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

Looking after all our water needs

Perth Shallow Groundwater Systems Investigation

Tangletoe Swamp

Hydrogeological record series

Report no. HG49
May 2011

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Preface

This report is based on work carried out as part of the Perth shallow groundwater systems investigation. This is a four-year (2007–10) investigation program being undertaken by the Groundwater Review Section of the Water Resource Assessment Branch within the Department of Water. Data interpretation for the report was carried out by Hydro Tasmania Consulting and Crisalis International Pty Ltd under commission to the Department of Water.

Funding for the program has been provided jointly by the Government of Western Australia and the federal government's Water Smart Australia Initiative.

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

The formulation of the investigation arose from the outcomes of a management area review conducted in 2006 (McHugh & Bourke 2007). This review summarised the current monitoring and management issues facing selected wetlands on Gnangara and Jandakot mounds and identified the information and data required to address these issues. The report recommended an investigation program that incorporates up to 28 wetlands on the Swan Coastal Plain, prioritised by a combination of ecological significance, management issues and geomorphic setting.

The specific objectives of the Perth SGS investigation were to:

- redesign and upgrade the existing monitoring infrastructure and install new monitoring networks at ecologically important sites
- investigate the hydrogeology of selected lakes, wetlands and remnant wetlands to determine the interactions and connectivity of surface water bodies and groundwater
- investigate the 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 this investigation will aid the development of management strategies based on site-specific, scientific data that will promote the sustainable use of the groundwater resources of the Gnangara and Jandakot mounds.

Summary

Tangletoe Swamp is one of the 28 sites in the Perth shallow groundwater system (SGS) investigation. Prior to this study, no detailed investigations on a local scale had been undertaken and the complex nature of this shallow system was not fully understood. Previous studies classified Tangletoe Swamp as a seasonally inundated sumpland supported by the Superficial aquifer.

In 2008, a cluster of groundwater monitoring bores was installed on the northern side of the swamp as part of the SGS investigation. A comprehensive 12-month sampling program of these monitoring bores has improved understanding of how the swamp functions hydrogeologically. A staff gauge was also installed in 2008, though no surface water has been present for many years. Although the monitoring period has been short, it is sufficient to assess the swamp's seasonal response to rainfall, climatic variation and other potential stressors over a year's cycle.

The SGS investigation has shown that Tangletoe Swamp is maintained by a shallow perched groundwater system lying above a sandy clay sequence; the Guildford Formation. These clays lie within the Bassendean Sands allowing the perched aquifer to sit approximately 4 m above the Superficial aquifer's watertable. The saturated thickness of this perched aquifer is approximately 2 m. The morphology of the perched aquifer system is unknown, but the system was intersected below the lakebed sediments and is assumed to be basin shaped below the swamp and surrounding area.

Long-term hydrographs show that the regional (superficial) watertable around Tangletoe Swamp remained reasonably stable between 1977 and 1987. Since 1987 regional groundwater levels have declined by 2 m to 4 m. This decline is associated with a decline in rainfall (hence recharge) over this period.

Groundwater levels in the Superficial aquifer are likely to have remained below those of the perched system since 1989 and perched groundwater levels are likely to have decreased sympathetically with those of the Superficial aquifer since that time. The decline in perched groundwater levels since 1989 has resulted in Tangletoe Swamp being rarely inundated, so that it has shifted from a sumpland (Hill et al. 1996) to a dampland.

The regional flow system of the Superficial aquifer has little influence on the hydrology of the swamp. The swamp's water balance is maintained by direct recharge from rainfall with discharge from the perched system via leakage through the sandy clays to the Superficial aquifer, and from evapotranspiration. Groundwater levels within the perched system appear to respond rapidly to rainfall as shown by the substantial rise in July 2008.

The water chemistry of the perched system is significantly different to that of the Superficial aquifer. Groundwater within the Superficial aquifer near the swamp is generally of sodium chloride type, whereas perched groundwater is enriched in sulfate and exceeds triggers for total nitrogen and ammonium. The differences are probably due to chemical processes associated with the swamp deposits. Analysis of

swamp sediments indicates the presence of potential acid sulfate soils at depths of less than 4 m. The drying of the acid sulfate soils have acidified the perched groundwater and leached metals from the swamp sediments and Bassendean Sands, specifically Al, Cr and Ni. These are all above trigger levels for south-west Australian wetlands (ANZECC & ARMCANZ 2000). The combination of stored acidity and shallow groundwater level variations in the future has the potential to produce further acidification of the system.

The oxidation of the swamp sediments has the potential to affect the regional groundwater system. The large rainfall event in July 2008 flushed the products of sulfidic sediment oxidation into the perched watertable. This flushing, combined with downward leakage, is the likely cause of the high metal concentrations in the SGS shallow and intermediate bores.

The current ecological values of Tangletoe Swamp are dependent on the perched groundwater system. Although vegetation monitoring results from 1999 to 2006 suggested that lowering of groundwater levels were causing declines in the condition and distribution of wetland vegetation, more recent monitoring has identified that acidification of the perched watertable is also contributing to the observed changes.

Although current perched aquifer levels are sufficient to meet the ecological water requirements of the existing wetland vegetation community, it is thought that the vegetation community may have already undergone shifts in distribution in response to previous water level and quality declines. It is likely that increasing acidity and high metal concentrations within the perched groundwater system is having an impact on the local ecosystem.

The conclusion of Froend et al. (2004a) that the vegetation community at Tangletoe Swamp was in relatively pristine condition at the time of the study suggests that any significant decline in perched groundwater levels and system degradation happened after 2000.

As Tangletoe Swamp is rarely inundated, information relating to water quality of the wetland is lacking. Should the swamp refill, its sediments may acidify the surface water and make it toxic to aquatic macroinvertebrate fauna. The progressive drying out of the system is the most likely cause of the declining richness and abundance of macroinvertebrate species.

As climate forecasts are predicting drier future conditions (CSIRO 2009), further water level declines in the perched aquifer are expected. Consequently, acidic conditions are expected to persist, leading to further deterioration of the ecological values associated with Tangletoe Swamp and increased terrestrialisation of the wetland.

Recommendations

These recommendations are subject to departmental priorities and the availability of resources.

Management actions

- Ecological water requirements (EWRs) have been identified for Tangletoe Swamp but should not be adopted as Ministerial criteria due to the reliance of the vegetation on the perched aquifer, rather than the regional groundwater system.
    - Implementation and responsibility: Department of Water to recognise in the next Gnangara water allocation plan.
- Develop a local area model that incorporates the new hydrogeological understanding gained from this study, and includes scenarios that model changes in recharge by managing the density of vegetation, rainfall variability and changes in abstraction.
    - Implementation and responsibility: Department of Water to develop the north Gnangara local area model to model future scenarios by June 2012. Results to be related to similar perched systems and inform the next Gnangara water allocation plan.

Future monitoring

- Continuous monitoring using data loggers at bore YY9, GB15, all bores installed in this investigation (TGT bores) and staff gauge to quantify the relationship between perched and regional groundwater levels. Water chemistry should be analysed every quarter. Should Tangletoe Swamp become inundated then include surface water levels, chemistry and biota to assess the potential impact of acidic waters on the ecology of the wetland.
    - Implementation and responsibility: Department of Water to design a suitable groundwater monitoring program, that includes water chemistry sampling to inform the next Gnangara water allocation plan.
- Review the suitability of the monitoring program after three to five years of data collection to ensure that this monitoring provides the data necessary to assess ecological and hydrogeological changes.
    - Implementation and responsibility: Department of Water to review the monitoring program and document in a resource review report by 2015.

Future investigation

- Shallow drilling and surface geophysical surveys (e.g. ground penetrating radar and electro-magnetics) and down hole geophysical logging (e.g. natural gamma, neutron) to determine the geometry and extent of the perched aquifer.
    - Implementation and responsibility: Department of Water to scope an investigative drilling program.

1 Context and objectives

Clifton and Evans (2001) described permanent wetlands of the Swan Coastal Plain as being entirely dependent on groundwater. Water levels in shallow groundwater systems are declining across the Gnangara Mound, and have been linked to ecological deterioration including loss of biodiversity (Clark & Horwitz 2005; Froend & Loomes 2004). The causes of these declines are a complex mix of natural and anthropogenic factors (Yesertener 2005). Regionally, the climate is becoming drier, reducing recharge and leading to lower groundwater levels. This trend is predicted to continue across the Swan Coastal Plain (Indian Ocean Climate Initiative 2002). Superimposed on this regional trend are the effects of localised land use, vegetation, urbanisation and abstraction. Water level declines in and around wetlands substantially increases the risks associated with acid sulfate soils (ASS) and is linked to environmental and groundwater degradation (Appleyard 2006).

Tangletoe Swamp is an ovoid sumpland of the Jandakot suite (Hill et al. 1996) and is a groundwater-dependent ecosystem (GDE) with a phreatophytic vegetation community. Due to its ecological significance, Tangletoe Swamp was identified as a priority management site in the 2004 review of the management of the Gnangara and Jandakot mounds (DoE 2004; DoE 2005). The progressive decline in groundwater levels observed over the last 20 years has resulted in the sumpland being rarely inundated, affecting the species richness of macroinvertebrates in the swamp, and the health of the surrounding vegetation.

The management area review of Shallow Groundwater Systems on the Gnangara and Jandakot mounds (McHugh & Bourke 2007) considered that it would be appropriate to undertake a hydrogeological investigation of Tangletoe Swamp. This was because the hydrogeology of the swamp was not well understood and the swamp supports regionally representative vegetation. The site was also known to support high macroinvertebrate species richness (Davis et al. 1993 as cited in Froend et al. 2004a) but given the decline in regional water levels it is unclear if this richness persists.

The management area review and the most recent review of Ministerial conditions on the Gnangara Mound (DoW 2008a) recommended that site-specific data be collected and analysed to determine the current groundwater–surface water connectivity, groundwater quality and groundwater flow into and out of the wetlands.

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

- install a groundwater monitoring network
- improve the department's understanding of how Tangletoe Swamp functions hydrogeologically
- determine the distribution of acid sulfate soils in and around the swamp and their effects on water chemistry
- link the hydrogeological and chemical understanding with ecological water requirements and determine the implications for ecological values of the swamp

- outline the implications of change in water and land use based on groundwater flow modelling results
- highlight water-use and land-use issues to be addressed in the next water management plan for the Gnangara Mound.

2 Background

2.1 Location and climate

Tangletoe Swamp is located south of Gingin Brook on the Gnangara Groundwater Mound, approximately 65 km north of Perth, on the northern part of the Swan Coastal Plain (Figure 1). Tangletoe Swamp is a seasonal sumpland located within the Bassendean North vegetation complex and is surrounded by an extensive state forest reserve of undisturbed vegetation (Table 1). The sumpland is located in the Gingin groundwater area.

Table 1 Summary attributes of Tangletoe Swamp

Wetland name	**Tangletoe Swamp**
AWRC No.	61710078
Location (coordinates)	E: 378632, N: 6530259
Elevation	approx. 44.5 m AHD
Wetland/GDE type & description	Sumpland
Ecological recognition	Conservation category wetland
Aboriginal heritage	No registered sites of significance
Wetland suite	Jandakot
Physiographic wetlands unit	Bassendean North complex (Yeal West vegetation community)

The Swan Coastal Plain experiences a Mediterranean type climate with hot, dry summers and mild, wet winters. Rainfall occurs mainly between May and September. The rainfall recorded from Gingin, the closest monitoring station to Tangletoe Swamp, over a 13-year period (1996–2009) is shown in Figure 2. The annual rainfall for each year from 1996 to 2009 is shown in Table 2.

Table 2 Annual rainfall at Gingin (1996 to 2009)

Year	Rainfall mm
1996	747
1997	612
1998	599
1999	882
2000	609
2001	570
2002	489
2003	683
2004	515
2005	737
2006	540
2007	675
2008	739
2009	693

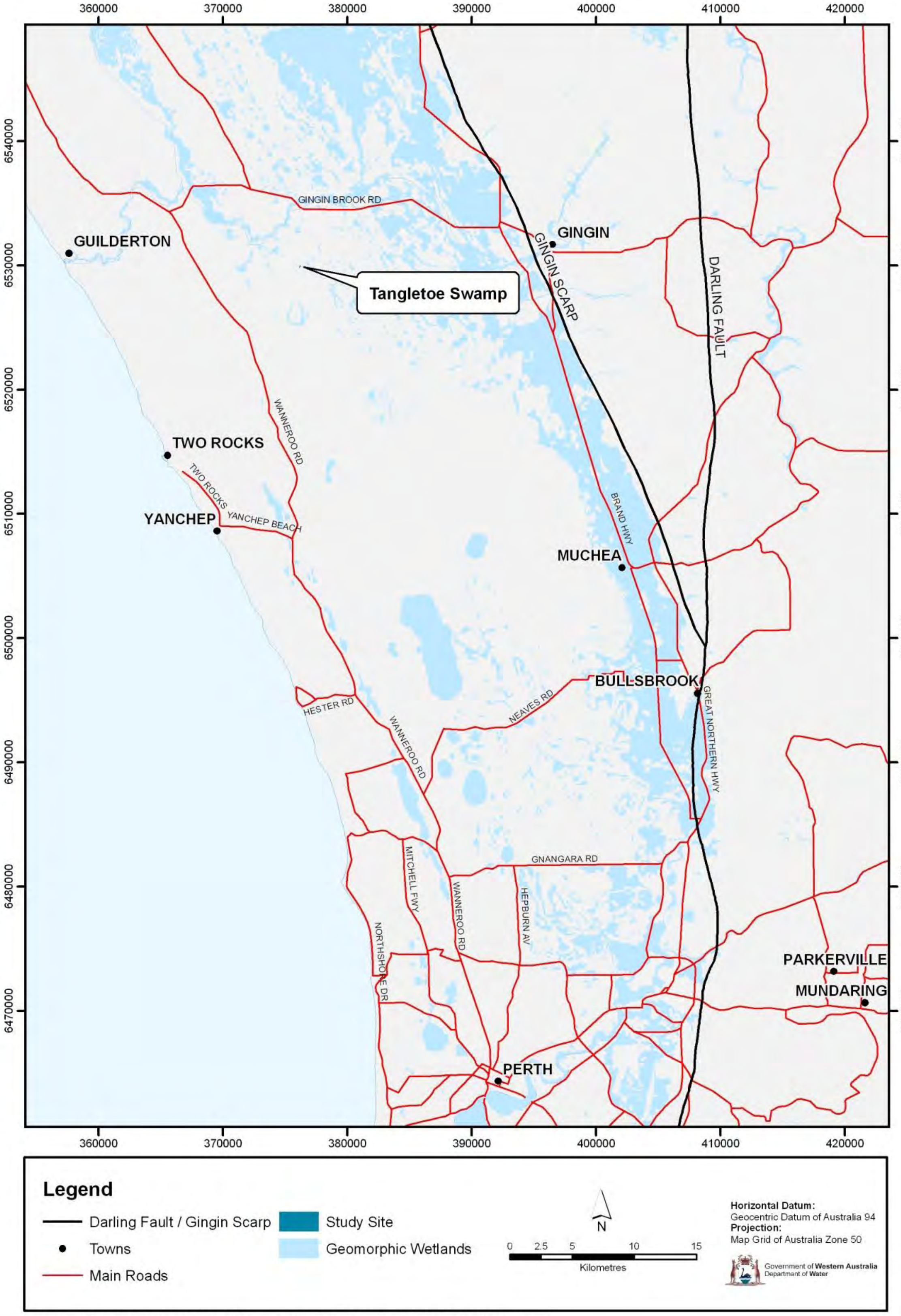

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Figure 1 Location of Tangletoe Swamp

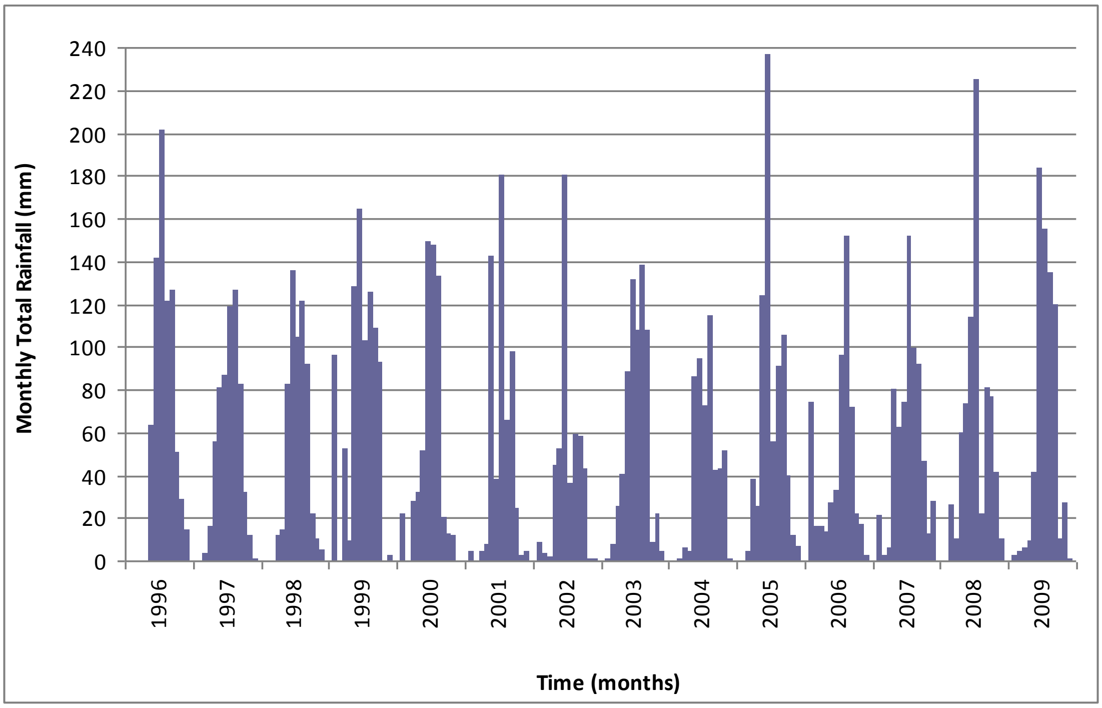

Figure 2 Monthly total rainfall at Gingin 1996 to 2009

2.2 Geology and geomorphology

2.2.1 Regional geology and geomorphology

Tangletoe Swamp is located on Quaternary sands of the superficial formations on the northern part of the Swan Coastal Plain which is about 35 km wide and bounded by the coast to the west and Gingin Scarp to the east. The dune sands between the Swan River, Moore River and Gingin Brook to the north, the Darling and Gingin scarps to the east and Indian Ocean to the west, form a north–south trending dune system of crests and swales.

In the Perth region, the superficial formations have four geomorphic units which trend sub-parallel to the present day coast. The oldest is the Pinjarra Plain, which comprises alluvial fans abutting the Darling Scarp. Adjacent to the Pinjarra Plain are a series of dune systems, which represent various shorelines, decreasing in age from east to west. These units, in order of deposition, are the Bassendean, Spearwood and Quindalup dunes. The latter are still forming and represent the present day coastline (Gozzard 2007). The Bassendean Dunes are generally of low relief with minor variations in topography.

Tangletoe Swamp sits in a subdued swale in the Bassendean Dunes system which is composed of Bassendean Sand (Figure 3 and Figure 4) (McArthur & Bettenay 1960; Davidson 1995). Bassendean Sand is described by Davidson (1995) as pale grey to white and includes fine to coarse sands, but is predominantly medium grained. It comprises moderately sorted, sub-rounded to rounded quartz sand and commonly exhibits fining upward textures. A layer of friable, limonite cemented sand, colloquially called ‘coffee-rock’ appears throughout most of the area near the watertable. Bassendean Sand unconformably overlies the Cretaceous and Tertiary strata and interfingers with the Guildford Clay Formation. To the west, it is unconformably overlain by the Tamala Limestone. Guildford Clay consists of pale-grey, blue to predominantly brown silty and slightly sandy clay.

2.2.2 Acid sulfate soils

Lakes and wetlands on the Swan Coastal Plain are often associated with acid sulfate soils. Acid sulfate soils naturally arise when soils are formed under waterlogged conditions that contain iron sulfide minerals (e.g. pyrite) or their oxidation products. When exposed to air, the sulfides in these soils oxidise generating sulfuric acid. Oxidation processes are commonly caused by the lowering of the watertable (Ahern et al. 2004). Sulfuric acid then releases and mobilises iron and other associated metals into the soil and groundwater (Fältmarsch et al. 2008). The resulting acidity then has the potential to mobilise other metals from the sediment profile into the groundwater flow system.

The term acid sulfate soils includes both potential and actual acidity. Potential acid sulfate soils (PASS) refers to the sediments which are still waterlogged or unoxidised. Actual acid sulfate soils (AASS) refer to sediments which have been exposed to air and have produced acidity.

Since many of the wetlands situated on the Gnangara Mound are progressively drying, the exposure of acid sulfate soils is a risk to the environment and may result in progressive groundwater degradation. Tangletoe Swamp is at risk of acidification due to the exposure of acid sulfate soils.

2.3 Hydrogeology

Tangletoe Swamp is located on the Gnangara Groundwater Mound, where groundwater generally flows outwards and westwards from Gingin scarp, flowing beneath the swamp towards the ocean (Figure 5).

Tangletoe Swamp lies within a zone of moderate hydraulic gradient (groundwater levels falling from 35 to 30 m AHD). Further to the west a steep hydraulic gradient has been documented (see Figure 5). The gradient changes where the calcareous sediments of the Spearwood Dunes (and underlying sediments) abut and overlie the Bassendean Dunes. Mesozoic semi-confined aquifers of the Leederville Formation unconformably underlie the Superficial aquifer.

A number of wetlands on the Swan Coastal Plain are considered to be ‘flow-through’ lakes where groundwater discharges into the lake on the up-gradient (eastern) side and surface water in the lake discharges into the groundwater system on the down-gradient (western) side (e.g. see Townley et al. 1991 and Townley & Trefry 2000).

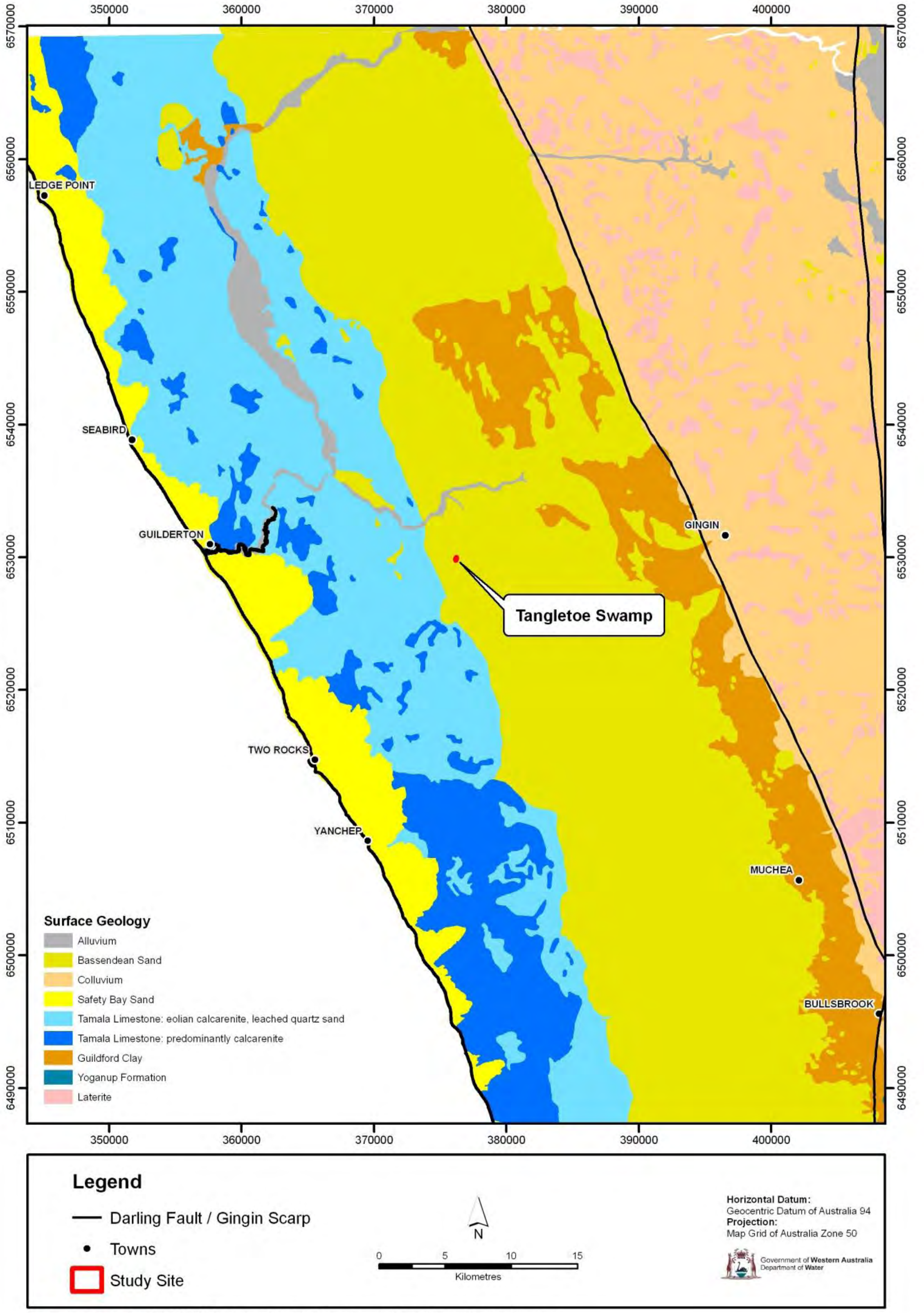

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Figure 3 Generalised surface geology in the Tangletoe Swamp area

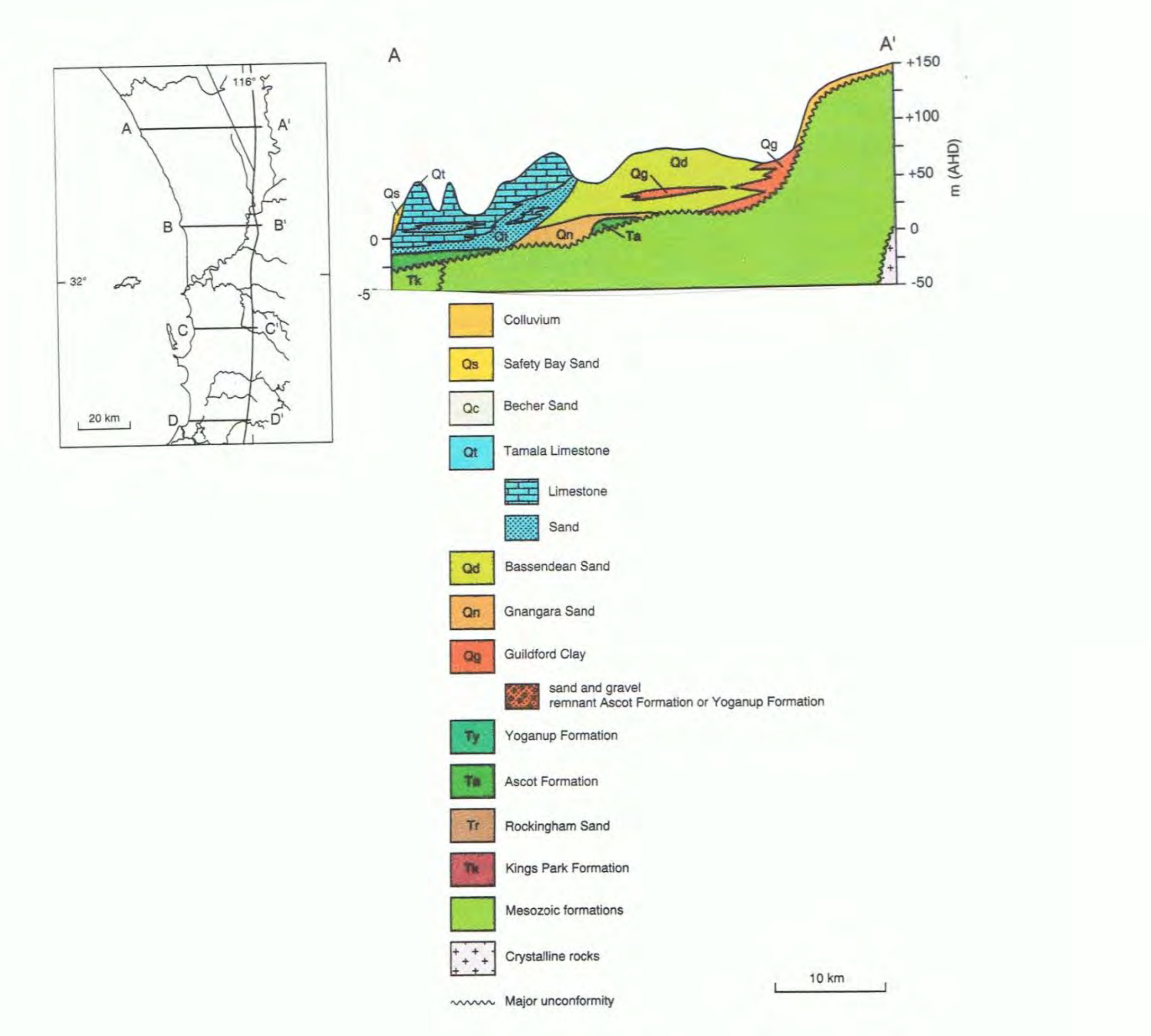

Figure 4 East–west geological cross-section through the superficial formation A-A' north of Tangletoe Swamp, from Davidson (1995)

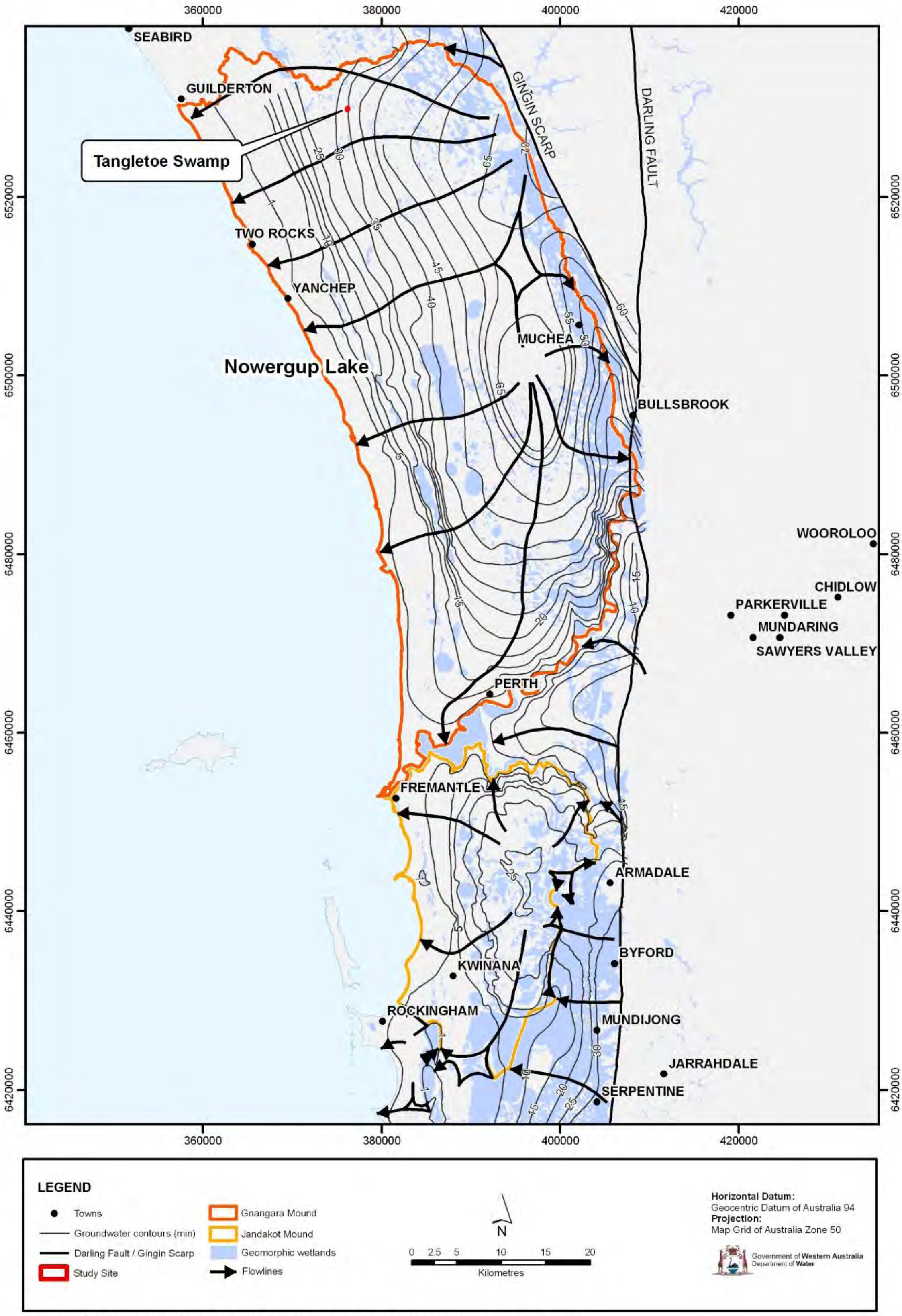

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Figure 5 Gnangara and Jandakot mounds showing groundwater flow lines

2.4 Previous studies

Despite an extensive literature search no information could be found regarding previous local hydrogeological or hydrological studies of Tangletoe Swamp.

