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

Looking after all our water needs

Perth Shallow Groundwater Systems Investigation

Egerton Seepage

Hydrogeological record series

Report no. HG53
July 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. That four-year investigation program was undertaken in 2007–10 by the Groundwater Review section of the Water Resource Assessment branch of the Department of Water. Funding for the program was jointly provided by the Government of Western Australia and the federal government‘s Water Smart Australia initiative.

The Perth shallow groundwater systems investigation focused on numerous wetlands situated on Gnangara and Jandakot groundwater mounds, the most significant sources of groundwater for the Perth metropolitan area. These 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.

Awareness of the need for an investigation arose from the outcomes of a management area review conducted in 2006 (McHugh & Bourke 2007). That review summarised the then-current monitoring and management issues faced by particular wetlands on the Gnangara and Jandakot groundwater mounds, and identified the information and data required to address those issues. The report recommended an investigation program that would incorporate up to 30 wetlands on the Swan coastal plain, and prioritised those wetlands with 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 water bodies and groundwater
- investigate the palaeoclimate of certain 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 the investigation will aid in the development of management strategies that are based on site-specific, scientific data, to promote the sustainable use of the groundwater resources of the Gnangara and Jandakot mounds.

Summary

Egerton Seepage is situated on the Gnangara Mound, approximately 20 kilometres to the north-east of Perth, Western Australia. Egerton Seepage is a conservation category wetland and ministerial criteria site that the Department of Water manages to conserve its flora and fauna (Hill et al. 1996, *Environmental Protection Act 1986*, WRC 1997).

The seepage is one of 28 sites examined in the Perth shallow groundwater system investigation.

In May 2007, the monitoring infrastructure at Egerton was expanded with the installation of a cluster of three monitoring bores, approximately 100 metres up-gradient from the seepage. A comprehensive, 12-month sampling program of the new and existing bores then improved understanding of how the seepage hydrogeologically functions.

At Egerton, the regional watertable of the Superficial aquifer intercepts the ground surface, creating a groundwater-dependant ecosystem. The ecological values of the seepage, including its significant club moss and liverwort species, its pristine, fringing vegetation and its rich assemblage of macroinvertebrates are dependent on groundwater levels in that aquifer.

The Egerton site has been described as a tumulus – Latin, meaning ‗little mound‘ – spring community, and is one of only four intact, vegetated tumulus spring communities on the Swan coastal plain. The seepage and surrounding vegetation is listed as a threatened ecological community and Bush Forever site (CALM 2006, Government of Western Australia 2000).

Tumulus spring communities occur at points where groundwater discharges through the ground surface, creating a permanent water supply around which continuous growth and breakdown of vegetation occurs, causing the formation of peat mounds. Those communities are of considerable ecological significance and high conservation value as they support unique plant and invertebrate species – including endemic species and Gondwanan relicts – that are adapted to the permanent water the seepage provides. This seepage area also probably acts as a refuge from climate change (drying) for certain species (CALM 2006).

Groundwater that is discharged through the ground surface in the Egerton area is also important to ensuring the longevity of a number of endangered aquatic macrofauna populations of Ellen Brook (Beatty et al. 2010).

Egerton was previously understood to function as a spring, with upward flow from the base of the Superficial aquifer, influenced by the interfingering of Bassendean sand with Guildford clay to the east of the site. This investigation showed the Egerton site is dominated by Bassendean sand, with only thin, discontinuous lenses of Guildford clay present in the area.

The results of this investigation show that Egerton:

- is a surface expression of groundwater
- is more influenced by topography than geology
- functions as a groundwater seepage.

Removal of native vegetation, modification of local geomorphology and extensive urbanisation around Egerton has altered the local hydrogeology and the flow regime at the seepage. The watertable around Egerton rose one metre since 2002 and resulted in increased groundwater discharge at the site. There is now strong flow at the seepage, despite the lower-than-average rainfall experienced by the region. Groundwater use down-gradient of the site is unlikely to affect groundwater discharge at Egerton, however, high levels of abstraction up-gradient have the potential to reduce flow.

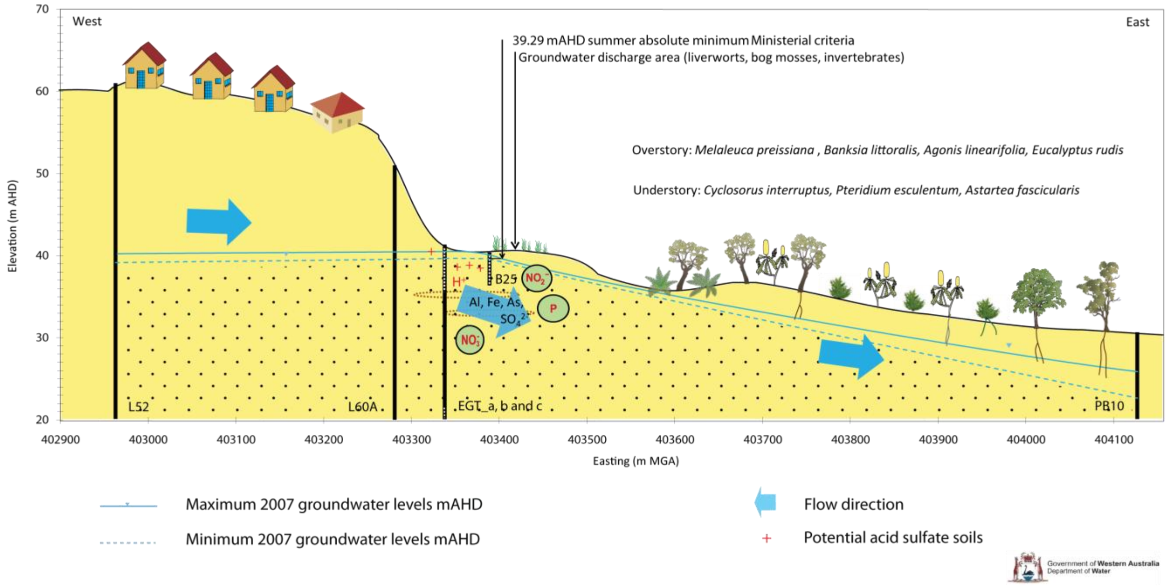
The current ministerial water level criteria for Egerton states that water levels should not fall below 39.29 metres Australian Height Datum (WRC 1997). That criteria is an absolute, summer minimum water level that is measured at monitoring bore B25 (AWRC 61618607), situated adjacent to the seepage. Due to rises in the watertable at Egerton, recent levels at bore B25 have easily met the ministerial criteria level and the permanent discharge of groundwater from the seepage is, at present, relatively assured.

The hydrogeochemical results from this investigation suggest that at present, groundwater quality at Egerton is more likely to affect the ecology than groundwater quantity. Groundwater quality issues that are possibly having an impact on the ecology of the seepage include declining pH values and increasing nutrient concentrations.

pH levels at Egerton are now below the minimum trigger value for wetlands in south-west Australia. The elevated SO_4–Cl ratios measured at the site during this investigation suggests that oxidation of acid sulfate soils (ASS) may be contributing to the declining pH trend at the seepage. The low pH at the area‘s watertable probably contributed to the mobilisation of aluminium into the groundwater and may be placing the site‘s vegetation at the risk of ‗acid toxicity‘. Should water levels at the site decline, oxidation of the potential ASS identified in this investigation could result in continued pH declines and lead to permanent changes to the ecology of the seepage.

The elevated levels of nitrogen (nitrate and nitrite, NO_x) and phosphorus measured in this investigation are likely to favour weed invasion and change the dynamics of the wetland ecosystem (CALM 2006). Those high levels of nutrients at Egerton may also influence water quality downstream and affect the endangered aquatic macrofauna in Ellen Brook. The high concentrations of NO_x at Egerton also have the potential to oxidise the potential ASS and cause further declines in pH at the site, despite high water levels. Those may contribute to the affects of acidity on ecology at the seepage. The elevated concentrations of nutrients at Egerton Seepage are probably a result of runoff from the northern catchment of the Ellenbrook development to the west of the seepage and from the Vale development that will eventually surround the Bush Forever site that contains the seepage.

An improved conceptual model of the relationships between the geology, hydrogeology, chemistry and the wetland ecosystem of Egerton was developed during the study (see below). This model, discussed in detail in section 6 (see figure 24), provides a basis for improved management strategies.



Conceptual model of the relationships between the hydrogeology, chemistry and the wetland ecosystem of Egerton

Recommendations

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

Management actions

- Bore B25 should be retained as the ministerial criteria bore at Egerton.
- Avoid issuing large licences directly up-gradient of the seepage.
- Continue with annual sampling of aquatic invertebrates.
    - *Implementation and responsibility*. Department to:
        - *continue to monitor the Ministerial criteria at bore B25*
        - *incorporate report recommendations into the allocation note guiding licensing decisions in relation to groundwater dependant ecosystems*
        - *secure funding for continued sampling of aquatic invertebrates*

Future monitoring

- A hydrochemical monitoring program should be initiated for this site, and hydrochemical triggers and management actions could be developed for the next water reform plan. Data from the hydrochemical monitoring program should be reviewed every two years to assess whether management objectives set out in the plan are being met and whether trigger values need improvement.
- The installation of continuous monitoring equipment along the eastern line of groundwater discharge on the Gnangara Mound to record the rate of discharge of water associated with other springs–seepages identified along that line.
    - *Implementation and responsibility*. Department to review the monitoring program and include in a resource review report by 2015–17.

Future investigation

- The nutrient management and drainage plans for the Ellenbrook and Vale developments should be reviewed and the metal concentration, acidity and nutrient management strategies investigated.

1 Context and objectives

The Egerton Seepage is a ministerial criteria site and conservation category wetland that is managed to conserve its flora and fauna (Hill et al. 1996, *Environmental Protection Act 1986*, WRC 1997). The seepage is valued for its significant club moss and liverwort species, its pristine fringing vegetation and for its rich assemblage of macroinvertebrates (Froend et al. 2004a).

Egerton Seepage has been described as a tumulus – Latin, meaning ‗little mound‘ – spring community, and is one of only four intact, vegetated tumulus communities on the Swan coastal plain. In 1995, these communities were determined as critically endangered and listed as endangered under the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999*. Tumulus communities are of considerable ecological significance and high conservation value as they support unique plant and invertebrate species that are adapted to the permanent water the seepage provides. Gondwanan relicts, which have relied on the maintenance of the moist habitat, have been found in the communities (CALM 2006).

As part of a management area review (MAR) of shallow groundwater systems on the Gnangara and Jandakot mounds (McHugh & Bourke 2007), the lack of understanding of groundwater seepages on Gnangara Mound was considered sufficient to warrant a local area hydrogeological investigation at Egerton. The management area review highlighted the need to investigate the possible impact of nearby development on groundwater levels and water quality, and supported earlier recommendations made in 1997 which called for an improved understanding of the site (WRC 1997).

The management area review recommended site-specific data be collected and analysed to determine the current status of Egerton Seepage in terms of groundwater–surface water connectivity, groundwater quality and flow into and out of the area.

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

- upgrade the groundwater monitoring network
- improve the Department of Water‘s understanding of how Egerton Seepage hydrogeologically functions
- determine the extent of acid sulfate soils near the seepage and their impacts on water quality
- develop a conceptual model of the relationships between wetland hydrogeology, chemistry and ecosystem function to provide a basis for improved management strategies
- outline the implications of change in water and land use
- 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

Egerton Seepage is a wetland situated on the eastern side of the Gnangara Mound in the north-west section of Egerton Stud, Ellenbrook, approximately 20 kilometres to the north-east of Perth, Western Australia (Figure 1).

Perth experiences a Mediterranean-type climate with hot, dry summers and mild, wet winters. The annual median rainfall recorded from the Wanneroo monitoring station, situated 18 km north-west of Egerton, from 1988 to 2008 is presented in Figure 2.

Rainfall recorded at the station ranged from 520 millimetres in 2006 to 956 mm in 1991 with an average rainfall of 743 mm per annum. Historically, the amount of rainfall on the Swan coastal plain decreases in an easterly direction towards the base of the Darling Scarp. Recent rainfall levels are lower than those in the early 1990s.

2.2 Geology

Regional geology and geomorphology

Egerton Seepage lies within the Perth Basin and is underlain by the Quaternary-aged Bassendean sand. The lithology is present over most of the central Perth region with a maximum thickness of 80 m and is part of the group collectively referred to as the superficial formations. The superficial formations are late Tertiary to Quaternary units and were deposited in the following order; Ascot formation (Ta), Yoganup formation (Ty), Guildford clay (Qg), Gnangara sand (Qn), Bassendean sand (Qb), Tamala limestone (Qt), Becher sand (Qc) and Safety Bay sand (Qs) (Figure 3).

Egerton Seepage is made up of swamp and lacustrine deposits within the Bassendean dune system. The seepage lies on a subdued dune-swale terrain which consists of peaty clay, dark grey and black with a variable sand content, with the majority of the dune made up of leached sands (Alan Tingay & Associates 1995, CSIRO 1967). Prior to 2000 dunes of up to 70 mAHD were located to the east of the Egerton site. These have since been levelled for urban development.

The Bassendean sand consists of pale grey to white and fine to coarse-grained, but predominantly medium-grained quartz sand which is moderately sorted, sub-rounded to rounded and commonly has an upward fining sequence in grain size (Davidson 1995).

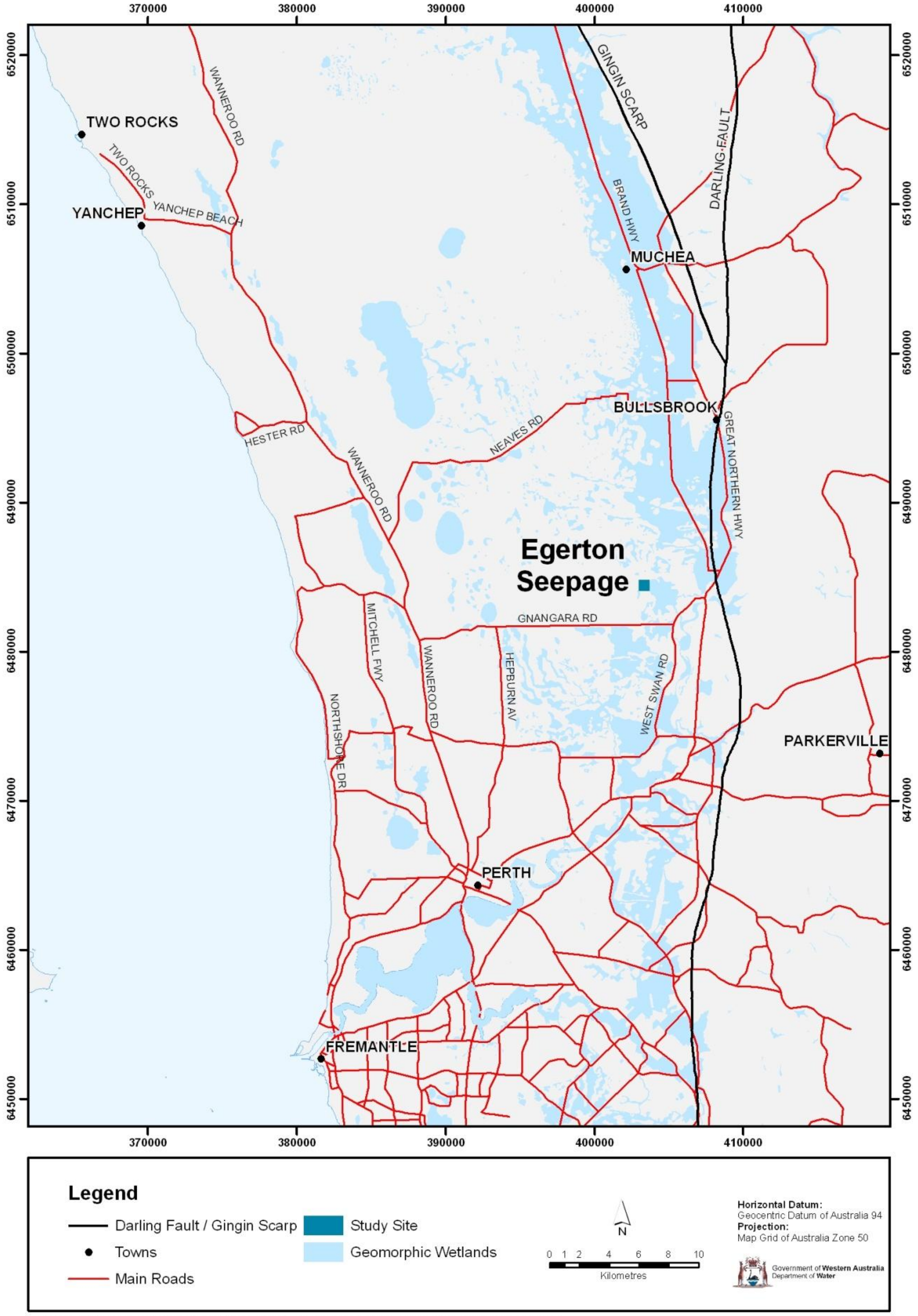


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Figure 1 Regional location of Egerton Seepage

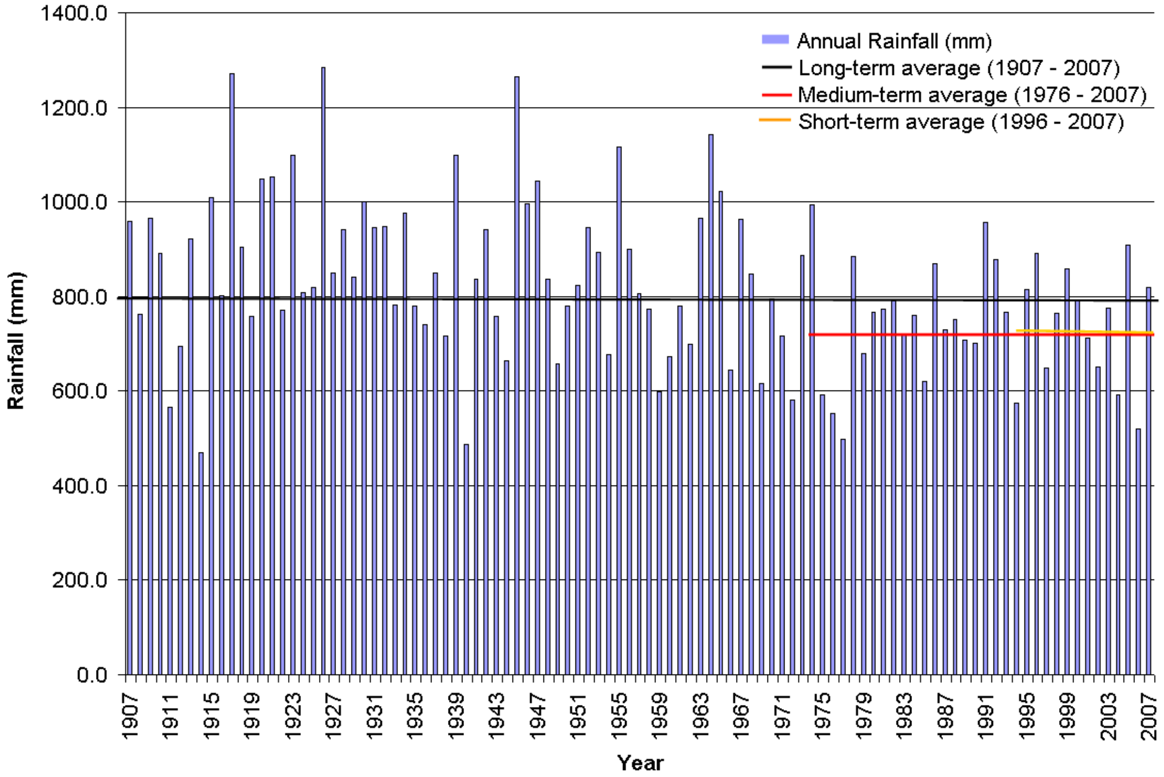

Figure 2 Annual rainfall for Wanneroo, showing long-term, medium-term and short-term averages

A layer of friable, limonite-cemented sand, commonly referred to as ‗coffee rock', occurs throughout most of the area near the watertable.

The Bassendean sand unconformably overlies the Cretaceous and Tertiary strata and interfingers with the Guildford clay, along the eastern margins of the Perth region near the base of the Darling Scarp.

The Guildford clay has been described as consisting of pale grey to blue, but predominantly brown, silty and slightly sandy clay and interfingers with the Bassendean sand and Gnangara sand. The unit is up to 35 m thick and commonly contains lenses of fine to coarsely grained, very poorly sorted, conglomeratic and (in places) shelly sand at its base, particularly in the Swan Valley area (Davidson 1995). These basal lenses, which occur randomly along the eastern margin of the coastal plain, are most likely remnant deposits of the Ascot formation or Yoganup formation (Baxter & Hamilton 1981).

Acid sulfate soils

The most recent sediments of the superficial formations include a range of lake and wetland deposits, typically found within the top few metres of the profile. These organic-rich sediments are commonly associated with acid sulfate soils (ASS).

ASS are naturally occurring soils, sediments or organic substrates formed under waterlogged conditions that contain iron sulfide minerals (e.g. pyrite) or their oxidation products. Within the Swan coastal plain, sulfidic peaty sediments are commonly associated with groundwater-dependent wetlands. These sediments can contain up to 15 per cent by weight of oxidisable sulfur and have the potential to cause groundwater acidification and metal contamination when exposed to air due to the lowering of watertable. When exposed to air, the sulfides in the sediments oxidise and release sulfuric acid and iron into the soil and groundwater (Fältmarsch et al. 2008).

The term acid sulfate soils includes both actual and potential acidity. Potential acid sulfate soils (PASS) refers to the sediments which are still waterlogged or unoxidised. Actual acid sulfate soils (AASS) refers to sediments that have been exposed to air and have produced acidity. Oxidation is commonly caused by lowering of the watertable (Ahern et al. 2004). As many of the wetlands on the Gnangara Mound are progressively drying, the exposure of ASS is a potential risk for environmental and groundwater degradation.

Egerton Seepage is considered to be at high risk of AASS and PASS that are less than 3 m from the ground surface (DoE 2004).

2.3 Hydrogeology

Regional hydrogeology

The Superficial aquifer, consisting of the formations described in section 2.2, is a major, unconfined, aquifer extending throughout the Swan coastal plain and extends from the coast to the Gingin and Darling scarps.

Groundwater elevations, caused by rainfall draining through permeable sediments, build up to create two substantial groundwater mounds, the Gnangara Mound to the north of Perth and the Jandakot Mound, to the south of the city.

The Gnangara and Jandakot mounds are dominant features of the Superficial aquifer and currently supply approximately 60 per cent of Perth‘s water requirements. Mounding of the watertable occurs in these locations because recharge from rainfall exceeds the ability of the aquifer to transmit water away from the recharge zone (Davidson 1995). Groundwater radially flows from the mounds (Figure 4) and locally, with some groundwater leaks into the underlying Mesozoic formations (Rockwater 2003).

For a full description of the geology and hydrogeology of the Perth region refer to Davidson (1995).

