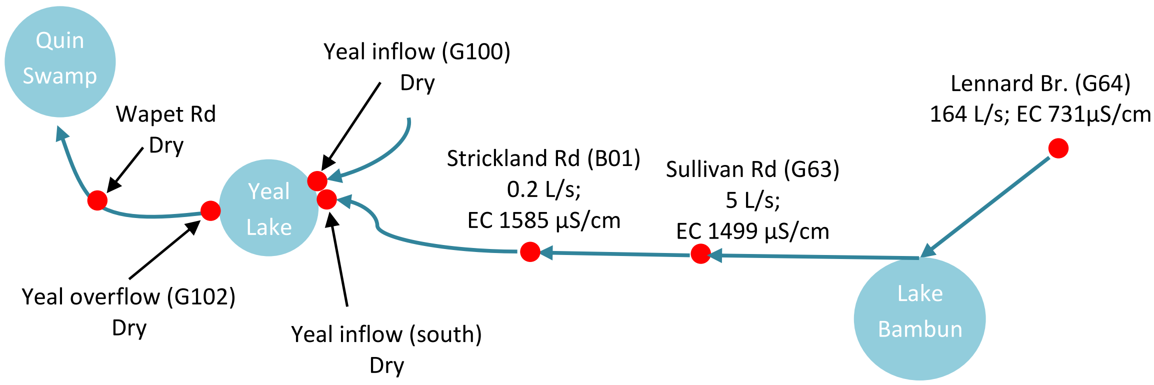
19 Oct 2011 – 10 mm rainfall prior 48 hrs



31 Oct 2011 – no rainfall prior 48 hrs



16 Nov 2011 – no rainfall prior 48 hrs



Appendix C — Bore installation, construction and lithology

All bores were installed using a GSD77 Aircore drill rig with aggregate samples of drill cuttings collected every metre to depth. Gamma and induction logs were undertaken for all deep bores following construction.

The shallow bores were screened across the shallowest watertable in the shallow Bassendean Sand above a potentially locally confining layer of sandy clays (CYWc; Table 4) and clayey sands and clays (QUNEc and QUNWc; Table 4). Intermediate depth bores were screened mid-depth in the aquifer beneath this layer (QUNEb, QUNWb and CYWb; Table 4) and the deep bores were screened in the lower Gnangara Sand (QUNEa, QUNWa and CYWa; Table 4). The single bore drilled at the Yeal Lake was screened across the shallowest watertable in the upper Bassendean Sand (YLc).

Selected bores were also logged using an NMR tool in June 2013 (Vista Clara Inc.; Walsh et al. 2013). Shallow cores were taken to the depth of the shallow bores using a Geoprobe 7720DT track mounted push-core rig. This obtained sequential 1.1 to 1.2 m length core samples for detailed assessment of lithology and acid sulfate soil testing.

Bores were cased with 50 mm Class 12 PVC to the surface with slotted 50 mm Class 12 PVC of varying lengths installed at the base of the holes (Table 4). Deep and intermediate depth bores were constructed with 2 m screens with 4 m of gravel pack and cement grouted to surface. The annulus of deep and intermediate bores was filled with gravel from the base of the hole to 2 m above the screened interval and then grouted to the surface. Shallow bores were constructed with 3 to 6 m screens, depending on the site and backfilled to near surface with gravel. Bores QUNWc, QUNEc and YLc were constructed with a bentonite plug (0.1–0.4 m thickness) above the gravel pack. Head works consisted of steel standpipes to 0.5 m above ground level set in a cement collar at just above ground level extending 0.2 – 0.4 mbgl.

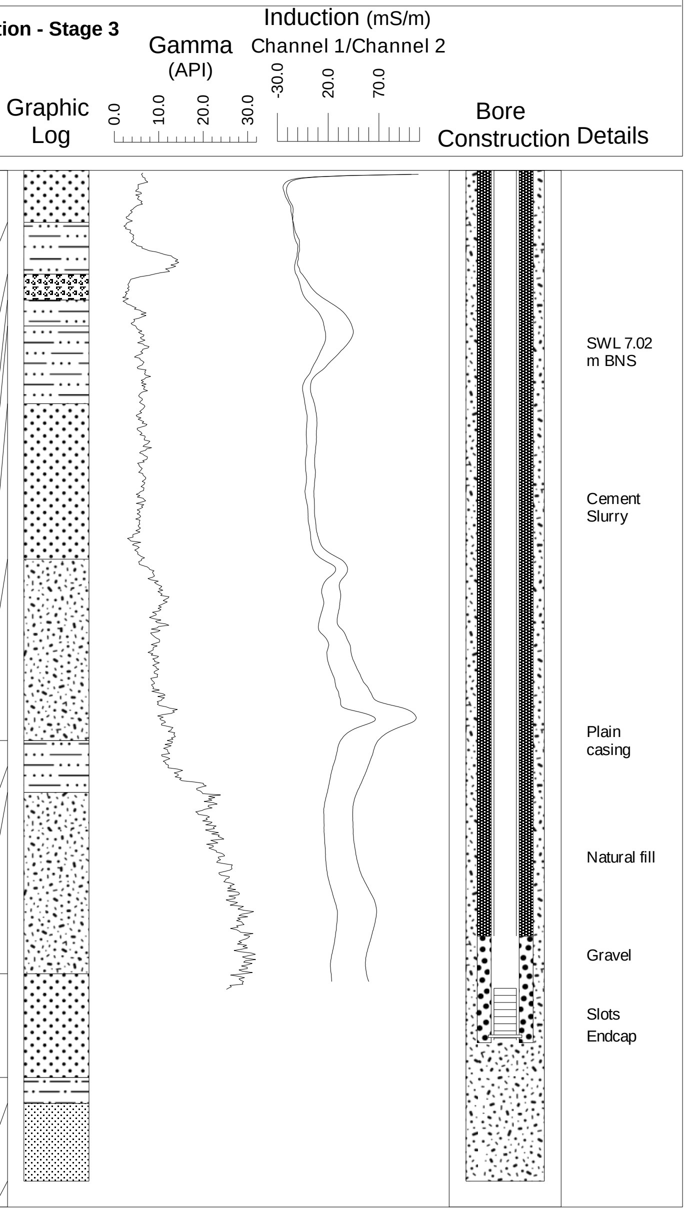
Bore construction diagrams for the deepest bores at each are reproduced from Searle 2009a, b. Note: Formations have been re-interpreted as per Table 7.

BORE COMPLETION DETAILS AWRC Name: **QUN_Ea**

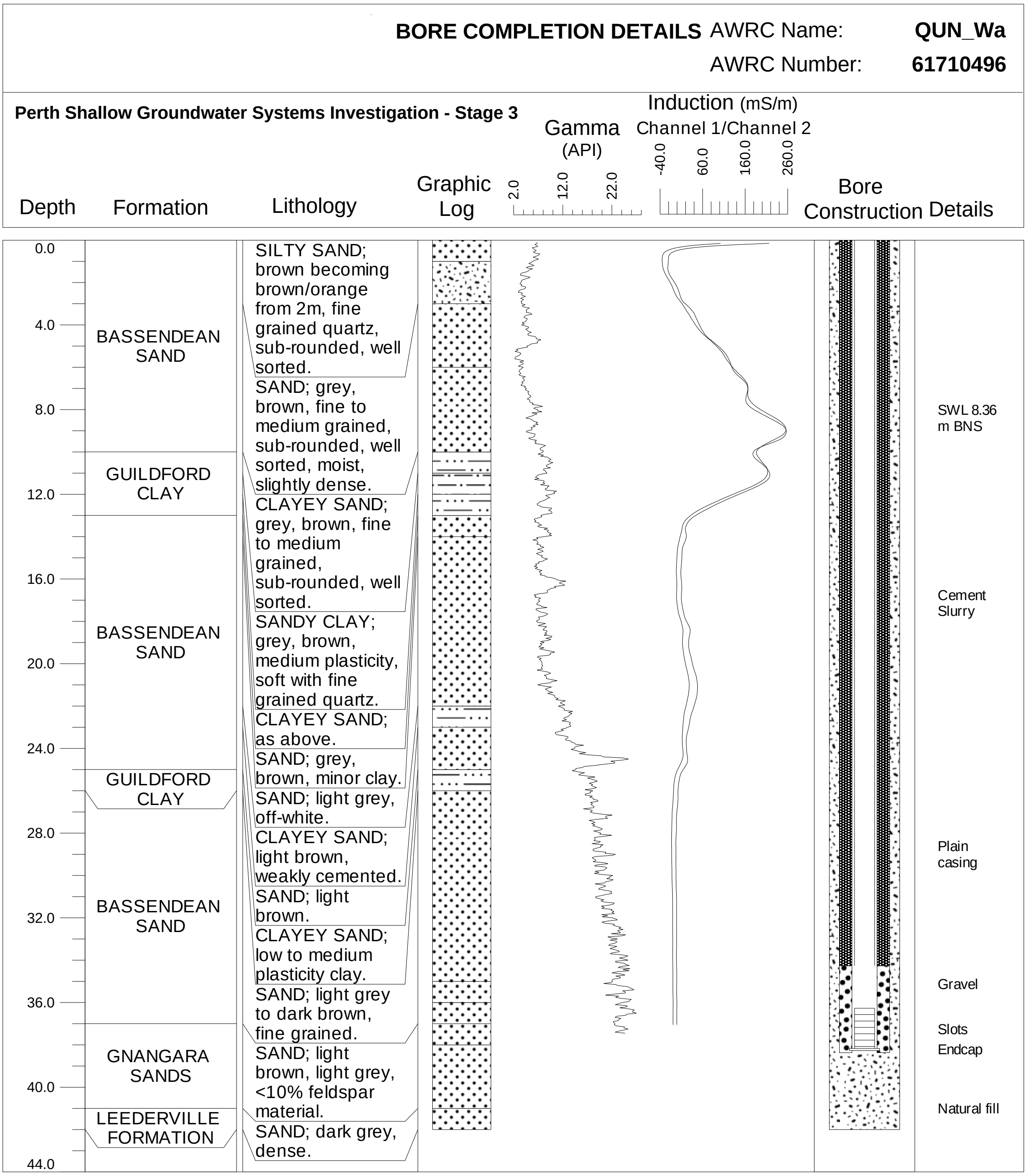
AWRC Number: **61710590**

Perth Shallow Groundwater Systems Investigation - Stage 3

Depth	Formation	Lithology
0.0	BASSENDEAN SAND	SAND Dark greyish brown, medium grained, well sorted.
2.0	GUILDFORD CLAY	SAND & CLAY Clay is reddish yellow and plastic, in chunks.
4.0	BASSENDEAN SAND	SANDSTONE?COFFEE ROCK Black, medium grained.
6.0	GUILDFORD CLAY	SAND & CLAY As at 2-4m.
8.0	BASSENDEAN SAND	CLAYEY SAND Brown, poorly sorted, very coarse to coarse.
10.0	GUILDFORD CLAY	SAND Very pale brown, coarse grained. Rare heavy minerals.
12.0	GNANGARA SAND	SILTY SAND Brown, poorly sorted. Common heavy minerals.
14.0	LEEDERVILLE FORMATION, WANNEROO MEMBER	CLAYEY SAND Very dark brown clay chunks.
16.0		CLAYEY SAND As at 15-22 but more clay/silt.
18.0		SILTY SAND Very pale brown, medium grained.
20.0		SAND Light grey very coarse grained to fine gravel.
22.0		SANDY CLAY Light brown. Fine grained sand.
24.0		SANDSTONE; grey, fine to medium grained.
26.0		
28.0		
30.0		
32.0		
34.0		
36.0		
38.0		
40.0		



Drilled by:	Geo Sonic Drilling	Northing (Z50):	6527976	Screens (m BNS):	31.56 - 33.56
Date drilled:	5/14/09	Easting (Z50):	384417	SWL (m BNS):	7.02
Logged by:	Josephine Searle	Surface (m AHD):	55.83	EC (mS/cm):	1.51
Aquifer:	Superficial	Drill depth (m BNS):	39	pH:	6.94



Drilled by:	Geo Sonic Drilling	Northing (Z50):	6528009	Screens (m BNS):	36.27 - 38.27
Date drilled:	4/22/09	Easting (Z50):	384106	SWL (m BNS):	8.36
Logged by:	Nathan Henderson	Surface (m AHD):	56.47	EC (mS/cm):	0.635
Aquifer:	Superficial	Drill depth (m BNS):	42	pH:	6.8

Department of Water
Government of Western Australia

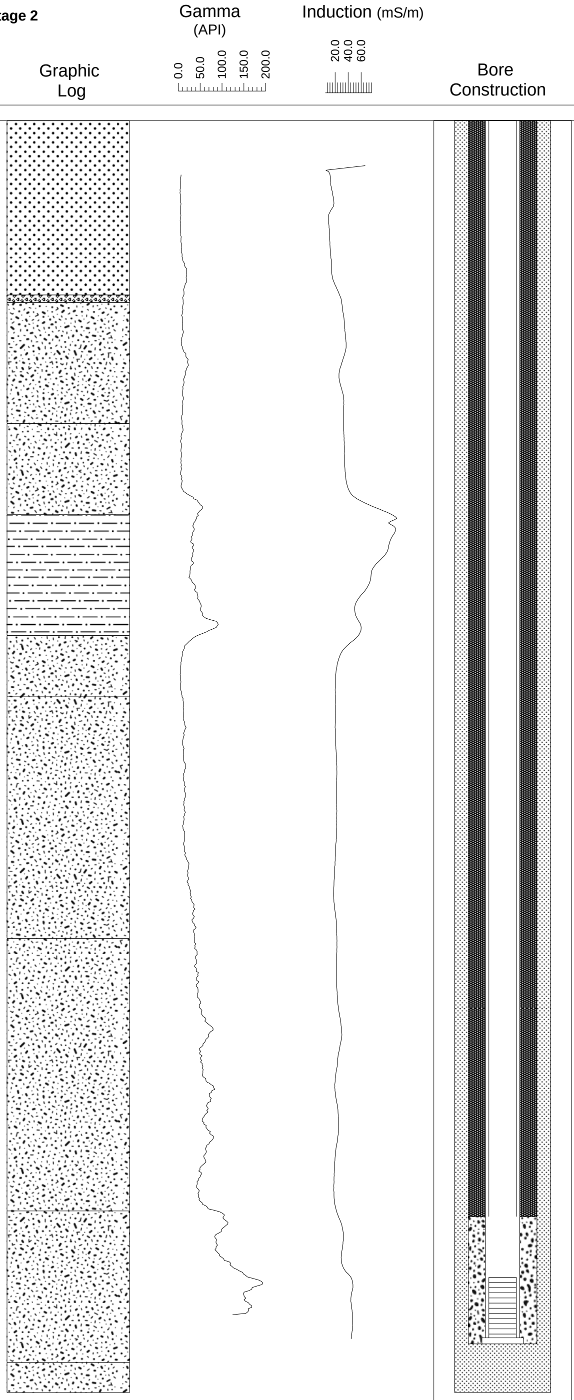
BORE COMPLETION DETAILS

AWRC Name: **CYW_a**

AWRC Number: **61710478**

Perth Shallow Groundwater Systems Investigation - Stage 2

Depth (m)	Formation	Lithology
0.0–5.7	BASSENDEAN SAND	TOPSOIL & SAND Pale brown, medium to coarse grained qtz sand. Rich in organic matter at top. Loose and slightly moist. Very minor silt component. Dark greyish brown at top and base of interval.
5.7–7.8	BASSENDEAN SAND	“COFFEE ROCK” Dark brown, medium to coarse grained qtz sand. Cemented and indurated.
7.8–10.0	BASSENDEAN SAND	SILTY SANDBrown to light brownish grey. Medium to coarse qtz sand, well sorted, sub-angular to sub-rounded. Loose, very moist.
10.0–13.0	BASSENDEAN SAND	SILTY SAND Dark reddish brown medium to coarse qtz sand. Iron staining/coating on most grains, loose and wet.
13.0–17.0	GUILDFORD CLAY	SANDY CLAY Very dark grey. No sand at top, grading into sandy clay. Very stiff and cohesive, plastic when wet. Dry at top, becoming very moist.
17.0–19.0	GNANGARA SAND	SILTY SAND Brown to light brownish grey. Medium to coarse qtz sand, well sorted, sub-angular to sub-rounded. Loose, very moist.
19.0–27.0	GNANGARA SAND	SAND & SILTY SAND Brown medium to coarse qtz sand. Loose and wet. Some very coarse rounded grains. Heavy minerals present. Becoming finer at bottom.
27.0–36.0	GNANGARA SAND	SILTY SAND Light yellowish brown to greenish grey. Fine to medium qtz sand. Wet and loose.
36.0–41.0	GNANGARA SAND	SILTY SAND Light brownish grey, coarse to very coarse grained. Angular feldspar grains throughout. Glauconite and sparse heavy minerals. Brown and clayey in parts.
41.0–42.0	GNANGARA SAND	SILTY SAND Dark greenish grey, abundant glauconite and shell fragments. Sandstone at base.



