



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

A baseline study of contaminants in groundwater at disused waste disposal sites in the Swan Canning catchment



Looking after all our water needs

Water Science
technical series

Report no. WST 4
December 2009

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Swan River Trust.

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Department of Water
168 St Georges Terrace
Perth Western Australia 6000
Telephone +61-8-6364 7600
Facsimile +61-8-6364 7601
www.water.wa.gov.au

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For more information about this report contact Sarah Evans, Water Science Branch, Department of Water.

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Executive summary

The *Baseline study of contaminants in groundwater at disused waste disposal sites in the Swan Canning catchment* is the third part of the four component Non-Nutrient Contaminant Program. Groundwater was sampled from investigation bores across three historical waste disposal sites in the Swan Canning catchment, in order to broadly characterise the groundwater as a potential source of contamination to the Swan Canning estuary when assessed against the *Australian Water Quality Guidelines for Fresh and Marine Waters* (ANZECC & ARMCANZ 2000).

The study showed that groundwater at all three sites was contaminated to some degree according to classification by the Department of Environment and Conservation (Department of Environment and Conservation n.d (b)). The extent and type of contamination is dependant on the form, age and quantity of waste, and biogeochemical reactions occurring within the groundwater itself. In general, the highest and most widespread groundwater contamination was detected at Woodbridge Riverside Park, followed by Bayswater Riverside Gardens and Bicentennial Adenia Park. The range of contaminants present reflects anecdotal reports of the type of fill dumped at each site with Woodbridge receiving waste from a broad range of residential and industrial sources, and Adenia receiving primarily green and inert waste.

Several guidelines were consulted when considering water quality trigger values including *Schedule B (1) Guideline of the investigation levels for soil and groundwater* (National Environment Protection Council 1999) and the draft document *Assessment levels for soil, sediment and water* (Department of Environment 2003c). Trigger values of both documents reflect the *Australian water quality guidelines for fresh and marine waters* (ANZECC & ARMCANZ 2000) and consequently this document was used as the primary reference in the current study. This is appropriate when considering the likely interaction between the superficial aquifer and the ecologically sensitive Swan and Canning Rivers, with the primary “use” of the receiving body being as an aquatic ecosystem. It is important to note however, that ANZECC & ARMCANZ (2000) trigger values are appropriate for comparison to concentrations measured in the receiving water body itself, rather than those measured in groundwater. An exceedance of a trigger value by a contaminant in groundwater therefore does not necessarily mean that the contaminant is causing ecological harm but rather that further investigations should be undertaken.

Lead, aluminium, chromium, copper, iron and zinc were found in concentrations more than a hundred times higher than ANZECC & ARMCANZ (2000) trigger values for freshwater, in at least one sample in the study. Arsenic, cadmium, manganese and nickel were present in concentrations that exceeded these trigger values in several samples.

Of the petroleum and polycyclic aromatic hydrocarbons included in the analysis, only naphthalene was present in concentrations that exceeded the trigger value. There were however, numerous other petroleum and polycyclic aromatic hydrocarbons detected in the study for which trigger values were not available. In some instances these may be harmful to aquatic organisms, as suggested by exceedance of alternative guidelines such as the *British Columbia approved water quality guidelines* (2006).

Polychlorinated biphenyls, herbicides and organochlorine and organophosphate pesticides were not detected in concentrations above the limit of reporting at any of the disused waste disposal sites.

Nutrients present in highest concentrations were ammonium, dissolved organic nitrogen and filterable reactive phosphorus. There were numerous detections of ammonium at concentrations that exceeded ANZECC & ARMCANZ (2000) guidelines by more than a hundred fold.

It is likely that groundwater from the waste disposal sites will discharge, or is currently discharging, to the Swan Canning system due to their close proximity to the Swan and Canning Rivers. The speed of this process, its impacts upon the Swan Canning estuary and subsequent toxicological effects are the subject of further studies (e.g. Nice 2009). In order to assess the risk to the river of waste disposal site leachate in more detail it is recommended that the groundwater surface and contaminated zones of the leachate plume are mapped to determine the passage and flow rates through the sites. In addition, further investigations are required to determine the zones of interaction between the groundwater and the adjacent water and bed sediments of the Swan Canning system. These more in-depth investigations should focus initially at Woodbridge Riverside Park, due to the greater degree of contamination detected in the study.

The results of this study along with the results from *A baseline study of contaminants in the Swan and Canning catchment drainage system* (Nice et al. 2009) enabled the prioritisation of sites for further investigation in the subsequent study, *A baseline study of contaminants in the sediments of the Swan and Canning estuaries* (Nice 2009).

1 Introduction

1.1 Background to the Non-Nutrient Contaminants Program (NNCP)

The Non-Nutrient Contaminants Program (NNCP) was a three year program in operation from 2006 to 2008 to determine the nature of contaminants delivered to and present in the Swan Canning system. For this program, the non-nutrient contaminants investigated included pathogens, heavy metals, low-level persistent organic compounds such as pesticides (including herbicides), polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs) and anionic surfactants as well as contaminants resulting from possible disturbance of acid sulphate soils and sediments.

The interest in conducting an assessment of 'non-nutrient' contaminants arose from earlier programs developed through the Swan River Trust and previous reviews and investigations conducted by the then Water and Rivers Commission operating as the Department of Environment. One such initiative, the Swan-Canning Cleanup Program (SCCP), was established by the Swan River Trust to investigate the symptoms of deteriorating environmental health in the Swan Canning system. The program focused predominantly on nutrient contaminants, however, the need to investigate other types of contaminants was identified within the SCCP Action Plan (Swan River Trust 1999a). Actions and recommendations included the need to review, measure and reduce contaminants within the Swan and Canning Rivers and contributing drainage networks in addition to the identification and management of contaminants leaching to groundwater from old waste disposal sites close to the Swan and Canning waterways (Swan River Trust 1999a).

Major findings from the 1999 SCCP review of contaminants in the Swan-Canning system (Swan River Trust 1999b) found datasets of metal concentrations in water, sediment and biota to be spatially and temporally irregular, with inconsistent sampling and analysis methods applied and unsuitable laboratory limits of reporting. In addition, there was a paucity of data for persistent organic compounds (such as pesticides, PAHs and PCBs) within the Swan Canning system. The review identified the need to conduct a comprehensive survey of non-nutrient contaminants in surface water, sediments and biota of the Swan Canning system. Additionally, an investigation of the impact of stormwater discharges to the rivers and estuary was recommended (Swan River Trust 1999b). Subsequent major drainage impact studies conducted by Department of Environment as a result of fish kills in the vicinity of drain outfalls to the Swan and Canning Rivers also highlighted the need for a more comprehensive understanding of the non-nutrient component of contaminants within and entering the Swan Canning system (Department of Environment 2003a; Department of Environment 2003b).