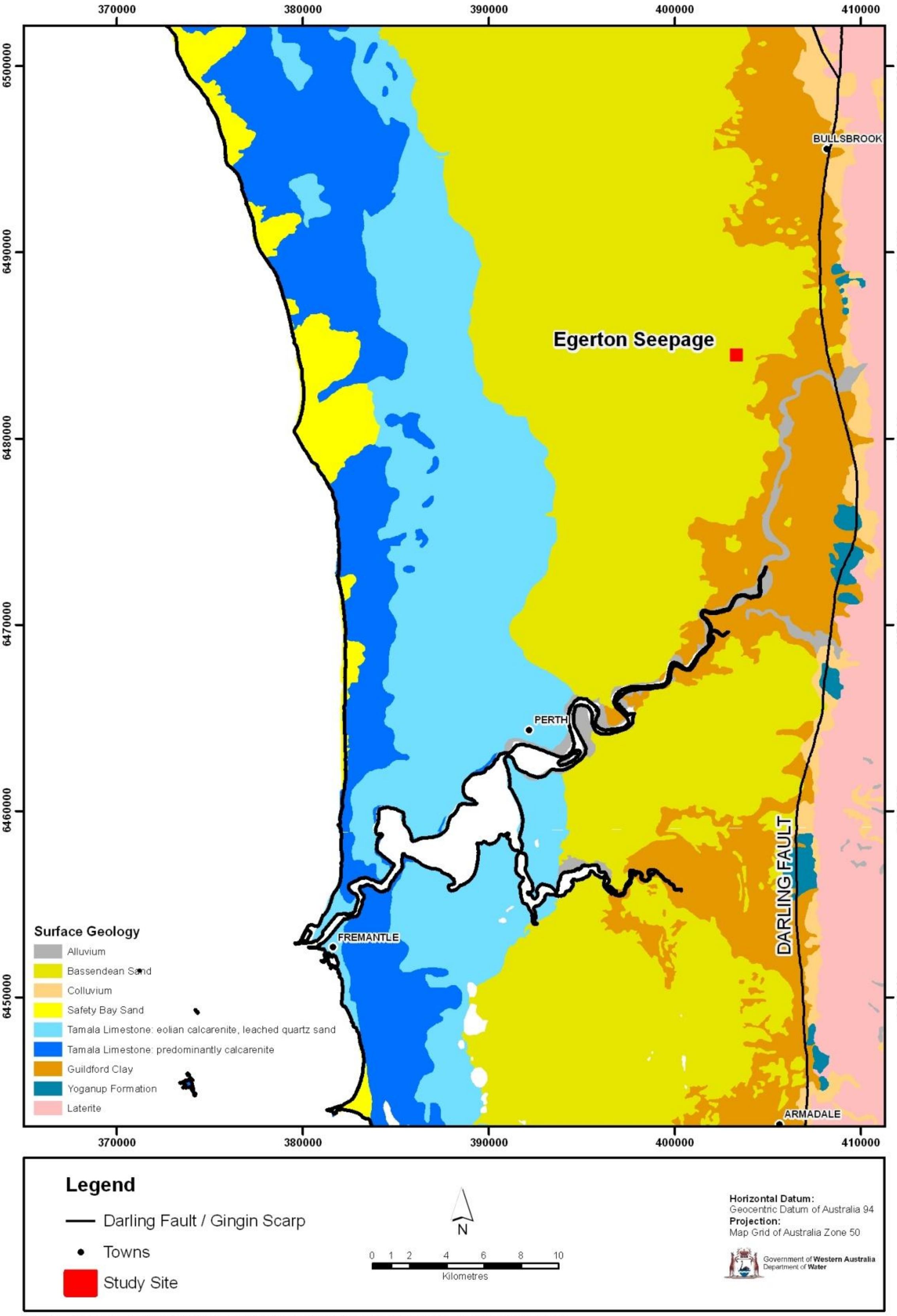

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Figure 3 Egerton Seepage surface geology

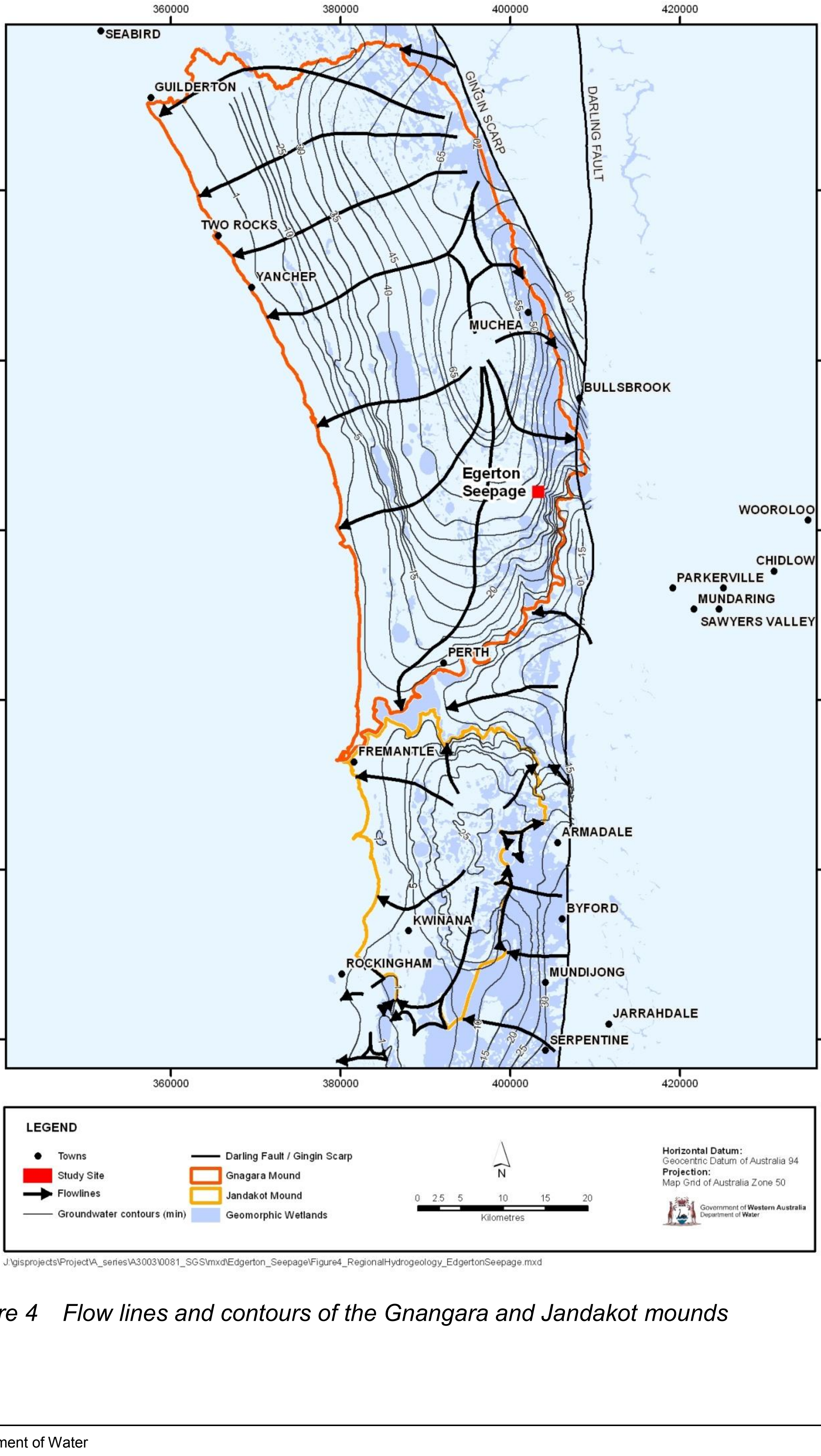

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Figure 4 Flow lines and contours of the Gnangara and Jandakot mounds

Previous investigations at Egerton Seepage

The unique, humid habitats the seepage creates, together with the flora and fauna that exist in these microhabitats, have prompted a number of studies within the Egerton Seepage area. Most of these studies were commissioned to comply with development proposals, though the Department of Water also funds ongoing studies into the seepage ecology.

A study into the origin of the seepage water used isotopes and was conducted by the Geological Survey of Western Australia in 1993. The study was undertaken to determine if Egerton Seepage discharged from the unconfined Quaternary Bassendean sand or from the upward leakage of the confined, artesian, cretaceous Leederville formation. Study results showed that the water at the seepage was relatively young with an immature chemical signature that matched the Gnangara Mound profile. The report also suggested that the seepage was created as a result of contact between the Bassendean sand and areas where the underlying Guildford formation is exposed (Thorpe 1993).

Ongoing research by the University of Western Australia (UWA) highlights that Egerton Seepage is of considerable scientific importance and worthy of detailed study into its structure and hydrological dynamics (Knott et al. 2008). The UWA research has found the seepage water is of good quality, and that water quality has been relatively constant over time, other than recent declines in pH levels.

2.4 Ecology

Egerton Seepage is a conservation category wetland and ministerial criteria site that is managed to conserve its flora and fauna (Hill et al. 1996, *Environmental Protection Act 1986*, WRC 1997). The seepage is valued for its significant club moss and liverwort species, its pristine fringing vegetation and for its rich assemblage of macroinvertebrates (Froend et al. 2004a).

The Egerton site has been described as a tumulus – Latin, meaning ‗little mound' – spring community, and is one of only four intact, vegetated tumulus spring communities located on the Swan coastal plain. These communities were assessed in November 1995 as critically endangered and listed as endangered under the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999*. The seepage and surrounding vegetation is also a listed threatened ecological community (approximately 3.6 hectares) and a Bush Forever site (approximately 20.3 ha) (Figure 5) (CALM 2006, Government of Western Australia 2000).

Tumulus spring communities occur at points where groundwater discharges through the ground surface, creating a permanent water supply, around which continuous growth and breakdown of vegetation occurs, causing the formation of peat mounds (CALM 2006). These peat mounds and surrounds create a series of humid microhabitats in the midst of an essentially xeric environment (Knott et al. 2009). The tumulus spring communities identified on the Gnangara Mound occur along a line of groundwater discharge on the eastern side of the mound from Ellenbrook in the south to Muchea in the north.

Studies of tumulus communities have found they are of considerable ecological significance and high conservation value. Many of the plant species and invertebrates found in the Egerton are adapted to the permanent moisture provided by the seepage. The area also probably acts as a refuge from climate change (drying) for certain species (Jasinska & Knott 1994). Gondwanan relicts, which have relied on the maintenance of the moist habitat, have been found in tumulus spring communities. Some of the relic species do not have dormant stages and would not survive if the peat mounds were to dry out (CALM 2006). At Egerton, research conducted by Jasinska and Knott (1994) identified an amphipod endemic to the site. The amphipod identified is a Gondwanic relic that is the only known species of a newly discovered genus.

Characteristic flora at Egerton Seepage includes some species that are commonly found only in the far south-west of the state in permanently moist habitat (Jasinska & Knott 1994). Examples of plants found in tumulus communities on the Gnangara Mound that are disjunct from or at the northern end of their southern range include several liverworts, ferns (*Cyclosorus gongyloides* and *Lycopodium serpentinum*), orchids, sedges (*Cyathochaeta teretifolia* and *Empodissima gracillima*), shrubs (*Hibbertia perfoliata* and *Boronia molloyae*) and trees (*Homalospermum firmum*) (DEC 2009).

Low reeds, rushes, liverworts and club mosses cover the peat mounds at Egerton. Around the seepage the overstorey consists of *Melaleuca preissiana*, *Banksia littoralis*, *Agonis linearifolia* and *Eucalyptus rudis*. Common understorey species include *Agonis linearifolia*, *Pteridium esculentum*, *Astartea fascicularis* and *Cyclosorus interruptus* (CALM 2006).The aquatic fauna at Egerton Seepage exhibits high species richness with all crustacean groups (amphipoda, cladocera, copepoda and ostracoda) represented and most in relatively high abundance (Knott et al. 2009).

Groundwater discharged through the ground surface in the Egerton area is also important in maintaining the health of downstream watercourses. At Egerton, groundwater discharge forms streams and these flow to Ellen Brook. A study by Beatty et al. (2010) suggested groundwater resources may be vital to ensuring the longevity of a number of endangered aquatic macrofauna populations in Ellen Brook.

The government‘s protection of the ecological values at Egerton Seepage began in the mid 1990s when the site was selected as a wetland of significance to be monitored in relation to east Gnangara water allocation and, in particular, the Lexia groundwater schemes (WRC 1997). The selection of the seepage recognised it supported a rich assemblage of macroinvertebrate and vegetation species, including some at the northern limit of their distribution. The Gnangara Sustainability Strategy recognised Egerton as one of 45 significant wetlands on the Gnangara Mound, in terms of biodiversity and ecological function (Gnangara Sustainability Strategy Taskforce 2009).

The existing ecological and water regime management objectives for Egerton Seepage, designed to protect its key ecological values, are as follows (WRC 1997):

- conservation of flora and fauna
- maintain fringing liverwort, bog club moss and other wetland vegetation
- maintain invertebrate species diversity.

The current ministerial water level criteria for Egerton Seepage states water levels should not fall below 39.29 mAHD (WRC 1997, statement 687). This criterion is an absolute summer minimum water level that should be measured at monitoring bore B25 (AWRC 61618607), situated adjacent to the seepage. The criteria became a legally binding criteria in 2005 (statement 687). Criteria levels are generally based on ecological water requirements (EWRs), which are the water regimes necessary to maintain a low level of risk to the ecological values (WRC 2000).

Since groundwater level monitoring of bore B25 commenced in 2000, water levels at Egerton Seepage have met the ministerial criteria in all years except 2003 and since 2003 there has been upward trend in water levels recorded at the bore (Figure 6).

In 2004, the ecological values of Egerton Seepage were re-assessed and EWRs were described for a number of the site‘s ecological values (Froend et al. 2004b). These EWRs are used by the department to assess the possible impact of current water levels on current ecological values. The study suggested:

- the club mosses and liverwort species found at the seepage require permanently saturated soil
- the macroinvertebrate assemblages at the seepage require permanently flowing surface water
- the maintenance of sediment processes (to prevent oxidation of ASS) requires sediments to remain saturated throughout summer each year.

There is no vegetation transect at Egerton Seepage, however, observations made during macroinvertebrate sampling and by Froend et al. (2004b) recorded the vegetation community as intact and in good condition. Monitoring by the University of Western Australia has shown that there have been no major changes in macroinvertebrate assemblages at the seepage (Knott et al. 2009).

Recent water quality measurements at the seepage have been generally indicative of good water quality. However, an upward trend in salinity and downward trend in pH has been observed since monitoring began in 2000. Egerton Seepage is also considered to be at high risk from acid sulfate soils which, if oxidised, could lead to further decreases in pH at the site. Concentrations of other water quality parameters measured at the seepage have been relatively consistent over time, though nitrogen concentrations measured in 2008 exceeded ANZECC/ARMCANZ guidelines (Knott et al. 2009).

The continuation of a downward trend in pH and excessive nutrient input are probably the most immediate threats to the ecology at Egerton Seepage. Further decreases in pH are likely to threaten to the survival of some of the unique tumulus spring species. Excessive nutrient input is likely to favour weed invasion and may change the dynamics of the wetland ecosystem. The ecology of the area is also at risk from fire and weed invasion (CALM 2006). These threats are primarily linked to land and water use surrounding Egerton Seepage. Of particular relevance is the encroaching urban development, which is likely to extend to the edge of the 20.3 ha area listed as a Bush Forever site.

Relationships between ecological function, geology (section 4), hydrogeology and chemistry (section 5) are discussed in section 6.

Figure 5 Bush Forever site (approximately 20.3 ha) at Egerton Seepage

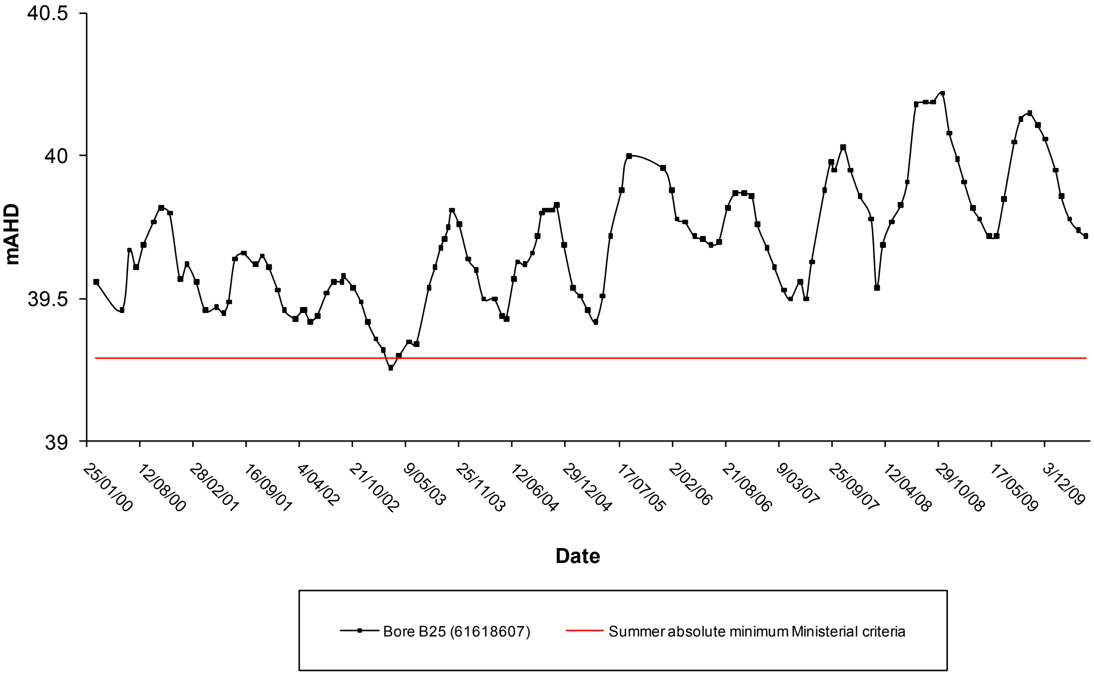

Figure 6 Hydrograph showing groundwater trends at Egerton monitoring bore B25

2.5 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 & Associates 2005).

There are four Aboriginal sites located near Egerton Seepage, which includes scattered artefacts and a camping ground which was used in the 1940s and 1950s Estill & Associates 2005). In addition, a Waugal (Serpent dreaming track) was identified within the creek lines.

Site works and disturbance during the investigation were kept to a minimum by using smaller, direct-push drilling methods where possible and by installing infrastructure within existing disturbed areas.

2.6 Land and water management

The Department of Water has the statutory authority to manage Western Australia's water resources. The department develops allocation water management plans which set a balance between taking groundwater for short-term use and retaining groundwater, to maintain ecology, meet social and cultural needs and provide for future public and private use.

The *Gnangara groundwater areas allocation plan* (2009) sets out the approach to allocation and licensing for all water users on the Gnangara Mound (Department of Water 2009). The department determines the volume and spatial distribution of water abstracted from the mound by assessing proximity to groundwater-dependant ecosystems (GDEs), ecological condition and rate and magnitude of groundwater-level change. For allocation purposes, the Gnangara Mound is divided into groundwater areas and subareas. Egerton Seepage is located in the Swan groundwater area and within the North Swan subarea (Figure 7).

Groundwater is abstracted from the Gnangara Mound by private licence holders, the Water Corporation, for the public water supply (Integrated Water Supply Scheme – IWSS) and by unlicensed, private users (for garden bores). Private, licensed abstraction and abstraction from garden bores occurs mostly from the Superficial aquifer. Abstraction for the IWSS occurs from both the Superficial and the confined Leederville and Yarragadee aquifers. In 2008–09, private, licensed entitlements on the Gnangara Mound totalled 112.54 gigalitres, approximately 1.49 GL less than in 2007–08 (Department of Water 2010). Abstraction for public water supply from the Superficial aquifer in 2008–09 amounted 48.51 GL, approximately 2.06 GL less than in 2007–08 (Department of Water 2010).

The allocation limit for groundwater abstraction in the North Swan subarea is set at 2 GL. The subarea is currently over-allocated, with approximately 2.98 GL of licensed abstraction in 2008 (Department of Water 2010). As the subarea is now over-allocated, no further licences will be issued and a policy to recoup unused entitlements has been initiated. In the subarea, groundwater is abstracted by private licence holders for irrigation and through garden bores for domestic use (Figure 7).

Egerton Seepage and the surrounding vegetation are listed as a threatened ecological community (approximately 3.6 ha) and a Bush Forever site, of approximately 20.3 ha (CALM 2006, Government of Western Australia 2000). The land surrounding the Bush Forever site is currently being developed for urban use. The encroaching urban development is likely to be having an affect on groundwater levels and water quality at the seepage.

The process of urban development at Egerton commenced in 1993, when a proposal was submitted to rezone 537 ha of land at the site from urban deferred to urban. The proposal was assessed as a consultative environmental review by the Environmental Protection Authority (EPA) in 1994 (Alan Tingay & Associates 1994, ATA Environmental 2005). The EPA concluded the proposal to rezone the land was environmentally acceptable and recommended the Minister for the Environment approve the rezoning proposal. The minister subsequently approved the proposed rezoning, subject to a number of conditions, including the preparation and implementation of a wetland management strategy, to be satisfied at various stages of the development (ATA Environmental 2005). In November 2004, it was announced that the Egerton area would be developed as a predominantly residential development to be known as ‗The Vale'. Once complete, the Vale development will border the Bush Forever site to the north, east and south (Figure 8).

Groundwater levels and water quality at the seepage are also probably affected by the Ellenbrook development that borders the Bush Forever site to the west.

Other land uses that may be affecting groundwater levels and water quality at the seepage include:

- pine plantations located to the north-west of Ellenbrook development
- a golf course and country club situated beyond the Vale development to the north-east
- a stud farm, which breeds cattle, sheep and horses, situated beyond the Vale development to the south-east.