2.5 Ecological value and significance

2.5.1 Ecological values and management objectives

A number of groundwater-dependent ecosystems on the Gnangara and Jandakot mounds have been identified as being ecologically significant following a series of reviews. Environmental water provisions (EWPs) were developed for groundwater-dependent ecosystems identified in 1995 (WAWA 1995), by examining the ecological water requirements of the wetlands, based on links between groundwater and surface water levels and ecological response. Where the EWPs were considered to protect the ecological values of a wetland, they were set as Ministerial criteria which must be complied with under the *Environmental Protection Act 1986*. EWPs have not been developed and Ministerial criteria have not been set for groundwater-dependent ecosystems identified through the 2004 review of the management of groundwater-dependent wetlands of the Gnangara and Jandakot mounds (DoE 2004).

Tangletoe Swamp is one of the groundwater-dependent ecosystems identified as being ecologically significant in the 2004 review (DoE 2004). The review identified Tangletoe Swamp as a priority management site due to the ecological value of its phreatophytic[1] vegetation community (Froend et al. 2004b). Froend & Loomes (2004) selected Tangletoe Swamp as representative of terrestrial vegetation with respect to structure, composition and faunal habitat of the Bassendean North vegetation complex. Tangletoe Swamp has been listed as a conservation category 1 GDE for its high conservation value terrestrial ecosystem and relatively pristine condition. Located in an extensive state forest reserve of undisturbed vegetation, the phreatophytic vegetation community is a mosaic of low, open *Banksia attenuata* and *B. menziesii* woodlands with *B. ilicifolia* shrublands. Previous work also identified an additional ecological value of supporting high macroinvertebrate species richness.

Froend et al. (2004a) listed a high species richness for Odonata and Coleoptera macroinvertebrates as a value of Tangletoe Swamp, based on a survey of macroinvertebrate richness. It is unclear whether the reduced frequency of open water has affected macroinvertebrate richness.

Understanding of the ecohydrology of this wetland is constrained by the limited monitoring that has been conducted at this site to date (DoW 2009c), although efforts have increased in recent years to address the identified knowledge gaps (Froend et al. 2004c; DoE 2004; McHugh & Bourke 2007; Rockwater 2003).

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[1] Phreatophytic: deep-rooted vegetation that obtains water from a permanent ground supply or from the watertable.

2.5.2 Impacts of declining water levels on ecological values

Across the Gingin groundwater area, groundwater levels have been declining since the late 1970s in response to low rainfall (CSIRO 2009; DoW 2008b). Although groundwater levels at Tangletoe Swamp have only been monitored since 2008 it is likely that similar historical declines have taken place due to decreasing rainfall and that this decline has had an adverse effecte on the ecological values of the site.

Vegetation monitoring has been carried out at Tangletoe Swamp since 1987, with assessments conducted in 1987, 1990, 1999, 2002 and 2005 (Mattiske Consulting 2006). In 2009, a new phreatophytic vegetation monitoring program began and a new vegetation transect was established at Tangletoe Swamp in association with the newly established SGS bore, TGT_C. As a consequence, the 2009 vegetation monitoring results cannot be directly compared to the previous vegetation data; however some broad conclusions can be drawn.

The vegetation community at Tangletoe Swamp is generally in good to pristine condition, but there is some evidence of degradation. Wilson et al. (2009) recorded the following indicators of vegetation degradation at Tangletoe Swamp:

- invasion of the dry wetland basin and wetter end of transect by weedy exotic species
- poor understorey health at wetter end of transect
- decreased canopy health at wetter end of transect.

The previous monitoring program (Mattiske Consulting 2000, Mattiske Consulting 2006) recorded changes in the condition and abundance of the following wetland species at Tangletoe Swamp:

- Species tolerant of excessive wetness
    - *Banksia littoralis* – decrease in condition and abundance since 1987, with temporary loss from transect
    - *Eucalyptus rudis* – lost from transect after 1990
    - *Melaleuca preissiana* – decrease in condition since 1987 and abundance since 1999
    - *Melaleuca rhaphiophylla* – decrease in condition and abundance since 1987
- Species with wide tolerance, but with maximum development on dry sites:
    - *Banksia attenuata* – decrease in condition since 1987
    - *Banksia menziesii* – decrease in condition since 1987 and abundance since 1990
- Species intolerant of extremes in moisture conditions:
    - *Banksia ilicifolia* – decrease in condition, particularly since 2002.

In combination, the old (Mattiske Consulting 2000; Mattiske Consulting 2006) and new (Wilson et al. 2009) monitoring program results suggest that vegetation changes have taken place across numerous species with a range of groundwater requirements in response to falling groundwater levels.

An assessment of macroinvertebrate richness by Davis et al. 1993 (cited in Froend et al. 2004a) found a total of 38 macroinvertebrate species at Tangletoe Swamp, representing 34 genera and 26 families. Although no rare taxa were identified in this study, 10% of the species were regionally endemic (Sommer et al. 2008). Decreasing groundwater levels are likely to have reduced macroinvertebrate habitat availability, leading to reduced richness and diversity.

2.5.3 Ecological water requirements

Where possible, EWRs have been developed for some of the significant species using the methodology developed by Loomes (2000; as cited in Froend et al. 2004b). As groundwater data was only available for 2009, the EWRs developed reflect the vegetation ranges at a time of decreasing vegetation distributions (Mattiske Consulting 2006) and thus may not accurately represent the true minimum water requirements for vegetation species at Tangletoe Swamp. The approximate minimum water level requirements identified are:

- *Baumea articulata* – minimum water level requirement of 43.47 m AHD
- *Astartea fascicularis* – minimum water level requirement of 42.55 m AHD
- *Melaleuca rhaphiophylla* – minimum water level requirement of 42.43 m AHD

Therefore a groundwater level of 43.47 m AHD (Figure 6) is considered the minimum required to support wetland vegetation at Tangletoe Swamp, based on the 2009 vegetation distribution data. Given that groundwater levels are known to have declined in the Gingin groundwater area and that vegetation condition has declined over time (Mattiske Consulting 2006), it is likely that groundwater levels have declined at Tangletoe swamp. Thus it is expected that the true minimum water requirements would be higher than those reported above.

2.6 Cultural significance

Wetlands across the Swan Coastal Plain are spiritually significant to Indigenous groups (Nyungar people) and were used extensively in traditional times (Wright 2007a). Many lakes and swamps were used as hunting and gathering areas for flora and fauna (McDonald et al. 2005).Tangletoe Swamp reflects these Indigenous values. The area falls under the Yued native title claim, which abuts the Perth metropolitan claim to the north. The wetlands south-west of Gingin were surveyed, using a team of six traditional owners plus an anthropologist and two archaeologists.

Most of the Gingin area has a mythological significance for Indigenous people. With the exceptions of the three artefact scatters (Department of Indigenous Affairs site IDs 18076, 18078 and 18079), all other sites registered within 5 km of the proposed water bore locations are mythological sites associated with the Dreamtime figure, the Waugul (Wright 2007b).

At Tangletoe Swamp the traditional owners identified a scarred tree. Scarred trees are relatively common cultural features which are the result of Indigenous people having cut a piece from the tree for a cultural purpose. The scarred tree is located very close to the location initially proposed for the drilling of the bores at Tangletoe Swamp (Wright 2007b). Wright (2007b) recommended that the proposed monitoring bore be moved away from the scarred tree, by at least 25 m.

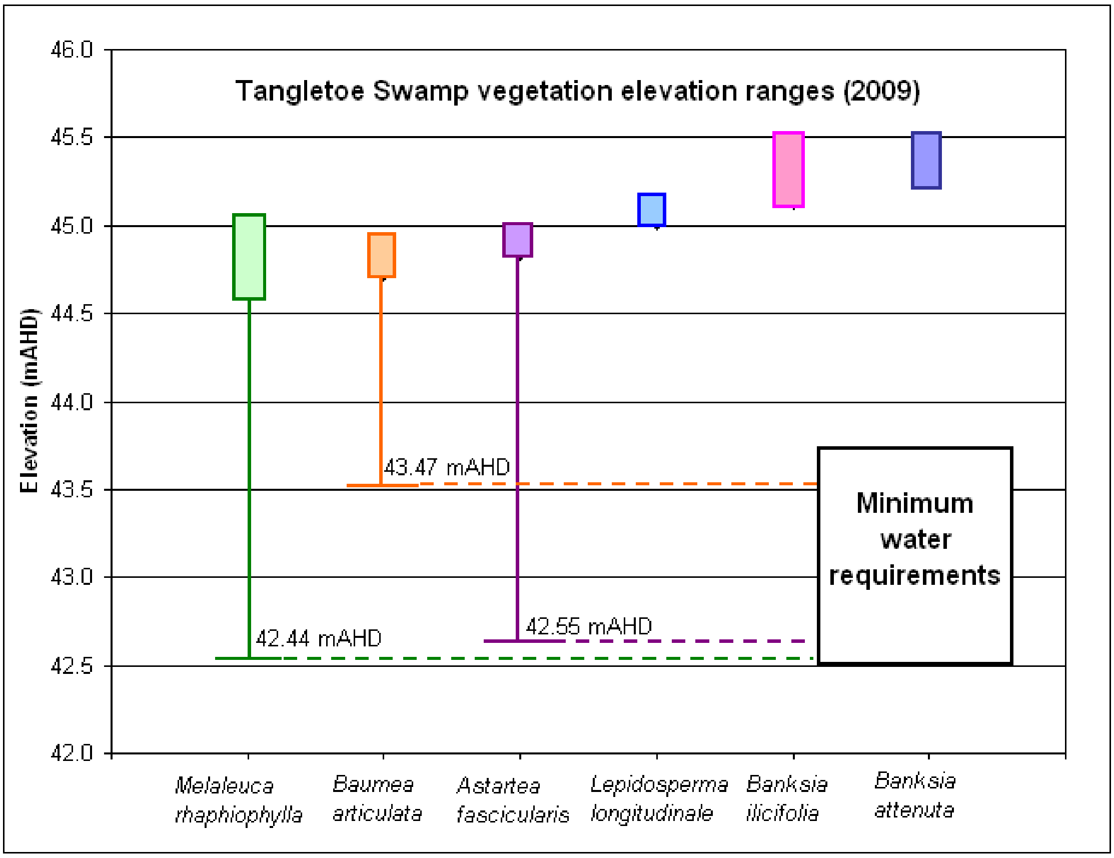


Figure 6 Relationships between vegetation distributional ranges and maximum ecohydrological water depths (minimum water level requirements)

2.7 Land and water management

The Gnangara Mound has been used for public and private groundwater abstraction for more than 35 years. The Water Authority of Western Australia (WAWA 1995) stated that the environmental impacts of abstraction were considered to have been minor compared to those of urbanisation, agriculture and silviculture. However, since that time there has been a significant increase in abstraction.

For the 2008–12 allocation plan (DoW 2009b), the department used a revised variable groundwater abstraction rule to set the annual groundwater allocation for the Gnangara and Jandakot mounds. The department will review the allocation of groundwater for the Integrated water supply system from 2012 following the commissioning of the Southern seawater desalination plant. The review will be informed by the land-use and water-use recommendations of the Gnangara sustainability strategy including the recommendation that the long-term total allocation should be reduced to 110 GL/yr (reduced from 145 GL/yr for 2008–12). The proposed 2012 statutory water management plan for Gnangara will set new allocation limits for the Gingin groundwater area in which Tangletoe Swamp is located.

In response to declining groundwater levels across the mound, the Department of Water has developed an internal policy (Policy 4.1.1 reported in DoW 2009b) to limit or restrict use of groundwater in environmentally sensitive areas. This policy informs assessors of water licence applications for areas where groundwater-dependent ecosystems are at high risk of impact from abstraction.

There are no private or public licences in the vicinity of Tangletoe Swamp (see Figure 7). DoW (2009c) considers that the decrease in ecologicalcondition at Tangletoe Swamp is not related to pumping 'as this transect is well beyond the influence of the borefields'. Instead, the decreasing trend in groundwater levels since 1989 is thought to be related to decreases in rainfall, given the low level of land development up-gradient of Tangletoe Swamp. In Zone 6 the Gnangara sustainability strategy recommends that fire management in Banksia woodland is optimised to help balance groundwater recharge and terrestrial and aquatic biodiversity values (DoW 2009a).

The *Gnangara groundwater areas allocation plan* (DoW 2009c) sets out the approach for allocation and licensing of all water users on the Gnangara Mound. The Department of Water determines the volume and spatial distribution of water abstracted from the mound by assessing proximity to groundwater-dependent ecosystems, ecological condition, and rate and magnitude of groundwater level change. For allocation purposes the Gnangara Mound is divided into groundwater areas and subareas.

Tangletoe Swamp is located in the proclaimed Gingin groundwater area and Beermullah Plain South groundwater subarea. Figure 7 shows the relationship between the groundwater bores at Tangletoe Swamp (TGT) and other bores in the region. Table 3 presents a summary of allocation data pertaining to the Superficial aquifer within the Beermullah Plain South subarea.

Table 3 Superficial aquifer allocation limits, licensed entitlements and water availability for new licences for the Beermullah Plain South groundwater subarea

Allocation limit	3.00 GL/yr
Licensed entitlements [1]	3.01 GL/yr
Public water supply (reserved)	-
Water available [2,3]	No

[1] Licensed entitlements include the total of private and public water supply licensed entitlements as at 5 August 2009.

[2] Water availability = allocation limit – total of Licensed Entitlements (private and public water supply), public water supply reserved (future use) and other commitments (e.g. staged developments).

[3] Resources less than 100% allocated but over 70% allocated have limited availability.

Adapted from Appendix H, DoW 2009c.

Allocation limits for the Superficial aquifer are based on hydrogeological and ecological condition assessments (in addition to data on the current use and demand for the resource); specifically:

- hydrograph trend analysis
- Perth regional aquifer modelling system (water balance)
- cumulative departure from mean (CDFM)
- groundwater-dependent ecosystems including the location and condition of environmental criteria sites.

Current and potential future land-use and water-use criteria for making allocation limit decisions are:

- reserving water for public water supply
- recognising existing water use
- allowing for water requirements to support land-use change and developments of significant public benefit
- the Department of Water's strategic direction in water management.

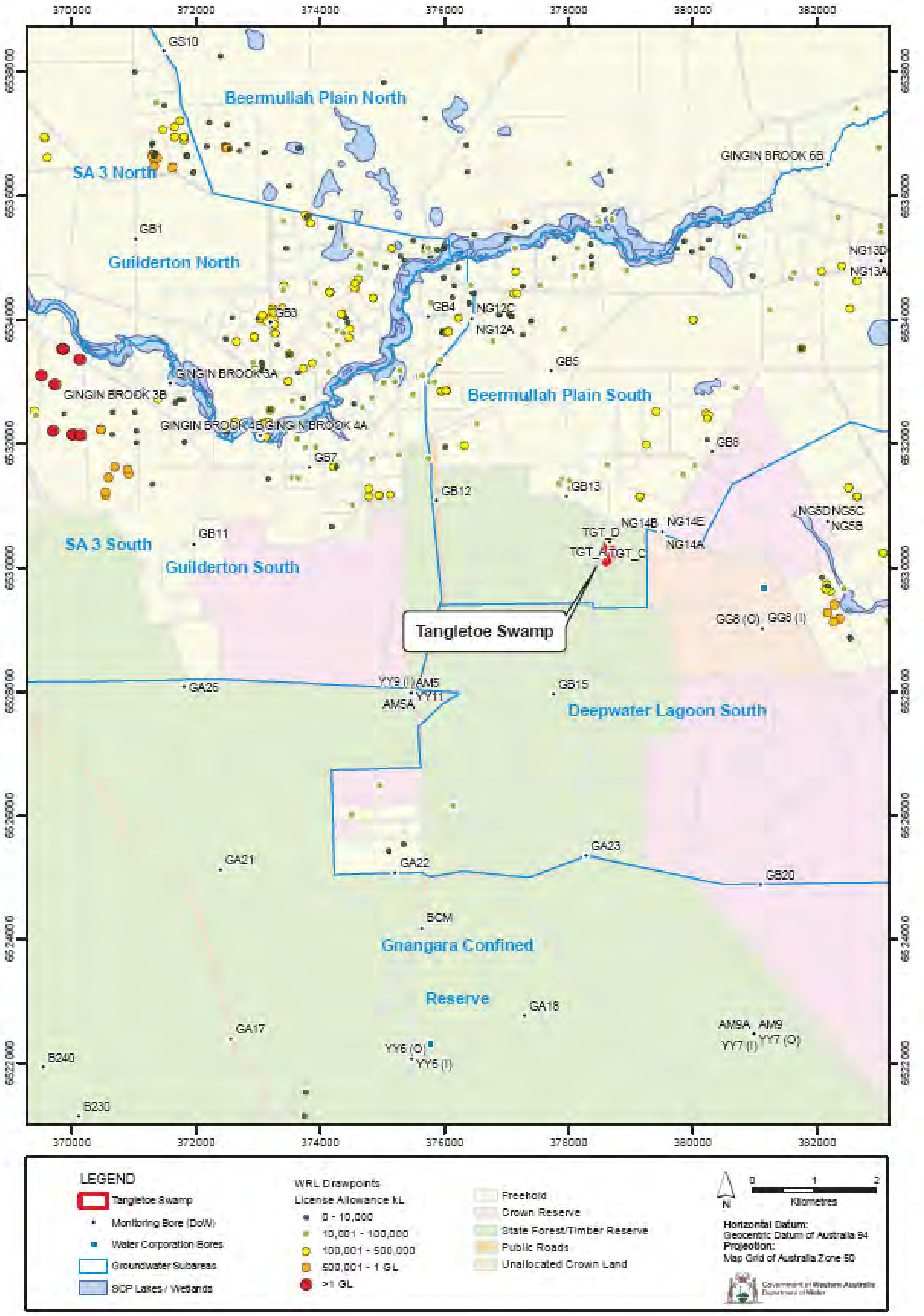


Figure 7 Groundwater areas and bore locations in the region of Tangletoe Swamp

3 Investigation program

3.1 Bore construction

The management area review (DoW 2009c) recommended upgrading the groundwater monitoring network at Tangletoe Swamp to enable hydrogeological, hydrochemical and geochemical investigations. To carry out this recommendation a cluster of four SGS bores was installed on the northern side of the swamp within what was interpreted as different units within the Superficial aquifer:

- TGT_A was screened over 2.00 m (2.52 m – 0.72 m AHD) in what was described as Ascot Formation.
- TGT_B was screened over 2.00 m (19.01 to 17.01 m AHD) within Gnangara Sand
- TGT_C was screened over 4.00 m (39.01 to 35.01 m AHD) within Bassendean Sand
- TGT_D was screened over 3.00 m (45.79 to 42.79 m AHD) within a shallow watertable within Bassendean Sand.

Figure 8 shows the location of the newly installed SGS bores and Table 4 provides general details for the bores and two swamp bed sampling sites (TGT_L1 and TGT_L2). These bores were installed in 2008 and the details of lithological and construction details are reported in Bourke (2008) and reproduced in Appendix A and Appendix C.

The shallow bores were installed using a Geoprobe 7720DT track mounted push-core rig, which provided continuous core samples to depth. Intermediate and deep bores were installed using a GSD77 Aircore drill-rig with aggregate samples of drill cuttings collected every metre to depth. A Roto Sonic EP 26 rig was also used to drill some holes. This method provides a continuous uncontaminated sample and can drill to depths of around 62 m.

Bores were cased with 50 mm Class 12 PVC, with slotted 50 mm Class 12 PVC of varying lengths installed at the base of the hole (Table 4). Shallow bores were backfilled to surface with gravel. The annulus of deep and intermediate bores was 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. Head works consist of either steel standpipes cemented in with a height of approximately 0.5 m above ground level, or flush mount well covers which sit close to the ground surface.

Figure 8 Location of bores (red line shows vegetation transect and the red marker shows the approximate locations of bores TGT_A to D)

Table 4 Bores and swamp bed sampling at Tangletoe Swamp

Depth	**AWRC name**	**AWRC number**	**Drilled depth (mbns)**	**Screen interval (mbns)**
Deep	TGT_A	61710467	61.00	44.30–46.30
Intermediate	TGT_B	61710468	30.03	28.03–30.03
Shallow	TGT_C	61710469	14.20	7.85–11.85
Perched	TGT_D	61710470	4.28	1.28–4.28
Shallow	TGT_L1	61710505	N/A	N/A
Shallow	TGT_L2	61710506	N/A	N/A

mbns – metres below natural surface

3.2 Acid sulfate soils testing

To determine the distribution and characteristics of sulfidic sediments in Tangletoe Swamp and the potential of these to affect groundwater quality, field and laboratory tests were conducted on a series of soil samples. Three samples were taken during the installation of SGS bore TGT_C, five from swamp bed core TGT_L1 and a further four from swamp bed coreTGT_L2.

Thirteen samples were analysed (including one duplicate – TGT_L2) for potential acid sulfate soils and actual acid sulfate soils according to the Department of Environment's *Investigation and identification of acid sulfate soils guide* (DoE 2006) (see Appendix B for full methods).

Further laboratory testing was conducted for net acidity by the National Measurement Institute (NMI). Samples were stored in such a way as to limit air entering into the samples and refrigerated until delivery at the NMI. Samples were taken to the laboratory either the same day as extracted from the ground, or the following day. NMI used the chromium reducible sulfur (CRS) suite as well as the suspension peroxide oxidation combined acidity and sulfur (SPOCAS) suite of analyses to conduct acid-base accounting (ABA) (see Appendix B for laboratory methods).

3.3 Water monitoring and sampling program

Groundwater sampling and analysis was undertaken to determine the hydrochemical characteristics of each site, the distribution and availability of potential pollutants and the interaction between the wetland and the aquifers. Water samples were collected using low flow pumping methods as outlined in Appendix B. Analyses of water samples were conducted for major ions, metals and nutrients.

3.4 Data accuracy and precision

There is a degree of uncertainty with measured chemical parameters and hence results from laboratory chemical analysis are not absolute. This uncertainty is caused by several contributing error sources, mainly precision 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. Accuracy or systematic errors reflect faulty procedures or interference during analysis. An electrical balance, 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), so that the sum of the cations in solution should equal the sum of the anions:

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

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

A deviation of more than 5% indicates that sampling and analytical procedures should be examined (Appelo & Postma 2005). For the SGS investigation, if the electrical balance was greater than 6%, without satisfactory explanation, then this sample was left out of the analysis.

Comparing the pH measured in the laboratory with those 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 for a difference between field and laboratory pH readings (and for other 'unstable' determinands such as dissolved oxygen (DO) and oxidation reduction potentials (ORP), including reactions involving oxidation, precipitation and release of dissolved gas. Only on-site analyses for pH, temperature, DO and ORP were used in the data analysis reported below to avoid introducing uncertainties (as recommended in state and national groundwater sampling procedures).

3.5 Data presentation and interpretation

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

- re-interpretation of historical lithological logs
- geological cross-sections from historical and Perth SGS investigation data
- analysis of hydrographs
- classification of redox processes
- groundwater contour mapping
- flow nets for both maximum and minimum groundwater levels
- Piper diagrams for major ions
- time-series plots for major ions, metals, nutrients, and physical properties.

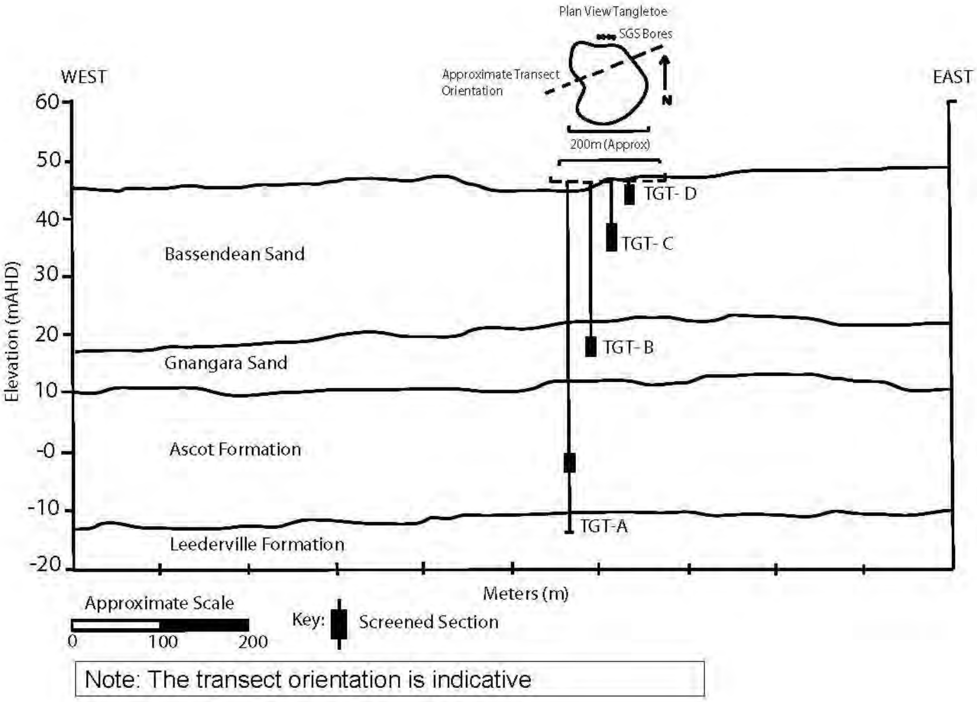
The chemical data set was filtered by investigation into ion balances as part of a quality assurance and quality control process described above.

4 Geology

4.1 Superficial and Mesozoic formations

The bore log for the deep bore TGT_A (Table 5) shows that the thickness of the superficial formations is 58 m. The bore log indicates that the Bassendean Sands consist of medium to coarsely grained silty sand and sand and are approximately 25m in thickness. Between 5 m and 7 m a 2 m thick layer of Guildford Clay was identified within the sands. Below the Bassendean Sand there is a facies change from coarse to very coarsely grained sands with abundant heavy minerals and lithic fragments, similar to lithology of the Gnangara Sands described in Davidson (1995). The Gnangara Sand is approximately 10 m thick and located between 25 m and 35 m below surface (refer to Figure 9).

Superficial sediments of the Ascot Formation were encountered beneath the Gnangara Sand. The Ascot Formation at Tangletoe Swamp is approximately 23 m thick and located between 35 m and 58 m below surface. The upper 11m of the formation was identified as being silty sand containing lithic fragments, shells and glauconite. The mid section of the unit comprises a 4 m section of shelly limestone with the base of the unit being sand. The Ascot Formation lies unconformably on the Leederville Formation at 58 m below surface, and at the site most likely consists of interbedded sandstones, siltstones and shales of the Wanneroo Member.



Note: The transect orientation is indicative

Figure 9 Geological cross-section for Tangletoe Swamp showing monitoring bore locations

Table 5 Bore log for the deep bore TGT_A drilled as part of the SGS project

Bore ID	**From**	**To**	**Formation**	**Code**	**Lithology**
TGT_A	0	5	Bassendean Sand	Qt	Sand
	5	7	Guildford Clay	Qt	Sandy clay
	7	25	Bassendean Sand	Qt	Silty sand
	25	35	Gnangara Sand	Qt	Silty sand &sand, sandy clay, silty sand, shelly
	35	58	Ascot Formation	Qt	Limestone & sand
	58	61	Leederville Formation	Kwl	Sand & mudstone

4.2 Lake deposits

Coring of the swamp bed showed that the sediments at Tangletoe range in thickness from around 3 m to 4 m and comprise black, greyish brown to very dark brown, finely laminated, organic silt with minor fine sand (Figure 10). These sediments are weakly consolidated, friable and are diatomaceous in parts. Light grey to light brownish grey and greyish brown, predominantly medium to coarsely grained, quartz silty sand, (Bassendean Sand) unconformably underlies the lakebed sediments. Within the silty sand, at depths of around 5.5 to 7.0 m is a dark greenish grey, stiff, cohesive, plastic sandy clay, presumably of the Guildford Formation.

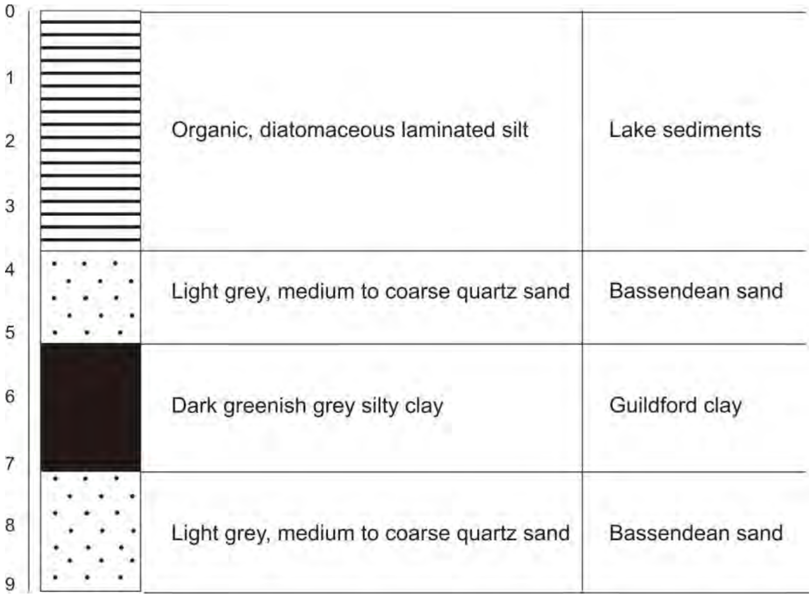


Figure 10 Lithological log of sediments within and beneath Tangletoe Swamp

4.3 Acid sulfate soils

Field testing at bore TGT_C (Figure 11 and Appendix D) indicated that potential acid sulfate soil is present in sediments at depths between 2.0 and 4.0 m. Samples for laboratory analyses were collected at 4.9 m, 5.4 m and 6.5 m and showed pH_{OX} of

6.8, 7.0 and 4.0 respectively. A pH_{OX} of 4.0 recovered from 6.5 m combined with a pH_{FOX} of < 4.0 recovered from 10.56 m indicates the potential for PASS to also be present at depths below 4.0 m. However further testing would be required to confirm these results.