Details:
- Plain casing - 50mm Class 12 PVC
- SWL 14.03 m BNS
- Cement grouted annulus
- Gravel packed annulus
- Slotted casing - 50mm Class 12 PVC
- Endcap - PVC
- Natural fill

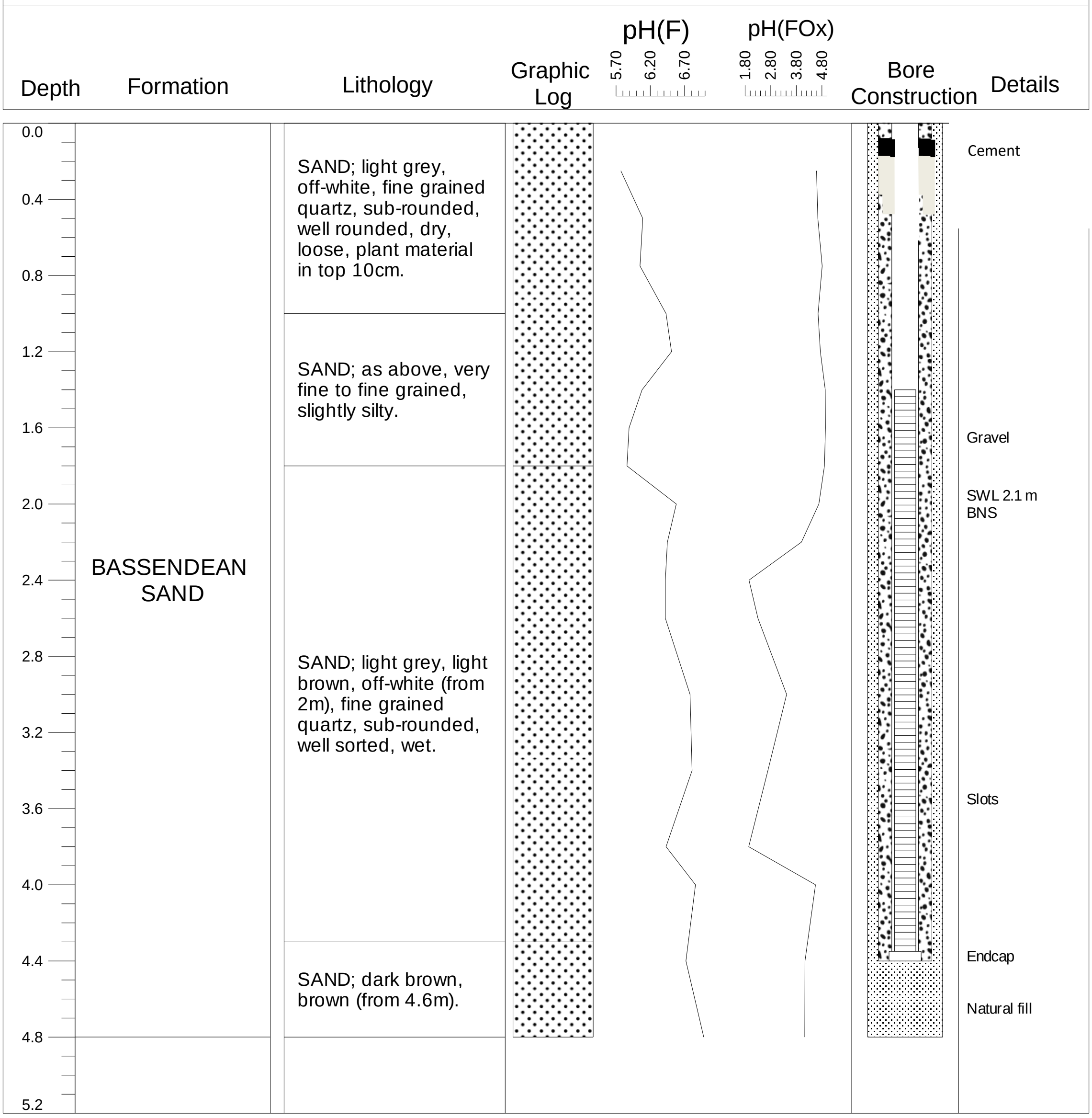
Drilled by:	Great Southern Drilling	Northing (Z50):	6526139.5	Screens (m BNS):	38.21 - 40.21
Date drilled:	2/21/08	Easting (Z50):	385948.79	SWL (m BNS):	14.03
Logged by:	Sandie McHugh	Surface (m AHD):	58.96	EC (mS/m):	21900
Aquifer:	Superficial	Drill depth (m BNS):	42	pH:	5.88

BORE COMPLETION DETAILS

AWRC Name: **YL_c**

AWRC Number: **61710494**

Perth Shallow Groundwater Systems Investigation - Stage 3



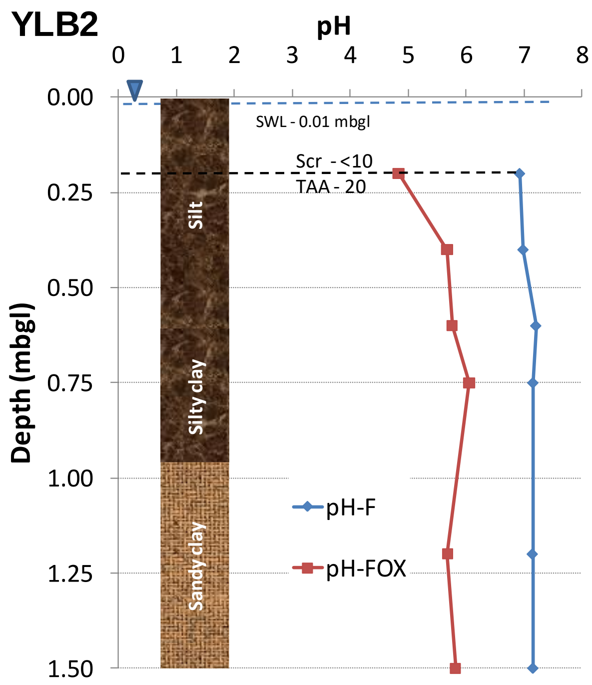
Drilled by:	Geo Sonic Drilling	Northing (Z50):	6525635	Screens (m BNS):	1.4 - 4.4
Date drilled:	4/30/09	Easting (Z50):	387958	SWL (m BNS):	2.1
Logged by:	Nathan Henderson	Surface (m AHD):	61.24	EC (uS/m):	2.04
Aquifer:	Superficial	Drill depth (m BNS):	4.8	pH:	5.9

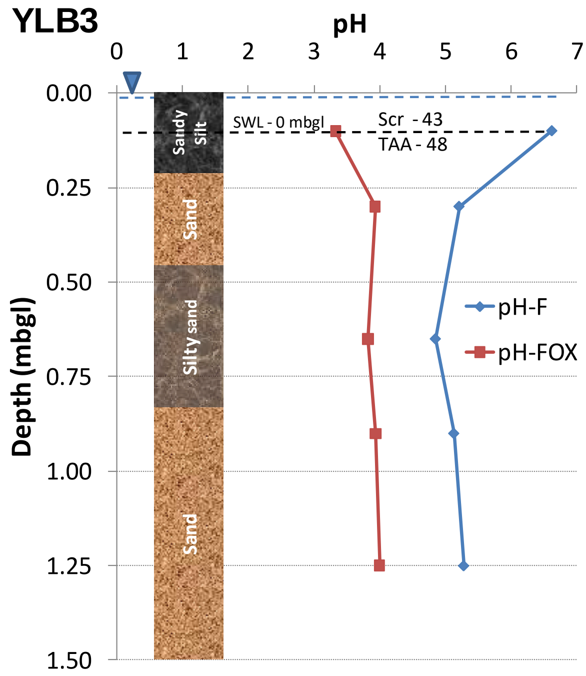
Appendix D — ASS sampling and analysis details, lake bed profiles and sediment metal concentrations

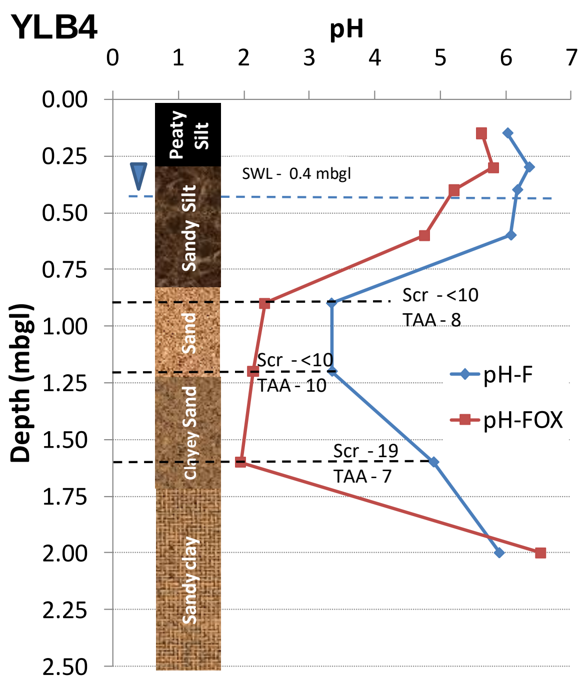
Samples for laboratory analysis were stored in ziplock plastic bags with all air excluded and frozen until delivery to the laboratory for analysis. Potential and actual acidity were analysed by the Chromium Reducible Sulfur (CrS) and the Suspension Peroxide Oxidation Combined Acidity and Sulfur (SPOCAS) suite of analyses (Ahern et al. 2004) by the National Measurement Institute (NMI). For the CrS suite this was carried out according to QASSIT methods 22B, 23A, 23F and 19A1 (Ahern et al. 2004) with the SPOCAS carried out according to QASSIT methods 23A, 23B, 23F, 23G, 23C to 23E (inclusive), 23V to 23X (inclusive), 23S to 23T (inclusive) and 23Q (Ahern et al. 2004). Acid neutralising capacity was not determined on any samples because pH_{KCl} was less than 6.5 (except for one sample at 4.5 m at QUNWc).

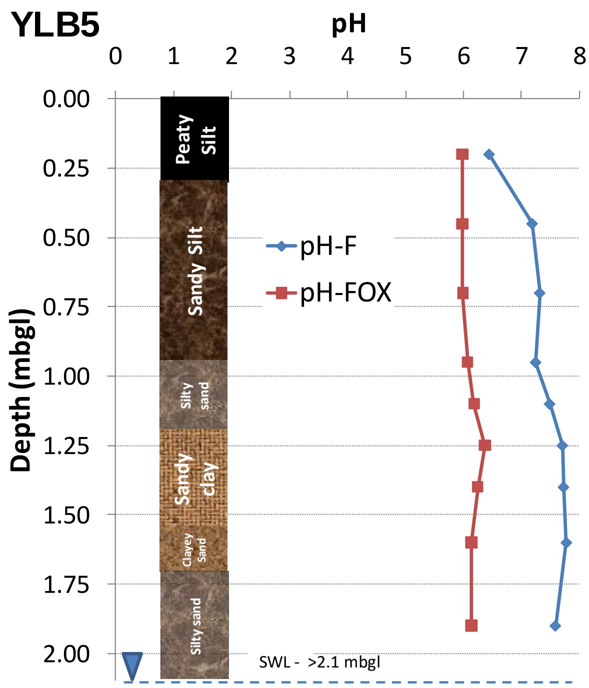
The capacity for the soil materials to generate acidity was assessed on net acidity content. This was calculated as the difference balance between acid generating materials indicated by Chromium reducible S (S_{Cr}) and neutralising materials indicated by acid neutralising capacity (after Ahern et al. 2004). Where there were no measurable neutralising materials, net acidity and potential acidity were considered the same. Acidification was a risk where net acidity exceeded 18.7 mol H^+/tonne (Department of Environment & Conservation 2009) or national minimum criteria of 6.2 mol H^+/tonne for sulfidic materials (Sullivan et al. 2010).

Samples were also analysed for major metals (Al, Fe and Mn), trace metals (Cd, Cr, Ni and Zn) and metalloids (As and Se). This involved nitric and hydrochloric acid digestion followed by extraction and analysis by inductively coupled plasma mass spectrometer (ICPMS) and inductively coupled plasma atomic emission spectrometer depending on the concentrations and detection limits required. Anhydride generation was carried out before ICPMS analysis for As and Se.


YLB2
pH
0 1 2 3 4 5 6 7 8
Depth (mbgl)
0.00
0.25
0.50
0.75
1.00
1.25
1.50
SWL - 0.01 mbgl
Scr - <10
TAA - 20
Silt
Silty clay
Sandy clay
pH-F
pH-FOX


YLB3
pH
0 1 2 3 4 5 6 7
Depth (mbgl)
0.00
0.25
0.50
0.75
1.00
1.25
1.50
SWL - 0 mbgl
Scr - 43
TAA - 48
Sandy Silt
Sand
Silty sand
Sand
pH-F
pH-FOX


YLB4
pH
0 1 2 3 4 5 6 7
Depth (mbgl)
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25
2.50
SWL - 0.4 mbgl
Scr - <10
TAA - 8
Scr - <10
TAA - 10
Scr - 19
TAA - 7
Peaty Silt
Sandy Silt
Sand
Clayey Sand
Sandy clay
pH-F
pH-FOX


YLB5
pH
0 1 2 3 4 5 6 7 8
Depth (mbgl)
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
SWL - >2.1 mbgl
Peaty Silt
Sandy Silt
Silty sand
Sandy clay
Clayey Sand
Silty sand
pH-F
pH-FOX

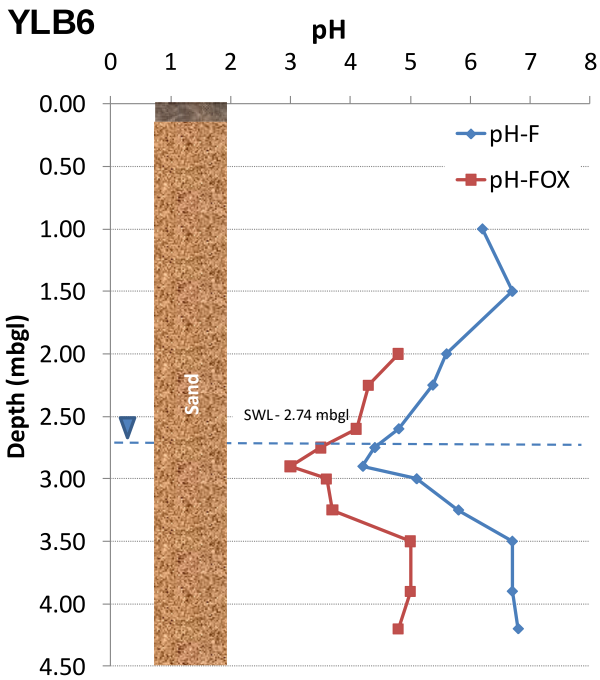


Figure D1 *Field (F) and peroxide (FOX) oxidised pH, summary lithology, potential (Scr) and available (TAA) acidity analyses (moles H⁺/tonne) in Yeal Lake. Note: no ANC in any samples.*

Table D1 Metals and metalloids in the shallow Superficial formations at Quin Brook, Quin Swamp and Yeal Lake

Drill site	Texture	Depth (mbgl)	Al	As	Cd	Cr	Fe	Mn	Ni	Se	Zn
			(mg/kg)								
Quin Brook (CYWc)	Sand	1.6	15	< 0.5	< 0.5	< 0.5	12	< 0.5	< 0.5	< 0.5	< 0.5
	Sand	2	7.2	< 0.5	< 0.5	< 0.5	14	< 0.5	< 0.5	< 0.5	< 0.5
	Sand	3.3	6.3	< 0.5	< 0.5	< 0.5	20	< 0.5	< 0.5	< 0.5	< 0.5
	Sand	4.2	4.2	0.5	0.5	0.5	25	0.66	0.5	0.5	0.5
Quin Swamp west (QUNWc	Sand	2.9	470	< 0.5	< 0.5	0.93	1240	3.7	< 0.5	< 0.5	3.5
	Sand	3.6	110	< 0.5	< 0.5	< 0.5	220	0	< 0.5	< 0.5	< 0.5
	Sand	4.4	140	< 0.5	< 0.5	1.1	610	2.3	< 0.5	< 0.5	3
Quin Swamp east (QUNEc)	Sand	1	210	< 0.5	< 0.5	1.6	770	6	< 0.5	0.59	7.9
	Sand	2.25	6550	0.53	< 0.5	8.7	300	1.3	0.87	1	3.1
	Sand	2.75	410	< 0.5	< 0.5	1.4	260	2.2	< 0.5	0.57	2.2
	Sand	4.25	2240	< 0.5	< 0.5	3.4	140	< 0.5	0.66	0.82	3.2
Quin Swamp bed (QUNLB)	Peat silt	0.2	11600	< 5	< 1	23	3980	< 5	9	6	7
	Sandy silt	0.5	3760	< 5	< 1	7	510	< 5	< 2	< 5	< 5
Yeal Lake (YLc)	Sand	2.4	50	< 0.5	< 0.5	< 0.5	89	< 0.5	< 0.5	0.53	< 0.5
	Sand	3.8	190	< 0.5	< 0.5	< 0.5	200	< 0.5	< 0.5	0.58	< 0.5
Yeal Lake (YLB2)	Silt	0.2	28300	8	< 1	45	5910	14	34	5	7
EIL			NA	20	3	50	NA	500	60	NA	200

NA = not available

EIL = Ecological investigation level (Department of Environment & Conservation 2010)