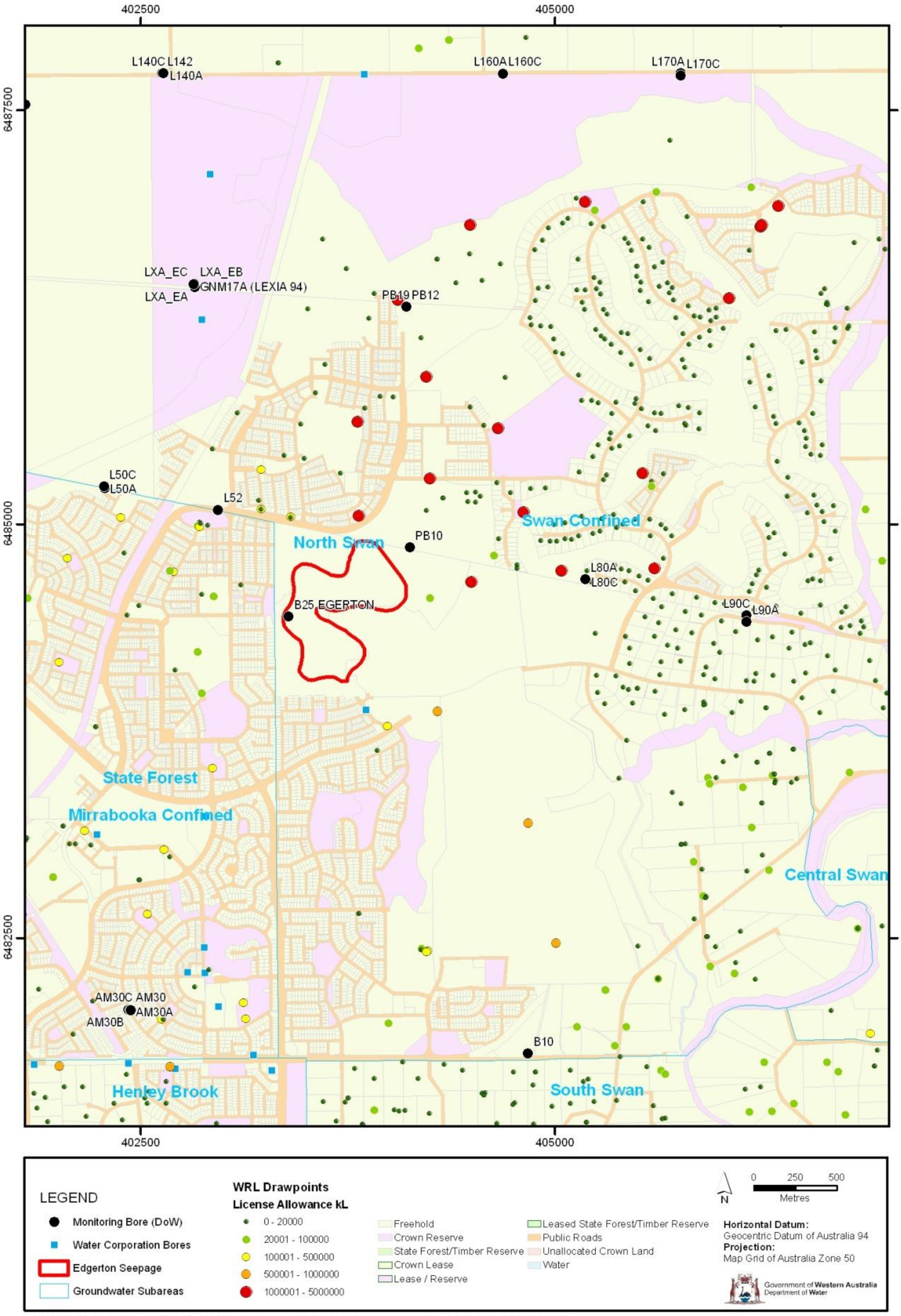

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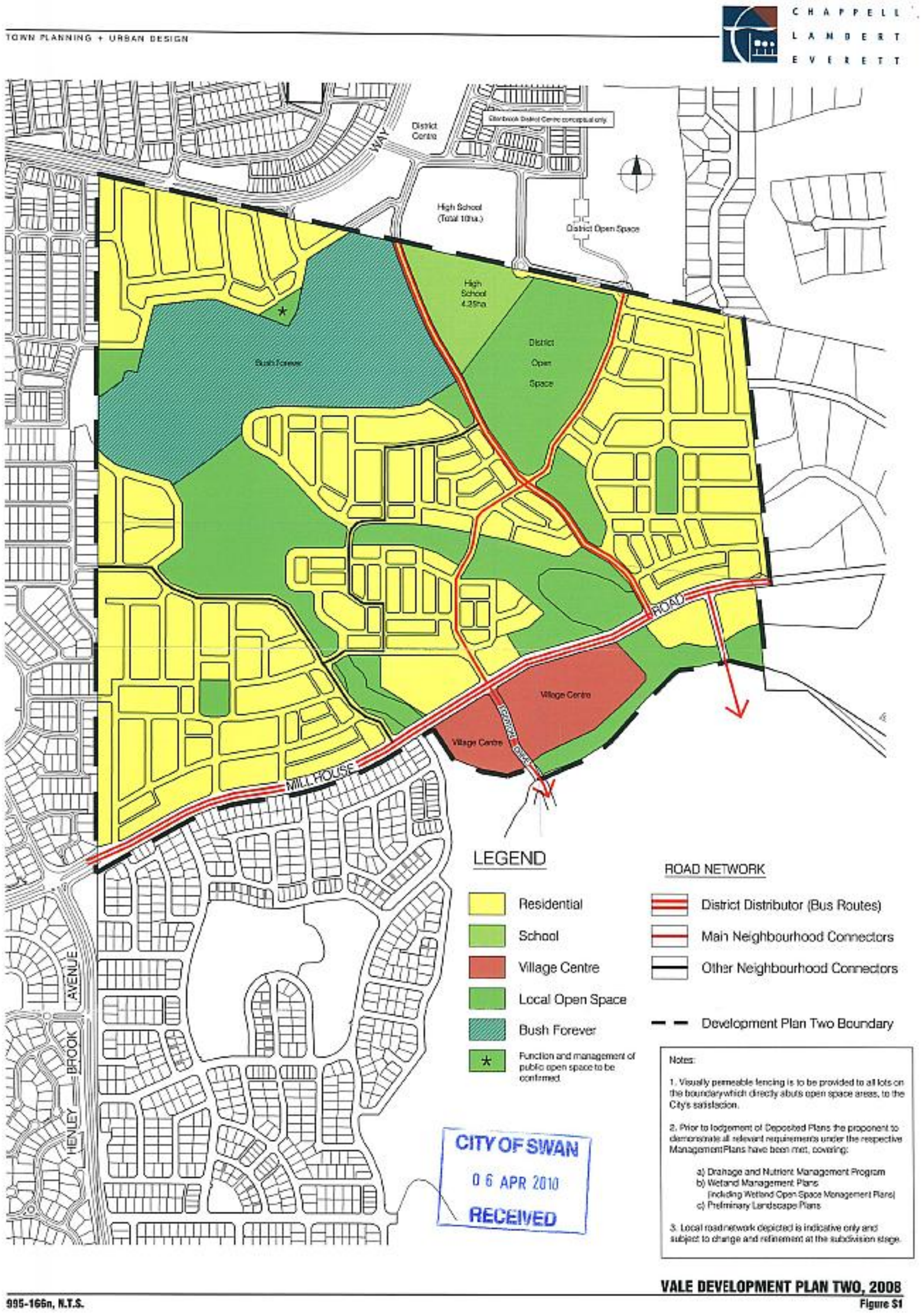
Figure 7 Water allocations around Egerton Seepage



Notes:

1. Visually permeable fencing is to be provided to all lots on the boundarywhich directly abuts open space areas, to the City's satisfaction.

2. Prior to lodgement of Deposited Plans the proponent to demonstrate all relevant requirements under the respective ManagementPlans have been met, covering:

   a) Drainage and Nutrient Management Program
   b) Wetland Management Plans (including Wetland Open Space Management Plans)
   c) Preliminary Landscape Plans

3. Local roadnetwork depicted is indicative only and subject to change and refinement at the subdivision stage.

Figure 8 The Vale development (source: Chapel Lambert Everett, Outline Development Plan 155, Vale Development Plan Two 2010)

3 Investigation program

The Water and Rivers Commission (1997) and the *Management area review of shallow groundwater systems on the Gnangara and Jandakot mounds* (McHugh & Bourke 2007) highlighted the need for site-specific information about wetland function to appropriately manage Egerton Seepage.

The management area review recommended that the shallow groundwater systems investigation construct new monitoring bores, and undertake water level measurements and water quality sampling at Egerton. Acid sulfate soils investigations were also recommended by the review and carried out in this investigation.

The drilling program consisted of installing three groundwater monitoring bores (EGT_A, EGT_B and EGT_C) approximately 100 metres up-hydraulic gradient from Egerton Seepage between May and June 2007. The new bores were designed to monitor trends in groundwater levels and quality within the Superficial aquifer near the seepage. Groundwater bore locations are shown in Figure 9.

3.1 Field methodology

Monitoring bores were installed by Great Southern Drilling and supervised by a Department of Water hydrogeologist. Lithological samples were logged, photographed and collected at 1 m intervals during the construction of deep monitoring bore EGT_A.

A shallow monitoring bore (EGT_C) was installed using a Geoprobe 7720DT track-mounted drill rig, which provided continuous core samples using push-tube techniques to depth. An intermediate (EGT_B) and deep (EGT_A) bore were installed using the GSD77 air-core drill rig, with aggregate samples of drill cuttings collected every metre to depth. All bores were screened in the Superficial aquifer, with the shallow bore screened at the water table, the intermediate bore screened approximately halfway through the Superficial aquifer and the deep bore screened at the base of that aquifer.

To determine the nature and extent of sulfidic sediments surrounding Egerton Seepage and their potential effect on groundwater quality, soil samples from EGT_C were collected and analysed approximately every 25–50 centimetres in the field for potential acid sulfate soils and actual acid sulfate soils. Samples were collected in accordance with the Department of Environment‘s (now Department of Environment and Conservation) *Draft investigation and identification of acid sulfate soils guide* (2006). The detailed field methodology is contained in Appendix C.

Results for the field testing are presented in Table 4.

Figure 9 Bore transect used for cross-sections

3.2 Bore construction

The management area review recommended upgrading the groundwater monitoring infrastructure at Egerton Seepage to enable hydrological and hydrogeochemical investigations. The infrastructure upgrade included a cluster of bores up-gradient of the site (EGT_A, EGT_B and EGT_C). Lithological and construction details are reported in Appendix A, and in Bourke (2008).

The bores were constructed using 50 millimetre class 12 PVC (polyvinyl chloride). The shallow bore was completed with gravel backfilled to the ground surface. The annulus of the deep and intermediate bores were filled with gravel pack from the base of the hole to 2 m above the screened interval, and then grouted to surface with cement slurry. They were developed with airlifting to remove silt material accumulated at the base of the bore. Head works consisted of steel standpipes cemented into the ground to a height of approximately 0.5 m above ground level at all locations. Once complete the deep bore was then geophysically logged using a gamma log probe.

Table 1 Monitoring bores installed at Egerton Seepage [i]

Depth	AWRC name	AWRC number	Drilled depth (m BNS)	Screened interval (m BNS)
Shallow	EGT_C	61611443	8.3	1.96–4.96
Intermediate	EGT_B	61611444	27.0	20.92–22.92
Deep	EGT_A	61611445	45.0	30.14–32.14

[i] Cluster bores (up-hydraulic gradient)

3.3 Water monitoring and sampling program

A monthly water monitoring and sampling program was designed to measure water levels and take samples from the three newly installed and one existing monitoring bore (B25) from June 2007 to June 2008.

Low-flow sampling methods were used to collect water samples for analysis, to assess seasonal trends in the groundwater and the seepage. The chemical analysis suites for soil and groundwater are outlined in Table 2 and the groundwater sampling methodology is described in Appendix C.

Table 2 Water analysis conducted by NMI

Ions	Ca, Na, Mg, K,SO^4, Cl, HCO^3, SiO^2, CO^3, F
Physical parameters	EC, TSS, TDS, pH, acidity, alkalinity
Total metals	Hg, Al, As, Cd, Cr, Fe, Mn, Ni, Se, Zn
Dissolved metals	Mg, B, Fe, Al
Nutrients and organics	$NH_{3-}N$, TN, TP, NO_x, FRP, DOC, DON
Herbicides and pesticides	Chlordane {Tech; a+g}, DDD-p,p, DDE-p,p, DDT-p,p, Dieldrin, Endosulf sulfate, Endosulf-a, Endosulf-b , Endrin, HCH (BHC) a,b,d, HCH (BHC), Heptachlor, Heptachlor epoxide, Hexachlorobenzene, Methoxychlor, Ocs

3.4 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 or accuracy errors. Precision or statistical errors result from random fluctuations in the analytical procedure. Precision can be calculated by performing repeat analysis on the same sample. Seven laboratory duplicates were analysed for the shallow groundwater systems (SGS) investigation at Egerton Seepage. Results from these indicate that laboratory precision is very good, with most duplicates being within five to 10 per cent, positive or negative, of the original sample.

Accuracy or systematic errors reflect faulty procedures or interference during analysis. An electrical balance (EB), also known as an ion balance, is used to check the accuracy of analytical results. The sum of positive and negative charges in the water should be equal (Appelo & Postma 2005), and as such the sum of the cations in solution should equal the sum of the anions.

$$\text{Electrical balance (EB per cent)} = \frac{\text{(sum cations + sum anions)}}{\text{(sum cations – sum anions)}} \times 100$$

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

Deviations of more than five per cent signal that sampling and analytical procedures should be examined (Appelo & Postma 2005). For the SGS investigation, if the EB was greater than six per cent, without satisfactory explanation, then this sample was left out of the analysis.

A comparison of the pH measured in the laboratory and those levels measured in the field immediately after sampling, can indicate that a water sample has been altered by the collection, transport or storage processes.

There are numerous causes of a difference in field and laboratory pH readings, including reactions involving oxidation, precipitation and the release of dissolved gas. These differences can highlight uncertainty in the reported chemical concentrations. Figure 10 compares the pH values taken in the field and from the laboratory for the SGS investigation at Egerton Seepage. The correlation coefficient between field and laboratory pH values indicates that the laboratory results were reasonably reliable (r = 0.918). All but one sample showed less than 1-pH-unit difference between the two pH readings.

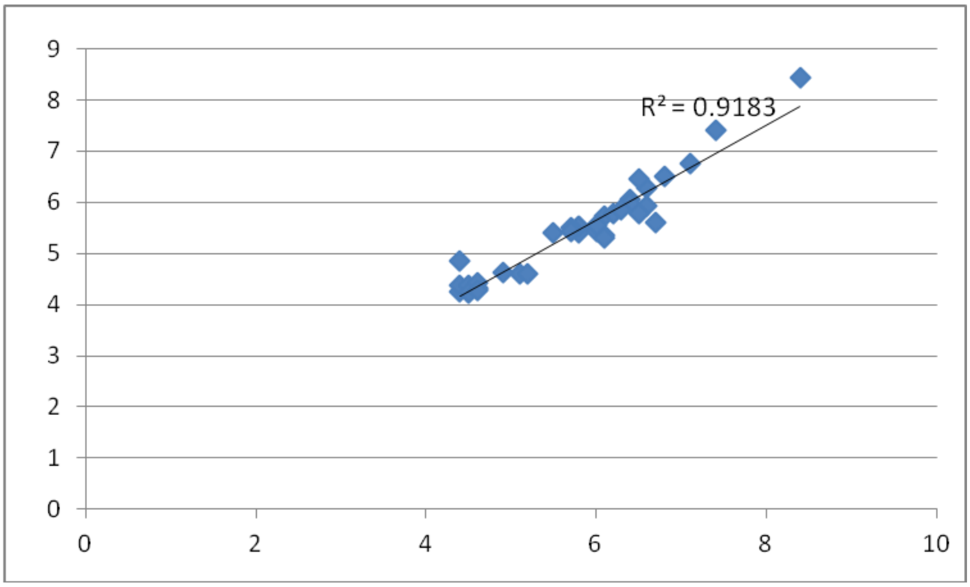


Figure 10 Comparison of field-measured pH with laboratory-measured pH

3.5 Data presentation and interpretation

The following data presentation and interpretation methods were used to determine the hydrogeological and hydrochemical characteristics of the Egerton Seepage area:

- interpretation of lithological logs
- geological cross-section
- analysis of hydrographs
- classification of redox processes
- groundwater contour maps for both maximum and minimum water levels
- flownets for both maximum and minimum water levels
- piper diagrams for major ions
- time series plots for major ions, metals, nutrients, herbicides and pesticides, and physical properties.

4 Geology

4.1 Local geology

The results of the shallow groundwater systems (SGS) drilling program, in combination with existing data, provide a better understanding of the geology of the superficial formations near Egerton Seepage. The west-east cross-section in (Figure 11) shows that from monitoring bore PB3 to L90, the thickness of the superficial formations to be approximately 60 metres near monitoring bore L60, and thinning to approximately 30 m in an easterly direction toward monitoring bore L90.

At Egerton, the superficial formations are approximately 40 m thick and unconformably overlie the Cretaceous Poisonhill greensand. Bassendean sand extends to a depth of 38 m. Poisonhill greensand is a dark-greyish-brown, light-grey, light-brownish-grey, pale-brown and dark-yellowish-brown fine-grained quartz sand with abundant glauconite and heavy minerals throughout.

Overlying the Poisonhill greensand is approximately 2 m of Gnangara sand, which comprises grey, medium-grained quartz sand with some feldspar. Bassendean sand overlies Gnangara sand and is dark-greyish-brown, light-grey and light-brownish-grey fine- to coarse-grained quartz sand, with sub-angular to rounded grains and minor silt at some 38 m thick. At Egerton, two Guildford clay lenses interfinger the Bassendean sand at the depths of 11.5 m (with a thickness of 1.5 m) and 15.7 m (1.3 m thickness). These lenses consist of greenish-grey and greyish-brown sandy clay (Table 3).

Table 3 Generalised stratigraphy of the Egerton Seepage area

Age	Unit	Thickness (m)	Lithology
Quaternary	Bassendean sand	35.2	Fine to coarse sand with some silt inter fingered with Guildford clay
Quaternary	Guildford clay	2.8	Sandy clay
Quaternary	Gnangara sand	2	Medium to coarse sand
Cretaceous	Poison Hill greensand	unknown	Sandy clay

4.2 Acid sulfate soils

During the drilling investigation, selected soil samples were taken to measure soil pH and to assess for actual and potential acid sulfate soils. The results from the field testing are outlined in Table 4 and show low field-pH values in the top 50 centimetres of sediment and could be considered actual acid sulfate soils.

At depths from 0 m to 1.2 m the oxidised pH ranged from 2.49 (0.1m) and 3.83 (1.0m), which is indicative of potential acid sulfate soils.

Table 4 Recorded values of soil pH during drilling investigation

		Field pH				
Borehole	**Soil texture**	**Depth m**	**pH$_F$**	**PH$_{FOX}$**	**Δ pH**	**Reaction**
EGT_c	Black organic matter (silt) with grey quartz sand and rootlets.	0.1	4.04	2.49	1.55	Low
EGT_c	Grey, medium-to-coarse quartz sand with organic matter and rootlets.	0.5	3.72	3.08	0.64	No
EGT_c	Light-grey-brown, medium quartz sand with roots.	1.0	5.29	3.83	1.46	No
EGT_c	Light-brown, mottled quartz sand with roots.	1.2	4.92	2.94	1.98	No
EGT_c	Light-grey-brown, medium-to-coarse quartz sand with roots.	1.5	5.55	4.82	0.73	No
EGT_c	Light-brown, medium-to-coarse quartz sand with roots.	2.0	4.52	4.81	–0.29	No
EGT_c	Light-brown-grey, medium-to-fine quartz sand.	2.5	4.66	5.11	–0.45	No
EGT_c	White, fine-to-medium quartz sand.	3.0	5.05	5.11	–0.06	No
EGT_c	As above	4.0	4.82	5.15	–0.33	No
EGT_c	As above	5.0	4.80	5.22	–0.42	No

Borehole	Soil texture	Field pH				Reaction
		Depth m	pH_F	PH_{FOX}	Δ pH	
EGT_c	As above	6.5	5.07	5.22	–0.15	No
EGT_c	Light-grey, fine-to-medium quartz sand.	7.5	5.66	5.17	0.49	No
EGT_c	Light-grey, fine-to-medium quartz sand.	8.0	5.53	5.14	0.39	No

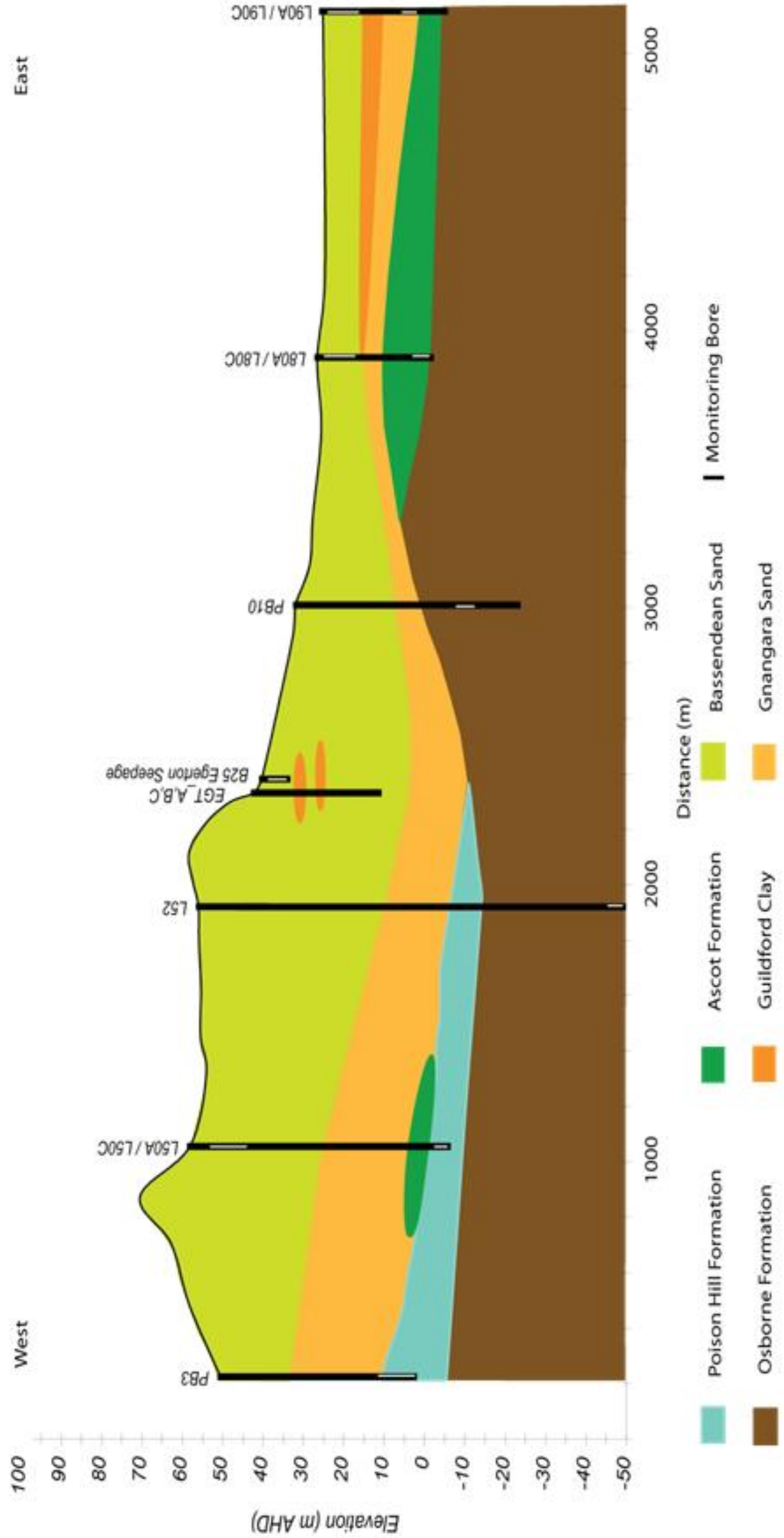


Figure 11 Geological cross-section through Egerton Seepage

5 Hydrogeology

5.1 Groundwater occurrence and flow

Groundwater around the Egerton site occurs in the Bassendean sands of the Superficial aquifer which has a saturated thickness of approximately 50 metres in this area.

Data from the shallow groundwater systems (SGS) investigation shows that in the Egerton area groundwater flows from west to east, generally following topography from the crest of the Gnangara Mound, and flows towards Ellen Brook where it discharges. The watertable varies by approximately 1 m between the winter maximum and summer minimum, while seasonal flow patterns are similar (Figure 12). The hydraulic gradient west of the site is shallow (0.003 m) then slightly steepens (~ 0.008 m) near the contact of Bassendean sand and Guildford clay. This indicates the higher hydraulic conductivity of the Bassendean sands up-gradient of the Egerton site. Near Egerton a 39m contour deflection suggests recharge in the area and the suggestion of a localised mound.

Comparison of the groundwater elevations derived from SGS investigation data with those from 1996 to 1997, shows that the watertable has risen by 1 m or so around the Egerton site (Figures 12 and 13).

Hydrogeological cross-sections of the flow paths surrounding Egerton Seepage indicate the flow within the superficial formations is linear in a horizontal direction with a downward hydraulic head (Figure 14). This suggests Egerton Seepage is a surface expression of the shallow depth-to-groundwater, rather than an upward potentiometric head from the base of the Superficial aquifer and underlying formations towards the ground surface.