The pH_F results at TGT_L1 (Figure 12 and Appendix D) were lower (pH_F 4.49–5.37) in the upper 1.0 m of the soil profile, where the sediments were composed of organic rich silts, as compared to the remainder of the sediment core (pH_F 7.09–8.23) where the sediments were sandy silts. The pH_{FOX} results were also lowest within the upper 1.0 m, ranging from pH 2.64 to 2.88 with the deeper sediments ranging from 1.98 (at 3.05 m) to 5.63. These results indicate the presence of PASS, especially within the organic rich silts from the upper 1.0 m of the soil profile.

The pH_F results at TGT_L2 (Figure 13 and Appendix D) all recorded > 4.0, with readings from 5.05 to 5.22. The pH_{FOX} results were significantly lower across most of the sample set (a strong indication of PASS). The lowest pH_{F0X} reading of 1.42 was taken at 0.78 m.

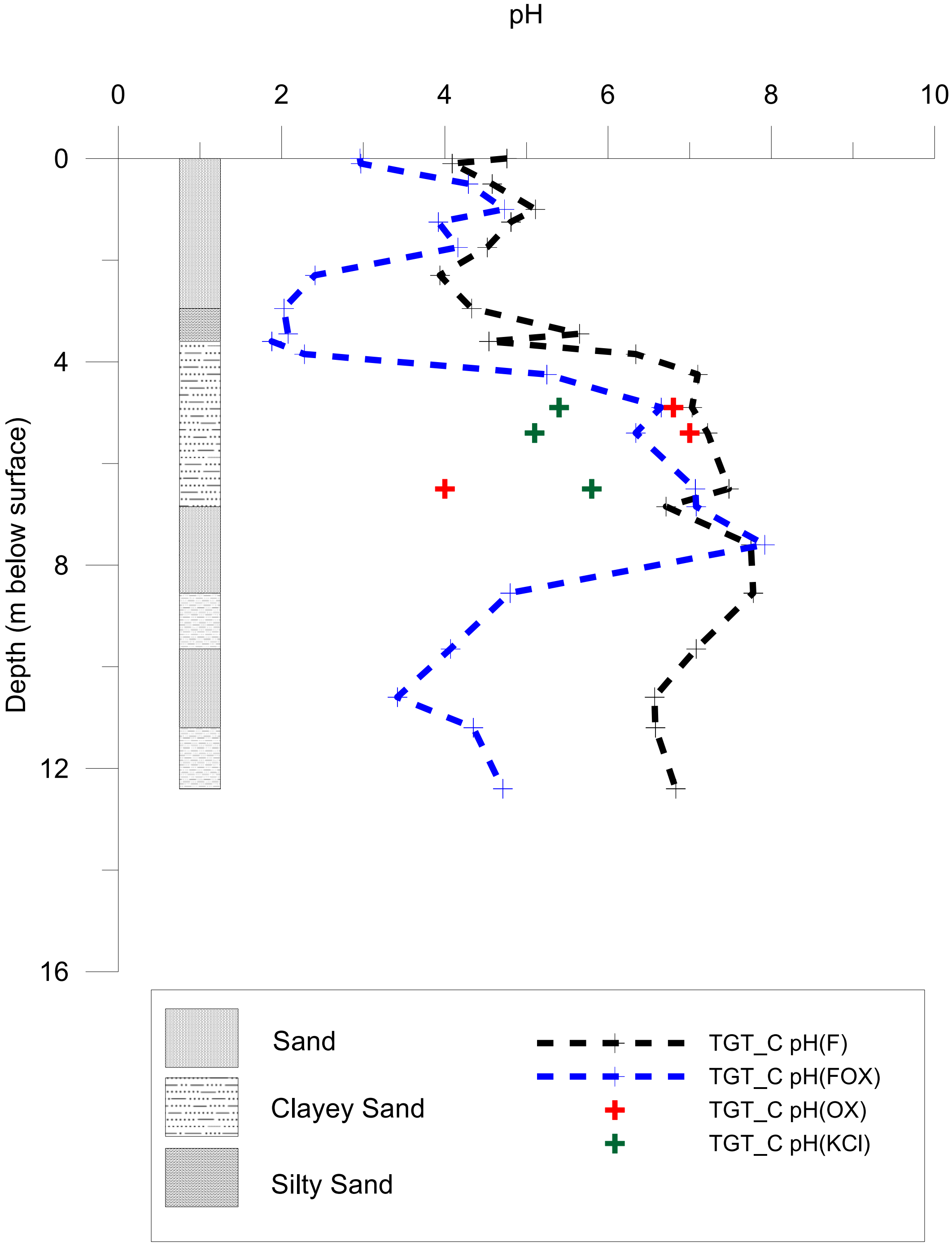


Figure 11 Field and laboratory results of natural and oxidised pH correlated with lithological units for TGT_C

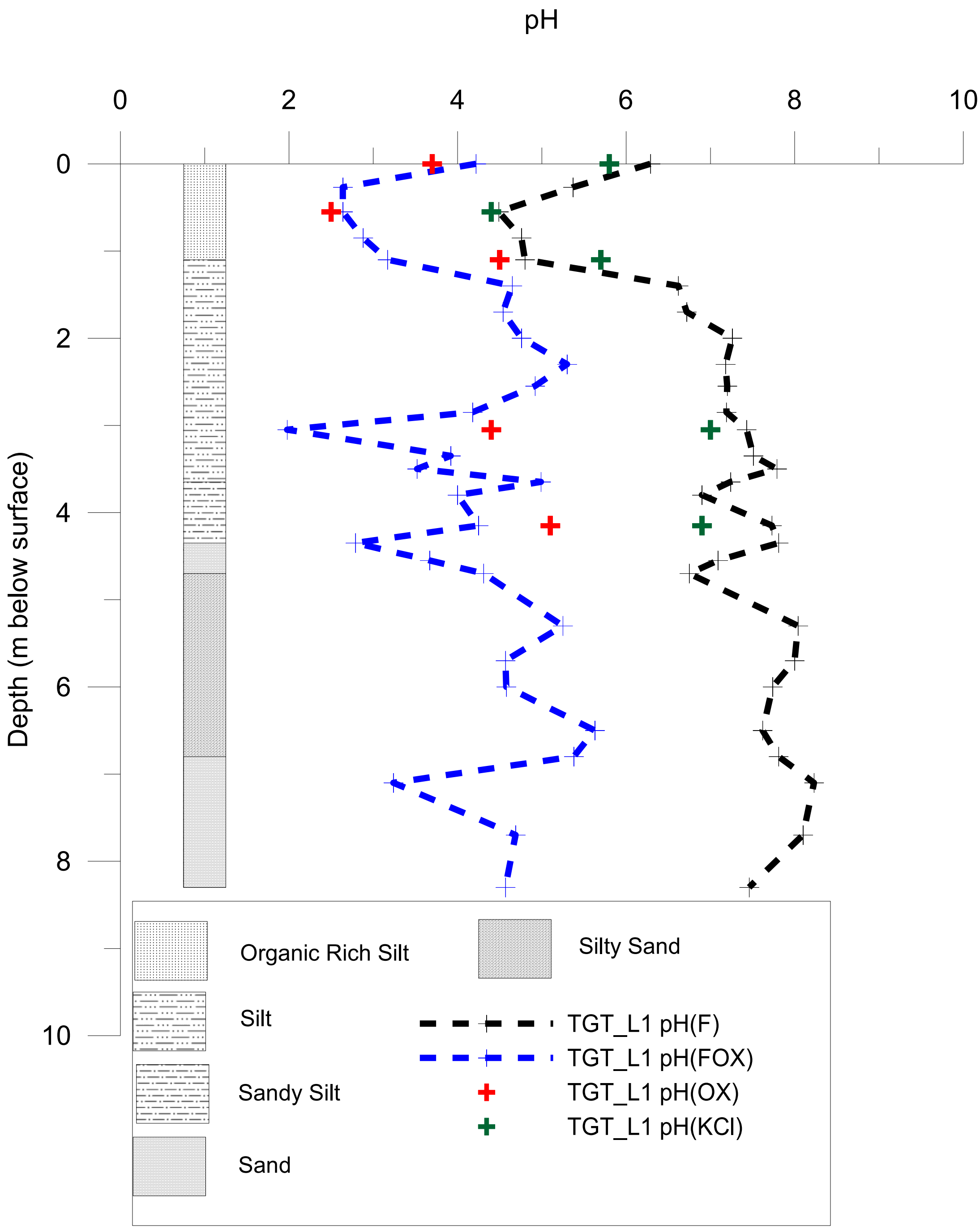


Figure 12 Field and laboratory results of natural and oxidised pH correlated with lithological units for TGT_L1

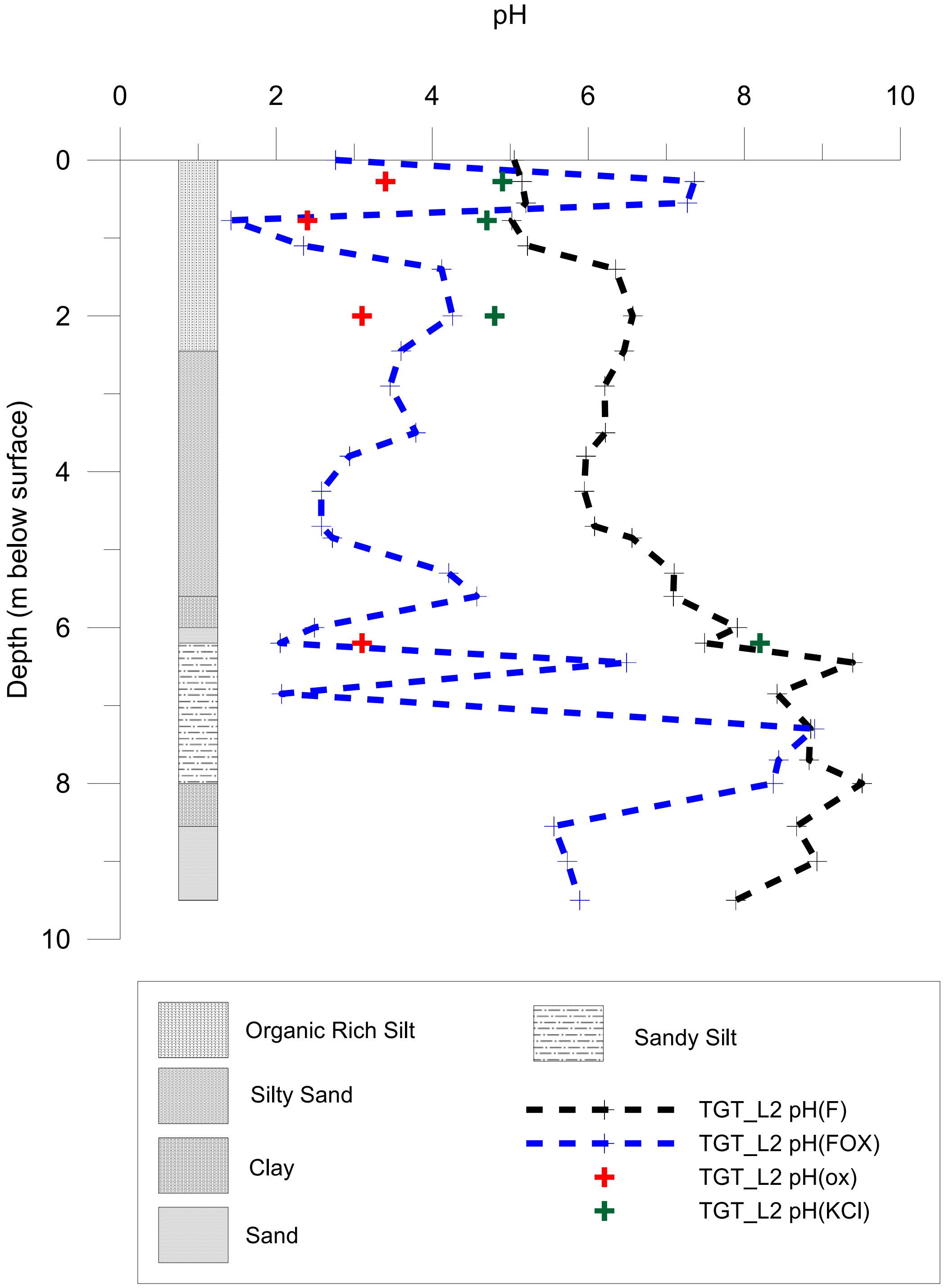


Figure 13 Field and laboratory results of natural and oxidised pH correlated with lithological units for TGT_L2

Laboratory analyses assess the net acidity of the sediments by measuring the effect of acid generating components of the sediments against neutralising (or basic) components. This is commonly known as acid base accounting. The overall equation for ABA is:

$$\textbf{Net acidity = potential sulfidic acidity + actual acidity + retained acidity - }\frac{\textbf{measured ANC}}{\textbf{fineness factor}}$$

Ahern et al. (2004) described the terms used in the net acidity equation:

- *Actual acidity* (TAA) is the soluble and exchangeable acidity already present in the soil
- *Potential sulfidic acidity* is latent acidity that will be released if the sulfide minerals in acid sulfate soil are fully oxidised
- *Retained acidity* is the 'less available' fraction of the existing acidity which may be released slowly into the environment
- *Acid neutralising capacity* (ANC) is a measure of the soil's ability to buffer acidity and resist the lowering of soil pH
- *Fineness factor* is a factor applied to the acid neutralising capacity to allow for the poor reactivity of coarser carbonate or other acid neutralising material.

Chromium ABA and SPOCAS ABA suites were used to determine the components of total net acidity. Net acidity is a measure of the presence of acid sulfate soil. It does not indicate AASS or PASS.

Sediments with a net acidity of 18.7 molH$^+$/t (0.03% sulfur) or greater for both ABA methods are considered an acidification risk (by the presence of ASS) and require careful management to prevent oxidation and/or to ameliorate any current acidity (DoE 2006).

The chromium ABA suite reported net acidities (Table 6) at TGT_C below the action criteria of 18 molH$^+$/t (DEC 2009), whereas TGT_L1 and TGT_L2 samples all exceeded the action criteria with the exception of two samples collected at depths of 4.15 m and 6.2 m respectively. Similar results were recorded from all sites using the SPOCAS ABA suite with the exception of the sample recovered from TGT_L2 at 6.2 m. Where a discrepancy exists between the two suites, Ahern et al. (2004) suggests that the chromium ABA results take precedence over the SPOCAS ABA results as the chromium ABA suite is not subject to any interference from sulfur in organic matter or other sulfate minerals present. Net acidities above the action criteria from TGT_L1 and TGT_L2 indicate the presence of acid sulfate soil. Hence Tangletoe Swamp is at high risk of acidification, particularly within the upper 4.0 m of the soil profile.

The dominance of actual acidity over potential acidity coupled with the lack of acid neutralising capacity indicates that oxidation of swamp sediments and underlying superficial sediments has already taken place. The combination of stored acidity and shallow hydraulic variation (in the future) has the potential to cause further acidification. This is largely confirmed by chemical analysis of groundwater sampled from the TGT bore series (as discussed in Section 6).

In order to assess possible sulfide oxidation within the swamp sediments, $Cl^-:SO_4^{2-}$ ratios[2] in SGS groundwater (surface water chemistry was unavailable due to the swamp's dry conditions) have been plotted (Figure 14). These have been compared with the average $Cl^-:SO_4^{2-}$ ratio of seawater, which is 7.2 (Ahern et. al. 2004). A Cl^- $:SO_4^{2-}$ ratio of less than four, is an indication of an extra source of sulfate from previous sulfide oxidation (Ahern et. al. 1998).

The $Cl^-:SO_4^{2-}$ ratios in bores TGT_B, TGT_C and TGT_D varied significantly, but the perched groundwater in TGT_D was the only sample to exhibit $Cl^-:SO_4^{-2}$ ratios consistently below the seawater ratio of 7.2 (Figure 14). The shallow bore TGT_C also showed ratios lower than those for seawater from June 2008 to January 2009, possibly reflecting recharge of the shallow Superficial aquifer by the acidic perched groundwater over winter. It seems likely that sulfide oxidation is taking place within the upper 4.0 m at the Tangletoe Swamp site, probably within swamp sediments close to the surface. This is discussed in more detail in Section 6.

Samples were also analysed for metals, metalloids and selenium concentrations. Samples analysed for metals were compared to ecological investigation levels (EILs) (DEC 2010) to determine whether their concentration levels pose a risk to the groundwater and environment at the Tangletoe Swamp site.

Samples collected from the upper 1.0 m at TGT_L1 and from 5.4 m at TGT_C recorded high concentrations for most metals (Table 7). However, with the exception of chromium none exceeded EILs. Chromium concentrations were also close to the EILs from samples collected at TGT_L2. Iron concentrations ranged from 2100 to 56 700 mg/kg, and aluminium concentrations ranged from 2020 to 26 500 mg/kg.

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[2] $Cl^-:SO_4^{-2}$ ratio in surface water or groundwater compared to that of seawater as recommended in guidelines by Ahern et.al (2004).

Table 6 Summarised ABA for SPOCAS and chromium reducible sulfur suite of analyses at Tangletoe Swamp

Site ID	**Depth m**	**pH_{KCl}**	**pH_{OX}**	**Acid neutralising capacity %$CaCO_3$**		**Potential acidity %S***		**Total Actual acidity $molH^+/t$**		**Net acidity $molH^+/t$**	
				S_{POS}	**S_{Cr}**	**S_{POS}**	**S_{Cr}**	**SPOCAS**	**S_{Cr}**	**SPOCAS**	**S_{Cr}**
TGT_C	4.900	5.4	6.8	<0.05	na	<0.01	<0.01	8	8	8	8
TGT_C	5.400	5.1	7.0	<0.05	na	<0.01	<0.01	5	5	5	5
TGT_C	6.500	5.8	4.0	na	na	0.02	<0.01	1	1	13	1
TGTL_1	0.000	5.8	3.7	na	na	0.37	0.03	10	10	241	29
TGTL_1	0.550	4.4	2.5	na	na	1.40	0.05	66	66	1009	167
TGTL_1	1.100	5.7	4.5	na	na	0.17	0.04	6	6	112	31
TGTL_1	3.050	7.0	4.4	na	na	0.07	0.06	<1	<1	25	37
TGTL_1	4.150	6.9	5.1	na	na	0.01	0.02	<1	<1	2	12
TGTL_2	0.270	4.9	3.4	na	na	0.70	0.03	28	28	465	47
TGTL_2	0.770	4.7	2.4	na	na	1.60	0.19	71	71	1069	190
TGTL_2	2.000	4.8	3.1	na	na	<0.01	0.06	46	46	46	83
TGTL_2	6.200	8.2	3.1	na	0.90	0.29	0.07	<1	<1	134	−76
TGTL_2 (D)	6.200	8.3	2.9	na	0.91	0.39	0.06	<1	<1	168	−84

na: Not analysed[3]

** Laboratory results for potential acidity was reported in %S only not $molH^+/t$*

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[3] According to laboratory methods guidelines (Ahern et al. 2004), when pH_{KCl} is higher than 6.5, acid neutralising capacity measurements will be required (i.e. there is ANC present), whereas when pH_{KCl} is less than 6.5, ANC measurement will not be required and ANC is effectively zero.

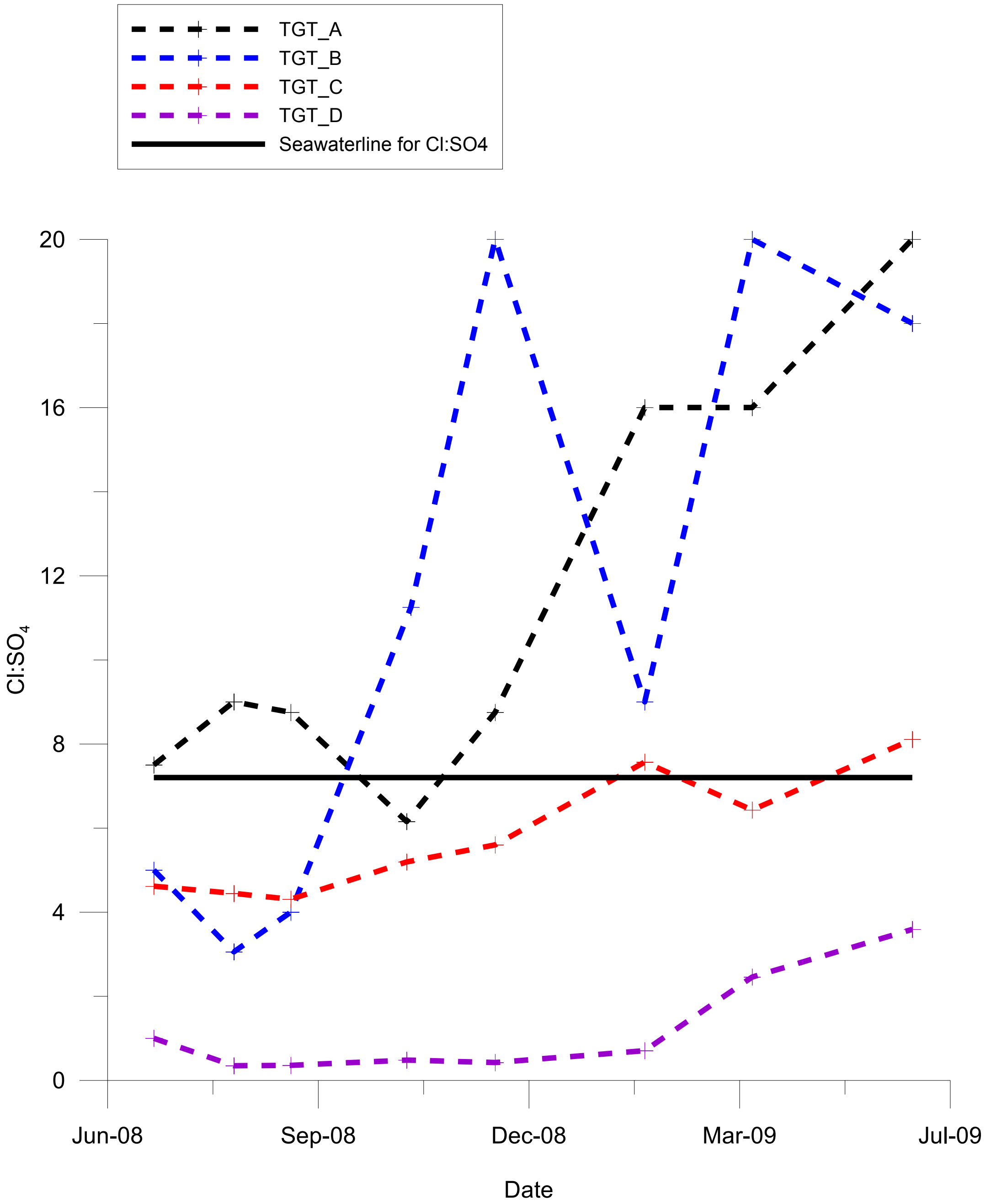

Figure 14 $Cl^-:SO_4^{2-}$ ratio plot for the SGS bores at Tangletoe Swamp

Table 7 Metals and metalloids in sediments at Tangletoe Swamp

Site reference number	**Sample depth m**	**Al mg/kg**	**As mg/kg**	**Cd mg/kg**	**Cr mg/kg**	**Fe mg/kg**	**Mn mg/kg**	**Ni mg/kg**	**Se mg/kg**	**Zn mg/kg**	**Total solids %**
TGT_C	4.900	7 790	<0.5	<0.5	25	5 600	5.3	5.3	<0.50	4.0	na
TGT_C	5.400	19 200	2.4	<0.5	69	56 700	8.2	18.0	0.87	3.2	na
TGT_C	6.500	2 020	<0.5	<0.5	22	2 100	6.1	1.5	<0.50	1.3	na
TGTL_1	0.000	25 300	4.8	<0.5	58	15 500	93.0	21.0	9.10	21.0	47.8
TGTL_1	0.550	23 200	4.4	<0.5	60	11 800	19.0	20.0	6.90	7.8	34.6
TGTL_1	1.100	26 500	8.0	<0.5	53	7 640	20.0	16.0	7.70	13.0	53.5
TGTL_1	3.050	21 900	3.4	<0.5	46	3 790	2.5	11.0	0.57	<0.5	81.4
TGTL_1	4.150	13 400	<0.5	<0.5	17	2 270	2.0	6.2	<0.50	<0.5	88.9
TGTL_2	0.270	18 800	3.9	<0.5	45	13 400	33.0	17.0	7.10	11.0	44.1
TGTL_2	0.770	18 400	7.6	<0.5	49	14 000	46.0	22.0	6.80	13.0	30.0
TGTL_2	2.000	9 110	2.5	<0.5	20	3 040	8.60	6.7	1.00	1.3	66.9
TGTL_2	6.200	16 700	0.7	<0.5	48	14 800	15.0	15.0	0.84	2.2	73.4
Ecological investigation level		na	20	3	50	na	500	60	na	200	na

na: Not analysed

Concentration of sulfur (S_{cr} and S_{POS}) was plotted against concentrations of the seven metals analysed from all samples collected (Figure 15 and Figure 16). High concentrations of sulfur (S_{cr} and S_{POS}) showed no correlation with high concentrations of aluminium, iron or any other metal analysed, probably as a result of the presence of clayey sediments (in the swamp and Guildford Clays) and oxidised

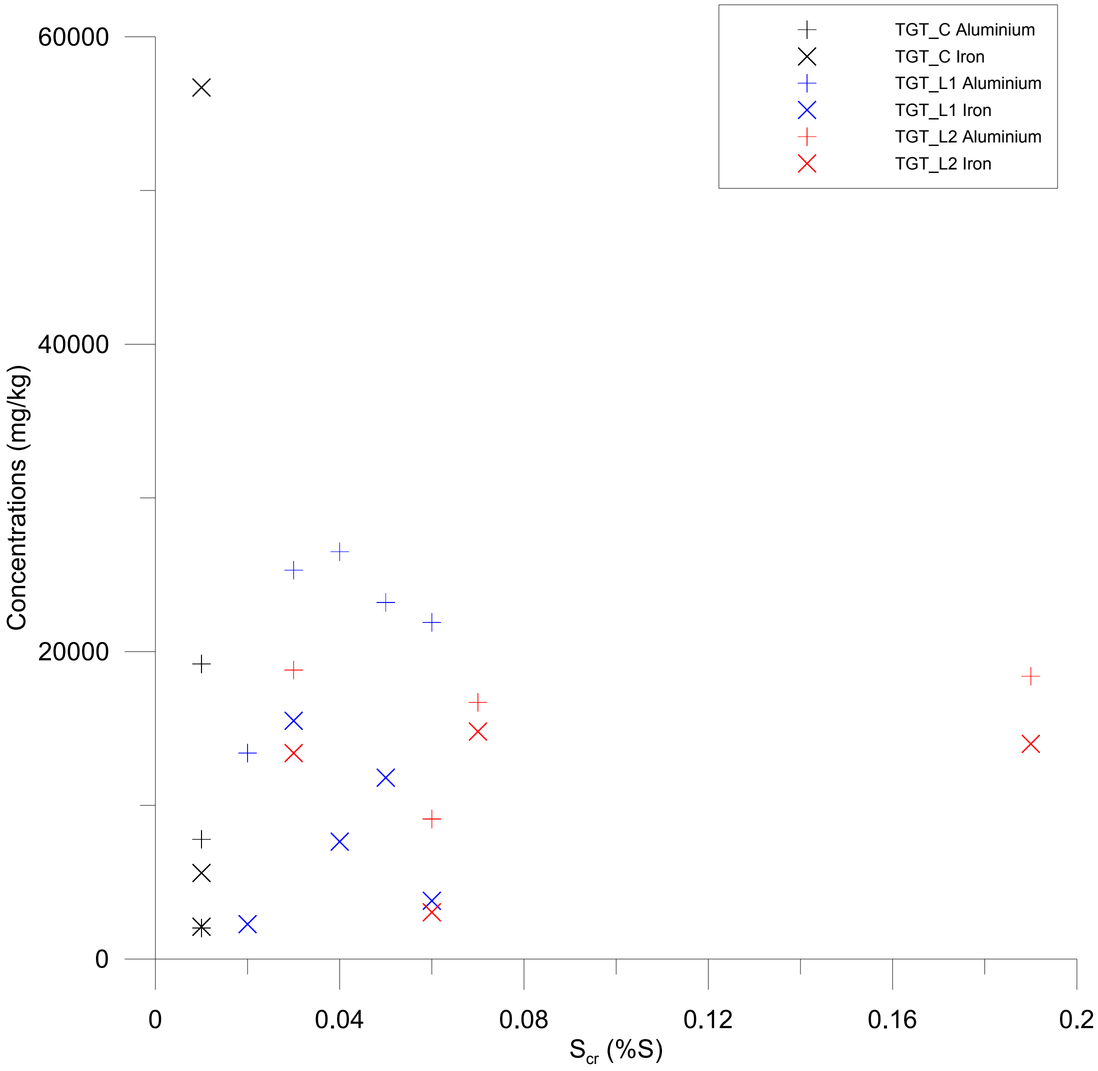

Figure 15 Relationship between aluminium and sulfur, and iron and sulfur in sediments at Tangletoe Swamp

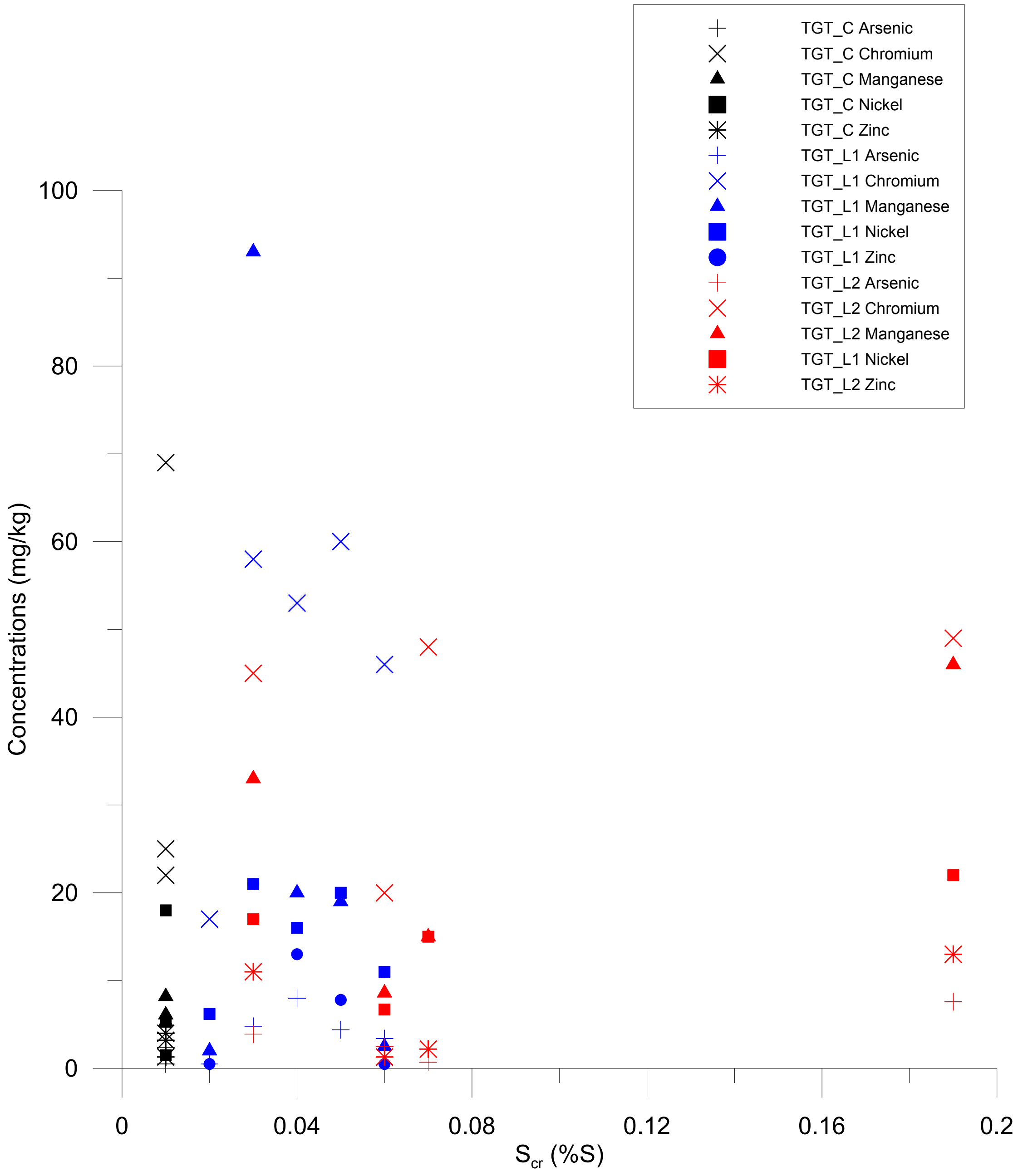

Figure 16 Relationship between various metals and sulfur in sediments at Tangletoe Swamp

5 Hydrogeology

5.1 Water levels

The network of bores established by the Department of Water in 2008 for this investigation and some non-SGS bores which provide 33 years of monthly data, were used in the analysis of groundwater levels to provide important information regarding the hydrogeology around Tangletoe Swamp (see Section 3.1 for bore details).