Appendix E — Regional monitoring bore summary data

Name	AWRC	Easting	Northing	Aquifer	Top of screen (mbgl)	Bottom of screen (mbgl)	Ground Level (mAHD)
AM9A	61715011	380972	6522461	Shallow Leederville	206	211	60.1
AM10A	61715017	392256	6521850	Shallow Leederville (Parmelia)	103.0	108.0	69.4
AM14B	61715007	386757	6516659	Shallow Leederville	139	144	75.5
BBNEc	61710486	394979	6522828	Shallow Superficial	0.8	6.8	69.5
BBNWa	61710481	394150	6522803	Deep Superficial	30.8	32.8	68.9
BBNWb	61710482	394150	6522806	Int. Superficial	14.6	16.6	69.0
BBNWc	61710483	394150	6522805	Shallow Superficial	2.0	8.0	68.9
BDRCa	61710490	381895	6519783	Deep Superficial	36.3	38.3	50.0
BDRCb	61710491	381895	6519783	Int. Superficial	22.8	24.8	50.0
BDRCc	61710492	381895	6519783	Shallow Superficial	4.8	10.8	50.0
BDREc	61710493	382232	6519432	Shallow Superficial	5.3	11.3	50.5
BDRWa	61710487	381809	6519877	Deep Superficial	43.9	45.9	52.7
BDRWb	61710488	381809	6519877	Int. Superficial	29.9	31.9	52.6
BDRWc	61710489	381809	6519877	Shallow Superficial	8.9	14.9	52.6
GA10	61710053	382473	6518086	Shallow Superficial	9.5	22.0	57.1
GA13	61710033	374979	6520139	Shallow Superficial	29.0	41.0	56.1
GA14	61710040	378464	6519488	Shallow Superficial	32.0	44.0	70.7
GA15	61710080	380689	6520291	Shallow Superficial	8.5	21.0	54.0
GA18	61710075	377289	6522761	Shallow Superficial	18.5	31.0	56.5
GA22	61710065	375208	6525069	Shallow Superficial	20.5	33.0	54.9
GA23	61710076	378284	6525341	Shallow Superficial	7.5	20.0	50.3
GA3	61710034	376888	6513573	Shallow Superficial	34.0	46.0	57.5
GA4	61710045	380572	6513670	Shallow Superficial	16.0	28.0	45.0
GA5	61610654	383844	6513732	Shallow Superficial	19.0	31.0	59.5
GA6	61610711	387140	6513983	Shallow Superficial	11.0	23.4	67.4
GA8	61710037	377814	6516460	Shallow Superficial	22.0	35.0	54.0
GA9	61710057	384084	6516569	Shallow Superficial	10.5	23.0	61.0
GB12	61710073	375869	6531079	Shallow Superficial	4.0	17.6	40.6
GB13	61710078	377961	6531142	Shallow Superficial	4.0	18.4	46.1
GB14	61710087	383302	6531013	Shallow Superficial	0.0	12.0	56.6
GB15	61710077	377757	6527956	Shallow Superficial	3.5	18.0	46.6
GB16	61710092	384936	6528303	Shallow Superficial	2.0	3.9	60.1
GB18	61710100	389694	6528866	Shallow Superficial	0.5	8.0	64.1
GB19	61710098	387414	6527158	Shallow Superficial	2.0	12.0	64.7
GB20	61710083	381097	6524879	Shallow Superficial	3.0	18.0	57.2
GB21	61710089	384439	6524929	Shallow Superficial	3.0	17.5	61.8

Name	AWRC	Easting	Northing	Aquifer	Top of screen (mbgl)	Bottom of screen (mbgl)	Ground Level (mAHD)
GB22	61710097	387022	6524698	Shallow Superficial	4.0	18.5	64.7
GB23	61710088	383649	6522639	Shallow Superficial	7.0	21.0	63.7
GB5	61710079	377725	6533178	Shallow Superficial	9.0	23.0	47.1
GB8	61710086	380313	6531873	Shallow Superficial	3.0	18.0	50.4
GB9	61710093	386104	6532765	Shallow Superficial	0.0	4.0	57.6
GC1	61710102	391314	6526592	Shallow Superficial	1.3	8.3	65.7
GC10	61611088	395259	6521529	Shallow Superficial	1.0	13.6	68.4
GC11	61710060	387159	6519921	Shallow Superficial	9.0	21.0	69.1
GC12	61710061	390369	6519657	Shallow Superficial	8.0	20.0	73.2
GC13	61611087	392830	6520154	Shallow Superficial	3.0	16.0	71.1
GC14	61610953	396359	6519429	Shallow Superficial	2.0	14.0	67.5
GC15	61611090	399149	6520444	Shallow Superficial	2.0	14.0	72.7
GC16	61610810	390206	6516900	Shallow Superficial	20.0	32.0	83.3
GC17	61610917	395948	6516980	Shallow Superficial	1.7	13.7	67.5
GC18	61610985	398857	6517501	Shallow Superficial	0.0	3.0	63.6
GC19	61610809	389804	6513597	Shallow Superficial	14.0	26.0	73.3
GC2	61710110	394781	6526441	Shallow Superficial	5.0	17.0	75.6
GC20	61610870	393410	6513302	Shallow Superficial	12.0	24.5	76.5
GC21	61610952	396482	6513658	Shallow Superficial	5.0	17.0	69.1
GC23	61710136	391308	6526605	Shallow Superficial	1.5	8.5	60.0
GC24	61710137	392572	6524486	Shallow Superficial	1.0	4.5	66.5
GC3	61710111	396663	6527667	Shallow Superficial	2.0	17.0	82.7
GC4	61710105	390667	6524840	Shallow Superficial	1.0	10.0	65.0
GC4	61710105	390667	6524840	Shallow Superficial	1.0	10.0	65.0
GC5	61710106	392538	6524459	Shallow Superficial	1.0	10.0	65.0
GC6	61611089	396969	6523373	Shallow Superficial	1.0	13.0	72.4
GC7	61611091	399357	6524938	Shallow Superficial	2.0	14.0	94.6
GC8	61710101	389982	6521654	Shallow Superficial	7.0	18.0	72.0
GC9	61710104	392240	6521849	Shallow Superficial	3.0	15.0	68.9
GG10	61710109	393122	6529583	Shallow Superficial	N/A	< 15.0	75.4
GG4 (I)	61610712	386784	6516670	Deep Superficial	44.4	62.4	75.0
MKBEa	61710471	384347	6532058	Deep Superficial	35.9	37.9	52.2
MKBEb	61710472	384346	6532060	Int. Superficial	20.1	22.1	52.2
MKBEc	61710473	384346	6532061	Shallow Superficial	8.0	10.0	52.2
MKBEd	61710474	384345	6532063	Perched groundwater system	1.0	4.2	52.1
MKBWa	61710476	383952.7	6532236	Deep Superficial	37.2	39.2	52.2
MKBWb	61710477	383954	6532235	Int. Superficial	21.6	23.6	52.1
MKBWc	61710475	383955.1	6532235	Shallow Superficial	1.0	7.0	52.1

Name	AWRC	Easting	Northing	Aquifer	Top of screen (mbgl)	Bottom of screen (mbgl)	Ground Level (mAHD)
NG10D	61710570	386157.7	6519340	Shallow Superficial	11.0	14.0	66.4
NG14E	61710582	379516.1	6530576	Shallow Superficial	12.0	18.0	52.0
NG15A	61710595	388165.8	6525962	Deep Superficial	43.0	46.0	62.6
NG15B	61710596	388170	6525964	Shallow Superficial	4.0	7.0	62.6
NG1C	61710583	384955.3	6528301	Deep Superficial	44.0	47.0	60.4
NG1D	61710584	384960.3	6528300	Shallow Superficial	17.0	20.0	60.3
NG2B	61710542	380723.4	6532679	Deep Superficial	39.0	42.0	49.8
NG2C	61710543	380728.5	6532678	Shallow Superficial	12.0	15.0	49.6
NG3C	61710546	386202.8	6523417	Deep Superficial	45.0	48.0	66.7
NG3D	61710547	386201.2	6523416	Shallow Superficial	12.0	15.0	66.7
NG4D	61710551	383210.9	6525938	Deep Superficial	48.0	51.0	59.7
NG4E	61710552	383211.6	6525932	Shallow Superficial	6.0	9.0	59.7
NG5C	61710585	382167.5	6530743	Deep Superficial	42.0	48.0	54.6
NG5D	61710586	382165.4	6530747	Shallow Superficial	14.0	17.0	54.5
NG7	Not registered	382261	6528305	Drill hole only	N/A	N/A	N/A
NG8E	61710562	384535.5	6521290	Shallow Superficial	12.0	15.0	62.3
NG9C	61710565	389007.6	6524553	Deep Superficial	44.0	47.0	67.6
NG9D	61710566	389005.2	6524558	Int. Superficial	18.0	21.0	67.6
NGS1	61710697	388803	6530738	Drill hole only (no bore)	N/A	N/A	62.1
NGS2	61710698	391140	6525515	Drill hole only (no bore)	N/A	N/A	65.3
NGS3	61710699	390720	6522230	Drill hole only (no bore)	N/A	N/A	68.2
TGTa	61710467	378660	6530401	Deep Superficial	44.3	46.3	47.0
TGTb	61710468	378662	6530400	Int. Superficial	28.0	30.0	47.0
TGTc	61710469	37866	6530399	Shallow Superficial	7.9	11.9	47.0
TGTd	61710470	378658	6530402	Shallow Superficial	1.2	4.3	47.1
TMUc	61611875	396907	6518530	Shallow Superficial	1.8	6.8	66.8
WC2a (1/06)	61700046	385608	6531224	Deep Superficial	44.3	50.3	60.9
WC5d (7/06)	61611880	382500	6516900	Int. Superficial	27.0	33.0	57.0
WC8c (5/06)	61700051	390406	6528103	Deep Superficial	39.2	45.1	65.5
Y100	61710054	381824	6517608	All Superficial	16.0	54.0	55.0
Y100B	61710498	381799	6517663	Shallow Superficial	16.0	25.0	54.2
Y110	61710049	381190	6518365	All Superficial	15.0	54.0	57.0
Y120	61710050	380908	6519312	All Superficial	15.0	52.0	53.6
Y40	61610676	385990	6513450	All Superficial	20.0	66.0	70.1

Name	AWRC	Easting	Northing	Aquifer	Top of screen (mbgl)	Bottom of screen (mbgl)	Ground Level (mAHD)
Y60	61710055	384724	6514836	All Superficial	15.0	64.0	61.9
Y80	61710052	383278	6516215	All Superficial	14.0	56.0	57.0
YY7 (I)	61710081	380966	6522451	Deep Superficial	36.5	54.0	60.1

Appendix F — Watertable trend analysis

Analysis methodology

Analysis of watertable trends was conducted using the HARTT analysis package (Hydrograph Analysis: Rainfall and Time Trends; Ferdowsian et al. 2001). This applies linear regression analysis to separate the effects of anomalous rainfall patterns from groundwater levels and other influences on water levels such as land use change or pumping. Anomalous rainfall patterns are represented by calculation of cumulative deviation from mean rainfall (CDFM) which in this analysis was best represented as by accumulated annual residual rainfall (AARR; Equation 1). This variable is similar to the CDFM variable previously used for analysis of hydrograph trends for the Gnangara groundwater system (Yesertener 2002, 2008).

$AARR_t = \sum_{i=1}^{t}(M_i - \frac{\overline{A}}{12})$ .... ……………Equation 1

where $AARR_t$ = annual accumulated residual rainfall for time t, *t* is the time in months from the start of the rainfall dataset, M_i is the rainfall in month *i* (a sequential index of time since the start of the rainfall dataset) and $\bar{A}$ is the long-term mean annual rainfall.

HARTT solves for Equation 2 (after Ferdowsian et al. 2001) allowing stepwise partitioning of variation due to rainfall trend alone from water level trends.

$Depth_t = k_0 + k_1.AARR_{t-L1} + k_2.t$ .... ……………………………………Equation 2

where $Depth_t$ is depth of groundwater at time *t*, $AARR_{t-L}$ is accumulated annual residual rainfall (AARR) for time *t* with the lag time *L1* (in months) between rainfall and its effect on groundwater, t is the months since observations began, and k_0, k_1, and k_2 are coefficients estimated by regression analysis. Parameter k_0 is approximately equal to the initial depth to groundwater, k_1 represents the impact of above- or below-average rainfall on the groundwater level, and k_2 *is* the trend (rate) of groundwater rise or fall over time due. HARTT includes the default 't' or time parameter for land use effects to represents a continuous background effect of land use throughout the period analysed (Equation 2; Ferdowsian et al. 2001). If there are no likely effects due to land or water use but this variable is statistically significant it may reflect variation that would otherwise be due to rainfall patterns (Kelsey 2014).

Additional variables can be included in the regression analysis to represent the onset of land uses changes or pumping where these improve the fit of the model (r^2 and the extent to which the model reproduces all parts of the water level record). This was generally included in the analysis as one or two variables (e.g. V1 to Vn in Equation 3; after Ferdowsian et al. 2001) increasing step-wise from a specified month and reaching a constant value if deemed to have no influence water levels after a particular time. These variables were only included where there was *a priori* physical evidence, however in some cases the variables may have an unknown origin and require further investigation to validate.

$Depth_t = k_0 + k_1.AARR_{t-L1} + k_2.V1_t + \cdots k_n.Vn_t$ …………….. Equation 3 where the variables are as for Equation 2 except *V1* to *Vn* are independent land or water use variables (*1 to n*) at time *t*, and k_2 to k_n are coefficients explaining the trend (rise or fall) due to these variables.

Subsequent re-runs of the regression analysis were conducted using the output data from HARTT and the multiple regression tool in the Excel data-analysis package.

Establishing a rainfall baseline

The best rainfall time series as a baseline for comparing land and water use effects was determined by the method in Kelsey (2014). This involves finding the best start date (origin) for the rainfall time series for ‘control’ bores in similar geology. ‘Control’ bores were those where the influence of land and water use is stable over the monitoring record, hence variation in water levels in bores must be explained by variation in rainfall patterns. A range of rainfall time series with different start dates were analysed using HARTT with the control bore hydrographs to find the dataset where most variation could be explained by rainfall patterns with no significant variation due to the default ‘time variable’ (Kelsey 2014) which is the ‘t’ variable in Equation 2. Once determined, the rainfall time series can be applied to analysis of water levels in bores of similar geology where land or water use has changed to determine the contribution of these to variation in water levels.

GB21 and GC12 were suitable control bores for the central and southern part of the nature reserve. These were in an area of largely undisturbed Banksia woodland several kilometres distant from any recharge from Quin Brook, and had no pumping from the Superficial aquifer within 3 km.

GB21 was also in an area where hydrograph analysis indicated that water level decline in the Leederville aquifer at this site was considered to have minor influence over most of the analysis period (1977 to 2012). This does not preclude an influence of Leederville drawdown that may be emerging after 2006–08, only that this factor was considered to have a minor effect relative to other factors for the more than 30 years prior to 2012. The nearest Leederville monitoring bore 4.5 km south-west of GB21 (at AM9a) indicated a steady, slight increase in vertical gradient between the Superficial and Leederville aquifers (Figure F1) that poorly corresponded with the pattern of increasing rates of watertable decline across the area. A trend in increasing vertical pressure gradient (0.1 m/yr) was evident from the beginning of monitoring before the advent of any deep aquifer pumping. The increase in gradient was steady during the 1990s (to 0.16 m/yr) to a peak in the mid-2000s, whereas declines in watertable levels in the area were generally evident earlier from the mid-1990s in most areas outside of the influence of the pine plantations.

In the reserve’s south, the trend in levels at GG4(I) compared with AM14b indicate a similar disconnect between the pattern of watertable decline relative to the decline in the Leederville aquifer. Watertable decline accelerates after 1997–99 (Figure 31) whereas the rate of increase in vertical pressure gradient (and therefore downward flow) has been slowing since the early 1980s (Figure F1). This suggests a delayed effect on the watertable of changes in vertical leakage gradients.

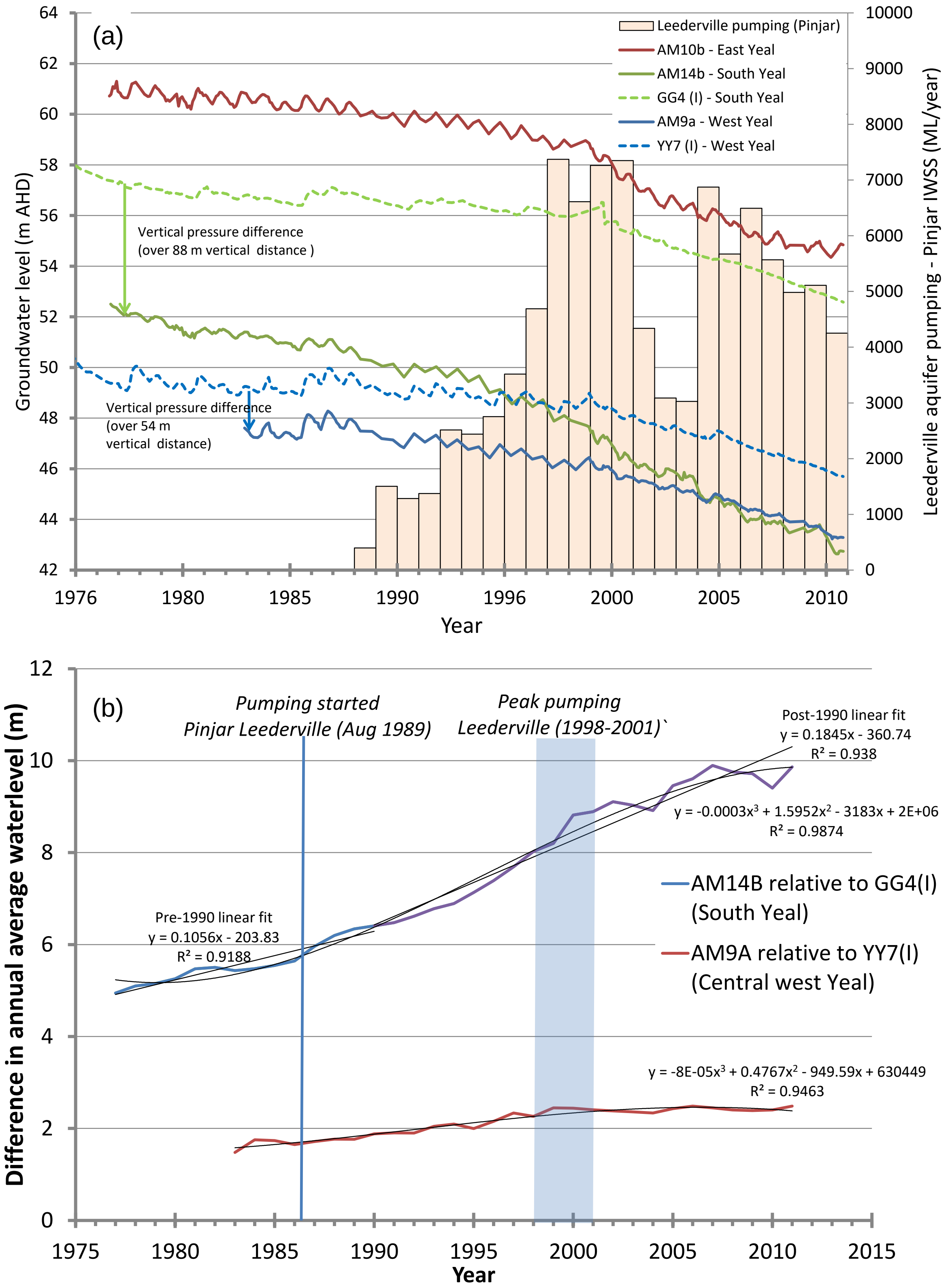


Figure F1 Leederville aquifer and corresponding deep Superficial aquifer water levels (a) and average annual pressure difference (b) in relation to pumping at the IWSS Pinjar borefield (> 6 km south).