5.2 Water-level trends

Analysis of monitoring bore hydrographs near Egerton (see Figure 9 for bore locations) shows that water levels within the Superficial aquifer have remained relatively stable in bores up-gradient of the site (PB3, L50C and L52). However, the seasonal amplitude at monitoring bore L80, situated along the southern margins of a gold course, 1.8 kilometres down-gradient of Egerton Seepage, has increased to 5 m. Minimum levels have fallen by some 4 m in 10 years, from 25.16 metres Australian Height Datum in April 1997 to 21.60 mAHD in 2008 (Figure 15). Peak winter levels show a slight declining trend.

Historical groundwater levels in monitoring bore L50, situated to the north of the Vale estate and approximately 1500 m to the north-west of Egerton Seepage, have generally had small seasonal fluctuations of approximately 0.5 m. However, since 2004, the seasonal amplitude has increased to more than 1 m. Peak water levels have also risen from 42.61 mAHD in September 2004 to 43.51 mAHD in September 2008.

Groundwater levels in L60C declined by 1 m in the 12 months from October 1998, declining from 40.69 mAHD to 39.68 mAHD in October 1999, prior to the destruction of the groundwater bore.

Historical groundwater levels in ministerial criteria bore B25 show that the seasonal amplitude is typically some 0.5 m and water levels have risen by approximately 0.5 m since 2004. Groundwater levels within the three newly installed bores were measured on a monthly basis from May 2007 to July 2008 and are also shown in Figure 14. The hydrographs of the Egerton monitoring network indicated groundwater elevations were higher in the shallow monitoring bore (EGT_C) than in the intermediate (EGT_B) and deep bore (EGT_A), which suggests a downward potentiometric head (Figure 16).

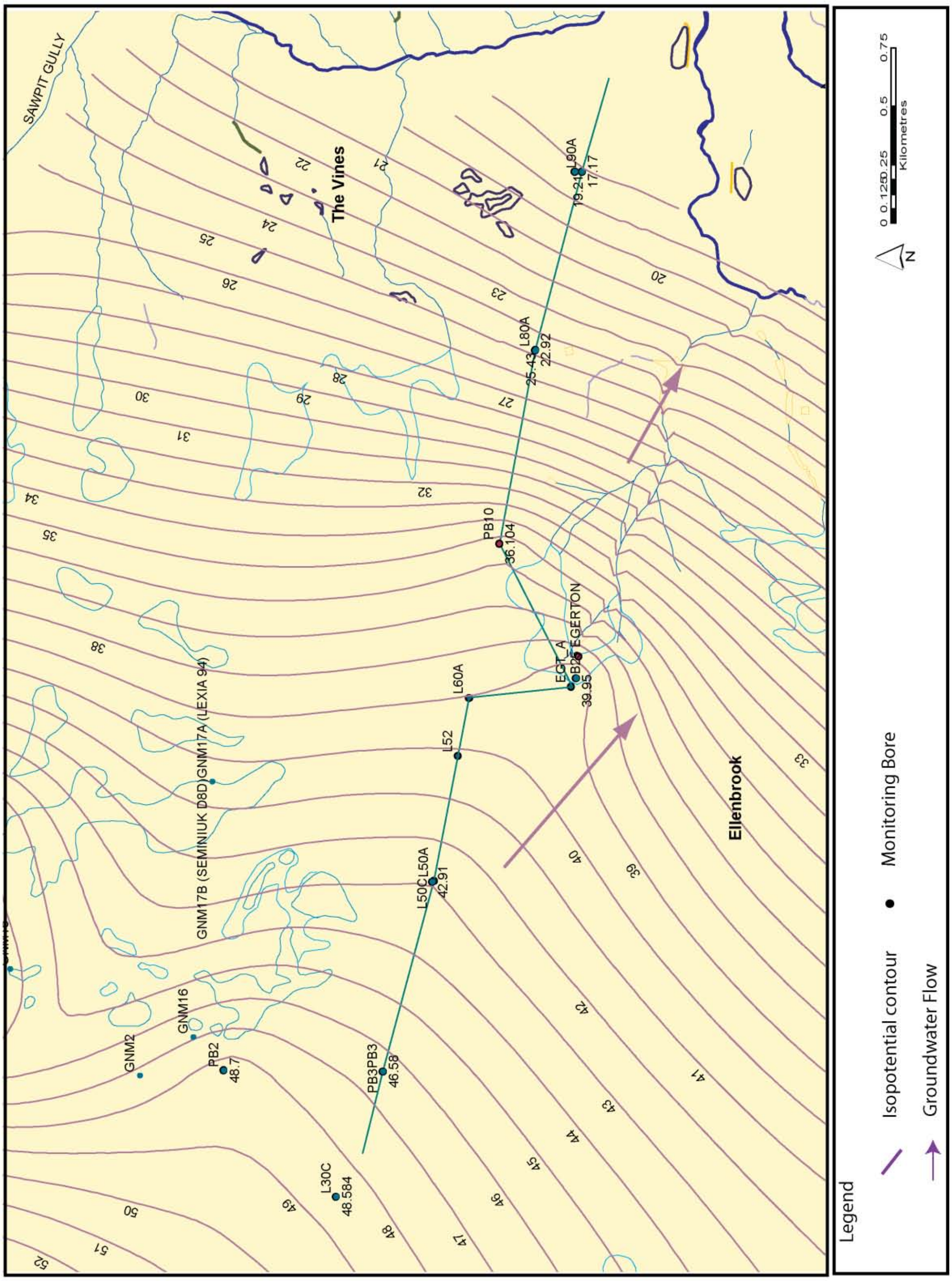


Figure 12 Inferred groundwater contours (October 2007)

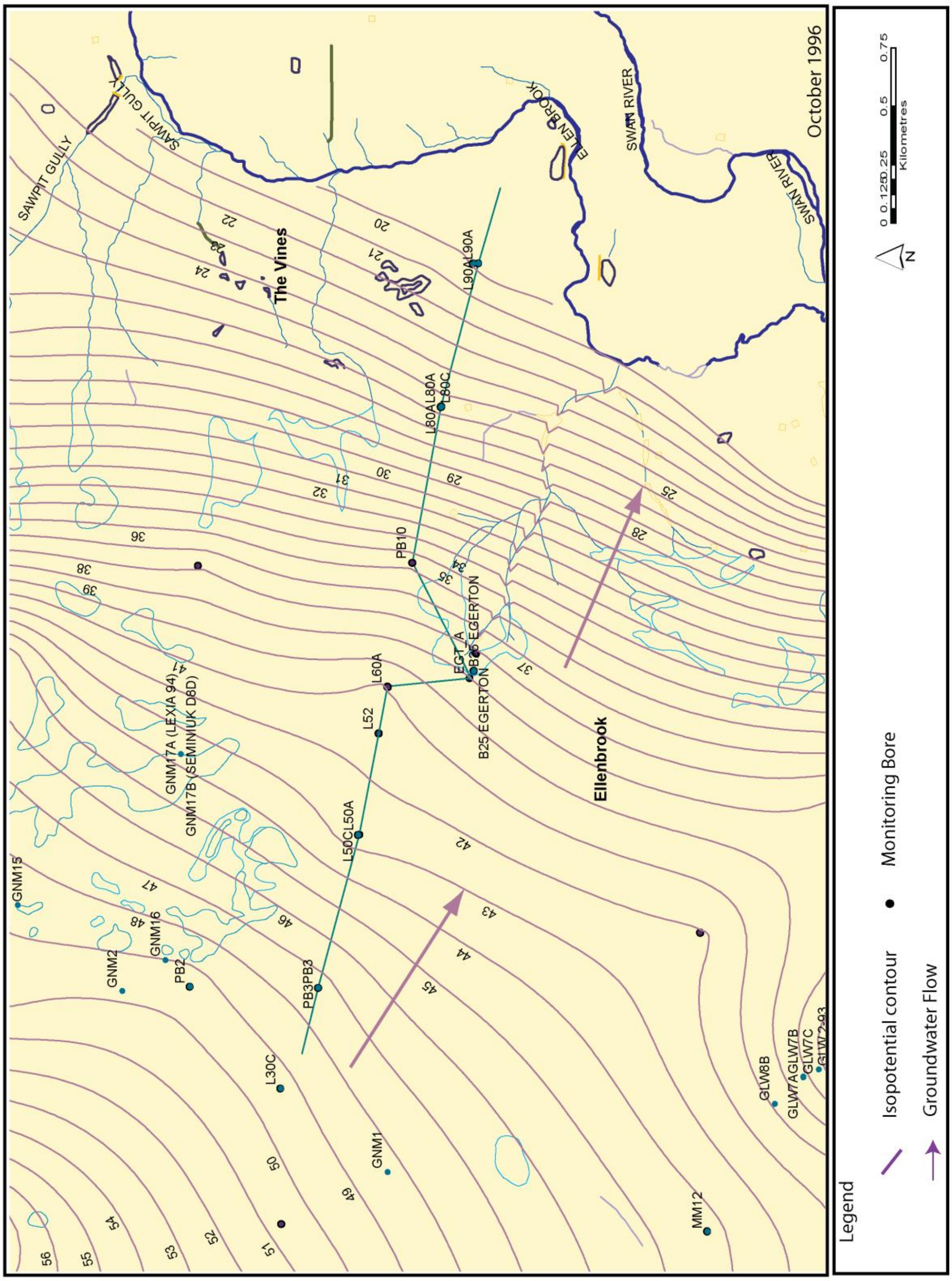


Figure 13 Inferred groundwater contours (October 1996)

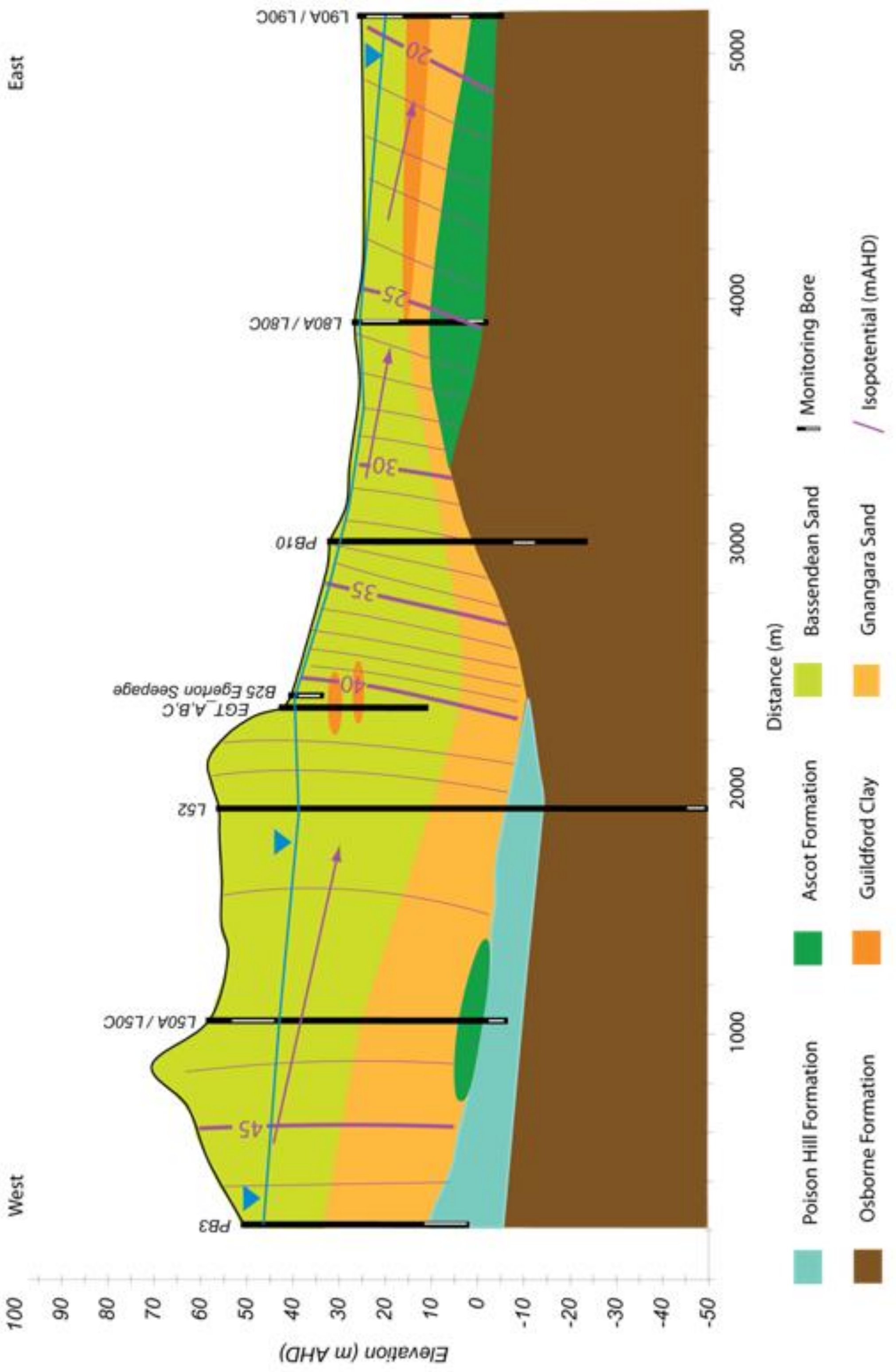


Figure 14 Hydrogeological flow paths (October 2008)

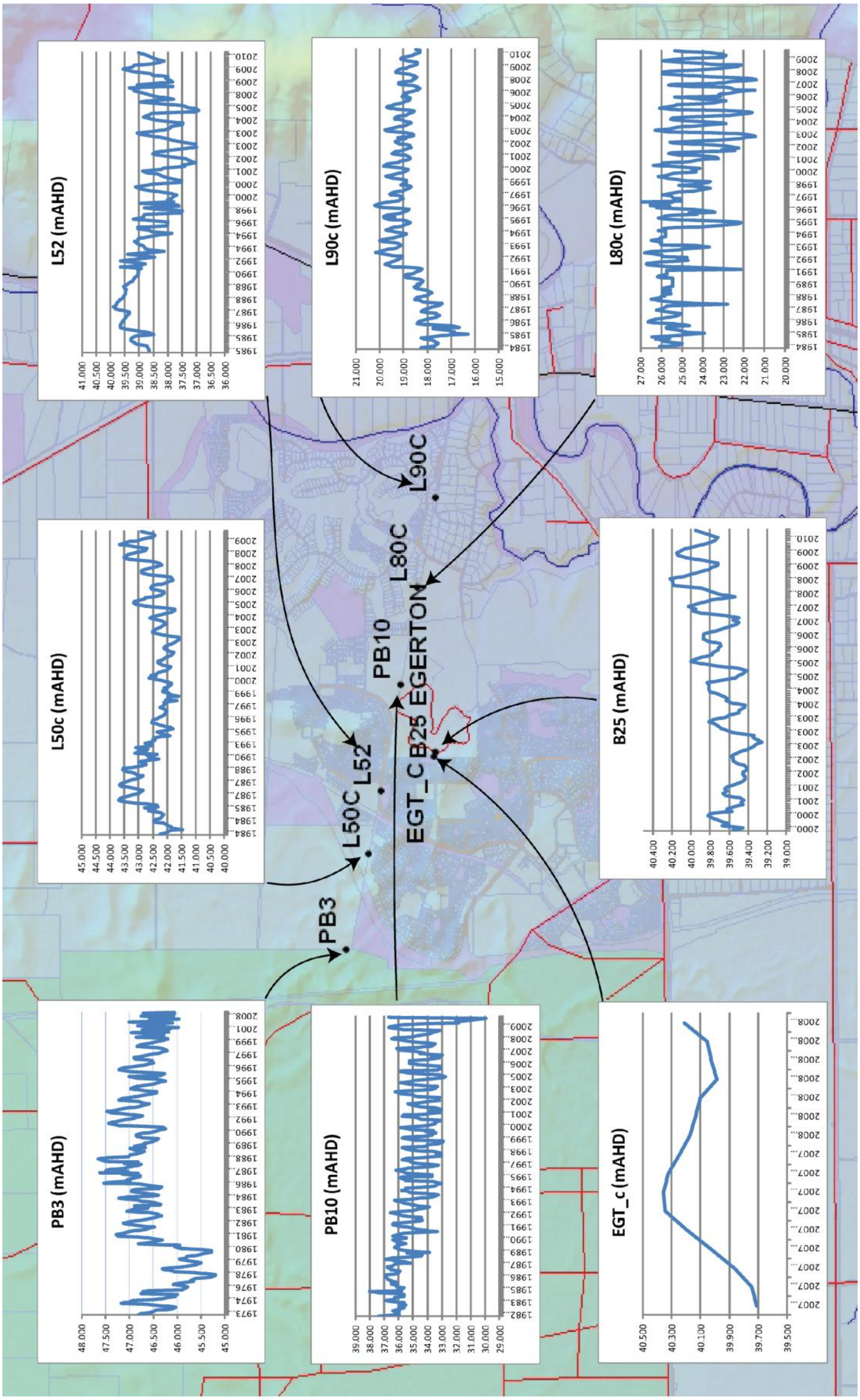


Figure 15 Egerton area hydrographs

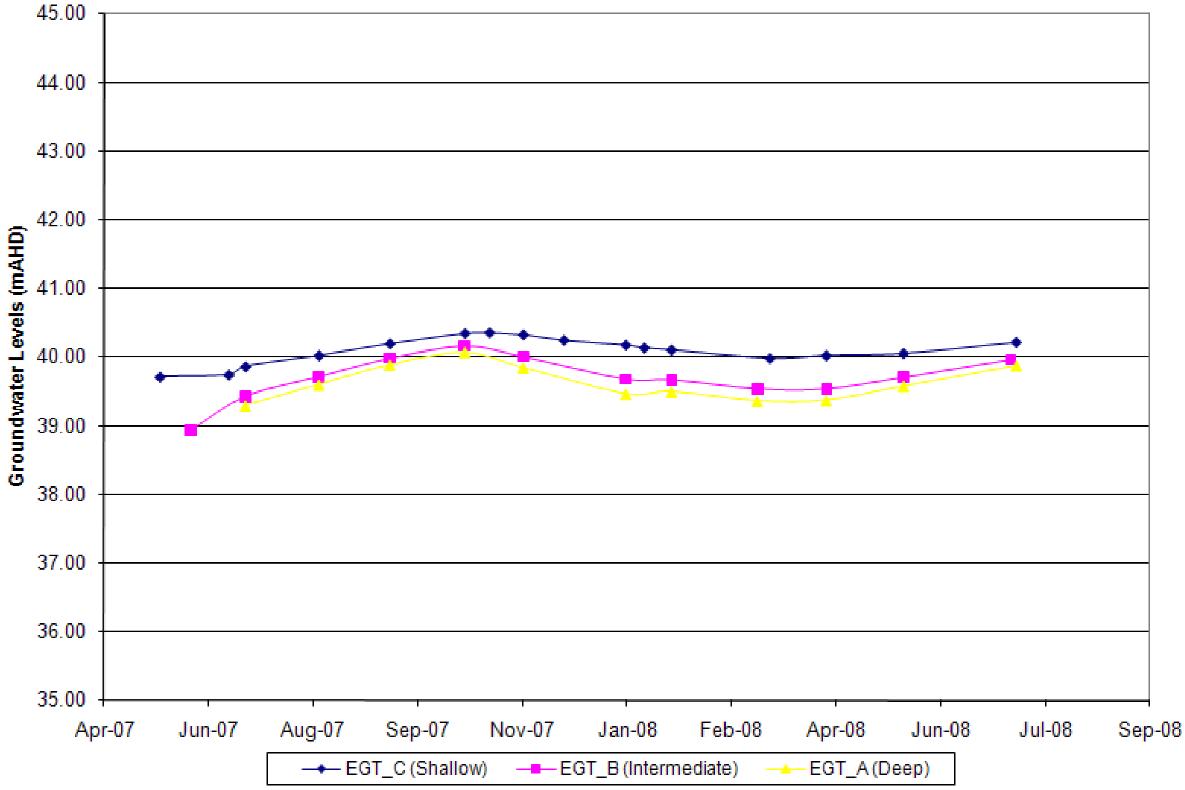


Figure 16 Hydrographs for Egerton bores EGT_a, b and c

5.3 Hydrogeochemistry

Chemical analysis of groundwater samples was used to determine the hydrochemical characteristics at Egerton Seepage, the presence, distribution and presence of potential pollutants, and the interaction between the site and the Superficial aquifer.

The chemical data was compared to appropriate groundwater criteria trigger values and assessment levels for various water uses and environments. Trigger values for fresh water, irrigation water and drinking water were sourced and applied in accordance with the Department of Environment and Conservations *Assessment levels for soils, sediment and water (*DEC 2010). These assessment levels were amalgamated from a number of sources. The fresh water and irrigation water assessment levels were taken from the *Australian and New Zealand guidelines for fresh and marine water quality* (ANZECC 2000). The drinking water assessment levels were taken from the *Australian drinking water guidelines* (NHMRC & ARMCANZ 1996).

Physical and chemical characteristics

Major ions

To characterise the water in the Superficial aquifer at Egerton, a range of ions and physical properties were measured. Concentrations of major ions – sodium, potassium, calcium, magnesium, chloride, bicarbonate and sulfate – were used to create piper diagrams. Piper diagrams are a simple-but-useful method to present and determine the geochemical nature of individual groundwater samples and, in turn, assist with a compare-and-contrast of samples with different chemical characteristics. Piper diagrams that plot all groundwater samples at Egerton for this investigation are presented in Figure 17. The diagrams show:

- groundwater from the shallow bore and intermediate bores was predominantly of sodium chloride (NaCl) composition and plotted similarly to groundwater samples taken from monitoring bores, screened in Bassendean sand, that are recharged by rainfall (Yesertener 2008)
- groundwater from the deep bore was relatively higher in its composition of carbonate, bicarbonate, sodium and potassium, compared to the shallower bores. Samples from this bore plot more closely to groundwater samples taken from monitoring bores screened into the calcareous Tamala limestone (Yesertener 2008).

In general, the data shows little seasonal variation in major ion composition. Concentrations of sodium remained stable within the different aquifer zones, ranging from 24 milligrams per litre to 35 mg/L, while concentrations of calcium, magnesium and potassium were less than 25 mg/L.

Chloride concentrations were low and were measured at 45 mg/L to 300 mg/L, similar to reported concentrations for the Superficial aquifer (Davidson 1995, Yesertener 2008). Sulfate concentrations ranged from less than the 5 mg/L laboratory level of reporting (LOR), up to 21 mg/L, with a decrease in concentration with depth.

Sulfate–chloride as mg/L ratios can be use to determine if groundwater is enriched in sulfate. This enrichment may be the result of fertiliser application or sulfide oxidation. Studies of the Gnangara Mound have shown that in some areas, sulfate–chloride ratios of greater than 0.9 indicate significant sulfide oxidation (Vogwill et al. 2005). The calculated SO_4^{2-}–Cl^-ratios for the groundwater sampled from the Egerton bores ranged from 0.07 in January 2008 to 0.43 in July 2007 (Figure 18).

Concentrations of bicarbonate were lowest within the shallow zone of the Superficial aquifer near Egerton (<1 mg/L to 12 mg/L) and increased with depth (from 10 mg/L to 63 mg/L in the intermediate zone and from 19 mg/L to 110 mg/L in the deeper parts of the aquifer).