The bores (TGT_A, TGT_B, TGT_C and TGT_D) display seasonal fluctuations over the SGS study period (February 2008 to June 2009 in Figure 17). The level of groundwater in bore TGT_D is approximately 4.0 m higher than the shallow, intermediate and deep bores, indicating that this shallow bore is screened within a perched aquifer above the Guildford Clay.

The lateral extent of the perched watertable is unknown because of the limited data from the SGS study and lack of lithological logs from non-SGS bores. However, groundwater in the perched aquifer is approximately 3.0 m below ground level (~44 m AHD)) at the location of the TGT_D bore, and saturated depth is approximately 2.0 m assuming the sandy clay layer is at a depth from 5.0 to 7.0 m, as in the logs for bores TGT_A and TGT_C.

The intermediate and shallow bores show similar water levels across the observation period, whereas the deep bore is slightly lower (by ~0.11 m) than the intermediate and shallow bores. All of the time-series profiles are similar (Figure 17). This indicates that levels in both the perched and Superficial aquifers are caused by the same factors but with slightly different responses. The response to rainfall at TGT_D is immediate (vertical ascent of the profile from June 2008) indicating recharge via direct percolation. The profiles for the other SGS bores exhibit a more gradual response to rainfall as the aquifers are recharged slowly via regional recharge and leakage through the deposits of the Superficial aquifer.

In addition to the observations made during the SGS study period, an estimation of the groundwater levels has been back-extrapolated (Figure 18) for the SGS bores by following the same spatial trend observed at non-SGS bore YY9(I) (refer to Figure 21 hydrograph transect 2). This provides indicative information as to the long-term trends in groundwater levels for both the perched and Superficial aquifers.

Due to the limited time frame of the SGS period it is not clear whether groundwater levels in the perched system have decreased over time. However, it is clear that levels in the regional system have fallen due to a decrease in recharge from rainfall. This would suggest that perched groundwater levels have also decreased to some extent since 1987, in line with trends in the regional system. In addition, the back extrapolation for TGT_C indicates that the regional groundwater is unlikely to have supported the swamp in the past (regional groundwater level does not intersect with elevation of Tangletoe Swamp at approx. 44.5 m AHD).

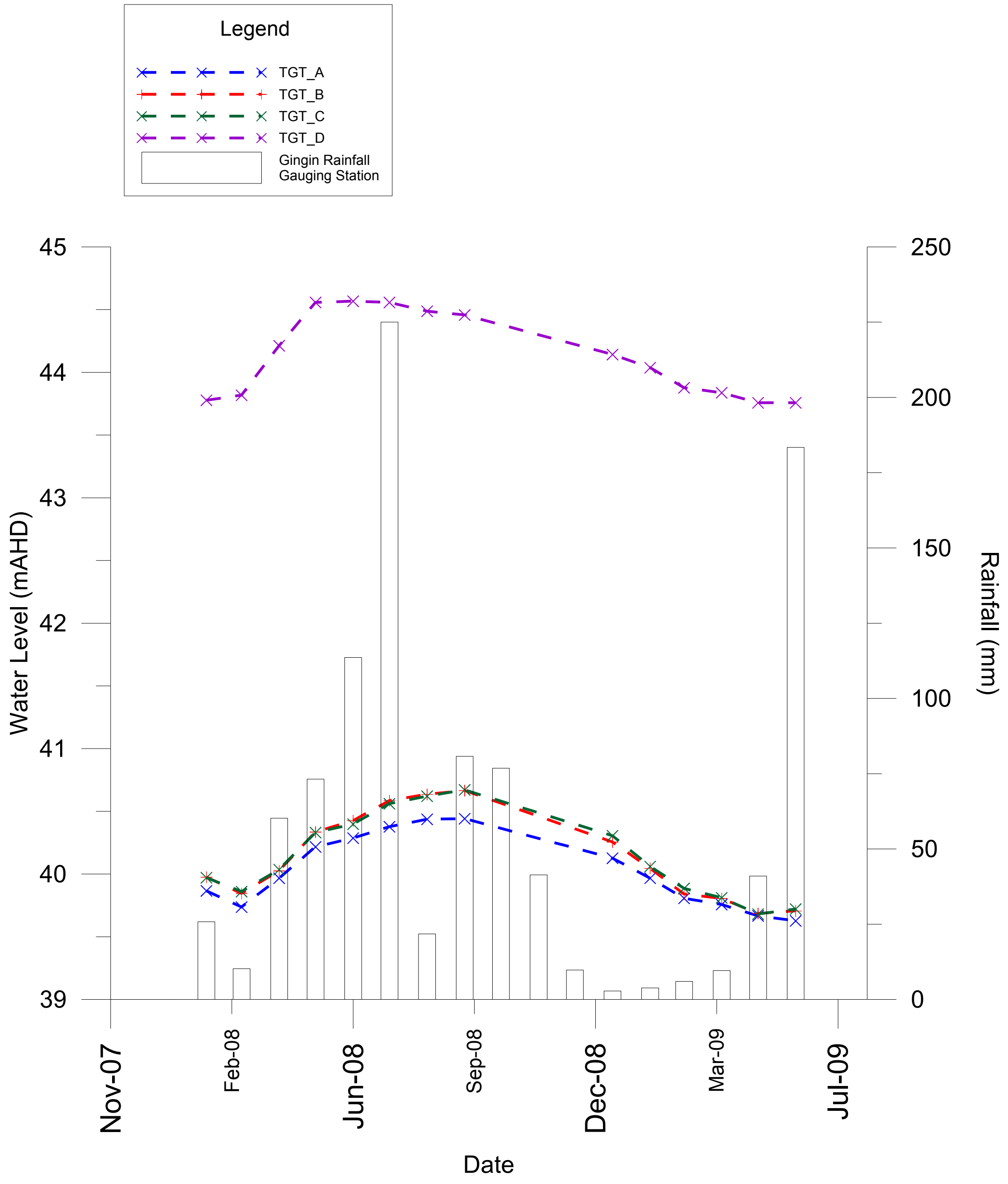

Figure 17 Hydrographs of TGT bores

The relationship between monthly water levels is spatially consistent for all other non-SGS bores (Transects 1 to 3, Figure 19). Transect 1 (GB8, GB13, GB12 and GB7) is located 1 km north of Tangletoe Swamp) (Figure 20), with GB8 on the up-gradient (eastern side) of the Tangletoe Swamp and GB12 and GB7 down-gradient of the swamp. Transects 2 and 3 are located to the south of Tangletoe Swamp.

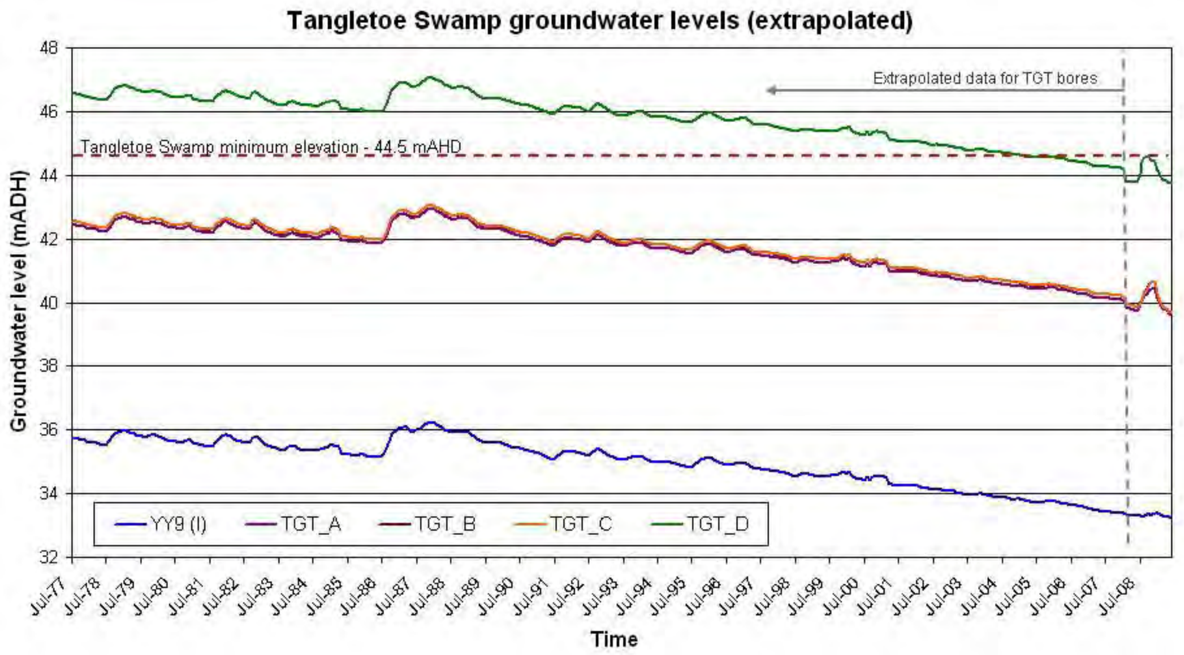

Figure 18 Estimated changes in groundwater levels at Tangletoe Swamp (data for TGT bores prior to 2008 has been extrapolated)

The non-SGS bores show varying seasonal trends in monthly groundwater levels from 1977 to 2009. The overall trend in groundwater levels ~1 km north of Tangletoe Swamp (east–west transect 1) showed a subdued increase over time to 1987 then a steady decline followed by some stabilisation in 2005. The regional groundwater levels generally have dropped by 2.0 m since 1987 (Figure 20).

Transect 2, located approximately 2 km south of Tangletoe Swamp (bores GG8(1), GB15 and YY9(1)) shows a similar pattern to transect 1 (Figure 21). Bores GB15 and YY9(1) are more variable and show a slight decrease in groundwater levels from 1973 to 1986, an increase from 1986 to 1987, then a continued decrease (~2 to 3 m) since 1987.

Transect 3, located approximately 4 km south of Tangletoe Swamp (bores GB20, GA23 and GA22) follows a similar pattern to Transects 1 and 2. The bores indicate long-term decline in groundwater levels with little seasonal variation[4]. In addition these bores have approximately 13 m to 15 m of screens, therefore the overall groundwater level response will be muted (Figure 22). Bore GA22 showed a decreasing trend in groundwater levels between 1985 and present day, from just below 35 m AHD to just over 32 m AHD, a decrease of ~ 3 m. Similarly, GB20 and GA22 also displayed about 3 m decrease in water level since 1987.

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[4] although this may not be a real effect but may be due to limited yearly water level records since 1999

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Figure 19 Location of the hydrograph transects in the Tangletoe Swamp area

The long-term declines in groundwater level since 1985–87 reflect the overall decline in the magnitude of rainfall across the observation period, given the low level of development within the area up-gradient of Tangletoe Swamp (Yesertener 2008).

There is no data available to determine whether there has been a decrease in the shallow watertable over time. Regional groundwater levels in the Bassendean Sands are likely to have remained well below those of the perched aquifer at Tangletoe Swamp at least since 1987. Perched groundwater levels were ~44 m AHD in 2008–09, whilst the TGT bores in Figure 18 showed regional groundwater levels at ~40 m AHD, somewhat higher than the groundwater water level in the nearest non-SGS bore GB13 of 38 m AHD in 2009 (Figure 20). It is likely that perched groundwater levels would have also decreased since 1987, as rainfall decreased. However, due to the short observation period there is only a limited indication of an overall decreasing trend in Figure 18.

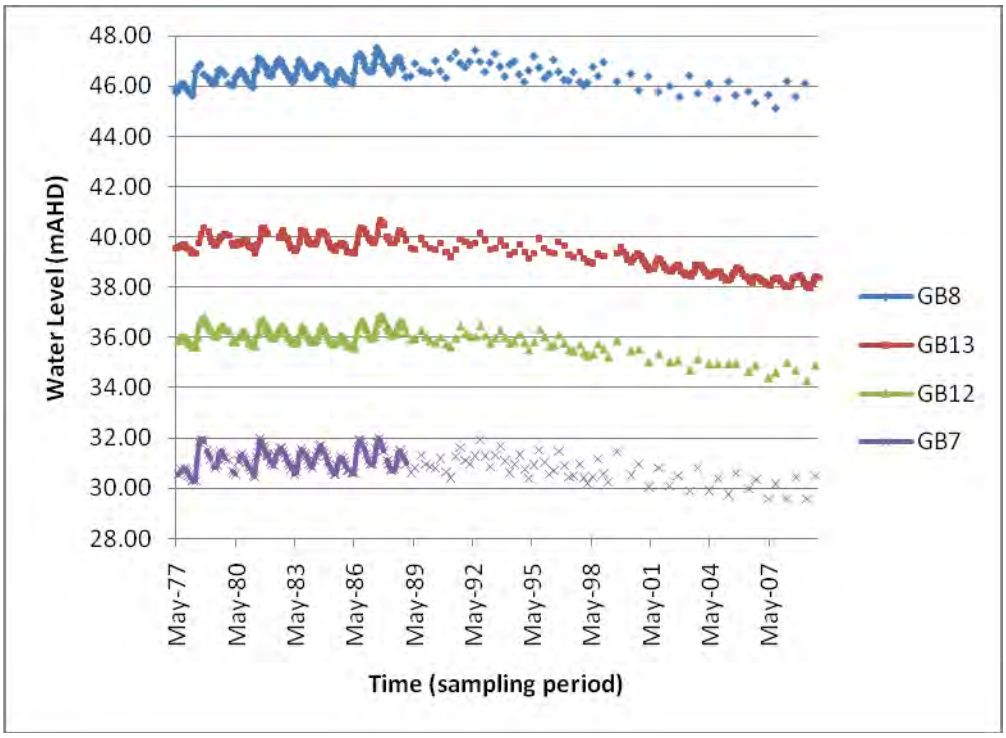


Figure 20 Hydrograph for non-SGS bores (transect 1) approximately 1 km north of Tangletoe Swamp

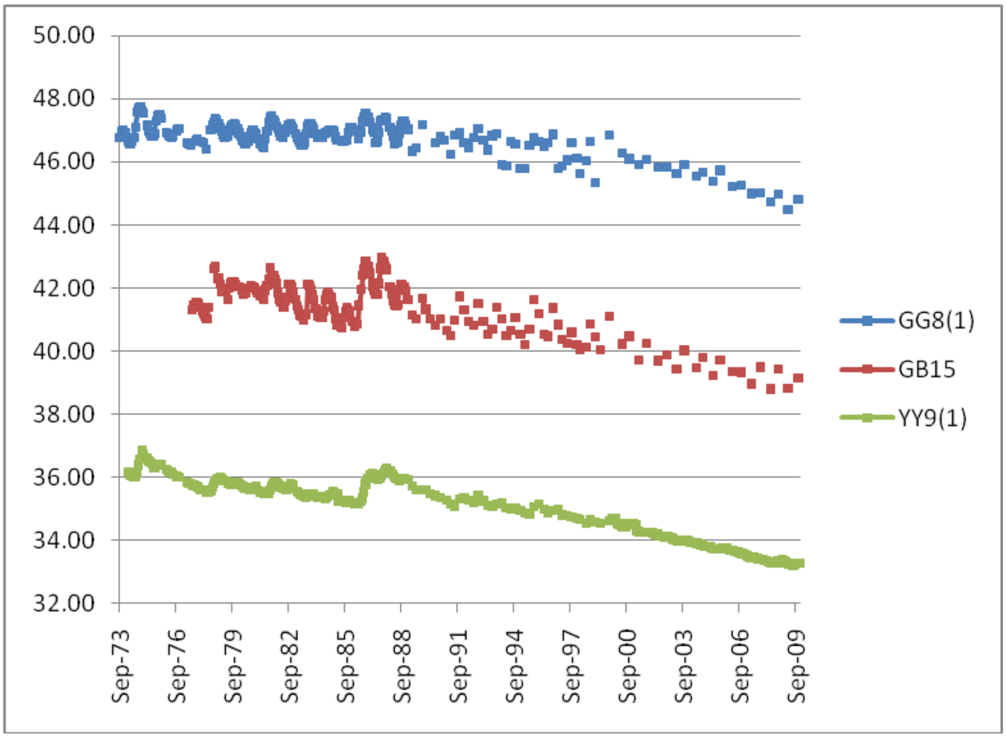


Figure 21 Hydrograph for non-SGS bores (transect 2) approximately 2 km south of Tangletoe Swamp

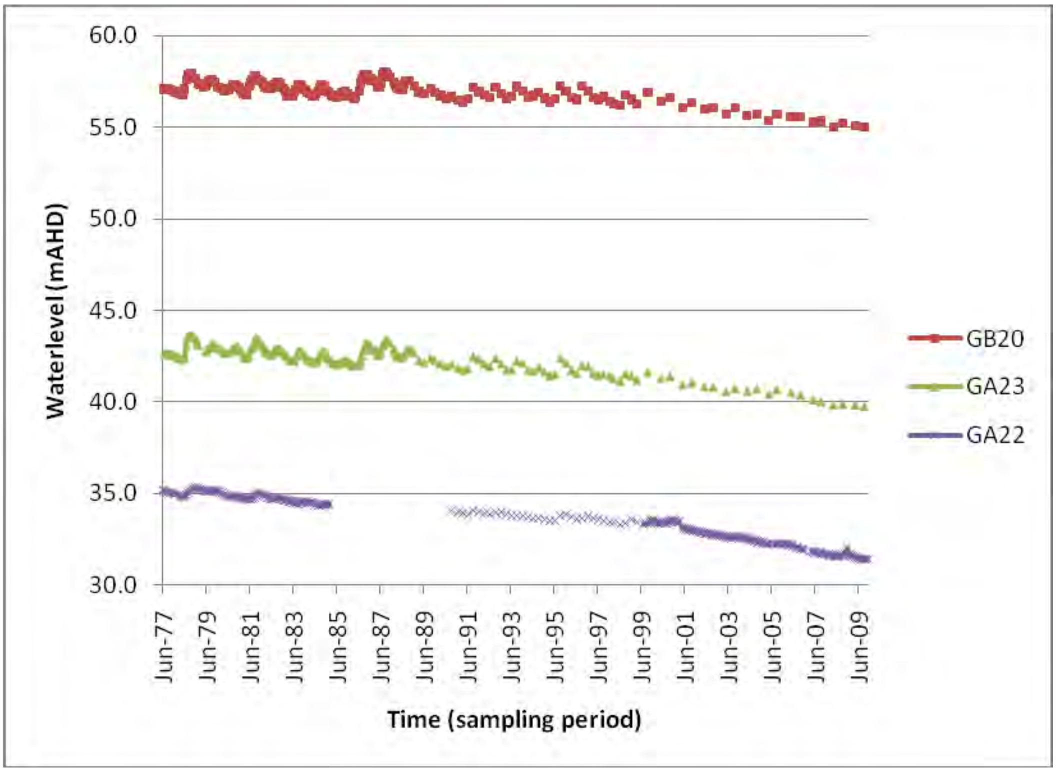


Figure 22 Hydrograph for non-SGS bores (transect 3) approximately 4 km south of Tangletoe Swamp

5.2 Groundwater flow

The overall thickness of the Superficial deposits is about 58 m with a saturation thickness of about 10–20 m in the region (transect 1 ~1 km north) of Tangletoe Swamp. The groundwater hydraulic heads follow the topography (Figure 5 in Section 2.3), exhibiting the highest values in the east (elevation of the Gingin Scarp) and lowest west of the swamp. As a result, groundwater flow is predominantly east to west.

The groundwater contours derived from the SGS monitoring program and nearby monitoring bores show regional groundwater flowing from the east to west. The groundwater gradient is relatively gentle on either side of the swamp and very flat near the ocean (Figure 23 and Figure 24).

The groundwater level in the perched bore is higher than the shallow, intermediate and deep bores, while the levels in the shallow and intermediate bores are somewhat higher than the deep bore (Table 8 and Figure 18). While the differences in water level between shallow, intermediate and deep bores over time are small, they suggest a subdued downward gradient from the shallow bore to the deep bore as a consequence of groundwater discharge from the lower part of the Superficial aquifer to the underlying Leederville Formation.

Table 8 SGS bore water level measurements (Feb 2008 to June 2009)

Sampling date	**TGT_A m AHD**	**TGT_B m AHD**	**TGT_C m AHD**	**TGT_D m AHD**
Feb-08	39.87	39.98	39.97	43.78
Jun-08	39.74	39.85	39.86	43.82
Jul-08	39.97	40.03	40.04	44.21
Aug-08	40.22	40.34	40.33	44.56
Sep-08	40.29	40.43	40.40	44.57
Oct-08	40.38	40.59	40.56	44.56
Nov-08	40.44	40.64	40.62	44.49
Dec-08	40.44	40.67	40.67	44.46
Jan-09	40.13	40.26	40.31	44.14
Feb-09	39.97	40.05	40.06	44.04
Mar-09	39.81	39.84	39.89	43.88
Apr-09	39.76	39.81	39.81	43.84
May-09	39.67	39.69	39.68	43.76
Jun-09	39.63	39.71	39.72	43.76

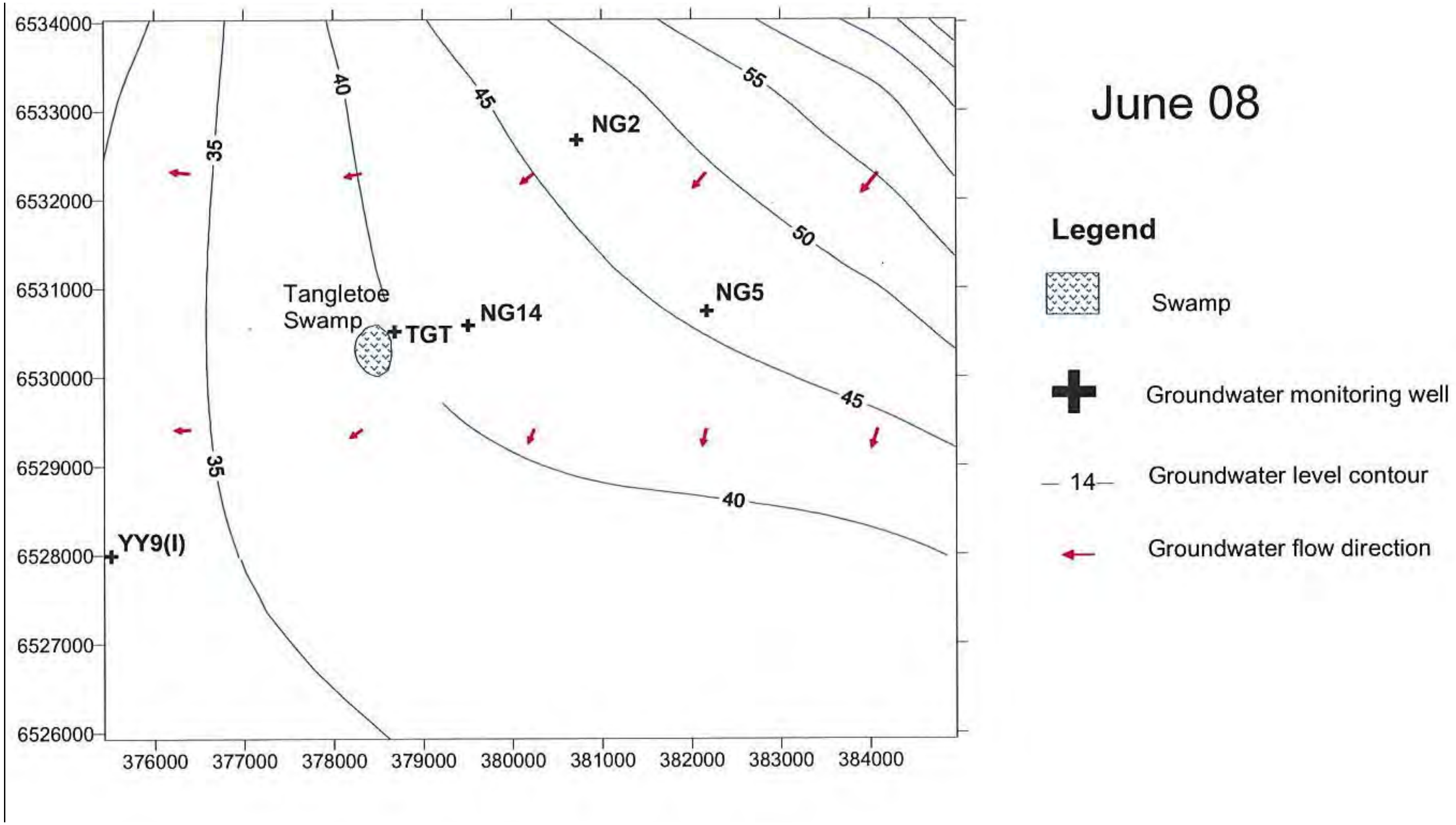


Figure 23 Superficial aquifer groundwater contours for June 2008 for Tangletoe Swamp

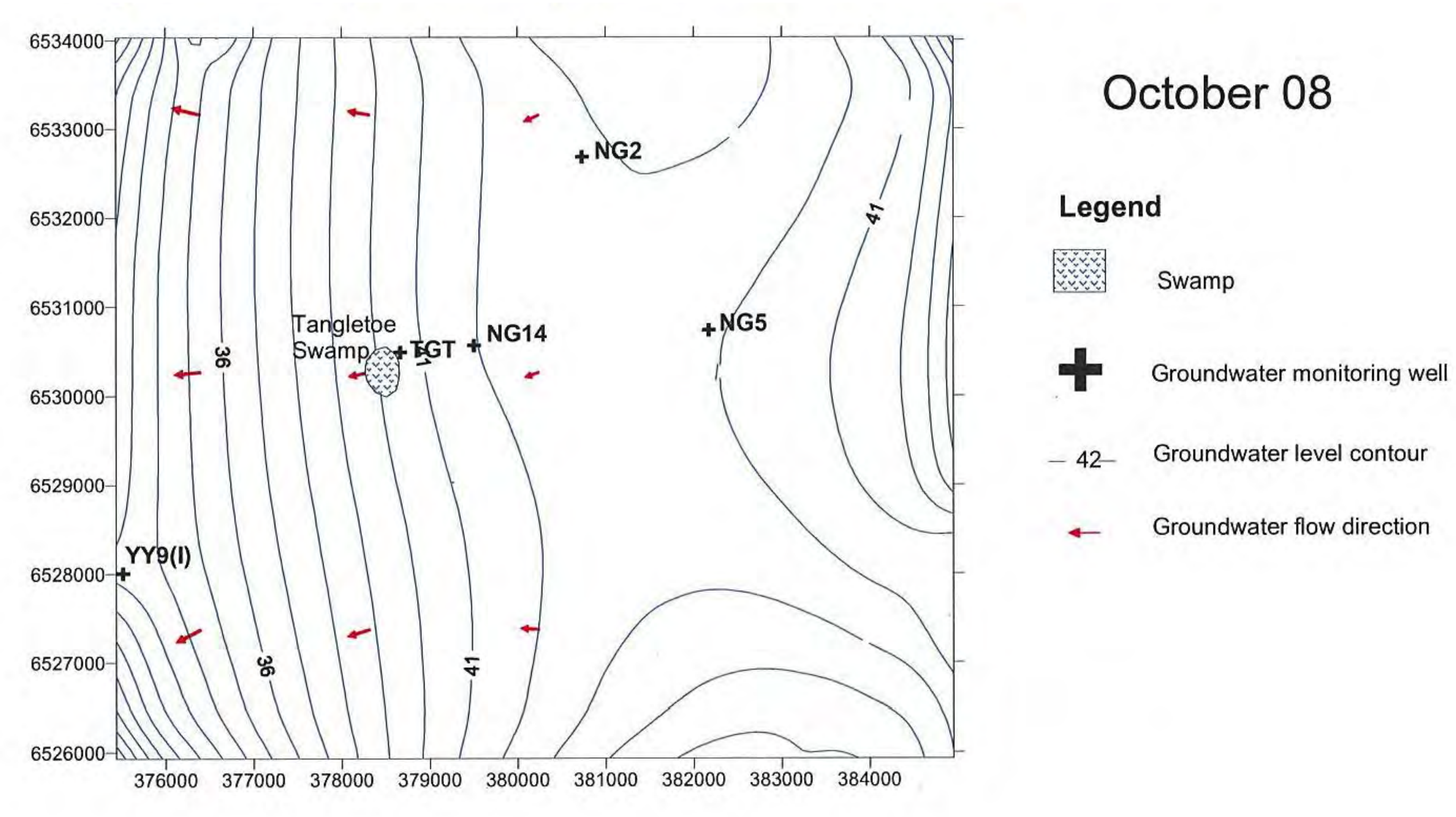


Figure 24 Superficial aquifer groundwater contours for October 2008 for Tangletoe Swamp

6 Hydrogeochemistry

6.1 Physical and chemical characteristics

The following section assesses the groundwater systems hydrochemical behaviour during the SGS investigation period. Eight sampling events were undertaken during the investigation. Representative groundwater samples were obtained from the SGS monitoring bores and were analysed for number of physical and chemical parameters.

6.1.1 Major cations and anions

The major ion data has been analysed using ternary (Piper) plots, Stiff diagrams and time-series plots. These plots have been used to identify the hydrochemistry of groundwater in the Tangletoe Swamp area and to identify possible flow relationships between groundwater, the swamp and perched groundwater.

A Piper diagram for major ions in groundwaters from bores TGT_A, TGT_B, TGT_C and TGT_D are shown in Figure 25.