This analysis indicates several things relevant for trend analysis: (1) that watertable levels have been influenced by a continuous background effect of declining water levels in the Leederville aquifer since the 1970s that for the most part can be assumed as having a constant influence, and (2) there is recent increased drawdown in the confined aquifer that has a delayed effect on watertables of more than 10 years.

A rainfall dataset origin of 1945 provided the best-fitting model for bores GB21 and GC12 that explained the most variation where the default time variable was small and not statistically significant ($P > 0.05$; Table F1). A longer period from 1935 to 2012 was also significant at GB20 but not at GC12.

Similar calibration was unsuccessfully attempted for control bore GC1/GC23 in different geology to the east of Yeal Lake. This bore met the criteria for stability with surrounding land use being largely unchanged since the 1960s and no significant shallow groundwater pumping nearby or influence of pumping from deeper aquifers. Despite this, there was no rainfall dataset (using origins from 1910 to 1990) that could explain the pattern of variation in groundwater levels where the time variable was not significant and $r2 > 0.6$. This result was attributed to groundwater levels irregularly influenced by patterns of surface water discharge and recharge which vary from year to year depending on local drainage processes.

Water levels east of Yeal Lake were influenced by surface water processes which limited the extent to which rainfall variation alone could explain variations in water levels. The model with best-fit for water levels between 1977 and 2012, using a range of rainfall patterns (with origins ranging 1910 to 1990), explained less than 53% of variation for calibration bore GC1/GC23 3.2 km east of Yeal Lake. There was only marginal gain in variation explained by rainfall when restricting modelling to data after 1992 when water levels were generally below ground level. While isolated from stream flows, water levels at this bore were seasonally at or within 0.5 m of ground level (66 mAHD), hence water levels are likely to be influenced by nearby surface pooling and runoff, which are not mathematically reproduced by rainfall patterns alone. This situation meant there was little confidence in modelling of GB19 to evaluate the contribution of rainfall patterns to water levels.

Table F1 Summary results for analysis of rainfall datasets with varying origin (start date) for bores GB21 and GC12 (parameters as per Equation 2).

Bore	Rainfall dataset	r^2 of regression analysis	Constant (k_0)	ARR coefficient (k_1)		Time coefficient (k_2)	
				Value	P value	Value	P value
GB21	1907–2012	0.9101	52.86	0.00207	< 0.00001	0.0044	< 0.00001
	1935–2012	0.9101	55.07	0.00207	< 0.00001	-0.0008	0.0016
	1945–2012	**0.9101**	**54.86**	**0.00207**	**< 0.00001**	**-0.00028**	**0.3118**
	1960–2012	0.9101	55.49	0.00207	< 0.00001	-0.00191	< 0.00001
GC12	1907–2012	0.9233	60.48	0.00230	< 0.00001	0.00548	< 0.00001
	1935–2012	**0.9233**	**62.95**	**0.00230**	**< 0.00001**	**-0.00032**	**0.1973**
	1945–2012	**0.9233**	**62.70**	**0.00230**	**< 0.00001**	**0.00027**	**0.3169**
	1960–2012	0.9233	63.48	0.00230	< 0.00001	-0.00155	< 0.00001

Analysis results

HARTT was applied to several bores across the nature reserve to represent spatial trends (GA10, GB22, GB23, GC11 and GC19). Other nearby bores were considered but not analysed because of several constraints. GB19 was suitable but was analysed because it was not possible to establish an appropriate rainfall origin using the GC1/GC23 'control' bore (see above). GC4 and GC5 were not analysed because these were influenced by surface water flows in Quinn Brook and GB16 had an incomplete record of groundwater minima since the early 1990s.

GB22 – near Yeal Lake

The best-fitting regression model for watertable trends at GB22 consisted of rainfall and an additional increasing variable after 1991 (r^2=0.92; Table A15). A model with rainfall alone (r^2=0.90) tended to increasingly underestimate water levels after 1999.

The variable having a positive effect on water levels (i.e. having the effect of increasing water levels) was interpreted to be recharge from Quin Brook. Earlier sections (Section 5.5) have discussed the change in groundwater interaction with the brook changing from being a groundwater discharge system to a groundwater recharge system after the mid-1990s. The increasing influence of surface water flow events on water levels at GB22 is also evident after the 1990s, becoming irregular larger seasonal peaks against the background declining trend (Figure 33). Clearest evidence was during 2008–09 when surface water runoff led to filling and overflow of Yeal Lake and a rise in water levels at GB22 much larger than previous or subsequent years. This is also corroborated by evidence from aerial images (Appendix A). Greater influence of surface water flows from 1991 to 2000 also corresponds with some of the highest surface water flows since 1962 in Lennard Brook (Molecap Hill gauging station; Figure 7) that feeds into Yeal Lake. The second variable was adjusted to qualitatively reflect these influences to achieve the model presented and would be further improved using time series surface water inflows to Yeal Lake.

While Quin Brook was also locally recharging groundwater before 1991 and no doubt played a role in regional recharge, this did not result in a distinct influence on water levels at GB22.

GA10, GC11, GC19 and GB23 – west and central

The water level model for GA10 included positive effects of downgradient clearing of Banksia woodland followed by an extended two-part negative effect of reduced recharge after pine planting and later confined aquifer drawdown (Table E2). Woodland was cleared between 1983 and 1985 (verified by aerial images) with the effect on water levels not evident until at least 1985, representing gradual upgradient propagation of higher water levels beneath the woodland (evident from 1983 in bore GA4). This effect was interpreted to have ended when water levels started to decline in about mid-1987 (Figure 34). The effect of plantation growth on recharge is progressive, reaching maximum impact at maximum leaf area, which is generally more than 14 years after planting when first thinning is carried out (URS 2008). The effects of drawdown in the confined aquifer began after 2004 with earlier and later fitting resulting in deviation in modelled water levels from the measured levels.

Regression modelling for GC11 was also best-fitting with a variable negatively affecting water levels in addition to rainfall decline (Table F2). The effects of confined aquifer drawdown were included as a second variable given the effects at GA10, but were very minor (Table F2). The best-fit was when confined drawdown started after 2006. As for GA10, this main extended factor driving levels down was similarly interpreted to be upgradient propagation of water level decline at the pine plantations. Modelling indicated that the plantation effect was after 2000. Although this was more than 15 years after the last pine trees were planted, the timing follows when higher water levels downgradient at GA10 diminished (when the actual water levels fell below that accounted for rainfall alone). Similar lateral effects of the pine plantations on water levels in the nature reserve have also been found using PRAMS. Modelling of plantation removal predicted a net rise of groundwater levels of up to 1.5 m extending upgradient at least 4 km into the Yeal Nature Reserve (De Silva 2009).

Table F2 Summary results for regression modelling to analyse effects of rainfall trends and other influences on water level trends.

Bore	**r^2**	**Constant (k_0)**	**ARR (rainfall trend) coefficient (k_1) (95% upper and lower CI)**	**Coefficient for variable 2 (k_2) (95% upper and lower CI)**	**Coefficient for variable 3 (k_3) (95% upper and lower CI)**	**Coefficient for variable 4 (k_4) (95% upper and lower CI)**
GB22	0.93	55.97	0.0026 (0.0023 – 0.0028)	SW recharge 0.0021 (0.0013 – 0.0029)	Confined drawdown effect –0.016 (–0.023 to –0.010)	N/A
GA10	0.99	45.50	0.0015 (0.0013 – 0.0016)	Clearing for pines 0.0059 (0.057 – 0.061)	Pine effect –0.013 (–0.014 to –0.012)	Confined drawdown effect –0.010 (–0.011 to –0.009)
GC11	0.96	57.39	0.0016 (0.0015 – 0.0018)	Pine effect –0.013 (–0.016 to –0.010)	Confined drawdown effect –0.0008 (–0.006 to –0.005)	N/A
GB23	0.90	58.41	0.0015 (0.0012 – 0.0018)	Pre-1974 planted pine effect –0.0008 (–0.0014 to –0.00014)	Mid-1980s planted pine effect –0.0055 (–0.0078 to –0.0033)	Confined drawdown effect –0.0099 (–0.020 to –0.0002)
GC19	0.99	58.07	0.0004 (0.0002 – 0.0006)	Pre-1977 planted pine effect –0.013 (–0.014 to –0.012)	1966–1975 wildfire effects –0.010 (–0.0094 to –0.0110)	Confined drawdown effect –0.011 (–0.013 to –0.0098)

All coefficients statistically significant ($P < 0.05$)

Rainfall trend explained the most of watertable decline at GA10 and GC11 up until the late 1990s, based on modelling reproducing most of the year to year patterns (Figure 34). Under-prediction during this time was probably mostly due to the short-term effects of increased recharge caused by wildfires (indicated in Figure 34). Additional variables were not added to capture the effects of the fires because these had only short-term effects on water levels (less than four years).

The effects of the pine plantations explained more than half of the watertable decline at GA10 and GC11 between 2000 and 2012 (Table F3). Although the effect of the pines was evident later at GC11, the effect on the rate of decline was similar at 0.16 m/yr (0.013 m/month being the coefficient for the k_3 in the regression model; Table F2). At GC19 in the south, the downgradient plantations also influenced watertable trends and had the same effect on the rate of watertable decline.

At GB23, the best-fitting model found rainfall decline explained half of the 3.4 m decline since the mid-1980s coupled with three variables starting at different times, reflecting the effect of the pine plantations and confined aquifer drawdown (Figure F2; Table F2; Table F3). There was a slight effect of confined aquifer drawdown (~0.4 m) that was only significant in the modelling when starting after 2009. The effects of the pines was captured using two variables – one reflecting the earlier large planting before 1974 and the second reflecting the closer planting in the mid-1980s (see planting dates in Figure 10). The later planting had an effect a few years earlier than at GC11 (after 1998) because the bore was 2 km closer to the plantations.

Table F3 Approximate metres of watertable decline at 2012 attributed to different variables based on best-fitting HARRT modelling.

Bore	Rainfall decline	Combined effects of pine plantations	Confined drawdown effect	Total decline (since mid-1970s)
GB22	3.5	0	0.6	4.1
GB23	1.7	1.3	0.4	3.4
GC11	2.0	2.3	1.0	5.3
GA10	2.6	1.7	0.05	4.4
GC19	1.8*	3.0	1.1	5.9

* *Includes effect of recession from pre-record wildfires in 1966 and 1972.*

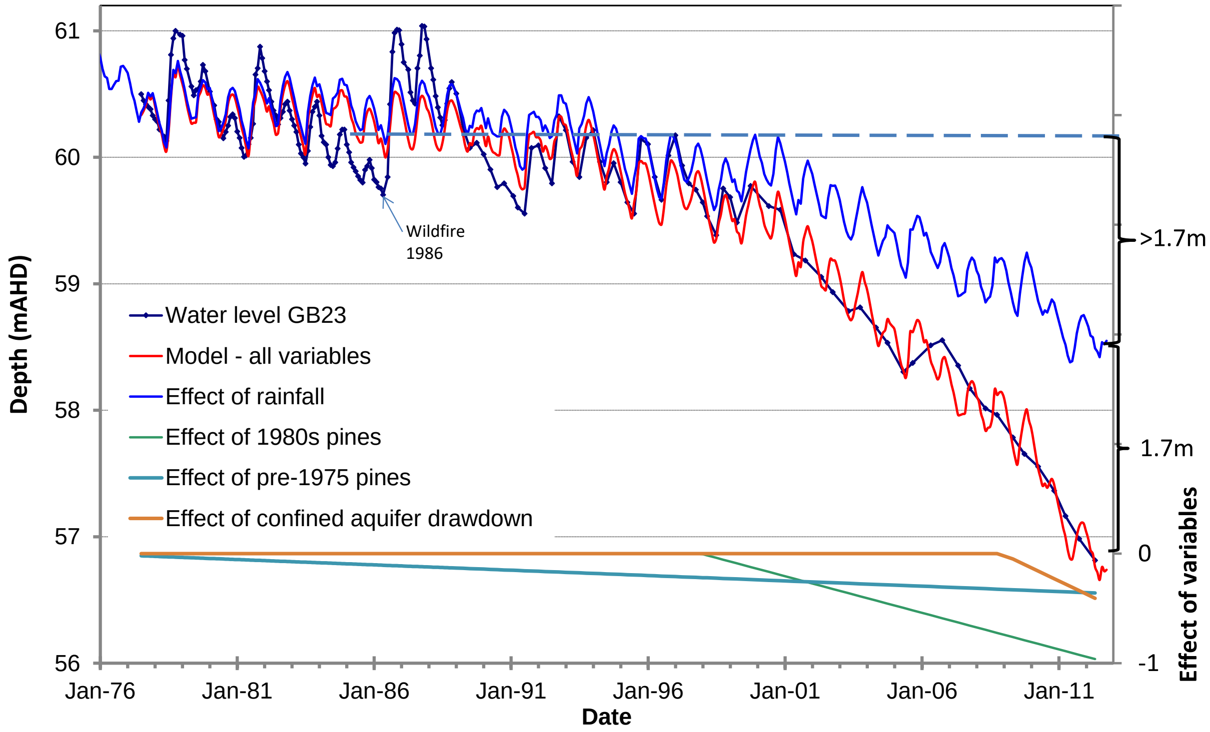


Figure F2 HARTT modelling of water level decline based on rainfall, land use and confined aquifer drawdown at GB23 in the central north of Yeal Nature Reserve.

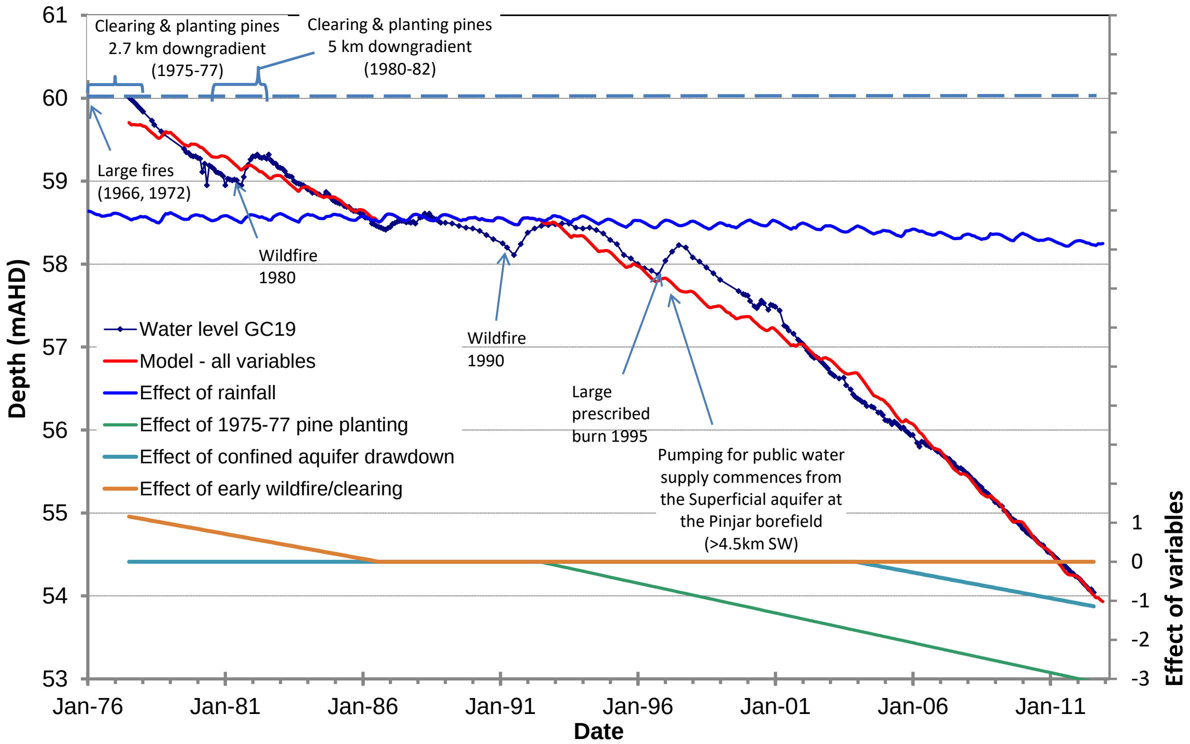


Figure F3 HARTT modelling of water level decline based on rainfall and land use variables at GC19 south of the Yeal Nature Reserve.

However, as at GC11, the onset of the pine plantation effects on water levels was similarly delayed by more than 10 years consistent with when leaf area cover, and therefore effects on recharge, was likely reaching maximum levels (URS 2008). The variable for the later pine planting (k_3 in Table F2) has a greater effect on watertable trends at GB23 than the earlier pine planting, but probably does not indicate a larger physical effect. This variable most likely captures the combined effects of the second planting and any additional effects of the earlier planting arising from ongoing rainfall decline. The relatively diminished effect of the pre-1974 planting was probably because this likely emerged in the mid-1980s and was largely offset by the effects of wildfires on recharge.

Watertable trends south of the reserve at GC19 also reflected the combined influence of rainfall decline, downgradient pine plantations and confined drawdown. HARTT modelling for this bore was limited by the large depth to watertable (> 15 m) with water levels providing limited reflection of seasonal recharge patterns (evident as no seasonal variation). The early part of the water level trend also includes a recession effect attributed to Banksia regrowth after a series of large wildfires in 1966 and 1972 (Department of Environment and Conservation 2012). The best-fitting model (Table F2) indicated that rainfall explained a third of the decline in watertable since the late 1970s but the largest effect was the pines (Table F3). The effect of the pines was greater than at GA10 but earlier with modelling showing little influence (on r^2 and visual fit) of delaying the plantation effects by up to five years. The effects of planting the pines probably includes the effects of the later planting in the early 1980s further downgradient, but this could not be easily distinguished and therefore was not included as a separate variable in the modelling. Wildfires also appear to cause short-term increases in water levels and if included, could further increase the fit of the model.

