Government of **Western Australia**
Department of **Water**

Looking after all our water needs

Perth Shallow Groundwater Systems Investigation

Lexia Wetlands

Hydrogeological record series

Report no. HG44
May 2011

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Disclaimer

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Preface

This report is based on work carried out as part of the Perth shallow groundwater systems investigation. This is a four-year (2007–10) investigation program being undertaken by the Groundwater Review Section of the Water Resource Assessment Branch within the Department of Water. Funding for the program has been provided jointly by the Government of Western Australia and the federal government's Water Smart Australia Initiative.

The investigation is focused on numerous wetlands situated on Gnangara and Jandakot groundwater mounds, the most significant sources of groundwater for the Perth metropolitan area. The groundwater mounds also sustain numerous ecosystems that depend on shallow groundwater. Many of these ecosystems are currently stressed by land-use changes, increased groundwater abstraction and a shift to a drier climate, resulting in a general deterioration in their social, cultural and environmental values.

The formulation of the Perth shallow groundwater systems investigation arose from the outcomes of a management area review conducted in 2006 (McHugh & Bourke 2007). This review summarised the current monitoring and management issues facing selected wetlands on the Gnangara and Jandakot mounds, and identified the information and data required to address these issues. The report recommended an investigation program that incorporates up to 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 shallow groundwater systems 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 waterbodies and groundwater
- investigate the palaeoclimate 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 will aid the development of management strategies based on site-specific, scientific data that will promote the sustainable use of the groundwater resources of the Gnangara and Jandakot mounds.

Summary

The Lexia wetlands are included in the 28 sites in the Perth shallow groundwater system (SGS) investigation. In April 2008 the monitoring network was upgraded by installing two clusters of groundwater monitoring bores on the eastern and western sides of the wetlands.

The Lexia Wetlands are made up of three separate wetlands (Lexia 86, Lexia 94 and Lexia 186). A monitoring bore is located adjacent to each wetland. Groundwater levels have declined by 0.4 m at each wetland over the period of record (1994 to present). The monitoring bores at these wetlands are used for assessing compliance with set Ministerial criteria and ecological water requirements.

The monitoring data indicate that groundwater discharge occurs to Lexia 86 occasionally. At Lexia 94 and Lexia 186, groundwater levels are below the wetland basin of the wetlands all year round.

The regional decline in the watertable at Lexia Wetlands appears to have affected the chemistry of both groundwater and, when in continuity, wetland water. These changes are considered to be due to several hydrogeochemical processes predominantly influenced by the sulfidic content of the sediment in the upper lithology which has become oxidised following drawdown of the watertable. The main findings from this hydrogeochemical assessment include:

- The groundwater in continuity with the wetlands is acidic due to storage of acidity in the sediments
- Al^{3+} concentration in groundwater indicates a risk to the ecology of the wetlands from elevated concentrations of pH-dependent heavy metals
- When the wetlands hold water it is likely to be acidic and to have elevated metal concentrations
- Based on historical data only, the interaction between groundwater and surface water is demonstrated by the low pH at GNM 16SG and shallow groundwater
- In both sediment and water systems, it is possible that acidification is being exacerbated by the general low alkalinity.

Poor water quality is probably the most immediate threat to the system, with concentrations exceeding some ANZECC (2000) guidelines.

There has been a decline in the ecological condition of the Lexia Wetlands. This implies that the observed ‘step down’ in groundwater levels has been significant (see Section 5.4). Groundwater levels have become increasingly detached from the wetlands and surrounding vegetation. Recent ecological monitoring at the Lexia Wetlands indicates there has been an encroachment of vegetation into wetland basins, a reduction in species richness and a decline in vegetation health.

In order to improve the ecological condition of the Lexia Wetlands, water levels need to rise. Numerical modelling (SKM 2009) suggests this may occur in the Superficial

aquifer by 0.5–1.0 m over the next 20 years if the pine plantation to the north is cleared and abstraction for the public water supply is reduced.

Based on these findings, the following management recommendations are suggested:

- The department should continue to endorse the Forest Products Commission pine harvesting schedule
- Further analysis of the risks of acid sulfate soils across the Lexia Wetlands should be undertaken
- The revised ecological water requirements documented in Froend et al. (2004b) should be used as the basis for developing environmental water provisions (EWPs)
- Further testing of groundwater model scenarios should be undertaken to determine the changes needed to land and water use to meet the revised EWPs
- Depending on results from the modelling, reducing abstraction should be considered as a way to meet the EWPs
- Monitoring of groundwater, surface water and ecological condition at the Lexia Wetlands should continue.

Recommendations

All recommendations are subject to department priorities and the availability of resources.

Management actions

- The department should continue to endorse the Forest Products Commission pine harvesting schedule.
- The revised ecological water requirements documented in Froend et al. (2004b) should be used to assess as the basis for developing environmental water provisions.
- Monitoring of groundwater, surface water and ecological conditions at Lexia Wetlands should continue.

    - Implementation and responsibility: Department of Water to recognise in the next Gnangara water allocation plan.

Future monitoring

- Further testing of scenarios using groundwater models should be undertaken to determine the changes to land and water use needed to meet the revised environmental water provisions.
- Depending on results from the modelling, reducing abstraction should be considered as a way to meet the environmental water provisions.
- Further analysis of the risks of acid sulfate soils at the Lexia Wetlands should be undertaken.

    - Implementation and responsibility: Department of Water to review the monitoring program and document in a resource review report by 2015.

1 Context and objectives

The Lexia wetlands complex is a Conservation Category wetland (Hill et al. 1996) and a Ministerial criteria site (*Environmental Protection Act 1986*). In 1988, water level criteria were established at the wetlands to protect its good water quality, rich aquatic fauna and wading waterbird habitat (WAWA 1995). However, due to a combination of land use, abstraction and climate, water levels at the wetlands have declined. This, combined with fire, physical disturbances and invasion of exotic species has caused declines in ecological condition. The most notable ecological impacts have been terrestrialisation and reduced occurrence of surface water. The wetlands are also at risk of acidification due to declining water levels and the drying of the wetland basins.

As part of the management area review (MAR) of shallow groundwater systems on the Gnangara and Jandakot mounds (McHugh & Bourke 2007), the decline in water levels and ecological condition was considered severe enough at the Lexia Wetlands to warrant a local area hydrogeological investigation.

The management area review and the most recent *Review of Ministerial conditions on the Gnangara Mound* (DoW 2008) recommended that site-specific data be collected and analysed to determine the current groundwater–surface water connectivity, groundwater quality and groundwater flow into and out of the wetlands. It was also recommended that the investigation include the installation of a new shallow monitoring bore at the vegetation transects.

In line with these recommendations, the objectives of this study were to:

- upgrade the groundwater monitoring network
- improve the understanding of the geological and hydrogeological setting at the site
- describe water quality and potential for acid sulfate soils
- develop a conceptual model 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 the water management plan for the Gnangara Mound.

2 Background

2.1 Location and climate

The Lexia Wetlands are located approximately 25 km north-west of central Perth on the Swan Coastal Plain (Figure 1). The wetlands complex has a natural environment characterised by a series of seasonal wetlands that are known to be at threat due to regional groundwater level decline. The wetlands are located in an urbanised area comprising the agglomeration of Ellen Brook and The Vines, which represents an important development corridor as Perth expands along the Swan River.

The Swan Coastal Plain experiences a Mediterranean type climate with hot, dry summers and mild, wet winters. Rainfall occurs mainly between May and September. The Bureau of Meteorology (BoM) station Pearce RAAF (number 9053) is located 3 km away from the north-eastern corner of the Lexia Wetlands area at an elevation of 40 m above sea level. The site has been monitored since 1937. While the average annual rainfall for the period since this date is 703 mm, the average from 1975 to 2009 was only 654 mm (Figure 2). For the period 1997 to 2009 a drier than average annual total of 614 mm has been recorded, though in 2003 and 2005 annual rainfall exceeded the long-term average of 703 mm.

2.2 Geology and geomorphology

Regional geology and geomorphology

The Lexia Wetlands complex is located on the Swan Coastal Plain within the Perth Basin. The Swan Coastal Plain comprises a series of sedimentary units which are bound to the east by the Darling and Gingin scarps, and by the Indian Ocean to the west (Figure 1).

In the Perth region, the Superficial formations correspond to four geomorphic units which trend sub-parallel to the present day coast. The oldest is the Pinjarra Plain, which comprises alluvial fans abutting the Darling Scarp. Adjacent to the Pinjarra Plain are a series of dune systems. These dunes represent various shorelines which decrease in age from east to west (Figure 3). These units, in order of deposition, are the Bassendean Dunes, the Spearwood Dunes and the Quindalup Dunes. The latter are still forming and represent the present day coastline (Gozzard 2007). The Lexia Wetlands are located over the Bassendean Dunes unit.

Superficial formations is a collective term used to describe the late Tertiary to Quaternary age sediments which range in thickness from 20 to 100 m (Rockwater 2003). The formations include (in order of deposition) the Ascot Formation, Yoganup Formation, Guildford Clay, Gnangara Sand, Bassendean Sand, Tamala Limestone, Becher Sand and Safety Bay Sand (Davidson 1995). These formations consist of sand, silt, clay and limestone in varying proportions, and are the surficial material over most of the Swan Coastal Plain.

Figure 4 provides an east to west regional cross-section at the Lexia Wetlands showing of key formations.

The Lexia Wetlands lie on the eastern side of the Bassendean Sand deposits, limited to the east by the Guildford Clay unit. The Superficial formations are underlain by the Poison Hill Greensand and Kardinya Shale.

The Kardinya Shale separates the Mirrabooka Member and the deeper Leederville Formation. The Leederville Formation is separated from the Yarragadee Formation by the South Perth Shale.

The detailed stratigraphic sequence for the Perth Basin is provided in Table 1, which summarises the stratigraphy of the sedimentary basin that is believed to be in the order of 12 000 m thick.

More detailed descriptions of the geology of the Coastal Plain are provided by Davidson (1995) and Moncrieff and Tuckson (1989).

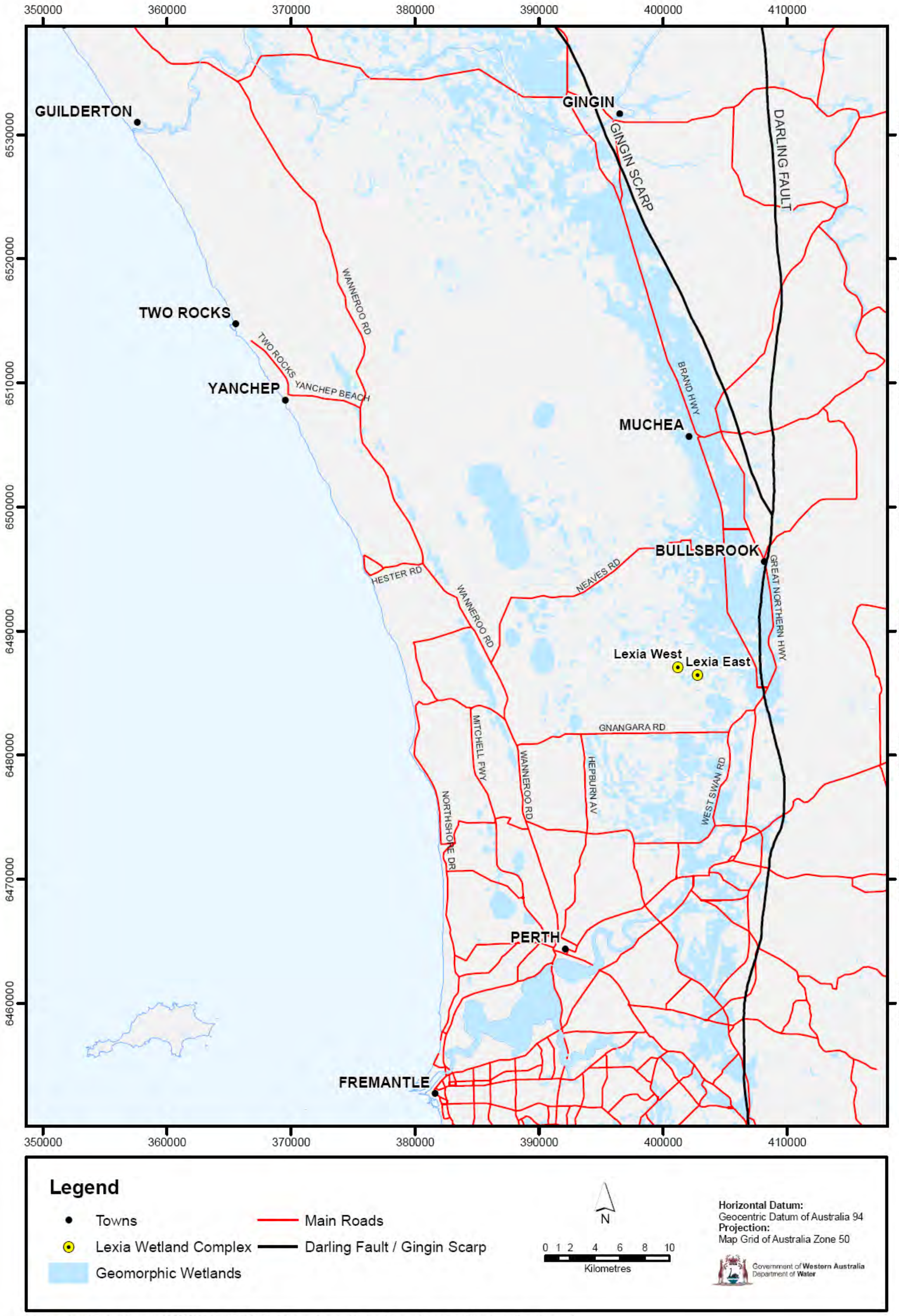

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Figure 1 Location of Lexia Wetlands

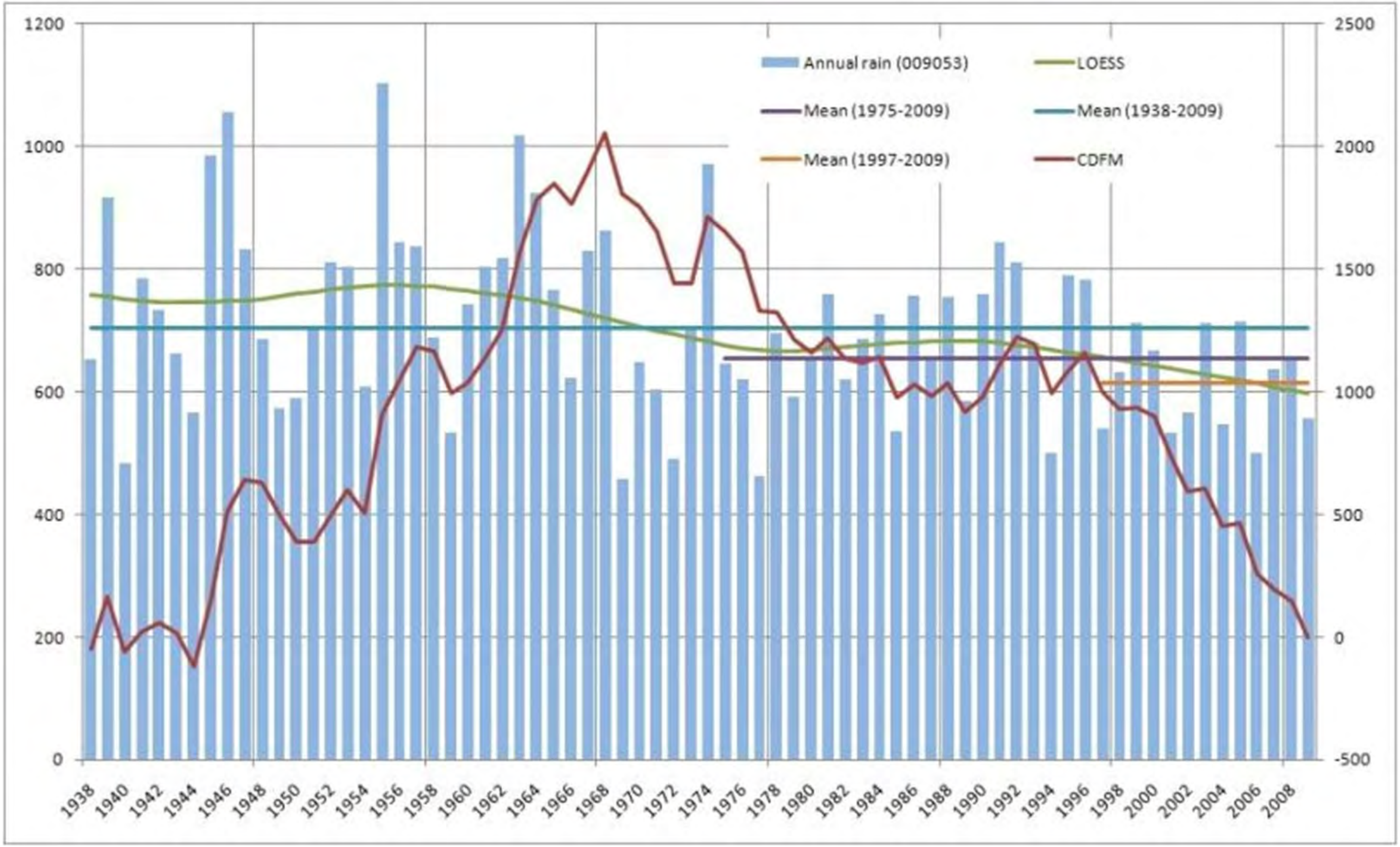

Figure 2 Annual rainfall data and trends (period 1938–2009) at BOM station no. 9053 (Pearce RAAF)

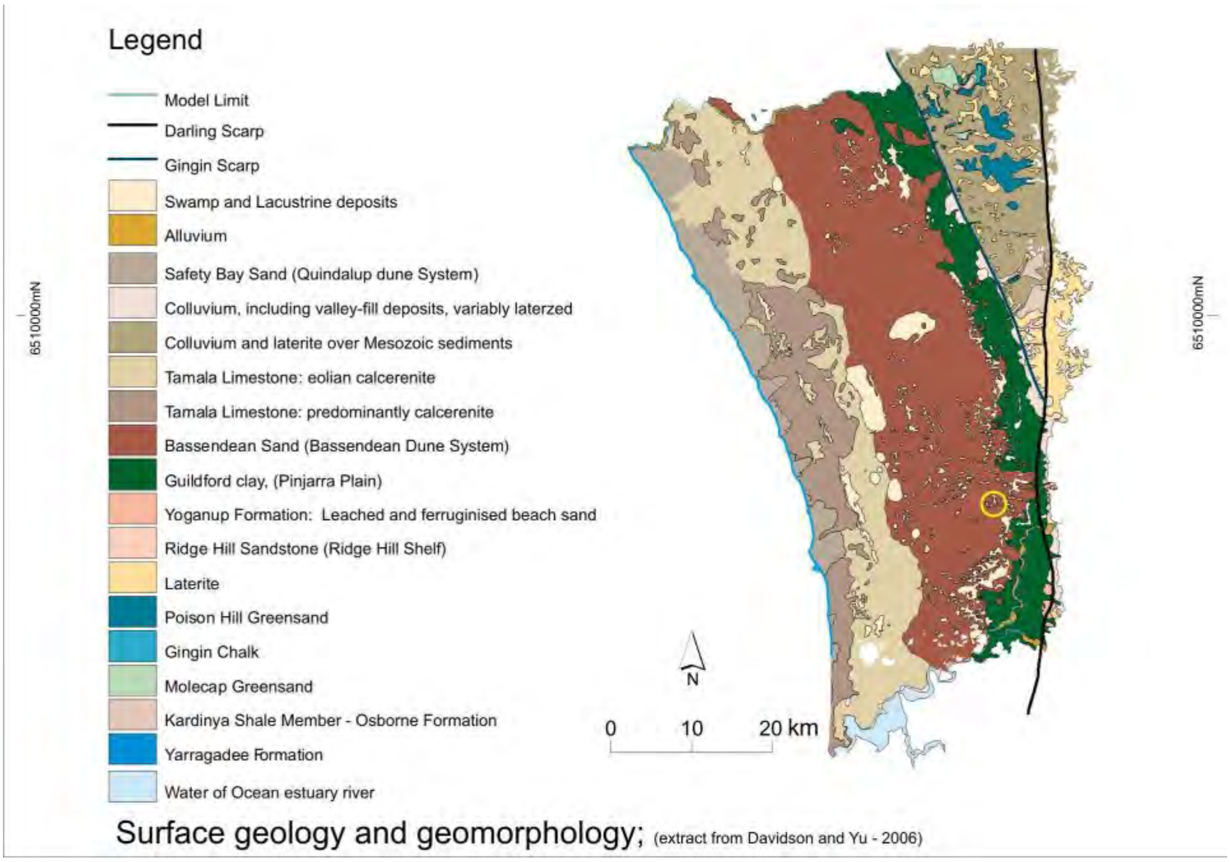

Figure 3 Regional geology around Lexia Wetlands

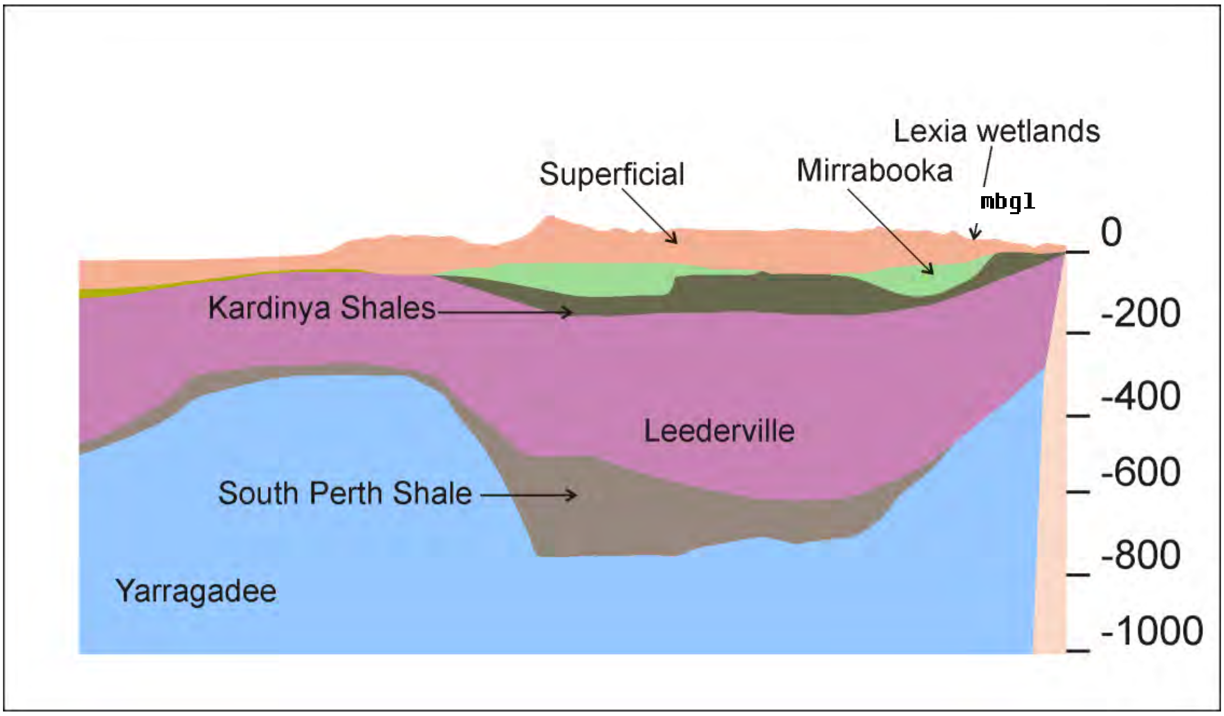

Figure 4 Regional geological cross-section

Table 1 Stratigraphic sequence of the Perth Basin (from Davidson 1995)

Era	Age	mya		Stratigraphy	Symbol	Max Thickness (m)	Lithology	Aquifer
Cainozoic	Quaternary - Late Tertiary		Superficial Formations	Safety Bay Sand	Qs	24	Sand and shelly fragments	Superficial aquifer
				Becher Sand	Qc	20	Sand, silt, clay and shell fragments	
				Tamala Limestone	Qt	110	Sand, limestone, minor clay	
				Bassendean sand	Qd	80	Sand and subordinate silt and clay	
				Gnangara Sand	Qn	30	Sand, gravel and subordinate silt and clay	
				Guildford Clay	Qg	35	Clay with subordinate sand and gravel	Local confining bed
		2		Yoganup Formation	Ty	10	Sand, silt, clay and pebbles	Superficial aquifer
		2		Ascot Formation	Ta	25	Limestone, sand, shells and clay	
		2		Rockingham Sand	Tr	110	Sand, silt and subordinate clay	Rockingham aquifer
	Early Tertiary	54		Kings Park Formation	Tk	530	Shale, calcareous and glauconitic siltstone, minor sand	Confining bed
				Mullaloo Sandstone Member	Tkm	200	Sand, clayey and glauconitic	Minor aquifers
				Como Sandstone Member	Tkc	57	Sand, minor clay	
Mesozoic	Cretaceous	80	Coolyena Group	Lancelin Formation	Kcl	120	Mudstone (marl), silty, clayey and glauconitic	Confining bed
				Poison Hill Greensand	Kcp	90	Sand, silty, clayey and glauconitic	Mirrabooka aquifer
		88		Gingin Chalk	Kcg	40	Chalk, sandy and glauconitic	Local confining bed
		98		Molecap Greensand	Kcm	80	Sand, clayey and glauconitic	Mirrabooka aquifer
		114		Osborne Formation	Kco	180	Sandstone, siltstone and shale	
				Mirrabooka Member	Kcom	160	Sandstone, siltstone and shale	
				Kardinya Shale Member	Kcok	140	Shale, siltstone, minor sandstone	Confining bed
				Henley Sandstone Member	Kcoh	100	Sand, silty, clayey and glauconitic	Leederville aquifer
		118	Warnbro Group	Leederville Formation	Kwl	600	Sandstone, siltstone and shale	
				Pinjar Member	Kwlp	150	Sandstone, siltstone and shale	
				Wanneroo Member	Kwlw	450	Sandstone, siltstone and shale	
				Mariginiup Member	Kwlm	250	Sandstone, siltstone and shale	
				South Perth Shale	Kws	300	Shale, siltsone, minor sandstone	Confining bed
				Gage Formation	Kwg	350	Sandstone, siltstone and shale	Yarragadee aquifer
	Cretaceous - Jurassic	140		Parmelia Formation	Kp	>287	Sandstone, siltstone and shale	
				Carnac Member	Kpc		Shale and siltstone	Local confining bed
				Otorowiri Member	Kpo		Shale and siltstone	
	Jurassic	146		Yarragadee Formation	Jy	>2000	Sandstone, siltstone and shale	Yarragadee aquifer
				Cattamarra Coal Measures	Jc	>500	Sandstone, siltstone and shale	

Acid sulfate soils

Due to regional watertable decline many of the wetlands on Gnangara Mound, including the Lexia wetlands, are progressively drying. The exposure of acid sulfate soils are a potential risk for environmental and groundwater degradation and require careful management.

Acid sulfate soils is a term used to describe soils or sediments that contain significant amounts of sulfide, which upon oxidation can generate sulfuric acid. During the last major sea level rise, rapid sedimentation led to the formation of new coastal landscapes. Bacteria in these waterlogged landscapes converted sulfate from seawater and iron present in the sediments to produce iron pyrite (FeS_2). When exposed to oxygen (for instance, due to the lowering of the watertable), this oxidises to sulfate, which is generated in the form of sulfuric acid and also releases iron and other associated metals into the soil and groundwater (Fältmarsch et al. 2008).

Acid sulfate soil can be either ‘potential’ or ‘actual’ acid sulfate soil:

- ‘Potential acid sulfate soils’ (PASS) are soils or sediments which contain sulfidic material that have not been oxidised (because they are below the watertable). The pH of these soils and sediments in their un-oxidised state is above pH 4. On contact with air the sulfide within potential acid sulfate soils will oxidise and generate sulfuric acid, and the pH of the soil or sediment will decrease to below pH 4
- ‘Actual acid sulfate soils’ are soils and sediments containing sulfidic material that has been oxidised and that has produced sulfuric acid, resulting in an existing pH of below pH 4 and often accompanied by a yellow and/or red mottling in the soil profile. Actual acid sulfate soils generally contain residual potential acidity (as sulfides) as well as existing (actual) acidity.

Acid sulfate soils are generally found in low lying areas within coastal plains and on the peripheries of waterbodies such as:

- flood plains
- river meanders
- oxbow lakes
- swamps
- morasses
- tidal flats.

The sulfuric acid produced by oxidation of iron sulfides affects both soil and water, and can significantly damage the environment. Most aquatic life needs a minimum pH of 6 to survive. The pH of drainage and waterbodies associated with acid sulfate soil can be as low as pH 2 and is often around pH 4. Massive fish kills can occur when sulfuric acid is washed into waterbodies. This particularly occurs following drawdown of the watertable and subsequent oxidation of the iron pyrite layer in the sediment (note that the rate of acid flux to a waterbody depends on several factors including the rate at which pyrite oxidises following exposure to oxygen). Drought breaking rains, a rebound of the water level or watertable and seiching[1] of exposed sediments by water from the waterbody can wash substantial quantities of acidity (and pH dependent metals) into waterbodies, resulting in significant detrimental effects to the ecosystem. In addition to acidification, there are a number of environmental risks associated with sulfidic materials:

- Elevated metal concentrations – oxidation of sulfidic materials can lead to significant increases in dissolved metal concentrations in surface water, including toxic species such as aluminium, iron and other metals that may be present in the soil (such as arsenic, lead, zinc, copper and cadmium). The increase in the solubility of metals under acidic conditions may be more harmful to biota than the low pH
- Water column de-oxygenation – when sediments rich in monosulfides are re-suspended they will rapidly oxidise, potentially removing most of the oxygen from the water column, leading to fish kills
- Noxious odours – foul odour problems have been encountered near areas of sulfide rich sediments after exposure, due to the production of hydrogen sulfide (‘rotten egg gas’).

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[1] Lateral ‘washing’ / leaching of soils by wind driven surface water

2.3 Hydrogeology

Regional hydrogeology

Groundwater occurs in the Superficial formations of the Swan Coastal Plain and in the deeper formations of the Perth Basin (Davidson 1995). There are six distinct aquifers separated by major confining layers (Davidson 1995). Four of these six aquifers are underlying the Lexia Wetlands – the Superficial, the Mirrabooka, the Leederville and the Yarragadee.

The Superficial and the underlying Mirrabooka aquifers are in direct hydraulic contact. The Kardinya Shale confining layer separates the Mirrabooka from the Leederville aquifer, which lies directly above the Yarragadee aquifer. The South Perth Shale which separates these two major aquifers is not present beneath the Lexia Wetlands.

This study focuses on the Superficial aquifer, which is a regional unconfined aquifer that occurs in the pore spaces between sediments of the Superficial formations. Table 2 outlines the physical and chemical properties of the Superficial aquifer taken from previous investigations.

The Superficial aquifer has hydraulic properties that can vary significantly depending on geology. The hydraulic conductivity of the Superficial aquifer can range from 0.1 m/day in the clayey sediments of the Guildford Clay in the east to 10–50 m/day, (average of 15 m/day) in the Bassendean and Safety Bay sands.

In the Lexia Wetlands area, the hydraulic conductivity of the Bassendean Sand is thought to range from 15 to 18 m/day.

Two substantial groundwater mounds are present – the Gnangara Mound to the north of Perth and the Jandakot Mound to the south (Figure 5). These groundwater mounds occur in areas where groundwater levels are elevated because the vertical infiltration of rainfall exceeds the ability of the aquifer to horizontally transmit water away from the recharge zone (Davidson 1995).

A series of permanent and seasonal lakes and wetlands currently occur where the watertable intersects the ground surface.

Lakes and wetlands

The groundwater system that operates within the Lexia Wetlands area is connected to the flow system associated with the Gnangara Mound. Most lakes and wetlands of the coastal plain are located where the watertable permanently or seasonally intersects the land surface. Surface water fluctuations are generally related to changes in groundwater levels. These lakes and wetlands are often in interdunal swales within the Spearwood Dunes and Bassendean Dunes, and at the contact between these geomorphic units. Townley et al. (1993) reported that most of the wetlands on the Swan Coastal Plain appear to act as flow-through lakes, which capture groundwater on the up-hydraulic gradient side and discharge lake water on the down-hydraulic gradient side. Rockwater (2003) found that wetlands on the Pinjarra Plain and Bassendean Dunes are also usually flow-through lakes and wetlands.

Table 2 Water quality of the Superficial aquifer

Parameter	**Range**		**Reference**
	low	**high**	
Ec	< 25 mS/m only near crest of mound	> 100 mS/m near the coast	PUWBS 1987
TDS	140 mg/L (only near crest of the mounds)	550 mg/L near coast	PUWBS 1987
	130 mg/L	12 000 mg/L but rarely exceeds 1000mg/L	Davidson 1995
pH	4.5–6.5 away from coast	6.5–7.5 in Limestone	PUWBS 1987
	4	8	Davidson 1995
Hardness ($CaCO_3$ mg/L)	< 50 mg/L (Bassendean Sand)	500 mg/L (Tamala Limestone) >1000mg/L (coast)	
Eh	No limit	> 0.3 V	PUWBS 1987
NO_3^-	Mostly within drinking water limits	29 mg/L	PUWBS 1987
	0	> 60 mg/L	Davidson 1995
PO_4^{3-}	0	> 0.1 mg/L	PUWBS 1987
	0	0.1 mg/L occasionally 0.2 mg/L	Davidson 1995
SO_4^{2-}	0	200 mg/L	PUWBS 1987
		100 mg/L	Davidson 1995
SO_4:Cl		> 1	PUWBS 1987
	0.05	0.1	Davidson 1995
Fe (total dissolved)	Generally 1–5 mg/L	> 5mg/L	PUWBS 1987
	< 1mg/L	> 50 mg/L	Davidson 1995
TOC	1 mg/L	> 50 mg/L	PUWBS 1987
Temperature	19 °C	23 °C	PUWBS 1987
Pesticides	All below potable limits		PUWBS 1987
Cd, Cr, Cu, Pb		Only localised elevated concentrations. No values.	PUWBS 1987

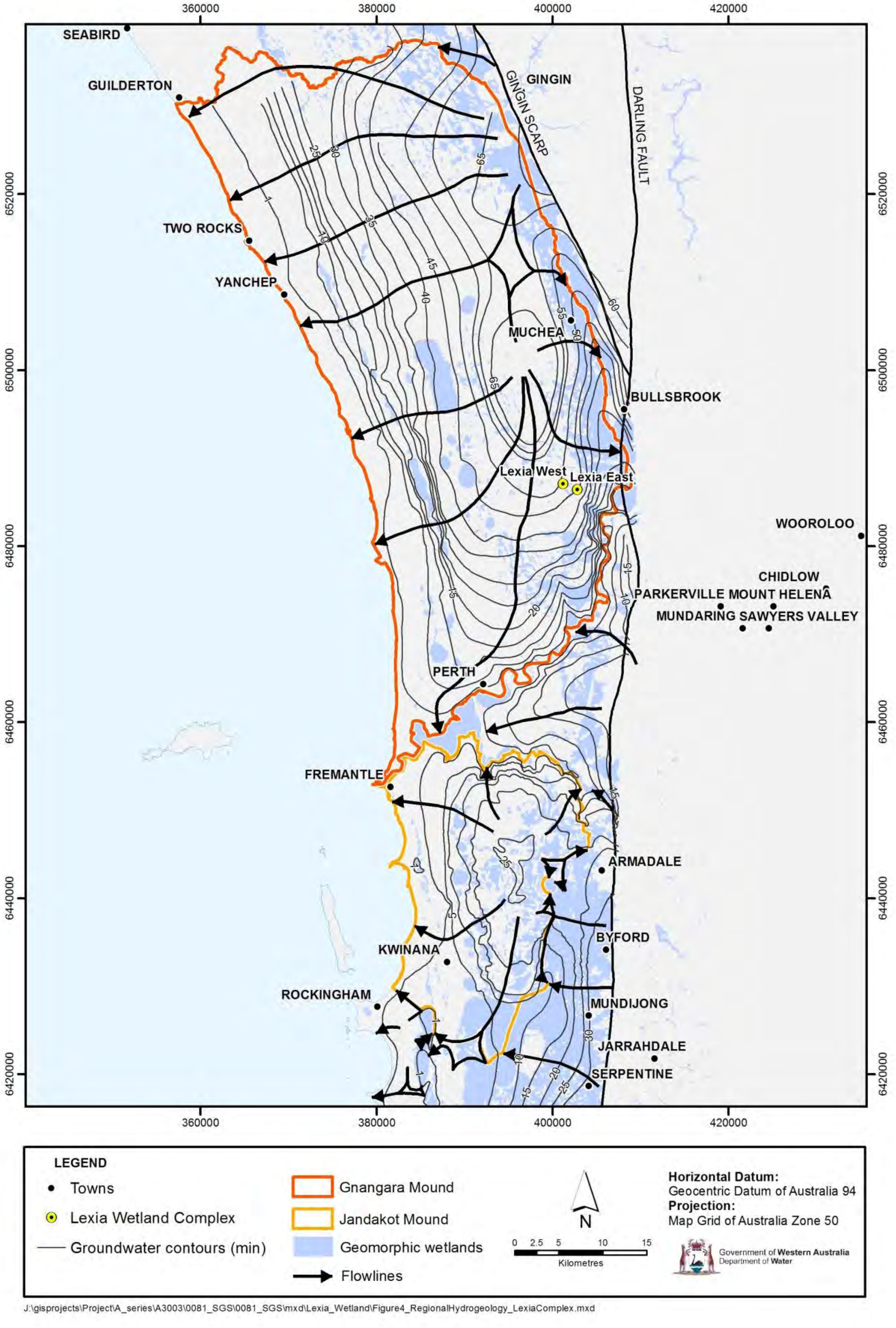

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Figure 5 Regional groundwater elevation contours and inferred flow directions

2.4 Previous studies

Allen (1975) outlined the extent and nature of the large groundwater resources in the Gnangara Mound based on the results of the drilling of 249 exploratory and production bores between 1962 and 1972.

Davidson (1995) presented a detailed summary of the state of knowledge of the hydrogeology and groundwater resources of the Perth region. This report was based on drilling in the region undertaken since 1961. It 'delineates the hydrogeological boundaries and quantifies the groundwater resources of the region'. In doing this Davidson estimated sustainable yields for both the unconfined (Superficial) and confined aquifers of the Perth region.