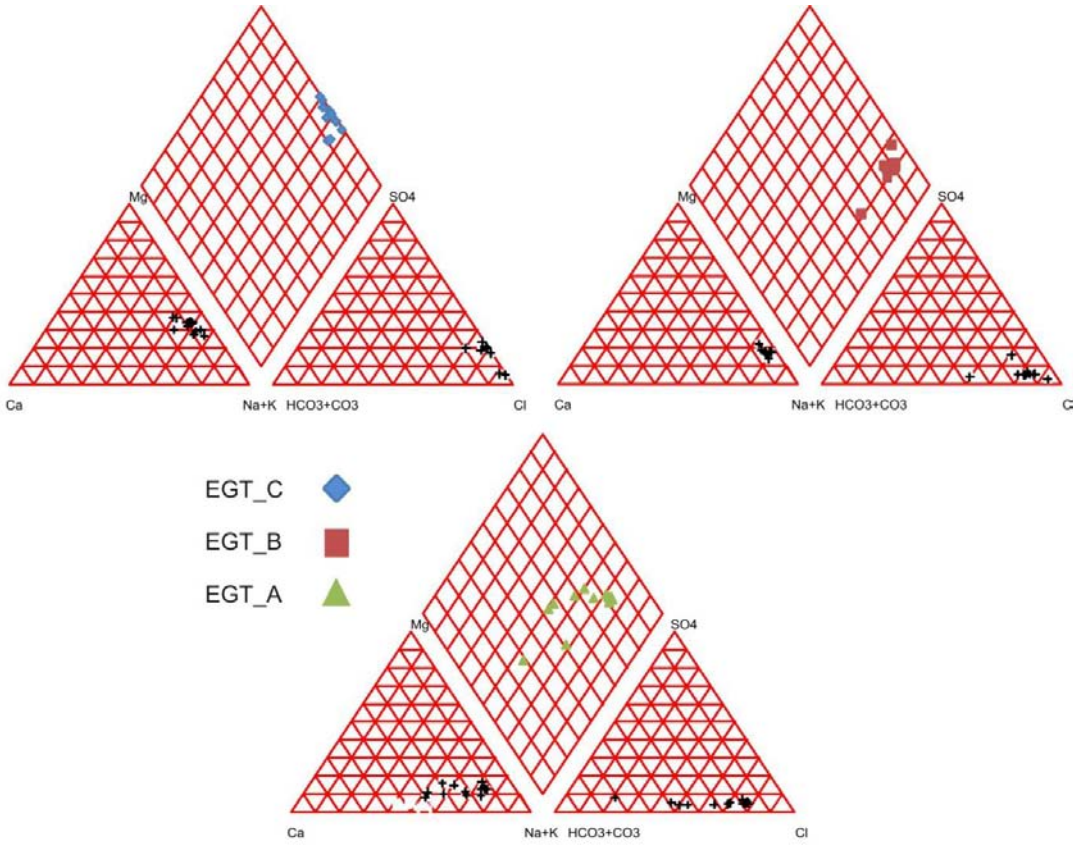


Figure 17 Piper diagrams for Egerton bores

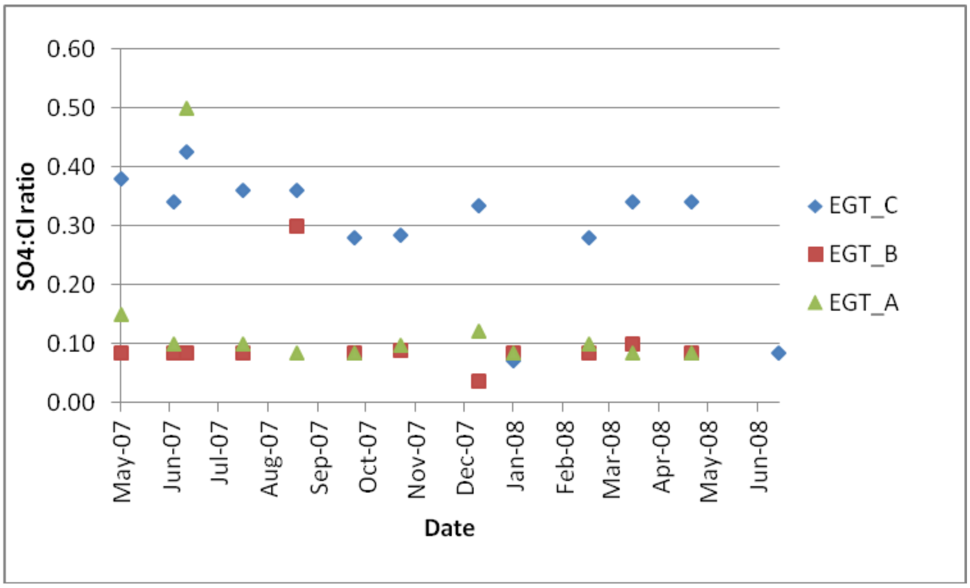


Figure 18 SO_4:Cl ratios of Egerton monitoring bores

Salinity as electrical conductivity and total dissolved salts

Groundwater salinity, mg/L total dissolved salts, as measured in the monitoring bores was fresh, ranging from 90 mg/L (EGT_A, EGT_B and EGT_C in March 2007) up to 380 mg/L in EGT_B (June 2007).

Electrical conductivity (EC) values recorded at the seepage between October 2000 and October 2007 ranged from 200 microsiemens per centimetre (µS/cm) to 300 µS/cm.

Acidity, alkalinity and pH

Recorded pH in Egerton bores indicated the groundwater was acidic in the shallow Superficial aquifer, becoming less acidic with depth (Figure 19). During the investigation, many samples showed pH values below the healthy range given by the Australian and New Zealand Environment Conservation Council for wetlands in south-west Australia (7–8.5). The pH levels spanned from 4.4 to 6.7 with an average of 4.8 in EGT_C, from 5.5 to 6.1 with an average of 5.9 in EGT_B, and from 6.2 to 8.4 with an average of 6.8 in EGT_A. The low pH recorded in the shallow zone of the aquifer (EGT_C) was likely to be affecting the ecology of the seepage.

The alkalinity of water is essentially its acid-neutralising capacity (ANC). Analysis of alkalinity can give greater insight into the characteristics of water and its possible behaviours than pH measurements alone, which only determine H^+ activity. Total alkalinity as calcium carbonate of groundwater from the Egerton bores was lowest in the shallow bore, ranging between <1 mg/L and 15 mg/L $CaCO_3$, and increased with depth. Total alkalinity of the deep bore ranged from 19 to 110 mg/L $CaCO_3$. A comparison of pH and alkalinity of groundwater (Figure 20, as an indication of alkalinity and buffering capacity of sediments) indicates that EGT_C had the least buffering capacity of all groundwater samples.

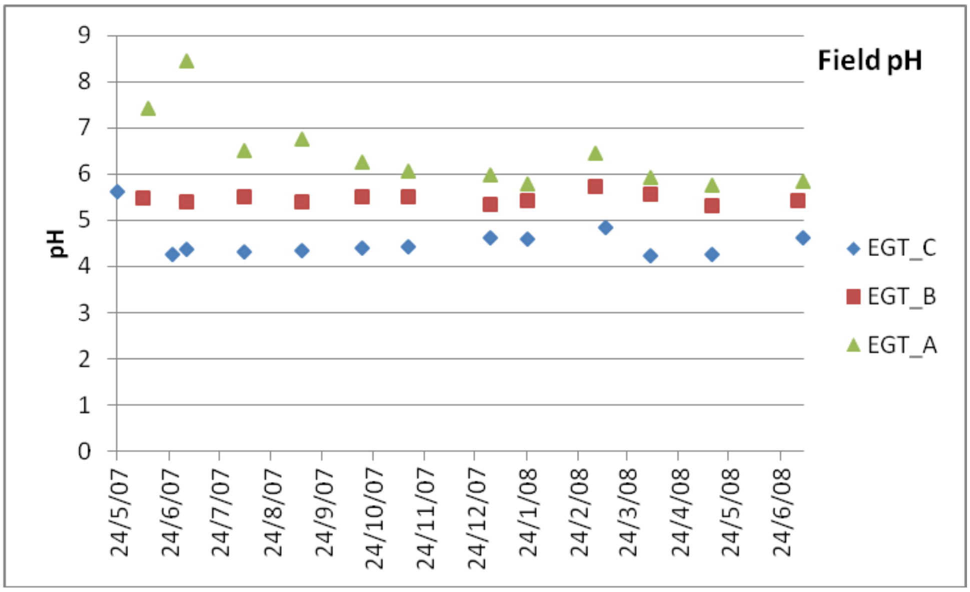


Figure 19 pH levels recorded at the Egerton monitoring bores

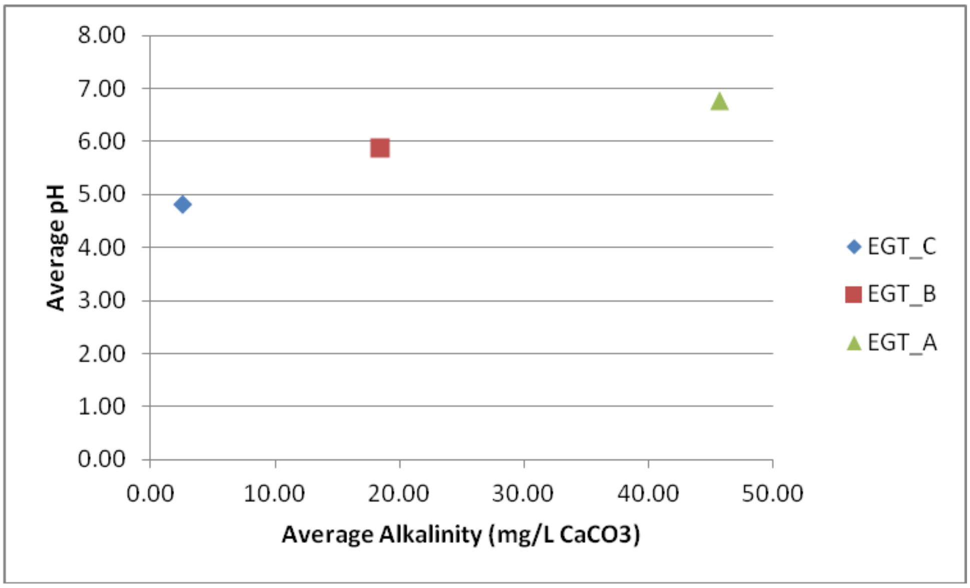


Figure 20 Average pH and average alkalinity of Egerton bores

Groundwater acidity, measured as mg/L of $CaCO_3$, was generally highest at the watertable (ranging from 46 mg/L to 94 mg/L in EGT_C) and decreased with depth (ranging from <1 to 41 mg/L in EGT_A).

Redox conditions

In situ measurements of dissolved oxygen (DO) and redox potential (Eh) were made at each sampling event. DO concentrations greater than 0.5 mg/L are considered to indicate an oxic environment, and concentrations less than 0.5 mg/L an anoxic environment (Apello & Postma 2005). Dissolved oxygen measurements are susceptible to interference from air bubbles in the line during sampling, which results in an erroneously high DO reading.

Measurements of Eh can provide an indication of possible reactions that may be occurring in the water column. A negative redox potential suggests reactions are dominated by reduction. Conversely, a positive redox potential suggests that reactions are dominated by oxidation processes. Instantaneous redox measurements are difficult to interpret as most natural waters are not in equilibrium.

Redox reactions in water are largely driven by bacteria that preferentially utilise oxidants to maximise their energy gain. The ecological redox sequence describes this order of preference: oxygen → nitrate → manganese → iron → sulfate → carbon dioxide.

Dissolved oxygen levels ranged from 1.6 mg/L (May 2007) to 2.96 mg/L (January 2008) in the shallow zone while the intermediate zone had 0.17 mg/L (January 2008) to 7.3 mg/L (June 2007) and the deep zone 0.18 mg/L (October 2007) to 6.46 mg/L (March 2008). These results generally indicated DO levels were decreasing with depth.

Redox potential ranged from –54 mV to 249 mV in EGT_C, with –240 mV to 61 mV in EGT_B and –297 mV to –89 mV in EGT_A. The largely positive Eh values recorded at the shallow monitoring bore (EGT_C) were indicative of an oxidising environment. The largely negative Eh values recorded at the intermediate and deep (EGT_B and EGT_A) monitoring bores were indicative of a reducing environment.

Water quality

Nutrients

Nutrient concentrations measured in this study were compared to trigger values for south-west Australian wetlands (ANZECC 2000) (Table 5). The monitoring bores (EGT_A, B and C) are located up-gradient from the seepage. As such, breaches of wetland trigger values in samples from the bores, especially samples from the shallow zone of the aquifer (EGT_C), could have negative impacts on the vegetation, macroinvertebrates and fauna at the site.

Nitrogen (TN, TON, NH3/NH4)

Laboratory analysis reported three parameters related to nitrogen concentrations. These parameters were total nitrogen (TN), total oxidised nitrogen (TON) and ammonia/ium (NH_3/NH_4).

Total nitrogen measured in the bores at Egerton was up to 9 mg/L and above the ANZECC guideline (1.5 mg/L) for wetlands in south-west Australia. TN in groundwater was the highest at the shallow monitoring bore (EGT_C), where all measured concentrations (3.5 mg/L to 9 mg/L) exceeded the ANZECC guideline.

Total oxidised nitrogen is a measure of inorganic NO_2 and NO_3 and is sometimes referred to as NO_x to reflect this species composition. NO_2 is commonly an intermediate product and TON is generally considered to be dominated by NO_3, particularly where it is exposed to oxygen. TON was highest at the shallow monitoring bore (EGT_C) where it ranged from 3.1 mg/L to 9 mg/L and averaged approximately 5 mg/L. All TON values measured in shallow groundwater were well above the trigger value (0.1 mg/L) for wetlands in south-west Australia.

Ammonia and ammonium are measured collectively and reported as one value that includes both species and, as such, are henceforth referred to as ammonia/ium. Ammonia/ium concentrations were highest (up to 0.24 mg/L) at the intermediate monitoring bore (EGT_B). Concentrations measured at the shallow monitoring bore (EGT_C) ranged from below 0.01 mg/L to 0.11 mg/L and occasionally exceeded the trigger value (0.04 mg/L) for wetlands in south-west Australia.

This high ratio of NO_x to ammonia/ium found in the shallow part of the aquifer, combined with an oxidising environment – as indicated by the largely positive Eh values – suggests that shallow groundwater was undergoing nitrification. Conversely, the intermediate and deep parts of the aquifer had lower (<0.015 mg/L) levels of NO_x and generally higher (>0.12 mg/L) levels of ammonia/ium. The proportionally high levels of ammonia/ium in deeper parts of the aquifer, along with reducing conditions

– as indicated by the largely negative Eh values – implied that groundwater at depth was undergoing de-nitrification.

It is likely that the NO_x and ammonia/ium measured in groundwater at Egerton originated from leaching of fertilizers used in residential gardens up-gradient to the west the seepage. Groundwater that laterally travels through the shallow part of the water table would be in an oxidising environment, undergoing nitrification with a large part of the ammonia/ium oxidising to NO_x by the time it reached the seepage. While any groundwater that flows into the deeper parts of the aquifer would start de-nitrification once it crossed the redox boundary into a reducing environment with the majority of NO_x reducing to ammonia/ium. There is no seasonal pattern evident for nitrogen compound concentrations.

Phosphorus (TP)

The concentration of total phosphorous (TP) ranged from 0.034 mg/L (March 2008) to 0.42 mg/L (November 2007) in EGT_C, from 0.023 mg/L (March 2008) to 0.21 mg/L (July 2007) in EGT_B, and from 0.044 mg/L (November 2007) to 0.087 mg/L (July 2007) in EGT_A.

Levels of TP recorded in shallow groundwater (EGT_C) at Egerton exceeded the trigger value (0.06 mg/L) for wetlands in south-west Australia.

Metals

Metal concentrations measured in samples from monitoring bores EGT_A, B and C in this study were compared to freshwater ecosystem trigger values (ANZECC 2000). Breaches of these values could have negative impacts on the ecosystem at the seepage.

Metal concentration was also compared to irrigation trigger values (ANZECC 2000) and to drinking-water trigger values. Drinking-water guidelines were also used to give perspective on sample water quality and where no irrigation trigger-level existed, were used for reporting purposes, in accordance with the methods described in the Department of Environment and Conservation‘s assessment guidelines (DEC 2010).

High metal concentrations in groundwater can pose a health risk if the water is used for these purposes (NHMRC 1996) (Table 6).

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

Soluble aluminium concentrations ranged from 0.12 mg/L (May 2007) to 0.82 mg/L (September 2007) in the shallow zone, from 0.076 mg/L (May 2008) to 1.7 mg/L (August) in the intermediate zone and from 0.12 mg/L (August 2008) to 7 mg/L (June 2007) in the deep zone (Figure 21). All concentrations measured in the investigation exceeded the ANZECC guideline for freshwater ecosystems (0.055 mg/L). Concentrations also exceed the *Australian drinking water guidelines* (0.20 mg/L) but are below the ANZECC guidelines for long-term irrigation use (5 mg/L).

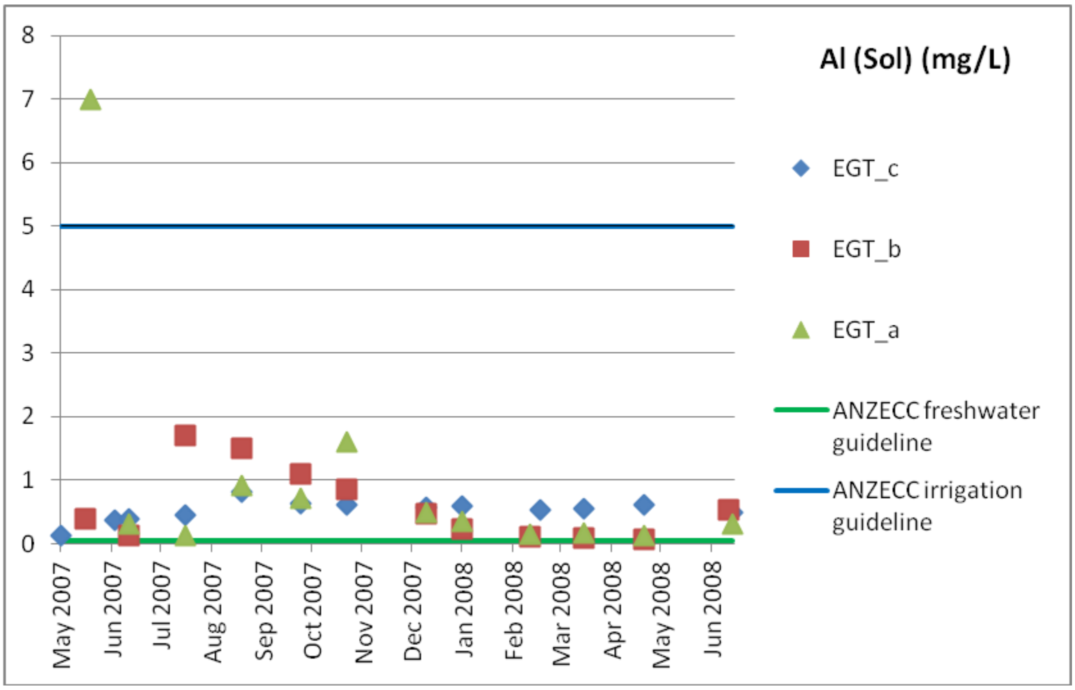


Figure 21 Soluble aluminium levels recorded at the Egerton bore cluster

All reported concentrations of arsenic within the shallow zone were below the laboratory LOR (<0.001 mg/L) except in May 2007 where a level of 0.001 mg/L was recorded (Figure 22). In the intermediate and deep zones, concentrations ranged from less than the laboratory LOR to 0.024 mg/L (June 2007). One measurement of arsenic recorded in the deep zone was equal to the ANZECC (2000) freshwater trigger value (0.024 mg/L) and two concentrations measured deep zone exceeded the trigger value for drinking water (0.007 mg/L).

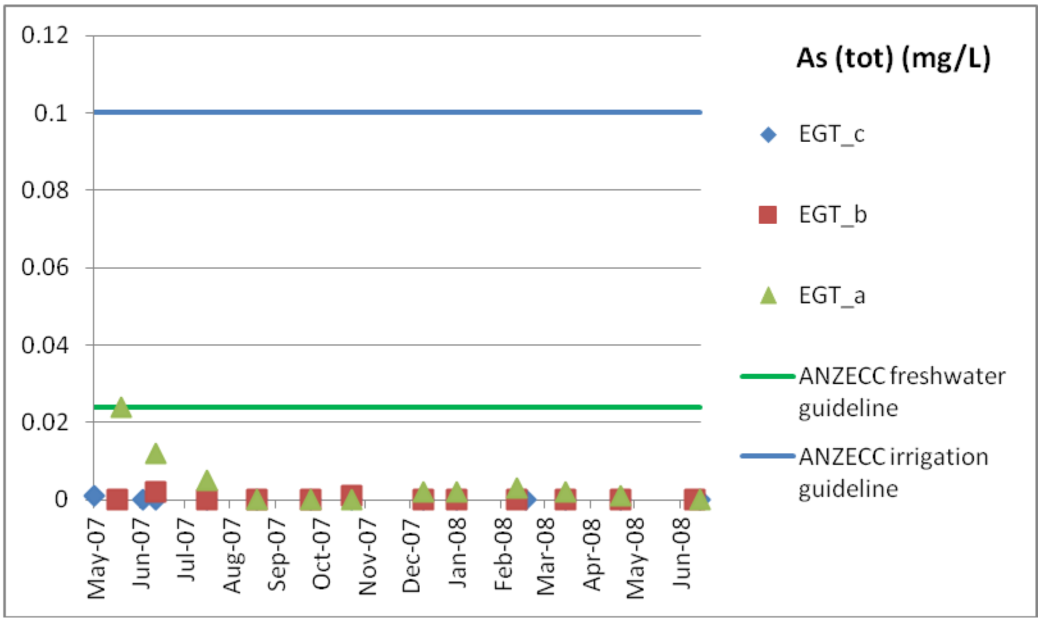


Figure 22 Arsenic levels recorded at the Egerton bore cluster

Soluble iron concentrations ranged from 0.017 mg/L (March 2008) to 2 mg/L (May 2007) in the shallow zone, from 0.13 mg/L (June 2007) to 0.93 mg/L (August 2007) in the intermediate zone, and from 0.068 mg/L (July 2007) to 2.8 mg/L (August 2007) in the deep zone. Concentrations exceed the ANZECC long-term irrigation trigger-value (0.20 mg/L) and the trigger value for drinking water (0.30 mg/L) (Figure 23).