A component of the decline emerging generally after 2004 in the reserve’s south and central parts was attributed to drawdown in the confined aquifer causing increased leakage from the Superficial aquifer. The trend emerged earlier at GA10 and GC9 (around 2004) but later in the north, being after 2006 at GC11 and after 2008 at GB23. These analyses suggest a northward propagating effect of confined aquifer drawdown that may eventually affect water levels in the reserve’s north at the Yeal and Quin brook wetlands. At the closest AM bore in this area (AM14a) the vertical gradient between the Leederville and Superficial aquifer (indicated by GG4(I)) has been steadily increasing at a rate of 0.1 m/yr since records began in 1978 (Figure F3). The gradient increases faster in the late 1990s then slows in the early 2000s, averaging 0.16 m/yr of which at least the 0.1 m/yr increase before 1990 would be a major part. This suggests that factors other than pumping at the nearest borefield (Pinjar) dominate the drawdown at AM14 for most of the monitoring record up until 2012. There is also a clear effect of the confined drawdown influence being greater in the reserve’s south (Figure F3) – also consistent with modelling of drawdown effects being earlier in the reserve’s south at GA10 and GC19 than the centre and west at GC11, GB22 and GB23 (Table F3).

Appendix G — NMR logging of water content and pore distribution in suitable bores

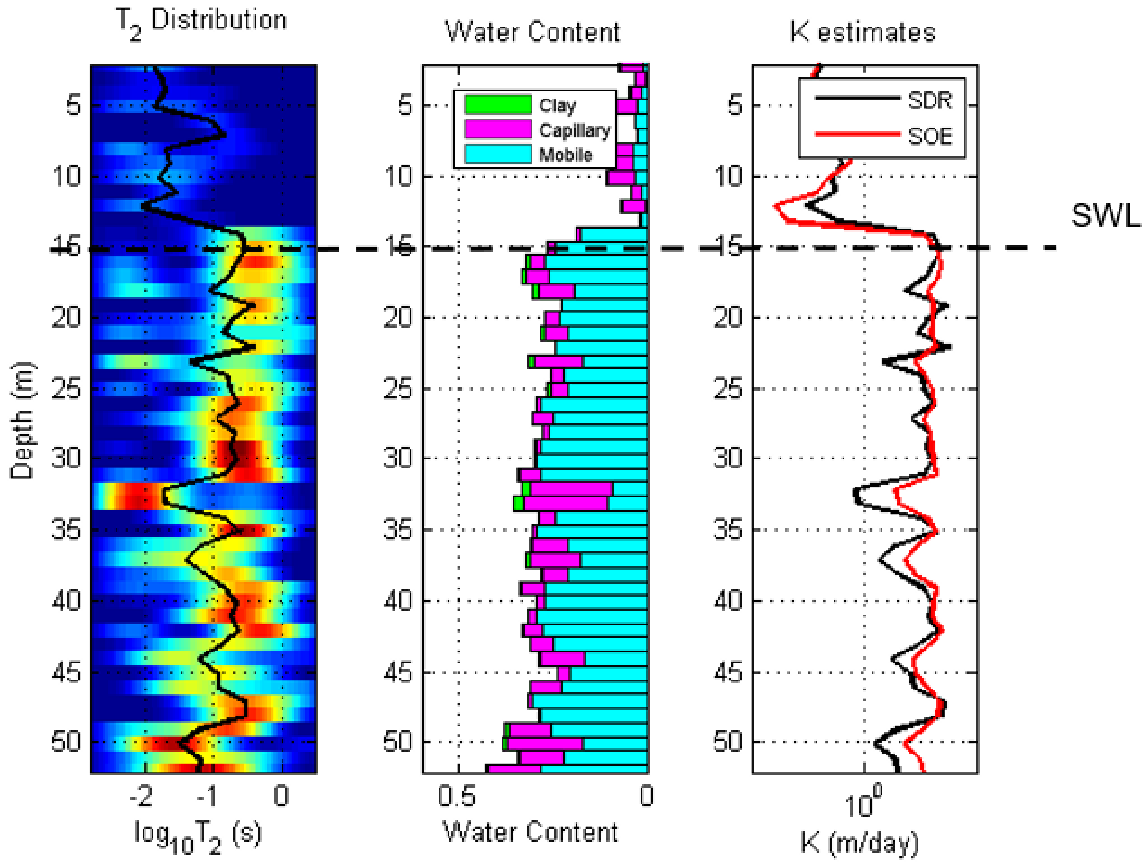
Nuclear magnetic resonance (NMR) logging of 11 bores were undertaken in and around the Yeal Nature Reserve. NMR logging involves the sensing of the properties of water in the formations outside of bore casing on the basis of pattern of decay in the magnetic response of water following tuned magnetic pulsing. The decay pattern can be used to determine water content and the general distribution of pore sizes in which the water is held (nominally clay pores, capillary water and mobile water).

Most bores in the area were unsuitable for NMR logging because they were either cased with steel or contained steel conductor casing liners outside of the PVC casing (as was the case for most of the NG bores penetrating the Superficial aquifer). Steel prevents sensing using magnetic pulsing. Another major factor determining the technique’s success was the drilling method used. The ideal bore for NMR logging is where the disturbance of the formation is inside of the maximum radial resolution of the NMR probe. This work found that drilling of Superficial aquifer bores using a cable tool (e.g. NG1c) resulted in the bore hole annulus being much greater than the tool bit diameter, which was then filled with cement grout.

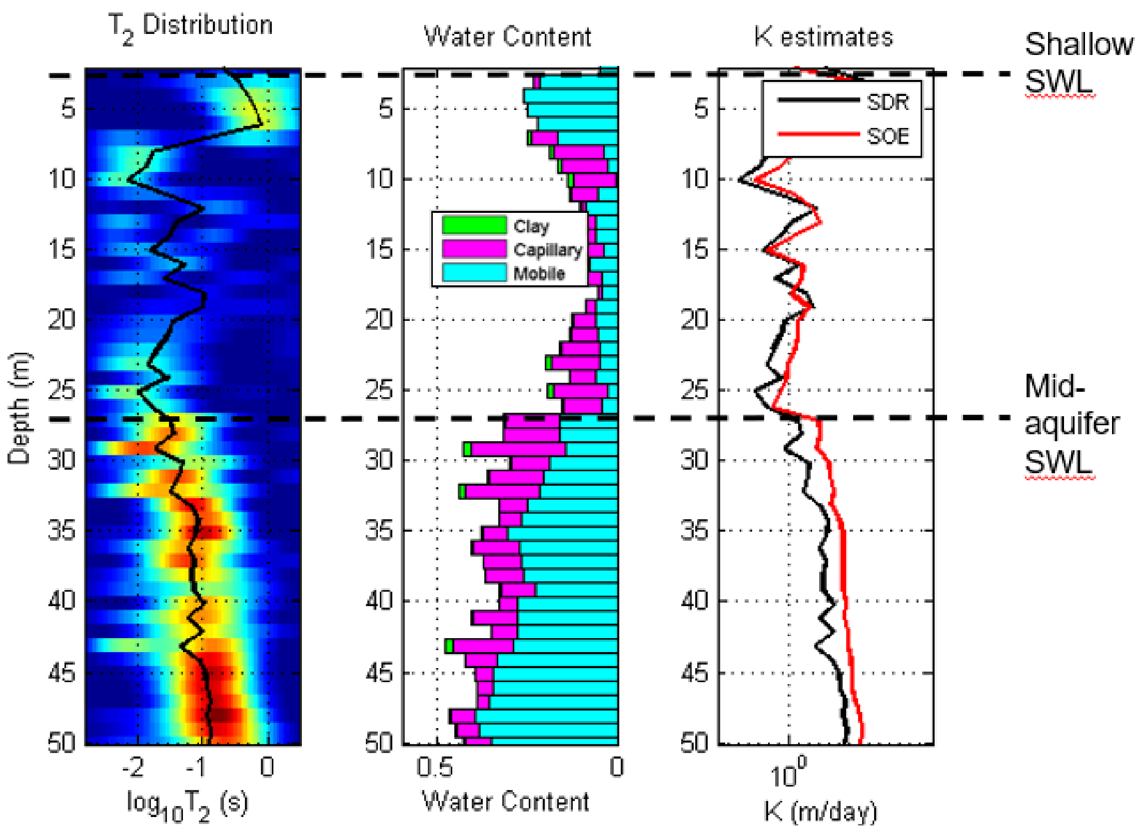
NMR logging was conducted in June 2013 using the Javelin 175C probe (Vista Clara Inc.) which was the only available probe suited to the 50 mm ID PVC bores. This probe had a radial distance of sensing (termed the radial depth of investigation or radial DOI) of 10 to 12 cm and was designed for logging in 1 m stepped increments.

Bore	Comments in relation to perching and intra-aquifer connectivity
NG3c	No confining beds with minor capillary water above watertable consistent with iron rich sands at 8–10 mgbl. Minor low porosity, low K in mid-aquifer sandy clay (~ 33–34 mgbl).
WC8c (5/06)	Perched with capillary water in sandy clays and clay beds 7–11 mbgl and an unsaturated zone of ~16 m in underlying sands.
WC2a (1/06)	Perched with capillary water in sandy clay beds 6.5–14 mbgl and an unsaturated zone of ~1 m in underlying sands.
NG9c	Unexplained mobile water identified in sandy formation above watertable at 15.6 mbgl. May be hydrated drilling muds in bore annulus. Minor lenses of low porosity, low K in mid-aquifer sands (~29 mbgl; 37–38 mbgl).
CYWa	Shallow groundwater isolated from deeper groundwater by approximately 4 m thickness of low conductivity (small pore sized), high water content materials consistent with sandy clays. Absence of unsaturated zone beneath this indicates not perched but likely poorly hydraulically connected. Mid-aquifer silty sands (25–42 mbgl) exhibit low porosity, low K.
NG4d	No low permeability beds with minor capillary water above watertable possibly due to iron rich sands (not noted in lithology log).
QUN_Ea	Shallow groundwater connected with deeper groundwater by sediments with high proportion of water as mobile water consistent with beds of clayey sands (6–9 mbgl). Low mobile water in clayey sands at approx. 22–24 mbgl may limit vertical hydraulic conductivity mid-Superficial aquifer.
QUN_Wa	Shallow groundwater isolated from deeper groundwater by approximately 3 m thickness of low mobile, low water content materials consistent with sandy clays and clayey sands. Absence of unsaturated zone beneath this indicates not perched but likely to be poorly hydraulically connected.
NG5c	Low permeability sandy clay beds 4–10 mbgl and a very small unsaturated zone of < 1m in underlying sands.

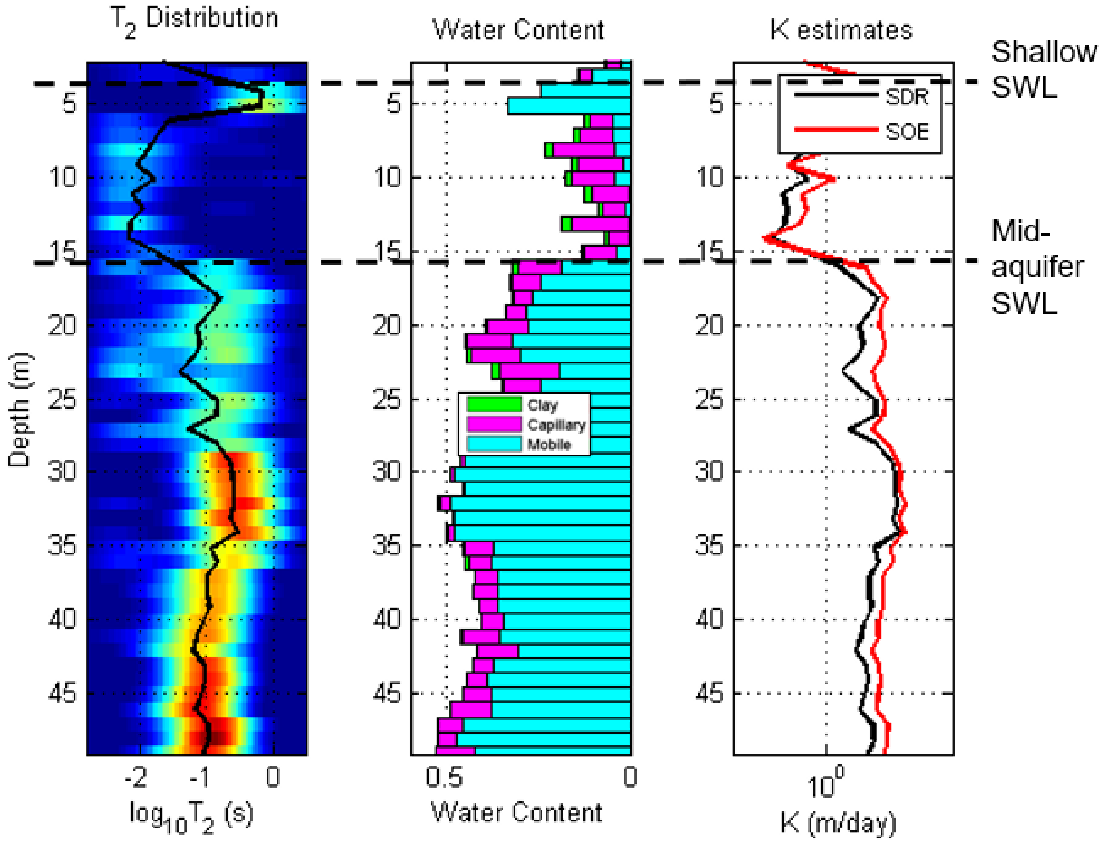
NG3c downhole NMR log (June 2013)



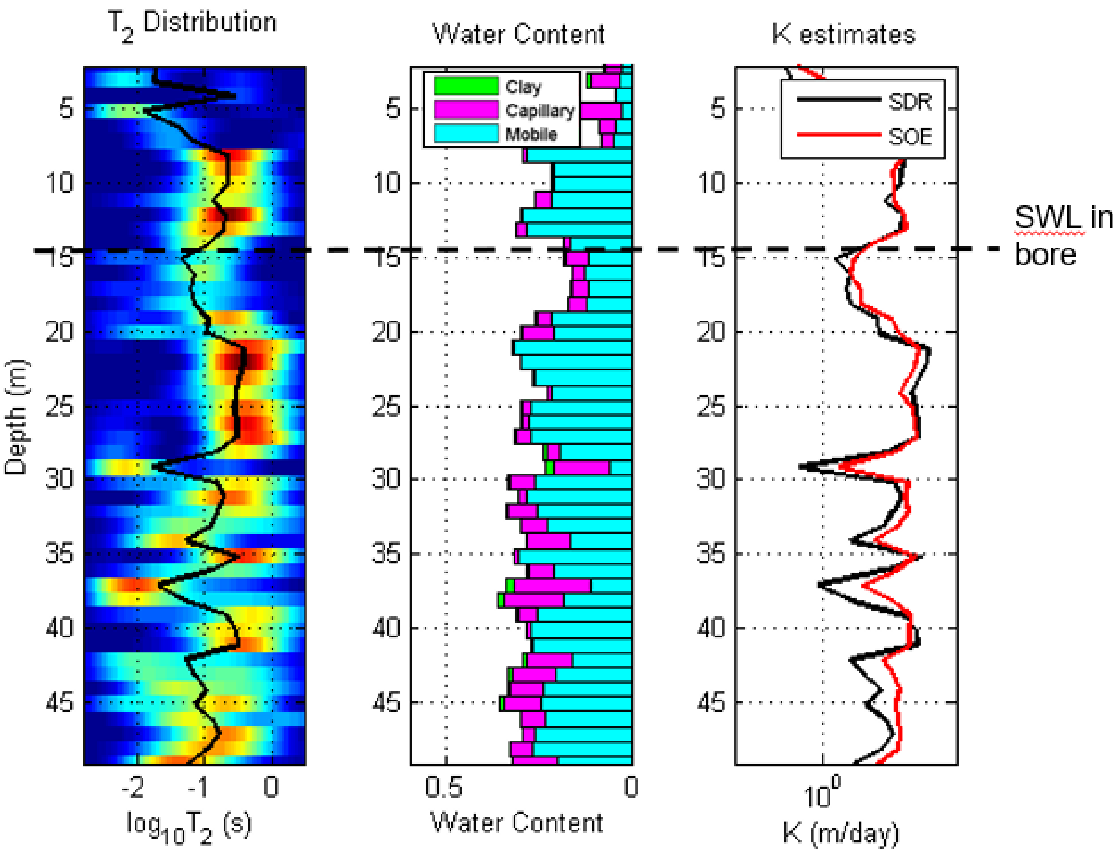
WC8c (5/06) downhole NMR log (June 2013)