Recently, Davidson and Yu (2008) presented a discussion on the geology and hydrogeology of the Perth region, as part of the reporting series on studies done with the Perth regional aquifer modelling system (PRAMS). The report expanded and updated Davidson's earlier work by covering a greater area and presenting estimates of hydraulic properties for 23 geologic units. This study also presented a detailed account of historical groundwater use and trends, and estimated rainfall recharge to the Superficial aquifer. The report provided a conceptual model, which was the basis for the PRAMS groundwater model.

There have been a number of studies commissioned by the Department of Environment and Conservation relating to the nature of the shallow groundwater and interactions with lakes and wetlands. These studies were conducted in response to the serious degradation that had occurred to the wetlands of the Swan Coastal Plain since settlement, and the recognition of the need to develop strategies and management techniques for the protection of wetland biodiversity. As a part of this work, Townley et al. (1993) presented a study of the interaction between lakes, wetlands and unconfined aquifers. The report had three specific objectives – the identification of groundwater capture zones, management of water levels and the development of effective parameters for groundwater models.

Yesertener (2008) undertook an analysis of trends in groundwater levels across the coastal plain and correlated trends with changes in rainfall, abstraction and land use. This study found a strong correlation between declining groundwater levels and decreasing rainfall, increasing groundwater abstraction and increased areas of pine plantations. Increases in groundwater levels were found to correlate with clearance of land for pine plantations, bushfires and thinning of pine plantations.

There have been few investigations of the Lexia Wetlands specifically, other than Rockwater (2003) who provided an initial conceptualisation of surface water–groundwater interaction at the site. Since that time there have been a number of ecological investigations to help define ecological water requirements (Froend et al. 2004b) and to monitor changes in ecological condition (e.g. Cullinane et al. 2009).

Recent local-scale numerical modelling undertaken for the Gnangara Sustainability Strategy (GSS) suggests that land-use change due to pine clearance and reduction of abstraction for the public water supply has the potential to increase water levels in the Superficial aquifer by 0.5 to 0.1 m over the next 20 years as shown in Figure 6. This figure has been taken from SKM (2009). The scenarios mentioned are:

- Base case – assume current climatic condition and reduction in groundwater abstraction by 3.5 GL (135 GL) and a progressive replacement of pine plantation by grass land
- Sc1 – assume an 11% drier climate
- Sc2 – assume immediate removal of pine plantation
- Sc3 – assume a progressive replacement of pine plantation by native vegetation (50%) and grass land (50%)
- Sc4 – assume current groundwater abstraction (138.5 GL).

On the hydrographs, some scenario outputs are hidden by those of other scenarios.

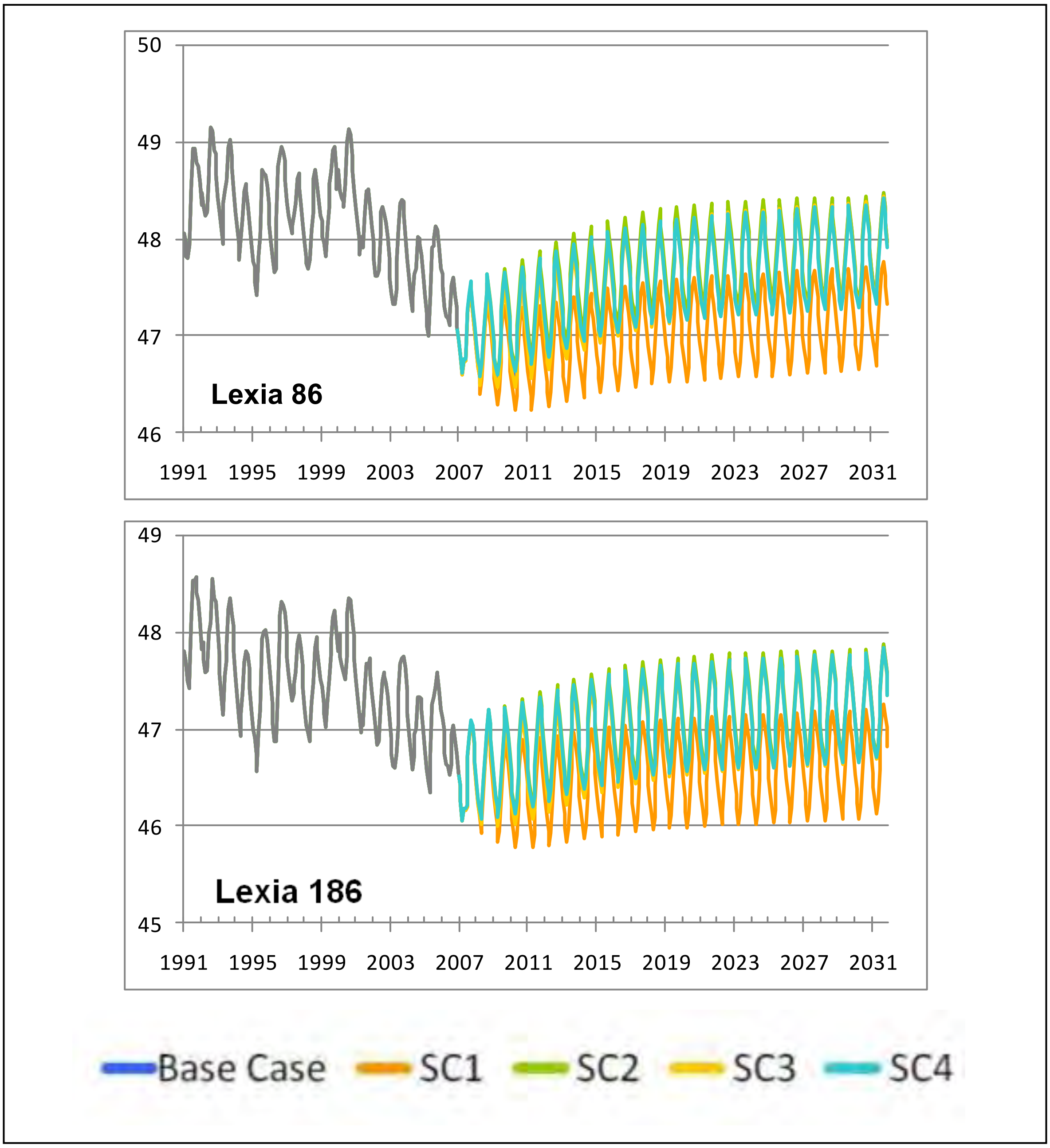


Figure 6 Numerical groundwater model prediction for various scenarios

2.5 Ecological value

Compliance with Ministerial criteria

The Lexia Wetlands are considered to have a very high conservation value. They support diverse fringing and wetland vegetation, invertebrate and vertebrate communities, and provide a range of habitat types (Froend et al. 2004b).

Ministerial criteria water levels have been set to assist in the protection of the ecological values at Lexia Wetlands.

Criteria have been set for three separate wetlands (Lexia 86, Lexia 94 and Lexia 186, Figure 7). These criteria levels were set to conserve ecological values and to protect current vegetation assemblages in and around the wetlands (DoW 2007).

Wetland vegetation monitoring has been carried out at Lexia Wetlands from 1996 to present with a monitoring transect located at each wetland (Cullinane et al. 2009; Wilson et al. 2010).

At Lexia 86, the Ministerial criteria indicate that water levels should not fall below 47.3 m AHD (preferred minimum) and 47.0 m AHD (absolute minimum) at a frequency of more than two occasions in six years (as measured at bore GNM16) with the absolute summer minimum criteria being 47.0 m AHD.

The monitoring data from Lexia 86 (presented in Figure 8) shows that groundwater levels have declined steadily by about 0.4 m in total since 1994, most likely in response to declining rainfall (Figure 2). Declining groundwater levels could also be attributed to abstraction from the Superficial and evapotranspiration from vegetation including nearby pine plantations (Yesertener 2008). Groundwater levels have generally remained above the Ministerial criteria levels, although the seasonal minimum in 2009 reached the preferred minimum criteria and the trend suggests that groundwater levels will fall below the criteria levels in the coming years.

Froend et al. (2004b) noted that the decline in groundwater levels at Lexia 86 coincided with a decline in ecological condition including a decline in health, occurrence of patch deaths and encroachment of fringing vegetation into the basin. They also noted an increase in the period that Lexia 86 remained dry.

Cullinane et al. (2009) noted that the distribution of wetland species has remained unchanged from a previous (2001) assessment, but a decline in species richness across all four plots has occurred at Lexia 86. The overstorey is dominated by *M. preissiana*. Mean tree health followed a decreasing trend between 1997 and 2007, but an improvement was noted in 2008 (Cullinane et al. 2009). Later work by Wilson et al. (2010) concluded that tree health had undergone a decline again during 2009.

At Lexia 94, groundwater should not fall below levels of between 45.8 m AHD and 45.5 m AHD at a frequency of more than two occasions in six years, with the absolute summer minimum criteria being 45.5 m AHD at bore GNM17A. No staff gauge is located at this site.

Since 1993, seasonal minimum groundwater levels have fallen below the preferred minimum criteria on 10 occasions in the 18 years of monitoring, which does not meet the requirements set by the Ministerial criteria of two in six (Figure 9).

Froend et al. (2004b) noted declining ecological condition at this site with loss of health in fringing vegetation and thinning of wetland shrubs and emergent macrophytes.

There has been no change to the distribution of wetland species at Lexia 94 since 2001, while the species richness has showed a notable decline across all four plots (Cullinane et al. 2009). Mean tree health rating along the transect was at its lowest in 2002 (poor rating) but has since improved with most trees having a 'good' health rating. Wilson et al. (2010) concluded that mean health ratings for vegetation at Lexia 94 had either remained the same or had undergone a decline during 2009.

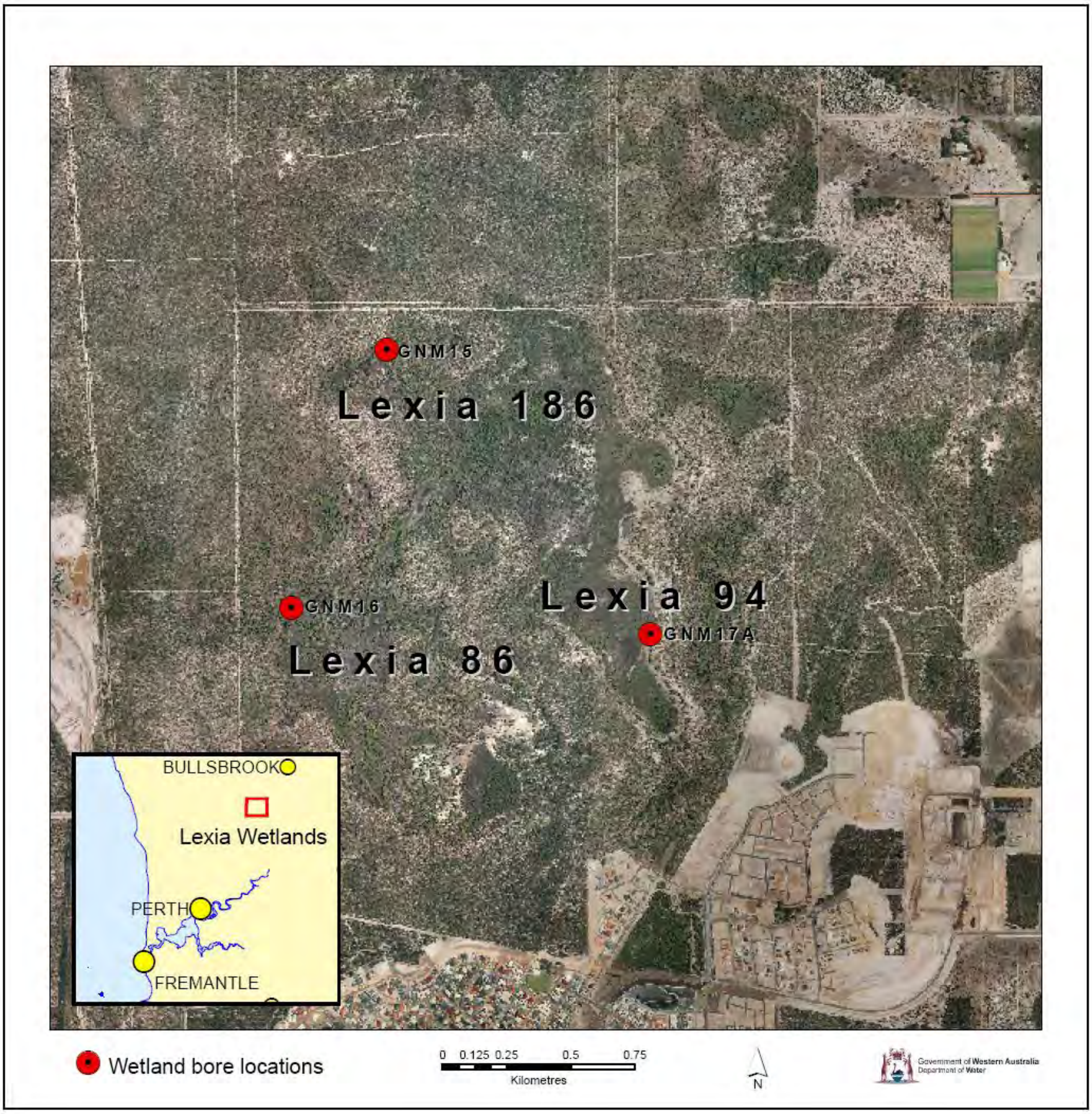
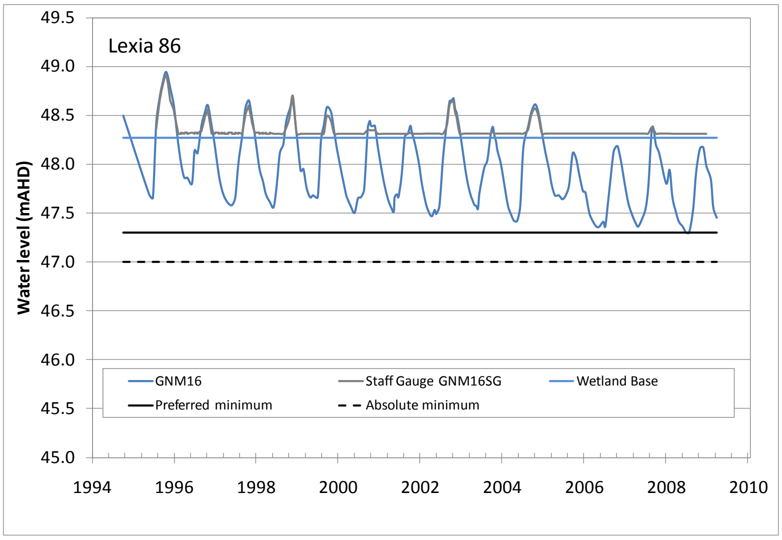
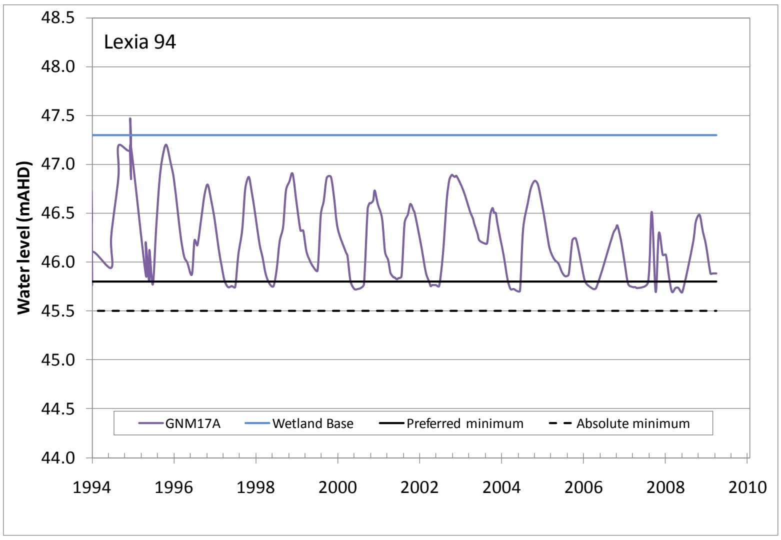


Figure 7 Location of Lexia Wetlands basins and Ministerial criteria compliance bores





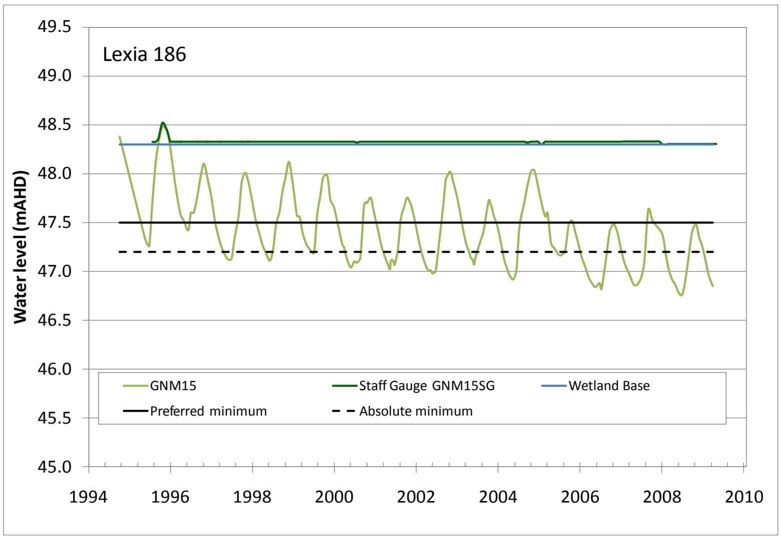


Figure 8 Hydrographs showing current Ministerial criteria and base elevation of the wetlands

At Lexia 186, groundwater levels should not fall below 47.5 m AHD and 47.2 m AHD at a frequency of more than two occasions in six years, with the absolute summer minimum criteria being 47.2 m AHD at bore GNM15. Since 1994 groundwater levels have consistently fallen below the preferred and absolute minimum criteria.

Froend et al. (2004a) noted declining ecological condition at this site with loss of health in fringing vegetation and encroachment of fringing tree species.

At Lexia 186, no change in the distribution of wetland species has occurred since the previous 2007 assessment. Unlike the situation at Lexia 86 and Lexia 94, species richness has increased at all four plots along the transect (Cullinane et al. 2009). Similarly to Lexia 94, mean tree health ratings fell to their lowest in 2002. Mean tree health has since improved at Lexia 186 with ratings of ‘good’ to ‘very good’ (Cullinane et al. 2009).

Compliance with revised ecological water requirements

In 2004, the ecological values for Lexia Wetlands were re-assessed and new ecological water requirements (EWRs) were proposed (Froend et al. 2004a and b). These EWRs have not been adopted as Ministerial criteria, but are used by the Department of Water to assess the possible impact of changes to groundwater levels on ecological values.

Froend et al. (2004b) proposed EWRs to support macroinvertebrates, invertebrates, sediment processes and groundwater-dependent vegetation (Table 3). Ecological monitoring at the Lexia Wetlands since 2004 has indicated that ecological condition has declined further (R Froend, ECU, pers. comm.).

Table 3 Revised EWRs (from Froend et al. 2004b)

Location	Revised ecological management objectives	Associated monitoring bore	Macro invertebrates maximum level m AHD	Vertebrates maximum level m AHD	Vegetation minimum level m AHD	Sediment processes minimum level m AHD
Lexia 86	Supports diverse fringing and wetland vegetation. Supports significant macro invertebrate and vertebrate communities.	GNM16	48.5 for two months each year	48.64	47.09	47.8

Location	Revised ecological management objectives	Associated monitoring bore	Macro invertebrates maximum level m AHD	Vertebrates maximum level m AHD	Vegetation minimum level m AHD	Sediment processes minimum level m AHD
Lexia 94	Supports diverse fringing and wetland vegetation. Fringing vegetation supports a range of habitat types.	GNM17A		47.28 for four months	44.28	
Lexia 186	Fringing vegetation supports a range of habitat types.	GNM15		48.02	47.71	47.8

Source: Froend et al. 2004b

At Lexia 86 (GNM16) peak groundwater levels have fallen below the EWR for macroinvertebrates and vertebrates since 2002 (Figure 9). Minimum groundwater levels have been below the EWR for sediment processes over most of the monitoring record. To maintain these processes, the sediments must remain saturated throughout the summer of each year (Froend et al. 2004b). The minimum groundwater levels are currently above the EWR for vegetation.

A decline in mean tree health and in species richness has been observed at Lexia 86 which correlates with the declining watertable. The current minimum groundwater levels are unprecedented in the monitoring record and are likely to have further impacts on ecological health. Groundwater level peaks need to increase by more than 0.5 m to prevent further degradation of sediment processes and habitat for vertebrates. Of significant concern is the loss of surface water habitat for aquatic fauna and flora during recent years. Current groundwater levels are likely to be adequate to maintain fringing vegetation, but at reduced vigour.

At Lexia 94 (GNM17A), the EWRs have been set for vertebrates and vegetation. The requirement for vertebrates has been set at the base of the wetland. No surface water has been present since 1995 but frogs are still found in the area though surface water is required by frogs for breeding (Froend et al. 2004b). The groundwater levels are above the requirement for wetland vegetation.

A reduced seasonal amplitude in groundwater levels at Lexia 94 means that peak water levels need to increase by 1.0 to 2.0 m to restore the health of the habitat for vertebrates. While the distribution of wetland vegetation has not been greatly affected, an overall decline in the number of species has been observed at Lexia 94. Mean tree health was at its lowest in 2002,which corresponds to the low watertable at that time (~46.5 m AHD). During 2003, the watertable reached a peak of ~46.9 m AHD which coincided with an the improvement in tree health along the transect. This has continued up until 2009.

At Lexia 186 (GNM15), minimum groundwater levels have fallen below the minimum EWR for vegetation and sediment processes. Groundwater has also been below the required level for vertebrates since 2005. The EWR for vertebrates is set to maintain inundation of the wetlands (generally for four months per year) to allow breeding to take place (Froend et al. 2004b).

There has been increased dryness of sediments at Lexia 186 (creating a greater risk of bushfire or peat fire), lost wetland plant species and reduced cover since 2004 (Culliane et al. 2009 and earlier ECU monitoring reports). As with Lexia 94, mean tree health was also at it lowest in 2002 and has since followed a trend of gradual improvement. The watertable at Lexia 186 has fallen below the absolute minimum Ministerial criteria since 1997.

In summary, the groundwater monitoring record indicates that the groundwater requirements of ecological systems at Lexia Wetlands are generally not being met, and that further adverse effects on the ecological value could be expected based on current trends.

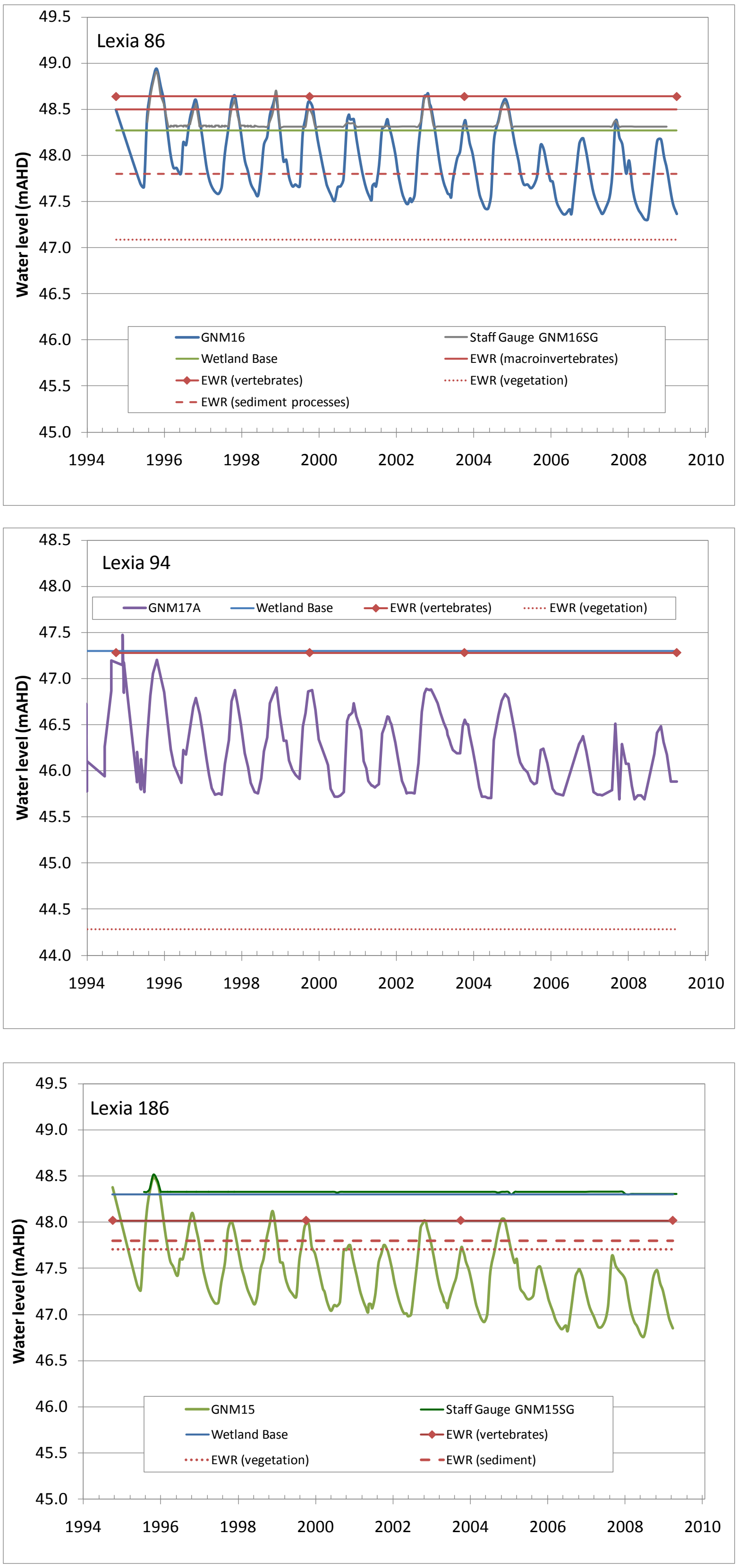


Figure 9 Hydrographs showing revised Froend et al. (2004b) EWRs and base elevation of the wetland basins

2.6 Cultural significance

Wetlands across the Swan Coastal Plain are spiritually significant to Indigenous groups, and were used extensively in traditional times (Wright 2007). Many lakes and swamps were used as hunting and gathering areas for flora and fauna (Estill 2005). Much of the native vegetation within the Gnangara Mound depends on groundwater and many wetlands provide important social and recreational values to both Indigenous and non-Indigenous people (Estill 2005).

In line with the *Aboriginal Heritage Act 1972* and the *Native Title Act 1993,* the Department of Water contracted two anthropologists and two traditional owners to undertake an ethnographic survey of the Lexia Wetlands region prior to the start of drilling works. The objectives of the survey were to determine the Indigenous heritage values of the wetland area and then to conduct archaeological and ethnographic surveys as required.

The Lexia Wetlands complex is not a registered Aboriginal heritage site (Estill 2005). Archaeological sites are unlikely to be located in low-lying, poorly drained or seasonally inundated areas, the latter being relevant to this site (Estill 2005).

No archaeological Aboriginal sites or isolated artefacts were identified during the survey at Lexia Wetlands (Eureka 2008). Previous studies indicate Aboriginal archaeological sites are typically associated with such wetlands. It is considered very unlikely that Aboriginal people would not have used areas adjacent to wetlands at some time and so there is still potential for archaeological material to be uncovered as a result of further ground disturbance (Eureka 2008).

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

2.7 Land and water management

The *Gnangara groundwater areas allocation plan* (DoW 2009a) sets out the approach for the allocation and licensing of all water users on the Gnangara Mound. The Department of Water determines the volume and spatial distribution of water extracted from the Mound by assessing proximity to groundwater-dependent ecosystems, ecological condition and rate and magnitude of groundwater level change. For allocation purposes the Gnangara Mound is divided into groundwater areas and subareas. Lexia Wetlands are located in the Swan proclaimed groundwater area, the Swan Confined groundwater subarea (confined) and the North Swan subarea (Superficial) (Figure 10).

The allocation limit for the Superficial aquifer in the North Swan subarea is 2.0 GL/yr (DoW 2009a). As, the subarea is over-allocated, no further licenses are being issued and unused entitlements are being recouped.

Water use in the area is linked to the dominant land use. Lexia Wetlands is surrounded by dryland agricultural land used for cropping purposes. Immediately to the west of the wetlands, the area is managed for resource protection and forestry.

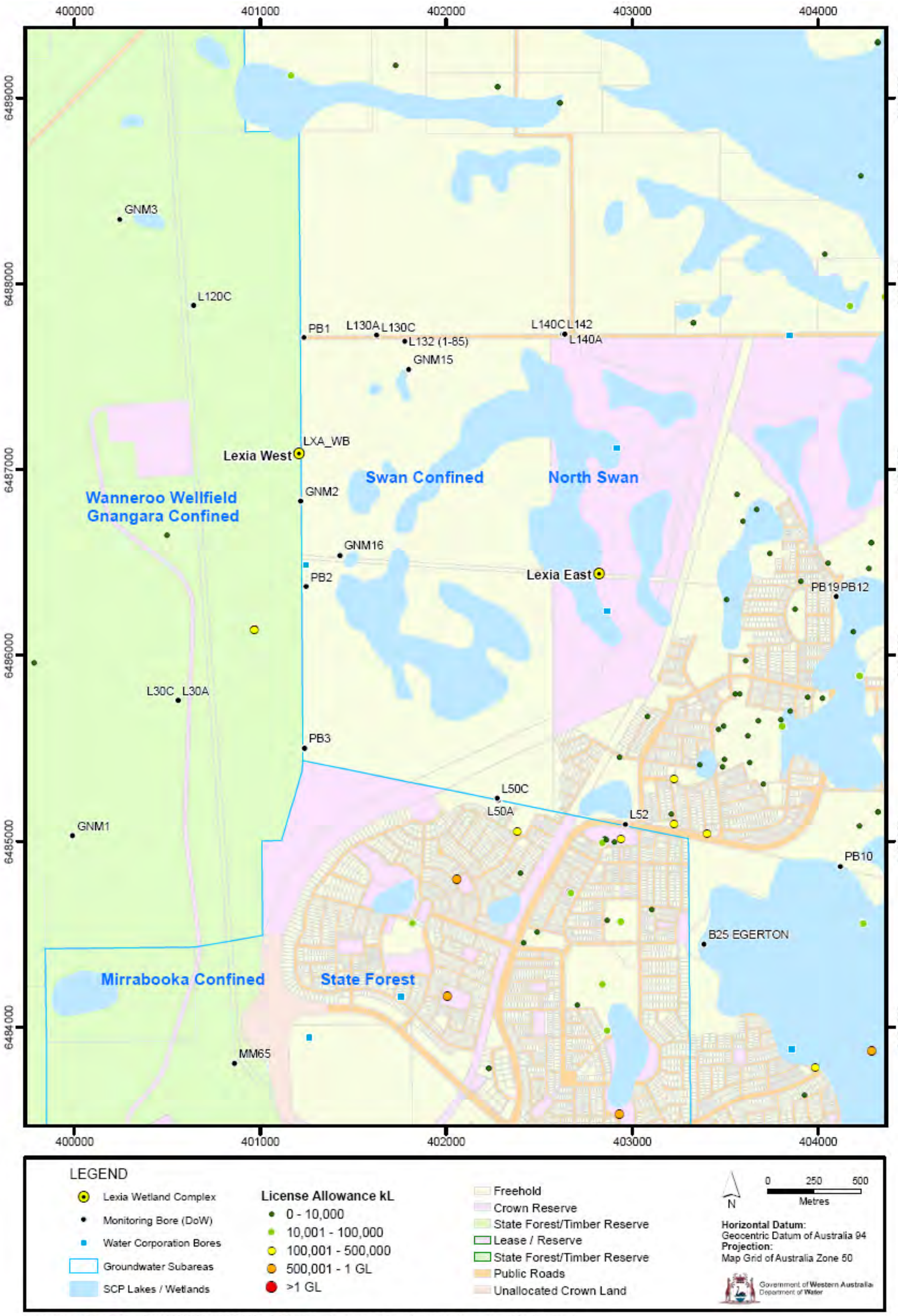


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Figure 10 Water allocation and land use around Lexia Wetlands

3 Investigation program

3.1 Background

The management area review of McHugh and Bourke (2007) highlighted the need for site-specific information about wetland function to appropriately manage the Lexia Wetlands and the shallow groundwater systems of the Gnangara and Jandakot mounds.

The management area review recommended that the shallow groundwater systems investigation construct new monitoring bores, and undertake water chemistry sampling and water level measurements at the Lexia Wetlands. Investigations of acid sulfate soils were also carried out.

3.2 Bore construction

Groundwater monitoring bores were installed in clusters of three: shallow (slotted interval at the watertable), intermediate (slotted interval approximately half way through the Superficial aquifer) and deep (slotted interval at the base of the Superficial aquifer). The clusters were positioned on the eastern and western side of the wetlands (Figure 11) so that both horizontal and vertical groundwater flow could be inferred. Lithological and construction details are provided in Appendix A, and DoW (2009b).

Table 4 provides general details of groundwater monitoring bores used for this investigation.

Table 4 SGS monitoring bore details

Depth	Wetland	AWRC name	AWRC number	Drilled depth m BNS	Slotted interval m BNS	Depth to groundwater July 2009 m BNS	Groundwater elevation July 2009 m AHD
Shallow	Lexia 94	LXA_Ec	61611849	6.9	0.9–6.9	2.25	48.69
Intermediate	Lexia 94	LXA_Eb	61611855	24.14	22.14–24.14	2.34	45.65
Deep	Lexia 94	LXA_Ea	61611854	51.0	38.58–40.58	4.59	43.37
Shallow	West of Lexia 86 and 186	LXA_Wc	61611848	8.0	0.8–6.8	4.23	48.31
Intermediate	West of Lexia 86 and 186	LXA_Wb	61611857	29.16	27.16–29.16	4.49	48.0
Deep	West of Lexia 86 and 186	LXA_Wa	61611856	72.0	49.05–51.05	5.27	47.22

Notes: AWRC – Australian Water Resources Council. m BNS – metres below natural surface

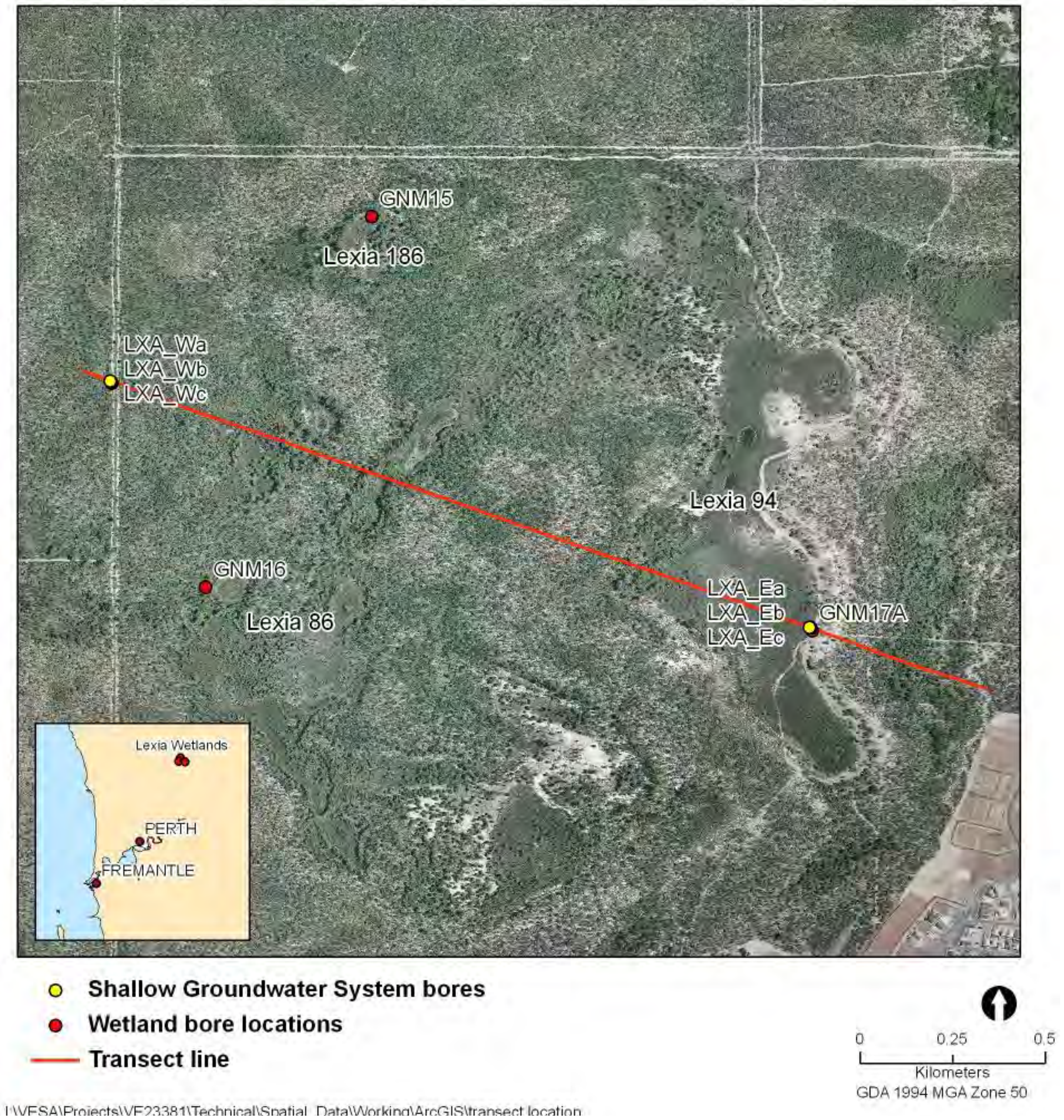


Figure 11 Location of SGS monitoring bores and wetland bore locations

3.3 Acid sulfate soils testing

To determine the distribution and characteristics of sulfidic sediments in and around the Lexia Wetlands, and the potential for these sulfidic sediments to affect groundwater quality, samples were collected from the two shallowest SGS bores within the clusters at the western and eastern extent of the wetlands (LXA_Wc and LXA_Ec). The testing and its results are discussed in Section 4.2.