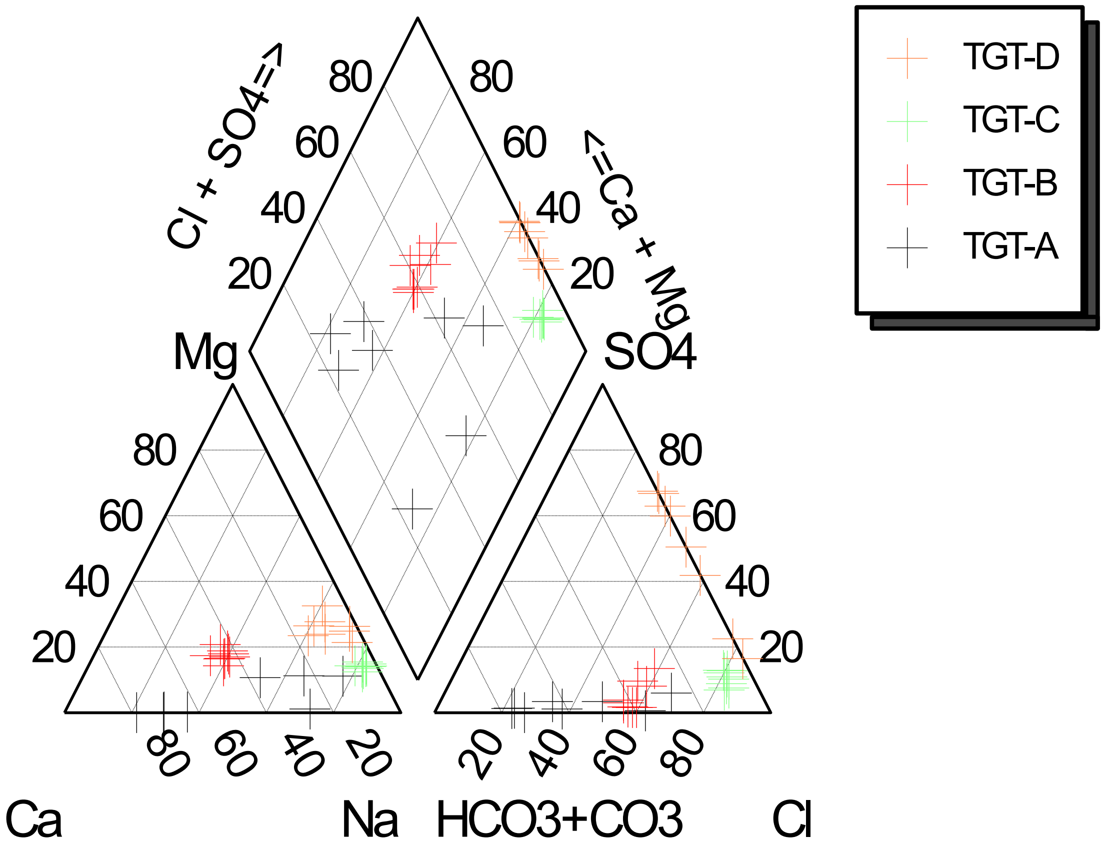


Figure 25 Ternary (Piper) plot of major cations and anions in Superficial aquifer and perched groundwater in Tangletoe Swamp

Major ions in Superficial groundwater at intermediate depths within Gnangara Sands are relatively enriched in calcium and bicarbonate compared with groundwater at shallow depths (TGT_C) and perched groundwater (Figure 25). There is no obvious reason for the enrichment in calcium and bicarbonate in the intermediate bore, unless the Gnangara Sands contain calcite or other carbonates. Davidson (1995) describes the lithology of the Gnangara Sands as quartz sands of fluvial or estuarine origin, with no indication of the presence of carbonate minerals. It is possible that the calcium and bicarbonate content is an artefact from contamination of groundwater by cement grout used during bore construction. The higher than expected pH of groundwater in the intermediate level bore would support this supposition.

The perched groundwater shows major differences in anionic composition compared with Superficial groundwater. Concentrations of bicarbonate are negligible and as such the perched system has limited buffering capacity and low pH readings (Table 9). Figure 25 also indicates the progressive and significant enrichment of sulfate as the samples are spread across the sulfate axis. It is assumed that the low pH and elevated sulfate are indicative of oxidation of sulfide minerals by atmospheric oxygen as perched groundwater levels decreased.

Stiff diagrams have been generated to compare Superficial groundwater at intermediate (TGT_B) and shallow level (TGT_C) with perched groundwater (bore TGT_D) associated with Tangletoe Swamp (Figure 26).

The relationships shown in the Stiff diagrams (Figure 26) for major ions confirm those shown in the Ternary plot, namely:

- relative enrichment in calcium and bicarbonate in intermediate level Superficial groundwater (although this may be an artefact of bore construction)
- sodium–chloride dominated shallow (regional) groundwater and much higher concentrations when compared to intermediate levels
- calcium–bicarbonate depletion in perched groundwater and significant sulfate enrichment

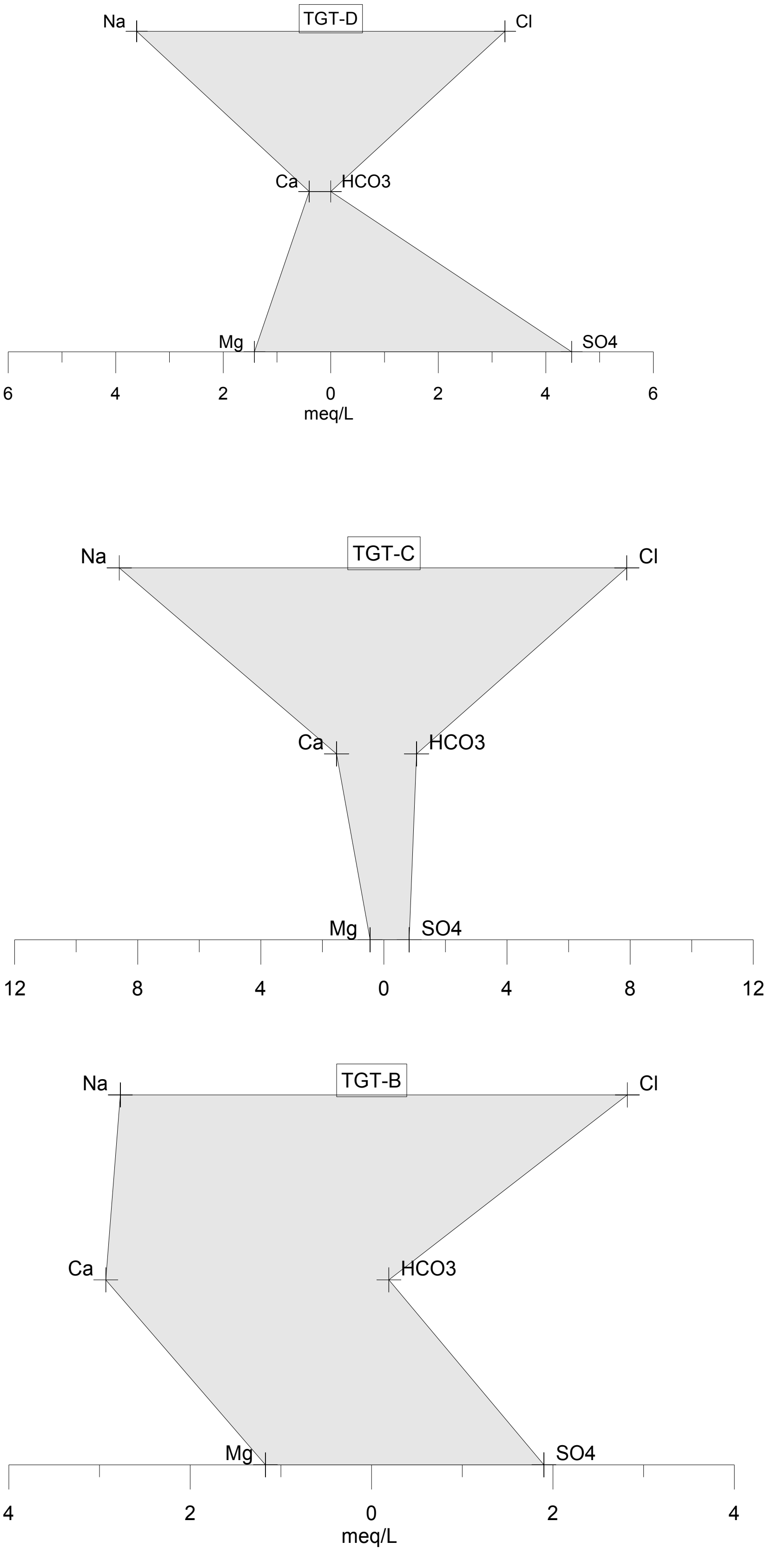


Figure 26 Representative Stiff diagram for mean cation and anion concentrations (meq/L) for groundwater in the vicinity of Tangletoe Swamp

6.1.2 On-site physical measurements (pH, dissolved oxygen and oxidation reducing potentials)

Summary statistics (minima, maxima and median values) for pH, dissolved oxygen and oxidation reducing potentials are shown in Table 9 for TGT_B and TGT_C and the perched watertable bore (TGT_D). Data from TGT_A and June 2008 data for bores TGT_B and TGT_C have been omitted as cement grout has affected the bore screen aquifer zone giving anomalously high pH, which may affect other parameters.

Table 9 Summary statistics for on-site pH, DO and ORP in SGS bores

	pH			DO mg/L			ORP mV		
	Min.	**Max.**	**Median**	**Min.**	**Max.**	**Median**	**Min.**	**Max.**	**Median**
TGT_B (intermediate depth)	6.62	7.16	6.82	0.15	1.85	0.36	−112	14	8
TGT_C (shallow depth)	5.8	6.44	6.2	0.11	5.28	0.41	−83	59	39
TGT_D (perched groundwater)	2.59	3.77	2.92	0.45	4.73	1.05	182	349	237

Groundwater at intermediate depths (where the bore is screened within Gnangara Sands) has pH somewhat higher than the range expected for Bassendean Sands (reported in Davidson 1995) while that at shallow depths (TGT_C screened within Bassendean Sands) is closer to that expected (Table 9). The higher pH in TGT_B may be due to cement grout used during bore construction, which has severely affected bore TGT_A.

The pH of perched groundwater is low, and well below the range expected for south-west Australia wetlands of 7.0 – 8.5 (ANZECC & ARMCANZ 2000). This data indicates considerable acidification of perched groundwater as indicated in Section 4.3. There is no historic data available for pH levels in Tangletoe Swamp.

The Superficial aquifer at intermediate and shallow depths appears to be anoxic, with median dissolved oxygen values of 0.36 and 0.41 mg/L, respectively. The perched groundwater is more oxygenated, with a median of 1.05 mg/L. Oxidation reduction potentials are typically much higher in the perched groundwater than in the Superficial aquifer. (Table 9).

As Tangletoe Swamp is rarely inundated, there is a lack of information relating to its water quality. Analysis of swamp sediments (Table 10) shows very low pH levels, suggesting that exposed sulfidic sediments have acidified. Upon refilling, these sediments will probably lead to the acidification of swamp waters, with subsequent effects on water chemistry of the swamp.

Table 10 pH of dry swamp sediments in Tangletoe Swamp

pH analysis method	Range	Mean
pH (H_2O_2)	2.4 – 5.1	3.58
pH (KCl)	4.4 – 8.2	5.82

6.1.3 Electrical conductivity and chloride

Variations over time in electrical conductivity (EC) and chloride in intermediate (TGT_B) and shallow level (TGT_C) groundwater of the Superficial aquifer and perched groundwater (TGT_D) are shown in Figure 27 and Figure 28.

EC in perched groundwater (Figure 27) shows a seasonal trend, with highest EC in winter (July to December 2008). EC in Superficial groundwater remains reasonably constant throughout the SGS monitoring with conductivity at shallow depths being much higher than at intermediate depths.

In contrast, Superficial groundwater at shallow depths shows higher concentrations of chloride than those of intermediate levels or perched groundwater (Figure 28). There is no obvious seasonal trend in chloride concentration in any of the bores.

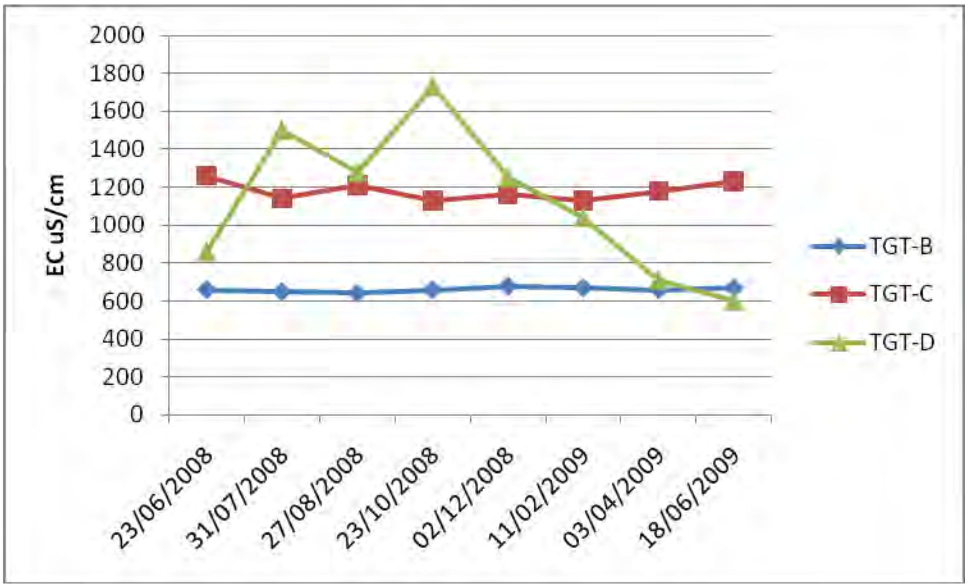


Figure 27 Variation over time of EC in Superficial (TGT_B and TGT_C) and perched groundwater (TGT_D)

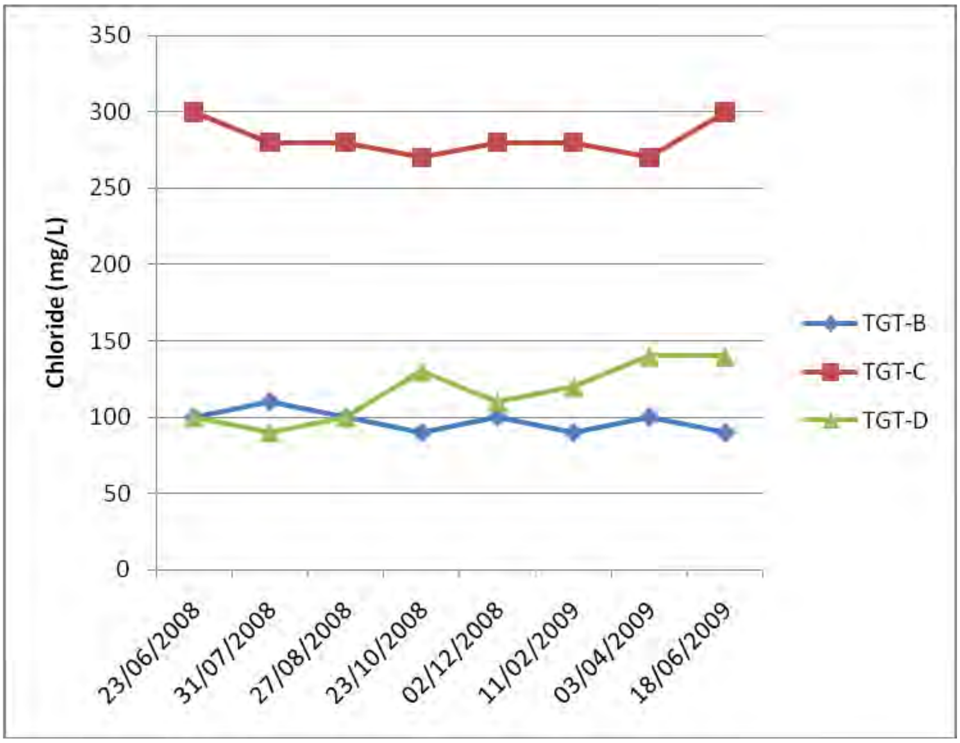


Figure 28 Variation over time of chloride in Superficial (TGT_B and TGT_C) and perched (TGT_D) groundwater

6.1.4 Sulfate

The concentration of sulfate (Figure 29) in groundwater within the Superficial aquifer is generally low, with the lowest concentrations being found at intermediate depths (TGT_B) which might indicate sulfate reducing conditions. Perched groundwater shows a distinct seasonal pattern with much higher concentrations of sulfate than those measured at SGS bores in the Superficial groundwater. The highest concentrations of sulfate were measured from July to December 2008, possibly associated with heavy rainfall in July 2008 which could have mobilised acidic soil water as the perched watertable was recharged. The likelihood of sulfide mineral oxidation was shown in Section 4.3 to be high.

Groundwater levels for the perched watertable (Figure 18 in Section 5.1) show that recharge took place around June and July 2008 and water levels remained high until December 2008, when they declined.

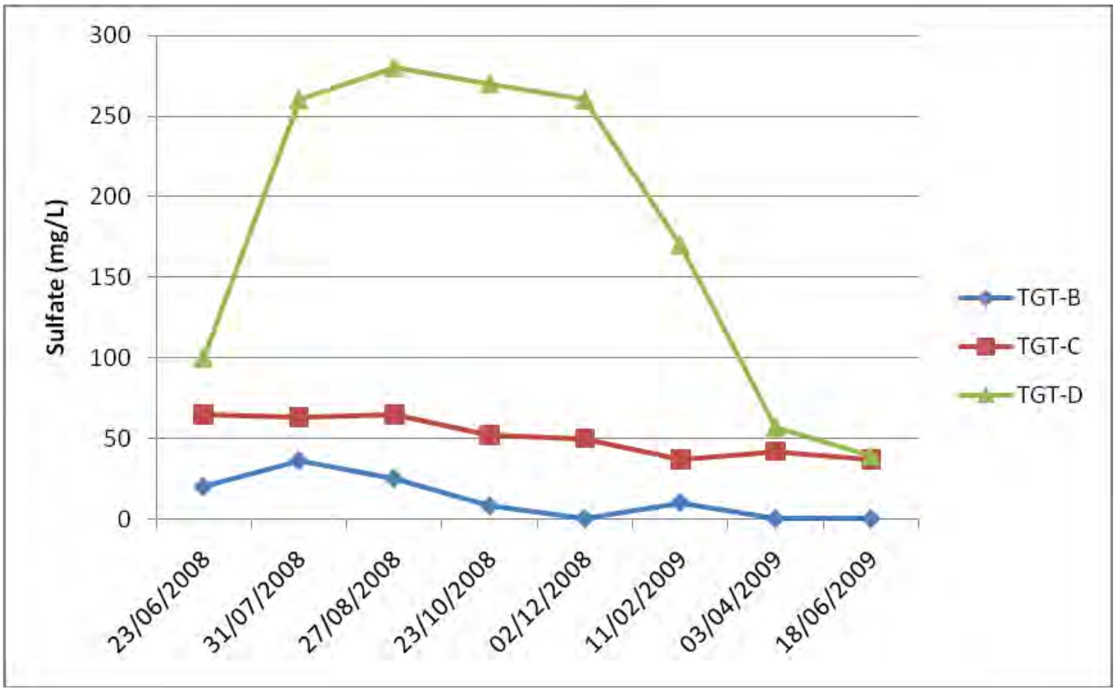


Figure 29 Variation over time of sulfate in Superficial (TGT_B and TGT_C) and perched (TGT_D) groundwater

6.1.5 Sodium and calcium

The concentrations of sodium and calcium in Superficial and perched groundwater near Tangletoe Swamp are shown in Figure 30 and Figure 31, respectively. Calcium is present in highest concentration in the intermediate level bore, TGT_B (Figure 30). Calcium concentrations in the Superficial aquifer at shallow depths and in perched groundwater are much lower. Perched groundwater has a marked seasonal trend in calcium concentration, with highest concentrations measured between July 2008 and December 2008. A similar seasonal trend was also found in sulfate concentrations in perched groundwater.

Shallow groundwater in the Superficial aquifer shows the highest concentration of sodium compared with that at intermediate depth in the Superficial aquifer and in perched groundwater (Figure 31). There is no clear seasonal trend in sodium concentrations at any bore.

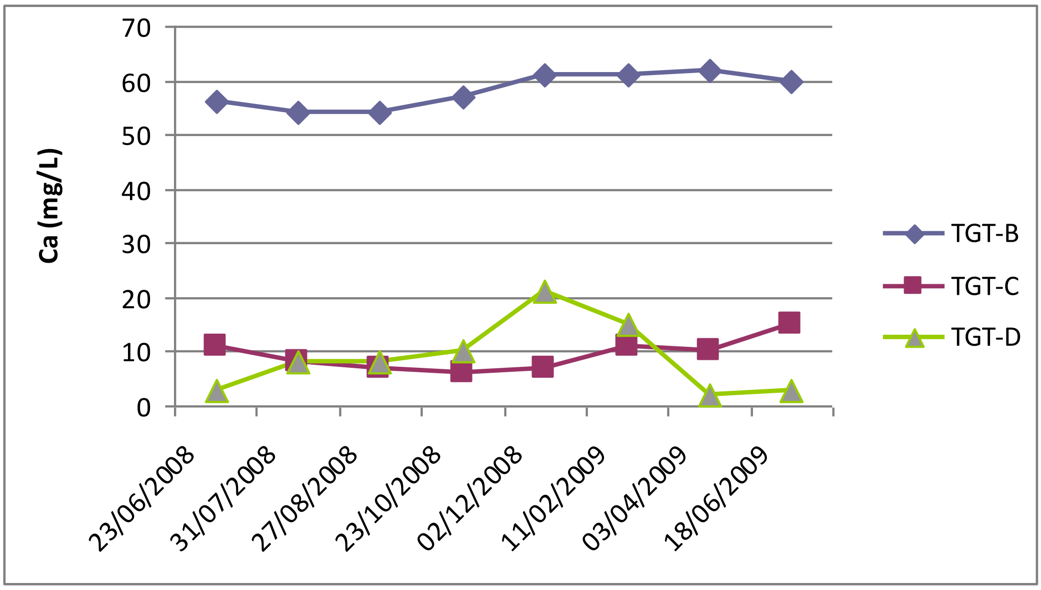


Figure 30 Variation over time of calcium in Superficial (TGT_B and TGT_C) and perched (TGT_D) groundwater

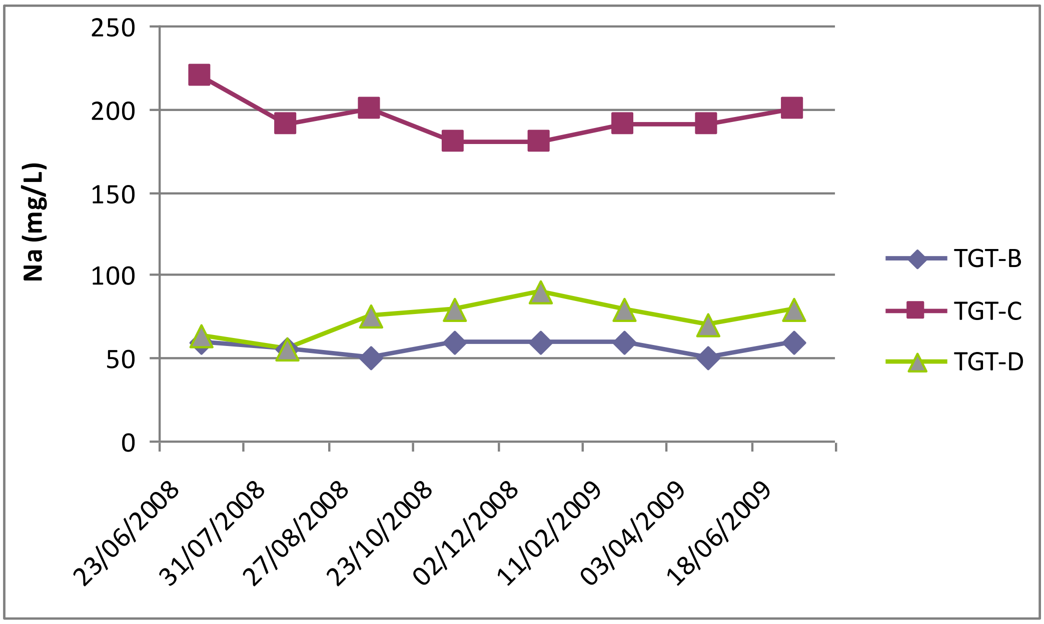


Figure 31 Variation over time of sodium in Superficial (TGT_B and TGT_C) and perched (TGT_D) groundwater

6.2 Water quality

6.2.1 Nutrients

Superficial groundwater at shallow and intermediate depths has similar concentrations of total nitrogen (Table 11 and Figure 32). Most of this was determined as total Kjeldahl nitrogen (TKN), which is dominated by organic forms of nitrogen, such as ammonium. There is little seasonal variability in total nitrogen in Superficial groundwater (Figure 32).

Perched groundwater is also dominated by TKN present at higher concentrations than in Superficial groundwater (Table 11). There is a distinct variability in total nitrogen in perched groundwater, with highest concentrations measured in June 2008, and between October and February 2009.

Perched groundwater exceeded the trigger values for south-west Australian wetlands (ANZECC & ARMZANZ 2000) (Table 11) for total nitrogen (TN), ammonium, nitrate, total phosphorus (TP) and soluble reactive phosphorus (SRP). TN was also exceeded at TGT_B. The intermediate bore TGT_B also exceeded the drinking water guidelines (NHMRC & NRMMC 2004) for ammonium.

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

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

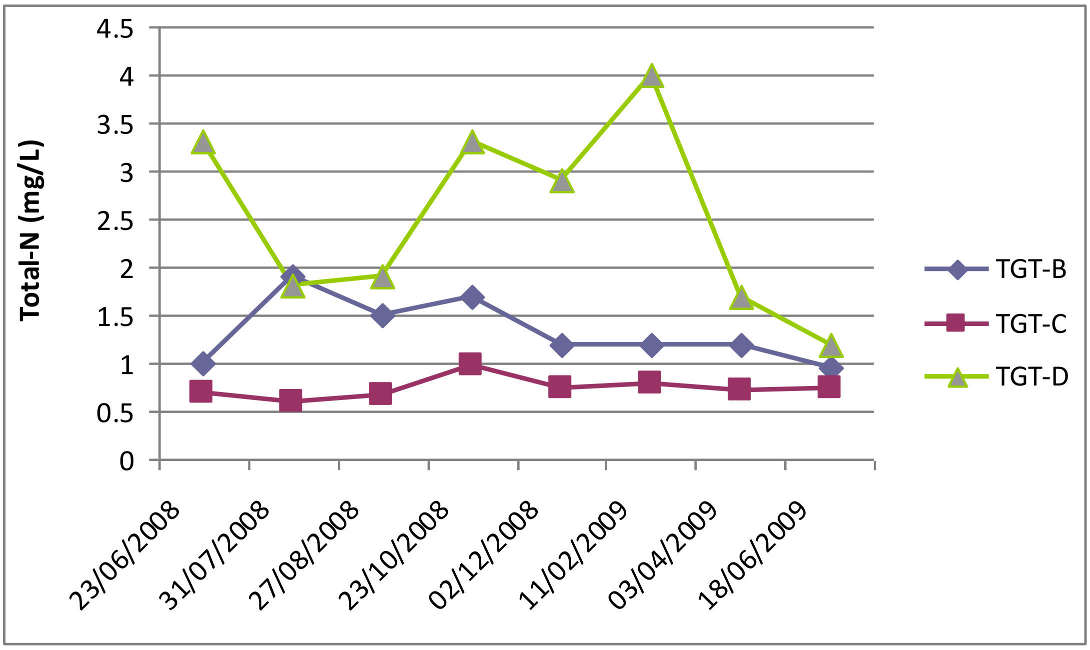


Figure 32 Variation over time of total nitrogen in Superficial (TGT_B and TGT_C) and perched (TGT_D) groundwater

Table 11 Summary statistics for nitrogen species in groundwater in the vicinity of Tangletoe Swamp

	TN mg/L			**TKN mg/L**			**Ammonium mg/L**			**Nitrate mg/L**		
	Min.	**Max.**	**Median**	**Min.**	**Max.**	**Median**	**Min.**	**Max.**	**Median**	**Min.**	**Max.**	**Median**
TGT_B Intermediate Superficial	0.96	1.90	1.20	0.95	1.90	1.20	0.43$^{\#}$	0.58$^{\#}$	0.49$^{\#}$	0.01	0.044	0.02
TGT_C Shallow Superficial	0.60	0.97	0.73	0.60	0.95	0.73	0.24	0.30	0.28	0.01	0.022	0.02
TGT_D Perched (Swamp)	1.20	4.00*	2.40*	1.20	4.00	2.25	0.22*	1.10*	0.57*	0.01	0.200*	0.05
Trigger values*		1.5		-				0.04			0.1 (NO_x)	
Drinking water guidelines$^{\#}$		-			-			0.4			10	

** Trigger value for south-west Australian wetlands (ANZECC & ARMZANZ 2000) and their exceedances in perched groundwater and up-gradient bores*

$^{\#}$Drinking water guideline maximum concentrations from NHMRC & NRMMC (2004) and their exceedances in down-gradient bores

The concentrations of TP and SRP in Superficial groundwater and in perched groundwater are given in Table 12. Generally, TP and SRP are present in highest concentrations in perched groundwater. SRP marginally exceeds the trigger level for south-west Australian wetlands in perched groundwater (ANZECC & ARMCANZ 2000).

Table 12 Summary statistics for TP and SRP in groundwater and perched groundwater compared with trigger values for south-west Australian wetlands

		TP mg/L			SRP mg/L	
	Min.	**Max.**	**Median**	**Min.**	**Max.**	**Median**
TGT_B Intermediate Superficial	0.08	0.15	0.11	0.005	0.048	0.014
TGT_C Shallow Superficial	0.011	0.083*	0.018	0.008	0.017	0.013
TGT_D Perched (swamp)	0.02	0.09*	0.04	0.011	0.036*	0.032*
Trigger value*		0.06			0.03	

** Trigger values are for south-west Australian wetlands (ANZECC & ARMCANZ 2000) and their exceedances*

6.2.2 Alkalinity

Total alkalinity and bicarbonate alkalinity as HCO_3 in groundwater was below detection limits (<1mg/L) across the entire data set at TGT_D. Therefore, the perched aquifer has negligible buffering capacity and reflects the mechanisms by which the shallow system is recharged. Observations made at TGT_C from July 2008 to June 2009 reported alkalinity from 67 to 110 mg/L. The Superficial aquifer data set also indicated that alkalinity slowly increased across the observation period, but as mentioned in Section 3.1, this could be as a result of contamination generated during bore construction. Further sampling is required to monitor this trend. Alkalinity observations made at TGT_B and TGT_A ranged from 150 to 200 mg/L and 160 to 700 mg/L respectively, reflecting the presence of carbonates in the Ascot Formation.

Alkalinity and acid neutralising capacity in soil has been assessed in Section 4.3 (although only limited ANC data was available at the time of compiling this report). Due to the presence of PASS, it is likely that the ANC of the shallow swamp sediments is minimal. Analyses undertaken as part of Section 4.3 reported net acidities above the action criteria from TGT_L1 and TGT_L2.

6.2.3 Minor and trace metals and metalloids

Summary statistics (minima, maxima and median values) for minor and trace metals and metalloids are shown in Table 13 for data collected in the SGS study. Data for perched groundwater are compared with trigger levels for toxicants in south-west Australian wetlands (ANZECC & ARMCANZ 2000) where data for Superficial bores are compared with drinking water guideline maximum concentrations water (NHMRC

& NRMMC 2004) given that drinking water is the highest beneficial use down-gradient of the swamp.

Perched groundwater showed exceedances of the wetland trigger levels for aluminium and chromium, with cadmium showing one maximum value exceedance (Table 13). The number of exceedances is clearly related to the very low pH of perched groundwater.