1.2 Overall scope of the NNCP

The NNCP has the overall objective of determining the nature (types, concentrations and spatial variability) of non-nutrient contaminants delivered to and present in the Swan-Canning system.

The NNCP was composed of the following studies:

- A baseline study of contaminants in the Swan and Canning catchment drainage system (Nice et al. 2009).

- An assessment of groundwater quality at disused waste disposal sites in the vicinity of the Swan and Canning waterways and drains (this report).
- A baseline study of organic contaminants in the Swan and Canning catchment drainage system using passive sampling devices (Foulsham et al. 2009).
- A baseline study of contaminants in the sediment of the Swan and Canning estuaries (Nice 2009).

1.3 Background to the baseline study of contaminants in groundwater at disused waste disposal sites in the Swan-Canning catchment

Extensive research in other systems has identified reclaimed waste disposal sites as a major source of groundwater contamination from leachates containing excessive nitrogen (primarily ammonium), heavy metals and organic compounds (Wakida & Lerner 2005). If contaminants are present in the superficial aquifer at sites located along the perimeter of the Swan and Canning Rivers there is potential for those contaminants to migrate through groundwater seepage to the river system (Westbrook et al. 2005). The groundwater assessment component of the NNCP was focused on identifying and quantifying non-nutrients (and nutrients) in the superficial aquifer of three disused waste disposal sites within the Swan and Canning catchment. These sites were Bicentennial Adenia Park, Riverton; Bayswater Riverside Gardens, Bayswater; and Woodbridge Riverside Park, Woodbridge. Commencing in May 2006, groundwater samples were initially collected and analysed to determine concentrations of metals, nutrients and major ions. In November 2006, the sampling was repeated, however the list of analytes was expanded to include a suite of organic compounds. The final sampling run was undertaken in May and June 2007 and included this more comprehensive list of analytes but with enhanced (i.e. lower concentration) limits of reporting.

1.4 Objectives of the study

The objectives of the groundwater assessment component of the NNCP were:

- to provide baseline information with regard to the quality and quantity of groundwater at three disused waste disposal sites situated along the perimeter of the Swan Canning system
- to identify potential contaminants of concern.

1.5 Contaminant selection

Representative compounds from the following groups of analytes were selected for determination within groundwater samples:

- polycyclic aromatic hydrocarbons (PAHs)
- total petroleum hydrocarbons
- polychlorinated biphenyls (PCBs)
- organochlorine pesticides
- organophosphorus pesticides
- herbicides

- major ions
- nutrients

The rationale for selection of analytes was based on the findings of previous studies within the Swan Canning system (e.g. Department of Environment 2003a; Department of Environment 2003b); the known toxicity of key contaminants such as those identified by the Stockholm Convention (2001) as persistent organic pollutants; the likelihood of contaminants being present due to historical land uses; and the ability of laboratories to accurately determine the analytes using endorsed methods.

1.6 Application of guideline values

Three Australian guidelines were consulted when considering groundwater trigger values for the superficial aquifer adjacent to the ecologically sensitive Swan and Canning Rivers, namely:

- *Schedule B (1) Guideline of the investigation levels for soil and groundwater* (National Environment Protection Council 1999)
- the draft document *Assessment Levels for soil, sediment and water* (Department of Environment 2003c)
- *Australian water quality guidelines for fresh and marine waters* (ANZECC & ARMICANZ 2000).

In the results section of this report, the *Australian water quality guidelines for fresh and marine waters* (ANZECC & ARMICANZ 2000) is cited as the primary reference for trigger values and will herein be referred to as ANZECC guidelines or trigger values. ANZECC & ARMICANZ (2000) includes the broadest range of analytes and when 'investigation levels', 'assessment levels' or 'trigger values' were available in the other above-mentioned Australian guidelines they were generally in agreement to ANZECC & ARMICANZ (2000). When there was a discrepancy between references, the alternative value was noted in addition to the ANZECC guideline within the results summary table and highlighted within the discussion of those analytes.

The ANZECC guidelines refer to 'trigger values', defined as 'concentrations that, if exceeded, will indicate a potential environmental problem, and so 'trigger' further investigation' (ANZECC & ARMICANZ 2000 pp. 2-5). Trigger values applied to this study are those stated for lowland rivers of south west Australia for the protection of 95% of species. This high level of protection was selected due to the ecologically sensitive nature of the Swan-Canning system. It is important to note however, that these ANZECC trigger values are appropriate for comparison to concentrations measured in the receiving body itself, rather than to those measured in groundwater. An exceedance of a trigger value by a contaminant in groundwater therefore does not necessarily mean that the contaminant is causing ecological harm, but rather that further investigations should be undertaken.

ANZECC guidelines were frequently unavailable for petroleum hydrocarbons and PAHs, and in these cases the British Columbia approved water quality guidelines (2006) were considered to provide a context for the results. It should be noted that the British Columbian guidelines are frequently more conservative than the ANZECC guidelines. For example, the freshwater criteria for naphthalene was 1 µg/L compared with the ANZECC trigger value of 16 µg/L.

The *Assessment levels for soil, sediment and water* (2003c) are used by the Department of Environment and Conservation to define the presence of 'contamination' when specific substances are recorded above these assessment levels (Department of Environment and Conservation n.d.(b)). This document (pp.17) states that the 'most appropriate groundwater quality assessment level is dependent upon the discharge location and the beneficial use of the groundwater resource'. In the current study, an interaction between the superficial aquifer and the Swan Canning system is acknowledged, and the primary 'use' being considered is as an aquatic ecosystem. While it is acknowledged that the Swan Canning system does also have recreational uses and as such, contaminated groundwater discharge has the potential for human health effects, these considerations were outside the scope of the study.