3.4 Water monitoring and sampling program

Groundwater sampling and analysis was undertaken to determine the hydrochemical characteristics at both the eastern and western sites, along with the distribution and availability of pollutants and the interaction between the wetlands and the Superficial aquifer.

The sampling regime comprised sampling for both water levels and water quality for the period between June 2008 and July 2009, for the six groundwater monitoring wells. Water samples were collected using low-flow pumping methods as outlined in Appendix C. Analyses of water samples were conducted for major cations and anions, metals, and selected pesticides.

Table 5 shows the analytes tested for during the SGS investigation.

Table 5 Laboratory water analysis

Metals (soluble)	Ca, Al, B, Fe, K, Mg, Na
Metals (total)	As, Cd, Cr, Mn, Hg, Ni, Se, Zn
Other	Acidity, alkalinity, Cl, SO_4, pH, pesticides

3.5 Data accuracy and precision

There is a degree of uncertainty with measured chemical parameters, and as such results from laboratory chemical analysis are not absolute. This uncertainty is caused by several contributing error sources, mainly precision errors and accuracy errors. Precision, or statistical, errors result from random fluctuations in the analytical procedure. Accuracy, or systematic, errors reflect faulty procedures or interference during analysis. An electrical balance, also known as an ionic balance, can be used to check the accuracy of analytical results. The sum of positive and negative charges in the water should be equal (Appelo & Postma 2007), so the sum of the cations in solution should equal the sum of the anions:

$$\text{electrical balance \%} = \frac{\text{sum cations + sum anions}}{\text{sum cations - sum anions}} \times 100$$

where ions are expressed as milliequivalents per litre (meq/L).

Deviations of more than 6% indicate that sampling and analytical procedures should be examined (Appelo & Postma 2007).

The ionic balance for all six groundwater samples collected as part of the Lexia study were assessed and are reported in Table 6.

The electrical balance assessment indicates that the majority of the groundwater samples display an adequate accuracy, with the exception of sample Lexia_Wa, which has a high relative percentage difference in terms of electrical balance, but is still within the required 6% limit.

Table 6 Average ionic balance of groundwater samples at Lexia Wetlands

Sample	**Average ionic balance %**
Lexia_Ea	1.0
Lexia_Eb	2.5
Lexia_Ec	1.9
Lexia_Wa	-5.2
Lexia_Wb	-1.5
Lexia_Wc	2.9

Another technique for assessing groundwater sample accuracy is to compare the calculated and measured electrical conductivity (Appelo & Postma 2007), where at 25 ^{o}C, the electrical conductivity divided by 100 will in most cases provide a good estimate of the sum of anions or cations (in meq/L):

$\sum$ anions = $\sum$ cations ≈ Ec/100 (µS/cm)

The majority of the samples display a relatively adequate agreement between the sum of cations (as meq/L) and adjusted Ec, with notably Lexia_Wa displaying one of the better agreements (Table 7).

Overall, it is considered that the data is suitable for assessment purposes.

Table 7 Comparison of sum of cations and electrical conductivity

Sample	**Ec µS/cm**	**Ec/100**	**Sum of cations meq/L**
Lexia_Ea	490	4.9	4.0
Lexia_Eb	560	5.6	4.8
Lexia_Ec	740	7.4	6.3
Lexia_Wa	190	1.9	1.6
Lexia_Wb	280	2.8	2.4
Lexia_Wc	390	3.9	3.1

4 Geology

4.1 Local geology and aquifer setting

The local geology has been characterised using data from the SGS drilling program, which is presented schematically in the cross-section provided in Figure 12. Water levels shown were recorded on 18 April 2008 (east cluster) and on 19 April 2008 (west cluster).Lithological logs were available for other non-SGS bores around the Lexia Wetlands but none of these intersected the chosen transect location.

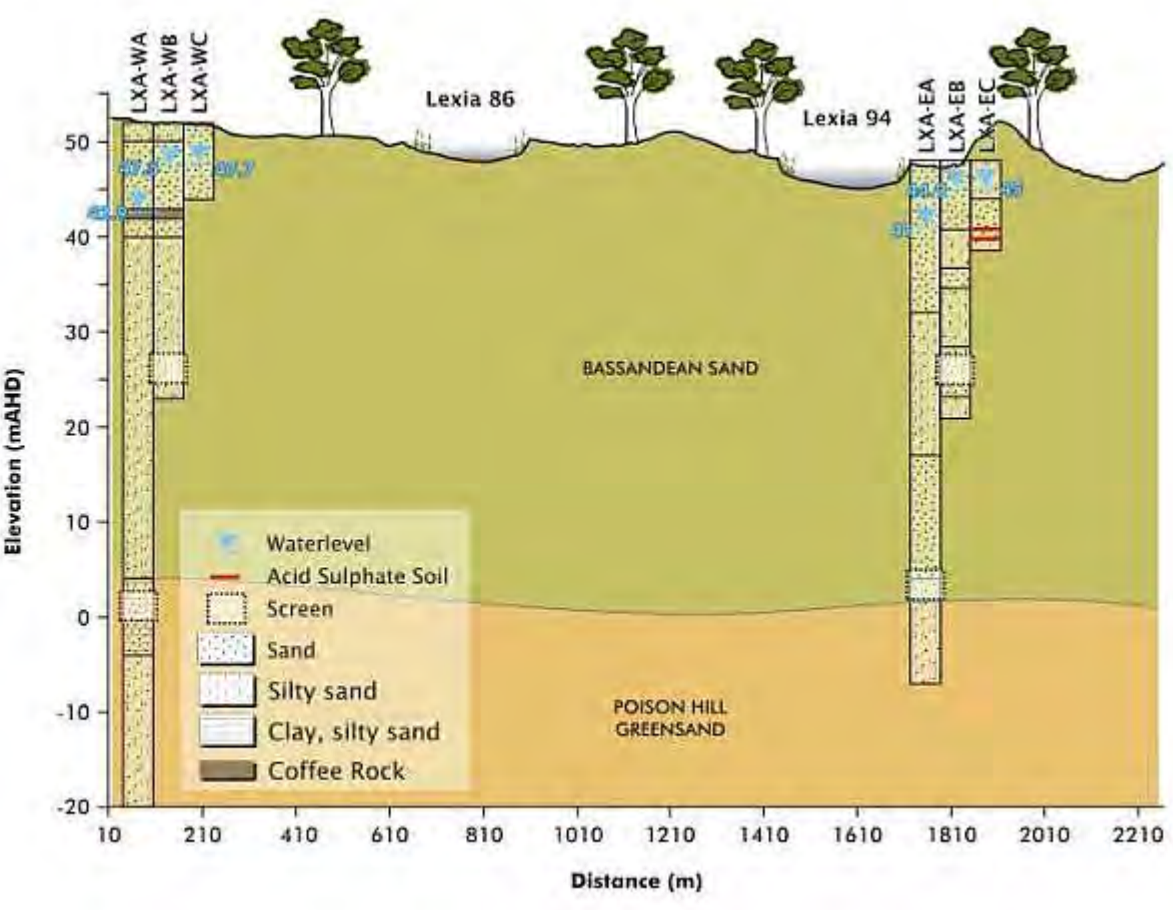


Figure 12 Cross-section using SGS stage 2 investigation data

On the western side of the wetlands the Bassendean Sand unit, which forms the Superficial aquifer, is logged to be approximately 48 m thick. This unit contains a 12 m thick layer of sand overlaying 36 m of clayey sand. The Bassendean Sand lies directly over a 4 m thick layer of silty sand and clay belonging to the Poison Hill Greensand unit. There is a layer of silty sand belonging to the Poison Hill unit from 52 to 72 m.

On the eastern side of the wetlands there is 44 m of Bassendean Sand overlying the silty sand of the Poison Hill Greensand. The Bassendean Sand contains a 16 m thick layer of sand lying over a 14 m thick layer of sand and silty sand, with another 14 m layer of better sorted sand.

The Poison Hill Greensand unit encountered at this site is part of the Mirrabooka aquifer which confirms the direct connection between the Superficial and Mirrabooka aquifers at the Lexia Wetlands location.

Based on the conceptualisation by Davidson (1995) it can be assumed that the Mirrabooka aquifer has a thickness of about 100 m at this site. The Kardinya Shale separates the Mirrabooka aquifer from the underlying Leederville aquifer.

4.2 Acid sulfate soils

Soil or sediment samples were collected from the two shallowest SGS bores within the clusters at the western and eastern extent of the wetlands (LXA_Wc and LXA_Ec). At both sites, samples were collected at intervals of every 30 to 50 cm, to a depth of 7 m, and analysed in the field for pH and oxidised pH (peroxide).

Following field analysis, a total of seven soil or sediment samples were submitted for laboratory analysis of the sulfide content in order to determine acid sulfate soil status. Sediment samples were placed in plastic bags, as much air expelled as possible, and frozen until delivery to the laboratory. Samples were taken to the laboratory either the same day as extracted from the ground, or the following day. The CRS (chromium reducible sulfur) and the SPOCAS (suspension peroxide oxidation combined acidity and sulfur) analytical suites were used to determine the sulfide content and to conduct acid-base accounting (see Appendix C for laboratory methods). The analytical results are reported and discussed below and listed in Appendix D.

The pH_F and pH_{FOX} for both the eastern and western shallow bores are presented in Table 8 and Table 9. The field analysis indicates that the oxidation reactions and decrease in pH following oxidation (i.e. difference between pH and pH_{FOX}) are more vigorous in the Lexia East location, with only marginal changes in pH following oxidation observed in Lexia West. This trend is presented in vertical depth pH profiles (Figure 13) which demonstrate the greater pH change in Lexia East throughout the profile compared to that of Lexia West.

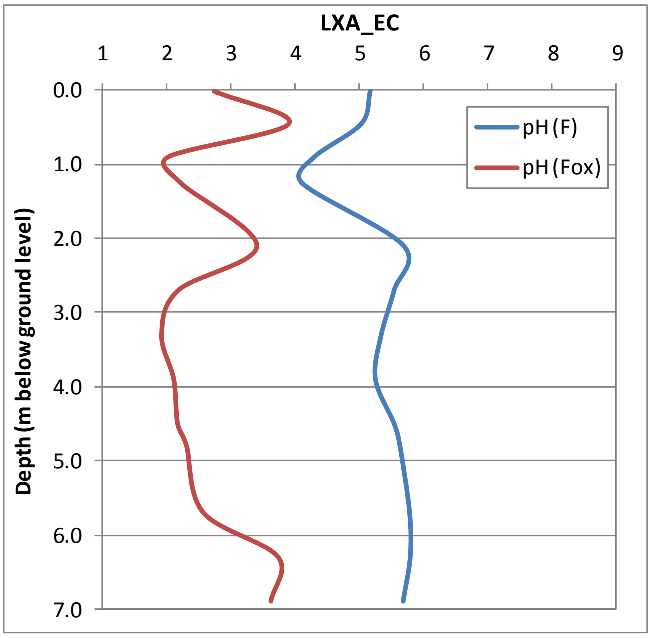
Table 8 pH_F and pH_{FOX} for Lexia East bore LXA_Ec

			Field pH	
Depth m	**Soil texture**	**pH_F**	**PH_{FOX}**	**Δ pH**
0.0	Grey OM, roots, M Qtz, dry	5.16	2.74	-2.42
0.5	M Qtz, some roots, M Qtz, dry	5.02	3.91	-1.11
0.9	Dark Grey, M Qtz, moist	4.29	2.02	-2.27
1.3	As above	4.10	2.22	-1.88
2.1	Grey, F Qtz, moist	5.68	3.41	-2.27

			Field pH	
Depth m	**Soil texture**	**pH_F**	**PH_{FOX}**	**Δ pH**
2.7	As above	5.53	2.18	-3.35
3.3	Light grey / brown, F Qtz, moist	5.33	1.92	-3.41
3.9	As above	5.24	2.11	-3.13
4.5	Brown, F Qtz	5.53	2.17	-3.36
4.8		5.62	2.31	-3.31
5.7		5.77	2.57	-3.20
6.3		5.78	3.74	-2.04
6.9		5.67	3.63	-2.04

Table 9 pH_F and pH_{FOX} for Lexia West bore LXA_Wc

	Soil texture		Field pH	
Depth m		**pH_F**	**PH_{FOX}**	**Δ pH**
0.2	Grey M to C Qtz sand	4.49	3.56	-0.93
0.5	As above	4.45	3.57	-0.88
0.8	As above	4.63	3.57	-1.06
1.2	As above	4.45	3.47	-0.98
1.5	As above	4.35	3.62	-0.73
1.9	As above, slight moist	4.26	3.44	-0.82
2.3	As above, slight moist	4.21	3.77	-0.44
2.6	As above, slight moist	3.95	3.88	-0.07
2.9	Light grey, M to C Qtz sand	4.48	4.33	-0.15
3.2	As above	4.41	4.45	0.04
3.5	As above	4.48	4.68	0.20
4.0	As above	4.64	4.72	0.08
4.5	As above	4.78	4.78	0.00
5.0	Light brown grey M to C Qtz sand	6.46	4.77	-1.69
5.5	As above	6.66	4.88	-1.78
6.0	White M Qtz sand, sulfur odour	6.5	5.07	-1.43
6.5	As above	6.54	5.13	-1.41



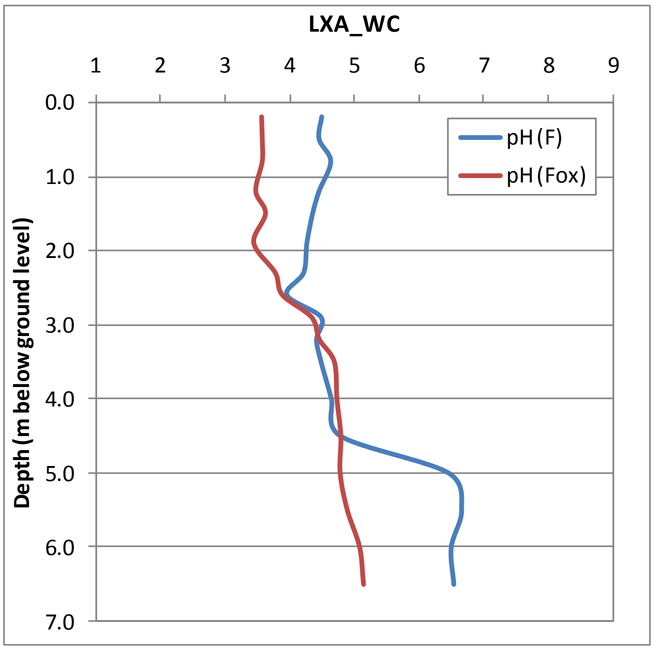


Figure 13 Field pH measurements at LXA_Ec and LXA_Wc)

The laboratory analytical program for the acid sulfate soils assessment was based on the outcomes of the field pH test results which indicated the possible presence of acid sulfate soil materials predominantly in the east. The selected soil samples were submitted to the laboratory for analysis of:

- pH
- KCl
- chromium reducible sulfur

- total actual acidity
- sulfidic acidity
- net acidity.

The submitted samples were as follows:

- Lexia East LXA_Ec – 0.9 m bns, 3.2 m, 4.5 m bns and 5.7 m bns
- Lexia West LXA_Wc – 1.9 m bns, 2.6 m bns, 3.5 m bns.

The DEC (2009) guideline values (Table 10) were used to determine the presence of potential acid sulfate soils.

Table 10 DEC acid sulfate soil guideline criteria

Soil or sediment texture	**Criteria**	
	Sulfur trail % oxidisable sulfur (oven dry basis)	**Acid trail mol H^+/t (oven dry basis)**
Sands to loamy sands	0.03	18
Sandy loams to light clays	0.06	36
Medium to heavy clays and silty clays	0.1	67

The clay content of soil influences the amount of sulfuric acid generated after disturbance. Soils with high clay content generally have a higher natural pH buffering capacity and can neutralise more acid than soils with low clay content. Therefore the amount of oxidisable sulfur in the soil that may need to be managed varies with the clay content of the soil.

The soil samples analysed generally comprised sands, and silty sands (refer to Appendix A), therefore the ‘sands to loamy sands’ criteria, being the most conservative, were chosen as appropriate for all sample assessment.

Soils were initially assessed against the sulfur trail criteria. However, this criteria generally only indicates the amount of oxidisable sulfur in the sample (i.e. the amount of sulfur that may be oxidised and thus acid generating) and does not account for other relevant parameters (actual acidity and acid neutralising capacity) which may influence the soils acidity. Therefore acid-base accounting (ABA) was undertaken using the laboratory results to determine the net acidity, based on actual and potential (oxidisable sulfur) acidity and acid neutralising capacity. Subsequently, the net acidity approach provides a basis for calculating the requirement (and potential quantity) for liming to neutralise acid soils.

Soil analytical results are presented in Table 11.

Table 11 Laboratory analysis of soil samples

				Lexia East LXA_Ec				**Lexia West LXA_Wc**		
			Sample number	24498731	24498730	24498729	24498728	24499079	24499080	24499081
			Depth m	0.8–1.0	3.1–3.3	4.4–4.6	5.5–5.7	1.8–2.0	2.5–2.7	3.4–3.6
			Sample type	Primary	Primary	Primary	Primary	Primary	Primary	Primary
Analyte	**Units**	**Acid sulfate guidelines**	**Limit of reporting**							
pH (lab)	pH		0.1	4.3	5.33	5.53	5.77	4.26	3.95	4.48
SPOCAS										
ph_{FOX}	pH		0.1	2.02	1.92	2.17	2.6	3.44	3.88	4.68
pH_{KCl}	pH		0.1	4.5	4.6	4.9	4.9	3.9	4	5.3
Titratable actual acidity	% pyrite S		2.0	4.0	1.0	1.0	2.0	7.0	4.0	1.0
Titratable potential acidity	% pyrite S		0.02	1	2	6	6	3	1	1
Titratable sulfuric acidity	% pyrite S			1	2	5	4	1	1	1
Chromium reducible sulfur	% S	0.03	0.01	< 0.01	< 0.01	0.2*	0.2*	< 0.01	< 0.01	< 0.01
Acidic chromium reducible sulfur	mole H^+/t	18	10							
$S_{(pos)}$				< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01

**Sample exceeds DEC (2009) acid sulfate soil guidelines*

Chromium suite

A summary of the chromium suite analysis undertaken on the soil samples, including an assessment of pH_{KCl}, chromium reducible sulfur and total actual acidity, is presented in Table 11 and discussed below.

Chromium reducible sulfur

Chromium reducible sulfur analysis provides an assessment of inorganic sulfur which is not subject to significant interferences from sulfur either in organic matter or sulfate minerals.

Chromium reducible sulfur (%S) was reported to be below the DEC (2009) guideline criteria for acid sulfate soil material (sandy soil) of 0.03% S in all seven samples with the exception of:

- Lexia East depth profile 4 4.0–4.6 m bns (0.20% S)
- Lexia East depth profile 5 5.0–5.7 m bns (0.20% S).

The remaining samples reported chromium reducible sulfur below laboratory limits of reporting (LOR 0.01% S).

Actual acidity

Total actual acidity is the soil's existing acidity prior to oxidation of sulfidic material. Reported pH_{KCl} ranged from 3.9 (LXA_Wc 1.8–2.0 m bns) to 5.3 (LXA_Wc 3.4–3.6 m bns) indicating that this strata does not have significant acid neutralising components. It is desirable to maintain the pH level of the material above 6.5 (Ahern et al 1998).

Titratable actual acidity was reported above the laboratory limit of reporting (2.0 mole H+/t) for each soil sample tested (maximum concentration of 7% S equivalent).

Potential acidity

Titratable sulfidic acidity is a measure of potential acidity and was reported above the laboratory limit of reporting (0.02% S) for each soil sample tested. The highest level was reported in the two samples which also reported elevated chromium reducible sulfur.

Net acidity

Net acidity is determined from the chromium reducible sulfur methods (Ahern et al. 2004). Samples are analysed such that net acidity can be calculated, according to an acid-base account, expressed by the following equation:

Net acidity = Potential acidity + existing acidity – acid neutralising capacity

where acid neutralising capacity is a measure of a soil's inherent ability to buffer acidity and resist the lowering of the soil pH. It is calculated by the laboratory for the purposes of calculating net acidity, which provides a determination of the actual acidity likely to be generated once the soil's neutralising capacity has been expended. The use of net acidity also allows easier onward calculation of required quantities of neutralising agent (e.g. lime) that would be required to adequately neutralise an acid soil.

The reported pH_{KCl} values indicate that the soils and sediments have a poor acid neutralising capacity. Where pH_{KCl} is below 6.5, acid neutralising capacity is not generally reported.

In order to provide a general overview of likely net acidity[2] in sediments sampled from the bores, the actual (i.e. existing) acidity[3] has been plotted for each depth profile (Figure 14).

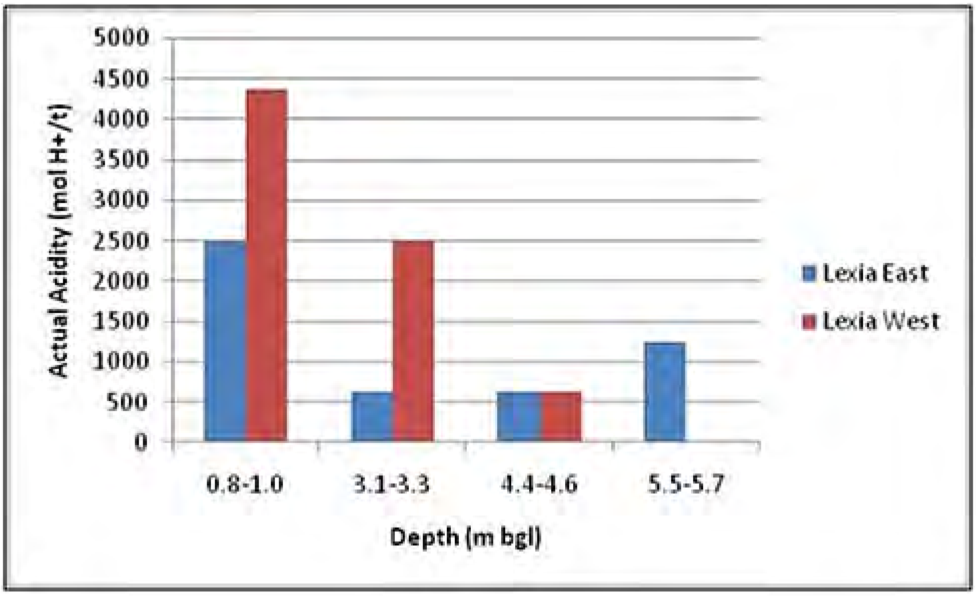


Figure 14 Actual acidity as indicator of net acidity

The distribution of actual acidity is notably weighted towards the shallow sediments, in the zone where elevated sulfide content is reported.

Summary of the analysis for acid sulfate soils

In summary, the analytical results indicate that there is a zone of acid soil located in the eastern bore (Lexia _Ec) at a depth of approximately 4.4 through to 5.7 m bns. The low actual acidity at this location indicates that the soil is a potential acid sulfate soil rather than an actual acid sulfate soil. It has not yet been oxidised and therefore there is a risk of increased or further generation of acidity should this strata be exposed, for instance by lowering of the groundwater level.

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[2] Net acidity is not calculated here as the actual acidity demonstrates a clearer picture of the current existing acidity in the sediment.

[3] Calculated by multiplying the % S pyrite result by 623.7, as per stoichiometry of sulfuric acid generation.

Based on the results of the field pH tests and the laboratory analytical results, it would appear that the eastern bore has intersected a layer of sulfidic material, the lateral extent of which is unknown. This layer may generate additional subsurface acidity following exposure such as that caused by watertable draw down.

The samples submitted for acid sulfate soil analysis were also analysed for nine heavy metals (see Table 12). The results for this analysis indicate that iron (Fe) and aluminium (Al) are the major metals. Note that the Al results are elevated in the two Lexia East samples which reported elevated chromium reducible sulfur (4.4–4.6 m bns and 5.5–5.7 m–bns). Aluminium is relatively insoluble above pH 4.5 (it is present as gibbsite generally) but increasingly soluble below pH 4.5.

This indicates that a notable concentration of aluminium could become geochemically mobile if the sediment became oxidised and the pH decreased to below pH 4.5.

Table 12 Metals and metalloids in soils

		Lexia East (LXA_Ec)				**Lexia West (LXA_Wc)**		
		Depth m bns				**Depth m bns**		
Analyte	**Unit**	0.8–1.0	3.1–3.3	4.4–4.6	5.5–5.7	1.8–2.0	2.5–2.7	3.4–3.6
Al	mg/kg	270	70	1490	1190	12	7.6	3.9
As	mg/kg	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Cd	mg/kg	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Cr	mg/kg	1.0	0.5	1.3	3.0	0.5	0.5	0.5
Fe	mg/kg	120	82	290	250	23	16	11
Mn	mg/kg	0.5	0.6	0.88	1.1	0.5	0.5	0.5
Ni	mg/kg	0.5	0.5	0.61	0.61	0.5	0.5	0.5
Se	mg/kg	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Zn	mg/kg	0.5	0.5	0.88	0.54	1.9	0.84	0.65

5 Hydrogeology

5.1 Groundwater occurrence at the Lexia Wetlands

The SGS investigation drilling program encountered groundwater within the Bassendean Sands at shallow depths ranging from 2.37 to 4.20 m bns (Figure 12) and within the deeper parts of the Bassendean Sands and Poison Hill Greensand ranging from 4.77 to 9.07 m bns.

Since construction in April 2008, the SGS wells have been monitored monthly. Hydrographs for each cluster of bores are provided in Figure 15.

The groundwater level in the shallow bore (Lexia_Wc) is about 0.4 m above the groundwater level of the intermediate bore (Lexia_Wb). The groundwater level in the deeper bore (Lexia_Wa) is about 0.8 m lower. An initial reading recorded at more than 4 m lower in April 2008 is probably an artefact due to the bore being completed in more clayey material and therefore needing longer to recover following drilling.

The groundwater levels measured in the shallow and intermediate bores in the eastern cluster are similar to each other, and the groundwater level in the deeper bores is about 2 m lower. This indicates a significant downward groundwater gradient within the Superficial aquifer at this site – most likely caused by variability in the hydraulic properties of the shallow aquifer (e.g. occurrence of silty sand beds). The downward gradient is also likely to be controlled by lower heads encountered in the Mirrabooka aquifer in this area.

5.2 Groundwater flow

The shallow groundwater data collected during the SGS investigation (LXA_Ec and LXA_Wc) was used with data from the regional groundwater monitoring program to construct groundwater elevation contours at the subregional scale for March 2009, when groundwater levels were at or near a minimum level (Figure 16), and September 2009, when groundwater levels were at or near a maximum level (Figure 17).

The groundwater elevation contours for March 2009 imply that groundwater flows in a south-easterly direction. The groundwater elevation gradient is flatter hydraulically up gradient of the Lexia Wetlands, which may indicate the presence of higher permeability strata in this region. The groundwater elevation gradient steepens to the south-east of the wetlands. The slight deflection of the 45 m AHD contour in the vicinity of the Lexia Wetlands may indicate additional recharge in this area.

The groundwater elevation contours for September 2009 imply a similar groundwater flow pattern. A comparison between the March and September 2009 contours indicates that the seasonal change in groundwater levels is not significant at Lexia within the subregional context.

The local-scale horizontal and vertical groundwater flow characteristics can be inferred from the SGS groundwater level data presented on the hydrogeological cross-section in Figure 12. The data indicate that shallow groundwater levels are approximately 2.5 m higher on the western side of the wetlands than on the eastern side.

There is a downward groundwater gradient between the Superficial and Mirrabooka aquifers, which is maintained throughout the year, on both the western and eastern sides of the wetlands.

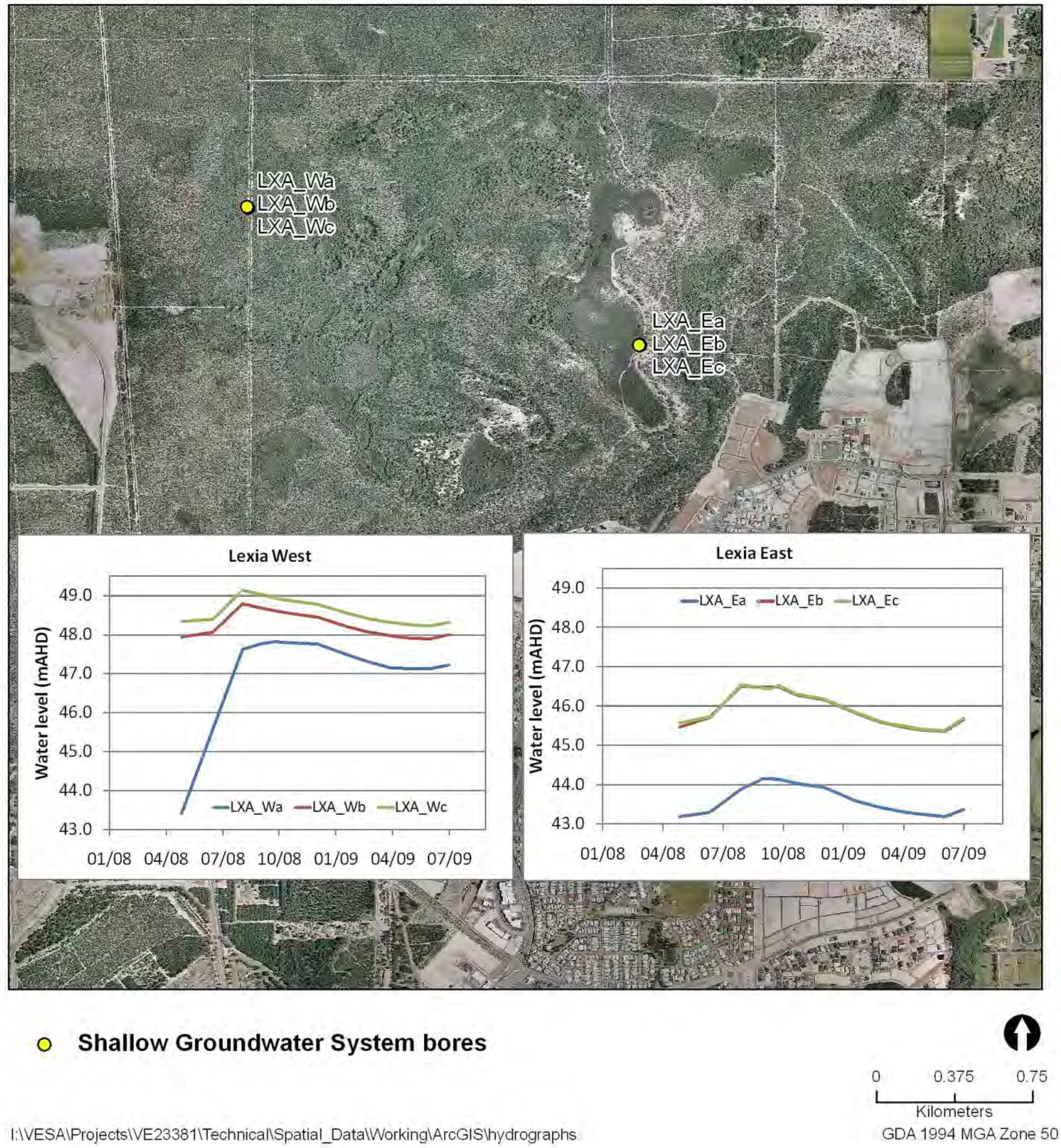
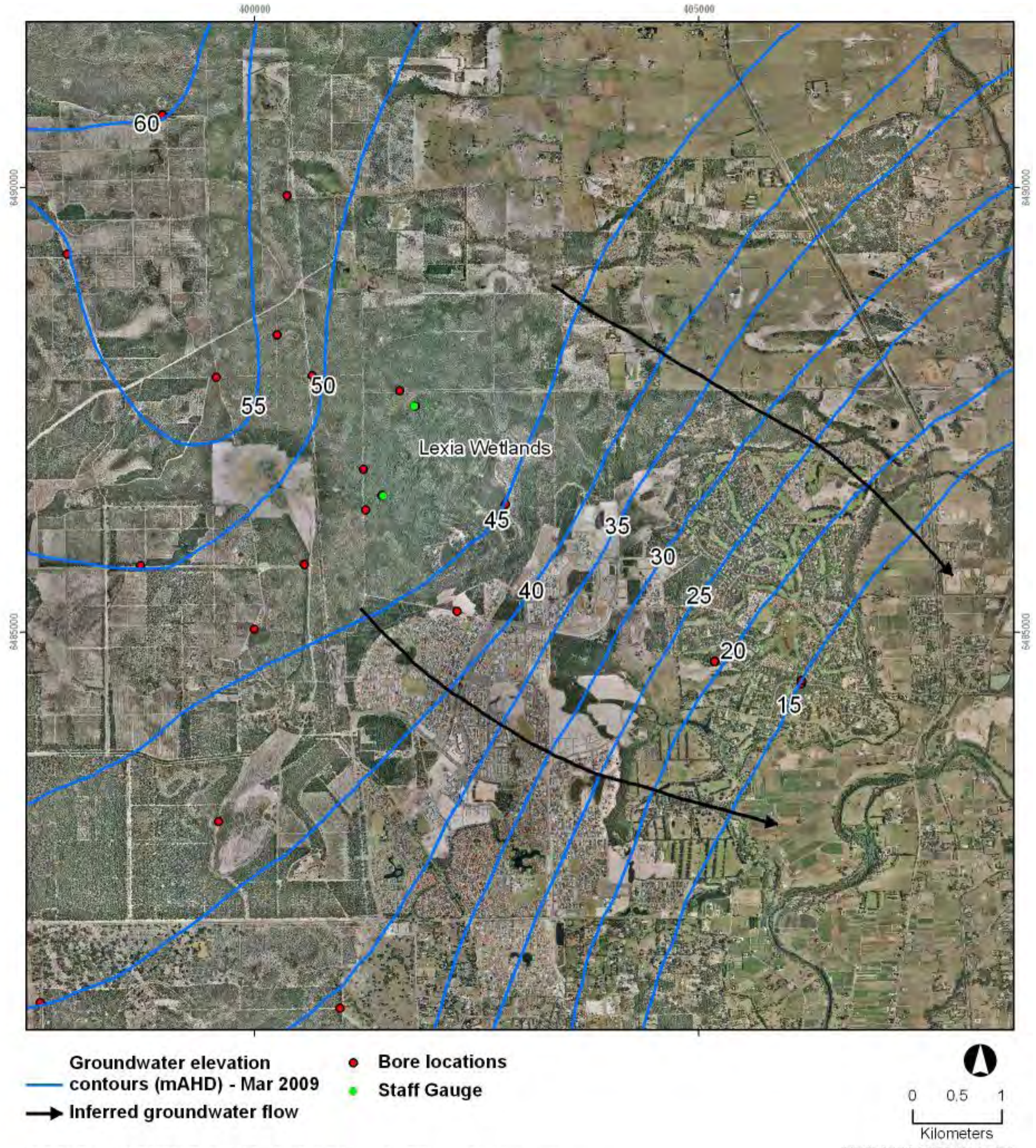


Figure 15 Time series water level data from SGS bores



I:\VESA\Projects\VE23381\Technical\Spatial_Data\Working\ArcGIS\groundwater contours

Figure 16 Groundwater elevation contours around the Lexia Wetlands in March 2009

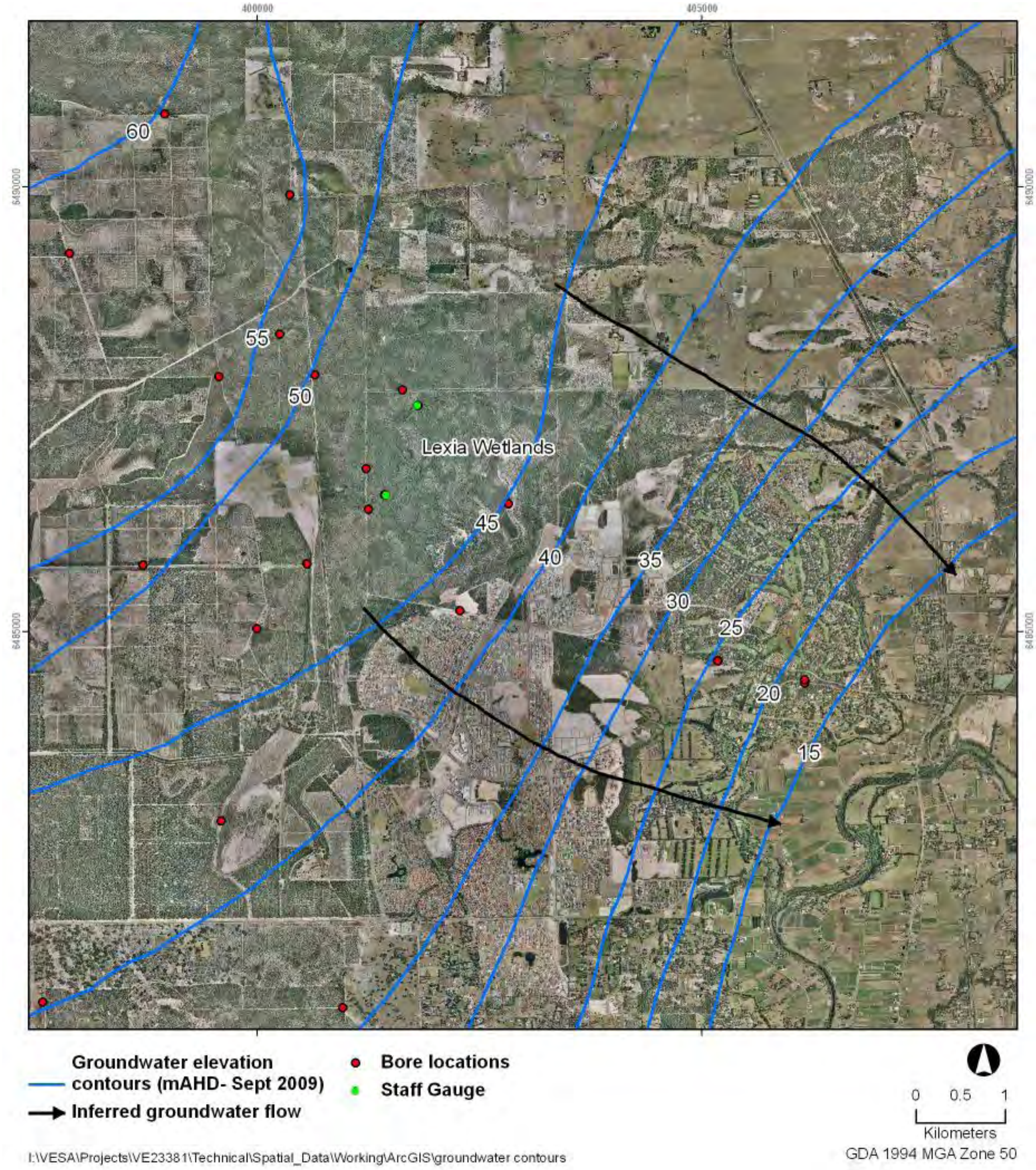


Figure 17 Groundwater elevation contours around the Lexia Wetlands in September 2009

5.3 Interaction with the regional flow system

On a regional scale, groundwater in the Superficial aquifer generally follows the slope of the ground surface flowing away from the crests of the Mound (Figure 5). For the Lexia Wetlands this is translated in a flow direction oriented from north-west to south-east in the direction of Ellen Brook and the Swan River. This is consistent with the subregional data interpretation (Figure 16 and Figure 17) and confirms the close connection between the local and regional groundwater flow systems in the Superficial aquifer.