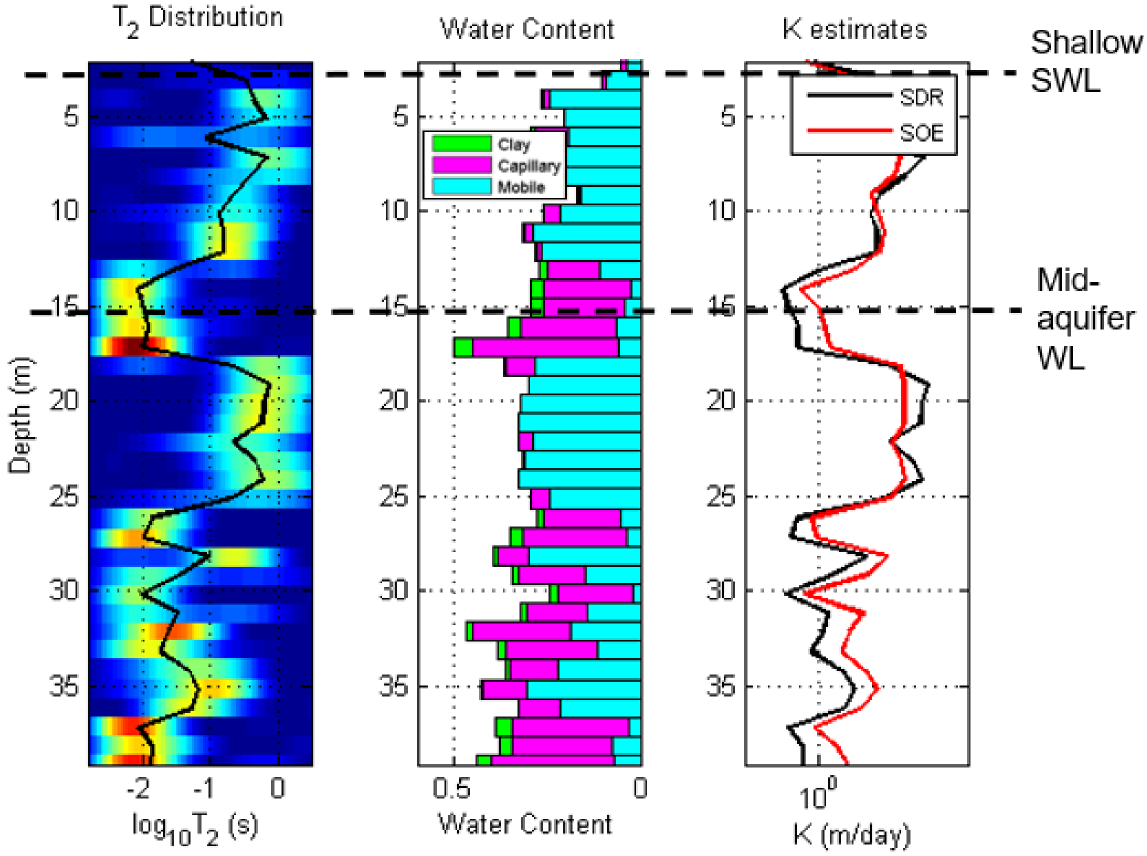
WC2a (1/06) downhole NMR log (June 2013)



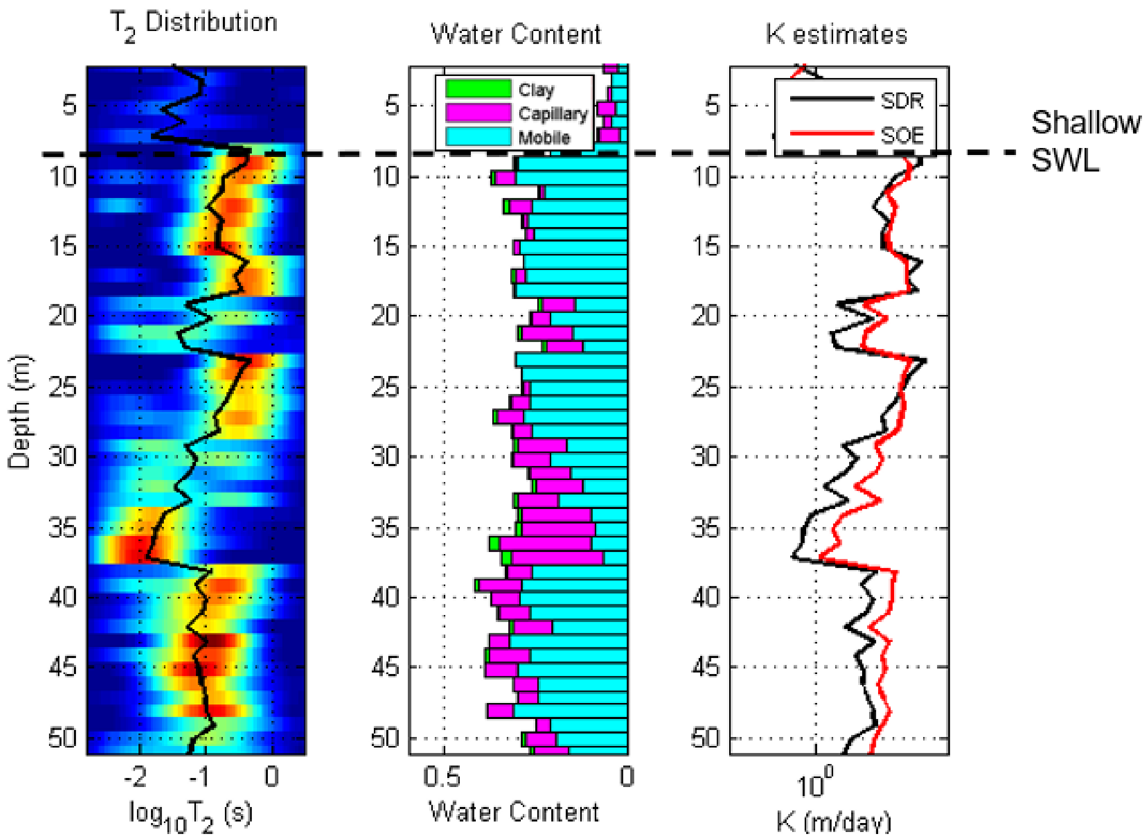
NG9c downhole NMR log (June 2013)



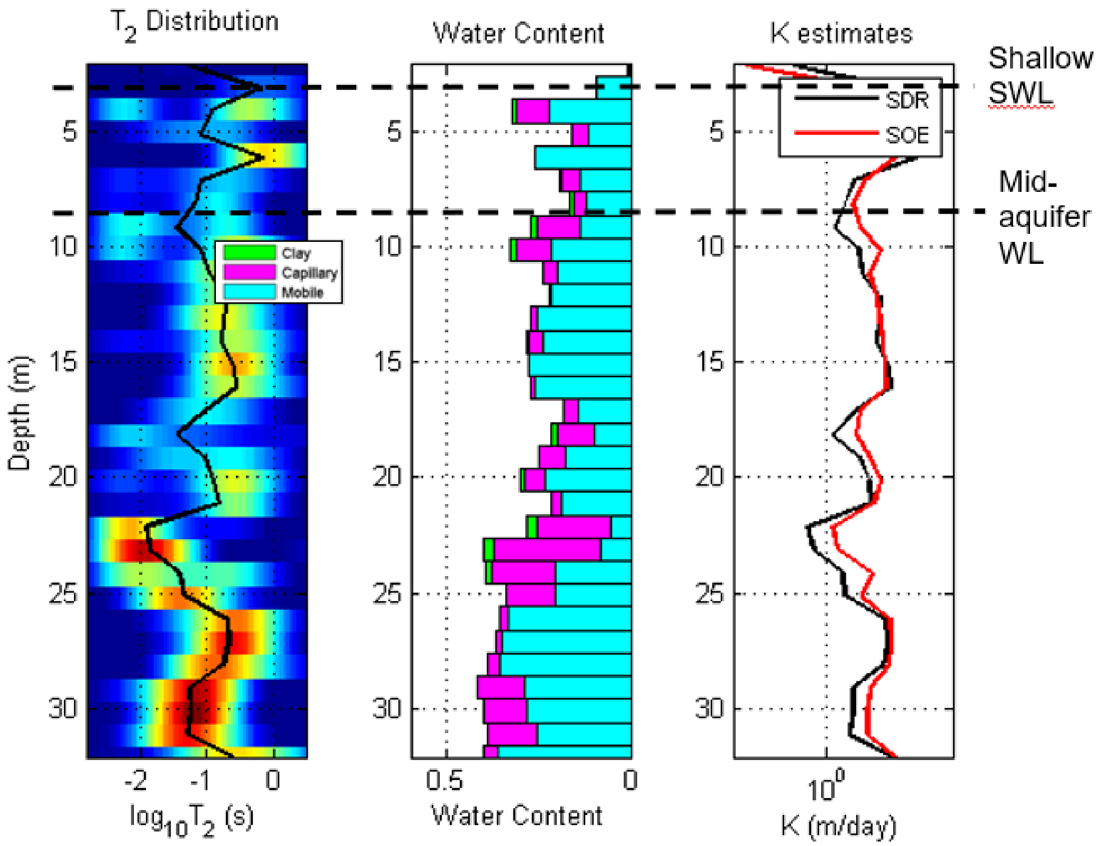
CYWa downhole NMR log (June 2013)



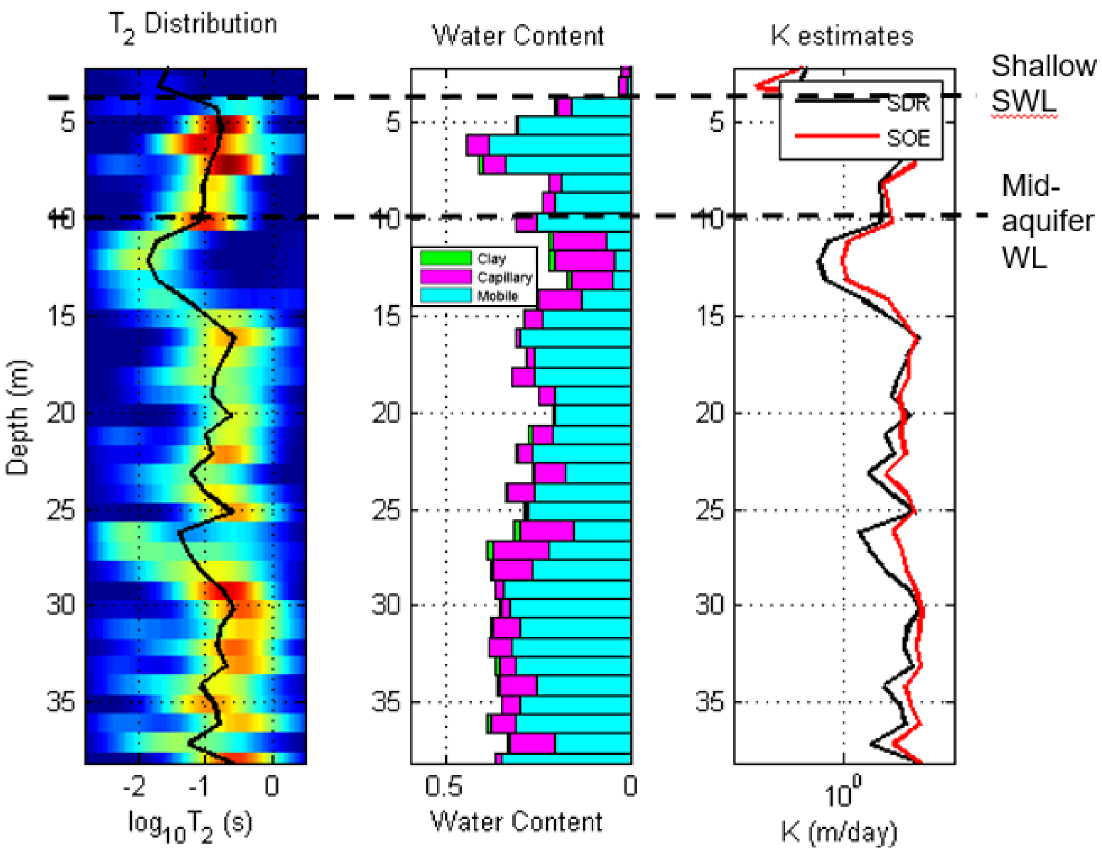
NG4d downhole NMR log (June 2013)



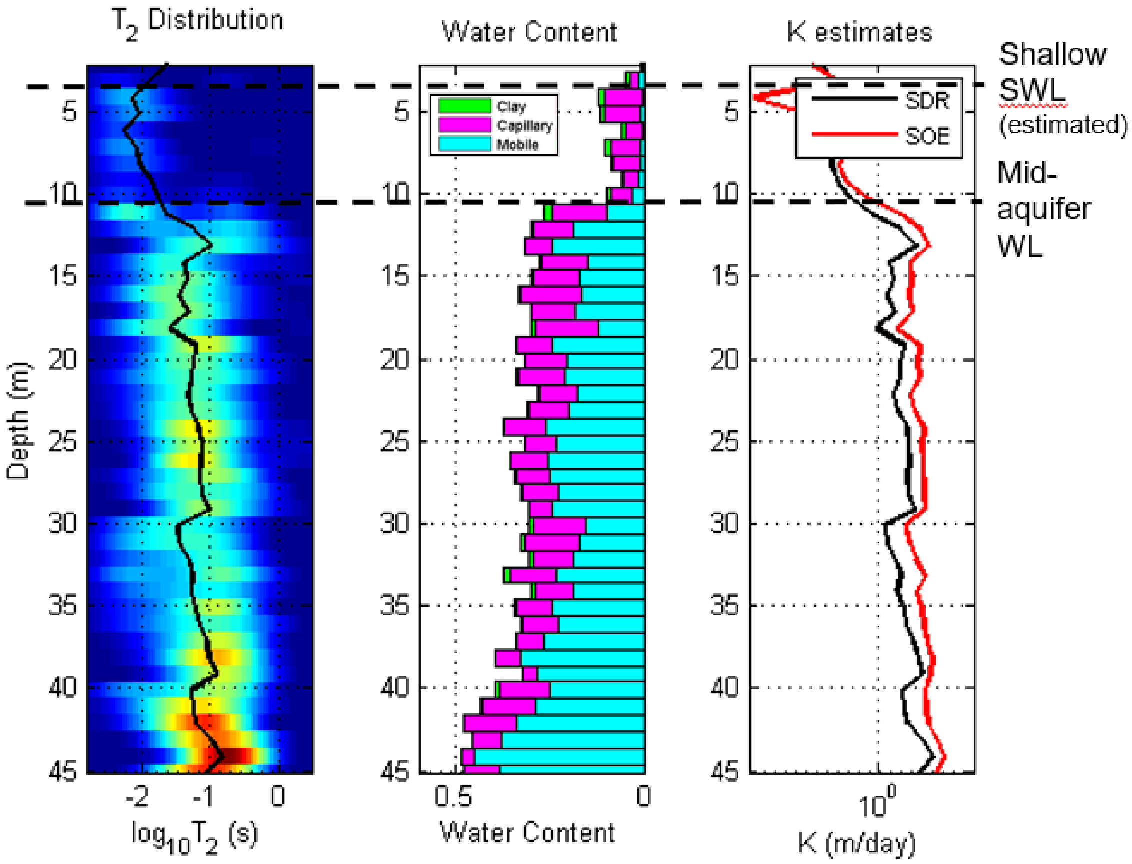
QUNEa downhole NMR log (June 2013)



QUNWa downhole NMR log (June 2013)



NG5c downhole NMR log (June 2013)



Appendix H — Average annual rate of watertable decline (2011–2012 relative to pre-1998) for bores in and around the Yeal Nature Reserve

Area	Bore	Average annual decrease watertable since end 1998[1] (m/yr)	Decrease in annual average watertable relative to pre-1998 watertable (m)	Watertable depth below ground-level (m)
East Yeal	GB19	0.09	1.03	≤5
	GB18	N/A	N/A	N/A
	GC2	0.03	0.21	≤5
	GC1/GC23	0.05	0.56	≤5
	GC4	0.05	0.52	≤5
	GC5/ GC24	0.02	0.29	≤5
	GC2	0.03	0.21	≤5
	GC9	0.13	1.71	≤5
	GC10	0.08	0.85	≤5
	GC6	0.04	0.39	≤5
	GC13	0.12	1.41	≤5
	GC14	0.12	1.48	≤5
South Yeal	GA9	0.31	4.18	10-20
	GG4 (O)	0.25	3.42	> 20
	GA6	0.34	4.64	10-20
	GC16	0.24	2.28	> 20
	GC19	0.32	3.99	10-20
	GG5 (O)	0.21	2.89	10-20
	GC20	0.27	3.35	10-20
	GC17	0.13	1.60	≤ 5
North Yeal	GB14	N/A	N/A	N/A
	GB9	0.05	0.52	≤ 5
	GB16	0.01	0.09*	≤ 5
	GB8	0.09	1.04	≤ 5
	GG8(O)	0.20	2.57	5-10
	GB15	0.21	2.64	5-10
	GB12	0.15	1.73	5-10
	GB13	0.14	1.72	5-10