1.7 Definition of a 'contaminated site'

The *Contaminated Sites Act 2003* defines a 'contaminated site' as; 'in relation to land, water or a site, having a substance present in or on that land, water or site at above background concentrations that presents, or has the potential to present, a risk of harm to human health, the environment or any environmental value'. Further, the Department of Environment and Conservation *Contaminated sites fact sheet* (Department of Environment and Conservation n.d.(b)) states that 'Contamination is deemed present if there are specific substances recorded above recommended concentrations, as listed in the Department of Environment and Conservation Guideline, *Assessment levels for soil, sediment and water*' (Department of Environment 2003(c)). As such, sites may be referred to as 'contaminated' if sampling shows concentrations above the Department of Environment and Conservation assessment levels, which for the majority of analytes, are identical to the ANZECC guidelines.

According to the *Contaminated Sites Act*, all sites of known or suspected contamination reported to Department of Environment and Conservation are classified into one of seven possible classifications ranging from 'report not substantiated' to 'decontaminated'. Woodbridge Riverside Park and Bayswater Riverside Gardens have been reported to the Department of Environment and Conservation and in 2007 were undergoing classification. At that time, Adenia Bicentennial Park was not reported as a potentially contaminated site. As none of the three disused waste disposal sites have been formally assessed by this Department of Environment and Conservation process it is inappropriate to refer to them as contaminated sites and we have therefore not done so in this report.

1.8 The superficial aquifer within the Perth metropolitan region

The superficial aquifer of the Perth metropolitan area is a major, multi-layered, unconfined or locally semi-confined aquifer which extends throughout the coastal plain. The age of the aquifer ranges from the present at the watertable to approximately 2000 years at the base, and has a maximum thickness of approximately 70 m (Davidson 1995). It consists of predominantly clayey sediments in the upper reaches of the Swan Canning estuary, through a sandy succession to sand and limestone at the coastal belt (Davidson 1995).

Groundwater discharge to the Swan Canning Estuary occurs from three distinct groundwater flow systems: the Gngangara Mound to the north, the Jandakot Mound to the south and the Cloverdale System to the east. The Cottesloe mound, a freshwater lens, also discharges to the Swan Canning estuary (Appleyard 1992).

1.9 Waste disposal site history

As is typical of municipal waste disposal sites closed since the introduction of *Environmental Protection Act 1986*, records of operation of the three waste disposal sites included in the study are poor. Anecdotal evidence was obtained from the local council for each site. The general design principle of waste disposal site construction in the 1960s and 1970s was to 'dilute and attenuate'. As a result, contaminated plumes are commonly associated with waste disposal sites of this era. In keeping with this principle, all three sites investigated here were neither capped for the prevention of leachate generation, nor lined for the prevention of leachate migration.

Woodbridge Riverside Park was opened in the mid 1960s and operated as an uncontrolled mixed use waste disposal site receiving domestic, industrial, putrescible and some medical waste until 1985. For approximately 10 years after closure, clay, bitumen, concrete and road and construction materials were stockpiled on the site (N Stawarz 2007 pers. comm).

Bayswater Riverside Gardens was also an uncontrolled municipal waste site. The western side of the site operated from 1957 until 1971 and the eastern side operated from 1971 until 1983 (J Maher 2007 pers. comm). Bicentennial Adenia Park operated for a much shorter time frame, from approximately 1975 until 1977 (J Howley 2007 pers. comm.). It is a shallow site that took only green and inert waste such as construction materials and rubble.

2 Methods

2.1 Site selection

The three sites were selected from the 'Land use, economic development, growth, agriculture, conservation and investment' (LEGACI) database of contaminated sites at the time the project was initiated (Figure 1). This database is no longer in operation, and has been superseded by the Department of Environment and Conservation's contaminated sites register. As discussed above, the three sites have not been formally classified for inclusion in this register.

Two sites were selected adjacent the Swan River; Baywater Riverside Gardens and Woodbridge Riverside Park in the upper reaches. The third site selected, Bicentennial Adenia Park, is adjacent to the Canning River.

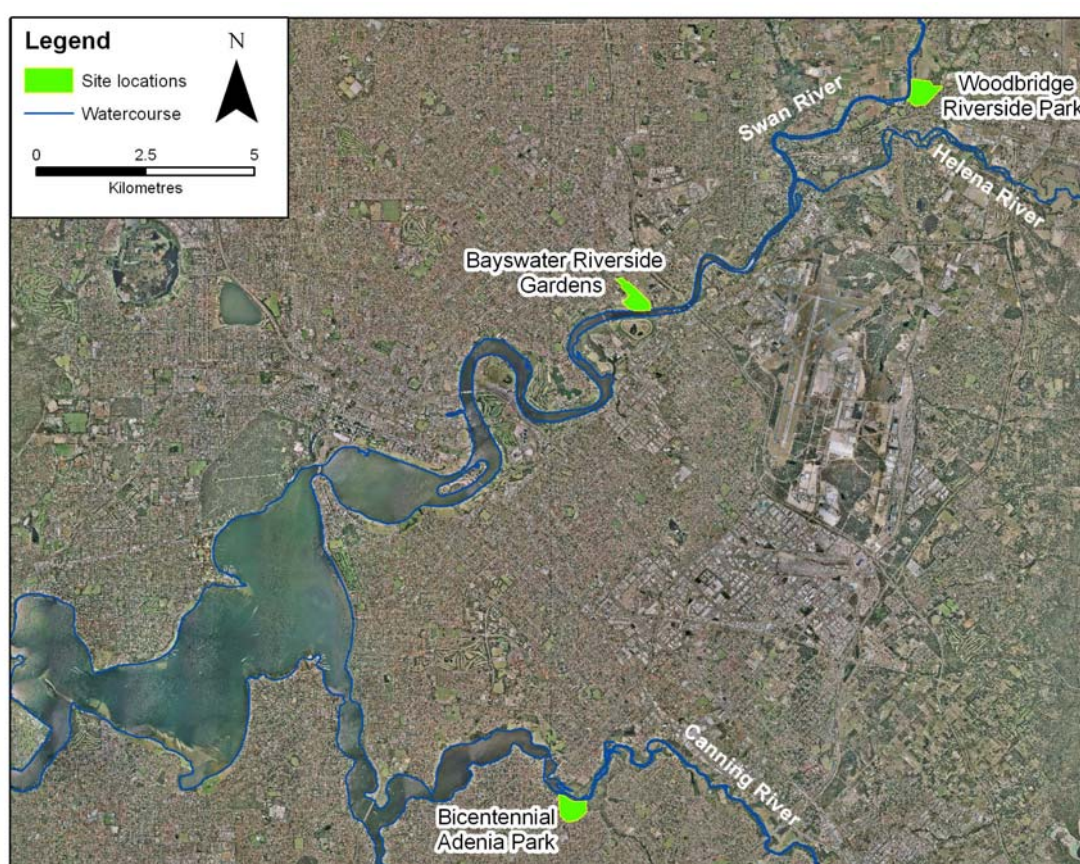


Figure 1: An aerial image of the three disused waste disposal sites included in the study

2.2 Bore installation

There were seven pre-existing bores at Woodbridge Riverside Park prior to the commencement of the study. In addition to these, two new shallow mini-piezometers were constructed for the then Department of Environment at the site in 2006. In January 2007 an additional nine bores were installed by consultants on behalf of the City of Swan Council which were added to the sampling program in May and June of 2007. The location of the eighteen bores are shown in Figure 2.