Superficial groundwater at Tangletoe Swamp shows concentrations above the drinking water standard for aluminium, arsenic, chromium, iron and nickel (Table 13). It is possible that these are a result of water discharges from Tangletoe Swamp. The data suggests that water in the perched aquifer has been acidified due to the exposure of potential acid sulfate soils associated with the swamp.

Table 13 Summary statistics for minor metals and metalloids in groundwater at Tangletoe Swamp

	Al			**As**			**B**			**Cd**			**Cr**		
	mg/L			**mg/L**			**mg/L**			**mg/L**			**mg/L**		
	Min.	**Max.**	**Median**	**Min.**	**Max.**	**Median**	**Min.**	**Max.**	**Median**	**Min.**	**Max.**	**Median**	**Min.**	**Max.**	**Median**
TGT_B Intermediate Superficial	0.130	2.40[#]	0.800[#]	0.039[#]	0.170[#]	0.067	0.013	0.26	0.02	<0.00001	0.0002	<0.0001	0.034	0.580[#]	0.110[#]
TGT_C Shallow Superficial	0.067	0.53	0.125	0.006	0.010[#]	0.009[#]	0.030	0.15	0.04		<0.0001		0.003	0.015	0.005
TGT_D Perched (Swamp)	1.300*	3.70*	1.750*	0.001	0.008	0.003	<0.010	0.11	0.02	<0.0001	0.0008*	<0.0001	0.010*	0.095*	0.020*
Trigger value*		0.055			0.013*			0.37			0.0002			0.001	
Drinking water guidelines[#]		0.200			0.007			0.30			0.0020			0.050	

* Trigger value for south-west Australian wetlands (ANZECC & ARMZANZ 2000) and their exceedances

[#] Drinking water guideline maximum concentrations from NHMRC & NRMMC (2004) and their exceedances

** value for As(III) shown; trigger level for As(IV) is 0.024 mg/L

Table 13 (continued)

	Fe (sol) mg/L			Mn mg/L			Ni mg/L			Zn mg/L		
	Min.	**Max.**	**Median**	**Min.**	**Max.**	**Median**	**Min.**	**Max.**	**Median**	**Min.**	**Max.**	**Median**
TGT_B Intermediate Superficial	$1.10^{\#}$	$2.2^{\#}$	$1.60^{\#}$	0.006	0.026	0.013	0.016	$0.13^{\#}$	$0.030^{\#}$	0.005	0.090	0.030
TGT_C Shallow Superficial	$0.55^{\#}$	$1.4^{\#}$	$0.93^{\#}$	0.030	$0.140^{\#}$	0.055	0.003	0.01	0.006	0.005	0.048	0.016
TGT_D Perched (Swamp)	0.94	39.0	27.00	0.002	0.036	0.010	0.003	0.09*	0.030*	0.005	0.590	0.130
Trigger value*		-						0.011			0.008	
Drinking water guidelines$^{\#}$		0.3			0.1			0.02			3	

* Trigger value for south-west Australian wetlands (ANZECC & ARMZANZ 2000) and their exceedances

$^{\#}$Drinking water guideline maximum concentrations from NHMRC & NRMMC (2004) and their exceedances

** value for As(III) shown; trigger level for As(IV) is 0.024 mg/L

6.3 Summary of trigger level breeches

Table 14 summarises breeches of water quality concentrations under ANZECC & ARMCANZ (2000) guidelines for south-west Australian wetlands.

Table 14 Summary of trigger level breaches

	ANZECC & ARMCANZ (2000) south- west Australian wetland trigger levels
pH	All pH values, (apart from the perched groundwater 2.59–3.77) were within the recommended range of 7.0–8.5 (overall range 7.3–7.9) The perched groundwater readings indicate acidification by sulfide mineral oxidation, driven by a decline in groundwater levels.
TN	Perched groundwater showed total nitrogen concentrations above the trigger level, with most total nitrogen being organic nitrogen.
NH_4-N	Ammonium is above the trigger level of 0.04 mg/L in all samples of perched groundwater.
NO_x	Perched groundwater showed concentrations of nitrate above the trigger level of 0.1 mg/L in only one sample.
TP	Total phosphorus in perched groundwater (TGT_D) exceeded the trigger level of 0.06 mg/L.
SRP	SRP was marginally above the trigger level of 0.03 mg/L (median 0.032 mg/L, varying between 0.011 and 0.036 mg/L).

	ANZECC & ARMCANZ (2000) south- west Australian wetlands trigger levels	NHMRC/NRMMC (2004) drinking water guidelines as main beneficial use
Al	Concentrations in perched groundwater were above the trigger levels in all cases, due to very low pH of groundwater.	Concentrations were above the guideline of 0.2 mg/L in most cases.
As	All groundwater concentrations were below trigger level.	Concentrations in Superficial groundwater were above the guideline of 0.007 mg/L in most samples.
B	All perched and Superficial groundwater concentrations was below trigger level.	All concentrations below guideline concentrations.
Cd	One perched groundwater sample was above the trigger level of 0.0002 mg/L.	Concentrations in groundwater in Superficial aquifer bores were below guideline level.
Cr	All perched groundwater concentrations were well above trigger level of 0.001 mg/L (varying between 0.01 and 0.095 mg/L).	Groundwater in Superficial aquifer at intermediate level were mostly above the guideline of 0.05 mg/L.
Ni	Perched groundwater was mostly above the trigger level of 0.011 (varying between 0.003 and 0.09 mg/L with a median of 0.03).	Concentrations in Superficial groundwater were mostly above the guideline of 0.02 mg/L (median 0.03 mg/L).
Zn	Perched groundwater concentrations were below trigger level.	All concentrations were below guideline concentrations.
Fe	Not applicable	Concentrations in all Superficial aquifer bores significantly exceed guideline value.

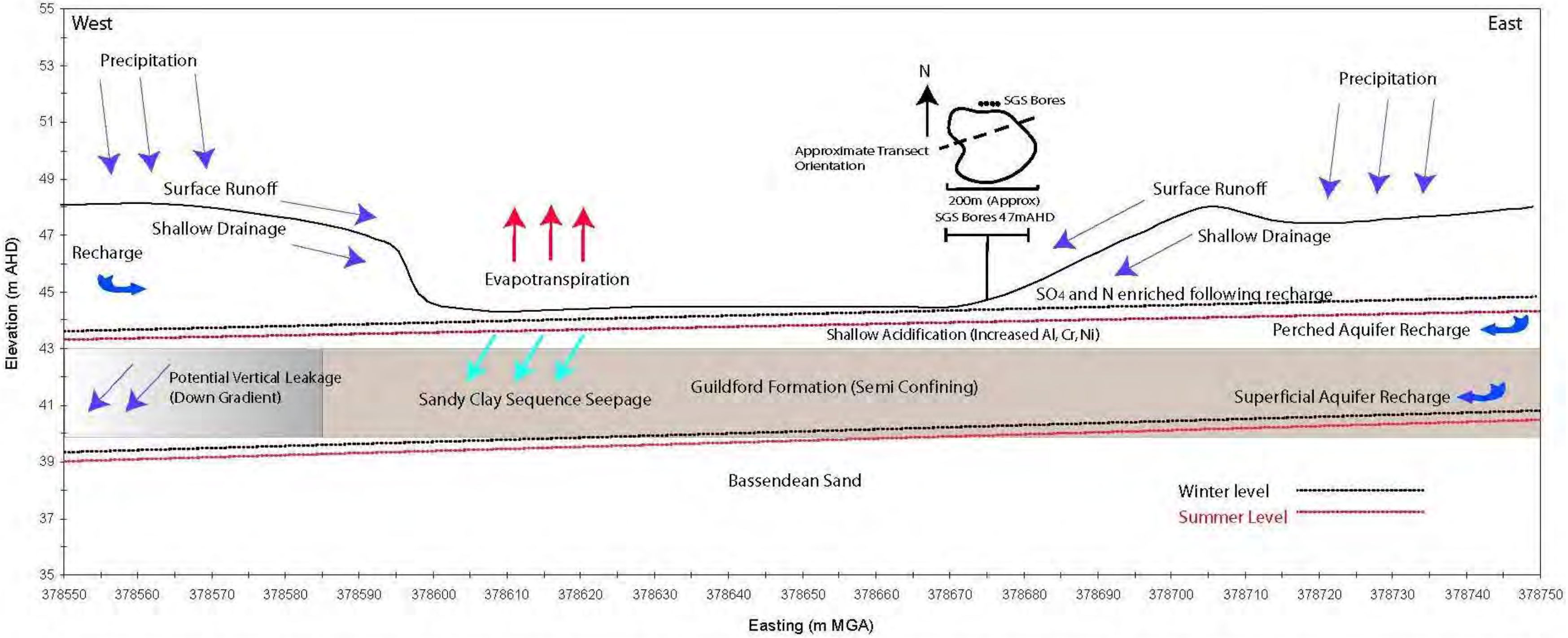
	ANZECC & ARMCANZ (2000) south- west Australian wetlands trigger levels	NHMRC/NRMMC (2004) drinking water guidelines as main beneficial use
Mn	Not applicable	Most samples of Superficial groundwater are lower than the guideline value of 0.1 mg/L.

7 Processes and interactions between surface water and groundwater

Analysis of the hydrogeology in the vicinity of Tangletoe Swamp allows an interpretation of hydrogeochemical processes and the interactions between surface water and groundwater to be made. These are shown conceptually in Figure 33 and Figure 34.

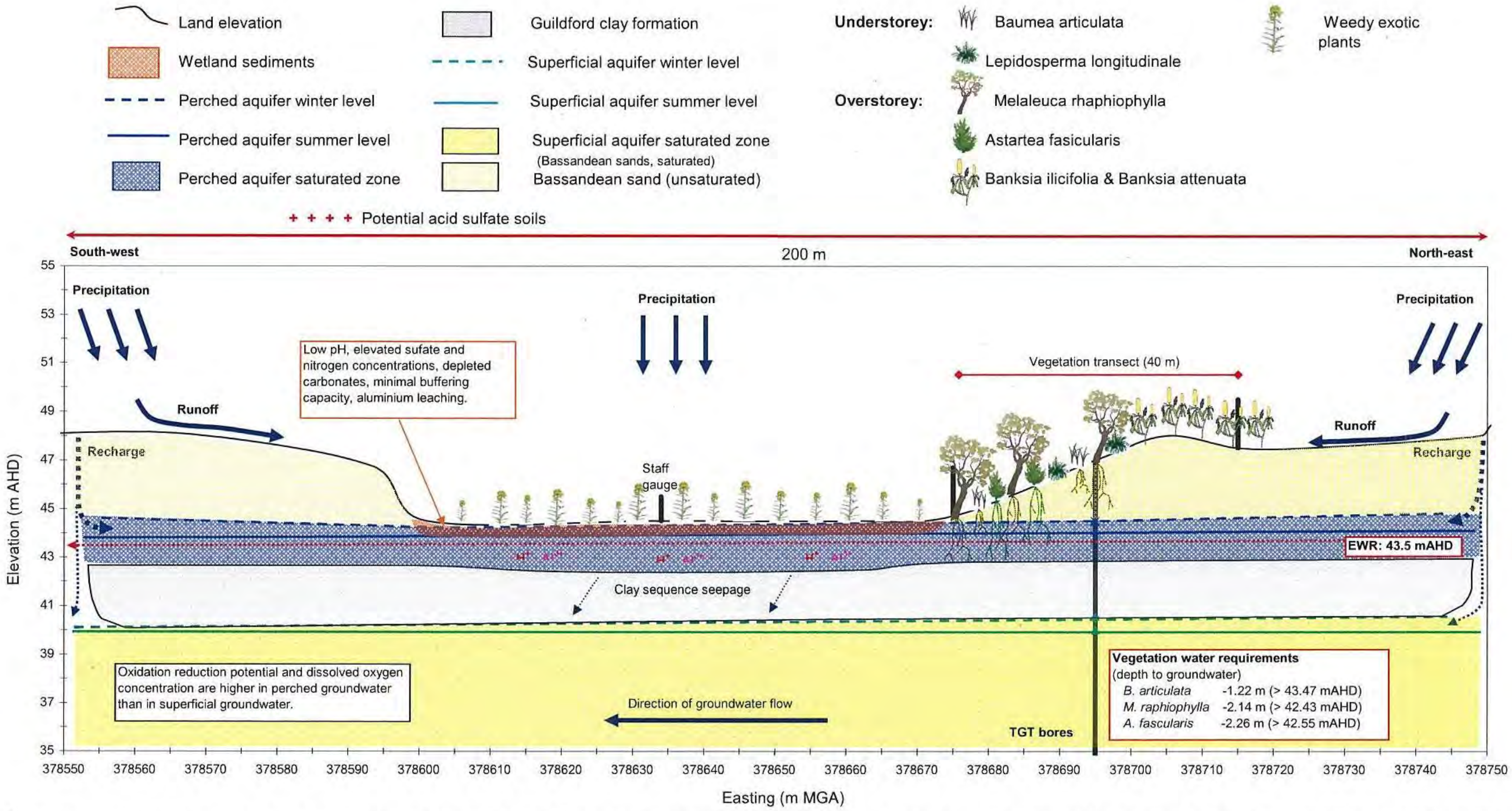
Previously, Tangletoe Swamp was classified as being groundwater dependent, although there was little data to confirm the swamp was connected to the Superficial aquifer (i.e. the regional groundwater flow system of the Gnangara Mound). The SGS investigation has shown conclusively the presence of a perched watertable within Bassendean Sands beneath the swamp, which lies above a 2.0 m thick layer of sandy clays of the Guildford Formation. The water level in the perched aquifer is 3.0 m below surface at the location of the TGT bores and 4.0 m above the regional watertable within the Bassendean sands. The saturated thickness of the perched groundwater is approximately 2.0 m on average, with the thickness increasing slightly in winter and decreasing by approximately 0.5 m in summer.

Regional groundwater levels near Tangletoe Swamp (Section 5.1) have fallen by 2.0 m since 1987. Given the matching trends, perched groundwater levels are likely to have declined over the same time period. Declining levels in the perched system have led to the oxidation of exposed sulfidic minerals in the swamp bed sediments and to acidification upon rewetting of the sediments (see Section 4.3).



Note: The transect orientation is indicative and took in to consideration local groundwater flow, the availability of geological information and the direction of the ecological vegetation transect.

Figure 33 Hydrogeological conceptual model for Tangletoe Swamp



Note: The transect elevation used in this diagram is a combination of a north-east to south-west cross section and the north-to-south vegetation transect. Elevations shown for the vegetation transect differ from those reported in Wilson et al. (2009). For a more accurate depiction of the rleationship between vegetation elevation and depth to groundwater, please refer to Figure 6.

Figure 34 Ecological conceptual model for Tangletoe Swamp

7.1 Groundwater hydrology

The groundwater hydrology of Tangletoe Swamp is controlled by the perched watertable and there is currently no influence on water levels in the swamp from the Superficial aquifer. The regional watertable associated with the Superficial aquifer appears to be below sandy clays that form the perched aquifer base (Figure 33 and Figure 34). Hence the focus of assessment of surface water–groundwater interaction is the relationship between the swamp and perched groundwater levels.

There is no geological data to delimit the lateral extent of the Guidford clay and perched groundwater or its recharge capture zone, although it is expected to extend some distance to the north of the swamp The geometry of the clay layer is not totally understood. However, it is assumed that it radiates to at least 20 to 30 m beyond the extent of the swamp.

The regional watertable coincided with the base of the Guildford Clay at the location of the TGT bores (Figure 34) in 2008–09. Given that groundwater levels in non-SGS bores have declined around 2 to 3 m since 1989, it would suggest that the regional watertable would have been close to the top of the clay historically. This would presumably have given a greater degree of hydraulic continuity between the perched and regional groundwater systems pre-1989. However, it still would have been unlikely that open water in the swamp would have been maintained by the regional groundwater system.

Regional groundwater levels probably have remained below those of the perched groundwater at least since 1989, so that the regional groundwater currently has little influence on the hydrology of the swamp.

The data suggest that some decline in the perched watertable has taken place as rainfall has decreased and this is supported by the assessments made in Section 6 and from the SGS bores (see Section 7.2). It seems likely that the decline in groundwater levels within the perched aquifer is much less than the 2 to 4 m observed for the regional groundwater system between 1977 and the present. Otherwise, the swamp and its associated vegetation would have shown greater degradation than reported by Froend & Loomes (2004).

It is concluded that the level of recharge to the perched aquifer is sufficient to maintain the swamp. It also appears to negate the losses resulting from possible small scale localised leakage (via thinner, more sandy sections of the Guildford Formation) and evapotranspiration.

7.2 Groundwater chemistry

The list below contains observations and conclusions from studying the hydrochemistry of major ions.

- Groundwater within the Superficial aquifer varies chemically from that in the zone of perched groundwater. While both shallow regional groundwater and perched groundwater are sodium–chloride dominated, perched groundwater is enriched in sulfate and to some extent also in nitrogen. The chemistry of the perched watertable is influenced by processes associated with the swamp and not by regional groundwater. However, leakage of perched groundwater into the regional groundwater system may affect groundwater quality in the Superficial aquifer, although there is no evidence for this at the location of the TGT bores.

- The significant sulfate enrichment in the perched system was recorded between July and December 2008. The onset of this rise coincided with a period of significant rainfall (July 2008) and subsequently increase in groundwater levels within the perched system. Sulfate concentrations declined as water levels declined in November and December 2008. Data for sulfate suggests that there must have been some oxidation of sulfide minerals and as a consequence, acidification of soil water within sediments has taken place. High rainfall in July 2008 would have recharged the perched watertable with acidic water as a result of this oxidation.
- It is unclear whether the acidic groundwater, which was perched on clays in 2008–09, is a recent phenomenon or whether this is typical of perched water in the area. It is presumed that a decline in perched groundwater levels has given rise to acidification of perched groundwater and may be affecting the local ecosystem. It suggests that there is little buffering capacity within the Bassendean Sands, which by nature generally are leached of any carbonate minerals and typically contain low pH groundwater.
- The low pH of perched groundwater has given rise to leaching of metals from the swamp sediments and Bassendean Sands, specifically of Al, Cr and Ni, which are all above trigger levels for south-west Australian wetlands (ANZECC & ARMCANZ 2000).
- Total nitrogen was found to be present in concentrations above the south-west Australian wetlands (ANZECC & ARMCANZ 2000) trigger level; this was mostly present as organic nitrogen. Although ammonium was present in much lower concentrations than organic nitrogen, ammonium was still above the wetland trigger levels. Soluble reactive phosphorus was also above the trigger levels.
- Tangletoe Swamp is regarded as being at high risk of acidification, particularly within the upper 4 m of the soil profile. The dominance of actual acidity over potential acidity coupled with the lack of an acid neutralising capacity poses a major threat of acidification of water within the perched groundwater system.

8 Implications for ecological values

8.1 Ecological implications

Declining groundwater levels in the Superficial aquifer have no effect on the ecology of Tangletoe Swamp. The swamp is supported by a shallow, perched aquifer and is not hydrologically connected to the regional groundwater system of the Gnangara Mound. The phreatophytic vegetation community is currently completely dependent on this perched aquifer and probably has been so since the 1970s or earlier. It is likely that water levels in this perched aquifer have experienced similar levels of decline in response to decreasing rainfall as in the underlying Superficial aquifer.

Vegetation monitoring in 2009 identified five wetland vegetation species (*Melaleuca rhaphiophylla*, *Baumea articulata*, *Lepidosperma longitudinale*, *Astartea fascicularis* and *Banksia ilicifolia*) that were thought to be at or beyond the driest extent of their known ranges (Wilson et al. 2009), based on the incorrect assumption that these plants were reliant on groundwater in the Superficial aquifer.

Current water levels in the perched aquifer are sufficiently high to meet the ecological water requirements of the wetland vegetation community based on the contemporary vegetation distribution (Figure 35). However, it is important to note that the vegetation distribution has changed over time and it is likely that the EWRs of the historical vegetation community are no longer being met.

The observed declines in vegetation condition and distribution have been driven by the combined effects of previous water level decline and current poor water quality within the perched aquifer. The water within the perched aquifer is currently highly acidic as a result of one or more acid sulfate soil acidification events. Exposure to acidified groundwater is known to negatively affect phreatophytic vegetation (NWPASS 2000) through:

- root damage and stunting through contact with low pH soil water, producing effects similar to water stress
- direct toxicity from high aluminium concentrations
- reduced growth and vigour from mineral deficiencies due to high soil metal concentrations
- increased susceptibility to plant pathogens and soil borne diseases (e.g. *Phytophthora*).

The combination of acidity and aluminium toxicity is likely to have contributed to declines in plant health observed at the site (Wilson et al. 2009; Mattiske Consulting 2006) through destruction of plant roots and disruption plant of ionic balance, as well as increasing plant susceptibility to disease and contributing to the observed reduction in species distribution (Mattiske Consulting 2006). Although *Phytophthora* has not yet been recorded at Tangletoe Swamp, this fungus may be involved in the observed vegetation decline (Froend et al. 2004c).

As recorded by Wilson et al. (2009), xerophytic plant species which do not draw water from the perched aquifer, will not be affected by the groundwater acidification and thus will remain healthy and move into areas previously colonised by phreatophytic species. While acidity persists, terrestrialisation is likely to continue, with xerophytic species eventually replacing the valued phreatophytic vegetation community at Tangletoe Swamp.

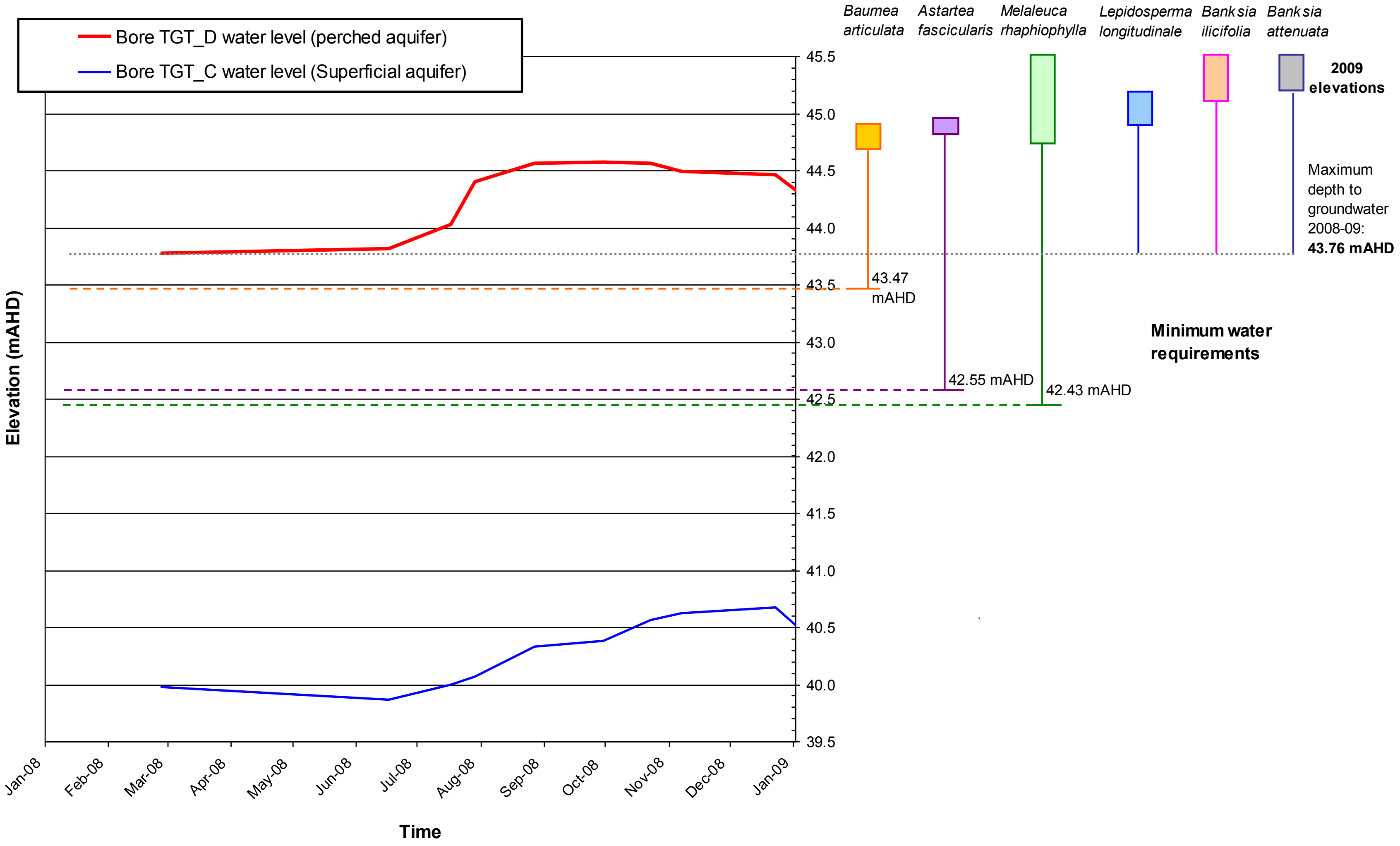


Figure 35 Relationships between groundwater levels, vegetation distribution and minimum water level requirements

Decreasing rainfall due to climate change is likely to trigger future acidification as potential acid sulfate soils become exposed and oxidised. Subsequent rainfall will rewet these sediments, releasing sulfuric acids and metals. Consequently, the poor water quality of the perched aquifer will persist and may worsen, placing further stress on the already affected phreatophytic vegetation community at Tangletoe Swamp.

Any surface water inundation of Tangletoe Swamp is likely to become acidified and have high metal concentrations, including toxic levels of aluminium. These conditions would be toxic to most species of aquatic macroinvertebrates, amphibians and water birds that may colonise the wetland post-inundation (Tulau 2007), leading to reduced richness and diversity of wetland fauna. These waters would also be toxic to vegetation, triggering the death of plants exposed to the water (Tulau 2007).

As the acidified groundwater is retained within the perched aquifer, the acidity cannot be easily dissipated. Due to the very low alkalinity of the groundwater (Section 6.1.2), the acidity cannot be neutralised by alkaline soil ions. The acidity of the water can only be reduced through dilution (increased rainfall, runoff and/or recharge).

As water levels in the perched aquifer have declined, surface water inundation of Tangletoe Swamp will have significantly decreased allowing terrestrial vegetation – particularly exotic weeds – to colonise the dry swamp bed (Wilson et al. 2009) and increasing the distribution of xerophytic plants. The reduced surface water availability has also contributed to a loss of macroinvertebrate richness and diversity.

Given the combined effects of reduced rainfall and groundwater acidification, it is anticipated that the swamp will continue to become terrestrial, leading to further deterioration of its ecological values. This terrestrialisation process was anticipated by Froend et al. (2004a, b), as documented in Section 2.5.1.

8.1.1 Land and water use

Tangletoe Swamp is located in state forest within the Gingin groundwater area in the northern region of the Swan Coastal Plain (Wilson et al. 2009). Although native vegetation surrounds the swamp, there is some dry land cropping to the north-east (DoW 2009c; McHugh & Bourke 2007). There is no known abstraction of groundwater from the perched aquifer that supports Tangletoe Swamp and as the perched aquifer is not connected to the regional groundwater system, the swamp is not affected by abstraction from the Superficial aquifer. Instead, changes in groundwater levels at Tangletoe Swamp are the result of local rainfall, with some possible contribution from runoff.

As warmer temperatures and lower rainfall have been recorded in the area since the 1970s (DoE 2005; Yesertener 2002), it is likely that perched aquifer levels have been lowered over that period in response to climate variation (DoE 2005; DoW 2008b). Climate driven declines in groundwater of about 2.0 to 2.5 m have been recorded from locations around Tangletoe Swamp (DoW 2008b) and it is likely that similar declines have taken place in the perched aquifer, although there is not sufficient data available to confirm that such declines have taken place.

Given the perched hydrology at Tangletoe Swamp, there are very few land management options for improving groundwater levels or quality. Managing the surrounding land use to maximise recharge and runoff may increase groundwater levels and reduce the further exposure of potential acid sulfate soils. Increasing runoff, however, would increase the rewetting of the sediments already exposed.

Recharge to the perched aquifer could possibly be increased by managing the density and burn regime of native *Banksia* woodlands surrounding the swamp.

Although less significant than the effects of climate, native vegetation density has been shown to have a significant impact on groundwater levels in the Gingin area, with high vegetation densities significantly reducing the extent of groundwater recharge (De Silva 2009; DoE 2005).

Analyses conducted by DoE (2005) found that the optimal native vegetation management scenario to maximise groundwater recharge across Gnangara Mound was through conducting annual burning and/or thinning of *Banksia* woodland across 7.5% of the total native vegetation area of the mound. In some cases, strategic burning of native vegetation can promote recharge and result in groundwater level rises by as much as 2.4 m over a period of 2 to 4 years (DoW 2008b; Yesertener 2002).

As the vegetation community surrounding Tangletoe Swamp consists largely of *Banksia* woodland (Froend et al. 2004a), it is likely that applying this vegetation management strategy would result in similar increases in groundwater levels within the perched aquifer. However, it is not yet known if the perched aquifer at Tangletoe Swamp extends significantly below the surrounding *Banksia* woodland. Further survey work would be required to determine the boundaries of the perched aquifer before evaluating the utility of controlled burning or thinning to improve groundwater levels in the perched aquifer.

Additionally, this land management practice is unlikely to prevent further degradation of the ecological values of the swamp as the vegetation will continue to be affected as long as groundwater in the perched aquifer remains acidic.

It must be noted that the effects of climate change on the Gnangara Mound are forecast to increase, with reduced rainfall driving declines in shallow groundwater systems across the Mound (CSIRO 2009; McHugh & Bourke 2007). Subsequently, implementing land management practices to increase recharge may not be sufficient to prevent future drying and rewetting of wetland sediments leading to further acidification events. Increasing recharge and runoff may, however, reduce the frequency and severity of future acidification events.

9 Recommendations

These recommendations are subject to departmental priorities and resources.