Groundwater in the deeper Mirrabooka aquifer is understood to flow from north to south (Davidson 1995) and is locally in conformity with the Superficial aquifer flow pattern.

Under the Lexia Wetlands, the Superficial aquifer is directly in contact with the Mirrabooka aquifer. Local vertical gradient suggests that the Superficial aquifer is recharging the Mirrabooka aquifer (Figure 18). The vertical gradient is reversed about 10 km to the south of the Lexia Wetlands where the Mirrabooka aquifer recharges the Superficial aquifer (Figure 18, from Davidson & Yu 1995). The black circle shows the location of the Lexia Wetlands.

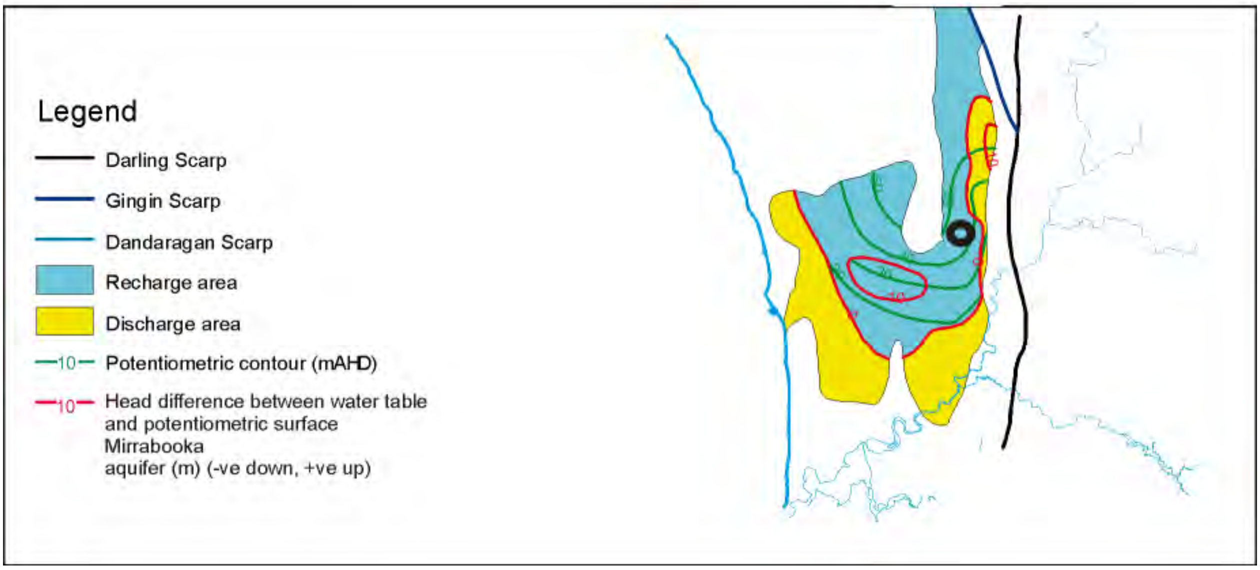


Figure 18 Head differences between the Mirrabooka and the Superficial aquifer

The linkages between the local and regional hydrogeological setting are captured by the schematic 3D conceptualisation shown in Figure 19. The significant features are:

- groundwater flows generally follow the slope of the ground surface
- the Lexia Wetlands are located at low elevation point where the regional groundwater level is near the surface
- the Superficial aquifer recharges the Mirrabooka aquifer at Lexia but the gradient is reversed some 10 km down hydraulic gradient where the Mirrabooka aquifer recharges the Superficial aquifer which then discharges in the Swan River
- the Leederville aquifer is isolated from the Superficial and Mirrabooka by the Kardinya Shale layer.

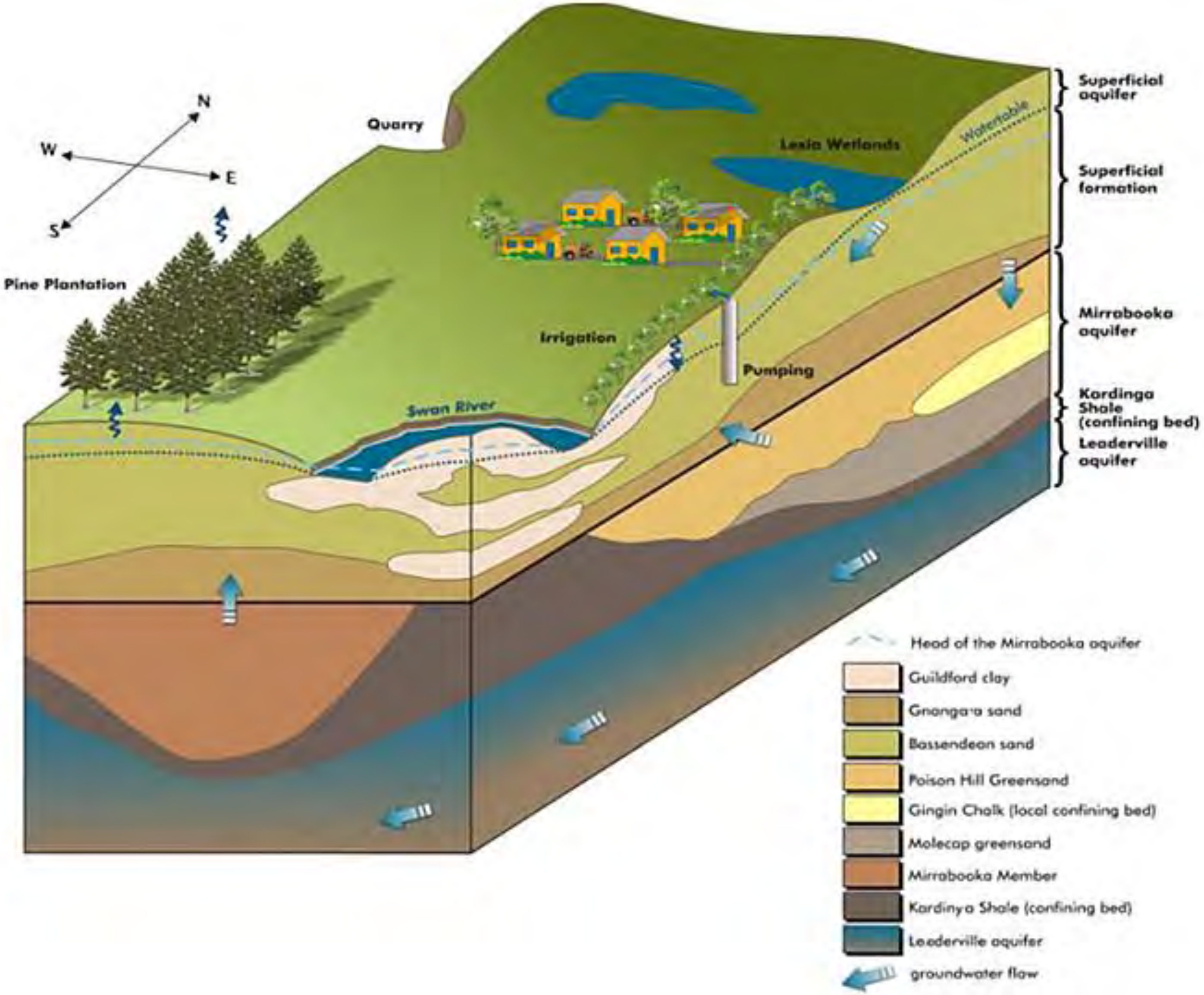


Figure 19 3D conceptualisation of the local and regional hydrogeological setting

5.4 Water level trends

The time series water levels show seasonal fluctuation with maximum groundwater levels in July–August and a minimum groundwater level in April–May. The maximum level is approximately 1 m higher than the minimum level.

The hydrographs with longer term records (Figure 20) show declining trend in the three monitoring wells which is estimated at:

- 3.8 cm/yr for Lexia 86 (bore GNM16)
- 4.8 cm/yr at Lexia 186 (bore GMN15)
- 3.9 cm/yr at Lexia 94 (bore GMN17A).

The decline has been accompanied by a reduction of surface water occurrences in the wetlands monitored at staff gauges GMN 15 (Lexia 186) and GMN16 (Lexia 86) and a series of below average rainfall years since the mid 1990s (refer to Figure 2).

The water level record is characterised by a series of ‘step downs’ in 1996, 2000, 2004 and 2006. The step down in groundwater levels suggest the influence of specific events.

Seasonal fluctuations in groundwater levels have also recently been reduced. Historically, the data shows that the variation between summer and winter groundwater levels is between 0.75 to 1.5 m. However, data since 2006 shows that seasonal fluctuations in groundwater level have typically been reduced to between 0.5 and 0.75 m. While the general decline in groundwater levels can be attributed to a reduction in rainfall and recharge and/or increases in groundwater abstraction, the reduction of seasonal amplitude is likely to be mainly influenced by a combination of a reduction in rainfall and recharge in the winter and a reduction in evapotranspirational losses in the summer.

During periods of high groundwater levels, the watertable at the site would be shallow enough to be within the root zone and consequently be affected by evapotranspirational losses. With these losses being greatest in summer and lowest in the winter, the corresponding high groundwater levels in the winter and low levels in the summer would ensure a large seasonal fluctuation in the watertable level. However, since 2006 the general decline in groundwater level at the site has reduced the amount of groundwater within the root zone and consequently this has also reduced evapotranspirational losses. The resultant seasonal fluctuation is therefore reduced and is more indicative of changes in recharge only.

The fall in summer groundwater levels is dampened due to the site being at or near a spring line. As shown by the contour plots in Appendix B, maximum regional groundwater levels were recorded between 1950 and 1970, with recent minimal levels being recorded in 2003. As shown in Figure 21, groundwater levels to the north of the Lexia Wetland have reduced more than those measured at the site and this is due to the dampening effect of the spring line.

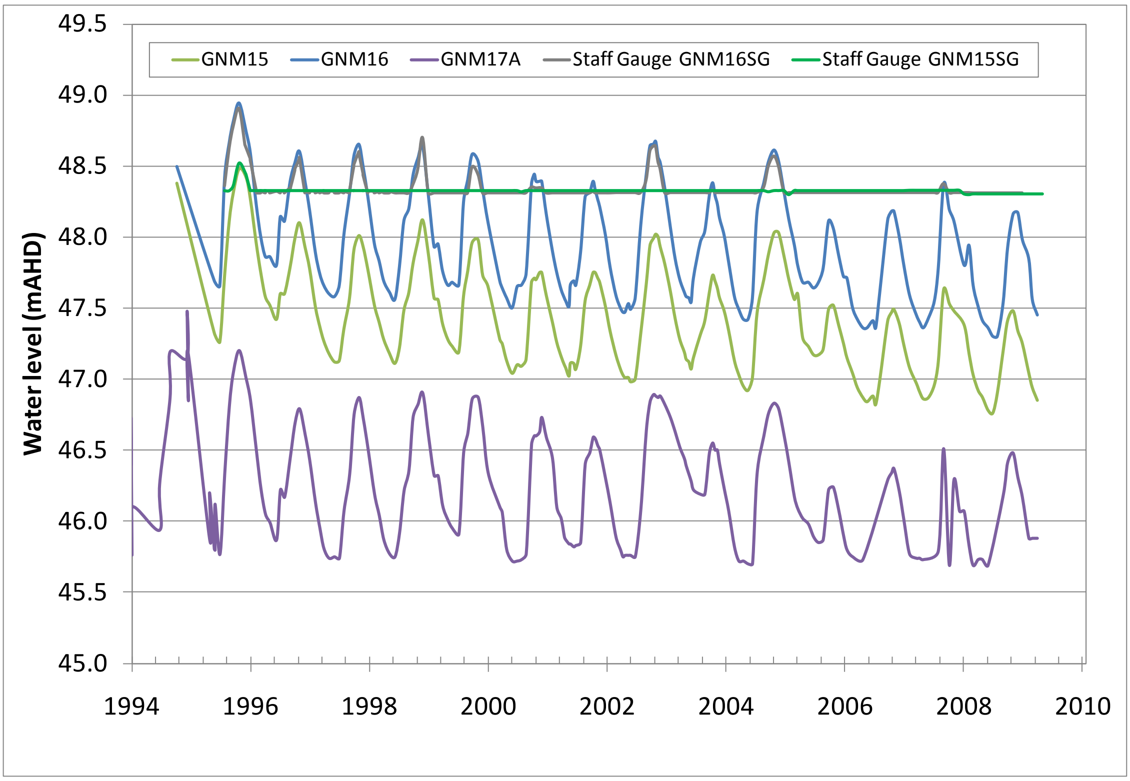


Figure 20 *Lexia Wetlands bore hydrographs and surface water level at GMN15SG and GM16SG*

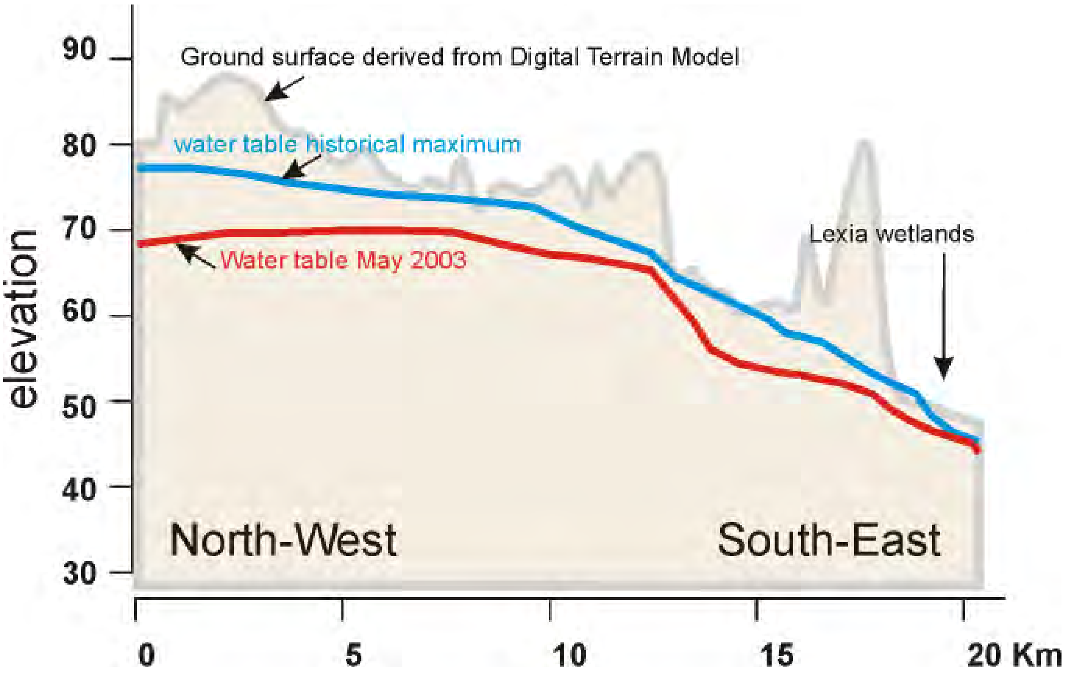


Figure 21 *Variation in watertable levels (AHD) between historical maximum (based on records from early 1950s through to 1970s) and May 2003*

5.5 Surface water–groundwater interaction inferred from groundwater level data

The groundwater monitoring data has been compared with the base elevation of each wetland (taken from February 2008 LiDAR) and the surface water level data available at staff gauges in Lexia 186 and 86 to determine the nature of surface water–groundwater interaction.

The data at Lexia 86 indicates that seasonal maximum groundwater levels have risen above the base of the wetland for a period of months several times since records began, creating a surface water pool within the wetland (with groundwater levels slightly higher than surface water levels). This has occurred 12 times since 1995, but only twice since 2004.

At all other times groundwater levels remain below the base of the wetland, but still generally within 1 m of the wetland base. It is likely that the capillary fringe is close to the wetland base and would provide moist (albeit unsaturated) conditions that may assist in maintaining sediment biochemical processes.

The groundwater level data at Lexia 94 indicate that groundwater levels have remained below the base of the wetland over the period of monitoring. Any surface water that is found within Lexia 94 is likely to be pooled runoff which is perched above the shallow groundwater system. This finding is consistent with the findings of Rockwater (2003). There is no surface water elevation monitoring at Lexia 94.

The monitoring record for Lexia 186 indicates that there have only been two occasions when the groundwater level has been above the base of the wetland; 1995 and 1996.

Summary of surface water-groundwater interactions

In summary, it appears that Lexia 86 is the only wetland where there has been seasonal (winter) groundwater discharge to the wetland since the mid 1990s, although the frequency of these events has reduced since 2004. There is no connection in the drier months. Groundwater has not discharged to Lexia 94 and Lexia 186 since 1996. The degree of hydraulic separation of the wetland and groundwater is increasing as groundwater levels decline over time.

There is no detailed sediment logging available to determine the hydraulic properties of the interface between the wetland basins and the shallow aquifer.

5.6 Influence of land and water use on groundwater conditions at the Lexia Wetlands

A groundwater model was developed by SKM (2009) to evaluate the potential effects of land and water use on the groundwater system. The groundwater model covers an area of 10 x 10 km centred on the Lexia Wetlands. Only the Superficial and Mirrabooka aquifers were modelled.

The model (assuming median climatic conditions of the 1996–2007 period), has demonstrated that the combination of harvesting pine plantations and the reduction in Water Corporation abstraction for the public water supply (by 3.5 GL/yr) within the

Lexia Wetlands area will result in a significant recovery in groundwater levels of 0.5 to 1.0 m over the next 20 years (SKM 2009). The modelling scenarios used are presented in Table 13.

The removal of the pine plantation is estimated to result in groundwater recharge increasing by about 1.5 GL/yr and at the same time simulations assume that groundwater abstraction for public water supply will decline by about 3.5 GL/yr (Table 13).

Table 13 Model scenarios

Scenario	Climate	Public abstractions	Private abstractions	Land-use change (pine harvest)*
Base case	Median climate of 1996 to 2007	Reduction by 3.5 GL/yr to 135.0 GL/yr	100% of current usage	Pines harvested as per LVL, replaced with grass
1	11% drier	As base case	As base case	As base case
2	As base case	As base case	As base case	Immediate (2008) pine removal, replace with grass
3	As base case	As base case	As base case	Pines harvested as per LVL, replaced with 50% grass, 50% native vegetation
4	As base case	Current rate of 138.5 GL/yr	As base case	As base case

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LVL – the Wood Processing (Wesbeam) Agreement Act 2002 *commits the state government to provide wood to the laminated veneer lumber (LVL) plant*

The modelling suggests that a drier climate is likely to have an impact on the level of groundwater recovery expected from pine harvesting and groundwater abstraction reduction. Hydrographs from the model finding are displayed in Figure 22.

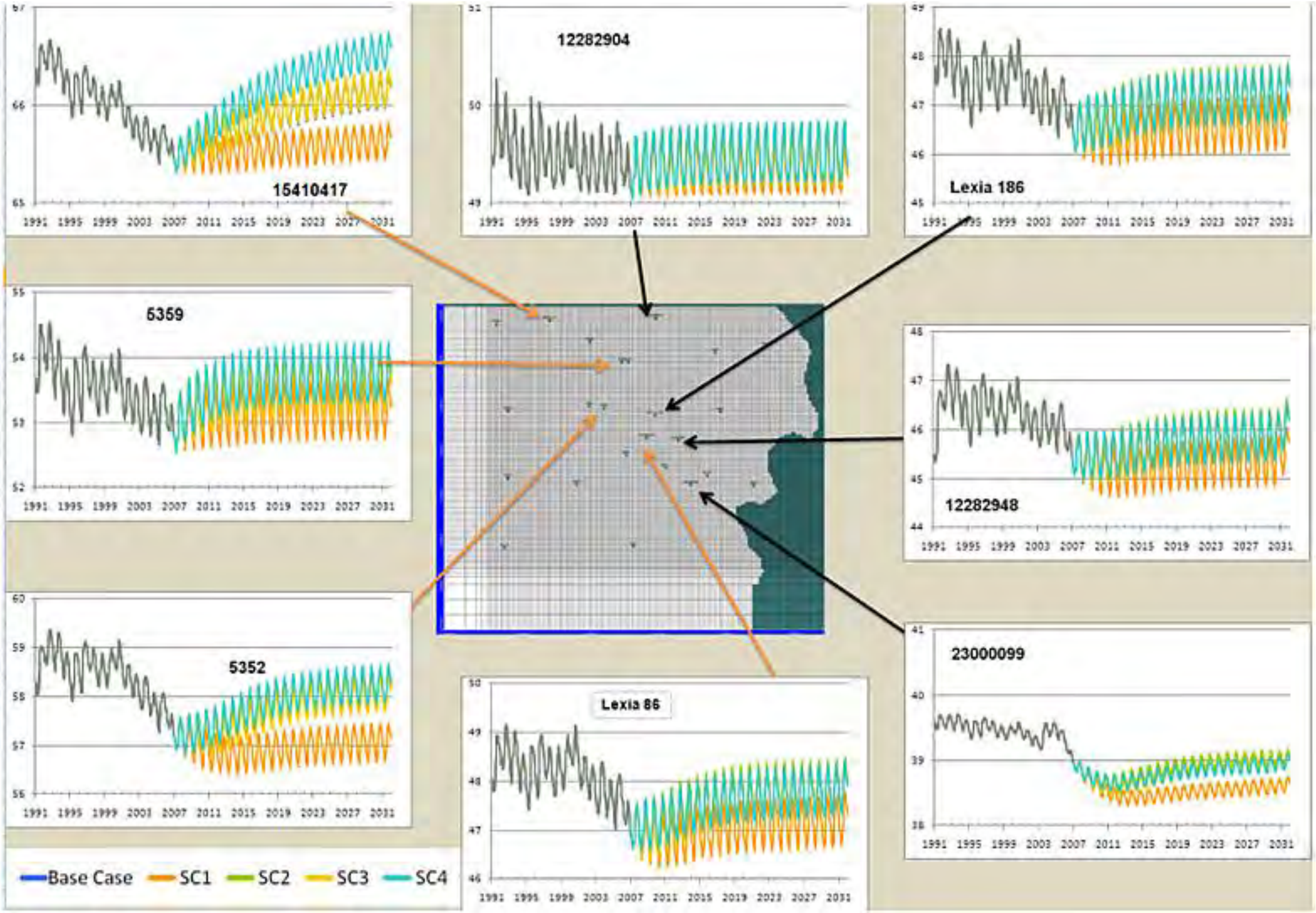

Figure 22 Water level time series determined through groundwater modelling (SKM 2009)

5.7 Hydrogeochemistry

Groundwater sampling and analysis were used to determine:

- the hydrogeochemical characteristics of the Lexia Wetlands
- the presence, distribution and availability of potential pollutants
- the interaction between the wetlands and the Superficial aquifer.

Chemical data were compared against appropriate groundwater criteria trigger values and assessment levels for various water uses and environments. Trigger values for fresh waters, irrigation water and drinking water applied in accordance with the Department of Environment and Conservation (DEC) 2010 *Assessment levels for soils, sediment and water*.

Drinking water guidelines were used to give perspective on sample water quality and where no irrigation trigger level existed, used for reporting purposes (in accordance with the methods described in the Department of Environment and Conservation's 2010 guidelines).

The department considers that any untreated waters taken from the environment is unsafe for human drinking.

The assessment levels for freshwater aquatic ecosystems in the DEC 2010 guidelines are considered the most relevant criteria for the wetlands and groundwater discharging into the wetlands.

Physical and chemical characteristics

Major ions

The reported concentrations of major ions (sodium, potassium, calcium, magnesium, chloride, bicarbonate, and sulfate) in each sample were used to create representative 'Piper' plots and 'Stiff' diagrams. Piper plots are a simple but useful method to present and describe the geochemical nature of individual groundwater samples. Stiff diagrams plot the major chemical components, in milli-equivalents per litre, as a polygonal shape created from four parallel horizontal axes extending on either side of a vertical zero axis. Stiff diagrams are useful to visually compare groundwater from different sources and to show how the ionic composition of groundwater changes along a known flow path, or vertically across differing strata.

For this investigation, the Piper plots and stiff diagrams were used to determine the characteristic water type of sampled groundwater from the nested well locations.

Piper plots plotting all groundwater samples during this investigation are presented in Figure 23 and representative Stiff plots in Figure 24.

These plots indicate that the groundwater sampled has a general 'sodium–chloride' composition, with the western wells reporting groundwater ion concentrations generally lower than the eastern wells. Note that these geochemical plots in this section (with the exception of metal concentrations) represent average concentrations.

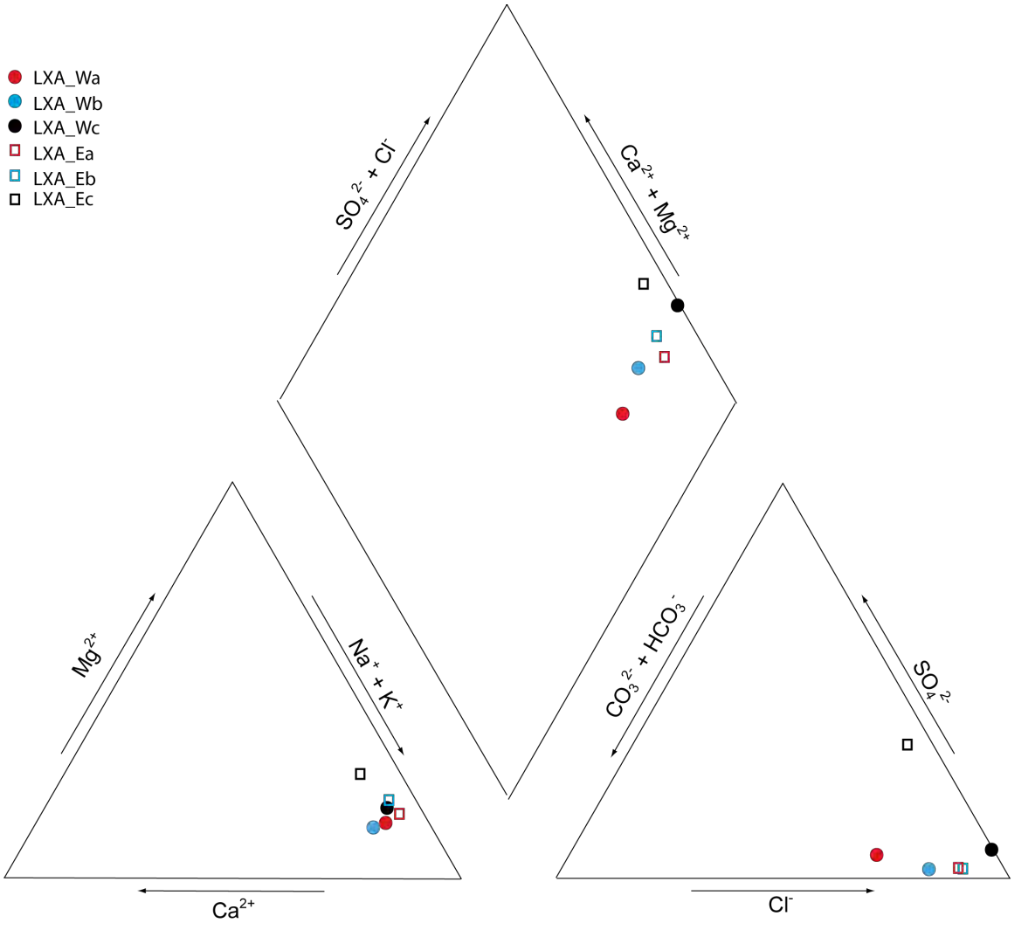

Figure 23 Piper plot of groundwater samples from Lexia Wetlands SGS bores

With respect to groundwater sampled from the western groundwater monitoring wells, the deepest (LXA_Wa) and the intermediate (LXA_Wb) wells reported groundwater of a similar composition[4], with bicarbonate (HCO_3^-) being the second most predominant anion, and magnesium (Mg^{2+}) being the second most predominant cation, after chloride and sodium respectively. Notably the intermediate well has a slightly higher ionic content than the deeper water, but the general shape (and thus composition) is essentially the same.

The shallowest groundwater well in the western nested arrangement (LXA_Wc) displays a markedly different composition to the deep and intermediate groundwaters, and is dominated by sulfate in an anionic sense (after chloride) while

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[4] Note that the sodium and chloride values have a ‘x 10’ multiplier in order to scale the plot appropriately. Therefore all samples are generally of a sodium–chloride composition. Data used to generate stiff plots are averages of eight monitoring events. Due to the conservative nature of most of the ions, and the necessity for comparison of differing groundwaters only, time series plots for major cations and anions are not included.

the calcium content (Ca^{2+}) is lower and magnesium is higher. This would suggest that the groundwater sampled from the shallow screened well is of a different composition to the deep and intermediate groundwaters at this location.

This trend is mirrored in the eastern nested location, although the difference in composition between the shallow (LXA_Ec) versus the deep (LXA_Ea) and intermediate (LXA_Eb) groundwater is clearer, with magnesium and sulfate becoming significantly more dominant in the shallow groundwater.

Thus magnesium and sulfate levels show a decreasing trend with depth at both LXA_E and to a lesser extent, LXA_W.

Figure 25 demonstrates the change in ionic composition across depths, with the eastern wells demonstrating a higher sodium and chloride composition than the western wells, but with both magnesium and sulfate becoming more dominant in the shallow groundwater.

Limited historical surface water data (n=1) is available for surface water monitoring site GNM16SG, located on the western side of the wetlands. This data was collected in 2000. A Stiff plot analysis of the GNM16SG data is presented in Figure 24 also, and indicates that the surface water collected in 2000 is of a similar general composition as the shallow groundwater sampled from the eastern and nested wells – it is dominated by both magnesium and sulfate as secondary cations and anions to sodium and chloride. This indicates that at the time of sampling (2000) that the surface water and shallow groundwater were in continuity. The absence of recent surface water monitoring data does not allow further comparison for current conditions.

A second trend observed at each site (in particular the western cluster), was that salinity (as sodium–chloride) was reported to decrease with depth.

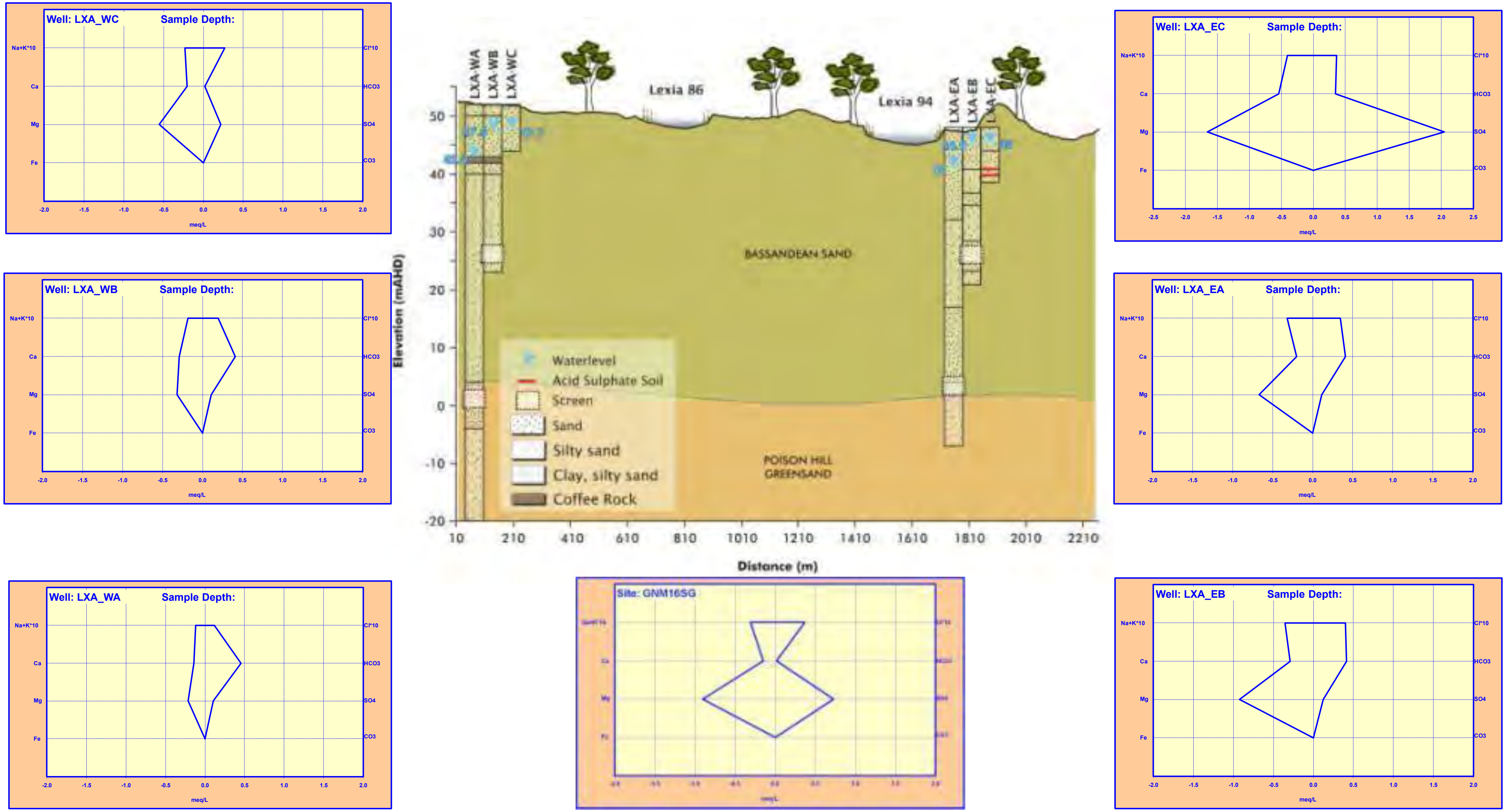

Figure 24   Representative Stiff diagrams for groundwater from Lexia Wetlands and SGS bores

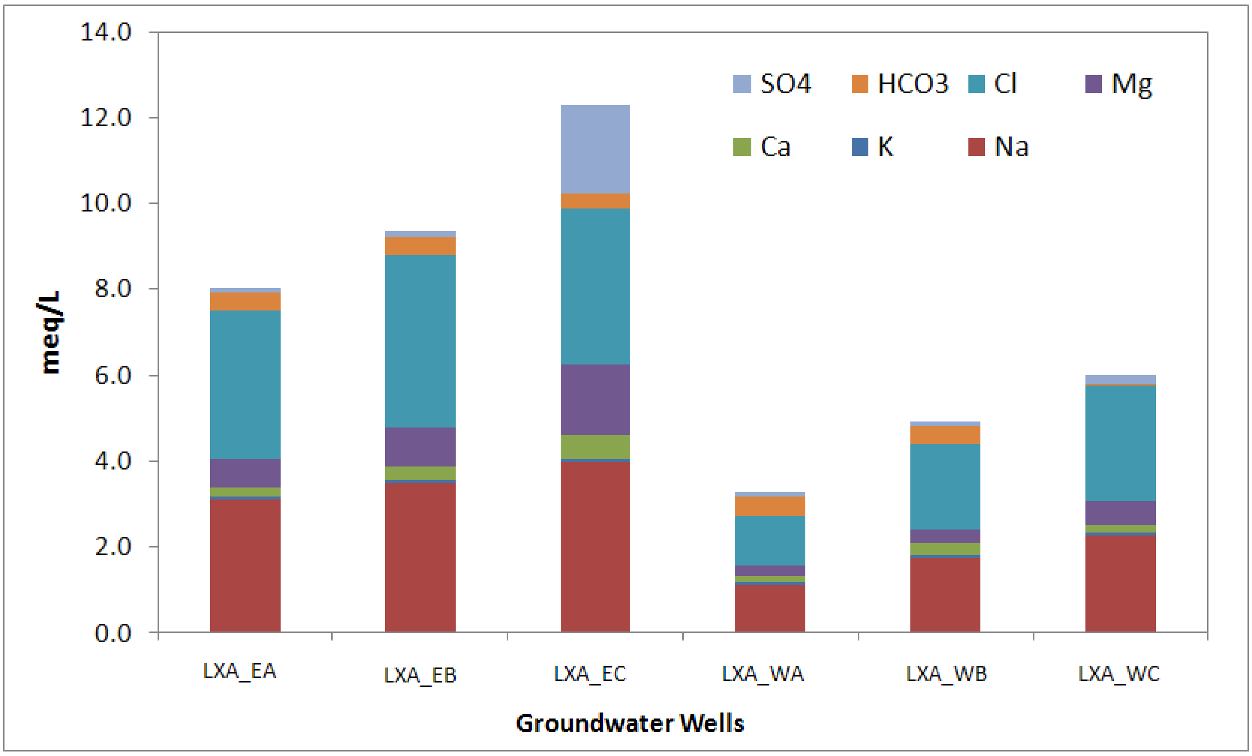

Figure 25 Concentration of cations and anions from Lexia Wetlands

A further assessment of sodium and chloride (Figure 26) shows that an average 1:1 ratio (as meq/L) is evident for groundwater sampled from the western cluster of wells across all depths, although as shown in Figure 21, the sodium and chloride concentrations generally decrease with depth.

Higher sodium and chloride concentrations were reported in groundwater sampled from the eastern side of Lexia Wetlands compared to those in the west, and these sodium:chloride ratios were more variable, with differences noted in the ratio between all three depths, but particularly in the shallow groundwater (LXA_Ec) where the ratio of sodium:chloride decreased.