As there were no pre-existing bores at either Bayswater Riverside Gardens or Bicentennial Adenia Park, six new shallow mini-piezometers were installed by the Department of Water at each of the sites prior to the commencement of the study. Bore locations are shown in Figure 3 and Figure 4 for Bayswater Riverside Gardens and Bicentennial Adenia Park respectively.

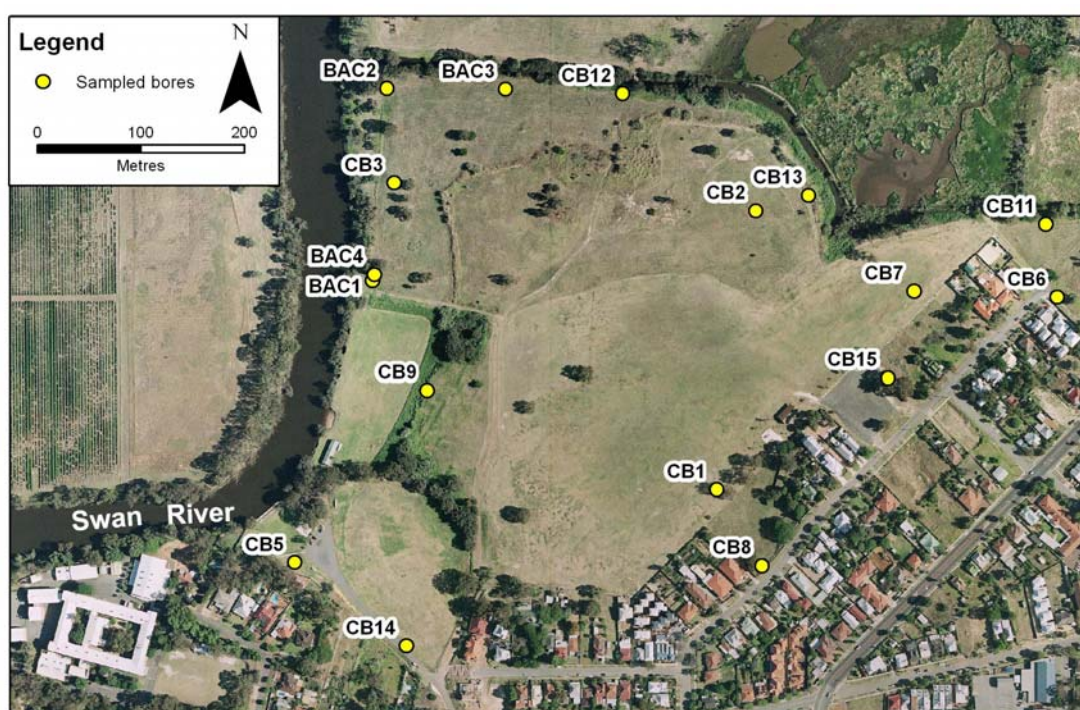


Figure 2: An aerial image of Woodbridge Riverside Park indicating the location of groundwater bores sampled

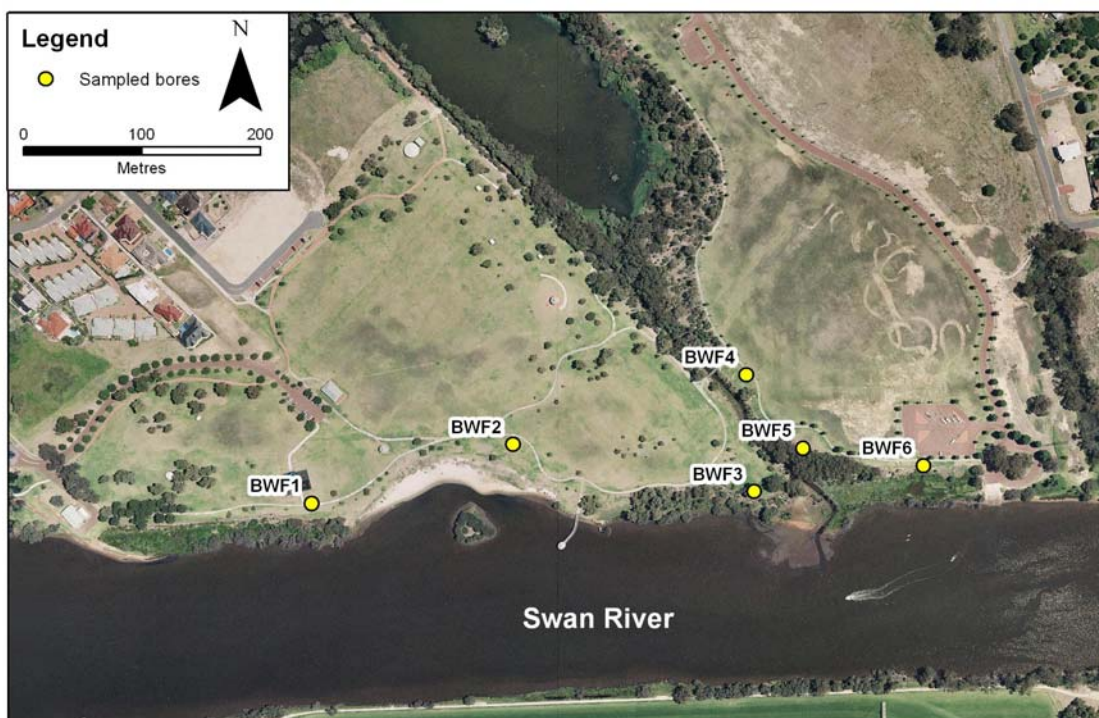


Figure 3: An aerial image of Bayswater Riverside Gardens indicating the location of groundwater bores sampled