Management Actions

- Environmental water requirements (EWRs) have been identified for Tangletoe Swamp but should not be adopted as Ministerial criteria due to the reliance of the vegetation on the perched aquifer, rather than the regional groundwater system.
    - *Implementation and responsibility: DoW to recognise in the next Gnangara water allocation plan due in 2012*
- Design a local area model that incorporates the new hydrogeological understanding gained from this study, and include scenarios that model changes in recharge through managing the density of vegetation, rainfall variability and changes in abstraction.
    - *Implementation and responsibility: DoW to design the north Gnangara local area modelling future scenario modelling by June 2012. Results to be related to similar perched systems and inform the next Gnangara water allocation plan due in 2012.*

Future Monitoring

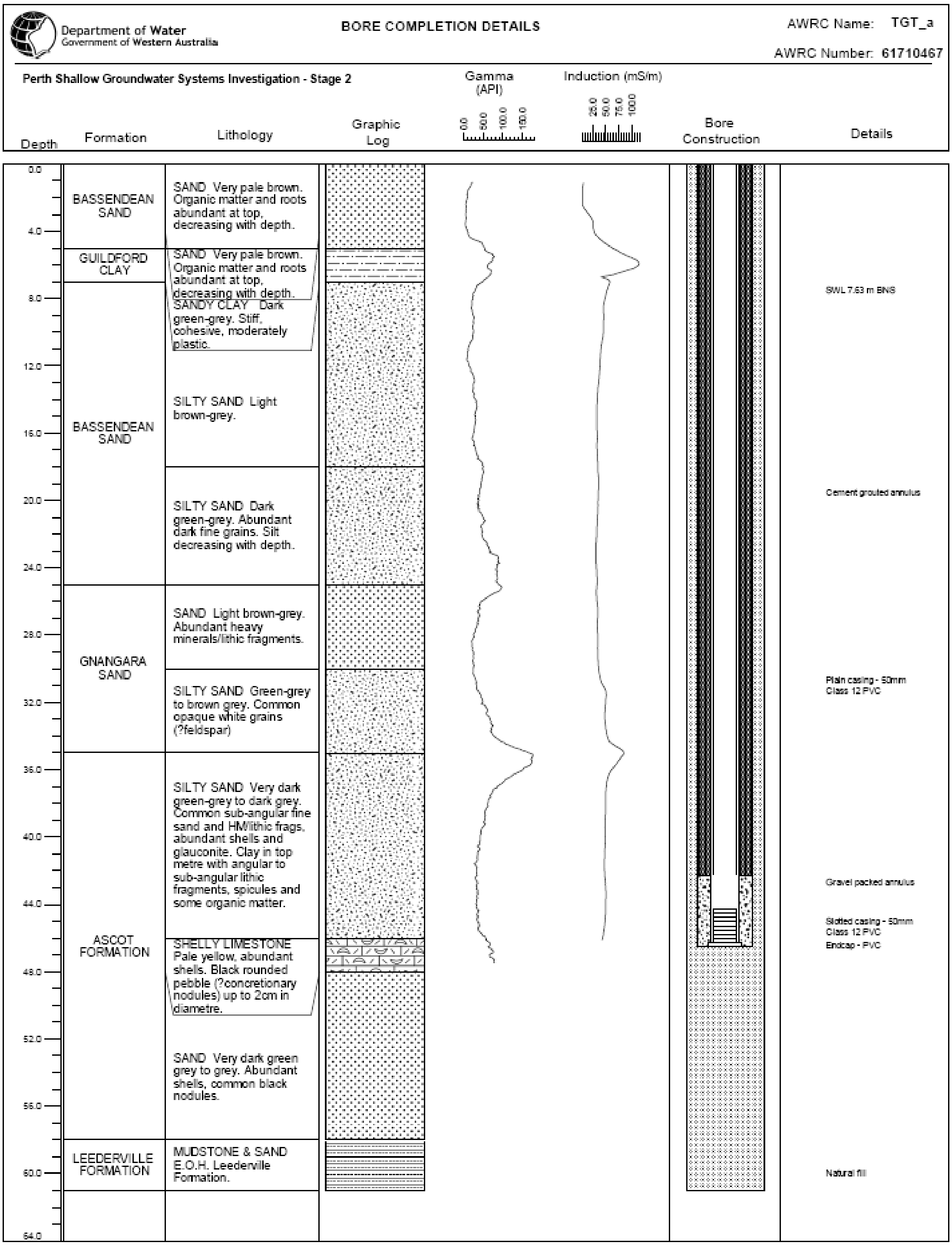
- Continuous monitoring using data-loggers at bore YY9, GB15, all bore installed in this investigation (TGT bores) and staff gauge to quantify the relationship between perched and regional groundwater levels. Water chemistry should be analysed every quarter. Should Tangletoe Swamp become inundated then include surface water levels, chemistry and biota to assess the potential impact of acidic waters on the ecology of the wetland.
    - *Implementation and responsibility: DoW to design a suitable groundwater monitoring program, that includes water chemistry sampling to inform the next Gnangara water allocation plan due in 2012.*
- Review the suitability of the monitoring program after three to five years of data collection to ensure that this monitoring provides the data necessary to assess ecological and hydrogeological changes.
    - *Implementation and responsibility: DoW to review the monitoring program and document in a resource review report by 2015/2017.*

Future Investigation

- Shallow drilling and surface geophysical surveys (e.g. ground penetrating radar, 'GPR', and electro-magnetics 'EM') and down-hole geophysical logging (e.g. natural gamma, neutron) to determine the geometry and extent of the perched aquifer.
    - *Implementation and responsibility: DoW to scope an investigative drilling program.*

Appendices

Appendix A — Construction diagrams



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BORE COMPLETION DETAILS

AWRC Name: TGT_a
AWRC Number: **61710467**

Perth Shallow Groundwater Systems Investigation - Stage 2

Formation	Lithology
BASSENDEAN SAND	SAND Very pale brown. Organic matter and roots abundant at top, decreasing with depth.
GUILDFORD CLAY	SAND Very pale brown. Organic matter and roots abundant at top, decreasing with depth.
BASSENDEAN SAND	SANDY CLAY Dark green-grey. Stiff, cohesive, moderately plastic.
	SILTY SAND Light brown-grey.
	SILTY SAND Dark green-grey. Abundant dark fine grains. Silt decreasing with depth.
GNANGARA SAND	SAND Light brown-grey. Abundant heavy minerals/lithic fragments.
	SILTY SAND Green-grey to brown grey. Common opaque white grains (?feldspar)
ASCOT FORMATION	SILTY SAND Very dark green-grey to dark grey. Common sub-angular fine sand and HM/lithic frags, abundant shells and glauconite. Clay in top metre with angular to sub-angular lithic fragments, spicules and some organic matter.
	SHELLY LIMESTONE Pale yellow, abundant shells. Black rounded pebble (?concretionary nodules) up to 2cm in diametre.
	SAND Very dark green grey to grey. Abundant shells, common black nodules.
LEEDERVILLE FORMATION	MUDSTONE & SAND E.O.H. Leederville Formation.

SWL 7.63 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):	6530400.66	Screens (m BNS):	44.3 - 46.3
Date drilled:	2/6/08	Easting (Z50):	378660.39	SWL (m BNS):	7.63
Logged by:	Sandie McHugh	Surface (m AHD):	47.04	EC (mS/m):	53700
Aquifer:	Superficial	Drill depth (m BNS):	61	pH:	8.8

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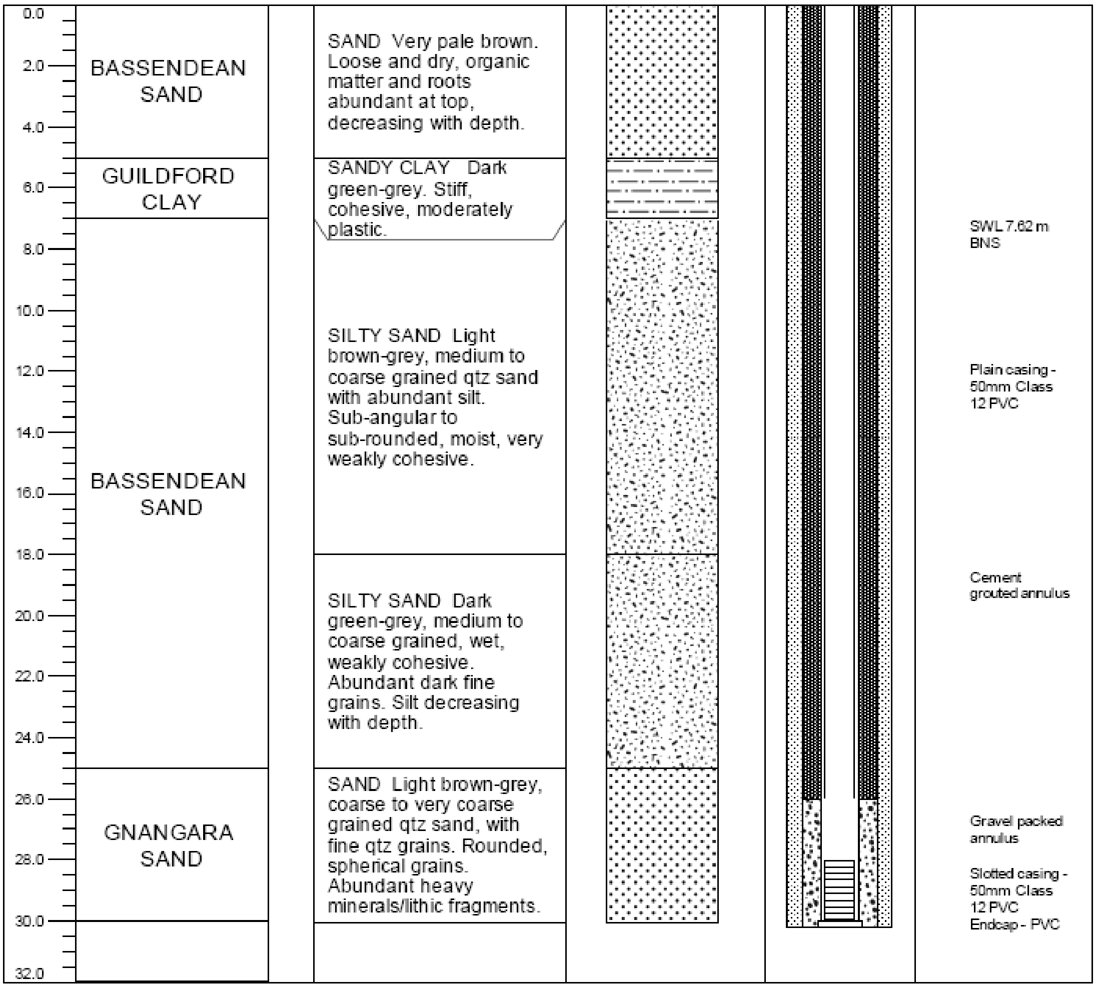
BORE COMPLETION DETAILS

AWRC Name: **TGT_b**
AWRC Number: **61710468**

Perth Shallow Groundwater Systems Investigation - Stage 2

Depth	Lithology	Formation	Graphic Log	Bore Construction	Details



Lithology	Formation
BASSENDEAN SAND	SAND Very pale brown. Loose and dry, organic matter and roots abundant at top, decreasing with depth.
GUILDFORD CLAY	SANDY CLAY Dark green-grey. Stiff, cohesive, moderately plastic.
BASSENDEAN SAND	SILTY SAND Light brown-grey, medium to coarse grained qtz sand with abundant silt. Sub-angular to sub-rounded, moist, very weakly cohesive.
	SILTY SAND Dark green-grey, medium to coarse grained, wet, weakly cohesive. Abundant dark fine grains. Silt decreasing with depth.
GNANGARA SAND	SAND Light brown-grey, coarse to very coarse grained qtz sand, with fine qtz grains. Rounded, spherical grains. Abundant heavy minerals/lithic fragments.

SWL 7.62 m BNS

Plain casing - 50mm Class 12 PVC

Cement grouted annulus

Gravel packed annulus

Slotted casing - 50mm Class 12 PVC
Endcap - PVC

Drilled by:	Great Southern Drilling	Northing (Z50):	6530399.87	Screens (m BNS):	28.03 - 30.03
Date drilled:	2/12/08	Easting (Z50):	378662.17	SWL (m BNS):	7.62
Logged by:	Sandie McHugh	Surface (m AHD):	47.01	EC (uS/m):	59600
Aquifer:	Superficial	Drill depth (m BNS):	30.03	pH:	7.4

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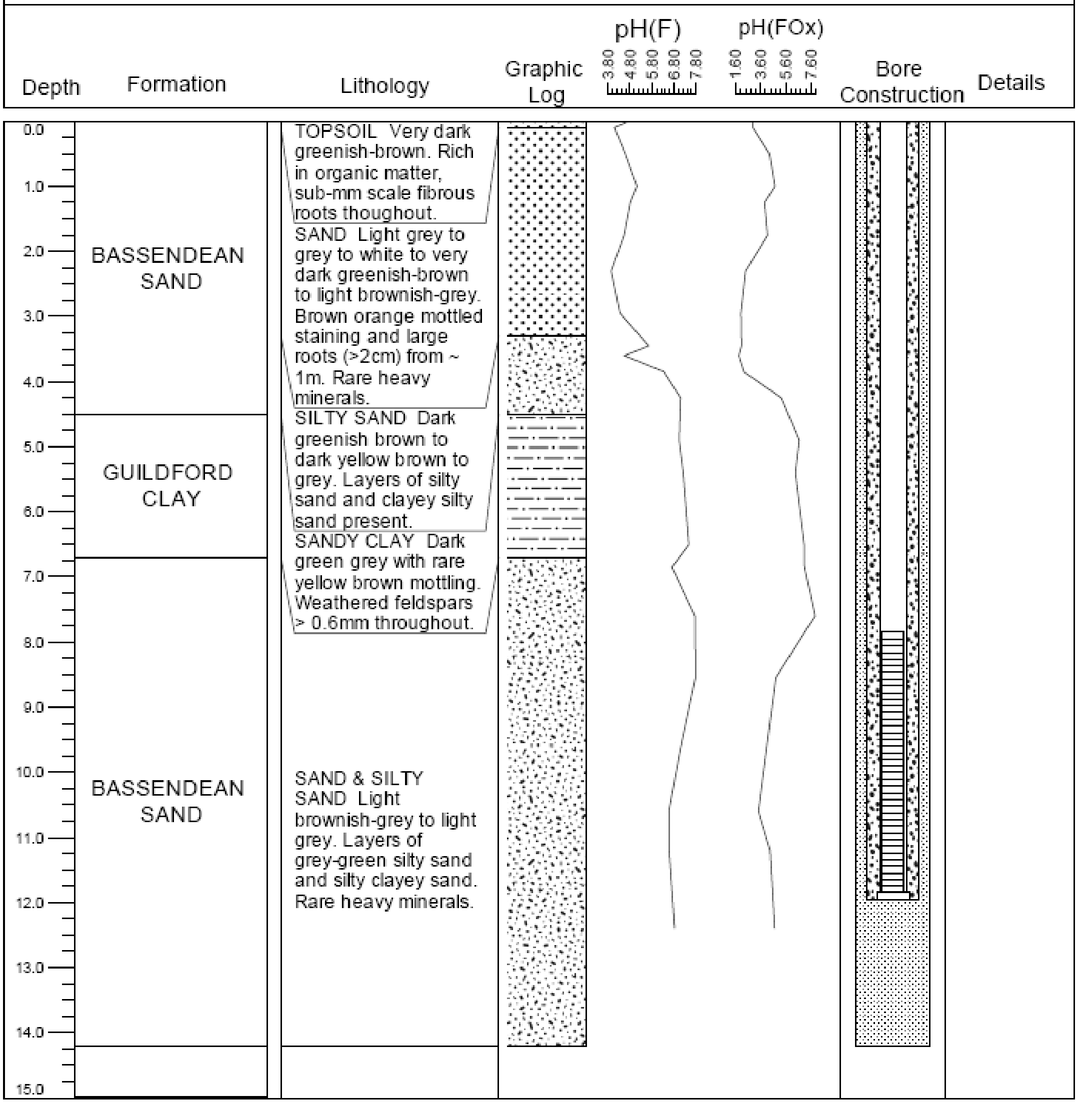
BORE COMPLETION DETAILS

AWRC Name: **TGT_c**
AWRC Number: **61710469**

Perth Shallow Groundwater Systems Investigation - Stage 2



TOPSOIL Very dark greenish-brown. Rich in organic matter, sub-mm scale fibrous roots thoughout.

SAND Light grey to grey to white to very dark greenish-brown to light brownish-grey. Brown orange mottled staining and large roots (>2cm) from ~ 1m. Rare heavy minerals.

SILTY SAND Dark greenish brown to dark yellow brown to grey. Layers of silty sand and clayey silty sand present.

SANDY CLAY Dark green grey with rare yellow brown mottling. Weathered feldspars > 0.6mm throughout.

SAND & SILTY SAND Light brownish-grey to light grey. Layers of grey-green silty sand and silty clayey sand. Rare heavy minerals.

Drilled by:	Great Southern Drilling	Northing (Z50):	6530398.95	Screens (m BNS):	7.85 - 11.85
Date drilled:	2/13/08	Easting (Z50):	378663.47	SWL (m BNS):	7.6
Logged by:	Sandie McHugh	Surface (m AHD):	47.01	EC (uS/m):	112100
Aquifer:	Superficial	Drill depth (m BNS):	14.2	pH:	7.1

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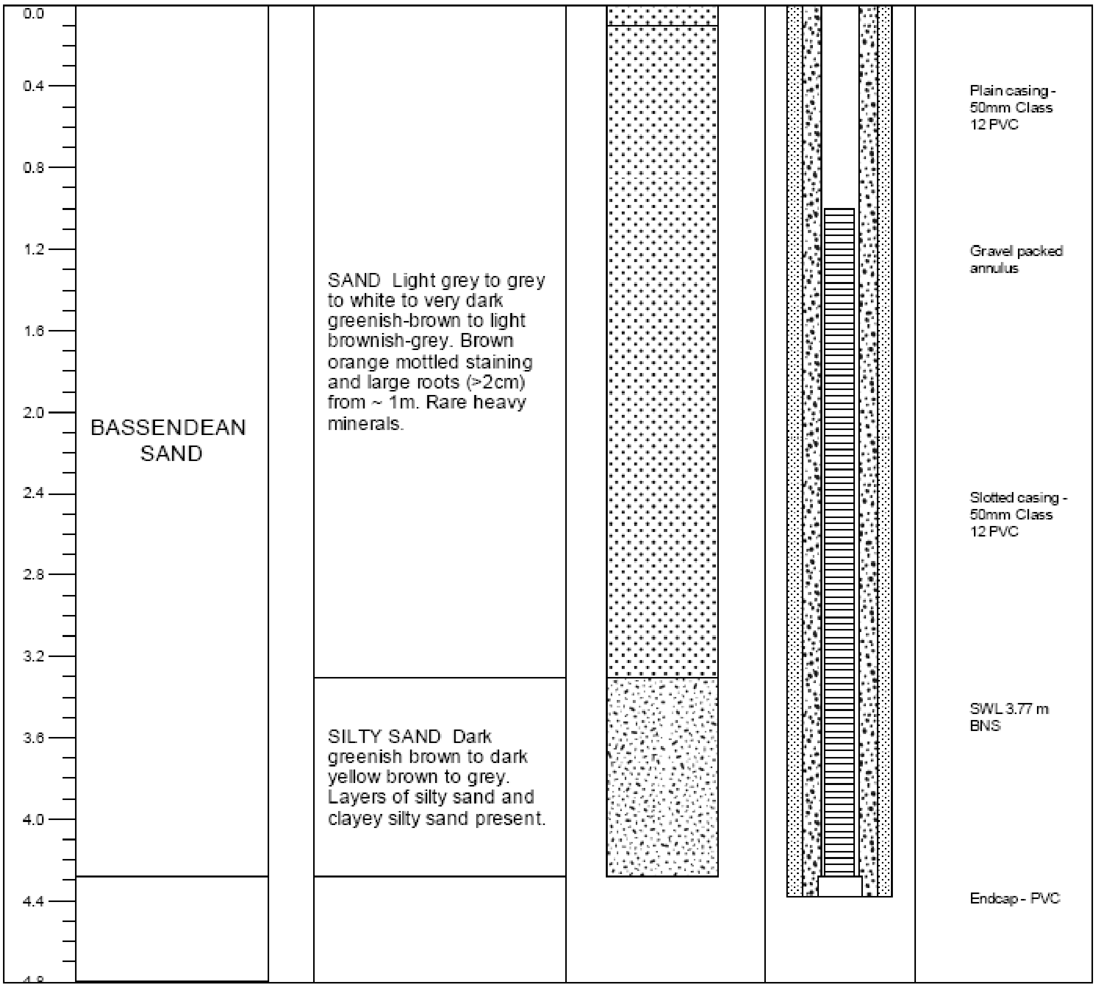
BORE COMPLETION DETAILS

AWRC Name:	**TGT_d**
AWRC Number:	**61710470**

Perth Shallow Groundwater Systems Investigation - Stage 2

Depth	Lithology	Formation	Graphic Log	Bore Construction	Details



BASSENDEAN SAND

SAND Light grey to grey to white to very dark greenish-brown to light brownish-grey. Brown orange mottled staining and large roots (>2cm) from ~ 1m. Rare heavy minerals.

SILTY SAND Dark greenish brown to dark yellow brown to grey. Layers of silty sand and clayey silty sand present.

Drilled by:	Great Southern Drilling	Northing (Z50):	6530402.37	Screens (m BNS):	1.28 - 4.28
Date drilled:	2/13/08	Easting (Z50):	375657.97	SWL (m BNS):	3.77
Logged by:	Sandie McHugh	Surface (m AHD):	47.09	EC (uS/m):	76500
Aquifer:	Superficial	Drill depth (m BNS):	4.28	pH:	2.59

Appendix B — Sampling methods and analysis

Groundwater sampling methodology

Water samples were collected using low-flow pumping methods. The low-flow sampling technique provides a low-stress, low-impact, minimal draw down purging method of groundwater sampling. The pump is lowered to the screened interval of the bore and purged until the water quality parameters of pH, EC and temperature have stabilised. Once stabilised in situ readings can be recorded and samples collected for further laboratory analysis. The method requires smaller volumes of water to be withdrawn than conventional techniques and potentially reduces the aeration or degassing of samples collected. 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) requires decontaminated prior to and after sampling at each site location. Decontamination is conducted by firstly rinsing with a mixture of Decon-910® and scheme water. A second thorough rinse is performed using just scheme water, and then a final very thorough rinse is conducted using the standard laboratory purchased deionised water
- Use new (disposable) air and water tubing for each sampling event
- Ensure water quality meters are functional and calibrated
- 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 0.5m below groundwater level
- Commence pumping, adjust air supply and discharge times
- Other field observations such as interesting sample colour, presence of large quantities of particulate matter, and smell to be noted
- Groundwater quality was measured for the in situ field parameters: pH, conductivity, temperature, redox and dissolved oxygen using multiprobe sensors installed in a flow cell. Measurements to be recorded every 5 minutes until the parameters stabilise then a final reading 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.

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 measuring equipment using appropriate solutions.

3 Adjust the pH of around 1L of 30% hydrogen peroxide (suitable for a day's worth of measurements) to between pH 4.5 and 5.5 using drop-wise addition of 1M NaOH.

4 Collect sediment cores and return to 'field laboratory' setup to perform field tests before oxidation of sediments is able to occur.

Field pH_F and pH_{FOX} testing

1 Take ½ teaspoon sized sample of sediment approximately every 25 cm or when a lithology change is noted (whichever is lesser), noting the depth of the sample

2 Place into beaker used for pH_F tests and add 12 ml of water from a clean syringe (marked pH_F) to make a 1:5 soil:water solution and shake well

3 Take another ½ teaspoon sized sample of sediment from the same place as the previous sample used for the pH_F measurement, and place into a beaker used for measuring pH_{FOX}

4 Add 12 ml of pH adjusted 30% hydrogen peroxide using a second syringe (marked 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 1 hour (during which time logging of cores can be done)

7 Regularly shake (i.e. every 5 to 10 minutes) all beakers to ensure maximum amount of sediment goes into solution

8 After 1 hour record pH_F and 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

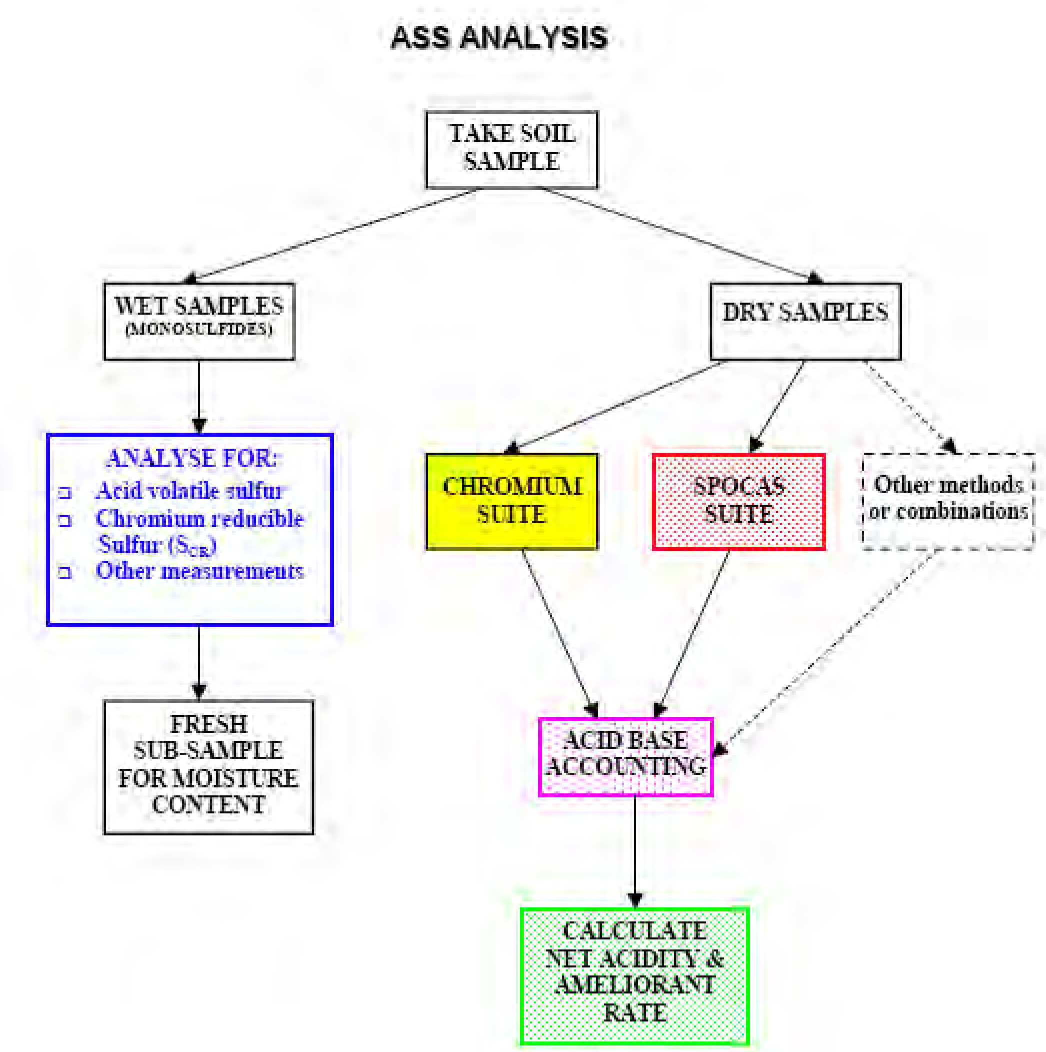
9 Dispose of solutions into an appropriate container (although hydrogen peroxide rapidly decomposes to water and oxygen so is not harmful to the

environment) and thoroughly clean all beakers, syringes and other equipment using Decon (detergent) and water.

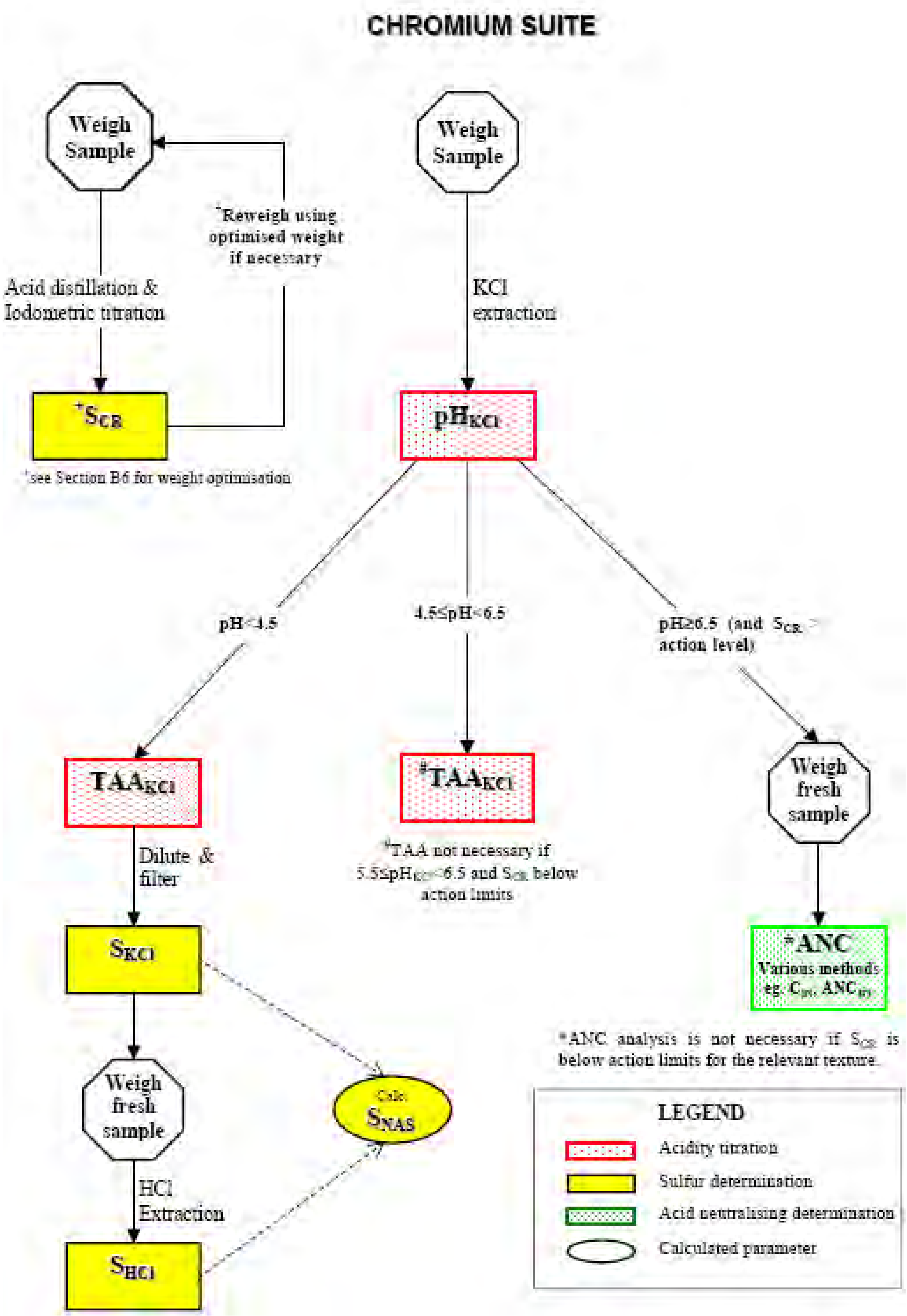
Laboratory methods

(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).