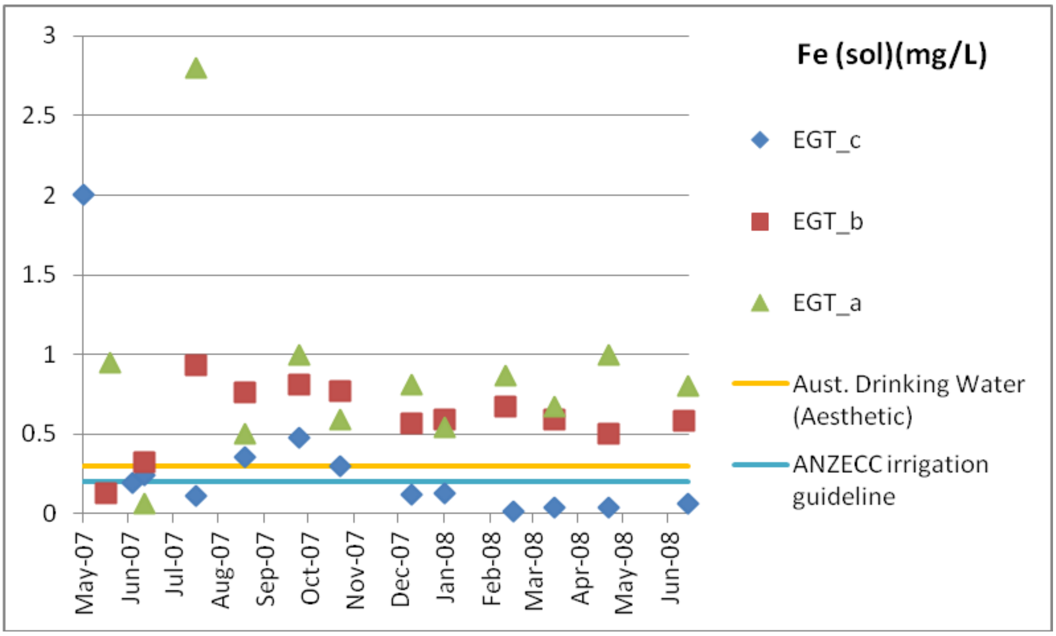


Figure 23 Soluble Iron levels recorded at the Egerton bore cluster

Reported, total zinc concentrations ranged from 0.02 mg/L (November 2007, January 2008 and March 2008) to 0.17 mg/L (May 2007) in the shallow zone, from 0.006 mg/L (August 2007) to 0.031 mg/L (March 2008) in the intermediate zone, and from 0.002 mg/L (October 2007) to 0.044 mg/L (August 2007) in the deep zone. Zinc concentrations recorded for all aquifer zones exceeded the freshwater trigger value (0.008 mg/L).

Analysis of the data collected from the first sampling event at Egerton showed anomalously high values for many parameters. The high values correspond to very high total suspended solids (TSS) readings, probably associated with bore construction. For this reason, the results from the first sampling event were discarded.

Table 5 Trigger values for pH and nutrients (ANZECC 2000)

	pH (lower limit)	**TN (mg/L)**	**TON (mg/L)**	**NH_3/NH_4 (sol) (mg/L)**	**TP (mg/L)**
Wetlands in south-west Australia	7	1.5	0.1	0.04	0.06

Table 6 Trigger values for heavy metals (ANZECC 2000)

Species	**Freshwater trigger**	**Drinking-water trigger**	**Irrigation-water trigger**
Al (sol) (mg/L)	0.055	0.2	5
As (tot) (mg/L)	0.024 (AsIII) 0.013 (AsV)	0.007	0.1
Fe (sol) (mg/L)		0.3[ii]	0.2
Zn (tot) (mg/L)	0.008	3	2

[ii] Guideline for aesthetic qualities

5.4 Processes and interactions between surface water and groundwater

Interpretation of surface water-groundwater interactions at Egerton Seepage can be made by analysis of the local hydrogeology, and detailed chemical analysis of groundwater and seepage water.

The findings of this investigation showed that Egerton Seepage was a surface expression of groundwater rather than a spring with an upward hydraulic head gradient. Springs can form where transmissive aquifers interfinger with clayey sediments forcing groundwater to vertically flow to the surface. This investigation shows that only thin lenses of Guildford clay were present at depth at the Egerton site. These results were also supported by previous work that compared the C^{14} age of groundwater discharge from Egerton Seepage to that of groundwater near the base of the Superficial aquifer and from the top of the Leederville aquifer. The results showed that the groundwater discharging at the surface was around 90 years old, which is considerably younger than the C^{14} age-of-groundwater near the base of the Superficial (>28 800 years) aquifer and from the top of the Leederville aquifer (12 700 years) (Thorpe 1993).

Extensive urbanisation and the modification of local geomorphology (from 2000) around Egerton were likely to have altered the local hydrogeology and the flow regime at the seepage. The dunes to the west of Egerton Seepage contained *Banksia* woodlands that were considered to be an important hydrological factor, with the seepage being recharged by groundwater flowing from the west (WRC 2003). The removal of native vegetation, the levelling of the dune and urban development resulted in a 1 m watertable rise around the Egerton site since 2000, and the suggestion of localised mounding.

Although the historical record of water levels at the Egerton site was relatively short, and no surface water monitoring was undertaken as part of this investigation, the data suggests that the watertable rise of the past 10 years has resulted in an increase in groundwater discharge from the seepage. Previous work showed that Egerton dried in the 1999–2000 summer, even though the annual rainfall for Perth for the previous winter was higher than 1997–98. This could have been due to interception of groundwater by the native vegetation or local dewatering for road construction of the Vale development during 1998–99. At the end of 2005 and 2007, the seepage was described as ‗flowing strongly', despite the lower-than-average rainfall experienced in the region since, approximately, the year 2006 (Knott et al. 2008). This suggested that while the seepage was still dependent on groundwater (Froend et al. 2004b; Evans & Clifton 2001) its hydrology was now more influenced by an increase in local recharge and runoff as a result of urban development.

Groundwater use down-gradient of the site, while increasing the seasonal amplitude of the watertable (e.g. monitoring bore L80C, section 5.1), does not appear to affect the discharge of groundwater at the Egerton site. However, groundwater use up-gradient of the site has the potential to reduce groundwater discharge (e.g. dewatering, see above).

The hydrogeochemical results from this and previous investigations suggested that groundwater quality around the Egerton seepage was more likely to impact the ecology than current groundwater-level changes. Although the groundwater that flows through the upper part of the Superficial aquifer is of NaCl type, the shallow bore had slightly elevated concentrations of SO_4^{2-} compared to deeper in the aquifer. While these concentrations can be considered quite low (< 20 mg/L) compared to other wetlands on Gnangara Mound (e.g. Lake Mariginiup), field tests indicated that actual and potential ASS were present in the top 1.2 m of the sediment.

Indicators of ASS oxidation are high concentrations of SO_4^{2-} and Fe, low pH values and high SO_4–Cl ratios. While the SO_4–Cl ratios at the watertable at Egerton were generally below the indicator value for ASS oxidation, the ratios were high enough to suggest some SO_4^{2-} enrichment. Furthermore, the declining pH trend at the Egerton site also suggested there were some changes to groundwater chemistry associated with ASS. Historical values of pH at Egerton ranged between 5.00 and 6.11 from 1999 to 2004, declining to 4.76 in 2005 and 4.36 in October 2007 (Cook & Janicke 2005). Over the 12 months of the SGS investigation, pH in the shallow bore was generally below 4.5.

High iron, arsenic and aluminium concentrations can also be indicators of ASS, with high iron and aluminium usually observed in the shallower zones. The higher concentrations of aluminium and iron in the deeper zones of the Superficial aquifer at Egerton were probably due to migration from the shallow to the deep aquifer zone by downward hydraulic head. The high arsenic concentrations in the deeper zones were likely related to the near neutral pH and negative Eh conditions observed in the deep bore that were suitable for arsenic solubility. The very high concentrations of aluminium, arsenic and iron in May and June 2007 could either be linked to lower groundwater elevations, since groundwater elevations were at their lowest point in May and June 2007, or to insufficient purging of the new bores during development.

The hydrochemical analysis at the watertable carried out by the Department of Environment and Conservation in the Ellenbrook region, suggested groundwater up-gradient of Egerton was a potential source of acidity. Field and laboratory measurements showed pH at the watertable was below 4, SO_4–Cl ratios of between 0.19 and 1.26, and high metal concentrations (above trigger levels) (Clohessy, pers. comm.).

Nutrient monitoring in 1999 and October 2003 indicated concentrations of nitrogen to be within the low end of the range, as typical of unpolluted waters as described by Wetzel (1975). Horwitz & Knott (2003) described the seepage as discharging good-quality fresh water with limited nutrient concentrations. Their study reported that seepage water quality met the NHMRC guidelines (1996) for drinking water. However, in 2007, monitoring showed that concentrations of nitrogen (TN, TON, NH_3/NH_4), especially concentrations measured in the shallow part of the aquifer, exceeded guidelines for wetlands in south-west Australia (ANZECC 2000).
The monitoring also showed that concentrations of phosphorus (TP) in shallow groundwater at Egerton exceeded the ANZECC guidelines for wetlands in south-west Australia.

The high concentrations of NO_x and positive Eh values observed in the shallow zone of the Superficial aquifer was suggestive of nitrification, which may also be contributing to acidic conditions observed at Egerton. Excess NO_x, presumably from fertiliser use in the area, undergoes nitrification, releasing H^+, and lowering the pH. However, if reducing conditions were established, nitrate reduction could couple to pyrite oxidation and accelerate groundwater acidification. This process can create similar water-quality issues as those caused by oxidation of ASS, but without needing falling water levels to trigger the process (Smolders et al. 2006).

6 Ecological implications

This hydrogeological investigation highlighted a number of potential threats to the tumulus spring community of Egerton Seepage. These threats relate to groundwater quality, increased weed invasion and fire, and are primarily linked to land and water use in the areas surrounding Egerton Seepage. Of particular relevance is encroaching urban development, which is likely to extend to the edge of the 20.6-hectare area listed as a Bush Forever site.

As the flora and fauna of the tumulus community at Egerton Seepage are likely to be entirely dependent on the permanent supply of fresh water, its conservation depends on the reliability of water supply (English & Blyth 2000, Jasinska & Knott 1994). Therefore, the preservation of the ecological values of the Egerton site is reliant on the maintenance of permanent discharge of groundwater from the seepage. The drying of the seepage, even for a short period, could result in the loss of plant and animal species adapted to permanent water, and species that use the area as a drought refuge. Gondwanan relic species that do not have dormant stages may also be lost if the seepage dried (CALM 2006).

Since monitoring of groundwater levels commenced at bore B25, the water level criteria for the seepage has been met on all but one occasion (March 2003). Since 2003 there has been upward trend in water levels recorded at the bore. A groundwater level of 40.22 metres Australian Height Datum, recorded at the end of 2008, was the highest level recorded since monitoring began. The increase in groundwater levels resulted in an increase in groundwater discharge from the seepage and, at the end of 2005, 2007 and 2008, the seepage was described as ‗flowing strongly' (Knott et al. 2007, Knott et al. 2008, Knott et al. 2009).

The increase in groundwater levels at bore B25 and the strong flows from the seepage were likely to be a result of an increase in local recharge and runoff associated with urban development that continues to encroach on the site. It was likely that substantial clearing and new houses immediately to the west of Egerton was significantly influencing flow at the seepage, as the site was recharged by groundwater flows from the west. With the recent increases in recharge and groundwater quantity at Egerton, the permanent discharge of groundwater from the seepage is, at present, relatively assured. This investigation suggests that groundwater use down-gradient of the site would not affect the discharge of groundwater at the Egerton site, but groundwater use up-gradient of the site has the potential to reduce groundwater discharge.

The hydrogeochemical results from this investigation suggest that, at present, groundwater quality at Egerton Seepage is more likely to be affecting the ecology than groundwater quantity. Groundwater quality issues that affect the ecology of the seepage include declining pH, high metal concentrations and increased nutrient concentrations.

An increase in the acidity of an aquatic ecosystem can be considered a stressor which is directly toxic (through the harmful effects of H^+ ions) to aquatic organisms

(ANZECC 2000, DEC 2009). As pH levels at Egerton were now below trigger value (7) for wetlands in south-west Australia, acidity was likely to be affecting the ecology of the seepage (Figure 24).

The elevated SO_4–Cl ratios found in this investigation suggest that oxidation of ASS may be contributing to the declining pH trend. Further oxidation of the actual and potential ASS found in this investigation could result in the further pH declines at the site. The continuation of the acidification trend at Egerton could result in irreversible changes to its ecology. This process already occurred in a number of wetlands on Gnangara Mound, including Lake Gnangara and Lake Mariginiup.

The increased acidity at Egerton was likely to be responsible for the leaching of aluminium and iron from the soil. Heavy metals at low pH are largely soluble and therefore available to be taken up by plants and exert potential toxic effects (Hutchinson & Collins 1978). The mobilisation of aluminium into the groundwater may put the site‘s vegetation at the risk of ‗acid toxicity‘. Acid toxicity can result in the loss of sensitive vegetation and the proliferation of invasive species. That toxicity occurs when the mobilisation of aluminium induces a reduction of the molar calcium–aluminium and magnesium–aluminium ratios in the groundwater, which reduces root growth, inhibits the uptake of calcium and magnesium by fine roots, and reduces the water conductivity of the roots (Caspary 1991). This is compounded by further depletion of calcium and magnesium from sediment by acidic groundwater. The loss of calcium from soils can lead to a progressive decline in the health of both wetland and woodland ecosystems, and the loss of plant and animal species (DEC 2009). The high concentrations of aluminium and iron found in the deeper zones of the Superficial aquifer at Egerton probably originated in the shallow zone where they may have impacted upon vegetation at the site. This study has not identified the source of high metal concentrations and associated acidity.

Nitrogen (nitrate and nitrite, NO_x) and phosphorus concentrations measured in this investigation exceeded the ANZECC guidelines for nutrients in wetlands (0.1 mg/L and 0.06 mg/L respectively) in south-west Australia (Figure 24). The enhanced nutrient levels at Egerton were likely to favour weed invasion and may alter water quality such that some components of the fauna cannot survive (CALM 2006). The high concentrations of nitrogen and phosphorus at Egerton could stimulate the growth of algae and cyanobacteria at the site, which could dominate and change the dynamics of the wetland ecosystem (ANZECC 2000). The high levels of nutrients at Egerton may also influence downstream water quality and affect endangered aquatic macrofauna in Ellen Brook.

As discussed in section 5.4, the high concentrations of NO_x at Egerton may also be exacerbating the declines in pH observed at the site, and contributing to the effects of acidity on the ecology of the seepage. Runoff from the northern catchment of the Ellenbrook development to the west of the seepage, and from the Vale development around the Bush Forever site that contains the seepage, was likely to be the primary source of the elevated nutrient levels at the site. It was unlikely that water allocations or abstraction in the area was affecting nutrient concentrations at Egerton.

The water-quality issues identified in this investigation highlighted that water quality, in addition to compliance with criteria water level, should be assessed when assigning causes for change in ecological condition.

Further threats to the ecological values at Egerton were weed invasion and fire. Weed species that affect tumulus spring communities on the Swan coastal plain include *Isolepis prolifera* and *Pennisetum clandestinum* (CALM 2006). These and other invasive weeds pose a serious threat to the biodiversity of the tumulus spring community at Egerton as they have the potential to modify its ecosystem processes and functions (DEC 2009). By altering plant diversity and habitat structure, weed invasion has flow-on effects to faunal communities through habitat alteration and changes in trophic interactions (DEC 2009). The urban development that surrounds the seepage is likely to aid the spread of weeds into the area.

Hot fires pose a major threat to the Egerton site, with the potential to burn out the peat mound upon which the mound‘s spring community is based. The risk of fire is increased by the presence of grassy weeds in the understory (CALM 2006). Fire at Egerton is also likely to cause oxidation of acid sulfate soils at the site and contribute to, or accelerate, acidification of the area.

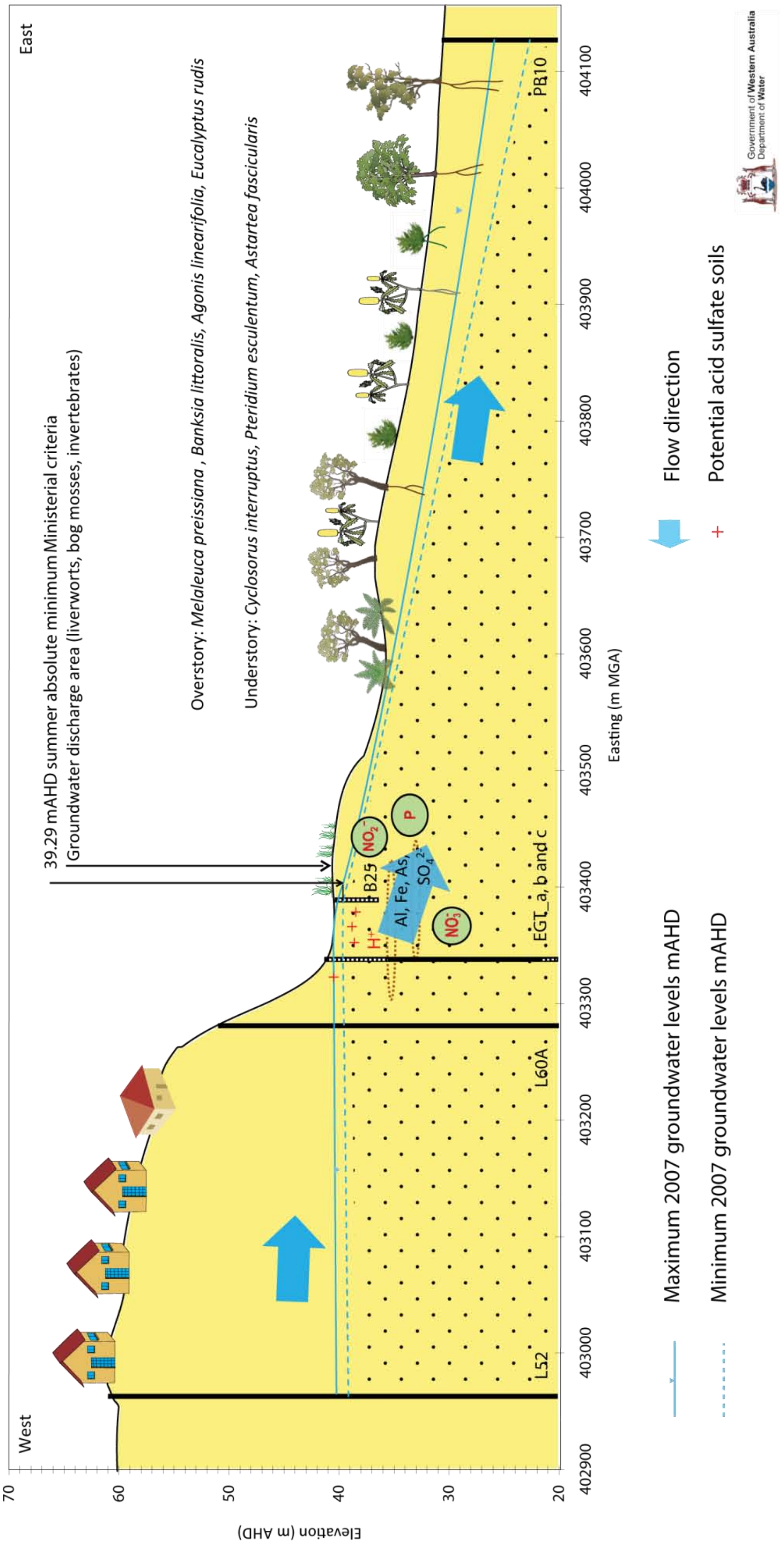


Figure 24 Conceptual model of the relationships between the hydrogeological chemistry and the wetland ecosystem of Egerton Seepage

7 Management of Egerton Seepage

7.1 Monitoring infrastructure

The monitoring infrastructure installed at Egerton in this investigation has improved understanding of how the seepage hydrogeologically functions.

This investigation found that the current ministerial criteria bore, bore B25 (61618607), was appropriate for measuring ministerial criteria water levels at Egerton. During the investigation period, water levels at bore B25 were in sync with water levels measured at the new bores (Figure 25). Bore B25 is located down-gradient of the shallow bore (EGT_C), installed as part of this investigation, and is closer to the outflow points of the seepage. Due to its proximity to the outflow points, bore B25 is likely to better-reflect outflow than bore EGT_C. As the preservation of the ecological values of the Egerton site is reliant on the maintenance of permanent outflow of groundwater from the seepage, and levels measured at bore B25 were considered to best reflect outflow, it is recommended that bore B25 be retained as the ministerial criteria bore.

To improve the Department of Water‘s ability to monitor other known seepages–springs on the Gnangara Mound, it is recommended that continuous-monitoring equipment be installed along the eastern line of groundwater discharge to the north of Egerton through Bullsbrook and Muchea. The installation of this equipment in this area would enable the monitoring of the rate of discharge of water associated with other springs–seepages identified along that line. The monitoring of discharge is this area would provide important evidence as to whether water levels in the Superficial aquifer were being maintained at an adequate level to ensure the permanaent flow of water at the seepages–springs, required to maintain the ecology of these systems. The installation of this equipment would be a valuable additon to the monitoring network on the Gnangara Mound and would provide important information on how the eastern area of the mound functions.

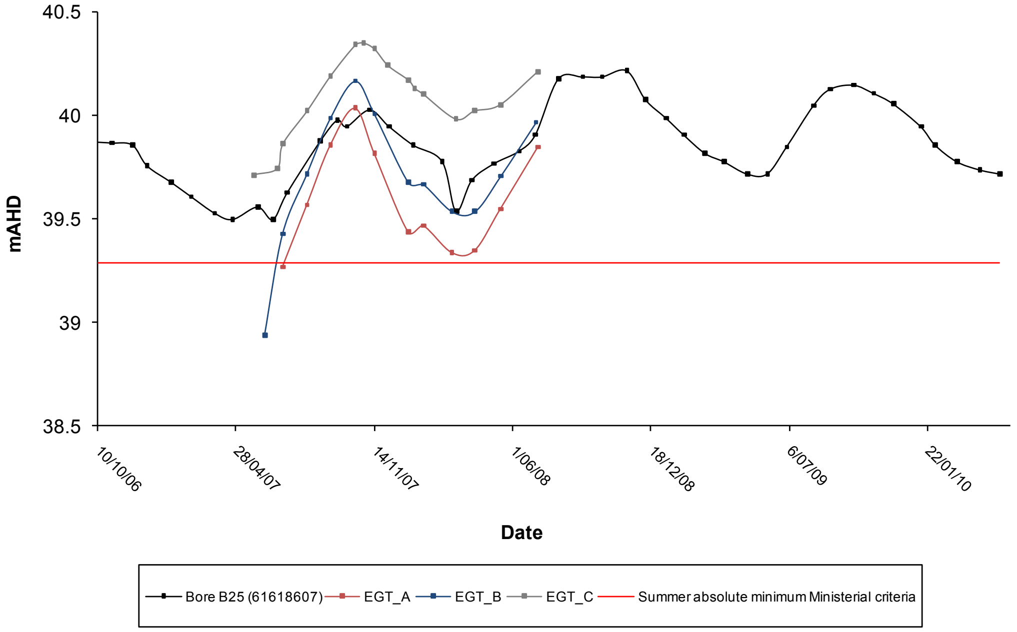


Figure 25 Hydrographs compare current ministerial criteria bore B25 with the bores installed as part of this investigation

7.2 Management recommendations

Results of the shallow groundwater systems investigation have provided an improved understanding of the local geology (chapter 4), hydrogeology and chemistry (chapter 5) at Egerton. This understanding has been linked with ecological function (chapter 6) to provide a basis for improved management strategies.

Due to the recent rise in the groundwater table at Egerton, recent levels at bore B25 have easily met the ministerial criteria level and the permanent discharge of groundwater from the seepage is, at present, relatively assured.

The hydrogeochemical results from this investigation suggested that, at present, groundwater quality (declining pH and increasing nutrient concentrations) at Egerton were more likely to be impacting the ecology than groundwater quantity.

To avoid further declines in pH at the site, further oxidation of acid sulfate soils found in this investigation must be prevented. To prevent the further oxidation of ASS at Egerton, the groundwater table must not drop below the layer capable of providing water to surface organics through capillary rise – approximately 0.5 m below ground surface) (Froend et al. 2004b).