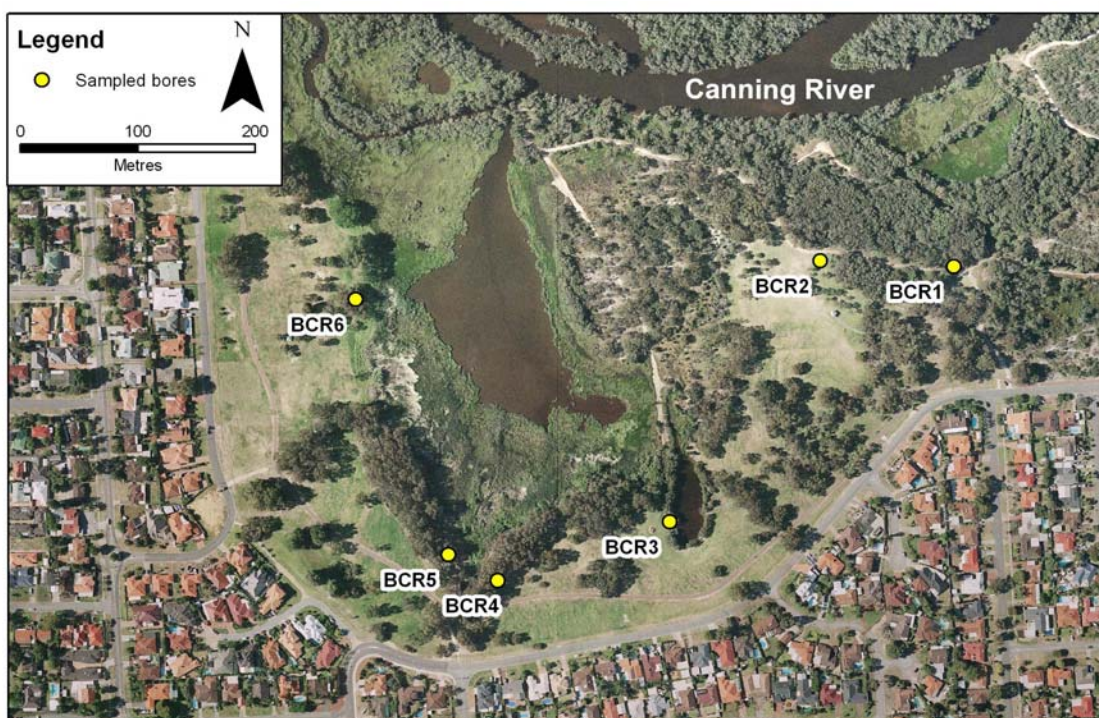


Figure 4: An aerial image of Bicentennial Adenia Park indicating the location of groundwater bores sampled

2.3 Water quality variables

Variables to be determined were selected based on land use activities within the catchments and the potential for the contaminant to cause environmental harm. These variables are described in Table 1, and may be summarised by grouping into the following categories:

- physical properties
- metals
- petroleum hydrocarbons and PAHs
- major ionic species
- herbicides
- organochlorine and organophosphorus pesticides
- PCBs
- nutrients

Table 1: Water quality variables

Parameter	Description
Temperature	Water temperature is a measure of the heat content. Since the solubility of oxygen (DO) decreases with increasing water temperature, high water temperatures limit the availability of DO for aquatic life. Also, water temperature regulates various biochemical reaction rates that influence water quality. Heat sources and sinks to a waterbody include various surface heat transfer mechanisms (that is, incident solar radiation, back radiation, evaporative cooling and heat conduction), thermal dischargers (for example power plants), tributary inflows and groundwater discharge. Units: °C
pH	pH is a measure of the relative acidity or alkalinity of water. It reflects the concentrations of hydrogen (H ⁺) and hydroxide ions (OH ⁻) in a water sample. Water with a pH of 7 is neutral; lower pH levels indicate increasing acidity, while pH levels higher than 7 indicate increasingly alkaline solutions. Units: N/A
Dissolved oxygen (DO)	Dissolved oxygen analysis measures the amount of gaseous oxygen (O ₂) dissolved in an aqueous solution. Oxygen concentrations increase in water by diffusion from the surrounding air, by aeration (rapid movement), and as a product of photosynthesis. Units: % saturation
Conductivity	Conductivity or specific conductance is the measure of the water's ability to conduct an electric current. Conductivity depends upon the number of ions or charged particles in the water. Conductivity provides an estimate of dissolved ionic matter in the water, and is dependent on the geology of the area. A sudden change in conductivity can indicate a direct discharge or other source of pollution into the water. Conductivity readings do not provide information on the specific ionic composition and concentrations. Lakes and rivers vary in conductivity based on the geology of an area. Water salinity may also be calculated from electrical conductivity. Units: µS/cm
Redox potential	Redox potential is the tendency of a solution to gain or lose electrons with the introduction of a new species. The higher the redox potential the more likely the solution will gain electrons from a new species, and thereby oxidise that species. The lower the redox potential, the more likely it is to gain electrons and reduce the new species. Redox potentials are defined relative to a standard hydrogen electrode, and field measurements taken with alternative reference electrodes are corrected accordingly. Units: mV
Total unfiltered metals	Total unfiltered metals includes analysis of an unfiltered water sample for a range of