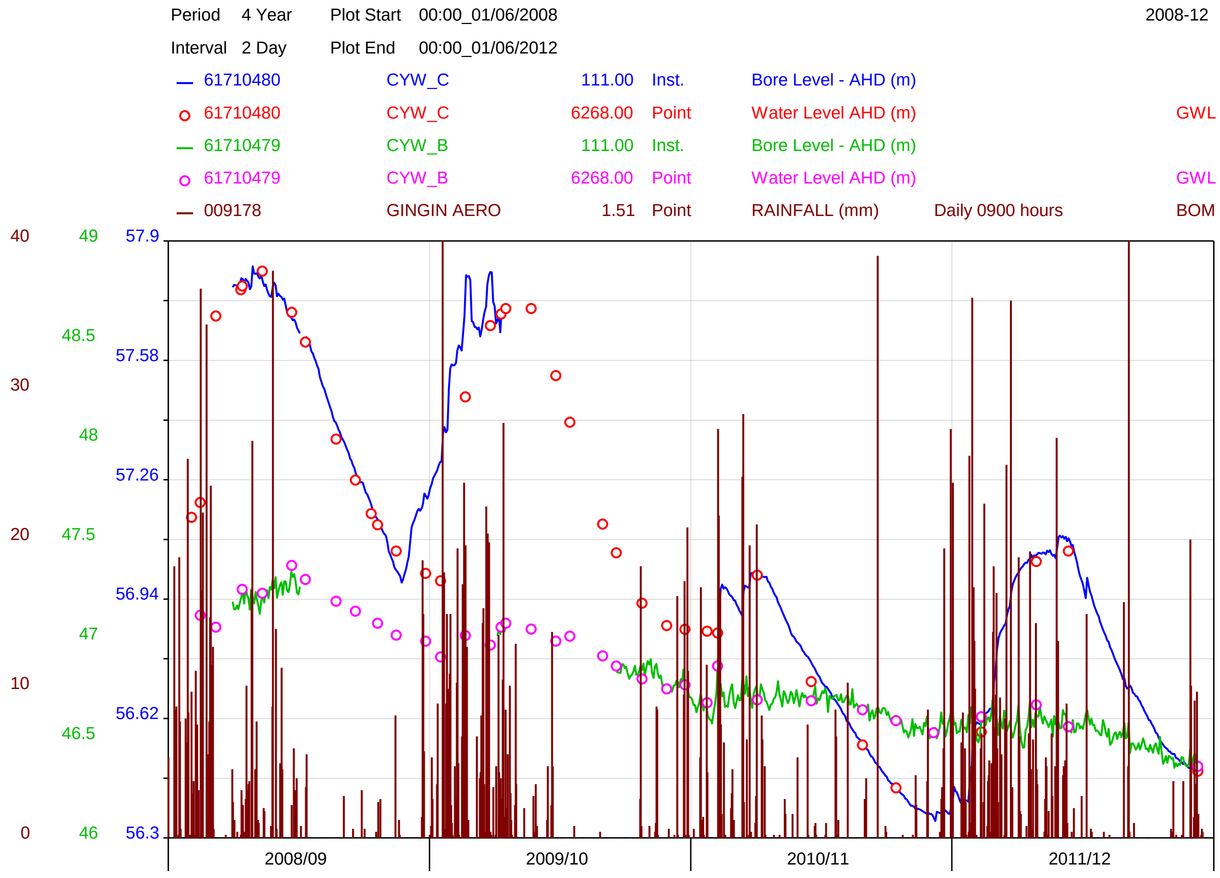
Area	Bore	Average annual decrease watertable since end 1998[1] (m/yr)	Decrease in annual average watertable relative to pre-1998 watertable (m)	Watertable depth below ground-level (m)
Central Yeal	GB22	0.28	2.26	5-10
	GB21	0.29	2.40	5-10
	GB23	0.23	2.74	5-10
	GB20	0.20	2.38	5-10
	GB24	N/A	N/A	N/A
	GC12	0.20	2.49	5-10
	GC11	0.28	3.50	10-20
	GC8	0.14	1.78	5-10
	GG6 (O)	0.31	3.88	10-20
West Yeal	GA22	0.23	2.97	> 20
	GA23	0.23	2.78	5-10
	GA18	0.23	2.89	> 20
	YY6 (O)	0.21	2.89	> 20
	YY7 (O)	0.26	3.21	10-20
	GA15	0.34	4.30	10-20
	GA14	0.28	3.65	> 20
	GA10	0.39	4.94	10-20
	YY4 (O)	0.41	5.35	10-20

* *Possibly underestimated because of sand accumulation in bore.*

[1] *Rate of decline calculated as average annual change in water level between 2011–2012 and pre-1998.*

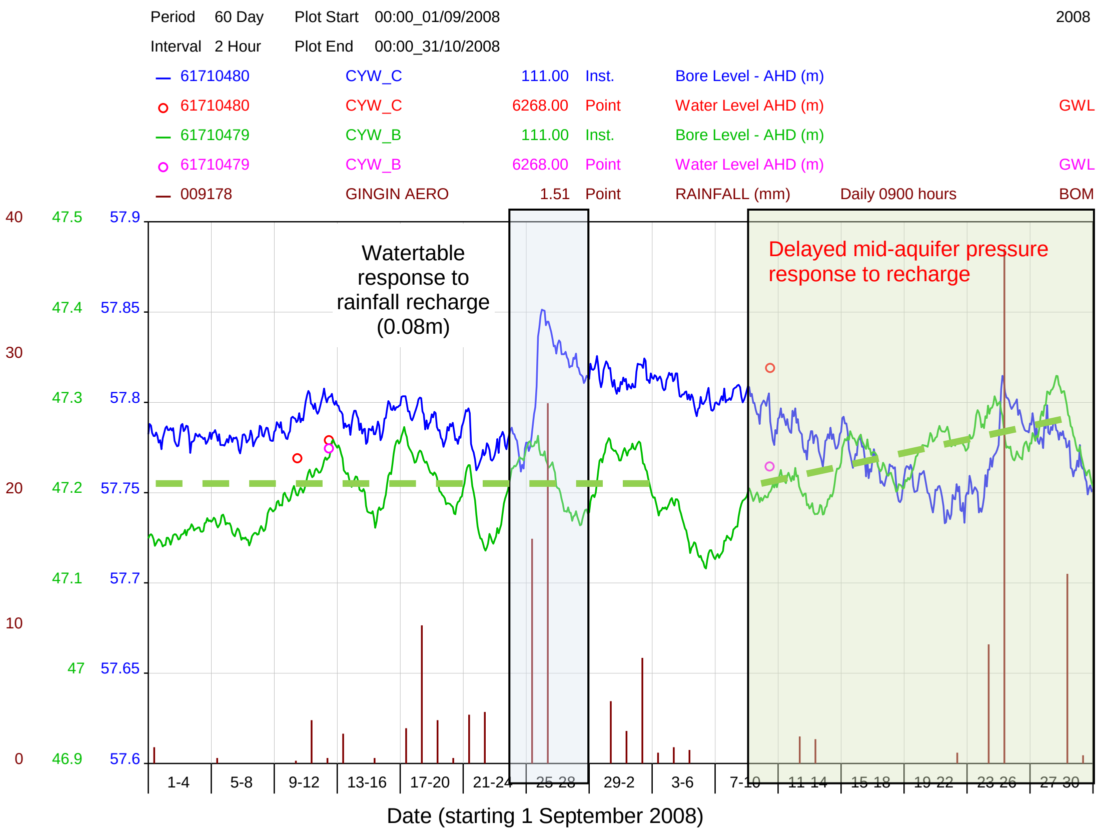
Appendix I — Hourly water levels and daily rainfall (Gingin airport) for north Yeal wetland bores

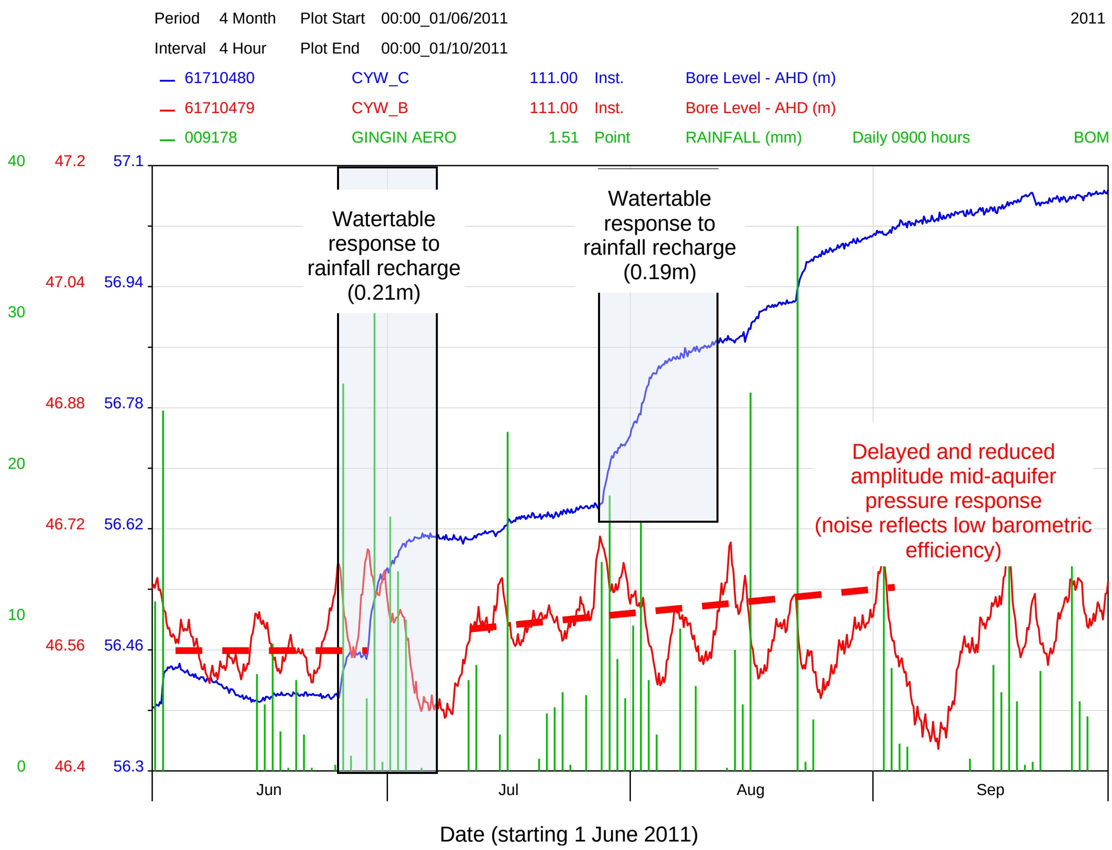
Quin Brook wetland – full record of dip and logger water levels in the watertable (CYWc) and mid-aquifer (CYWb) bores in relation to daily rainfall.



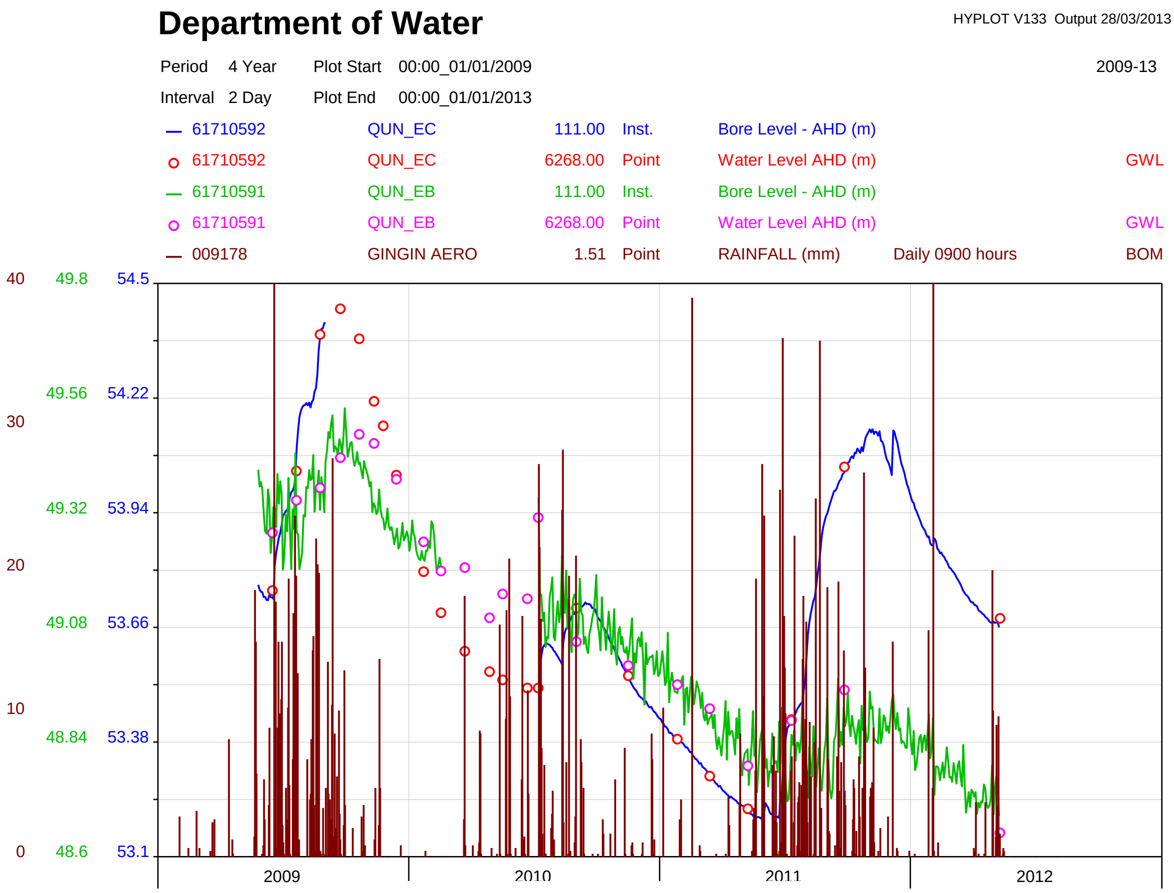
Date (starting 1 June 2008)

Quin Brook wetland – propagation of watertable recharge response (shallow bore CYWc) to mid-aquifer groundwater (CYWb).



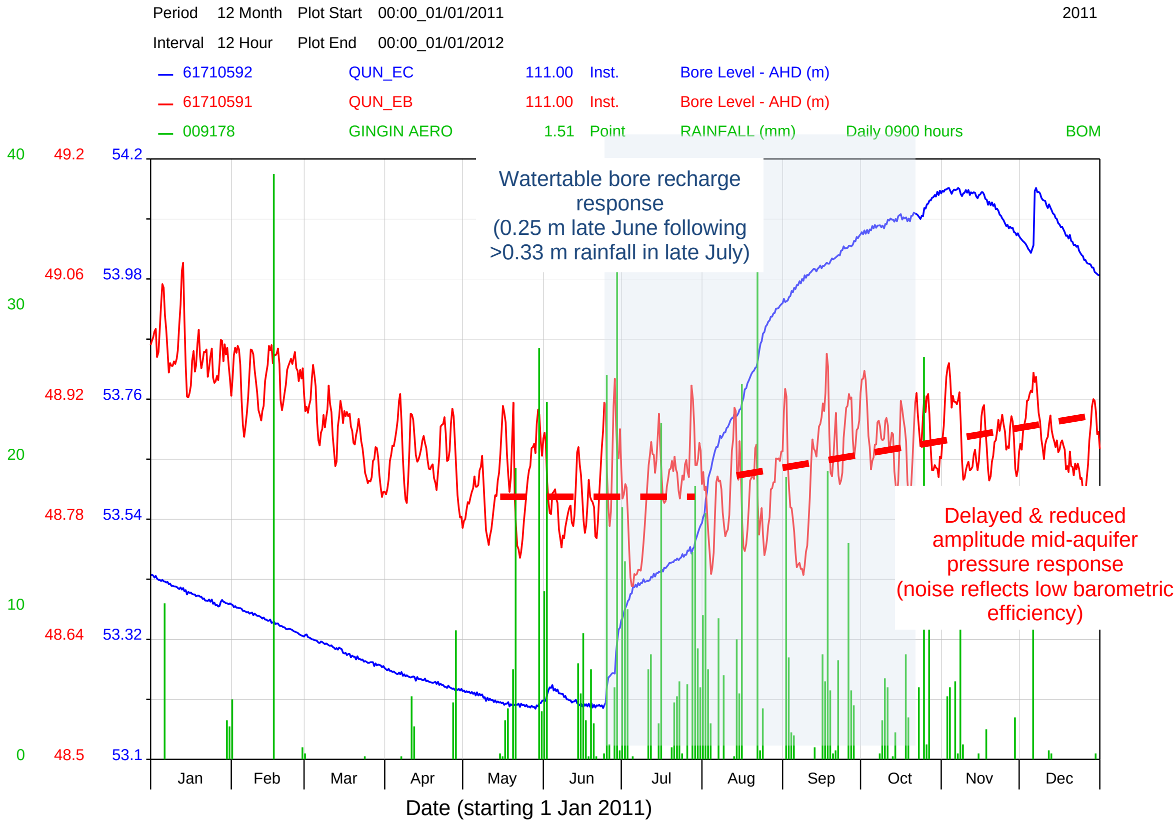


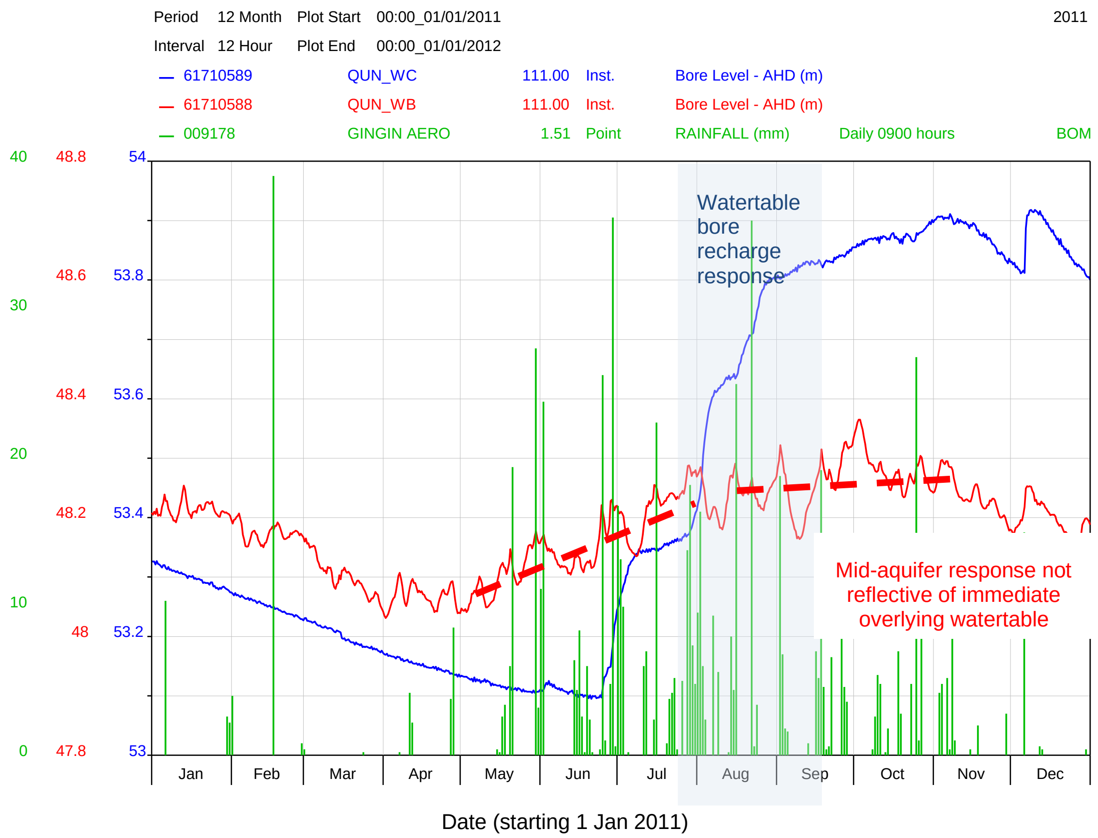
Quin Swamp – dip and logger water levels in watertable (QUNEc and QUNWc) and mid-aquifer (QUNEb and QUNEb) bores in relation to daily rainfall.