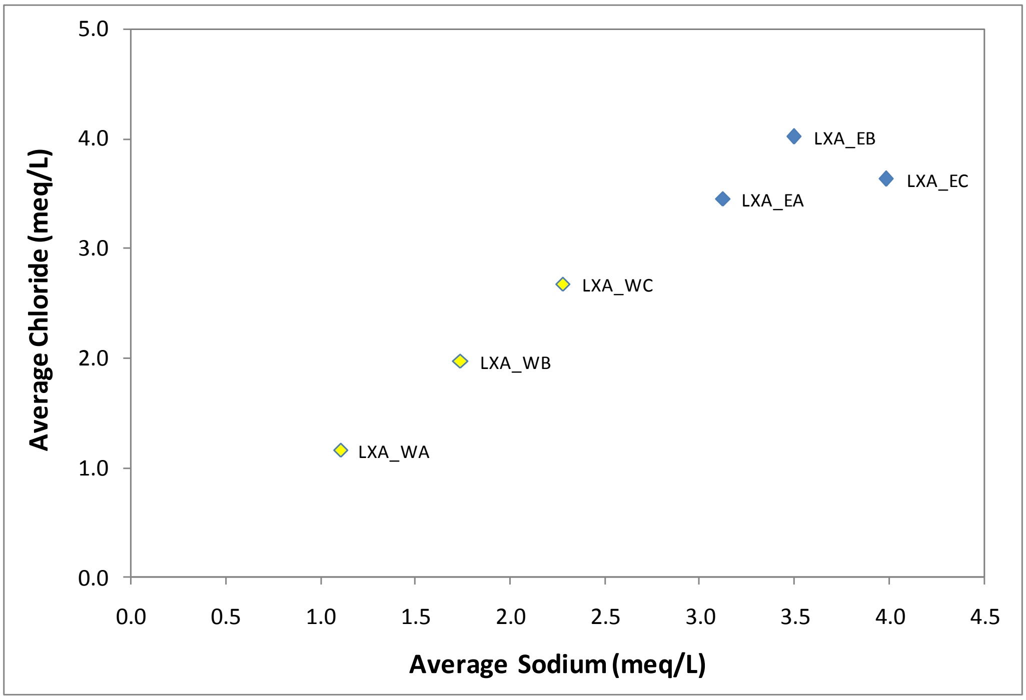

Figure 26 Sodium and chloride concentrations

The ratio of sulfate (SO_4^{2-}) to chloride generally increases with depth, with sulfate concentrations constant at ~0.1 meq/L and chloride concentrations decreasing with depth at both sites. However, groundwater LXA_Ec is an exception, as the significantly higher sulfate concentration reported in this groundwater skews the ratio considerably (Figure 27).

This ‘detached’ ratio would indicate that the sulfate concentration of the shallow groundwater sampled from well LXA_Ec has an ‘abnormal’ sulfate concentration in comparison to the other sampled groundwater, and is being affected by a process uncommon to the other slotted intervals.

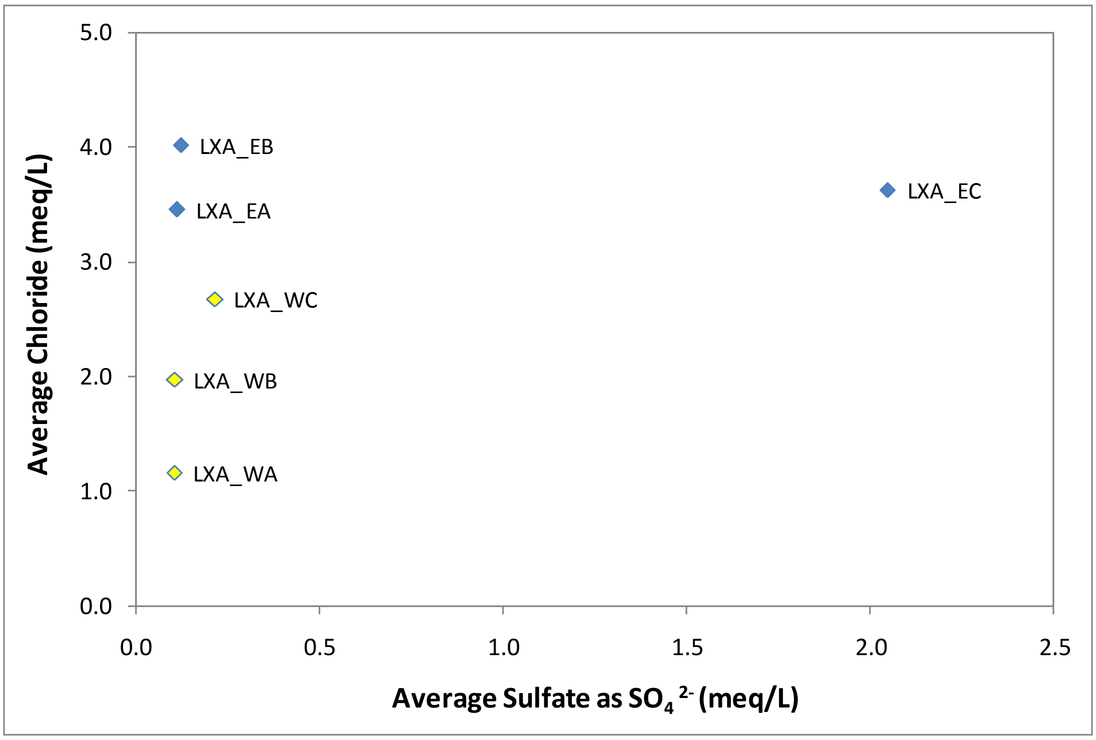

Figure 27 Sulfate and chloride concentrations in groundwater at Lexia Wetlands

The sulfate:chloride ratios as mg/L (as opposed to meq/L presented in Figure 27) are presented in Table 14. High SO_4^{2-}:Cl^- ratios in groundwater can indicate acid sulfate soils and oxidation of sulfide. The SO_4^{2-}:Cl^- ratio of natural groundwater is around 0.03–0.05 (Hirschberg 1984), seawater is 0.15 and rainwater has an SO_4^{2-}:Cl^- ratio of 0.25 (Yesertener 2008). Ratios higher than 0.5 can indicate sulfide oxidation. Values greater than 0.9 indicate significant sulfide oxidation (Vogwill et al. 2005). The calculated SO_4^{2-}:Cl^-ratios for the groundwater sampled from both sets of nested wells are generally within the range of natural groundwater, with the exception of LXA_Ec, which is significantly above the natural groundwater range (Table 14).

Table 14 Sulfate concentration versus chloride concentration

Location	**Sulfate as SO_4^{2-} mg/L**	**Chloride mg/L**	**SO_4^{2-} : Cl^- ratio**
LXA_Ea	5.375	122.50	0.044
LXA_Eb	5.875	142.50	0.041
LXA_Ec	98.375	128.75	0.764
LXA_Wa	5.000	41.25	0.121
LXA_Wb	5.125	70.00	0.073
LXA_Wc	10.375	95.00	0.109

Acidity and alkalinity

The reported pH of groundwater sampled at each screened depth is generally consistent at the LXA_E site and ranges between 5.4 and 5.6 across all depths (Figure 28). The LXA_W site has a similar pH to the lower screened depths (a and b) although the shallow groundwater (LXA_Wc) has a notably lower pH of 4.2.

The Department of Environment and Conservation guidelines (DEC 2010) have established a pH range of 6.5–8.5 for fresh and drinking water, and a lower limit of pH 7 for wetlands in south-west Australia (ANZECC 2000). The reported pH of the sampled groundwater is below the fresh and drinking water limits, and all samples were reported below the lower limit for wetlands (Figure 28).

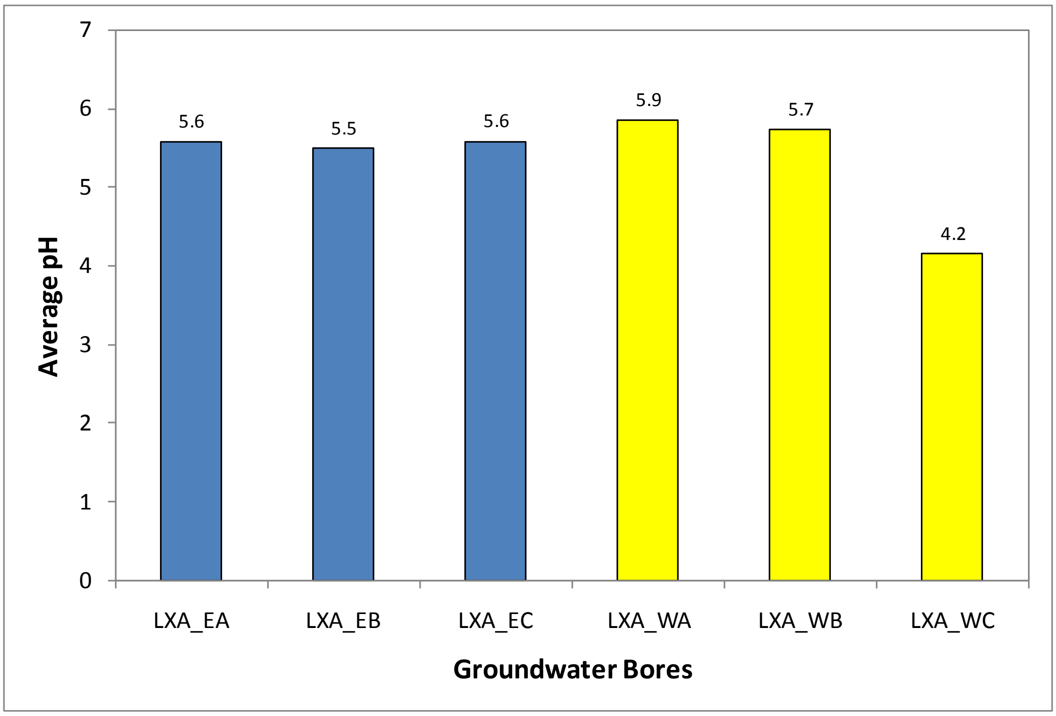

Figure 28 pH values in groundwater at Lexia Wetlands

Each groundwater sample reported a relatively low pH reading (acidic) which may be attributable to the poor buffering capacity associated with sand formations (due to low concentrations of carbonate buffering) and as evidenced by the lack of acid neutralising capacity reported in the acid sulfate soil analysis.

However, the pH reported in LXA_Wc was notably lower than the other sampled groundwaters. The initial interpretation of this lower pH was that it may be associated with the increased sulfate content as a function of oxidation of pyrites in the respective strata (i.e. oxidation of sulfur to sulfate).

However, although no acid soil assessment was undertaken at these depths, no indication of potential acid sulfate soil was reported in the western nested wells (i.e. no elevated sulfide content). A further comparison of pH and carbonate hardness of sampled groundwaters (Figure 29) as an indication of alkalinity and buffering capacity of sediments indicates that LXA_Wc has the least buffering capacity of all sampled groundwaters, and this may be the predominant reason for the reported low pH, perhaps in conjunction with some oxidation of sulfidic material and subsequent generation of sulfuric acid.

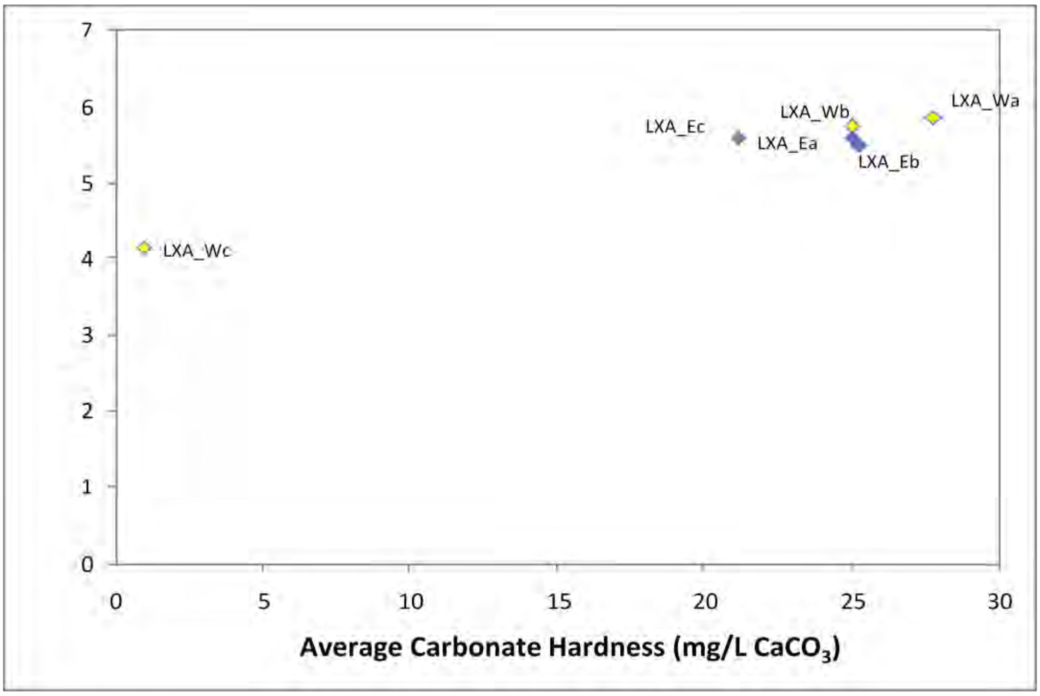

Figure 29 Carbonate hardness versus pH in groundwater at Lexia Wetlands

The alkalinity of water is essentially its acid neutralising capacity. Analysis of alkalinity can give greater insight into the characteristics of water and its possible behaviours than pH measurements alone, which only measure H^+ activity.

Total alkalinity as $CaCO_3$ of groundwater ranges between 1 mg/L in LXA_Wc and 28 mg/L in LXA_Wa (Figure 30).

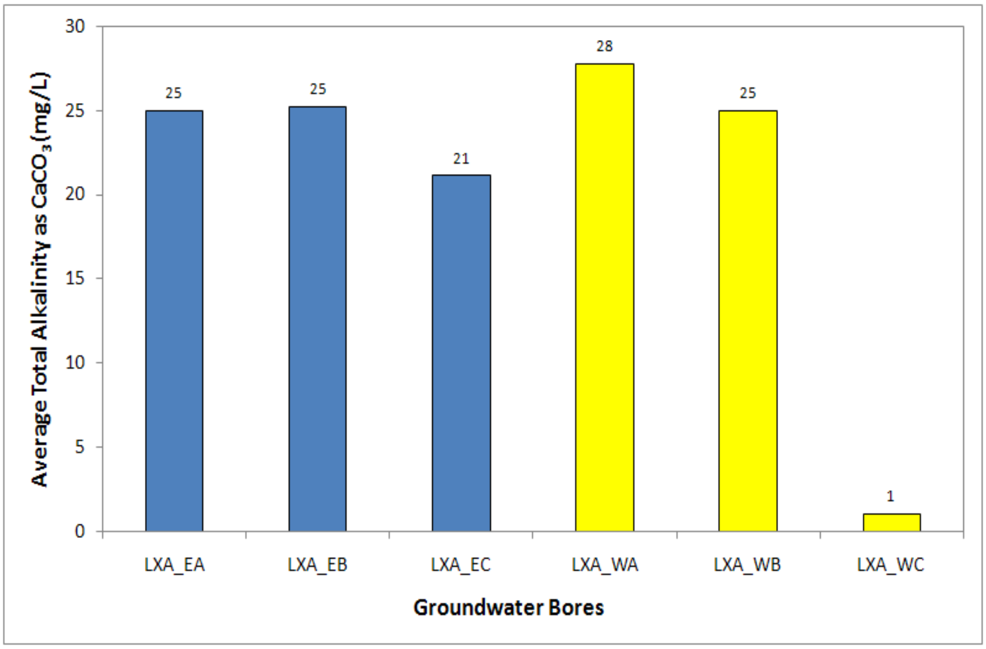

Figure 30 Alkalinity in groundwater at the Lexia Wetlands

Total alkalinities of groundwater at both nested sites are generally of similar concentrations (approximately 25 mg/L) with the exception of LXA_Wc where total alkalinity was 1 mg/L. A low alkalinity reading (less than 20 mg/L) indicates a poor buffering capacity (Hollier and Reid 2005).

Total acidity$_{0.95}$ can be used as an interpretation of the total metal content (i.e. cationic) of groundwater. The total acidity$_{0.95}$ ranges from 0.26 mg/L to 0.32 mg/L in the eastern nested wells, and between 0.055 mg/L and 0.19 mg/L in the western wells (Figure 31).

Total acidity is generally higher in groundwater sampled from the eastern wells than the western wells, and shows a marginal increase at depth. The western wells report the highest total acidity in the shallow groundwater.

The higher total acidity in the shallow groundwater in the western nested wells may be attributable to the lower pH, which would generally facilitate the increased mobilisation of metals from the sediment into pore water.

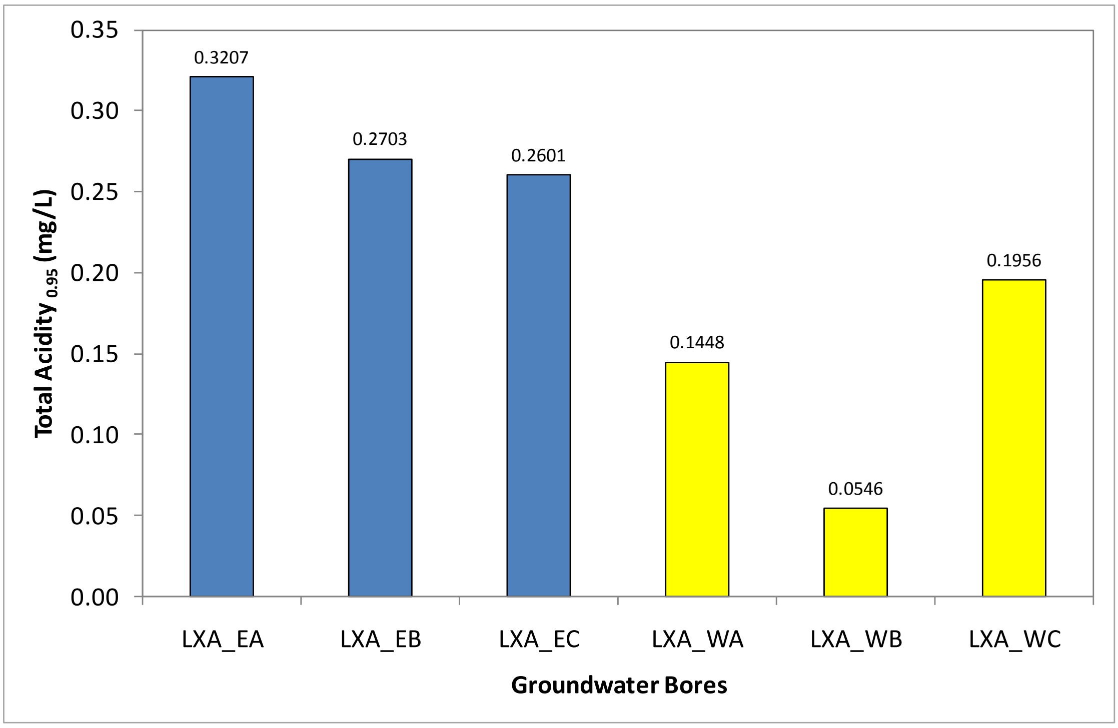

Figure 31 Total acidity$_{0.95}$ in groundwater at the Lexia Wetlands

Total hardness and non-carbonate hardness

Total hardness (as $CaCO_3$) of groundwater is calculated to range from 45 mg/L to 110 mg/L in groundwater sampled from the eastern wells, and from 18 mg/L to 38 mg/L as $CaCO_3$ in western wells (Figure 32). Total hardness shows a decreasing trend with depth at both sites. Again, concentrations at the eastern site show overall higher levels compared to those reported from the west. It is assumed that the total hardness is predominantly $CaCl_2$.

Carbonate hardness is the measure of total dissolved minerals (generally calcium and magnesium carbonates). This carbonate system provides the acid buffering via the presence of bicarbonate and carbonate in the water. As discussed previously, carbonate content (and carbonate hardness) is virtually non-existent in the shallow groundwater sampled from the western nested wells.

Overall, each groundwater sample exhibited hardness concentrations characteristic of ‘soft’ water (< 75 mg/L $CaCO_3$).

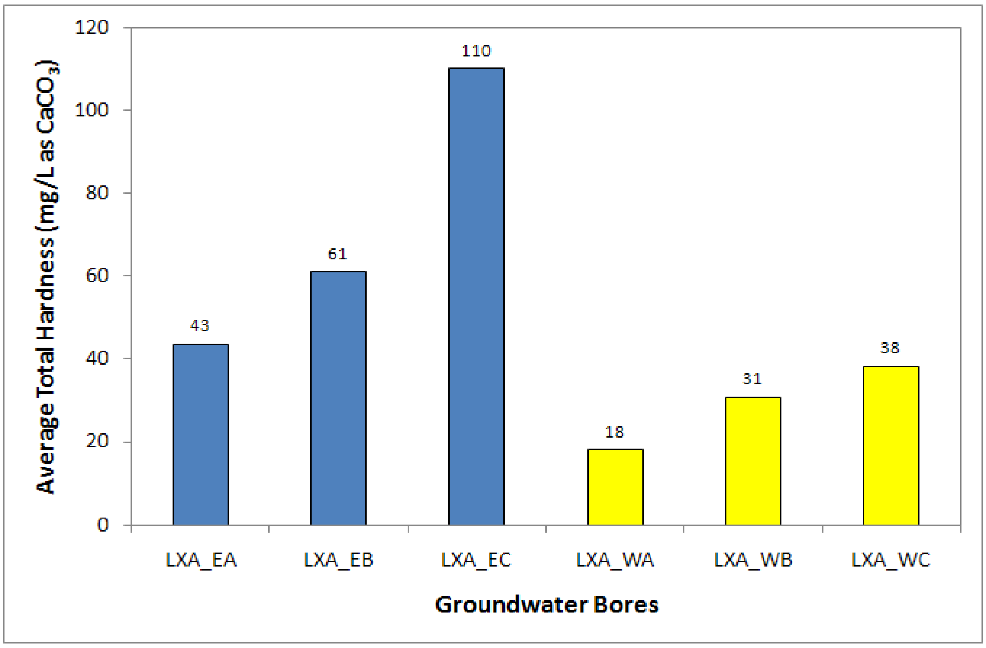

Figure 32 Total hardness of groundwater at Lexia Wetlands.

Alkalinity and hardness values are generally similar due to calcium, magnesium, bicarbonate and carbonate being derived in equivalent quantities (Hollier and Reid 2005). Total hardness of waters from each well were calculated to be higher than alkalinity, which is a function of non-carbonate hardness (i.e. $CaCl_2$, Figure 33). This is most evident at LXA_Ec.

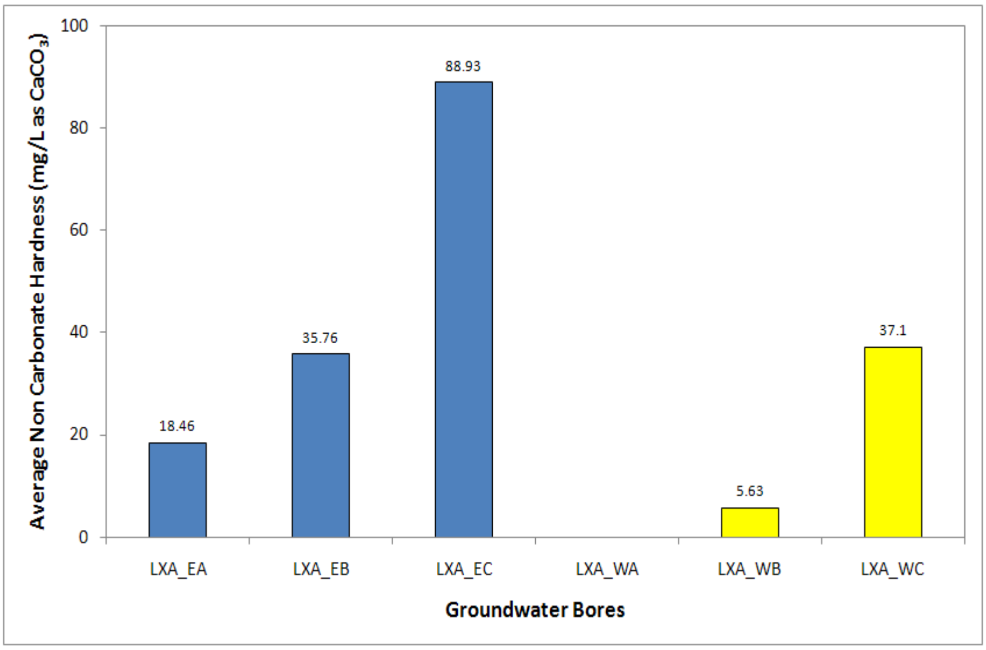

Figure 33 Non-carbonate hardness of groundwater at the Lexia Wetlands

Salinity as Ec

Electrical conductivity (Ec) of groundwater was reported to range between 200 µS/cm in LXA_Wa to 640 µS/cm in LXA_Ea (Figure 34).

Ec of waters sampled at both sites show a decreasing trend with depth with overall higher levels found in the eastern groundwater wells, commensurate with the increased NaCl concentrations reported in the shallow groundwater.

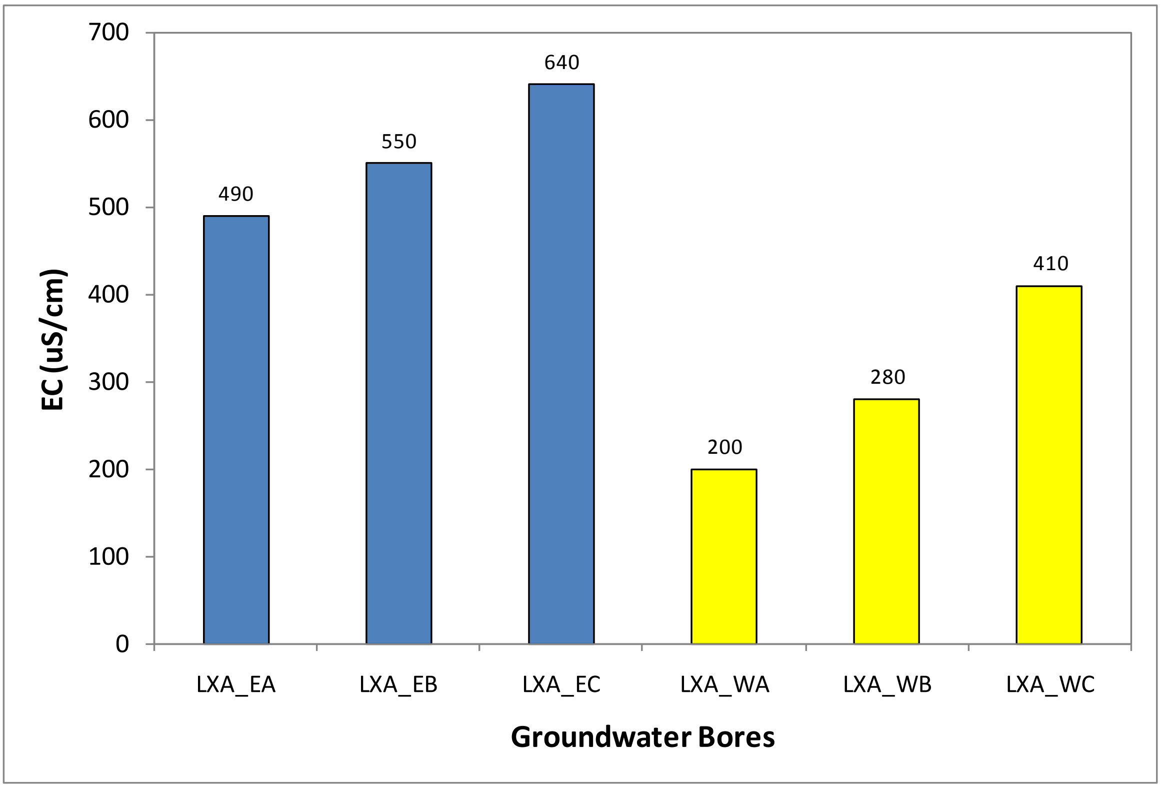

Figure 34 Ec of groundwater at the Lexia Wetlands

Redox conditions

Eh measurements are useful to give a qualitative indication of redox conditions. LXA_Wc had the highest Eh reading (16.6 mV). All other groundwater samples had negative readings (ranging to –107.9 mV) indicating that much of the aquifer around the Lexia Wetlands is a reducing environment (Figure 35).

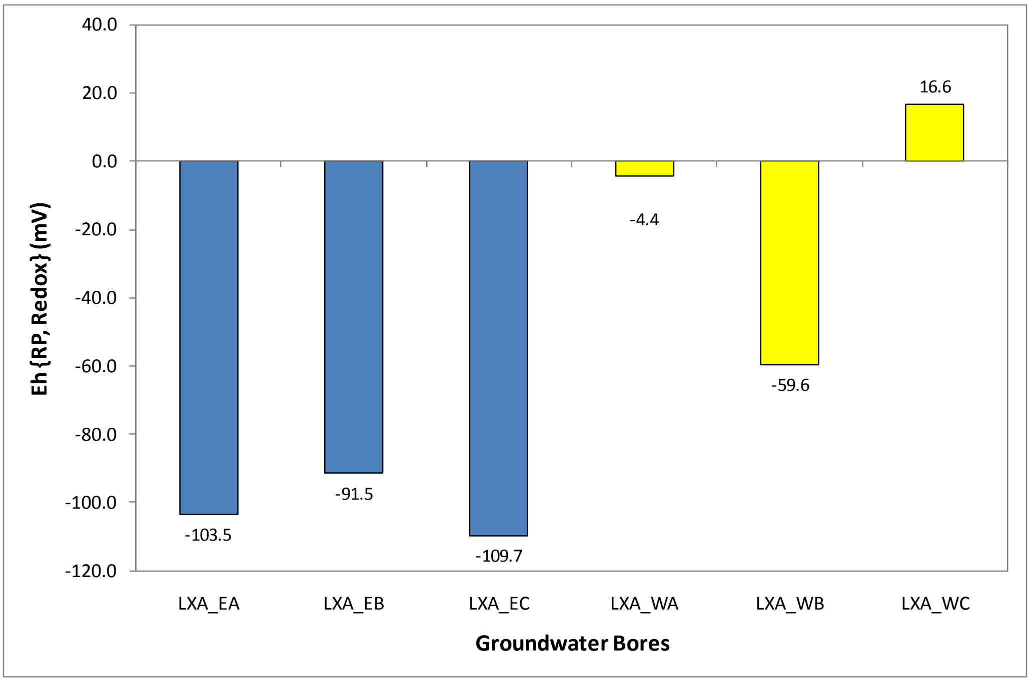

Figure 35 Redox conditions of groundwater at Lexia Wetlands

Water quality

Nutrients

Nutrients were analysed in the groundwaters sampled from each nested well arrangement.

Total nitrogen concentrations (TN) ranged from 210–5700 µg/L. The majority of samples were greater than the 350 µg/L trigger value for freshwater lakes and most samples had TN concentrations which exceeded the trigger value of 1500 µg/L for wetlands in the south-west of Australia (ANZECC 2000). Generally, TN concentrations were greater on the eastern side of the lake than on the western side.

Nitrate and nitrite concentrations (NO_x) were generally highest in the intermediate wells.

All samples from all wells exceeded the trigger values for ammonium and ammonia for wetlands in south-west of Australia (40 µg/L NH_3-N/NH_4-N (sol)), as well as the trigger for freshwater lakes (10 µg/L).

In samples from the eastern wells, the ratio of N_{ox} (nitrate + nitrite) to organic N (i.e. as represented by total Kjeldahl N, TKN) decreases with depth, indicating that the highest ratio of NO_x to TKN was reported in the shallow groundwater. However, generally, the predominant form of nitrogen was organic (TKN) across all depths. The organic nitrogen was predominantly composed of dissolved organic nitrogen, rather than ammonium, which marginally increased with depth, indicating organic nitrogen was more predominant in the shallow groundwater.

In groundwater sampled from the western wells, the ratio of NO_x (nitrate + nitrite) to organic nitrogen does not appear to significantly change with depth. However, the organic nitrogen balance changes significantly with depth, with ammonium increasing in depth significantly in comparison to the shallow depths.

Total phosphate (total P) concentrations in the deep and intermediate western wells were higher than all other wells (Figure 36). A peak in total P concentrations was evident in the winter of 2009.

The eastern wells generally recorded a higher total P concentration in 2008 as opposed to 2009, with the shallow well reporting higher concentrations generally.

In summary, total P concentrations ranged from 7 to 300 µg/L (Figure 36). Around 44% of samples had total P concentrations which exceed the ANZECC wetland trigger value (60 µg/L). These were from the western deep and intermediate wells. Concentrations of soluble reactive phosphorus (SRP) were generally at or below limits of reporting, which is the freshwater trigger value of 5 µg/L. Some samples from the deep and shallow eastern bores were elevated at around 20 µg/L in the September 2008 sampling event but did not exceed the trigger value for south-west Australian wetlands (30 µg/L).

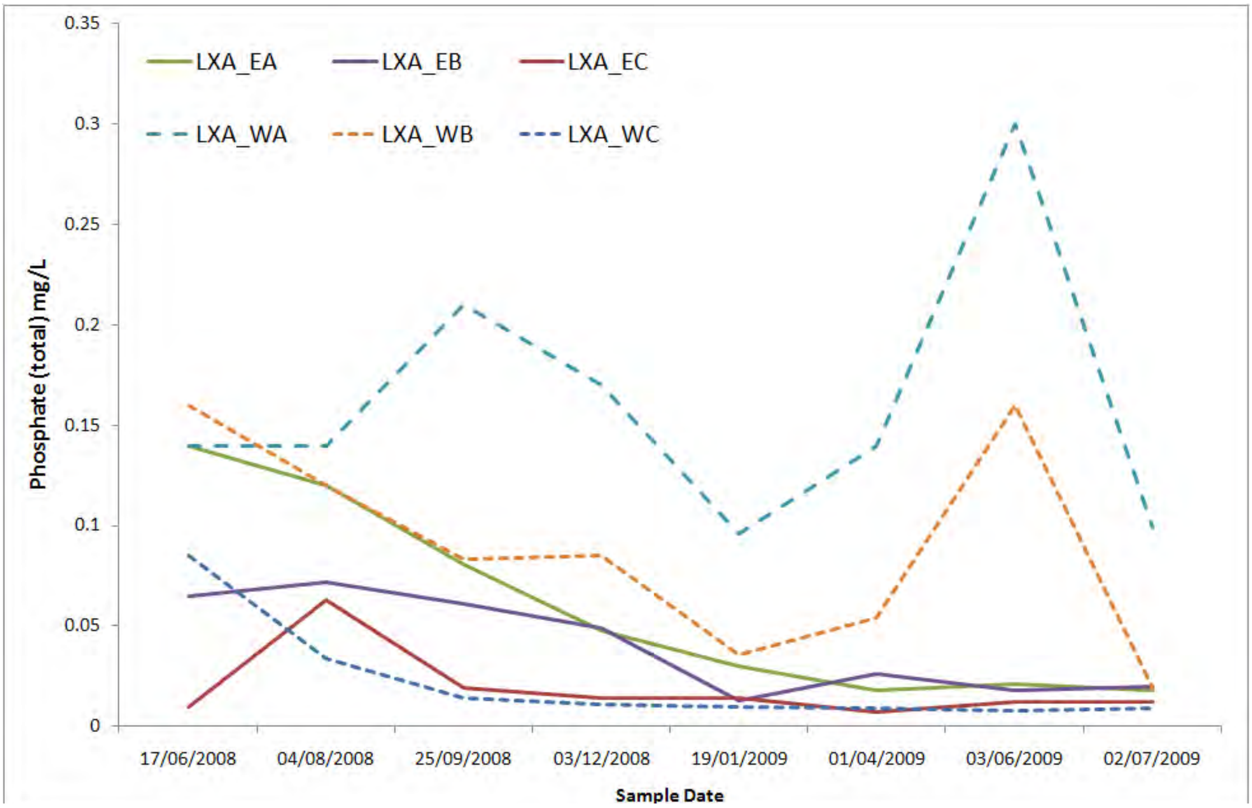

Figure 36 Concentrations of total phosphate in Lexia Wetlands groundwater

Metals

The full list of sampling results is presented in Appendix D.

Time series data are available for 8 sampling events during 2008 and 2009. Time series plots for all metals (2008–09), are presented in Appendix D, with the exception of mercury which was generally at or below laboratory limits of reporting on the eight sampling events.

The time series data for soluble species (aluminium, boron and iron) indicate that the highest concentrations of dissolved metals are generally associated with the beginning of the sampling period (June 2008). This is particularly true for aluminium, which reported a maximum concentration of 5.5 mg/L in August 2008, in the deep eastern well (LXA_Ea). The intermediate depth in the eastern cluster also reported its highest Al^{3+} concentrations during this event. The eastern groundwater (all depths) then reported lower Al^{3+} concentrations over the remaining samplings.

The western wells and the shallow eastern wells generally reported reasonably consistent Al^{3+} concentrations over the sampling period.

The boron concentrations were much more variable, with the western wells having a peak concentration at all depths during September 2008. The eastern wells, with the exception of the shallow well (LXA_Ec) generally had higher concentrations in 2008 than 2009.

With respect to soluble Fe, groundwater sampled from the shallow eastern groundwater monitoring well displays the most variable trend across the sampling period, and the highest concentrations. The deep western well (LXA_Wa) also displays a variable trend in Fe concentration, although the variation is restricted to within approximately 1 mg/L, which is relatively insignificant compared to the variation reported in the shallow eastern well Fe concentration.

Most metals reported as ‘total’ had their highest reported concentrations in the beginning of the sampling period (i.e. June 2008).

The average concentrations for metals reported in groundwater sampled at Lexia Wetlands are shown in Table 15.

Dissolved aluminium (Al^{3+}) concentrations ranged from 0.18 mg/L to 2.23 mg/L. All samples exceeded the guidelines for freshwater ecosystems (0.055 mg/L) but were below the irrigation water assessment level (5 mg/L, DEC 2010). Some samples from LXA_Ea and LXA_Wa exceeded the drinking water level (0.2 mg/L).