Parameter	Description
	metals: Al, As, Cd, Co, Cr, Cu, Fe, Hg, Mn, Mo, Ni, Pb, Se, Zn Units: mg/L or µg/L
BTEX/TRH (Benzene, Toluene, Ethylbenzene, Xylenes; total recoverable hydrocarbon fractions, TRH:C6-C9, TRH:C10-C14, TRH:C15-C28, TRH:C29-C36)	Benzene, toluene, ethylbenzene, and xylene isomers (BTEX) make up part of the C6 to C9 petroleum hydrocarbons and are characteristically volatile. BTEX compounds are more soluble in water than most of the other C6 to C9 petroleum hydrocarbons. For total recoverable hydrocarbons (TRHs) or the total petroleum hydrocarbons (TPHs) analysis, hydrocarbons are categorised into the following ranges; C6 to C9; C10 to C14; C15 to C28; and C29 to C36. Units: µg/L
Polycyclic aromatic hydrocarbons (PAHs)	PAHs are a group of over 100 different hydrocarbon compounds which have multiple aromatic rings in their structure. They can be formed during the incomplete burning of coal, oil and gas, garbage, or other organic substances such as tobacco or charbroiled meat, and are typical components of asphalts, fuels, oils, and greases. Some PAHs are manufactured. PAHs are found in coal tar, crude oil, creosote, and roofing tar, but a few are used in medicines or to make dyes, plastics, and pesticides. Units: µg/L
Chloride (filtered) [Cl-]	Chloride is one of the most abundant anions to be found in water and sewage. Small amounts of chloride are required for normal functions in plant and animal life. Chlorides have no biochemical sources or sinks in a waterway. Its presence in large amounts may be due to natural processes such as the passage of water through natural salt formations in the earth (natural geological sources) or it may be an indication of sea water intrusion or pollution from industrial or domestic waste (anthropogenic sources). Potable water should not exceed 250 mg/L of chloride. When calcium or magnesium is the cation, up to 1000 mg/L can be tolerated without a salty taste to the water. Units: mg/L (mg/L Chloride)
Fluoride (filtered) [F-]	Fluoride exists naturally in waterways and is derived from the element fluorine. Fluoride in the water is essential for protection against dental cavities and weakening of the bones, but higher levels can have an adverse effect on human health. Units: mg/L (mg/L Fluoride)
Sulphate as SO42- (filtered) [SO42-]	Sulphate (SO42-) is a divalent anion that occurs naturally in waterways as a result of the weathering of rocks or the breakdown of leaves in water and atmospheric deposition. Anthropogenic sulphate sources include municipal or industrial discharges, acid sulphate drainage or runoff from fertilised agricultural lands. Units: mg/L (mg S per L)
Total alkalinity (as CaCO3)	The total alkalinity of water is its ability to neutralise an acid to a designated pH (its 'acid-neutralising capacity'). It is the sum of all titratable bases, which generally includes carbonates, bicarbonates, and hydroxides, and also borates, phosphates, silicates and other bases if they are present. Units: mg/L CaCO3
Total acidity (as CaCO3)	The total acidity of water is its ability to neutralise a base to a designated pH (its 'base-neutralising capacity'). It is the sum of all titratable acids. Units: mg/L CaCO3
Herbicides	Herbicides are a group of chemicals that are used to destroy, control or inhibit the growth of plant pests, especially weeds. As such, they are a subset of a larger group of chemicals known as pesticides. Selective herbicides kill certain target plants while leaving the desired plants relatively unharmed. Some of these act by interfering with the growth of the weed and are often based on plant hormones. Herbicides used to clear waste ground are non-selective and kill every plant with which they come into contact. Units: µg/L
Organochlorine and organophosphorus (OC/OP) pesticides	A pesticide is an all-encompassing term to refer to a substance or mixture of substances intended to prevent, destroy, repel or mitigate pests or defoliate or desiccate plants. The organochlorine and organophosphorus pesticides determined in this investigation are insecticides. Units: µg/L

Parameter	Description
Polychlorinated biphenyls (PCBs)	<p>Polychlorinated biphenyls (PCBs) are a family of synthetic chemicals that contain 209 individual compounds with varying levels of toxicity. Many of PCBs sold in the United States are mixtures identified by their industrial trade name, Aroclor.</p> <p>It is not practical to identify and quantify all 209 PCBs in environmental samples. Instead, in this investigation we determined the concentration of commercially produced mixtures of PDB congeners, namely Aroclor 1016, 1221, 1232, 1242, 1248, 1254 and 1260. For example Aroclor 1254 and Aroclor 1260 were manufactured for use as a dielectric fluid and are possible carcinogens. The suffixes 54 and 60 in these names refer to the approximate percentage of the molecular weight attributed to chlorine. In general, the more chlorinated the PCB, the greater its resistance to biodegradation and therefore the greater its persistence in the environment. The composition of the Aroclor mixtures might change with biodegradation, but we would expect Aroclor 1260 and Aroclor 1254 to be more persistent than the other mixture of congeners.</p> <p>Units: µg/L</p>
Total nitrogen (TN)	<p>TN is the sum of concentrations of all forms of nitrogen, including (in order of decreasing oxidation state) nitrate, nitrite, ammonia, and organic nitrogen.</p> <p>Units: mg/L nitrogen</p>
Ammonium nitrogen (NH ₃ -N/NH ₄ -N)	<p>Ammonium and ammonia species are determined using the same analytical method. The proportion of each species is dependent on the pH of the solution. At higher pH, ammonia (NH₃) predominates. At pH 5 - 8, the species exists as predominantly ammonium (NH₄⁺).</p> <p>Units: mg/L nitrogen</p>
Total oxidised nitrogen (NO _x -N), or nitrate (NO ₃ -) + nitrite (NO ₂ -)	<p>NO_x-N is the sum of the nitrate (NO₃⁻) and nitrite (NO₂⁻) concentrations. Alternatively, the nitrate and nitrite species can be determined separately.</p> <p>Units: mg/L nitrogen</p>
Dissolved organic nitrogen (DON)	<p>Dissolved organic nitrogen (DON) includes all organically bound nitrogen e.g. urea and amino acids in the filtrate of a water sample through a 0.45 µm filter. It can be utilised directly by algae.</p> <p>Units: mg/L nitrogen</p>
Total phosphorus (TP)	<p>Phosphorus occurs in natural waters and in wastewaters almost solely as phosphates. These are classified as orthophosphates (PO₄³⁻), condensed phosphates (pyro-, meta-, and other polyphosphates), and organically bound phosphates. Total phosphorus is the sum of the concentration of these species. They occur in solution, in particles or detritus, or in the bodies of aquatic organisms.</p> <p>Units: mg/L phosphorus</p>
Filtered reactive phosphorus (FRP)	<p>Filtered reactive phosphorus (FRP) describes the concentration of phosphates that pass through a 0.45 µm filter and respond to colorimetric tests without preliminary hydrolysis or oxidative digestions of the sample. FRP is largely a measure of orthophosphate (PO₄³⁻), however a small fraction of any condensed phosphate present is usually hydrolysed unavoidably in the analytical procedure. Reactive phosphorus occurs in both dissolved and suspended phosphorus.</p> <p>Units: mg/L phosphorus</p>
Dissolved organic carbon (DOC)	<p>DOC represents all the soluble organic carbon (or carbon covalently bonded in organic molecules) that can pass through a 0.45 µm filter. The inorganic carbon is purged before analysis, resulting in the loss of some volatile organic species from the sample. DOC is therefore reported as non-purgeable organic carbon.</p> <p>Units: mg/L or µg/L (µg/L carbon or µg/L non-purgeable organic carbon).</p>

2.4 Sampling procedure

The detail of the sampling procedure is documented in the *Sampling and analysis plan* for this program, available from the Department of Water (Department of Water 2007). It is briefly described here.