The elevated concentrations of nutrients, low pH and high metal concentration at Egerton Seepage are likely to be a result of runoff and groundwater flowthrough from the northern catchment of the Ellenbrook development to the west of the seepage and from the Vale development which will eventually surround the Bush Forever site that contains the seepage. Both the Ellenbrook and Vale developments required the preparation of nutrient and drainage management plans as part of conditions set by the Minister for Environment through the rezoning process. Strategies detailed in the nutrient management plans for the developments include the use of water pollution–control ponds, designed as artificial wetlands with adequate areas of macrophytes to optimise nutrient–pollution removal from drainage water and community education incentives to encourage the use of organic and low-phosphate fertilisers (JDA 2004, JDA 2006). The nutrient concentrations measured in this investigation suggested the current nutrient management strategies for the Ellenbrook and Vale developments were not adequately reducing nutrients entering run-off that affects groundwater flow into the seepage area.

This investigation proposes the following management recommendations and are subject to departmental priorities and the availability of resources:

1. Install continuous monitoring equipment along the eastern line of groundwater discharge on the Gnangara Mound, to monitor the rate of discharge of water associated with other springs–seepages identified along that line
2. Retain bore B25 should as the ministerial criteria bore at Egerton
3. Avoid issuing large licences directly up-gradient of the seepage
4. Initiate a hydrochemical monitoring program for this site, while hydrochemical triggers and management actions could be developed for the next water reform plan. Data from the hydrochemical monitoring program should be reviewed every two years to assess whether management objectives set out in the plan are being met and whether trigger values need improvement. The following hydrochemical sampling regime is recommended:
    - a Monthly sampling of pH, major ions and nutrients in the surface water discharged from the seepage
    - b Quarterly sampling of pH, major ions and nutrients in groundwater
    - c Annual sampling of heavy metal concentrations in groundwater. Groundwater data should be collected on the same date as surface water data, when possible
5. Continue annual sampling of aquatic invertebrates
6. Review the nutrient management and drainage plans for the Ellenbrook and Vale developments and investigate additional nutrient management strategies

Appendices

Appendix A — Borelogs

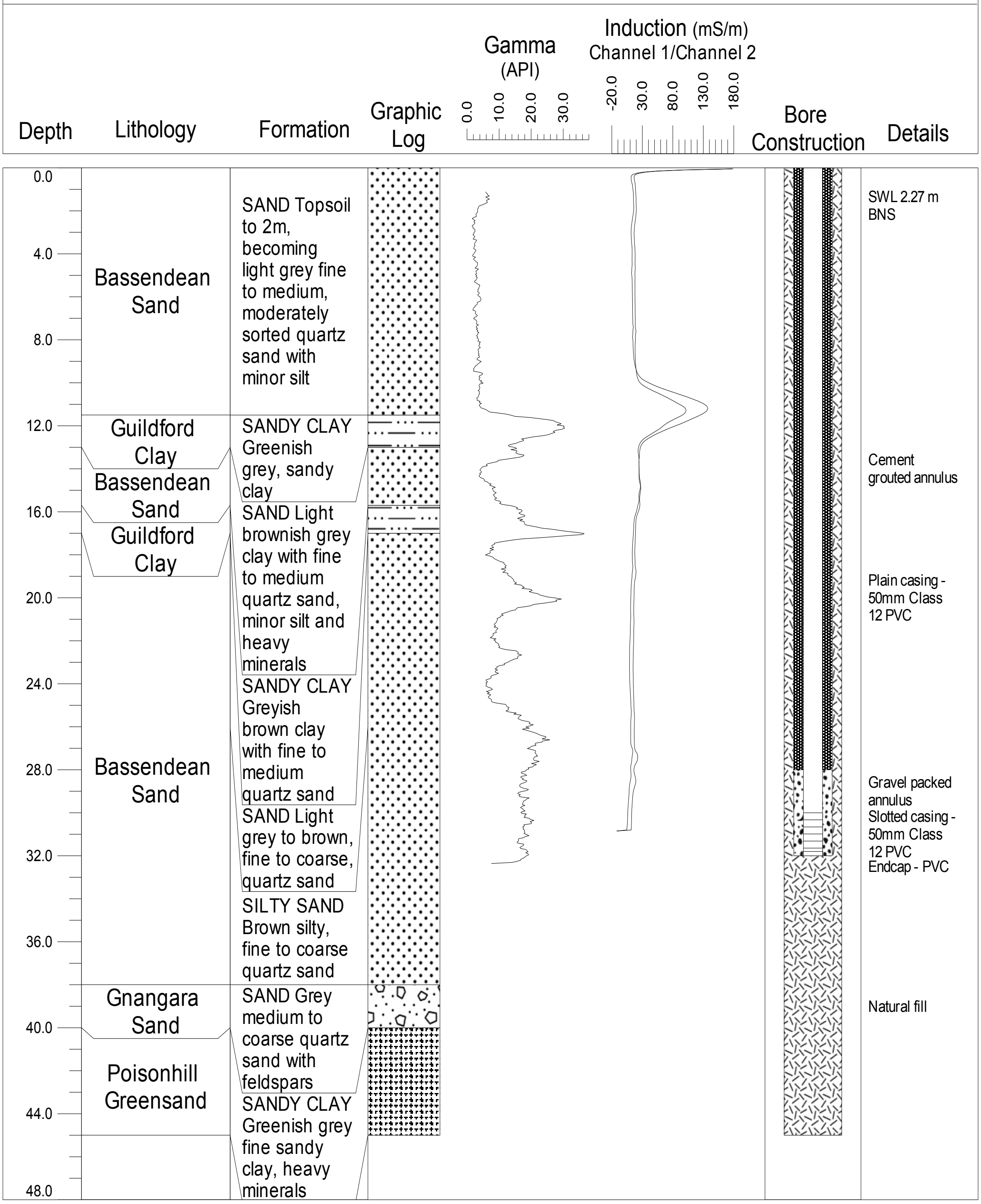
BORE COMPLETION DETAILS

Department of Water
Government of Western Australia

Perth Shallow Groundwater Systems Investigation - Stage 1

AWRC Name: **EGTa**

AWRC Number: **61611445**



SAND Topsoil to 2m, becoming light grey fine to medium, moderately sorted quartz sand with minor silt

SANDY CLAY Greenish grey, sandy clay

SAND Light brownish grey clay with fine to medium quartz sand, minor silt and heavy minerals

SANDY CLAY Greyish brown clay with fine to medium quartz sand

SAND Light grey to brown, fine to coarse, quartz sand

SILTY SAND Brown silty, fine to coarse quartz sand

SAND Grey medium to coarse quartz sand with feldspars

SANDY CLAY Greenish grey fine sandy clay, heavy minerals

SWL 2.27 m BNS

Cement grouted annulus

Plain casing - 50mm Class 12 PVC

Gravel packed annulus

Slotted casing - 50mm Class 12 PVC

Endcap - PVC

Natural fill

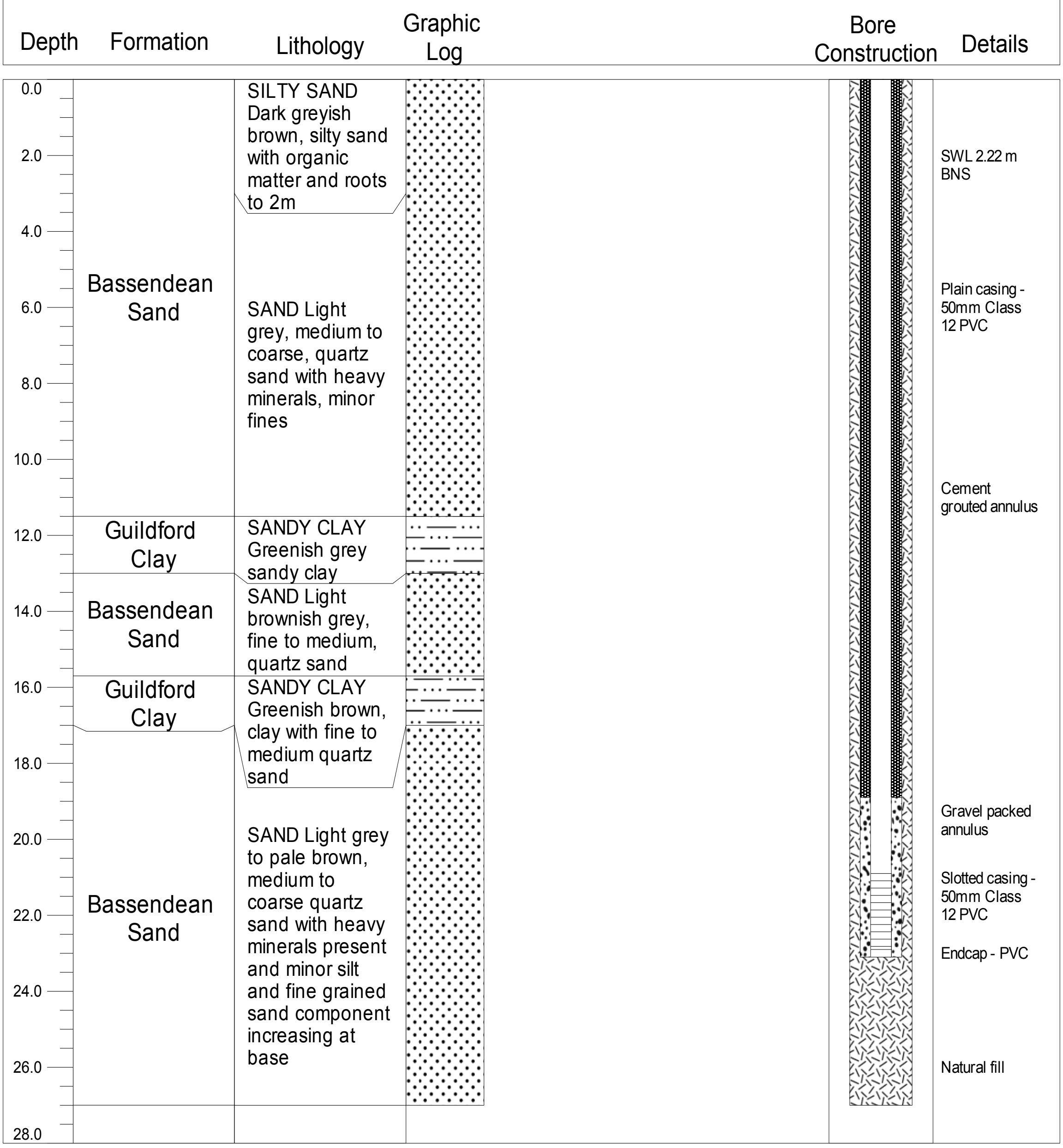
Drilled by:	Great Southern Drilling	Northing (Z50):	6484469.686	Screens (m BNS):	30.14 - 32.14
Date drilled:	6/5/07	Easting (Z50):	403341.374	SWL (m BNS):	2.27
Logged by:	Sarah Bourke	Surface (m AHD):	41.527	EC (mS/cm):	0.238
Aquifer:	Superficial	Drill depth (m BNS):	45	pH:	6.27

BORE COMPLETION DETAILS

Perth Shallow Groundwater Systems Investigation - Stage 1

Department of Water
Government of Western Australia

AWRC Name: **EGTb**
AWRC Number: **61611444**



Formation	Lithology
Bassendean Sand	SILTY SAND Dark greyish brown, silty sand with organic matter and roots to 2m
	SAND Light grey, medium to coarse, quartz sand with heavy minerals, minor fines
Guildford Clay	SANDY CLAY Greenish grey sandy clay
Bassendean Sand	SAND Light brownish grey, fine to medium, quartz sand
Guildford Clay	SANDY CLAY Greenish brown, clay with fine to medium quartz sand
Bassendean Sand	SAND Light grey to pale brown, medium to coarse quartz sand with heavy minerals present and minor silt and fine grained sand component increasing at base

Details

SWL 2.22 m BNS

Plain casing - 50mm Class 12 PVC

Cement grouted annulus

Gravel packed annulus

Slotted casing - 50mm Class 12 PVC

Endcap - PVC

Natural fill

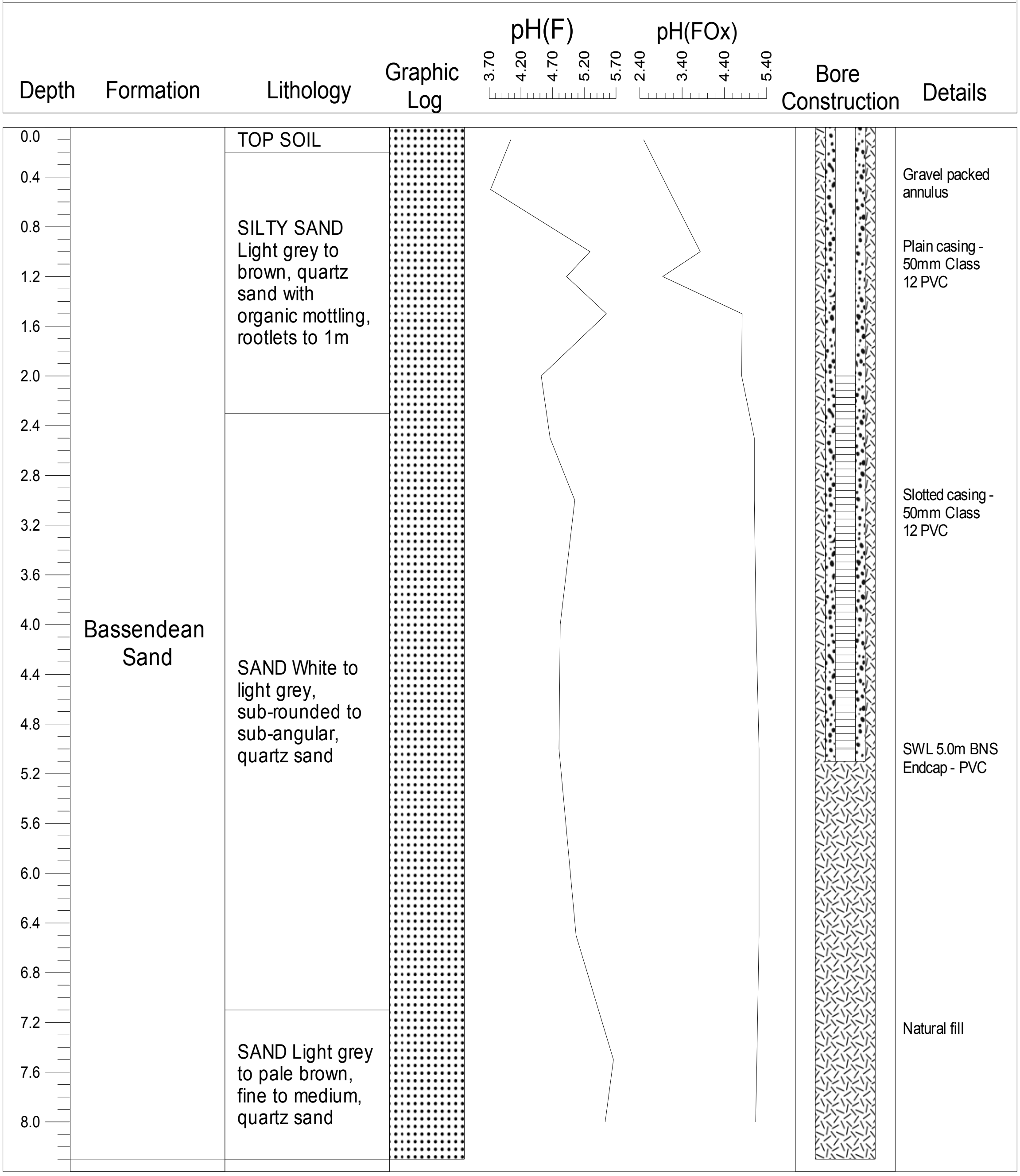
Drilled by:	Great Southern Drilling	Northing (Z50):	6484467.537	Screens (m BNS):	20.92 - 22.92
Date drilled:	6/6/07	Easting (Z50):	403339.304	SWL (m BNS):	2.12
Logged by:	Sarah Bourke	Surface (m AHD):	41.503	EC (mS/cm):	0.213
Aquifer:	Superficial	Drill depth (m BNS):	27	pH:	5.96

BORE COMPLETION DETAILS

Perth Shallow Groundwater Systems Investigation - Stage 1

Department of Water
Government of Western Australia

AWRC Name:	**EGTc**
AWRC Number:	**61611443**



Bassendean Sand

TOP SOIL

SILTY SAND Light grey to brown, quartz sand with organic mottling, rootlets to 1m

SAND White to light grey, sub-rounded to sub-angular, quartz sand

SAND Light grey to pale brown, fine to medium, quartz sand

Gravel packed annulus

Plain casing - 50mm Class 12 PVC

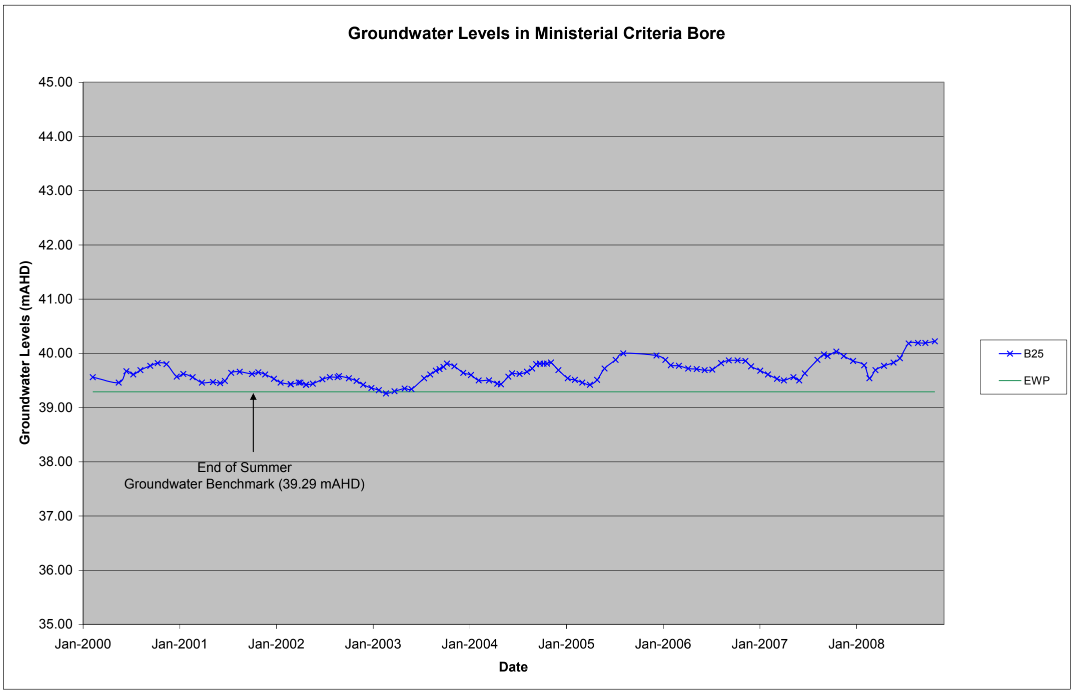
Slotted casing - 50mm Class 12 PVC

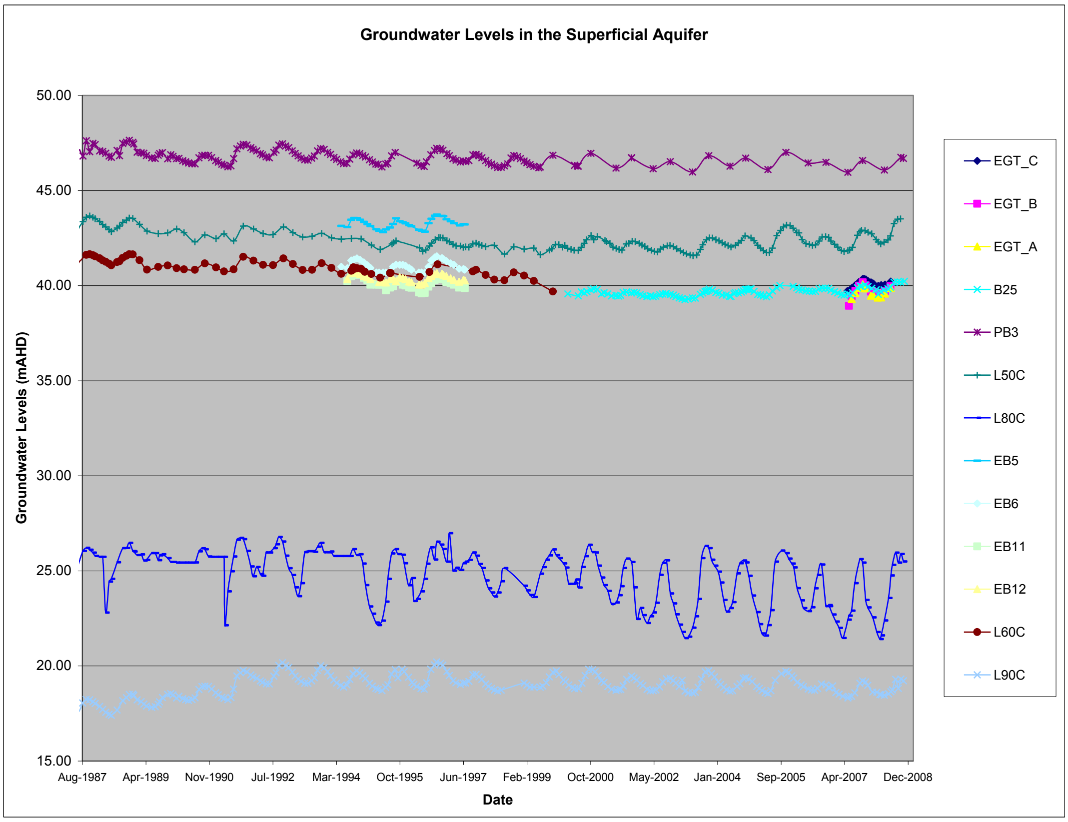
SWL 5.0m BNS
Endcap - PVC

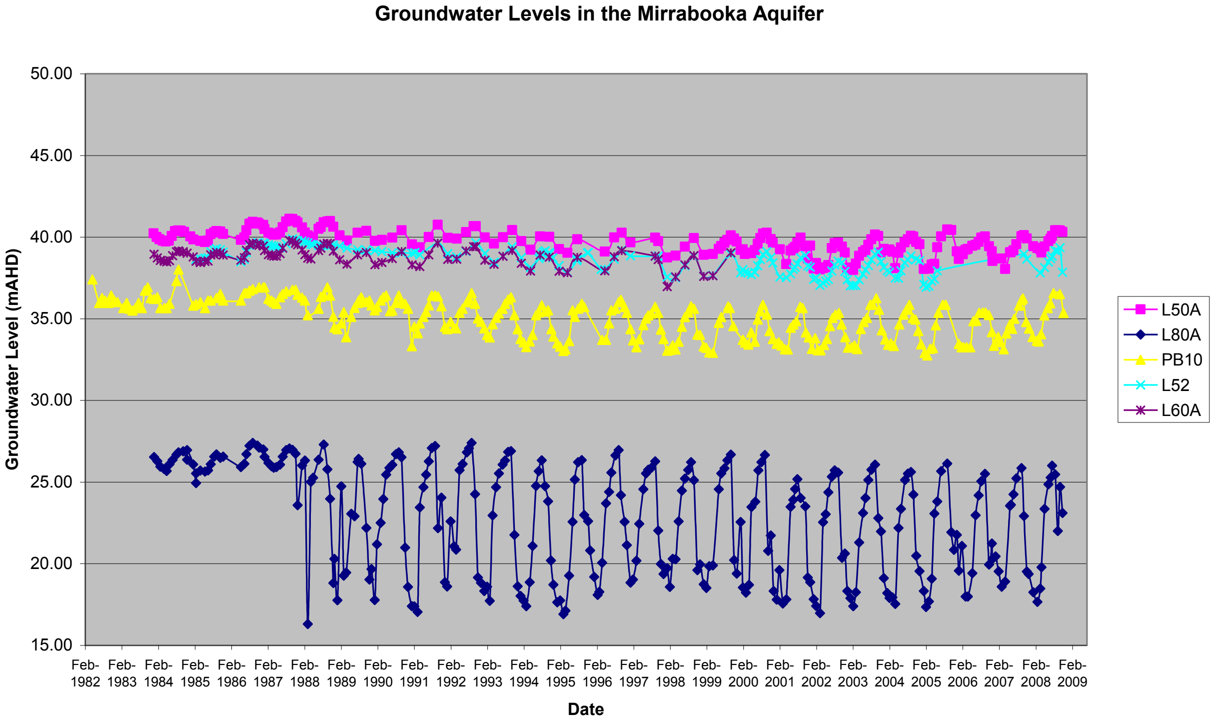
Natural fill

Drilled by:	Great Southern Drilling	Northing (Z50):	6484462.6	Screens (m BNS):	1.96 - 4.96
Date drilled:	5/23/07	Easting (Z50):	403337.774	SWL (m BNS):	5
Logged by:	Sarah Bourke	Surface (m AHD):	41.344	EC (mS/cm):	0.218
Aquifer:	Superficial	Drill depth (m BNS):	8.3	pH:	5.52

Appendix B — Hydrographs






Groundwater Levels in the Mirrabooka Aquifer
Groundwater Level (mAHD)
50.00
45.00
40.00
35.00
30.00
25.00
20.00
15.00
Feb-1982
Feb-1983
Feb-1984
Feb-1985
Feb-1986
Feb-1987
Feb-1988
Feb-1989
Feb-1990
Feb-1991
Feb-1992
Feb-1993
Feb-1994
Feb-1995
Feb-1996
Feb-1997
Feb-1998
Feb-1999
Feb-2000
Feb-2001
Feb-2002
Feb-2003
Feb-2004
Feb-2005
Feb-2006
Feb-2007
Feb-2008
Feb-2009
Date
L50A
L80A
PB10
L52
L60A

Appendix C — Sampling methods and analysis

Groundwater sampling methodology

Water samples were collected using low-flow pumping methods. The sampling technique provides a low-stress, low-impact, minimal-drawdown purging method of groundwater sampling. The pump was lowered to the screened interval of the bore and purged until the water-quality parameters of pH, EC and temperature were stabilised. Once stabilised in situ readings can be recorded and samples collected for further laboratory chemical analysis.