The guidelines consider the dissolved concentration of arsenic (As) as a trigger value whereas the SGS investigation reports the total concentration. Although not interchangeable (and should not be used for assessment purposes), qualitative comparison to the guidelines was undertaken to provide a broad reference. Arsenic is a concern over much of the Swan Coastal Plain. Reported As concentrations were below irrigation trigger values for all bores at the Lexia Wetlands. The latest available data indicates arsenic concentrations are below the trigger level. Concentrations ranged from 0.001 mg/L to 0.019 mg/L.

Total chromium concentrations ranged from 0.018 mg/L to 0.38 mg/L. At LXA_Wa, most samples exceeded irrigation guideline criteria (0.1 mg/L) and drinking water criteria (0.05 mg/L). All samples exceeded the freshwater trigger level (0.01 mg/L).

Total cadmium concentrations were relatively low. The guidelines use the dissolved concentration as a trigger value whereas the SGS investigation reports the total concentration. Although not interchangeable, comparison to the guidelines was still carried out to provide a reference. No samples exceeded irrigation or drinking water trigger values. Initial samples from LXA_Wa (June 2008) exceeded the freshwater trigger value, but levels have since decreased below this level.

Soluble iron concentrations were generally elevated across all samples, with the maximum concentration reported in LXA_Ec. All samples had concentrations which exceeded both the irrigation and drinking water guidelines of 0.2 mg/L and 0.3 mg/L respectively.

Total nickel concentrations ranged from 0.001 mg/L to 0.024 mg/L. Samples from each bore exceeded fresh water levels (0.011 mg/L) and drinking water levels (0.02 mg/L) until January 2009, with the exception of LXA_Wb. Since this date, all samples have been below these trigger levels. All samples had Ni concentrations below the irrigation water assessment level (0.2 mg/L).

One sample from LXA_Wb exceeded all threshold levels for selenium concentration; freshwater (0.005 mg/L), drinking water (0.01 mg/L) and irrigation water (0.002 mg/L). All other samples had selenium concentrations of acceptable levels.

Two samples from LXA_Wa had total manganese concentrations of that exceeded the irrigation water level (0.2 mg/L). Manganese concentrations ranged from 0.01 mg/L to 0.31 mg/L. No samples exceed drinking water levels.

The majority of samples had zinc concentrations that exceeded freshwater levels (0.008 mg/L). Concentrations ranged from 0.001 mg/L to 0.11 mg/L with a decreasing trend experienced in all bores from June 2008 to July 2009. All samples were below the irrigation limit (2.0 mg/L) and drinking water levels (3.0 mg/L).

Boron and mercury were below trigger values.

Pesticides

Pesticide concentrations were below laboratory limits of reporting in all groundwater monitoring wells during each sampling event.

Table 15 *Water quality (metals) at the Lexia Wetlands (2008–09)*

Site	**Collection date**	**Sample Depth (m)**	**Al (sol) mg/L**	**As (tot) mg/L**	**B (sol) mg/L**	**CD (tot) mg/L**	**Cr (tot) mg/L**	**Mn (tot) mg/L**	**Hg (tot) mg/L**	**Ni (tot) mg/L**	**Se (tot) mg/L**	**Zn (tot) mg/L**	**Fe** (tot) Mg/L
LXA_Ea	12/06/2008	40.0	5.1	0.038	0.084	0.0001	0.063	0.033	ND	0.042	0.002	0.007	2.2
LXA_Ea	30/07/2008	40.0	5.5	0.032	0.038	0.0001	0.2	0.011	0.0002	0.053	0.001	0.024	20.0
LXA_Ea	26/09/2008	40.1	2.1	0.023	0.033	0.0001	0.033	0.009	0.0001	0.04	0.001	0.042	1.1
LXA_Ea	04/12/2008	40.1	1.9	0.011	0.011	0.0001	0.025	0.007	0.0001	0.034	0.001	0.049	0.88
LXA_Ea	19/01/2009	40.0	1.4	0.007	0.026	0.0001	0.012	0.006	ND	0.009	0.002	0.019	0.86
LXA_Ea	02/04/2009	40.1	0.64	0.005	0.033	0.0001	0.02	0.006	0.0001	0.005	0.001	0.007	0.68
LXA_Ea	04/06/2009	40.1	0.86	0.004	0.027	0.0001	0.012	0.007	0.00005	0.003	0.001	0.007	0.61
LXA_Ea	03/07/2009	40.1	0.34	0.004	0.024	0.0001	0.018	0.006	0.0001	0.004	0.001	0.003	0.63
LXA_Ea average			**2.23**	**0.02**	**0.03**	**0.00**	**0.05**	**0.01**	**0.00**	**0.02**	**0.00**	**0.02**	**1.12**
Standard deviation			**1.99**	**0.01**	**0.02**	**0.00**	**0.06**	**0.01**	**0.00**	**0.02**	**0.00**	**0.02**	**0.63**
LXA_Eb	12/06/2008	23.5	3.5	0.007	0.058	0.0001	0.024	0.024	ND	0.014	0.004	0.011	1.3
LXA_Eb	30/07/2008	23.0	2.8	0.004	0.035	0.0001	0.034	0.014	0.0001	0.011	0.003	0.02	1.2
LXA_Eb	26/09/2008	23.7	2.9	0.003	0.031	0.0001	0.077	0.014	0.0001	0.034	0.005	0.047	1.1
LXA_Eb	04/12/2008	23.7	1.9	0.001	0.01	0.0001	0.025	0.01	0.0001	0.025	0.001	0.034	0.71
LXA_Eb	19/01/2009	23.0	1.5	0.001	0.025	0.0001	0.009	0.009	ND	0.003	0.002	0.025	0.66
LXA_Eb	02/04/2009	23.7	0.83	0.001	0.025	0.0001	0.033	0.008	0.0001	0.004	0.002	0.006	0.58
LXA_Eb	04/06/2009	23.7	1.3	0.001	0.023	0.0001	0.023	0.009	0.00007	0.003	0.002	0.012	0.5
LXA_Eb	03/07/2009	23.7	0.61	0.001	0.023	0.0001	0.039	0.008	0.0001	0.003	0.002	0.005	0.53
LXA_Eb average			**1.92**	**0.00**	**0.03**	**0.00**	**0.03**	**0.01**	**0.00**	**0.01**	**0.00**	**0.02**	**0.8225**
Standard deviation			**1.05**	**0.00**	**0.01**	**0.00**	**0.02**	**0.01**	**0.00**	**0.01**	**0.00**	**0.01**	**0.32**

ND No data

Site	Collection date	Sample Depth (m)	Al (sol) mg/L	As (tot) mg/L	B (sol) mg/L	CD (tot) mg/L	Cr (tot) mg/L	Mn (tot) mg/L	Hg (tot) mg/L	Ni (tot) mg/L	Se (tot) mg/L	Zn (tot) mg/L	Fe (tot) Mg/L
LXA_Ec	16/06/2008	5.0	1.3	0.001	0.06	0.0001	0.026	0.092	ND	0.019	0.001	0.013	4.8
LXA_Ec	30/07/2008	4.0	1.8	0.001	0.051	0.0001	0.038	0.077	0.0001	0.019	0.001	0.016	2.7
LXA_Ec	26/09/2008	4.0	0.91	0.001	0.038	0.0001	0.014	0.16	0.0001	0.012	0.001	0.025	2.2
LXA_Ec	04/12/2008	4.0	0.87	0.001	0.02	0.0001	0.014	0.11	0.0001	0.018	0.001	0.013	3.4
LXA_Ec	19/01/2009	2.6	0.92	0.001	0.011	0.0001	0.023	0.09	ND	0.021	0.002	0.05	5.4
LXA_Ec	02/04/2009	4.0	0.91	0.001	0.047	0.0001	0.01	0.016	0.0001	0.001	0.001	0.001	0.59
LXA_Ec	04/06/2009	4.0	1.2	0.001	0.056	0.0001	0.009	0.014	0.00005	0.001	0.001	0.002	0.34
LXA_Ec	03/07/2009	4.0	1.8	0.001	0.057	0.0001	0.009	0.053	0.0001	0.008	0.001	0.013	0.94
LXA_Ec average			**1.21**	**0.00**	**0.04**	**0.00**	**0.02**	**0.08**	**0.00**	**0.01**	**0.00**	**0.02**	**2.55**
Standard deviation			**0.39**	**0.00**	**0.02**	**0.00**	**0.01**	**0.05**	**0.00**	**0.01**	**0.00**	**0.02**	**1.90**
LXA_Wa	16/06/2008	50.5	0.71	0.066	0.02	0.001	1.0	0.31	ND	0.063	0.021	0.097	0.79
LXA_Wa	04/08/2008	50.0	0.18	0.03	0.01	0.0006	0.98	0.24	0.0004	0.045	0.007	0.067	0.75
LXA_Wa	25/09/2008	50.6	0.41	0.013	0.065	0.0004	0.29	0.18	0.0001	0.037	0.003	0.11	1.7
LXA_Wa	03/12/2008	50.6	0.44	0.01	0.01	0.0002	0.27	0.094	0.0001	0.017	0.002	0.16	2.5
LXA_Wa	19/01/2009	50.5	0.2	0.005	0.01	0.00	0.11	0.062	ND	0.014	0.002	0.076	2.5
LXA_Wa	01/04/2009	50.6	0.6	0.004	0.013	0.00	0.16	0.053	0.0001	0.005	0.001	0.01	2.0
LXA_Wa	03/06/2009	50.6	0.012	0.003	0.01	0.00	0.1	0.043	0.00005	0.003	0.001	0.026	1.8
LXA_Wa	02/07/2009	50.6	0.014	0.003	0.01	0.00	0.09	0.033	0.0001	0.003	0.001	0.01	1.8
LXA_Wa average			**0.32**	**0.02**	**0.02**	**0.00**	**0.38**	**0.13**	**0.00**	**0.02**	**0.00**	**0.07**	**1.73**
Standard deviation			**0.26**	**0.02**	**0.02**	**0.00**	**0.39**	**0.10**	**0.00**	**0.02**	**0.01**	**0.05**	**0.67**

ND No data

Site	Collection date	Sample Depth (m)	Al (sol) mg/L	As (tot) mg/L	B (sol) mg/L	CD (tot) mg/L	Cr (tot) mg/L	Mn (tot) mg/L	Hg (tot) mg/L	Ni (tot) mg/L	Se (tot) mg/L	Zn (tot) mg/L	Fe (tot) Mg/L
LXA_Wb	17/06/2008	28.500	0.65	0.006	0.077	0.0002	0.25	0.028	ND	0.014	0.27	0.039	0.3
LXA_Wb	04/08/2008	28.000	0.078	0.004	0.013	0.00	0.2	0.018	0.0003	0.009	0.096	0.028	0.4
LXA_Wb	25/09/2008	28.600	0.15	0.002	0.048	0.00	0.061	0.011	0.0001	0.016	0.013	0.024	0.6
LXA_Wb	03/12/2008	28.600	0.23	0.001	0.01	0.00	0.046	0.01	0.0001	0.01	0.016	0.029	0.64
LXA_Wb	19/01/2009	28.500	0.12	0.001	0.01	0.00	0.019	0.007	ND	0.003	0.007	0.026	0.48
LXA_Wb	01/04/2009	28.600	0.13	0.001	0.015	0.00	0.039	0.008	0.0001	0.002	0.016	0.005	0.3
LXA_Wb	03/06/2009	28.600	0.066	0.001	0.01	0.00	0.059	0.01	0.00011	0.002	0.028	0.013	0.28
LXA_Wb	02/07/2009	28.600	0.037	0.001	0.011	0.00	0.043	0.007	0.0001	0.002	0.019	0.004	0.3
LXA_Wb average			**0.18**	**0.00**	**0.02**	**0.00**	**0.09**	**0.01**	**0.00**	**0.01**	**0.06**	**0.02**	**0.41**
Standard deviation			**0.2**	**0.00**	**0.02**	**0.00**	**0.09**	**0.01**	**0.00**	**0.01**	**0.09**	**0.01**	**0.14**
LXA_Wc	17/06/2008	6.000	0.94	0.001	0.018	0.0001	0.099	0.021	ND	0.02	0.001	0.032	1.1
LXA_Wc	04/08/2008	4.000	0.48	0.001	0.015	0.0001	0.074	0.035	0.0001	0.021	0.001	0.036	0.72
LXA_Wc	25/09/2008	5.000	0.62	0.001	0.081	0.0001	0.017	0.017	0.0001	0.009	0.001	0.021	0.42
LXA_Wc	03/12/2008	5.000	1.0	0.001	0.01	0.0001	0.012	0.006	0.0001	0.03	0.001	0.067	0.58
LXA_Wc	19/01/2009	4.600	1.5	0.001	0.011	0.0001	0.009	0.004	ND	0.018	0.002	0.058	0.33
LXA_Wc	01/04/2009	5.000	0.94	0.001	0.019	0.0001	0.005	0.004	0.0001	0.001	0.001	0.001	0.19
LXA_Wc	03/06/2009	5.000	0.67	0.001	0.01	0.0001	0.004	0.004	0.00005	0.001	0.001	0.003	0.17
LXA_Wc	02/07/2009	5.000	0.33	0.001	0.013	0.0001	0.003	0.003	0.0001	0.001	0.001	0.001	0.15
LXA_Wc average			**0.81**	**0.001**	**0.02**	**0.00**	**0.03**	**0.01**	**0.00**	**0.01**	**0.00**	**0.03**	**0.46**
Standard deviation			**0.37**	**0.00**	**0.02**	**0.00**	**0.04**	**0.01**	**0.00**	**0.01**	**0.00**	**0.03**	**0.33**

ND No data

Summary of trigger level breaches

Trigger values for fresh water, irrigation water and drinking water were taken from and applied in accordance with the Department of Environment's 2010 *Assessment levels for soils, sediment and water*. Table 16 shows which parameters were found to be in breach of the various trigger values.

Significant breaches of assessment levels are:

- Values of pH breach assessment levels for all uses.
- Irrigation water trigger levels for Cr, Mn, Se and Fe were breached for some groundwater samples from the various bores.
- Freshwater guidelines were breached by groundwater samples for a number of metals – Al, As, Cd, Ni, Se, and Zn. Cr did breach levels but must be noted that guideline values use dissolved concentrations.
- Drinking water guideline concentrations were exceeded by of Al, As, Cr, Fe, Ni and Se.

Table 16 Trigger level breaches

	Australia wide trigger values		
	Fresh waters	**Irrigation water**	**Drinking water**
pH	All below lower limit of 6.5	N/A	As for Australian fresh water
Al	All samples exceed	Below	All exceed except some from LXA_Wa and LXA_Ea
As	Some samples from LXA_Ea and LXA_Wa exceeded	Below	Some samples from LXA_Ea and LXA_Wa exceeded
Cd	All below except some from LXA_Ea	Below	Below
Cr	All samples exceeded	One sample exceeded at LXA_Wa	Some samples exceeded
Fe	N/A	All exceed except some samples from LXA_Wc	All exceed except some samples from LXA_Wc
Mn	Below	Below, but one sample exceeded at LXA_Wa	Below
Ni	Some samples exceeded at all bores	Below	Some samples exceeded at all bores
Se	LXA_Wb exceeded on one occasion	LXA_Wb exceeded on one occasion	LXA_Wb exceeded on one occasion
Zn	Majority of samples exceeded	Below	Below

5.8 Findings

The regional decline of the watertable appears to have affected the chemistry of both groundwater and (when in continuity), wetland water[5]. These changes are considered to be due to several hydrogeochemical processes predominantly influenced by the sulfidic content of the sediment in the upper lithology (the Bassendean Sands), which becomes oxidised following drawdown of the watertable as follows:

$$FeS_2 + 7/2\ O_2 + H_2O \rightarrow Fe^{2+}\ 2H^{+} + 2SO_4^{2-}$$

where FeS_2 indicates sulfidic material as pyrite. This process leads to the generation of sulfuric acid, and a subsequent decrease in groundwater pH.

The SGS investigation reported elevated sulfidic content in the eastern cluster of wells (41.4 to 42.5 m AHD) which is below the current reported groundwater elevation (Figure 37). This sulfidic sediment is representative of potential acid sulfate soil. As the groundwater is currently inundating this layer, there would appear to be a low risk of this layer becoming exposed to oxygen and generating further acidity.

However, the groundwater sampled from the shallow watertable (above the elevated zone of sulfidic material) indicates a significant sulfate content in comparison to groundwater at depth, as well as a low pH (although groundwater across all depths generally has a low pH). Elevated concentrations of soluble Fe are also evident in the shallow groundwater, which is considered to be associated with solubilisation of Fe as a result of pyrite (FeS_2) oxidation.

The Lexia Wetlands groundwater samples generally have a sodium–chloride composition, as noted in Gnangara Mound groundwaters sampled in the course of other studies (DoW 2010). That is, the groundwater composition is considered to be a result of rainfall recharge. Therefore the reported elevated sulfate concentrations in the shallow groundwater would appear to be uncommon to regional groundwater (as evidenced by the lower concentrations of sulfate in groundwater sampled at depth). In particular, the eastern shallow groundwater reports a significantly elevated sulfate content, which has a significantly different sulfate:chloride ratio to the other groundwaters sampled.

It is considered that the elevated sulfate concentration in the shallow groundwater has probably originated from the oxidation of sulfidic material, with the sulfate generated being present as sulfuric acid.

Thus the regional shallow watertable decline has led to stored acidity in the soil above the shallow watertable. This process has been observed across the Gnangara Mound (Appleyard and Cook 2008).

The combined effect of low precipitation and lowering of the regional watertable leads to the groundwater becoming acidic with pH values being generally less than pH 5.

---

[5] Based on comparison of limited historical major cation–anion surface water data indicating connectivity between surface water and groundwater at the wetlands.

Elevated concentrations of pH sensitive heavy metals are also generally observed (e.g. as per the elevated concentrations of Al^{3+} in the eastern nested wells).

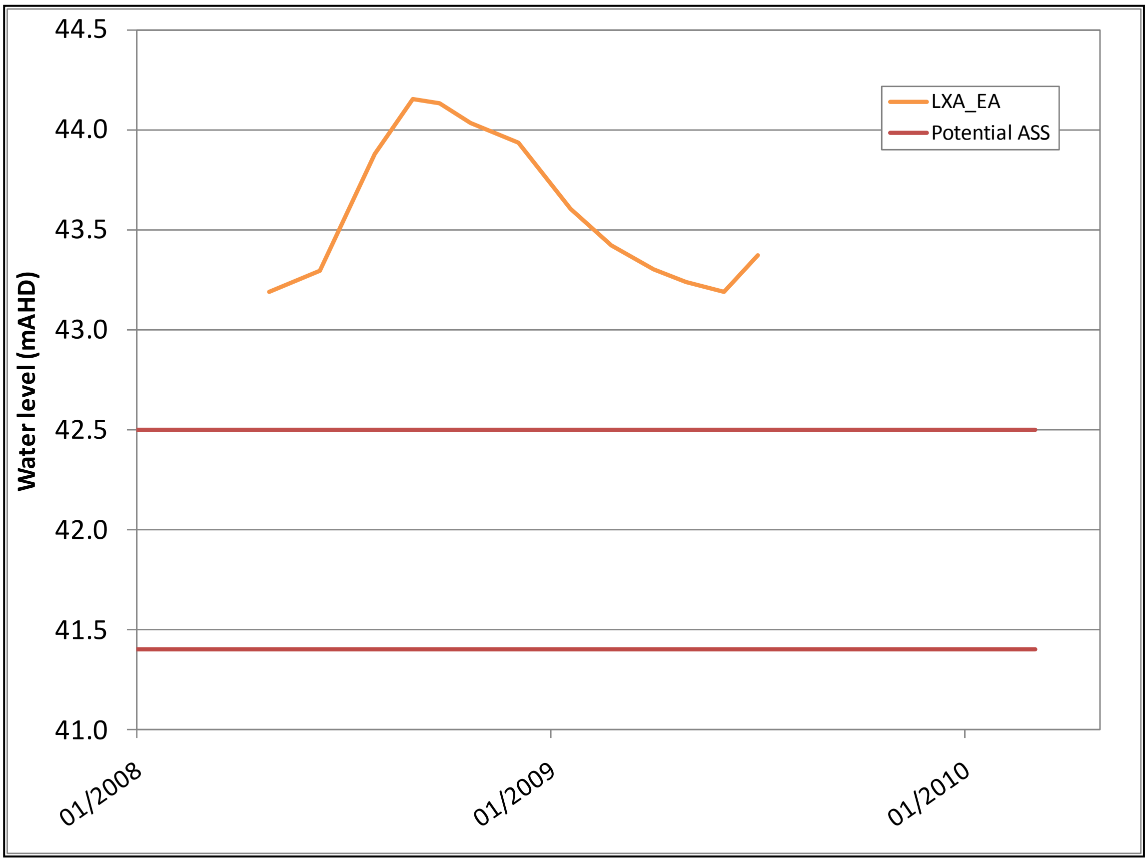

Figure 37 Zone of sulfidic material in relation to shallow groundwater fluctuation

As noted by Simonsson et al. (1999) and Appleyard and Cook (2008), the progressive drying of these sediments (and decrease in pH), considerably increases the solubility of Al^{3+}, which generally is increasingly soluble below pH 4.5.

As with shallow hydrogeochemical processes observed at Lake Mariginiup (DoW 2010), the low pH groundwater observed in the shallow groundwater could also be partly attributed to two other major processes:

- Natural acidification caused by decomposition of vegetation, creating organic acids through CO_2 production and root respiration. However, this process is unlikely to produce pH values below 4.6 (Appelo & Postma 2007)

- Acidification via nitrification. The high concentrations of NO_x, positive Eh values and acidic conditions reported in the shallow eastern groundwater is suggestive of nitrification. Excess ammonium (e.g. from regional fertiliser use up hydraulic gradient) undergoes nitrification, releasing H^+, and lowering the pH, as follows:

$$NH_3 + CO_2 + 1.5\ O_2 + \textit{Nitrosomonas}\ \text{spp.} \rightarrow NO_2^- + H_2O + H^+$$

$$NO_2^- + CO_2 + 0.5\ O_2 + \textit{Nitrobacter}\ \text{spp.} \rightarrow NO_3^-$$

$$NH_3 + O_2 \rightarrow NO_2^- + 3H^+ + 2e^-$$

$$NO_2^- + H_2O \rightarrow NO_3^- + 2H^+ + 2e^-$$

Oxidation of organic rich sediments within the lake basin could also be contributing to nutrient enrichment in the wetland area, through a process known as internal eutrophication. Water level decline can lead to the progressive oxidation of organic rich sediments near wetlands, which can release both nitrogen and phosphorus into the groundwater (Smolders et al. 2006). Note that ammonium generally decreases with depth. In the eastern nested wells, this may at least be partly attributable to nitrification, which appears to be particularly evident in the eastern nested wells where NO_x was reported in the shallow zone.

A fourth possible source of elevated acidity in groundwater maybe the absence of buffering of carbonic acid derived from rainfall, which may make a token contribution to groundwater acidity, as the influx of CO_2 drives carbonate equilibria away from bicarbonate to carbonic acid, particularly given that there is little bicarbonate buffering available in the sediment and groundwater:

$$CO_{2(g)} \rightarrow CO_{2(aq)}$$

$$CO_{2(aq)} + H_2O \rightarrow H_2CO_3$$

$$H_2CO_3 \leftrightarrow H^+ + HCO_3^-$$

$$HCO_3^- \leftrightarrow H^+ + CO_3^{2-}$$

$$CaCO_3 \leftrightarrow Ca^{2+} + CO_3^{2-}$$

However, of all the possible acidification processes, it is considered that pyrite oxidation, that is the exposure of sulfidic material, is the predominant acid generating mechanism, especially in the shallow lithology, as evidenced by:

- the presence of significant sulfidic material within the shallow lithology (eastern aspect of wetlands), below the zone of groundwater fluctuation, indicating that historical sulfidic material above the sulfidic zone has possibly been oxidised and generated sulfuric acid (H_2SO_4)
- a significant and uncommon (in relation to vertical profiling of groundwater) sulfate concentration in the shallow groundwater

- significantly elevated SO_4^{2-}:Cl^- ratio indicative of sulfide oxidation
- elevated Fe concentrations as a result of liberation of Fe previously bound in pyrite.

In addition, in low oxygen environments (i.e. sediments inundated by groundwater) the oxidising potential of nitrate is nearly as strong as oxygen (Smolders et al. 2006). Nitrate reduction can couple to pyrite oxidation and accelerate groundwater acidification (Figure 38). This process can create similar water quality problems as those caused by oxidation of acid sulfate soils, but without needing falling water levels to trigger the process. Elevated concentrations of SO_4^{2-} produced by pyrite oxidation can outcompete PO_4^{3-} for anion adsorption sites and cause an increase in PO_4^{3-} in anoxic conditions (Smolders et al. 2006; Beltman et al. 2000).

Nitrate which is not used in pyrite oxidation either undergoes denitrification and is lost to the system as a gas, or undergoes partial denitrification to ammonia (dissimilatory nitrate reduction to ammonium). Partial reduction of nitrate towards the base of the aquifer is thought to be responsible for the elevated concentrations of ammonia and ammonium. This is indicated by the physical and chemical properties of samples from the deep and intermediate down-gradient (western) bores. The samples were reducing and anoxic, and were depleted in nitrate and were enriched in ammonia and ammonium.

In summary, the groundwater in continuity with the wetlands is acidic (and likely to be continually acidic) due to the store of acidity in the sediments, which is present as a result of fluctuation (and overall decline) of groundwater level, causing oxidation of acid generating sulfidic sediment.

An assessment of the reported Al^{3+} concentration in groundwater indicates the risk to ecology from elevated concentrations of pH dependent heavy metals. Any dilution effect of groundwater with lower metal concentrations discharging into the wetlands may be lost due to less of the regional groundwater flow interacting with the wetlands, compared to assumed historical flow.

As a result, when the wetlands do hold water it is likely to be acidic and have elevated heavy metal concentrations, which is of concern to wetlands ecology.

The interaction process between groundwater and surface water may be demonstrated by the low pH historically reported in surface water at sampling site GNM 16SG (pH 4.4), which has historically reported a similar composition to the shallow groundwater[6]. In both the sediment and water systems, the problem of acidification is possibly being exacerbated by the general low alkalinity.

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[6] The composition of surface water is based on one sample from 2000, and therefore the surface water dataset, and the assessment of groundwater and surface water interaction is limited to an historical assessment only.

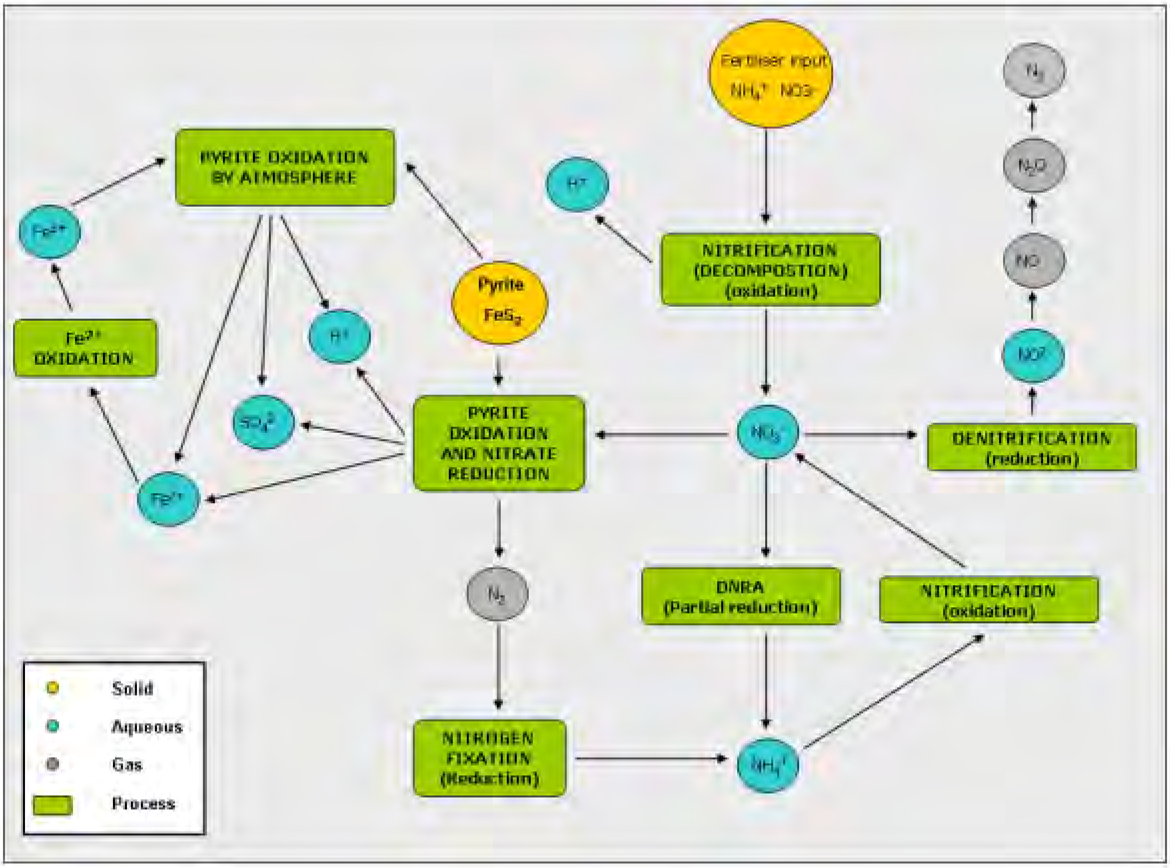


Figure 38 Possible interaction of the nitrogen and sulfur cycles at the Lexia Wetlands (after DoW 2010)

6 Implications for ecological values and management recommendations

The results of the investigation have provided an understanding of the local hydrogeology and hydrogeochemistry at the Lexia Wetlands. This understanding can be applied to the ecological trends observed at the wetlands and this combined with local area modelling will inform management recommendations.

6.1 Monitoring infrastructure

The monitoring infrastructure installed during the SGS investigation has improved the ability to monitor water levels, water quality and hydrogeochemistry in and around the Lexia Wetlands. Lexia 86 and Lexia 186 were last inundated in 1996 and 2008 respectively. (refer to Figure 8, Section 2.5).

Groundwater levels at these wetlands correspond well with surface water levels when the wetlands are inundated. As such groundwater levels at these sites can be used to measure EWRs determined for the wetlands.

There is no staff gauge at Lexia 94. Froend et al. (2004b) reported that no surface water has been present at this wetland for a number of years. It is recommended that a staff gauge is installed at this site to record surface water if present.

Froend et al. (2004b) stated that GNM15, GNM16 and GNM17A should be used to measure groundwater levels for the EWRs set for vegetation. These three monitoring bores are quite shallow (less than 3 m deep) (McHugh & Bourke 2007). If water levels continue to decline, they may decrease to a level that can not be measured at these bores.

6.2 Summary wetland conceptualisation

The updated conceptualisation of the Lexia Wetlands is shown in Figure 43 (represented by data from Lexia 86 and Lexia 94). It is assumed, for the purpose of this summary, that the broad concepts at these two basins are applicable across the whole of the Lexia Wetlands.

The new drilling has confirmed that the Lexia Wetlands lie in an area that is underlain by mostly sandy sediments (Bassendean Sands) that are approximately 48 m thick. The presence of medium grained sands (and lack of clayey soils that may create perching) beneath the wetlands suggests a relatively low water holding capacity. This means that seasonal rainfall recharge may not be retained for long periods in the soil profile and consequently, terrestrial vegetation is more likely to rely on moisture from depth at the capillary fringe that lies above the watertable.

Groundwater is relatively shallow in this area (2 to 5 m), but is not currently connected with the wetland basins. respectively. At Lexia 86 the groundwater level intersected the base of the wetland every 2 to 3 years in the 1990s and early 2000s, however, this has only occurred once since 2005. This indicates that EWRs for vertebrates and macroinvertebrates are no longer met. These EWRs are unlikely to be met in the future if the trends measured over that past 10 to 15 years persist. A seasonal pattern in groundwater level fluctuation occurs at this site highlighting the influence of rainfall recharge in winter–spring and evapotranspiration in summer–autumn. Evapotranspiration is a significant control on groundwater levels (given the shallow watertables in this area) and buffers regional influences on groundwater levels.

It is likely that groundwater levels are also influenced by regional groundwater abstraction. Monitoring has shown a series of steep declines in groundwater levels since the mid 1990s rather than continuous (gradual) declines, suggesting that groundwater levels may be responding to specific events.

The groundwater system operating in the vicinity of the Lexia Wetlands is considered to be in hydraulic connection with the regional groundwater system. There is a downward vertical groundwater gradient measured between the shallow (Superficial) and deeper (Mirrabooka) aquifers at this site, and the regional groundwater elevation data suggests the local groundwater flow pattern at Lexia is in continuity with the regional flow patterns.

The strong connection between the local and regional systems means that land and water practices occurring remote from Lexia (such as changing rates of abstraction and changing area of pine plantations) could affect groundwater levels locally, via the regional flow system. For example, groundwater modelling has indicated that a reduction in the area of pine plantation and reduction in abstraction is likely to result in groundwater level increases at Lexia to levels similar to those measured in the 1990s.

While the focus of the EWR concept is on groundwater levels, water quality issues that were evident from the chemical sampling and analysis undertaken should also be taken into account. Furthermore, the decline in groundwater levels could affect the chemistry of groundwater and the unsaturated soil.

There is a plume of dissolved metals, nutrients and acidity that migrates through the wetlands with the regional direction of groundwater flow (west to east). If groundwater level falls, acidity is generated and pH dependent heavy metals (e.g. aluminium) are released into the environment. If the pH falls below 5, aluminium ions are mobilised. This can lead to the stunting of root growth (for species that have roots exposed in this groundwater flux zone) and may result in an overall slowing of plant growth and development.

This suggests that even if groundwater level remains above the accepted vegetation EWR there may still be risks to vegetation health.

Trees derive their nutrition from dissolved ions in the soil including calcium, magnesium and potassium. When leaching of these ions occurs, they are washed deeper into the subsoil or into the groundwater system and migrate through the wetlands where they are no longer available for roots of plants. The migration of dissolved metals, nutrients and acidity through the wetland could have undesirable effects on vegetation and has contributed to ecological decline.

6.3 Land and water use

In order to improve the ecological condition of groundwater-dependent ecosystems at the Lexia Wetlands, water levels need to rise. Local-scale numerical modelling (SKM 2009) predicted that the greatest gains in water levels (0.5–1.0 m) would occur under the combined effect of harvesting pine plantations and reduced abstraction for the public water supply (by 3.5 GL/yr). This was discussed previously in Section 5.6.

This best-case scenario (base case), would allow for a 0.5–1.0 m rise in the watertable over the next 20 years. If this rise is experienced at each wetland, groundwater levels will be above the wetlands' respective Ministerial criteria (absolute minimum and preferred minimum). This magnitude of rise would eventually lead to an improvement in vertebrate and macroinvertebrate communities with the watertable being above their respective EWR levels. Improvement is dependent on the ability of the ecosystems to persist under current conditions until water level and water quality improve.

The implications of watertable rise on water quality are uncertain. Raising the water levels around the Lexia Wetlands will help prevent further oxidation of acid sulfate soils and increase water availability for groundwater-dependent ecosystems. It is likely that some seasonal flushing of metals into the groundwater occurs as the watertable rises during winter (Figure 43). Further investigation is required to determine the rates of reactions that lead to the flushing of such metals.

Modelling indicated that reduction in groundwater abstraction for the public water supply combined with pine clearing yielded positive results. A modelling scenario was also carried out under a drier climate regime (scenario Sc1) which suggested there will be an impact on the level of groundwater recovery. Perth is expected to experience a drier climate into the future (IPCC 2007) which is likely to affect groundwater levels across the Gnangara Mound. This suggests scenario Sc1 is a likely representation of future groundwater levels.

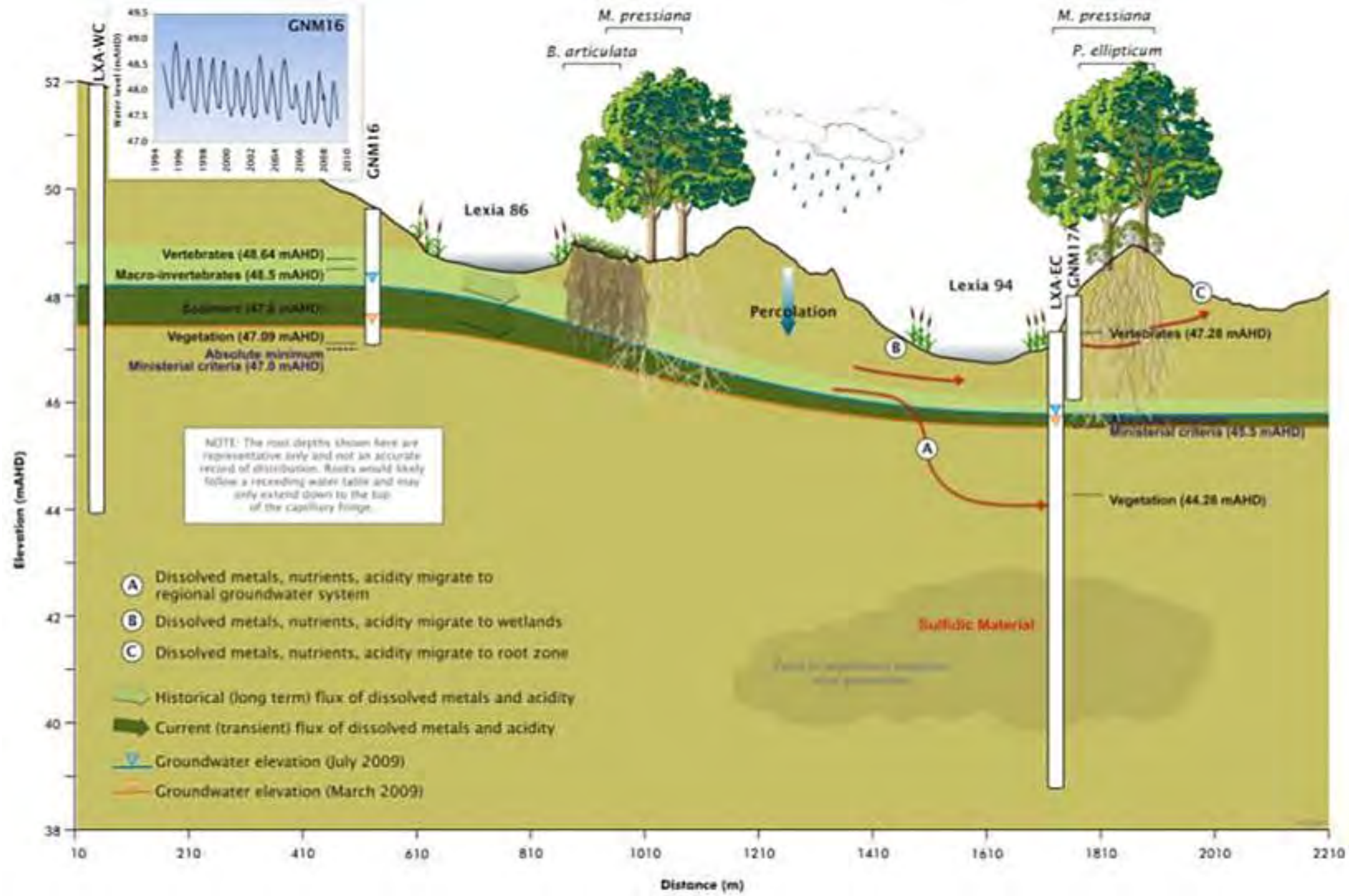


Figure 39 EWRs for groundwater dependent ecosystems at Lexia Wetlands

6.4 Soil and groundwater quality implications

An increase in the acidity of an aquatic ecosystem can be considered a stressor which is directly toxic to aquatic ecosystems (ANZECC 2000). The pH level of surface water measured at the Lexia Wetlands during sampling conducted in 2000 was below the trigger values for freshwater ecosystems and wetlands in south-western Australia.