Frequency

Snap-shot sampling occurred at approximately six monthly intervals; April 2006, November 2006 and May to June 2007.

Sample collection

Avoiding cross contamination is a particular concern in the sampling of groundwater. Samples were collected using a peristaltic pump on the first two occasions with decontamination of the pumping equipment, hoses, and standing water level recorders between each site. On the third sampling occasion, the sample collection procedure was modified to further reduce the risk of any sample cross contamination. A disposable 36 mm bailer was used for sampling each bore with 50 mm diameter casing and disposable pump hosing with a peristaltic pump was used for bores with a casing diameter of 20 mm.

On all occasions, samples were collected after purging at least three casing volumes of groundwater from the bore. After the purging of each casing volume, a container was filled with groundwater and values of pH, conductivity, temperature, oxidation-reduction (redox) potential and dissolved oxygen were recorded. Purging continued until values of these variables were within 10% in consecutive casing volumes of purged groundwater. Sample bottles were filled by the specific sample preparation outlined in the *Sampling and analysis plan* (Department of Water 2007). Requirements for filtering, pre-rinsing and bottle filling were specific for each variable.

In instances where bores were dry or contained insufficient water for adequate purging, samples were not collected for analysis, and therefore there are no results for these bores. This was the case for four bores at Woodbridge Riverside Park namely CB2, CB6, CB7 and CB8 and one at Bicentennial Adenia Park, BCR2.

2.5 Laboratory analysis

All samples were delivered to the Perth laboratories of the National Measurement Institute (NMI) within 48 hours of collection. Samples were analysed according to methods and limits of reporting specified in the *Sampling and analysis plan* (Department of Water 2007). In cases where required limits of reporting could not be obtained at NMI in Perth, analysis was undertaken by NMI's laboratories in Sydney as noted in the *Sampling and analysis plan*.

Limits of reporting

There was some variability in the limits of reporting for samples collected on different sampling occasions. Upon analysis of samples from the first collection, it was evident that significantly lower limits of reporting were required for many of the analytes, in particular some of the metals. Consideration of the limits of reporting was particularly important with the introduction of petroleum hydrocarbons, PAHs, herbicides and pesticides in the second and third sampling occasions. After reviewing TPH and PAH results from the second occasion, a refinement in the chosen methods of analysis was required to provide increased sensitivity. For example, anthracene was not reported at the Woodbridge CB5 site in the

second sampling occasion with a limit of reporting of 1 µg/L but was detected in the third sampling occasion when the limit of reporting was 0.01 µg/L.

On the third sampling event in May to June 2007, limits of reporting were at least as low as the ANZECC trigger values (where available) for all analytes except the organophosphate pesticides. For the numerous analytes that do not have appropriate ANZECC trigger values, the limits of reporting were constrained by the cost of analysis. Despite all efforts to maximise sensitivity of the determination of these analytes, instances where concentrations failed to exceed limits of detection should be treated with caution, as the effects of many of these chemicals in the environment have not yet been determined.

2.6 Quality control

Each batch of samples included laboratory quality control measures whereby one duplicate sample in every 10 (randomly selected) and one blank matrix test per batch of samples (method test) was analysed. In addition, field blanks were collected using both disposable bailers and the peristaltic pump with disposable tubing to determine any possible contamination in sample collection. All quality control and field blank results were reviewed to confirm data integrity.

2.7 Data analysis and presentation

All data was managed by the Water Information Branch of the Department of Water. Data was compiled in tabular form for each site, and individual data points compared between sampling events (when more than one sample was taken from the bore), between each waste disposal site and with ANZECC trigger values. Summary statistics were not applied to the data set due to limitations in the replication of the data and the variability across each waste disposal site.

ANZECC guideline trigger values are shown when available for each analyte. If either *Schedule B (1) Guideline on the investigation levels for soil and groundwater* (National Environment Protection Council 1999) or the *Assessment levels for soil, sediment and water* (Department of Environment 2003) specified an alternative trigger concentration for an analyte, it has been included in the results table for visual comparison. Where concentrations exceeded the ANZECC trigger value by less than 10-fold, the value is highlighted in green, where concentrations were 10 - 100 times that of the trigger value it is highlighted in purple and where concentrations exceeded the trigger value by more than 100 times they are highlighted in red. As petroleum hydrocarbons and PAHs may be harmful at extremely low concentrations but rarely have ANZECC guideline trigger values, any detection above the limit of reporting was shown in bold.

3 Results

Physical properties and concentrations of major ions, metals, polycyclic aromatic hydrocarbons (PAHs), petroleum hydrocarbons and nutrients are presented for Woodbridge Riverside Park, Bayswater Riverside Gardens and Bicentennial Adenia Park in Table 2, Table 3 and Table 4 respectively. Bores CB2, CB6, CB7 and CB8 at Woodbridge Riverside Park and BCR2 at Bicentennial Adenia Park have not been included in Table 2 and Table 4 as these bores contained insufficient groundwater at the time of sampling. PCBs, organochlorine and organophosphate pesticides, and herbicide concentrations have not been included in the results tables as none were detected at concentrations above the limits of reporting at any site. Further details for these analytes are included in Appendix A.

Summary

- In general, the highest concentrations of metals were detected at Woodbridge Riverside Park, followed by Bayswater Riverside Gardens and Bicentennial Adenia Park.
- Lead, aluminium, chromium, copper, iron and zinc were present in concentrations that exceeded the ANZECC trigger values at all three historical waste disposal sites and by more than 100-fold in at least one bore at Woodbridge Riverside Park.
- Cadmium and nickel were present in concentrations that exceeded the ANZECC guidelines in several bores at Woodbridge Riverside Park.
- Arsenic and manganese were present in concentrations that exceeded the ANZECC guidelines at Bayswater Riverside Gardens and Woodbridge Riverside Park.
- Of the petroleum and PAHs determined, only naphthalene was present in concentrations that exceeded the ANZECC trigger value.
- Numerous other petroleum hydrocarbons and PAHs were detected for which ANZECC trigger values were not available. Of these, phenanthrene and benzo(a)pyrene exceeded British Columbian guidelines at Woodbridge Riverside Park.
- Reported concentrations of petroleum hydrocarbons and PAHs were more frequent at Woodbridge Riverside Park than both Bayswater Riverside Gardens and Bicentennial Adenia Park.
- Of the nutrients investigated in the study, the highest concentrations recorded were those of ammonium (as nitrogen) and dissolved organic nitrogen.
- Soluble reactive phosphorus was detected in concentrations that exceeded ANZECC guidelines by more than 10-fold at Bicentennial Adenia Park.
- There were no detections of PCBs, herbicides or organochlorine and organophosphorus pesticides above detection limits at any of the bores sampled in the study.