Date (starting 1 January 2009)

Quin Swamp – propagation of watertable recharge response (shallow QUNEc, QUNWc bores) to mid-aquifer groundwater (QUNEb, QUNEb bores).





Appendix J — Mapping potential watertable perching in the Yeal Nature Reserve

A spatial assessment of vertical hydraulic connectivity between the regional aquifer and the watertable across the Yeal Nature Reserve was mapped in ArcGIS from point assessments of connectivity. This is to assist interpretation of modelling regional groundwater levels in PRAMS where conceptualisation may not include shallow confining beds or poorly captures the extent of the Guildford Formation. Low vertical hydraulic connectivity is an indicator of watertable perching.

The assessments (all at bores) combined multiple lines of evidence from several methods where the likely vertical hydraulic connectivity between the watertable and deep aquifer was rated. Vertical hydraulic connectivity was assessed at 50 sites in the area by considering:

- vertical propagation of event and seasonal water level pressures into the Superficial aquifer
- lithology
- moisture distribution logging of bores (using NMR), and
- long-term vertical pressure gradient analysis.

Vertical pressure responses and lithology were used to assess vertical connectivity at 27 bores (TableTable D1). Low connectivity was evident at 13 bores where it took several months for seasonal recharge pressure responses to reach deep in the aquifer and there was evidence of low permeability layers in drill logs or NMR sensing. High connectivity was evident by rapid (within a week) propagation of recharge watertable rise to the mid or deep aquifer combined with no significant low permeability beds in drilling logs or NMR sensing (e.g. <1 m thickness clayey beds) indicated high vertical hydraulic connectivity. This subjective analysis is a simplification of the detailed harmonic analysis of recharge that can be applied to quantitatively determine vertical hydraulic characteristics (Boldt-Leppin & Hendry 2003; van der Kamp 2001). Only adjacent watertable and deep aquifer bores were analysed where there was data from water level loggers or monthly measurements (NG series and SGS bores at Tangletoe Swamp, Lake Muckenburra, Lake Bindiar and Lake Bambun).

A further 16 sites were assessed using long-term trends between watertable and deep aquifer bores (TableTable F1) which identified five sites with evidence of low vertical connectivity in the aquifer. Vertical hydraulic connectivity was qualitatively assessed using the decadal response of the watertable relative to the deep aquifer at a location only where other bore information was absent. The assessment is based on the logic that in areas with essentially uniform recharge (such as Banksia woodland across Yeal Nature Reserve), differential decline in watertable relative to the deeper aquifer may indicate low vertical hydraulic conductivity (see van der Kamp 2001). In this case, paired comparisons were made between watertable and deep aquifer water level trends with the deep aquifer trends extrapolated from bores often several kilometres downgradient, where paired bores were not available. Assessment was based on using linear regression to analyse the trends in differences between annual average water levels for pairs of deep and shallow bores. The slope of the regression line reflected the annual average increase in vertical gradient between the watertable and deeper Superficial aquifer. A large increasing trend (>2.5 m/decade) indicated that the watertable had low hydraulic connection with the deeper Superficial aquifer whereas the absence of a trend (where watertable levels declined in parallel with water levels) indicated high vertical hydraulic connectivity.

Plotting of the combined assessments of vertical hydraulic connectivity for the 50 bores indicated that the watertable across most of the Yeal Nature Reserve was hydraulically connected with the deep Superficial aquifer (Figure J1). This can be interpreted to mean that future watertable decline would be at a rate similar to regional water level decline in the Superficial aquifer.

Areas with spatially consistent lower hydraulic connectivity appear to be largely limited to the reserve's north-eastern part (hashed area in Figure J1). Yeal Lake, Quin Swamp and the chain of wetlands along Quin Brook are on the edge of an area where lower connectivity occurs and defines the western extent of the Guildford Formation. Lower hydraulic connectivity occurs locally but is not extensive in the north-west towards Tangletoe Swamp and south-east towards Lake Bambun (Figure J1).

A small area of localised lower connectivity is also evident at Yeal Swamp. This is indicated in long-term water level trends (e.g. GA9 and GA10) and independent evidence of low permeability lithology towards the base of the aquifer at the only drill log in the area (WC5d (7/06)). Further investigation is required to verify the extent and significance of the low vertical hydraulic connectivity indicated by the analysis.

Areas of low hydraulic connectivity can be interpreted to mean that future watertable decline would be at a rate less than or independent of regional water level decline in the Superficial aquifer. This mapping would encompass areas where watertable decline may result in formation of perched groundwater systems where complete hydraulic disconnection occurs. The likelihood of this occurring is greater where low permeability lithology occurs shallow in the Superficial aquifer. While this has been determined for some wetlands (e.g. Tangletoe Swamp), this can only be verified for other GDEs by local investigation.

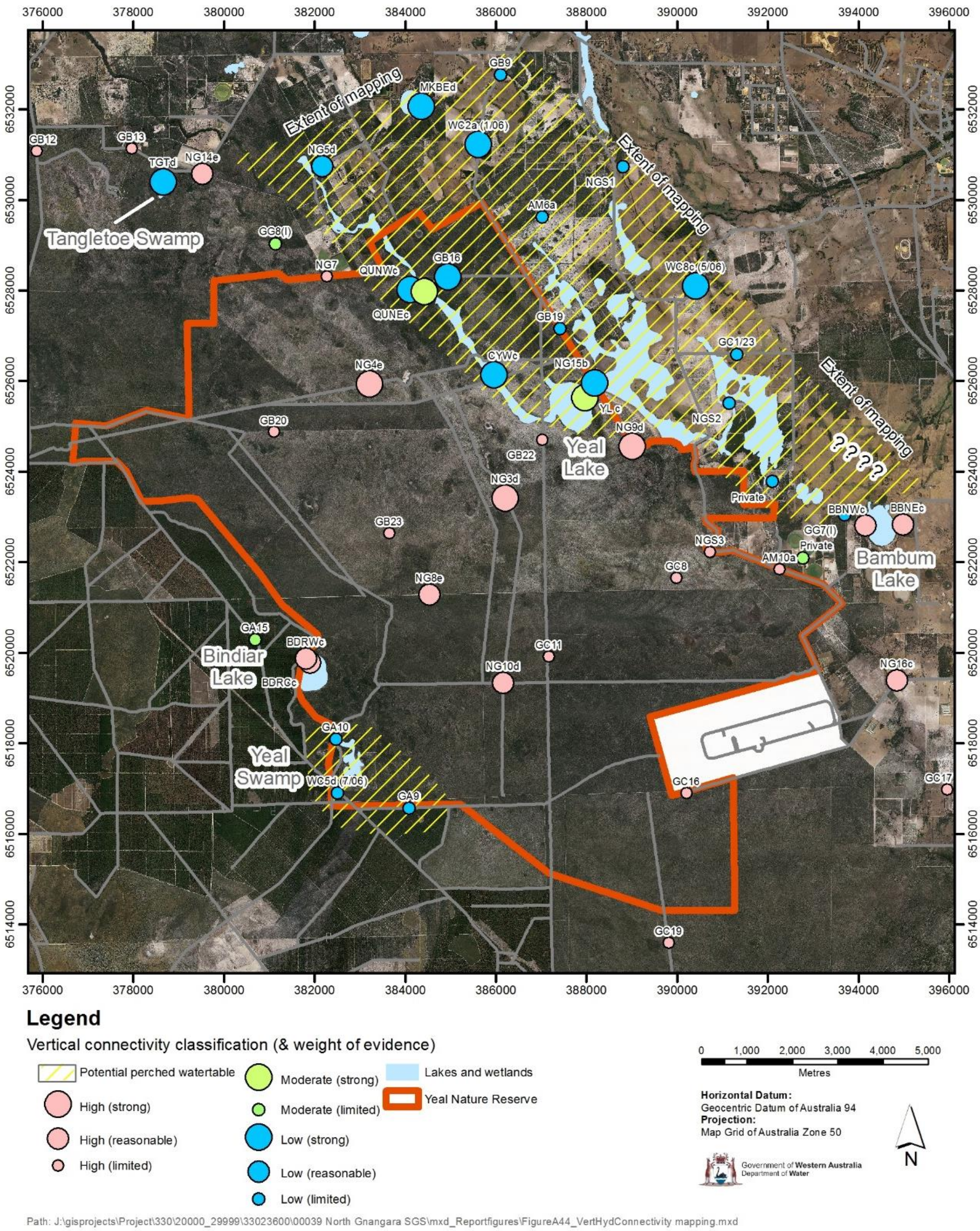


Figure J1 Regional mapping of perched watertables in the Yeal Nature Reserve based on assessment of vertical hydraulic connectivity.

Table J1 Assessment of vertical hydraulic connectivity between the watertable and regional Superficial aquifer based on vertical pressure propagation, lithology or NMR sensing.

Bore/ site	Assessment of vertical hydraulic connectivity	Confidence	Basis of assessment
AM10a	H	3	Lithology only. No low permeability materials.
AM6a	L	3	Lithology only. Low permeability materials (4 m sandy clay) shallow aquifer and towards base of aquifer (3 m sandy clay).
BBNEc	H	2	Rapid propagation of recharge and seasonal water level response to mid-aquifer (BBNEb). Contrasts with lithology.
BBNWc	H	2	No low permeability materials in lithology log. Rapid propagation of recharge and seasonal water level response to mid-aquifer (BBNWb).
BDRCc	H	2	No low permeability materials in lithology and rapid propagation of seasonal water level response to mid-aquifer (BDRCb,a).
BDRWc	H	2	No low permeability materials in lithology log and rapid propagation of seasonal water level response to mid-aquifer (BDRWb,a).
GB16	L	1	Low permeability materials (>8 m thickness sandy clay) present in shallow aquifer at NG1. Slow propagation of seasonal pressure response to mid-aquifer – NG1d (this report).
GG7 (I)	L	3	Drilling log indicates low permeability bed (~3 m sandy clay) in shallow aquifer.
GG8 (I)	M	3	Drilling log indicates low permeability bed (3 m sandy clay) towards base of aquifer.
MKBEd	L	1	Low permeability materials in lithology, slow propagation of recharge response to base of aquifer seasonal, hydrogeology (Degens et al. 2012) and NMR.
NG10d	H	2	Rapid propagation of seasonal pressure response to base of aquifer (NG10c) and no low permeability materials in lithology.
NG14e	H	2	No low permeability materials in lithology log. Rapid propagation of seasonal pressure response to base of aquifer (NG14d) but bore construction may aid pressure response.
NG15b	L	1	Low permeability materials, unsaturated zone (drilling observation) and slow propagation of seasonal recharge response to base of aquifer – NG15a (this report).
NG16c	H	2	No low permeability materials in lithology log. No event or seasonal recharge responses to assess vertical propagation.

Bore/ site	Assessment of vertical hydraulic connectivity	Confidence	Basis of assessment
NG3d	H	1	Rapid propagation of seasonal pressure response to base of aquifer (NG3c). No low permeability materials in lithology log or in NMR sensing (this report).
NG4e	H	1	Rapid propagation of seasonal pressure response to base of aquifer (NG4d). No low permeability materials in lithology log or in NMR sensing (this report).
NG5d	L	2	Low permeability materials (>6 m sandy clay) in shallow aquifer and confirmed with NMR sensing (this report).
NG7	H	3	Lithology only. No significant low permeability materials in drilling log (<1 m clayey sand mid aquifer).
NG8e	H	2	No low permeability materials in lithology log. Rapid propagation of seasonal pressure response to base of aquifer (NG8d) but bore construction may aid pressure response.
NG9d	H	1	Rapid propagation of seasonal pressure response to base of aquifer (NG9c). No low permeability materials in lithology log or in NMR sensing (this report).
NGS1	L	3	Lithology only. Low permeability materials (2 m sandy clay bed) in shallow aquifer and mid-aquifer.
NGS2	L	3	Lithology only. Low permeability materials (4 m sandy clay bed) towards base of aquifer.
NGS3	H	3	Lithology only. No low permeability materials in log.
TGTd	L	1	Combination of lithology, slow seasonal and event hydraulic responses to underlying aquifer (TGTc,b), hydrogeology (DoW 2011c).
WC2a (1/06)	L	1	Low permeability materials (>7.5 m clays) in shallow aquifer and underlying unsaturated zone confirmed with NMR sensing (this report).
WC5d (7/06)	L	3	Lithology only. Low permeability materials (3 m silt and 5 m sandy clay) in mid-aquifer.
WC8c (5/06)	L	1	Low permeability materials (>4 m clays) in shallow aquifer and underlying unsaturated zone confirmed with NMR sensing (this report).

Table J2 Analysis of long-term trends in vertical pressures and interpreted vertical hydraulic connectivity in the Superficial aquifer.

Location in Yeal Nature Reserve	Water table bore[1]	Deep aquifer comparison bore	Likely vertical flow direction	Decline in deep Superficial aquifer (since early 1990s)	Average watertable decline (m)[2]	Trend in vertical head pressures (m/decade)[3]	Rated hydraulic connectivity between watertable and deep Superficial aquifer
North west	GB12	YY9 (I)	Upward	~2.5 m	1.7	0.27 m (1991–11)	High
	GB13	YY9 (I)	Upward	~2.5 m	1.7	0.23 m (1991–11)	
	GB15	YY9 (I)	Upward	~2.5 m	2.6	-0.09 m (1991–11)	Indeterminate. Watertable decline > deep aquifer decline.
West	GB20	YY7(I)	Downward	~3 m	2.4	0.52 m (1997–11)	High
	GB23	YY7(I)	Downward	~3 m	2.7	0.24 m (1997–11)	
South west	GA9	YY4(I)	Downward (inferred)	~4.5 m	4.2 m	2.53 m (1989–97)	Low Large increase in vertical pressure developed over part of record. Decreasing gradients later in record largely due to greater decline at WT. Guildford clay 22–27 mbgl at WC5 1 km east of GA9.
	GA10	YY4(I)	Downward (inferred)	~4.5 m	4.9 m	2.56 m (1989–97)	
	GA15	YY4(I)	Downward (inferred)	~4.5 m	4.3 m	1.97 m (1989–97)	Moderate hydraulic connectivity
Central	GB22	GG6 (I)	Downward	~4 m	2.3	0.88 m (1997–11)	High
	GC8	GG6 (I)	Downward	~4 m	1.8	1.01 m (1997–11)	High
South	GC11	GG4 (I)	Downward	~3.8 m	3.5	0.24 m (1998–11)	High
	GC16	GG4 (I)	Downward	~3.8 m	2.3	0.76 m (1998–11)	High
	GC19	GG4 (I)	Downward	~3.8 m	4.0	-0.08 m (1998–11)	High
South east	GC17	GG5 (I)	None to slight downward	~4 m	1.6	0.80 m (1997–11)	High

Location in Yeal Nature Reserve	Water table bore[1]	Deep aquifer comparison bore	Likely vertical flow direction	Decline in deep Superficial aquifer (since early 1990s)	Average watertable decline (m)[2]	Trend in vertical head pressures (m/decade)[3]	Rated hydraulic connectivity between watertable and deep Superficial aquifer
East	GC5 &GC24	GG7 (I)	Downward	1–1.5 m	0.3	0.56 m (1996–11)	Indeterminate. Limited deep water level decline.
	GC9	GG7 (I)	Downward	1–1.5 m	1.7	N/A	Indeterminate. Limited deep water level decline.
	GC10	GG7 (I)	Downward	1–1.5 m	0.8	0.12 m (1996–11)	Indeterminate. Limited deep water level decline.
North east	GB19	AM6a[4]	Downward (inferred)	>5 m	1.0	2.78 m (1996–11)	Low
	GC1 &GC23	AM6a[4]	Downward (inferred)	>5 m	0.6	3.18 m (1996–11)	Low. Limited confidence because comparison bore >5 km NW.
	GB9	AM6a[4]	Downward (inferred)	>5 m	0.6	3.21 m (1996–11)	Low

[1] *Only watertable bores with levels > deep Superficial aquifer bore were analysed. Some bores are combined datasets (e.g. GC1 and GD23).*

[2] *Decline in average water levels pre-1998 to 2009–2011.*

[3] *Based on analysis of trend in differences between deep Superficial and watertable bores for periods of consistent decline in deep aquifer pressures.*

[4] *AM6a considered to reflect relative water level trend at the base of the Superficial aquifer based on the similarity with faulty bore GG9 (O).*

Shortened forms

AHD	Australian height datum
ASS	Acid sulfate soil
DOC	Dissolved organic carbon
GDE	Groundwater-dependent ecosystem
FRP	Filterable reactive phosphate (effectively soluble phosphate)
K	Saturated hydraulic conductivity (m/day)
NH_4-N	Nitrogen present as ammonia
NOx	Nitrogen present as oxidised inorganic forms (nitrate and nitrite)
NMR	Nuclear magnetic r
mbgl	Metres below ground level
mbTOC	Metres below top of casing (for a bore)
SWL	Standing water level (in a bore) often as mbTOC or mbgl
S_{Cr}	Chromium reducible S (a measure of acidic S in ASS)
TAA	Titratable actual acidity
TDS	Total dissolved salts
TN	Total nitrogen
TP	Total phosphorus
TSS	Total suspended solids

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Department of Water and Environmental Regulation
Prime House, 8 Davidson Terrace, Joondalup Western Australia 6027
Phone: 08 6364 7000 Fax: 08 6364 7001
National Relay Service 13 36 77
dwer.wa.gov.au

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