High concentrations of heavy metals, which are known to be directly toxic to aquatic ecosystems, are associated with acid flux from pyritic sediments, and would exacerbate the decline in ecosytem health (ANZECC 2000). Heavy metals (e.g. Al^{3+}) were reported, particulary on the eastern aspect of the wetlands, which may migrate to the waterbody.

The high acidity of the groundwater may also pose a threat to the riparian vegetation. In particular, the mobilisation of Al^{3+} into the groundwater may put the vegetation at risk of 'acid toxicity'. Acid toxicity occurs when the mobilisation of Al^{3+} induces a reduction of the molar Ca:Al and Mg:Al ratios in the groundwater which reduces root growth, inhibits the uptake of Ca^{2+} and Mg^{2+} by fine roots, and reduces the water conductivity of the roots (Caspary 1991). This is compounded by further depeletion of Ca^{2+} and Mg^{2+} from sediment by acidic groundwater.

It is possible that acid toxicity is partially responsible for the declining health of riparian vegetation at the Lexia wetlands. This highlights that groundwater quality, in addition to compliance with criteria levels and ecological water requirements, should be assessed when assigning causes for change in ecological condition.

Further investigation into the diffusion rates of oxygen (and other oxidants) in organic-rich silty sediments is required to fully understand the rates of acid sulfate soils oxidation, the formation of products and the depths of water levels required to keep acid sulfate soils -bearing sediments from oxidising.

Increasing water levels around Lexia may help prevent further oxidation of acid sulfate soils, and increase water availability to the ecosystem. However, in the short term, it could also mobilise more metals into the system. Watertable rise is likely to mobilise more Al^{3+} from previously desiccated soils.

The acidification processes and commensurate effects (and vertical and lateral fluxes) in the shallow lithology could be better understood via PHREEQC modelling.

The elevated level of nutrients in the groundwater may also have negative effects on wetland ecology. NH_4, and TN exceed trigger levels for freshwater ecosystems and wetlands in south-western Australia. NH_4 can be directly toxic to aquatic ecosystems, particularly fish, and excessive nitrogen can indirectly affect the ecosystem by causing algal growth and cyanobacterial blooms.

6.5 Management considerations

To improve the ecological condition of Lexia Wetlands and reduce the threat of condition declines, groundwater levels need to increase. However, a rise in groundwater levels may lead to further environmental impacts relating to the creation or exacerbation of acidic groundwater. Changes in groundwater quality associated with any rise in groundwater levels should be monitored.

The main management considerations are:

- What can be done to increase groundwater levels at the Lexia Wetlands?
- How will an increase in groundwater levels affect groundwater quality and ecological condition?

Groundwater modelling may assist in determining what actions should be taken to increase groundwater levels. Possible actions include:

- reducing nearby groundwater abstraction
- increasing recharge though schemes such as SWALES
- removal of the neighbouring pine plantation.

The ecological and groundwater monitoring data indicates that the revised ecological water requirements developed by Froend et al. in 2004 should be used as a guide to managing the hydrological requirements of ecological assets. It is clear that current groundwater conditions do not generally meet these requirements at the Lexia Wetlands.

The following management recommendations are suggested:

- The department should continue to endorse the Forest Products Commission pine harvesting schedule.
- Further analysis of the risks of acid sulfate soils at the Lexia Wetlands should be undertaken.
- The revised ecological water requirements documented in Froend et al. (2004b) should be used to assess as the basis for developing environmental water provisions.
- Further testing of scenarios using groundwater models should be undertaken to determine the changes to land and water use needed to meet the revised environmental water provisions.
- Depending on results from the modelling, reducing abstraction should be considered as a way to meet the environmental water provisions.
- Monitoring of groundwater, surface water and ecological conditions at Lexia Wetlands should continue.

Appendices

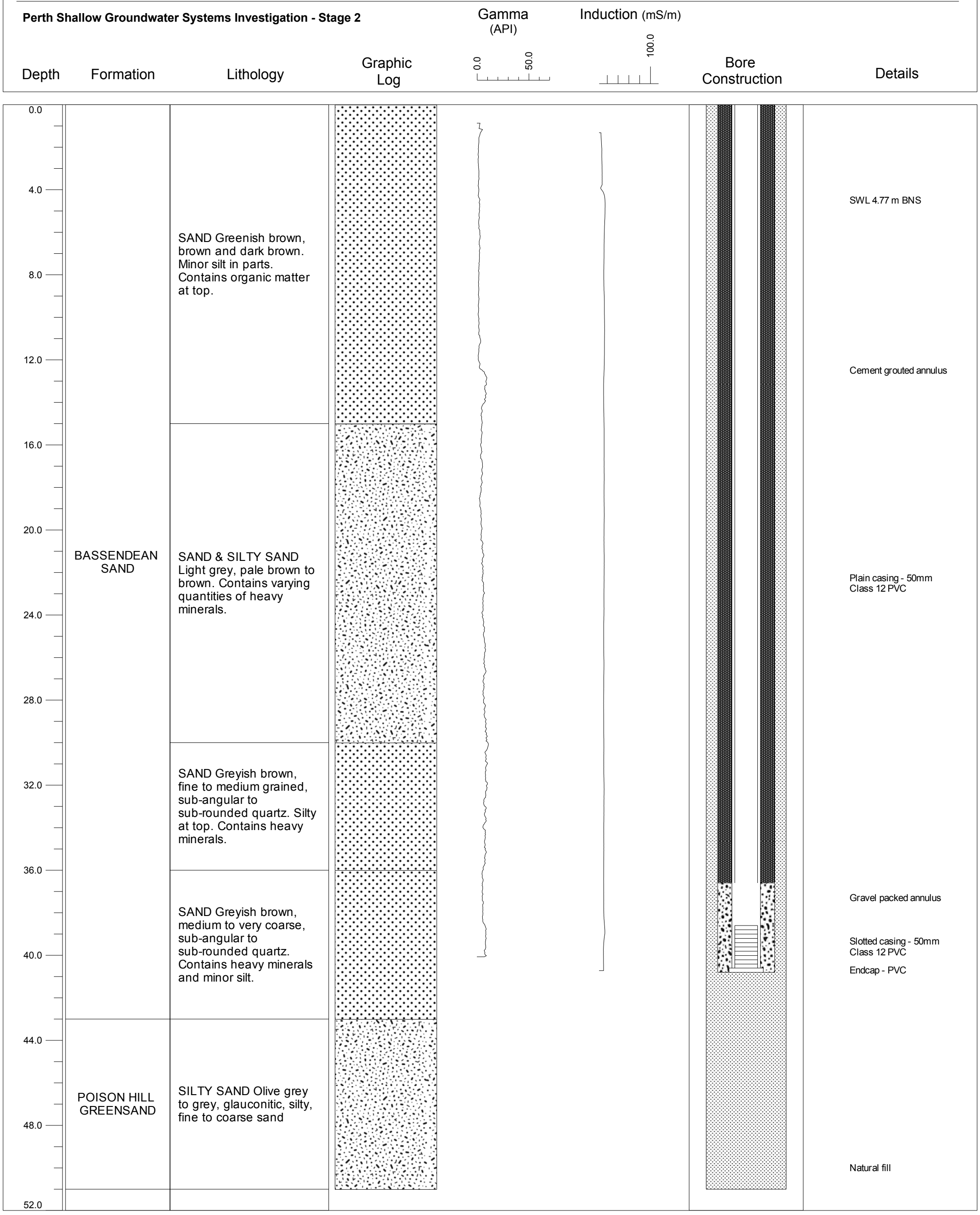
Appendix A – Bore construction diagrams

Department of Water
Government of Western Australia

BORE COMPLETION DETAILS

AWRC Name: **LXA_Ea**
AWRC Number: **61611854**

Perth Shallow Groundwater Systems Investigation - Stage 2



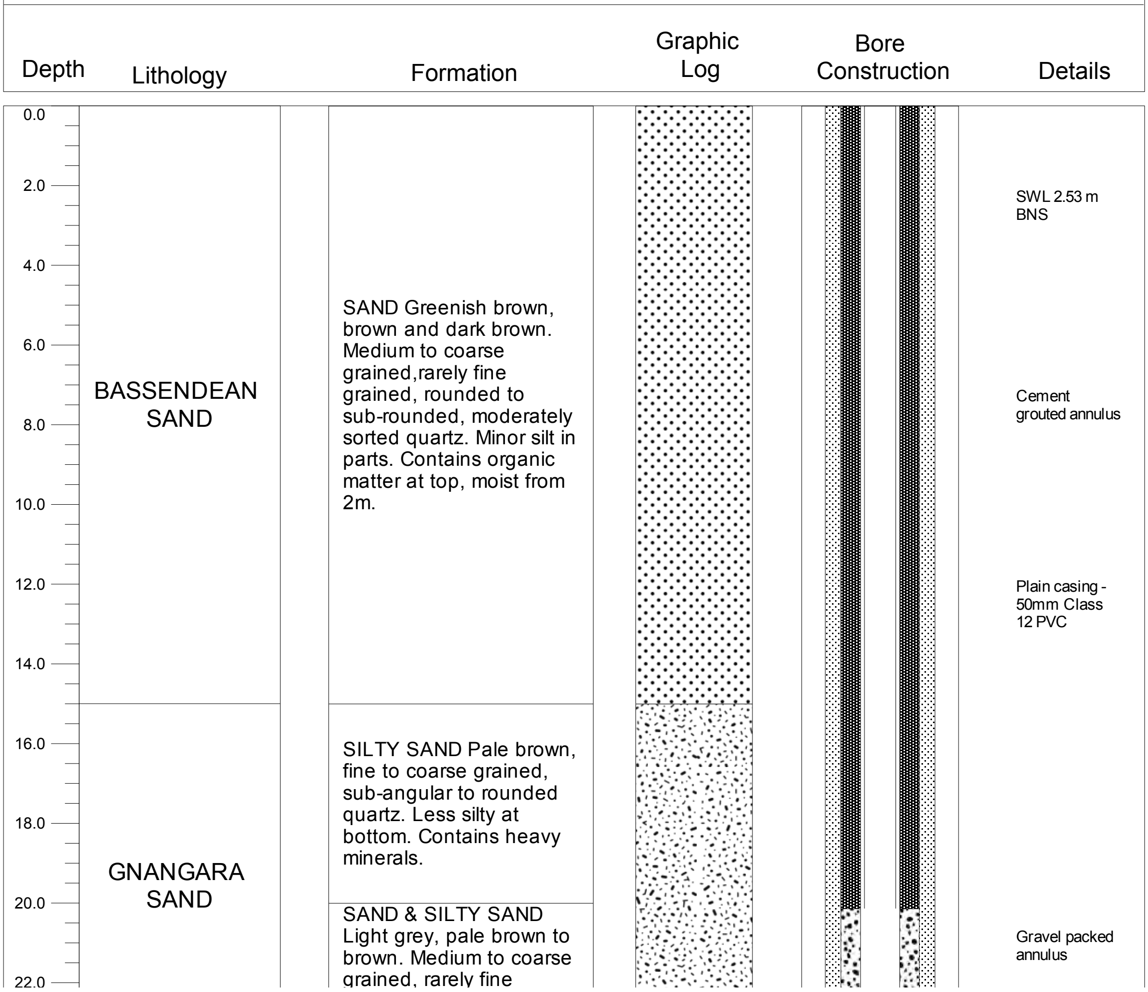
Drilled by:	Great Southern Drilling	Northing (Z50):	6486440.39	Screens (m BNS):	38.58 - 40.58
Date drilled:	4/18/08	Easting (Z50):	402821.89	SWL (m BNS):	4.77
Logged by:	Sarah Bourke	Surface (m AHD):	47.41	EC (mS/m):	46000
Aquifer:	Superficial	Drill depth (m BNS):	51	pH:	5.8

Department of Water
Government of Western Australia

BORE COMPLETION DETAILS

AWRC Name:	**LXA_Eb**
AWRC Number:	**61611855**

Perth Shallow Groundwater Systems Investigation - Stage 2



SAND Greenish brown, brown and dark brown. Medium to coarse grained,rarely fine grained, rounded to sub-rounded, moderately sorted quartz. Minor silt in parts. Contains organic matter at top, moist from 2m.

SILTY SAND Pale brown, fine to coarse grained, sub-angular to rounded quartz. Less silty at bottom. Contains heavy minerals.

SAND & SILTY SAND Light grey, pale brown to brown. Medium to coarse grained, rarely fine

SWL 2.53 m BNS

Cement grouted annulus

Plain casing - 50mm Class 12 PVC

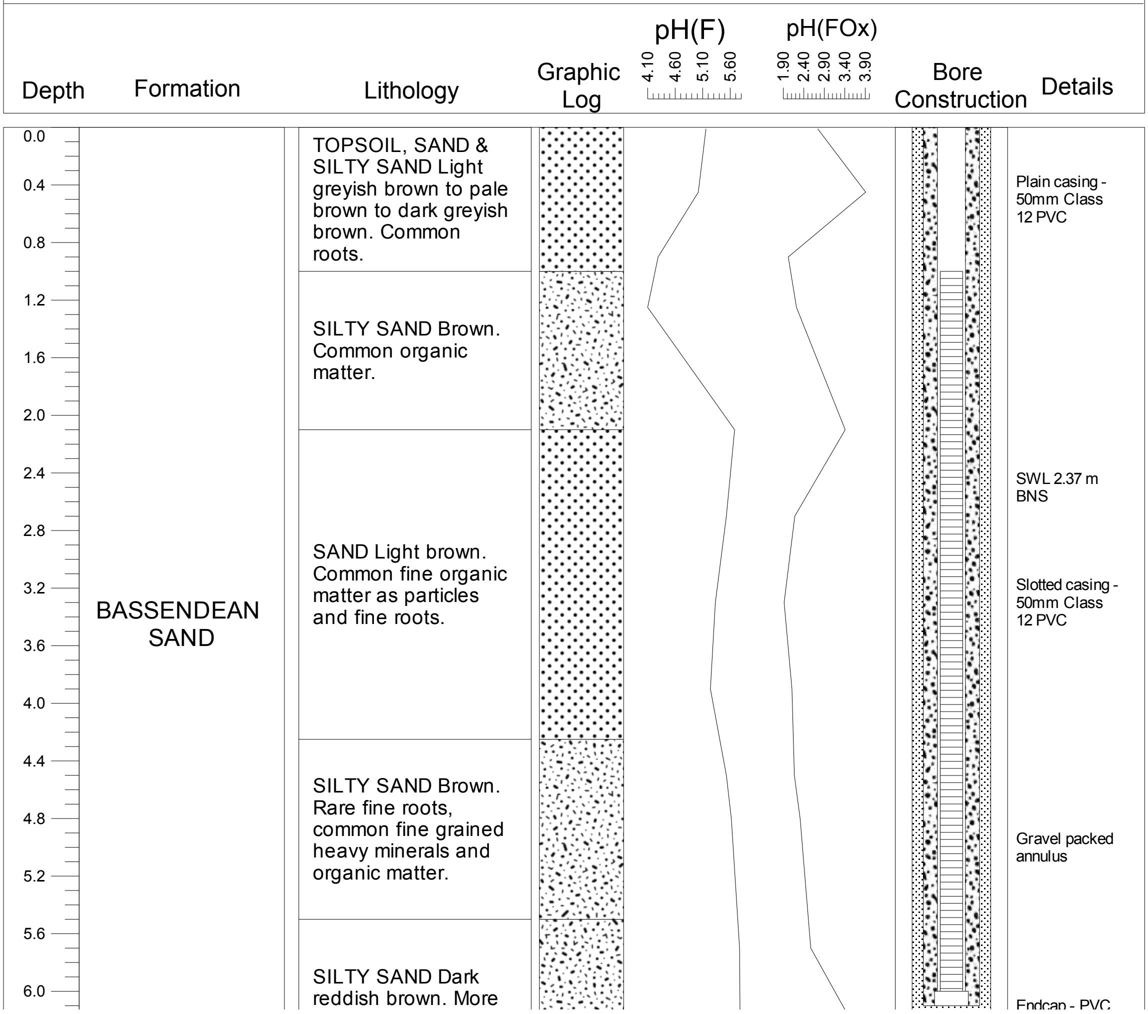
Gravel packed annulus

Department of Water
Government of Western Australia

BORE COMPLETION DETAILS

AWRC Name: **LXA_Ec**
AWRC Number: **61611849**

Perth Shallow Groundwater Systems Investigation - Stage 2



TOPSOIL, SAND & SILTY SAND Light greyish brown to pale brown to dark greyish brown. Common roots.

SILTY SAND Brown. Common organic matter.

SAND Light brown. Common fine organic matter as particles and fine roots.

SILTY SAND Brown. Rare fine roots, common fine grained heavy minerals and organic matter.

SILTY SAND Dark reddish brown. More

Plain casing - 50mm Class 12 PVC

SWL 2.37 m BNS

Slotted casing - 50mm Class 12 PVC

Gravel packed annulus

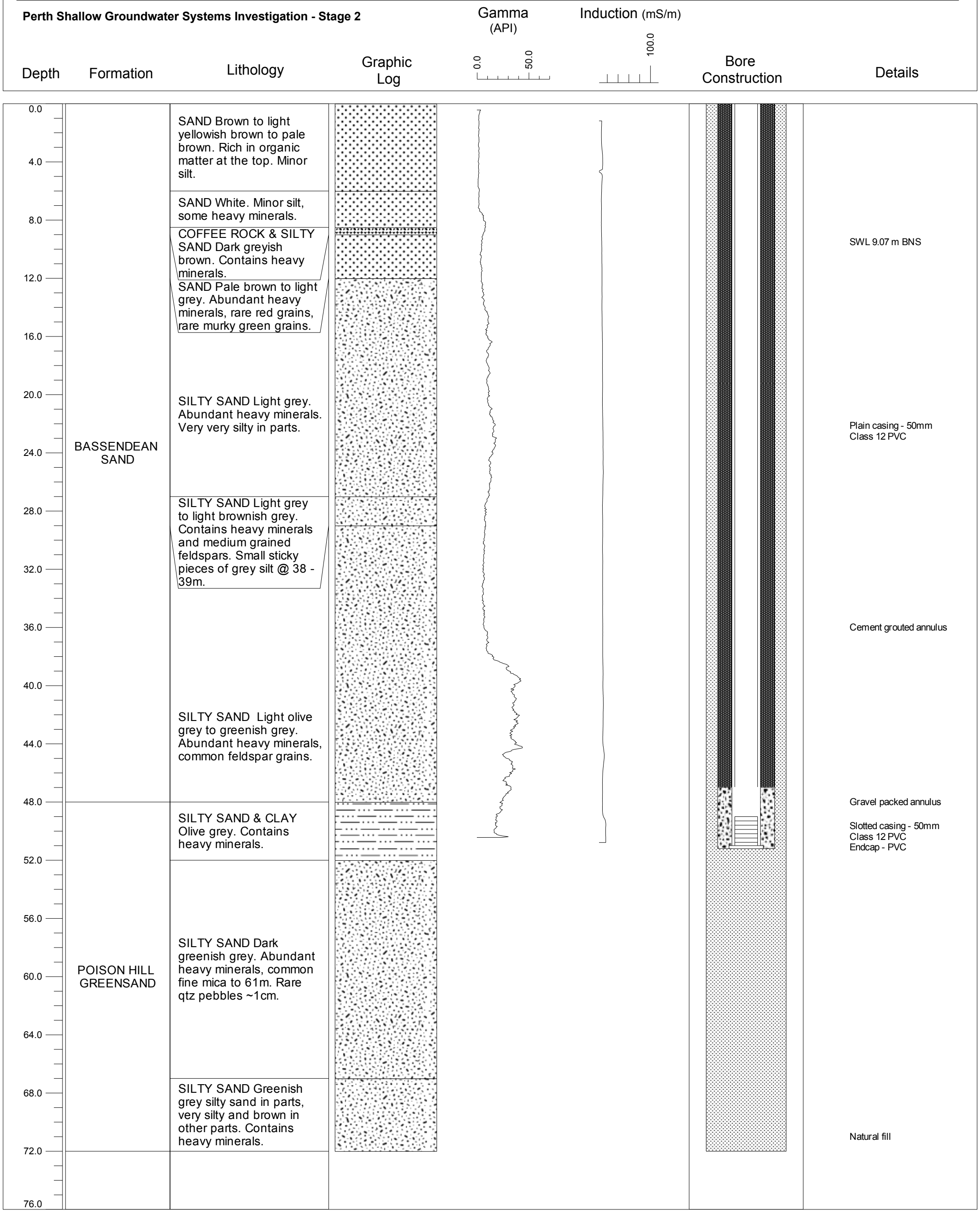
Endcap - PVC

Department of Water
Government of Western Australia

BORE COMPLETION DETAILS

AWRC Name: **LXA_Wa**
AWRC Number: **61611856**

Perth Shallow Groundwater Systems Investigation - Stage 2



BASSENDEAN SAND

SAND Brown to light yellowish brown to pale brown. Rich in organic matter at the top. Minor silt.

SAND White. Minor silt, some heavy minerals.

COFFEE ROCK & SILTY SAND Dark greyish brown. Contains heavy minerals.

SAND Pale brown to light grey. Abundant heavy minerals, rare red grains, rare murky green grains.

SILTY SAND Light grey. Abundant heavy minerals. Very very silty in parts.

SILTY SAND Light grey to light brownish grey. Contains heavy minerals and medium grained feldspars. Small sticky pieces of grey silt @ 38 - 39m.

SILTY SAND Light olive grey to greenish grey. Abundant heavy minerals, common feldspar grains.

POISON HILL GREENSAND

SILTY SAND & CLAY Olive grey. Contains heavy minerals.

SILTY SAND Dark greenish grey. Abundant heavy minerals, common fine mica to 61m. Rare qtz pebbles ~1cm.

SILTY SAND Greenish grey silty sand in parts, very silty and brown in other parts. Contains heavy minerals.

SWL 9.07 m BNS

Plain casing - 50mm
Class 12 PVC

Cement grouted annulus

Gravel packed annulus

Slotted casing - 50mm
Class 12 PVC
Endcap - PVC

Natural fill

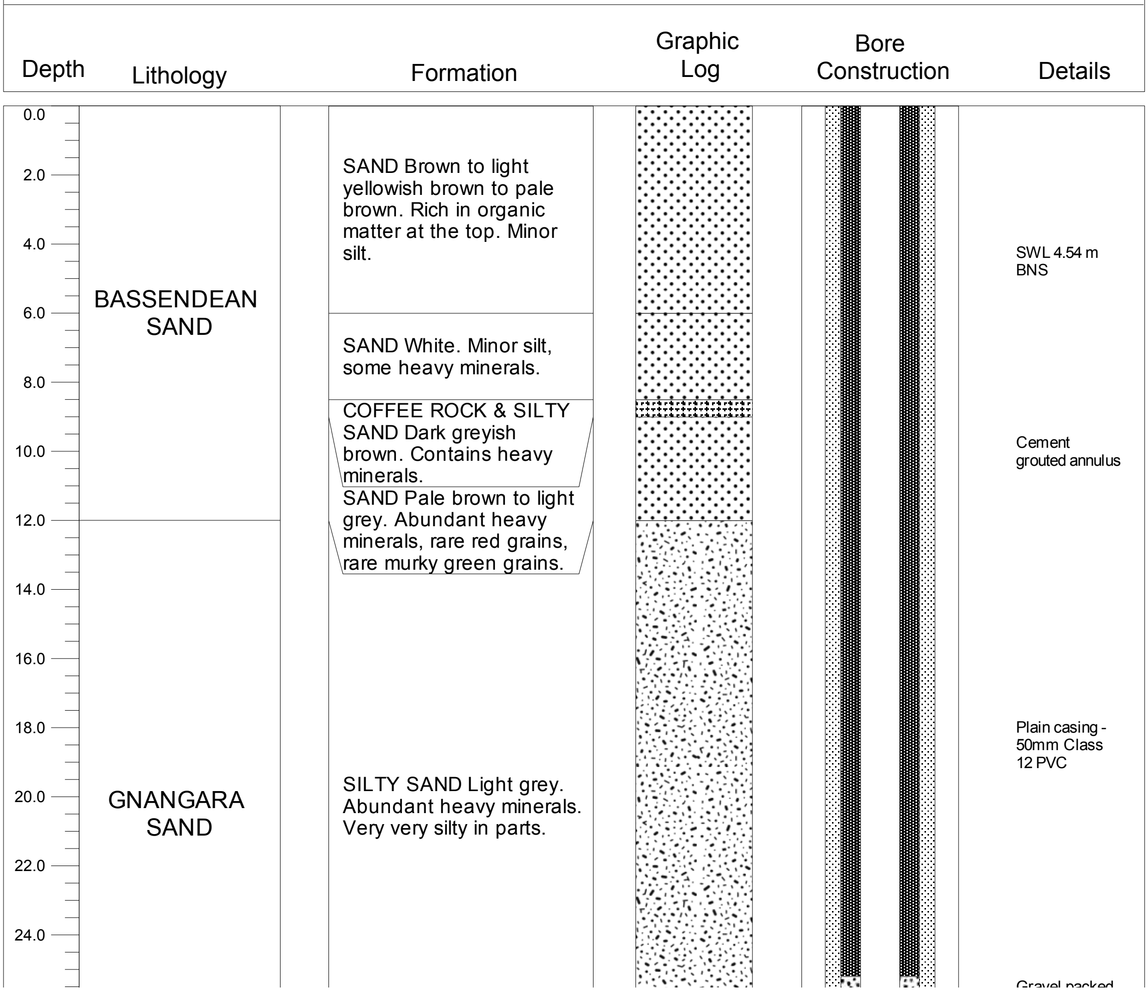
Drilled by:	Great Southern Drilling	Northing (Z50):	6487083.52	Screens (m BNS):	49.05 - 51.05
Date drilled:	4/22/08	Easting (Z50):	401208.52	SWL (m BNS):	9.07
Logged by:	Josephine Searle	Surface (m AHD):	51.94	EC (mS/m):	20000
Aquifer:	Superficial	Drill depth (m BNS):	72	pH:	6.4

Department of Water
Government of Western Australia

BORE COMPLETION DETAILS

AWRC Name:	**LXA_Wb**
AWRC Number:	**61611857**

Perth Shallow Groundwater Systems Investigation - Stage 2



SAND Brown to light yellowish brown to pale brown. Rich in organic matter at the top. Minor silt.

SAND White. Minor silt, some heavy minerals.

COFFEE ROCK & SILTY SAND Dark greyish brown. Contains heavy minerals.

SAND Pale brown to light grey. Abundant heavy minerals, rare red grains, rare murky green grains.

SILTY SAND Light grey. Abundant heavy minerals. Very very silty in parts.

SWL 4.54 m BNS

Cement grouted annulus

Plain casing - 50mm Class 12 PVC

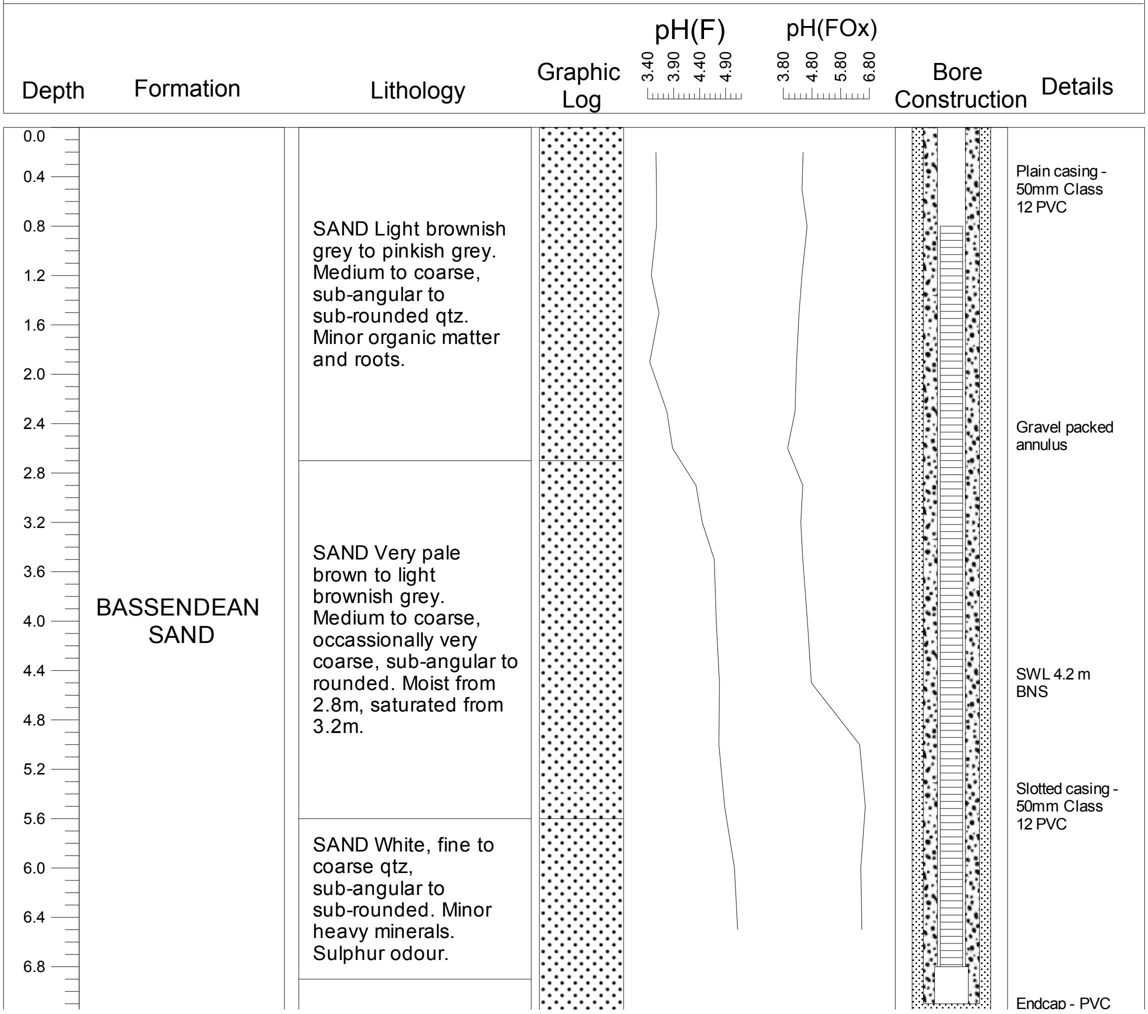
Gravel packed

Department of Water
Government of Western Australia

BORE COMPLETION DETAILS

AWRC Name: **LXA_Wc**
AWRC Number: **61611848**

Perth Shallow Groundwater Systems Investigation - Stage 2



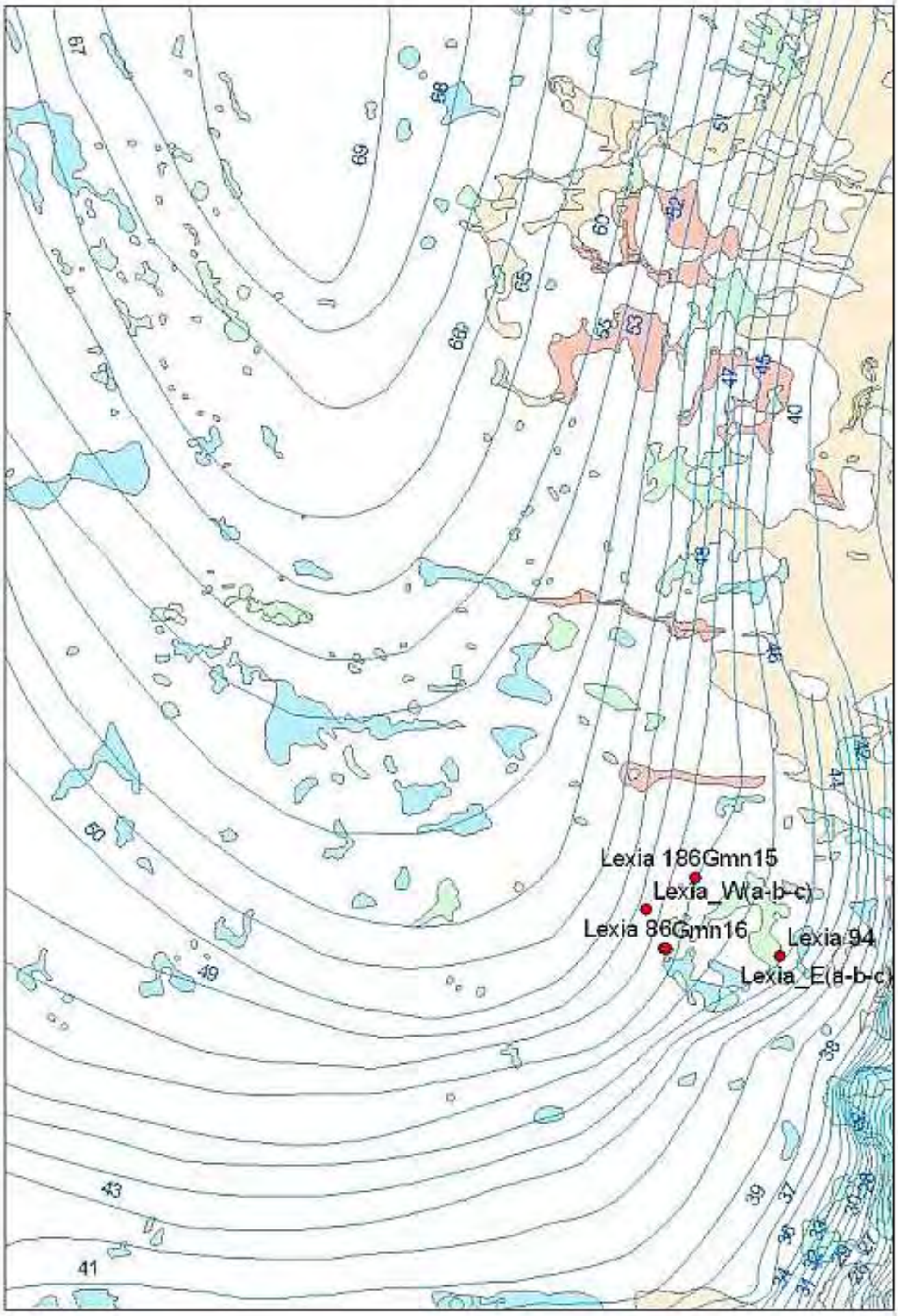
SAND Light brownish grey to pinkish grey. Medium to coarse, sub-angular to sub-rounded qtz. Minor organic matter and roots.

SAND Very pale brown to light brownish grey. Medium to coarse, occassionally very coarse, sub-angular to rounded. Moist from 2.8m, saturated from 3.2m.

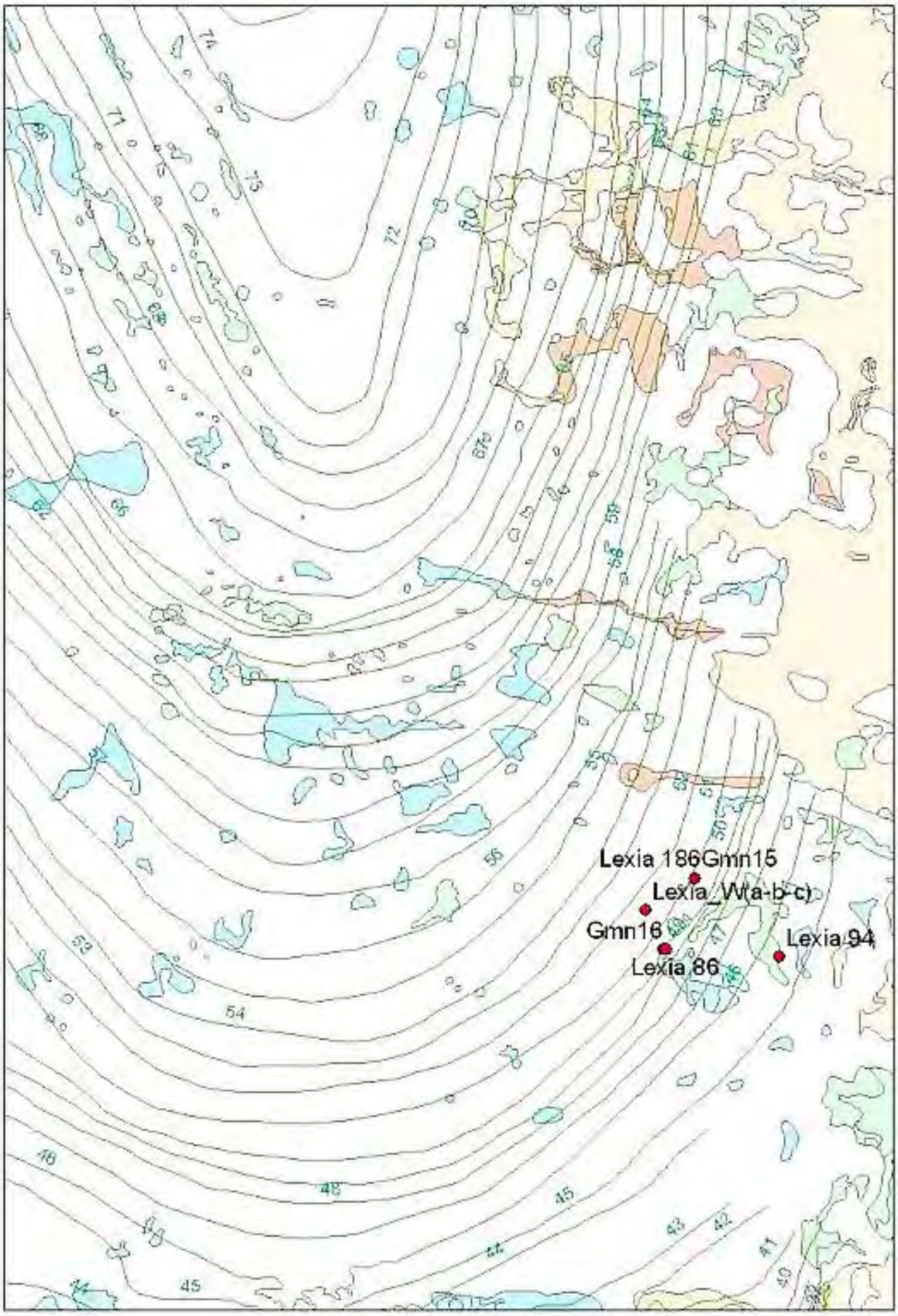
SAND White, fine to coarse qtz, sub-angular to sub-rounded. Minor heavy minerals. Sulphur odour.