The method requires smaller volumes of water to be withdrawn than conventional techniques and potentially reduces the aeration or de-gassing of collected samples. It also minimises the disturbance within the water well column and surrounding materials, potentially reducing 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

- Ensure all equipment is washed and decontaminated.
    - 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 Perth scheme water. A second thorough rinse is performed using only Perth 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.
- Dip bore for groundwater level and record.
- 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 0.5 metres 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,
- Note other field observations, such as interesting sample colour, presence of large quantities of particulate matter and smell.
- Measure groundwater quality for the in situ field parameters: pH, conductivity, temperature, redox and dissolved oxygen using multiprobe sensors installed in a flow cell. Measurements are recorded every five minutes until the parameters stabilise, then a final reading is recorded.

- Record results on a field observation form for submission to the Department of Water database.

Once physical, in situ field parameters have stabilised and been recorded, collect samples for laboratory analysis. All sample bottles should 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 centimetres 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 (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-measurement equipment using appropriate solutions
3. adjust the pH of close to one litre of 30 per cent 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 a half-teaspoon-sized sample of sediment approximately every 25 cm or when a lithology change is noted (which ever is lesser), noting the depth of the sample.
2. Place into beaker used for pH$_f$ tests and add 12 millilitres of water from a clean syringe (marked pH$_f$) to make a 1:5 soil–water solution and shake well.
3. Take another half-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 per cent hydrogen peroxide using a second syringe (marked pH$_{fox}$) 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 one hour (during which time logging of cores can be done).
7. Regularly shake (i.e. every five to 10 minutes) all beakers to ensure maximum amount of sediment goes into solution.

8 After 1 hr record pH_f and pH_{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).

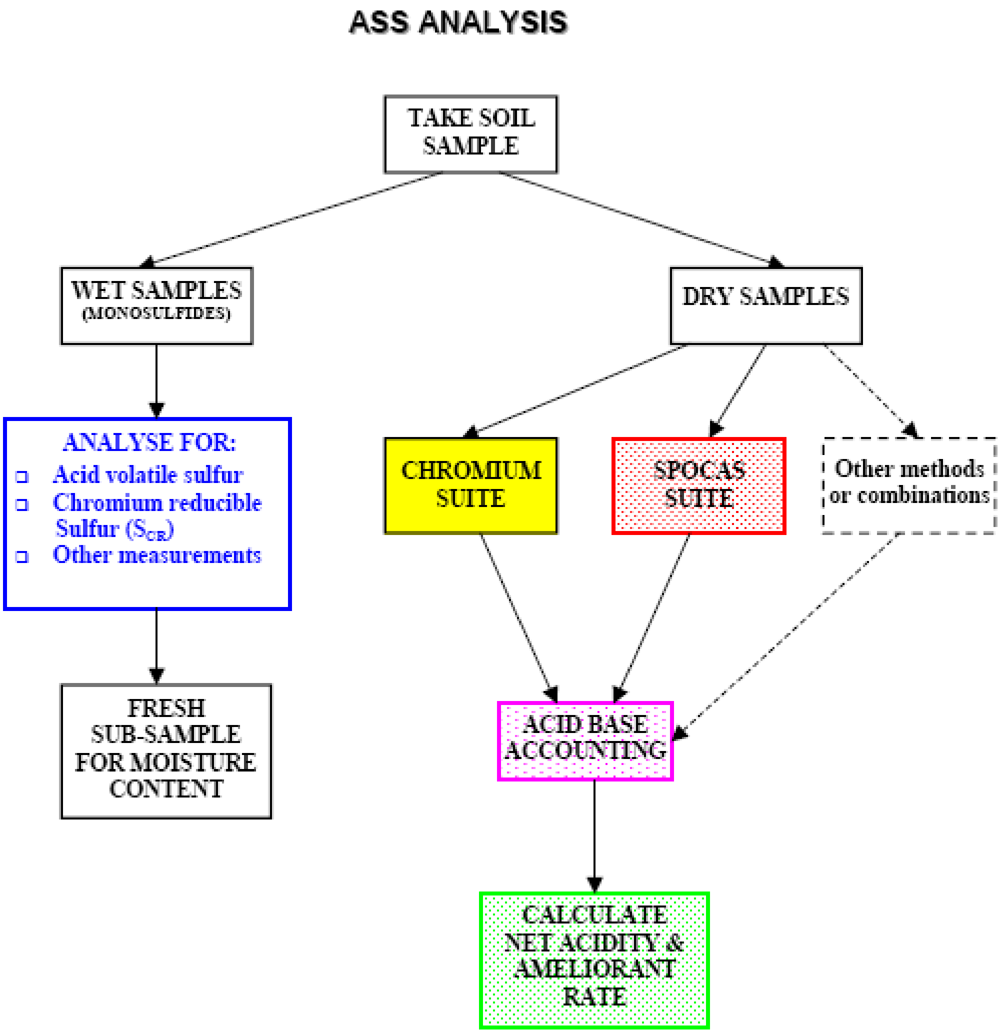


Figure 1 Flow diagram for overall methods used in the quantitative analyses of ASS

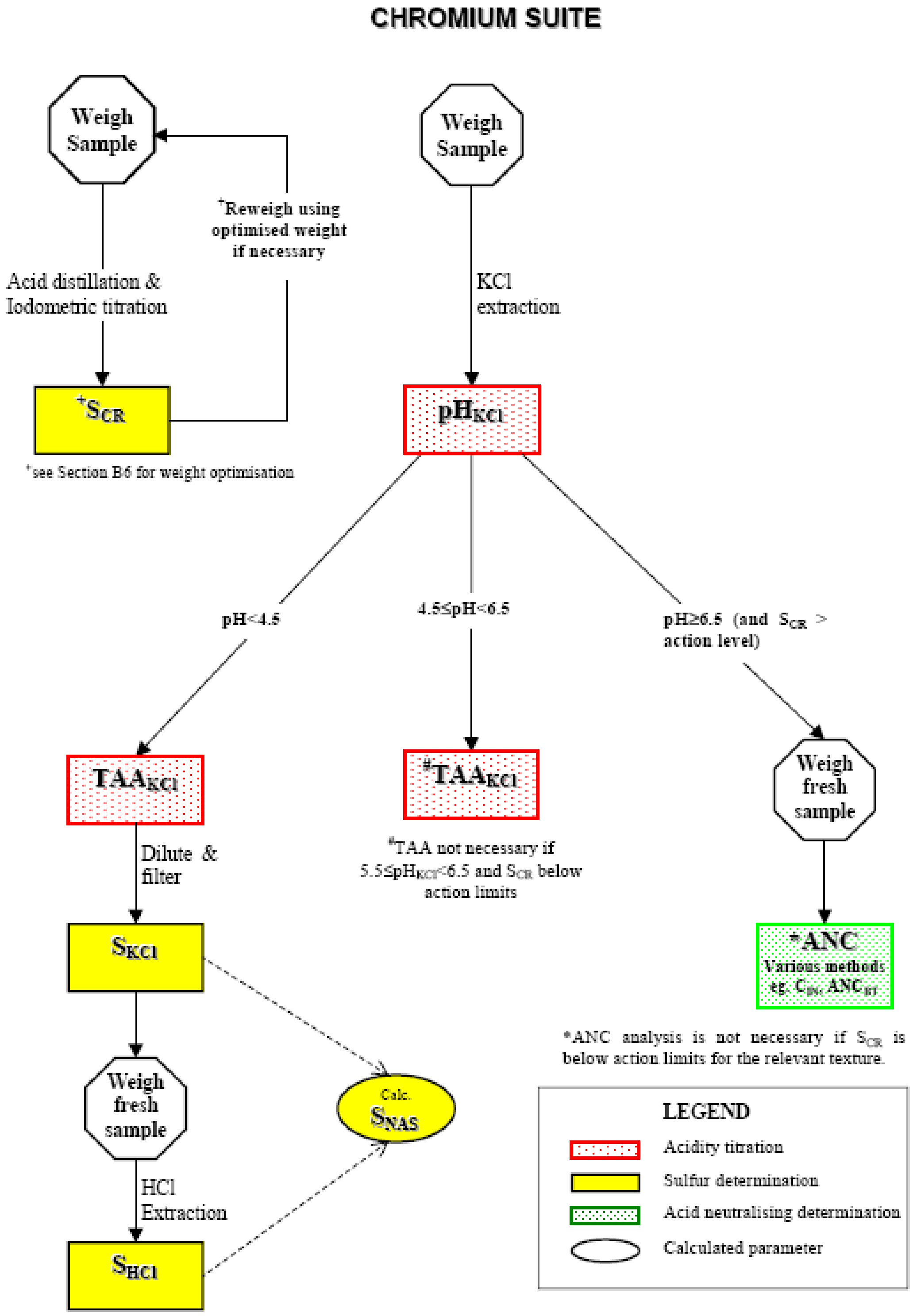


Figure 2 Flow diagram of steps involved using the Chromium suite

SPOCAS: FLOW DIAGRAM

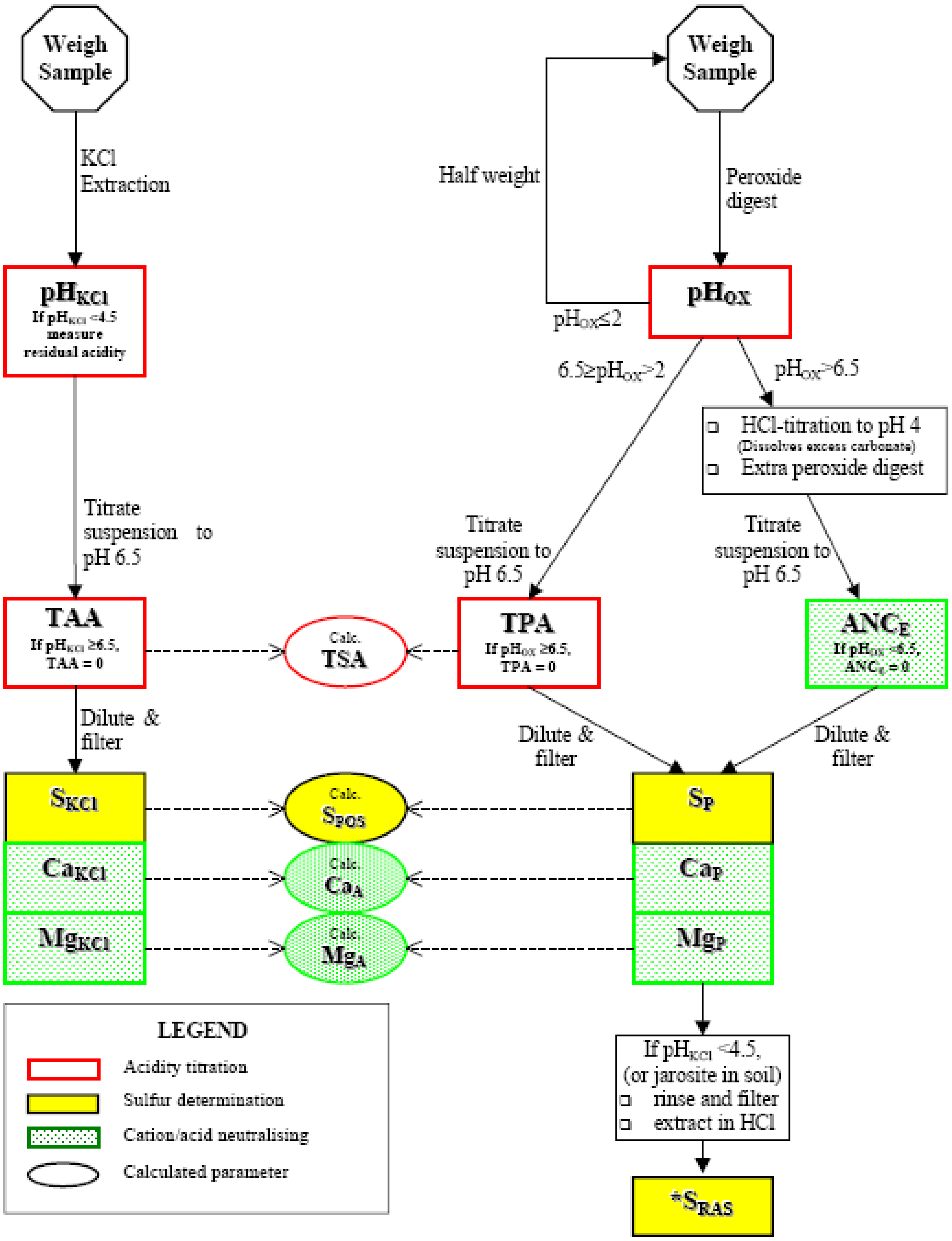


Figure 3 Flow diagram of steps involved in analysis using the SPOCAS suite

Appendix D — Water-level data

Name	Collected date	Converted level (mAHD)
EGT_A	Jul-2007	39.296
EGT_A	Aug-2007	39.596
EGT_A	Sep-2007	39.886
EGT_A	Oct-2007	40.066
EGT_A	Nov-2007	39.846
EGT_A	Jan-2008	39.466
EGT_A	Jan-2008	39.496
EGT_A	Mar-2008	39.366
EGT_A	Apr-2008	39.376
EGT_A	May-2008	39.576
EGT_A	Jul-2008	39.876
EGT_B	Jun-2007	38.939
EGT_B	Jul-2007	39.429
EGT_B	Aug-2007	39.719
EGT_B	Sep-2007	39.989
EGT_B	Oct-2007	40.169
EGT_B	Nov-2007	40.009
EGT_B	Jan-2008	39.679
EGT_B	Jan-2008	39.669
EGT_B	Mar-2008	39.539
EGT_B	Apr-2008	39.539
EGT_B	May-2008	39.709

Name	Collected date	Converted level (mAHD)
EGT_B	Jul-2008	39.969
EGT_C	May-2007	39.714
EGT_C	Jun-2007	39.744
EGT_C	Jul-2007	39.864
EGT_C	Aug-2007	40.024
EGT_C	Sep-2007	40.194
EGT_C	Oct-2007	40.344
EGT_C	Oct-2007	40.354
EGT_C	Nov-2007	40.324
EGT_C	Dec-2007	40.244
EGT_C	Jan-2008	40.174
EGT_C	Jan-2008	40.134
EGT_C	Jan-2008	40.104
EGT_C	Mar-2008	39.984
EGT_C	Apr-2008	40.024
EGT_C	May-2008	40.054
EGT_C	Jul-2008	40.214

Shortened forms

AASS	Actual acid sulfate soils
ABA	Acid-base accounting
AHD	Australian height datum
ANC	Acid neutralising capacity
ANZECC	Australia and New Zealand Environment and Conservation Council
ARMCANZ	Agriculture and Resource Management Council of Australia and New Zealand
ASS	Acid sulfate soils
CRS	Chromium reducible sulfur suite of analyses
DEC	Department of Environment and Conservation
DO	Dissolved oxygen
EC	Electrical conductivity
EWP	Environmental water provision
EWR	Ecological water requirement
FRP	Filterable reactive phosphorus
NMI	National Measurement Institute
PASS	Potential acid sulfate soils
SPOCAS	Suspension peroxide oxidation combined acidity and sulfur suite of analyses
SRP	Soluble reactive phosphorus
TAA	Titratable actual acidity
TDS	Total dissolved salts
TKN	Total Kjeldahl nitrogen
TN	Total nitrogen
TP	Total phosphorus
TSA	Titratable sulfidic acidity
TSS	Total suspended solids

Glossary

Abstraction	The permanent or temporary withdrawal of water from any source of supply, so that it is no longer part of the resources of the locality.
acid-buffering capacity	A measure of the resistance to changes in pH following the addition of an acid.
Acid sulfate soils	Naturally occurring, these are soils that contain 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.
Acidification	The process by which soil, or water becomes more acidic (decreasing pH).
AHD	Australian height datum, which is equivalent to: mean sea level (MSL) plus 0.026 metres, low water mark Fremantle (LWMF) plus 0.756 m.
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	Annual volume of water set aside for use from a water resource.
Aquifer	A geological formation or group of formations able to receive, store and/or transmit large amounts of water.
Biodiversity	Biological diversity or the variety of organisms, including species themselves, genetic diversity and the assemblages they form (communities and ecosystems). Sometimes biodiversity includes the variety of ecological processes within those communities and ecosystems.
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 is added
Buffering capacity	A measure of the ability of a solution to resist changes in pH.

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 layer	Sedimentary bed of very low hydraulic conductivity.
Conformably	Sediments deposited in a continuous sequence without a break.
Conglomeratic	Formed into a mass or cluster.
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.
Correlation	Indicates the strength and direction of the linear relationship between two random variables.
Cretaceous	Final period of Mesozoic era, 65–144 million years ago.
Decline	The difference between the elevation of the initial watertable and its position after a decrease in recharge (i.e. rainfall).
Dewatering	Short-term abstraction of groundwater to lower the watertable and permit the excavation of 'dry' sediment.
Discharge	The water that moves from the groundwater to the ground surface or above, such as a spring. This includes water that seeps onto the ground surface, evaporation from unsaturated soil and water extracted from groundwater by plants (see evapotranspiration) or engineering works (see groundwater pumping).
Dissolved Oxygen	The concentration of oxygen dissolved in water, normally measured in milligrams per litre (mg/L).
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.
Ecological values	The natural ecological processes that occur within water-dependent ecosystems and the biodiversity of these systems.

Ecosystem	A community or assemblage of communities of organisms, interacting with one another, and the specific environment in which they live and with which they also interact, e.g. lake, to include all the biological, chemical and physical resources and the interrelationships and dependencies that occur between those resources.
Environmental water provisions	The water regimes that are provided as a result of the water allocation decision-making process, taking into account ecological, social, cultural and economic impacts. They may meet in part, or in full, the ecological water requirements.
Environmental water requirements	The water regime needed to maintain the ecological values (including assets, functions and processes) of water-dependent ecosystems at a low level of risk.
Equilibrium	The condition of a system or reaction in which competing influences are balanced.
Eutrophic	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 (Water and Rivers Commission 2001a).
Fault	A fracture in rocks or sediments along which there has been an observable displacement.
Feldspar	Group of mineral silicates.
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.
Geomorphic	Pertaining or related to the form of the earth or its surface features.
Glauconitic	Of the mineral glauconite, which is an iron potassium phyllosilicate (mica group) mineral of characteristic green colour.
Groundwater	Water that occupies the pores within the rock or soil profile.
Groundwater gradient	The rate of change of total-head per unit distance of flow at a given point and in a given direction.

Groundwater area	Are the boundaries that are proclaimed under the *Rights in Water and Irrigation Act 1914* and used for water allocation planning and management.
Groundwater-dependent ecosystem	An ecosystem that is dependent on groundwater for its existence and health.
Groundwater level	An imaginary surface representing the total head of groundwater. Defined by piezometer readings.
Groundwater mound	A mound-shape formation of the water-table that results from rainwater trickling down into the open space between particles in an elevated area of deep sand or other porous material. Groundwater will move slowly away from the central area to discharge into wetlands, rivers and oceans.
Groundwater recharge	The rate at which infiltration water reaches the watertable.
Groundwater subarea	Areas defined by the Department of Water within a groundwater area, used for water allocation planning and management.
Guidelines	Values or ranges of acceptable or unacceptable levels of a chemical, beyond which management response is usually triggered.
Head	The height of the free surface of a body of water above a given sub-surface point.
Hydraulic	Pertaining to water motion.
Hydrogeology	The hydrological and geological science concerned with the occurrence, distribution, quality and movement of groundwater, especially relating to the distribution of aquifers, groundwater flow and groundwater quality.
Hydrograph	A graph that shows the height of a water surface above an established datum plane for level, flow, velocity or other property of water with respect to time.
Interdunal	Between dunes.
Ion	An atom which has lost or gained electrons and therefore carries an electrical charge.
Leach	Remove soluble matter by percolation of water.

LOR	Limit of reporting. The lower limit of reliability given by the laboratory responsible for carrying out the analysis. Greater than the limit of detection (LOD).
Mesozoic	An era of geological time between 250 to 65 million years ago. It included the Triassic, Jurassic and Cretaceous periods.
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 (H_2O).
Organism	Is a living system. In at least some form, all organisms are capable response to stimuli, reproduction, growth and development, and maintenance of homeostasis as a stable whole.
Oxidation	A process that results 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.
Palaeoclimatology	The study of climate through geological time.
pH	The negative logarithm of the concentration of hydrogen ions.
Precipitate	The solid formed when two ionic solutions are mixed together to produce an insoluble product.
Quaternary	Relating to the most recent period in the Cainozoic era, from two million years ago to present.
Recharge	Water that infiltrates into the soil to replenish an aquifer.
Redox	Chemical reactions leading to changes in the oxidation sate of atoms.
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). 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.
Screen	A special form of bore liner used to stabilise the aquifer or gravel pack, while allowing the flow of water through the bore into the casing and permitting the development of the screened formation by an appropriate process.
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.
Terrestrial	Refers to an organism (or ecosystem) being of land origin.
Tertiary	The first period of the Cainozoic era; 2 to 65 million years ago.
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.
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.
Volumetric	Relating to measurement by volume.
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.
Xeric	Relating or adapted to a dry habitat.

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