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

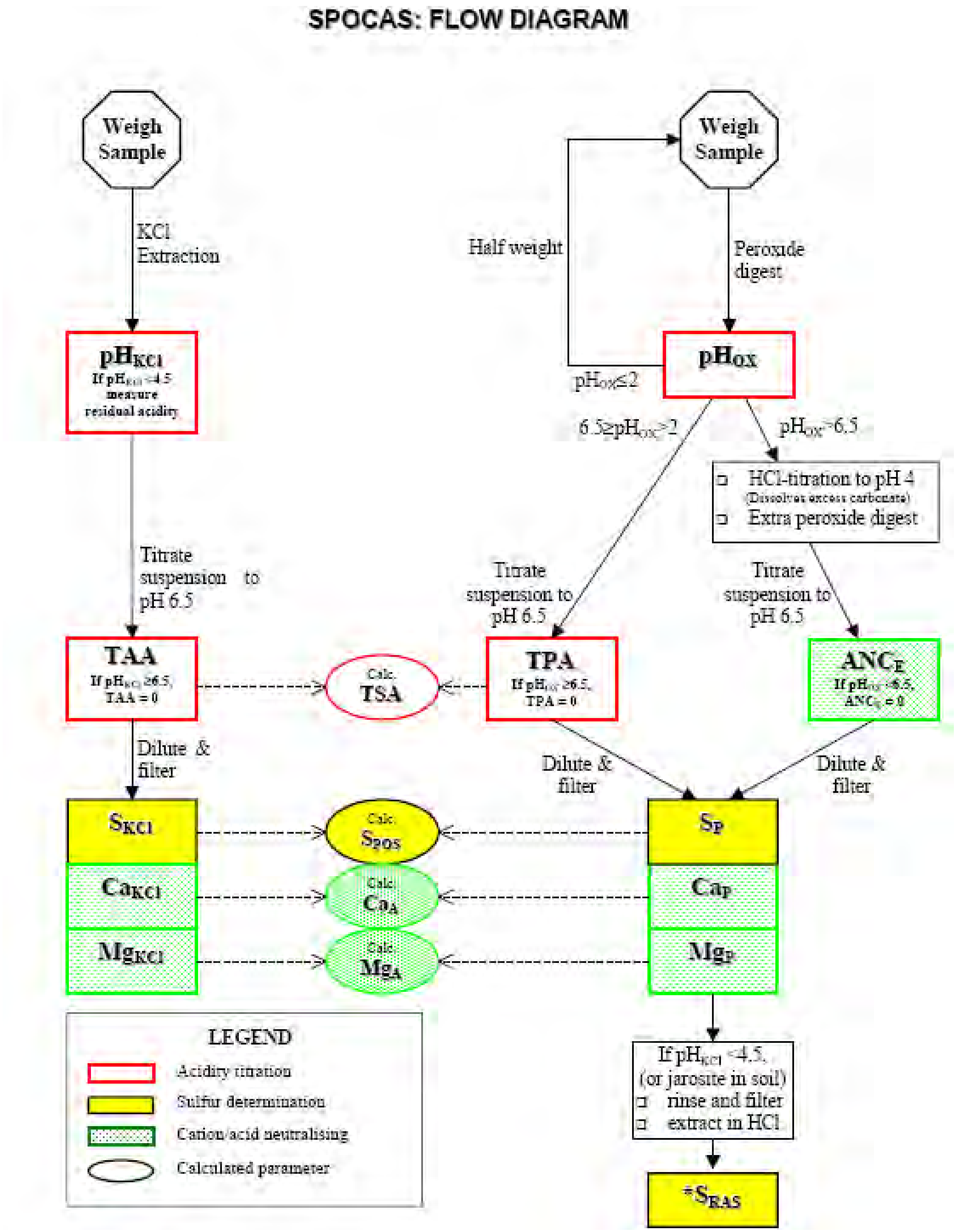


$^{+}$see Section B6 for weight optimisation

$^{\#}$TAA not necessary if $5.5 \leq pH_{KCl} < 6.5$ and S_{CR} below action limits

*ANC analysis is not necessary if S_{CR} is below action limits for the relevant texture.

Flow diagram of steps involved using the chromium suit (from Ahern et al. 1998)



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

The metal and metalloids samples were prepared and digested with HNO_3/HCl at 100°C for two hours and diluted prior to analysis. The concentrations of acid extractable elements in sediments were determined by an inductively coupled plasma mass spectrometer (ICPMS) and inductively coupled plasma atomic emission spectrometer depending on the concentrations and detection limits required.

Anomalously high concentrations which may have been due to matrix interferences were crosschecked once more using the ICPMS.

Appendix C — SGS investigation bore lithology logs

DEPTH (m)	LITHOLOGICAL DESCRIPTION (TGT_a)	
0 – 5	**Sand**	Very pale brown, medium to coarse grained quartz sand with minor fine sand. Low sphericity, sub-angular to sub-rounded, moderately sorted. Loose and dry, organic matter and roots abundant at top, decreasing with depth.
5 – 7	**Sandy Clay**	Dark green-grey. Stiff, cohesive, moderately plastic.
7 – 11	**Sand**	Light brown-grey, medium to coarse grained quartz sand. Sub-angular to sub-rounded, loose, slightly moist.
11 – 18	**Silty Sand**	Light brown-grey, medium to coarse grained quartz sand with abundant silt. Sub-angular to sub-rounded, moist, very weakly cohesive.
18 – 25	**Silty Sand**	Dark green-grey, medium to coarse grained, wet, weakly cohesive. Abundant dark fine grains. Silt decreasing with depth.
25 – 30	**Sand**	Light brown-grey, coarse to very coarse grained quartz sand, with fine quartz grains. Rounded, spherical grains. Abundant heavy minerals/lithic fragments.
30 – 35	**Silty Sand**	Green-grey to brown grey, medium to coarse grained quartz sand. Wet, common opaque white grains (?feldspar)
35 – 36	**Sandy Clay**	Very dark green-grey. Cohesive, abundant shell fragments, possible glauconite and heavy minerals/lithic fragments. Angular to sub-angular lithic fragments. Spicules and some organic matter.
36 – 46	**Silty Sand**	Very dark green-grey to dark grey. Common sub-angular fine sand and HM/lithic frags, abundant shells and glauconite. Wet.
46 – 48	**Shelly Limestone**	Pale yellow, abundant shells. Black rounded pebble (?concretionary nodules) up to 2cm in diameter.
48 – 58	**Sand**	Very dark green grey to grey, coarse grained quartz sand with minor silt. Angular to rounded grains. Wet, loose, abundant shells, common black lithic/nodules
58 - 61	**Sand/Mudstone**	EOH

DEPTH (m)	**LITHOLOGICAL DESCRIPTION (TGT_b)**	
0 – 5	**Sand**	Very pale brown, medium to coarse grained quartz sand with minor fine sand. Low sphericity, sub-angular to sub-rounded, moderately sorted. Loose and dry, organic matter and roots abundant at top, decreasing with depth.
5 – 7	**Sandy Clay**	Dark green-grey. Stiff, cohesive, moderately plastic.
7 – 11	**Sand**	Light brown-grey, medium to coarse grained quartz sand. Sub-angular to sub-rounded, loose, slightly moist.
11 – 18	**Silty Sand**	Light brown-grey, medium to coarse grained quartz sand with abundant silt. Sub-angular to sub-rounded, moist, very weakly cohesive.
18 – 25	**Silty Sand**	Dark green-grey, medium to coarse grained, wet, weakly cohesive. Abundant dark fine grains. Silt decreasing with depth.
25 – 29	**Sand**	Light brown-grey, coarse to very coarse grained quartz sand, with fine quartz grains. Rounded, spherical grains. Abundant heavy minerals/lithic fragments.

DEPTH (m)	**LITHOLOGICAL DESCRIPTION (TGT_c)**	
0 – 0.1	**Topsoil**	Very dark greenish-brown medium to coarse grained quartz sand with minor fines. Sub-angular to sub-rounded. Rich in organic matter, sub-mm scale fibrous roots throughout. Loose and moist.
0.1 – 2.2	**Sand**	Light grey to grey to white. Medium to coarse quartz grained sand with minor fines, as above. Organic matter more abundant at top, becoming rare. Brown orange mottled staining and large roots (>2cm) from ~ 1m. Mostly dry and loose, becoming moist @ 2m. Rare heavy minerals.
2.2 – 3.3	**Sand**	Very dark greenish-brown to light brownish-grey. As above, with brown orange mottling and rare organic matter.
3.3 – 4.5	**Silty Sand**	Dark greenish brown to dark yellow brown to grey. Medium grained quartz sand with minor coarse component, sub-rounded to sub-angular, wet and loose. Layers of silty sand and clayey silty sand present, often stiff and cohesive.
4.5 – 6.7	**Sandy Clay**	Dark green grey with rare yellow brown mottling. Sand grains are medium to coarse sub-angular to sub-rounded quartz. Stiff, cohesive, weakly plastic to plastic. Weathered feldspars > 0.6mm throughout.
6.7 – 11.6	**Sand**	Light brownish-grey to light grey, medium to coarse grained quartz sand, becoming finer grained and more silty towards base. Moderate sphericity. Layers of grey-green silty sand and silty clayey sand @ 8.2 and 9.4m respectively. Rare heavy minerals.
11.6 – 14.2	**Silty Sand**	E.O.H. Light brownish-grey to light grey, silty sand. Less silty in parts (13.5 - 13.7m). Minor heavy minerals.

DEPTH (m)		**LITHOLOGICAL DESCRIPTION (TGT_d)**
0 – 4.74	**Sand**	Very pale brown, medium to coarse grained quartz sand with minor fine sand. Low sphericity, sub-angular to sub-rounded, moderately sorted. Loose and dry, organic matter and roots abundant at top, decreasing with depth.

Appendix D — Acid sulfate soils lab and field results

Bore ID	**Date**	**Soil texture**		**Field pH**			
			Depth m	**pH$_F$**	**PH$_{FOX}$**	**Δ pH**	**Reaction**
TGT_C	07/02/2008	Top soil organic, M to C Qtz sand	0.00	4.76	2.96	−1.80	Slight
TGT_C	07/02/2008	As above, less organic matter	0.10	4.09	2.97	−1.12	
TGT_C	07/02/2008	M to C Qtz sand	0.50	4.58	4.29	−0.29	
TGT_C	07/02/2008	As above	1.00	5.11	4.73	−0.38	
TGT_C	07/02/2008	As above with OM staining and roots	1.25	4.81	3.92	−0.89	
TGT_C	07/02/2008	As above	1.75	4.52	4.16	−0.36	
TGT_C	07/02/2008	As above with brown OM mottling	2.30	3.94	2.41	−1.53	
TGT_C	07/02/2008	L grey, M to C sand	2.95	4.33	2.03	−2.30	Slight
TGT_C	07/02/2008	Silty, M to C Qtz Sand	3.45	5.65	2.08	−3.57	Moderate
TGT_C	07/02/2008	M to C sand, silt	3.60	4.54	1.88	−2.66	Slight
TGT_C	07/02/2008	Silty clayey sand	3.85	6.34	2.28	−4.06	Moderate
TGT_C	07/02/2008	As above	4.25	7.10	5.25	−1.85	Slight
TGT_C	07/02/2008	D grey clay, grey sandy clay	4.90	7.03	6.65	−0.38	vigorous
TGT_C	07/02/2008	As above	5.40	7.22	6.34	−0.88	vigorous
TGT_C	07/02/2008	D green grey clayey sand	6.50	7.48	7.07	−0.41	vigorous
TGT_C	07/02/2008	As above	6.85	6.71	7.08	0.37	Slight
TGT_C	07/02/2008	M to C qtz sand light brown grey	7.60	7.75	7.92	0.17	
TGT_C	07/02/2008	As above	8.55	7.78	4.80	−2.98	
TGT_C	07/02/2008	Grey clay, silty / clayey sand	9.65	7.08	4.07	−3.01	
TGT_C	07/02/2008	M to C qtz sand	10.60	6.57	3.42	−3.15	
TGT_C	07/02/2008	Light grey, medium – coarse qtz sand	11.20	6.58	4.35	−2.23	
TGT_C	07/02/2008	As above with increased silt content	12.40	6.83	4.71	−2.12	
TGT_L1	01/04/2008	Black organic rich silt	0	6.29	4.22	2.07	Moderate
TGT_L1	01/04/2008	Black organic rich silt – iron staining	0.27	5.37	2.64	2.73	Volcanic
TGT_L1	01/04/2008	Black organic rich silt – laminated	0.55	4.49	2.64	1.85	Moderate
TGT_L1	01/04/2008	As above	0.85	4.76	2.88	1.88	Moderate
TGT_L1	01/04/2008	As above	1.1	4.8	3.17	1.63	Moderate
TGT_L1	01/04/2008	Grey brown silt	1.4	6.62	4.65	1.97	Low
TGT_L1	01/04/2008	Very dark grey silt	1.7	6.72	4.54	2.18	Low
TGT_L1	01/04/2008	Very dark grey silt	2	7.26	4.76	2.5	Low
TGT_L1	01/04/2008	Very dark grey silt	2.3	7.18	5.3	1.88	Low
TGT_L1	01/04/2008	Very dark grey silt	2.55	7.2	4.92	2.28	Low
TGT_L1	01/04/2008	Very dark grey silt	2.85	7.19	4.18	3.01	Low
TGT_L1	01/04/2008	Very dark grey silt	3.05	7.43	1.98	5.45	Moderate
TGT_L1	01/04/2008	Greenish brown silt	3.35	7.51	3.92	3.59	Low
TGT_L1	01/04/2008	Very dark grey silt with medium grained quartz sand	3.5	7.79	3.52	4.27	Low
TGT_L1	01/04/2008	Greenish brown silt	3.65	7.24	4.99	2.25	Low

Bore ID	Date	Soil texture	Field pH				
			Depth m	pH$_F$	PH$_{FOX}$	Δ pH	Reaction
TGT_L1	01/04/2008	Light grey silt with medium grained quartz sand	3.8	6.9	4	2.9	Low
TGT_L1	01/04/2008	Very dark grey silt with medium grained quartz sand	4.15	7.73	4.25	3.48	Low
TGT_L1	01/04/2008	Sandy silt	4.35	7.81	2.79	5.02	Low
TGT_L1	01/04/2008	Light grey silt with medium grained quartz sand	4.55	7.09	3.67	3.42	Low
TGT_L1	01/04/2008	As above	4.7	6.75	4.31	2.44	Low
TGT_L1	01/04/2008	Dark green brown silty sand	5.3	8.04	5.25	2.79	None
TGT_L1	01/04/2008	Dark green brown silty sand	5.7	8	4.57	3.43	None
TGT_L1	01/04/2008	Dark green brown silty sand	6	7.74	4.58	3.16	None
TGT_L1	01/04/2008	Dark green brown silty sand	6.5	7.62	5.63	1.99	None
TGT_L1	01/04/2008	Light brown grey sandy silt	6.8	7.81	5.38	2.43	None
TGT_L1	01/04/2008	Light brown grey medium to coarse quartz sand	7.1	8.23	3.24	4.99	None
TGT_L1	01/04/2008	Light brown grey medium to coarse quartz sand	7.7	8.1	4.69	3.41	None
TGT_L1	01/04/2008	Light brown grey medium to coarse quartz sand	8.3	7.46	4.57	2.89	None
TGT_L2	01/04/2008	Black org rich silt, FeO	0	5.05	2.76	2.29	High
TGT_L2	01/04/2008	Black org rich silt, FeO	0.275	5.15	7.36	−2.21	Volcanic
TGT_L2	01/04/2008	Black org rich silt, FeO	0.55	5.2	7.27	−2.07	Volcanic
TGT_L2	01/04/2008	Black org rich silt, FeO	0.775	5.02	1.42	3.6	Volcanic
TGT_L2	01/04/2008	Black org rich silt, FeO	1.1	5.22	2.35	2.87	Volcanic
TGT_L2	01/04/2008	Black sandy silt	1.4	6.35	4.12	2.23	High
TGT_L2	01/04/2008	Black sandy silt	2	6.57	4.26	2.31	High
TGT_L2	01/04/2008	Very dark grey sandy silt	2.45	6.46	3.6	2.86	High
TGT_L2	01/04/2008	Light brown grey med to course Qtz sand	2.9	6.21	3.46	2.75	None
TGT_L2	01/04/2008	Greyish brown Med to course Qtz sand & silt	3.5	6.22	3.79	2.43	Low
TGT_L2	01/04/2008	Greyish brown Med to course Qtz sand & silt	3.8	5.97	2.94	3.03	None
TGT_L2	01/04/2008	Greyish brown Med to course Qtz sand & silt	4.25	5.95	2.58	3.37	None

Bore ID	**Date**	**Soil texture**	**Field pH**				
			Depth m	**pH_F**	**PH_{FOX}**	**Δ pH**	**Reaction**
TGT_L2	01/04/2008	Greyish brown Med to course Qtz sand & silt	4.7	6.08	2.58	3.5	Low
TGT_L2	01/04/2008	Silty sand	4.85	6.56	2.72	3.84	Moderate
TGT_L2	01/04/2008	Silty (clayey) sand	5.3	7.1	4.21	2.89	None
TGT_L2	01/04/2008	Light yellow silty (clayey) sand	5.6	7.09	4.57	2.52	None
TGT_L2	01/04/2008	Green clay	6	7.91	2.49	5.42	Volcanic
TGT_L2	01/04/2008	Light grey sand	6.2	7.49	2.05	5.44	Volcanic
TGT_L2	01/04/2008	Clayey sand (green)	6.45	9.39	6.49	2.9	None
TGT_L2	01/04/2008	Clayey sand (brown)	6.85	8.42	2.07	6.35	None
TGT_L2	01/04/2008	Sandy silt	7.3	8.85	8.9	−0.05	Volcanic
TGT_L2	01/04/2008	Sandy silt / silty sand green / orange	7.7	8.83	8.44	0.39	Volcanic
TGT_L2	01/04/2008	Sandy silt – predom orange	8	9.51	8.37	1.14	Volcanic
TGT_L2	01/04/2008	Dark green clay	8.55	8.67	5.56	3.11	Volcanic
TGT_L2	01/04/2008	Sand	9	8.93	5.73	3.2	Moderate
TGT_L2	01/04/2008	Sand	9.5	7.89	5.89	2	Moderate

NMI lab number	Client sample number	ANC_{bt}	S_{Cr}	TAA	S_{NaS} (Calc)					Soil	Soil
		Acid neutralising capacity back titration	**Potential sulfidic acidity**	**Actual acidity**	**Retained acidity**	**Net acidity**	**Net acidity**	**Fineness factor**	**Safety factor**	**Bulk density**	**Liming rate for Ag lime**
		% $CaCO_3$	**% S**	**$molH^+/ t$**	**% S**	**as % S**	**as $molH^+/ t$**			**t/ m^3**	**kg $CaCO_3/ t$**
Limit of reporting		<0.05	<0.01	<1	<0.01						
W07/07822	200720802		0.03	10		0.05	29	1.5	1.5	1.0	2.2
W07/07823	200720803		0.05	66	0.15	0.27	167	1.5	1.5	1.0	13
W07/07824	200720804		0.04	6		0.05	31	1.5	1.5	1.0	2.4
W07/07825	200720805		0.06	<1		0.06	37	1.5	1.5	1.0	2.9
W07/07826	200720806		0.02	<1		0.02	12	1.5	1.5	1.0	1.0
W07/07827	200720807		0.03	28		0.07	47	1.5	1.5	1.0	3.7
W07/07828	200720808		0.19	71		0.30	190	1.5	1.5	1.0	15
W07/07829	200720809		0.06	46		0.13	83	1.5	1.5	1.0	6.5
W07/07830	200720810	0.90	0.07	<1		−0.12	−76	1.5	1.5	1.0	−6.0
W07/07830-D	200720800	0.91	0.06	<1		−0.13	−84	1.5	1.5	1.0	−6.6

Client sample number	ANC_E	ANC_E	pH_{KCl}	TAA	TAA	TAA	TPA	TPA	TSA (Calc)	TSA	TSA
	Excess acid neutralising capacity	Excess acid neutralising capacity	pH of KCl extract	Titratable actual acidity	Titratable actual acidity	Titratable actual acidity	Titratable peroxide acidity	Titratable peroxide acidity	Titratable sulfidic acidity	Titratable sulfidic acidity	Titratable sulfidic acidity
	as % S	as $molH^+$/ t		$molH^+$/ t	as %S	as $molH^+$/ t	$molH^+$/ t	as $molH^+$/ t	$molH^+$/ t	as %S	as $molH^{+/}$ t
Limit of reporting				<1			<1		<1		
200720802	0	0	5.8	10	0.016033	10	910	910	900	1.443001443	900
200720803	0	0	4.4	66	0.10582	66	1600	1600	1500	2.405002405	1500
200720804	0	0	5.7	6	0.00962	6	46	46	39	0.062530063	39
200720805	0	0	7	<1	0	0	15	15	15	0.024050024	15
200720806	0	0	6.9	<1	0	0	<1	0	<1	0	0
200720807	0	0	4.9	28	0.044893	28	1000	1000	1000	1.603334937	1000
200720808	0	0	4.7	71	0.113837	71	1800	1800	1800	2.886002886	1800
200720809	0	0	4.8	46	0.073753	46	200	200	160	0.25653359	160
200720810	0	0	8.2	<1	0	0	110	110	110	0.176366843	110
200720800	0	0	8.3	<1	0	0	130	130	130	0.208433542	130

Client sample number	**Ca_A (Calc)**	**Ca_A**	**Ca_A**	**Mg_A (Calc)**	**Mg_A**	**Mg_A**	**S_{NaS} (Calc)**	**S_{NaS}**	**S_{NaS}**	**S_{POS} (Calc)**	**S_{POS}**	**S_{POS}**
	Reacted Ca	**Reacted Ca**	**Reacted Ca**	**Reacted Mg**	**Reacted Mg**	**Reacted Mg**	**Retained acidity**	**Retained acidity**	**Retained acidity**	**Potential sulfidic acidity**	**Potential sulfidic acidity**	**Potential sulfidic acidity**
	% Ca	**as %S**	**as $molH^+$/ t**	**% Mg**	**as %S**	**as $molH^+$/ t**	**% S**	**as %S**	**as $molH^+$/ t**	**% S**	**as %S**	**as $molH^+$/ t**
Limit of reporting	<0.1			<0.1			<0.01			<0.01		
200720802	<0.1	0	0	<0.1	0	0		0	0	0.37	0.37	230.769
200720803	0.1	0.08	49.9	<0.1	0	0	0.15	0.1125	70.1662	1.4	1.4	873.18
200720804	<0.1	0	0	<0.1	0	0		0	0	0.17	0.17	106.029
200720805	<0.1	0	0	<0.1	0	0		0	0	0.07	0.07	43.659
200720806	<0.1	0	0	<0.1	0	0		0	0	0.01	0.01	6.237
200720807	<0.1	0	0	<0.1	0	0		0	0	0.7	0.7	436.59
200720808	<0.1	0	0	<0.1	0	0		0	0	1.6	1.6	997.92
200720809	<0.1	0	0	<0.1	0	0		0	0	<0.01	0	0
200720810	<0.1	0	0	<0.1	0	0		0	0	0.29	0.29	180.873
200720800	<0.1	0	0	<0.1	0	0		0	0	0.39	0.39	243.243

Client sample number	Net acidity	Alternative calculation	Net acidity	Alternative calculation			Soil		Alternative calculation
		Net acidity		Net acidity	Fineness factor	Safety factor	Bulk density	Liming rate for ag lime	Liming rate for ag lime
	as % S	as % S	as molH^{+}/ t	as molH$^{+/}$ t			t/ m^{3}	kg CaCO$_3$/ t	kg CaCO$_3$/ t
200720802	0.386033	0.386033	240.769	240.769	1.5	1.5	1	18.82891	18.82891
200720803	1.61832	1.61832	1009.346	1009.346	1.5	1.5	1	78.93411	78.93411
200720804	0.17962	0.17962	112.029	112.029	1.5	1.5	1	8.761027	8.761027
200720805	0.039367	0.07	24.553	43.659	1.5	1.5	1	1.920123	3.414274
200720806	0.003333	0.01	2.079	6.237	1.5	1.5	1	0.162584	0.487753
200720807	0.744893	0.744893	464.59	464.59	1.5	1.5	1	36.33243	36.33243
200720808	1.713837	1.713837	1068.92	1068.92	1.5	1.5	1	83.59297	83.59297
200720809	0.073753	0.073753	46	46	1.5	1.5	1	3.597347	3.597347
200720810	0.214245	0.29	133.6243	180.873	1.5	1.5	1	10.44985	14.14485
200720800	0.268956	0.39	167.7477	243.243	1.5	1.5	1	13.1184	19.02238

Site reference number	WRC reference number	Sample depth m	Aluminium mg/kg	Arsenic mg/kg	Cadmium mg/kg	Chromium mg/kg	Iron mg/kg	Manganese mg/kg	Nickel mg/kg	Selenium mg/kg	Zinc mg/kg	Total solids %
TGTL_1	200720802	0	25300	4.8	<0.5	58	15500	93	21	9.1	21	47.8
TGTL_1	200720803	0.55	23200	4.4	<0.5	60	11800	19	20	6.9	7.8	34.6
TGTL_1	200720804	1.1	26500	8	<0.5	53	7640	20	16	7.7	13	53.5
TGTL_1	200720805	3.05	21900	3.4	<0.5	46	3790	2.5	11	0.57	<0.5	81.4
TGTL_1	200720806	4.15	13400	<0.5	<0.5	17	2270	2	6.2	<0.5	<0.5	88.9
TGTL_2	200720807	0.275	18800	3.9	<0.5	45	13400	33	17	7.1	11	44.1
TGTL_2	200720808	0.775	18400	7.6	<0.5	49	14000	46	22	6.8	13	30
TGTL_2	200720809	2	9110	2.5	<0.5	20	3040	8.6	6.7	1	1.3	66.9
TGTL_2	200720800	6.2	16700	0.7	<0.5	48	14800	15	15	0.84	2.2	73.4
TGTL_2	200720800-D											

Site reference number	WRC reference number	Sample depth m	ANC_{bt} as $CaCO_3$ %	pH_{KCl}	pH_{ox}	S_{Cr} %	TAA $molH^+/ t$	TPA $molH^+/ t$	TSA (Calc) $molH^+/ t$
TGTL_1	200720802	0		5.8	3.7	0.03	10	910	900
TGTL_1	200720803	0.55		4.4	2.5	0.05	66	1600	1500
TGTL_1	200720804	1.1		5.7	4.5	0.04	6	46	39
TGTL_1	200720805	3.05	0.37	7	4.4	0.06	<1	15	15
TGTL_1	200720806	4.15		6.9	5.1	0.02	<1	<1	<1
TGTL_2	200720807	0.275		4.9	3.4	0.03	28	1000	1000
TGTL_2	200720808	0.775		4.7	2.4	0.19	71	1800	1800
TGTL_2	200720809	2		4.8	3.1	0.06	46	200	160
TGTL_2	200720800	6.2	0.9	8.2	3.1	0.07	<1	110	110
TGTL_2	200720800-D		0.91	8.3	2.9	0.06	<1	130	130

Site reference number	WRC reference number	Sample depth	Ca_A (Calc)	Ca_{KCl}	Ca_P	Mg_A (Calc)	Mg_{KCl}	Mg_P	S_{HCl}	S_{KCl}	S_{NaS} (Calc)	S_P	S_{POS} (Calc)
		m	%	%	%	%	%	%	%	%	%	%	%
TGTL_1	200720802	0	<0.1	2.5	0.6	<0.1	0.6	0.5		1.4		1.8	0.37
TGTL_1	200720803	0.55	0.1	1.1	1.2	<0.1	0.6	0.6	1.1	0.96	0.15	2.4	1.4
TGTL_1	200720804	1.1	<0.1	0.4	0.4	<0.1	0.3	0.3		0.24		0.41	0.17
TGTL_1	200720805	3.05	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1		0.05		0.12	0.07
TGTL_1	200720806	4.15	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1		0.03		0.04	0.01
TGTL_2	200720807	0.275	<0.1	0.7	0.3	<0.1	0.6	0.6		0.72		1.4	0.7
TGTL_2	200720808	0.775	<0.1	1.2	0.5	<0.1	0.9	0.8		1.3		2.9	1.6
TGTL_2	200720809	2	<0.1	0.6	0.3	<0.1	0.4	0.2		0.59		0.56	<0.01
TGTL_2	200720800	6.2	<0.1	0.2	0.2	<0.1	0.4	0.3		0.1		0.39	0.29
TGTL_2	200720800-D		<0.1	0.2	0.2	<0.1	0.4	0.4		0.09		0.48	0.39

Shortened forms

AASS	Actual acid sulfate soils
ABA	Acid-base accounting
AHD	Australian height datum
ANC	Acid neutralising capacity
ANZECC	Australian and New Zealand Environment and Conservation Council
ARMCANZ	Agricultural and Resource Management Council of Australia and New Zealand
ASS	Acid sulfate soils
CRS	Chromium reducible sulfur suite of analyses
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DO	Dissolved oxygen
EC	Electrical conductivity
EIL	Ecological investigation level
EWP	Environmental water provision
EWR	Ecological water requirement
GDE	Groundwater-dependent ecosystem
mbns	Metres below natural surface (below ground level)
NHMRC	National Health & Medical Research Council
NMI	National Measurement Institute
NRMMC	Natural Resource Management Ministerial Council
NWPASS	National Working Party on Acid Sulfate Soils
ORP	oxidation reduction potential
PASS	Potential acid sulfate soils
SGS	Shallow groundwater systems
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
TPA	Titratable peroxide acidity
TSA	Titratable sulfidic acidity

Glossary

Abstraction	The withdrawal of water from any water resource.
Acid buffering capacity	A measure of the resistance to changes in pH following the addition of an acid.
Acid neutralising capacity	A measure of the soil's ability to buffer acidity and resist the lowering of soil pH.
Acid sulfate soils	Naturally occurring, these are soils containing significant quantities of reduced sulfur (pyrite and other sulfides). When these soils are disturbed the reduced sulfur is oxidised resulting in the release of acidity and often toxic metals.
Acidification	The process by which soil, or water becomes more acidic (decreasing pH).
Actual acidity	The soluble and exchangeable acidity already present in the soil.
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.
Aquifer	A geological formation or group of formations able to receive, store and/or transmit large amounts of water.
Buffer	A solution which resists changes in pH when a small amount of strong acid or base are added
Buffering capacity	*see* Acid-buffering capacity.
Confined aquifer	A permeable bed saturated with water and lying between an upper and a lower confining layer of low permeability, the hydraulic head being higher than the upper surface of the aquifer.
Confining bed	Sedimentary bed of very low hydraulic conductivity.

Contaminants	A substance that is either present in an environment where it does not belong or is present at levels that might cause harmful effects to humans or the environment.
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).
Evapotranspiration	The combined loss of water by evaporation and transpiration. Includes water evaporated from the soil surface and water transpired by plants.
Fineness factor	A factor applied to the acid neutralising capacity to allow for the poor reactivity of coarser carbonate or other acid neutralising material.
Formation	A group of rocks or sediments that have certain characteristics in common, were deposited about the same geological period, and that constitute a convenient unit for description.
Groundwater	Water that occupies the pores within the rock or soil profile.
Groundwater-dependent ecosystem	An ecosystem that depends on groundwater for its existence and health.
Hydraulic gradient	The rate of change of total head per unit distance of flow at a given point and in a given direction.
Ion	An atom which has lost or gained electrons and therefore carries an electrical charge.
Leach	Remove soluble matter by percolation of water.
Metalloid	An element whose properties are between those of metals and non-metals.
Neutralisation	The chemical reaction in which an acid and a base react to produce salt and water.

Oxidation	A process resulting in the loss of electrons from a chemical species accompanied by an increase in oxidation state. This process does not necessarily require the presence of oxygen.
pH	The negative logarithm of the concentration of hydrogen ions.
Phreatophytic vegetation	Vegetation that obtains its water from the watertable or the capillary zone above it.
Potential sulfidic acidity	The latent acidity that will be released if the sulfide minerals in acid sulfate soil are fully oxidised.
Redox potential	In aqueous solutions, the reduction potential is the tendency of the solution to either gain or lose electrons and is measured in volts (V), millivolts (mV), or Eh (1 Eh = 1 mV mV). Because the absolute potentials are difficult to accurately measure, reduction potentials are defined relative to the standard hydrogen electrode which is arbitrarily given potential of 0.00 V.
Reduction	A process resulting in the gain of electrons by a chemical species accompanied by a decrease in oxidation state.
Retained acidity	The 'less available' fraction of the existing acidity which may be released slowly into the environment.
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
Stressor	An agent, condition or other stimulus that causes stress to an organism or ecosystem.
Sulfate reduction	In the aquatic environment, the microbially catalysed process which converts sulfate to sulfide.
Surficial	Pertaining to the surface.

Toxicity	The degree to which a substance is able to damage an exposed organism.
Transpiration	The loss of water vapour from a plant, mainly through the leaves.
Trigger level	Concentrations of key indicators, above or below which there is a risk of adverse biological effects.
Unconfined aquifer	A permeable bed only partially filled with water and overlying a relatively impermeable layer. Its upper boundary is formed by a free watertable or phreatic level under atmospheric pressure.
Xerophytic	Vegetation relating to, or growing in dry conditions that does not require access to water from a permanent ground supply or from the watertable.
Watertable	The surface of a body of unconfined groundwater at which the pressure is equal to that of the atmosphere.

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