Appendix B – Historical groundwater elevation contours

Groundwater elevation contours using data from May 2003



Groundwater elevation contours using data from early 1950s to 1970s



Appendix C – Sampling methods and analysis

Groundwater sampling methodology

Water samples were collected using low-flow pumping methods. The low-flow sampling technique provides a low stress, low impact, minimal drawdown purging method of groundwater sampling. The pump is lowered to the screened interval of the bore and purged until the water quality parameters of pH, Ec and temperature have stabilised. Once stabilised, in situ readings can be recorded and samples collected for further laboratory analysis. The method requires smaller volumes of water to be withdrawn than conventional techniques which reduces the aeration or degassing of samples collected. It also minimises the disturbance within the water well column and surrounding materials which reduces turbidity. This is particularly important when sampling for in situ physical water quality and total nutrient concentrations or metallic based contaminants in groundwater. The unit used for this investigation project was a Geotech stainless steel bladder pump.

Low flow bladder pump and water quality procedures

- All instrumentation and equipment (i.e. pumping equipment, hoses, and standing water level recorders) is to be decontaminated prior to and after sampling at each site location. Decontamination is conducted by firstly rinsing with a mixture of Decon-910® and scheme water. A second thorough rinse is performed using just scheme water, and then a final very thorough rinse is conducted using the standard laboratory purchased deionised water.
- Use new (disposable) air and water tubing for each sampling event
- Ensure water quality meters are functional and calibrated.
- Record bore groundwater level.
- Identify screen depth from records and lower low flow bladder pump to midway between screened interval. If sampling a shallow bore (full length screen) lower pump to 0.5m below groundwater level.
- Connect air tubing to air supply.
- Connect water outlet tubing to instrument flow cell.
- Apply air to pump, adjust air supply and discharge time to commence pumping.
- Other field observations such as interesting sample colour, presence of large quantities of particulate matter, and smell were noted.
- Measure in- situ field parameters: pH, conductivity, temperature, redox and dissolved oxygen using multiprobe sensors installed in a flow cell. Record every five minutes until parameters stabilise then record final reading.
- Record results on field observation form for submission to the Department of Water database.

Once the physical parameters stabilise, collect samples for laboratory analysis. Sample bottles to be filled to the shoulder of the bottle leaving a small airspace at the top of the bottle.

Surface water parameters were collected by wading close to installed staff gauges, flushing bottles three times with lake water and filling from 10 cm below the surface. In situ field parameters and surface water levels were also recorded.

In situ water quality parameters were monitored with Hydrolab test equipment (Quanta and multiprobe sensors).

Field pH testing methods

After Ahern et al. (1998), modified from the Department of Environment and Conservation (2006).

Field pH testing

Before sampling:

1. Set up clean, dry beakers in rack designed to measure pH_F on the right and pH_{FOX} on the left.
2. Calibrate pH measuring equipment using appropriate solutions.
3. Adjust the pH of around 1L of 30% hydrogen peroxide (suitable for a day's worth of measurements) to between pH 4.5 and 5.5 using drop-wise addition of 1M NaOH.
4. Collect sediment cores and return to 'field laboratory' setup to perform field tests before oxidation of sediments is able to occur.

Field pH_F and pH_{FOX} testing

1. Take ½ teaspoon sized sample of sediment approximately every 25 cm or when a lithology change is noted (whichever is lesser), noting the depth of the sample.
2. Place into beaker used for pH_F tests and add 12 ml of water from a clean syringe (marked pH_F) to make a 1:5 soil:water solution and shake well.
3. Take another ½ teaspoon sized sample of sediment from the same place as the previous sample used for the pH_F measurement, and place into a beaker used for measuring pH_{FOX}.
4. Add 12 ml of pH adjusted 30% hydrogen peroxide using a second syringe (marked H_{FOX}) to make a 1:5 soil:peroxide solution, and shake well.
5. Repeat above steps until entire core has been sampled.
6. Shake all beakers well and leave for approximately 1 hour (during which time logging of cores can be done).
7. Regularly shake (i.e. every 5 to 10 minutes) all beakers to ensure maximum amount of sediment goes into solution.

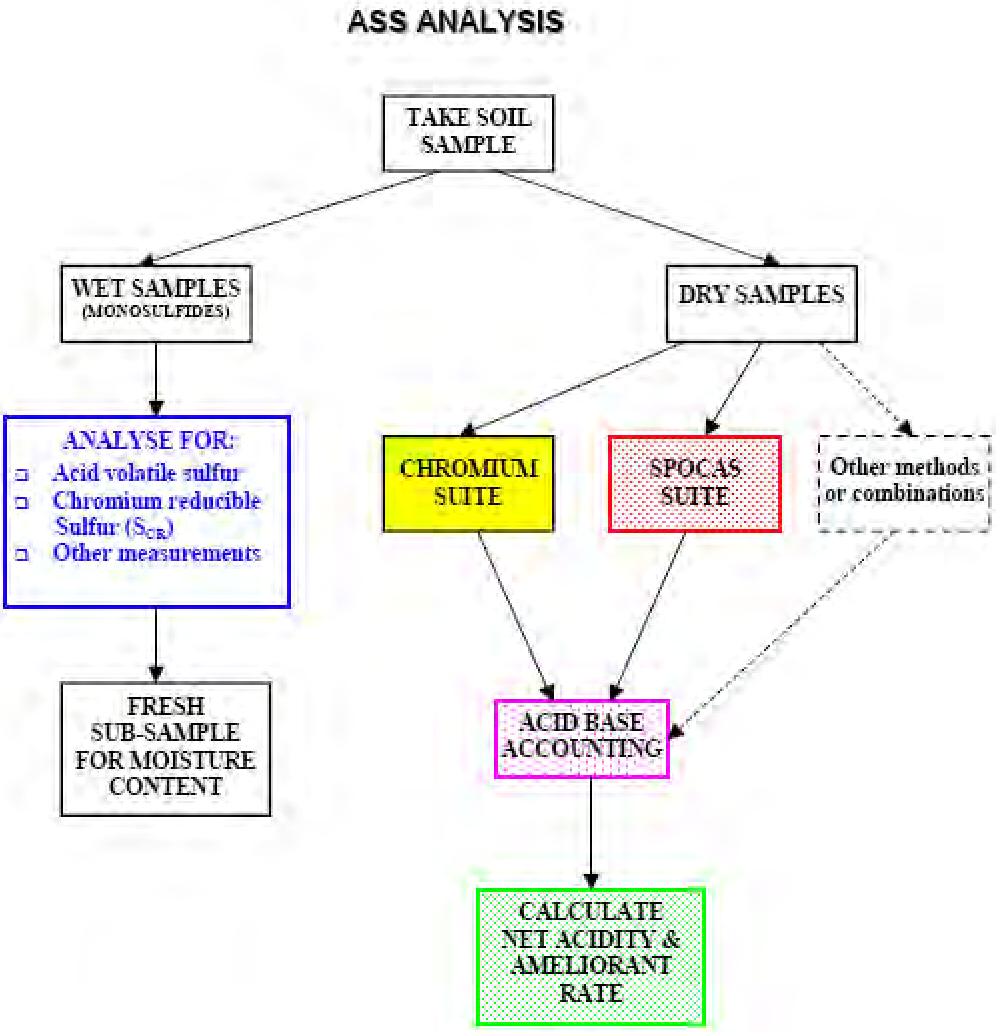
8 After 1 hour record pH_F and H_{FOX} readings, taking all pH_F measurements first (to ensure no contamination with peroxide and also to allow maximum time for peroxide to react with the sediments). Clean pH probe with distilled water between each reading.

9 Dispose of solutions into an appropriate container (although hydrogen peroxide rapidly decomposes to water and oxygen so is not harmful to the environment) and thoroughly clean all beakers, syringes and other equipment using Decon (detergent) and water.

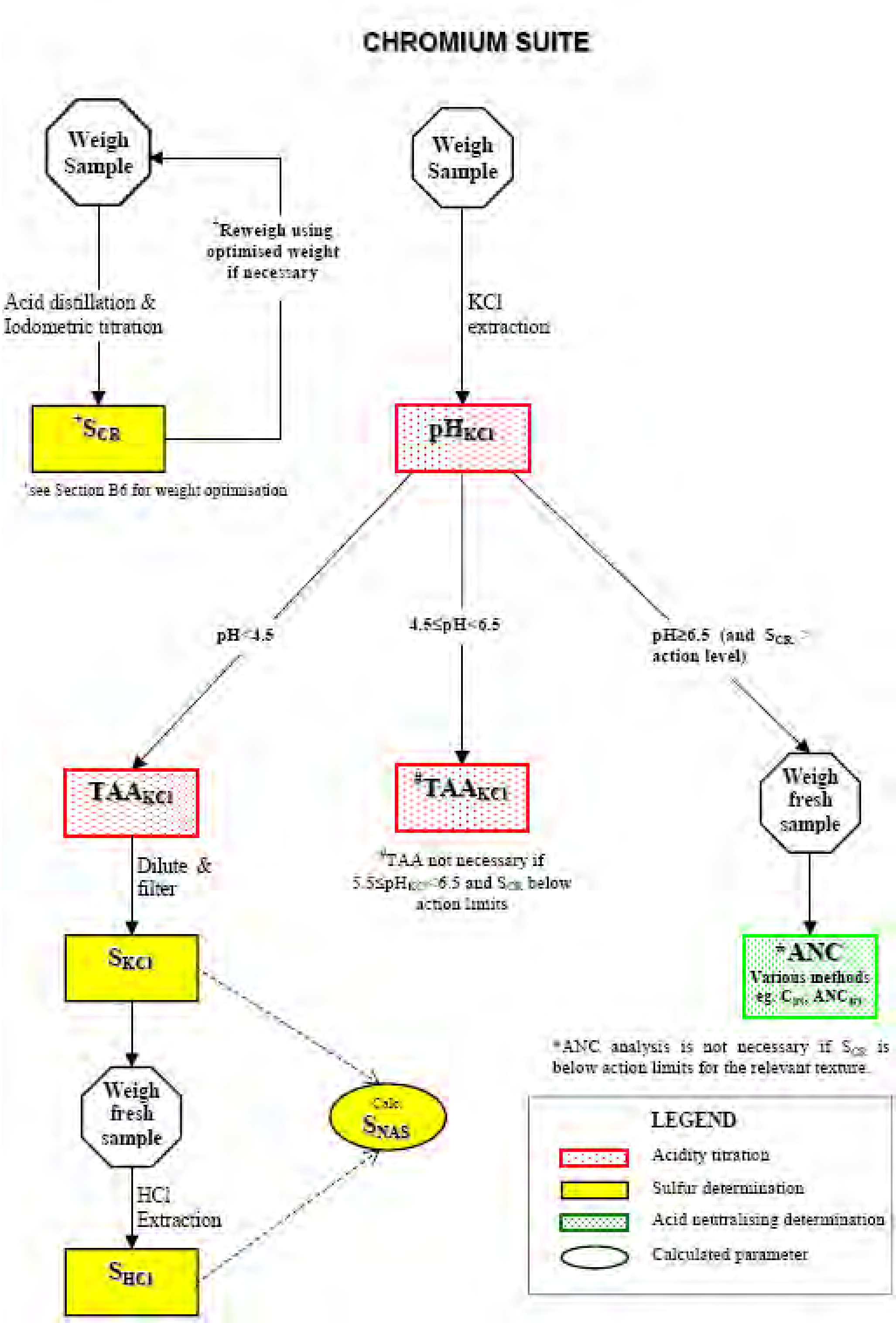
Laboratory methods

After Ahern et al. 2004.

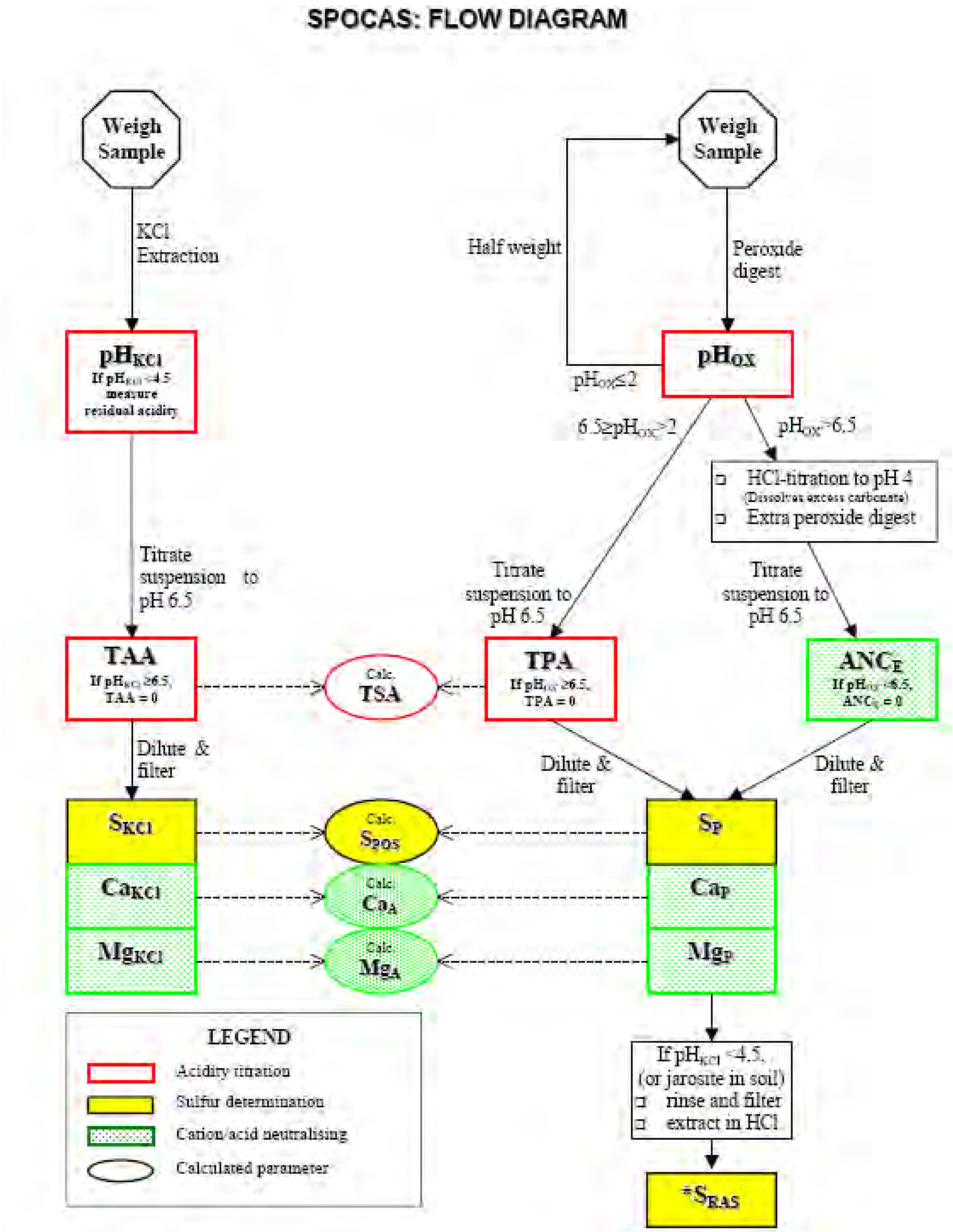
Flow diagram representation of methods followed when analysing acid sulfate soils. For full method description, refer to Ahern et al. (2004).



Flow diagram for overall methods used in the quantitative analyses of acid sulfate soils (From Ahern et al. 1998)

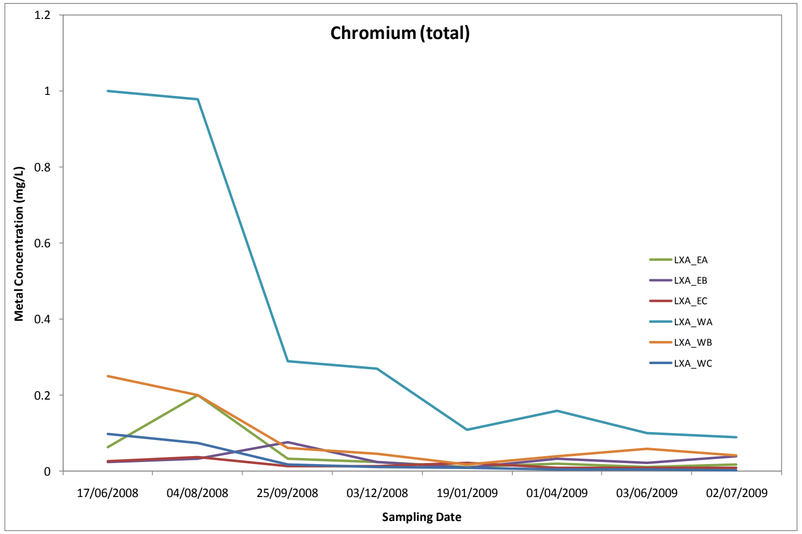


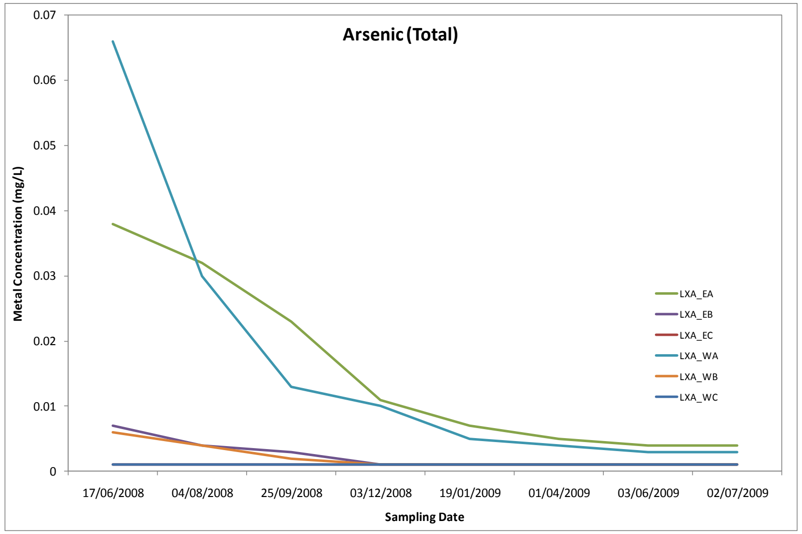
Flow diagram of steps involved using the chromium suite (From Ahern et al. 1998)

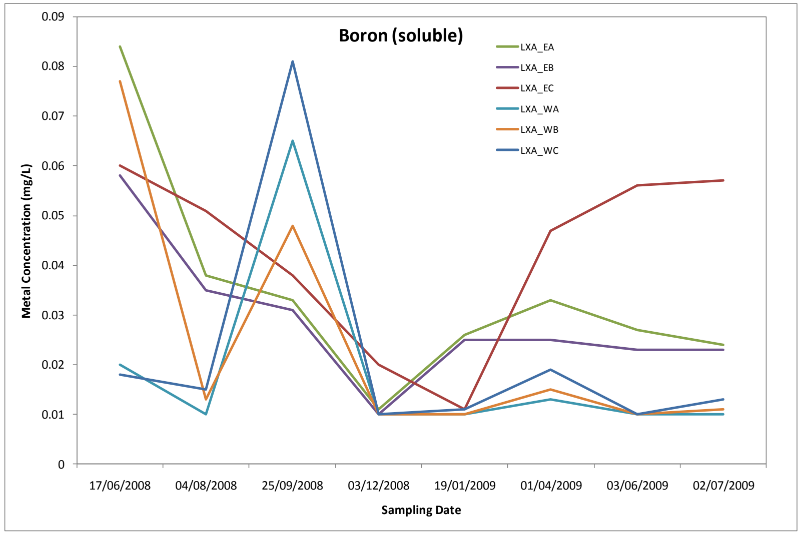


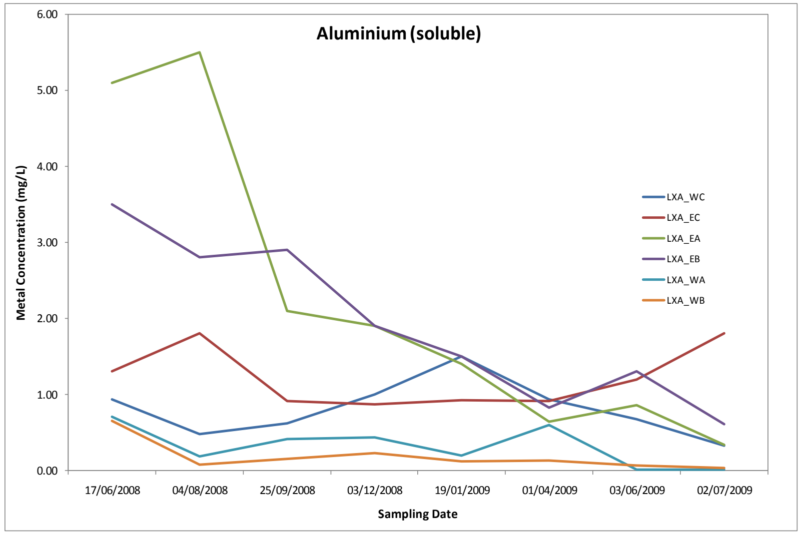
Flow diagram of steps involved in analysis using the SPOCAS suite (From Ahern et al. 1998)

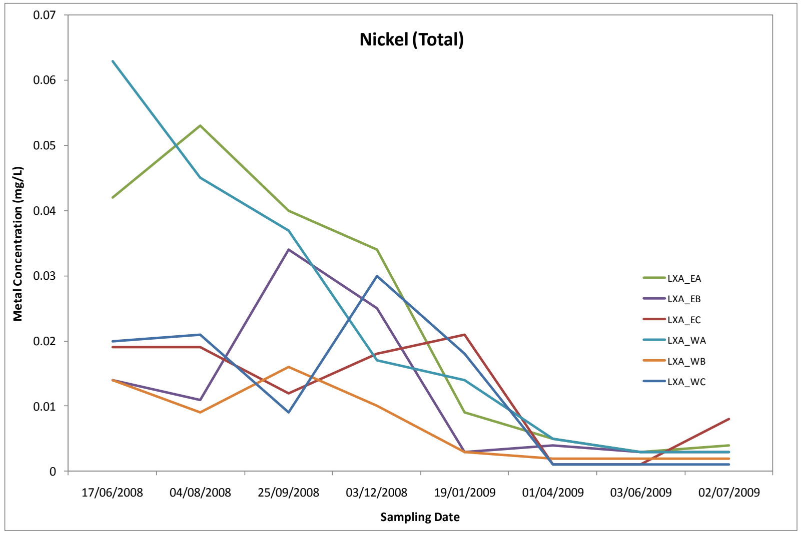
Appendix D – Water quality time series data

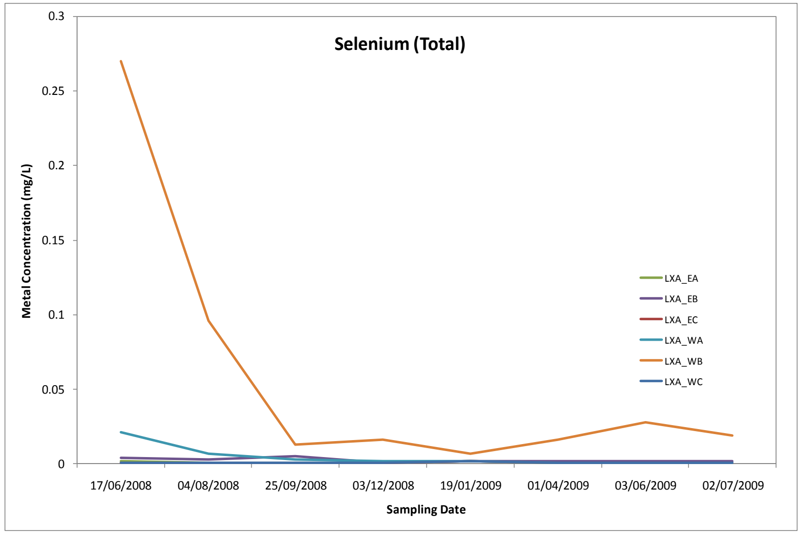


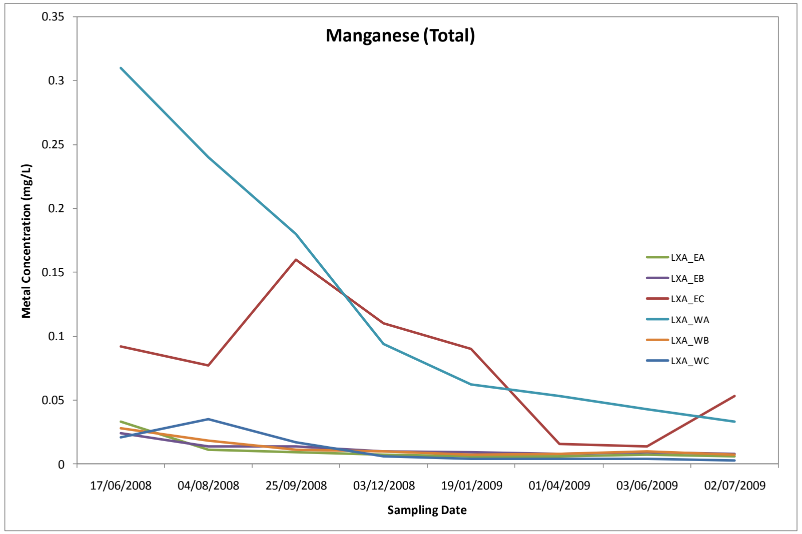


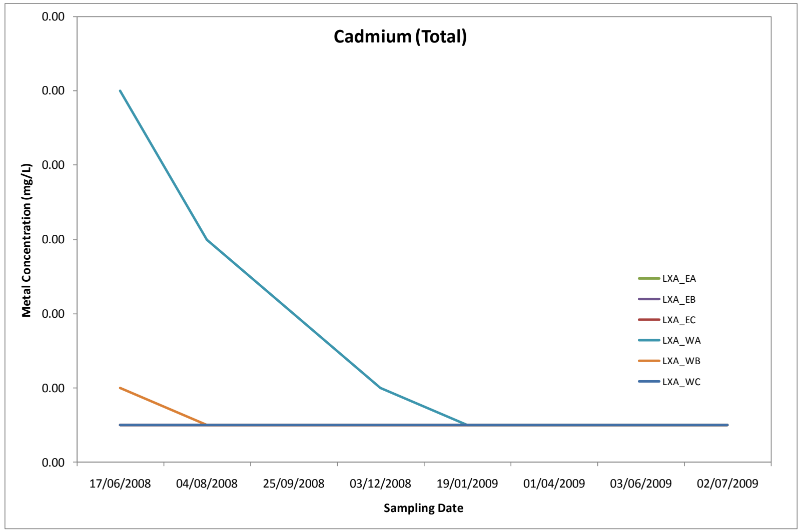





Nickel (Total)
Metal Concentration (mg/L)
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
17/06/2008
04/08/2008
25/09/2008
03/12/2008
19/01/2009
01/04/2009
03/06/2009
02/07/2009
Sampling Date
LXA_EA
LXA_EB
LXA_EC
LXA_WA
LXA_WB
LXA_WC


Selenium (Total)
Metal Concentration (mg/L)
0.3
0.25
0.2
0.15
0.1
0.05
0
17/06/2008
04/08/2008
25/09/2008
03/12/2008
19/01/2009
01/04/2009
03/06/2009
02/07/2009
Sampling Date
LXA_EA
LXA_EB
LXA_EC
LXA_WA
LXA_WB
LXA_WC


Manganese (Total)
Metal Concentration (mg/L)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
17/06/2008
04/08/2008
25/09/2008
03/12/2008
19/01/2009
01/04/2009
03/06/2009
02/07/2009
Sampling Date
LXA_EA
LXA_EB
LXA_EC
LXA_WA
LXA_WB
LXA_WC


Cadmium (Total)
Metal Concentration (mg/L)
0.00
0.00
0.00
0.00
0.00
0.00
0.00
17/06/2008
04/08/2008
25/09/2008
03/12/2008
19/01/2009
01/04/2009
03/06/2009
02/07/2009
Sampling Date
LXA_EA
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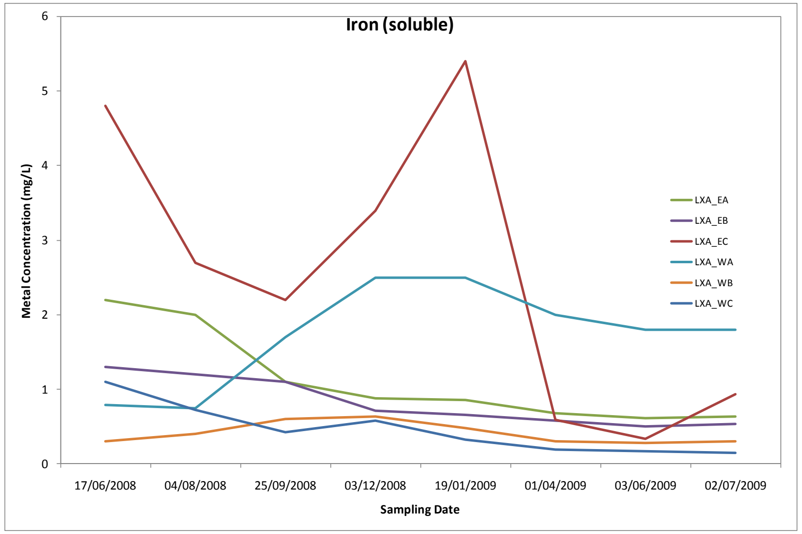
LXA_EC
LXA_WA
LXA_WB
LXA_WC


Iron (soluble)
Metal Concentration (mg/L)
0
1
2
3
4
5
6
17/06/2008
04/08/2008
25/09/2008
03/12/2008
19/01/2009
01/04/2009
03/06/2009
02/07/2009
Sampling Date
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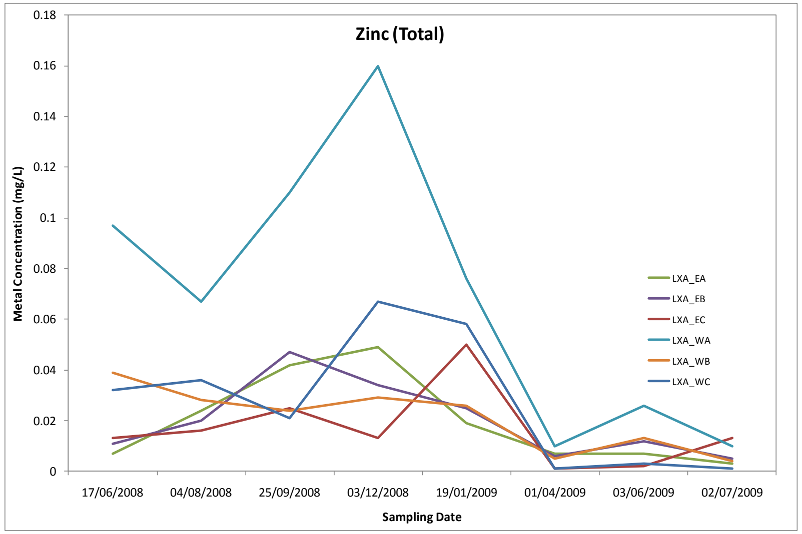
LXA_WA
LXA_WB
LXA_WC


Zinc (Total)
Metal Concentration (mg/L)
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
17/06/2008
04/08/2008
25/09/2008
03/12/2008
19/01/2009
01/04/2009
03/06/2009
02/07/2009
Sampling Date
LXA_EA
LXA_EB
LXA_EC
LXA_WA
LXA_WB
LXA_WC

Shortened forms

AHD	Australian height datum
ANZECC	Australian and New Zealand Environment and Conservation Council
ARMCANZ	Agriculture and Resource Management Council of Australia and New Zealand
bns	below natural surface (below ground level)
CRS	chromium reducible sulfur suite
DEC	Department of Environment and Conservation
DoW	Department of Water
EWP	Environmental water provision
EWR	Ecological water requirement
IPCC	Intergovernmental Panel on Climate Change
LiDAR	Light detecting and ranging
LVL	The *Wood Processing (Wesbeam) Agreement Act 2002* commits the state government to provide wood to the laminated veneer lumber (LVL) plant
NHMRC	National Health and Medical Research Council
PRAMS	Perth regional aquifer modelling system
PHREEQC	pH, Redox, and Equilibrium – C Language
SGS	Shallow groundwater system
SPOCAS	Suspension peroxide oxidation combined acidity and sulfur suite of analyses
SRP	Soluble reactive phosphorus
TDS	Total dissolved salts

Glossary

Abstraction	The withdrawal of water from any water resource.
Acid sulfate soils	Naturally occurring, these are soils containing significant quantities of reduced sulfur (pyrite and other sulfides). When these soils are disturbed the reduced sulfur is oxidised resulting in the release of acidity and often toxic metals.
Acid buffering capacity	A measure of the resistance to changes in pH following the addition of an acid.
Acidification	The process by which soil, or water becomes more acidic (decreasing pH).
Algal blooms	The rapid excessive growth of algae, generally caused by high nutrient levels and favourable conditions. Can result in water column deoxygenation when the algae die.
Alkalinity	A measure of a solution's ability to resist changes in pH due to the addition of an acid. In natural waters this usually relates to the amount of bicarbonate, carbonate and hydroxide compounds present in the water.
Allocation limit	The volume of water set aside for annual licensed use.
Aquifer	A geological formation or group of formations able to receive, store and/or transmit large amounts of water.
Bore	A narrow, normally vertical hole drilled into a geological formation to monitor or withdraw groundwater from an aquifer (*see also* Well).
Buffer	A solution which resists changes in pH when a small amount of strong acid or base are added
Buffering capacity	*see* Acid-buffering capacity.
Confined aquifer	A permeable bed saturated with water and lying between an upper and a lower confining layer of low permeability, the hydraulic head being higher than the upper surface of the aquifer.
Confining bed	Sedimentary bed of very low hydraulic conductivity.

Contaminants	A substance that is either present in an environment where it does not belong or is present at levels that might cause harmful effects to humans or the environment.
Dissolution	The process of dissolving a solid to produce a solution.
Drawdown	The difference between the elevation of the initial piezometric surface and its position after pumping or gravitational drainage.
Ecological water requirement	The water regime needed to maintain the ecological values (including assets, functions and processes) of water-dependent ecosystems at a low level of risk).
Eutrophication	An excess of nutrients (nitrogen and phosphorus) in an ecosystem, often resulting in excessive primary production.
Evapotranspiration	The combined loss of water by evaporation and transpiration. Includes water evaporated from the soil surface and water transpired by plants.
Fault	A fracture in rocks or sediments along which there has been an observable displacement.
Flux	Flow
Formation	A group of rocks or sediments that have certain characteristics in common, were deposited about the same geological period, and that constitute a convenient unit for description.
Groundwater	Water that occupies the pores within the rock or soil profile.
Groundwater-dependent ecosystem	An ecosystem that depends on groundwater for its existence and health.
Hydraulic	Pertaining to water motion.
Hydraulic gradient	The rate of change of total head per unit distance of flow at a given point and in a given direction.
Ion	An atom which has lost or gained electrons and therefore carries an electrical charge.

Leach	Remove soluble matter by percolation of water.
Metalloid	An element whose properties are between those of metals and non-metals.
Neutralisation	The chemical reaction in which an acid and a base react to produce salt and water.
Oxidation	A process resulting in the loss of electrons from a chemical species accompanied by an increase in oxidation state. This process does not necessarily require the presence of oxygen.
pH	The negative logarithm of the concentration of hydrogen ions.
Redox potential	In aqueous solutions, the reduction potential is the tendency of the solution to either gain or lose electrons and is measured in volts (V), millivolts (mV), or Eh (1 Eh = 1 mV mV). Because the absolute potentials are difficult to accurately measure, reduction potentials are defined relative to the standard hydrogen electrode which is arbitrarily given potential of 0.00 V.
Reduction	A process resulting in the gain of electrons by a chemical species accompanied by a decrease in oxidation state.
Salinity	A measure of the concentration of total dissolved solids in water. 0–500 mg/L fresh 500–1500 mg/L fresh to marginal 1500–3000 mg/L brackish > 3000 mg/L saline
Scarp	A line of cliffs (steep slopes) produced by faulting or by erosion.
Stressor	An agent, condition or other stimulus that causes stress to an organism or ecosystem.
Sulfate reduction	In the aquatic environment, the microbially catalysed process which converts sulfate to sulfide.
Surficial	Pertaining to the surface.

Toxicity	The degree to which a substance is able to damage an exposed organism.
Transmissivity	The rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient.
Transpiration	The loss of water vapour from a plant, mainly through the leaves.
Trigger level	Concentrations of key indicators, above or below which there is a risk of adverse biological effects.
Unconfined aquifer	A permeable bed only partially filled with water and overlying a relatively impermeable layer. Its upper boundary is formed by a free watertable or phreatic level under atmospheric pressure.
Watertable	The surface of a body of unconfined groundwater at which the pressure is equal to that of the atmosphere.
Well	An opening in the ground made or used to obtain access to underground water. This includes soaks, wells, bores and excavations.

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