Table 2: Groundwater sampling results at Woodbridge Riverside Park in May 2006 (1), November 2006 (2) and May/June 2007 (3)

		Alternative Guideline Reference	Alternative Guideline Value	Guideline ANZECC 2000 ¹	LOR	Woodbridge Riverside Park																											
Site						BAC1			BAC2			BAC3		BAC4		CB1			CB3			CB5			CB9	CB10	CB11	CB12	CB13	CB14	CB15		
Physical	Sampling event ²					1	2	3	1	2	3	1	3	3	1	2	1	2	3	1	2	3	3	3	3	3	3	3	3				
	Water temperature (in situ) (deg C)			N/A		23.0	21.8	23.2		21.8	22.9	22.7	22.6	25.7		25.9		25.7	24.3		23.9	19.9	24.2	22.5	20.5	22.4	23.0	23.1					
	pH ((none))			6.5 - 8.5		6.57		6.67	6.87		6.77	7.10	6.24	6.58	6.71		6.79		6.69	6.62		6.58	6.23	6.71	6.42	6.82	6.71	6.43	6.64				
	O - DO % (%)			N/A		41.9		18.4	29.1		23.8		11.6	15.2	40.0		13.5		11.2	15.0		19.4	9.6	18.9	15.5	22.4	3.9	11.4	3.9				
	Cond comp 25 deg C (in situ) (mS/cm)			N/A		3.06		7.60	4.84		7.08	2.49	2.36	7.38	2.23		3.27		3.27	2.84		2.78	3.92	1.66	3.68	3.65	3.39	6.20	2.53				
	Eh (RP, Redox) (mV)			N/A		-66		81	34		173		175	44		-11		162		105		181	157	150	151	155	109	171	98				
Metals	Al (tot) (mg/L)			0.06		0.51	0.49	2.80	0.95	0.02	0.11	4.70	3.70	8.00	0.06	0.05	0.02	0.10	0.79	0.01	0.01	3.10	7.00	8.60	5.50	0.91	26.00	58.00	32.00				
	As (tot) (mg/L)	(A)	0.05	0.013	<0.001	<0.001	<0.001	0.003	0.002	<0.001	<0.001	0.004	0.003	0.004	0.013	0.006	0.012	0.008	0.002	<0.001	<0.001	0.002	0.003	0.002	0.003	<0.001	0.26	0.017	0.008				
	Cd (tot) (mg/L)			0.0002	<0.0001	<0.0001	<0.0001	0.0002	<0.0001	<0.0001	<0.0001	<0.0001	0.0002	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0007	<0.0001	<0.0001	<0.0001	<0.0001	0.0005	0.0005	<0.0001	0.0130	0.0002	0.0004				
	Co (tot) (mg/L)			0.090	<0.001	0.004	0.003	0.009	0.004	0.002	0.003	0.006	0.012	0.019	0.001	0.001	0.003	0.003	0.004	0.031	0.018	0.031	0.013	0.011	0.020	0.003	0.022	0.037	0.030				
	Cr (tot) (mg/L)			0.001	<0.001	0.004	0.002	0.008	0.005	<0.001	0.001	0.029	0.018	0.028	<0.001	<0.001	0.002	<0.001	0.004	<0.001	<0.001	0.004	0.023	0.032	0.016	0.005	0.074	0.190	0.092				
	Cu (tot) (mg/L)	(A)	0.002	0.001	<0.001	0.006	0.004	0.024	0.005	<0.001	<0.001	0.030	0.019	0.009	0.003	<0.001	<0.001	0.004	0.014	0.001	<0.001	0.013	0.013	0.200	0.017	0.002	0.080	0.150	0.097				
	Fe (tot) (mg/L)	(A)		1.0	0.3		5.0	6.7	8.4	9.8	4.7	4.0	28.0	16.0	25.0	18.0	19.0	10.0	9.2	13.0	1.0	1.8	7.3	77.0	16.0	20.0	3.4	86.0	200.0	130.0			
	Hg (tot) (mg/L)	(A)	0.0001	0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0002	<0.0001	<0.0001			
	Mn (tot) (mg/L)			1.90		<0.05	0.37	0.18	0.34	0.38	0.26	0.31	0.20	1.30	0.84	<0.05	0.06	<0.05	<0.05	<0.05	0.69	0.45	0.56	2.10	2.20	1.90	0.69	1.30	0.44	0.59			
	Mo (tot) (mg/L)			0.034		<0.001	<0.001	<0.001	0.001	<0.001	<0.001	0.009	0.007	0.003	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.003	0.004	0.006	<0.001	0.006	0.004	0.003			
	Ni (tot) (mg/L)	(A)	0.015	0.011	<0.001	0.004	0.002	0.007	0.003	0.001	0.003	0.005	0.037	0.024	0.360	0.004	<0.001	0.004	0.013	<0.001	<0.001	0.003	0.017	0.027	0.038	0.006	0.089	0.066	0.068				
	Pb (tot) (mg/L)	(A)	0.001	0.003	<0.001	0.004	0.003	0.037	0.005	<0.001	<0.001	0.017	0.008	0.009	0.002	0.001	<0.001	<0.001	0.008	<0.001	<0.001	0.009	0.009	0.048	0.082	0.002	0.500	0.130	0.190				
	Se (tot) (mg/L)	(A) / (B)	0.005	0.011	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001			
	Zn (tot) (mg/L)	(A)	0.005	0.008	<0.001	0.006	0.008	0.100	0.062	0.002	0.003	0.026	0.033	0.030	0.027	0.013	<0.001	0.014	0.160	0.009	0.012	0.031	0.048	0.250	0.130	<0.001	5.500	0.110	2.200				
	Petroleum and Polycyclic Aromatic Hydrocarbons	Benzene (tot) (ug/L)			950.0	<1	<1	<1		<1	<1		<1	<1		<1		2.7	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	6.3	<1	<1
Toluene (tot) (ug/L)				300	<1	<1	<1		<1	<1		<1	<1		<1		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	
Ethyl benz (tot) (ug/L)				N/A	<1	<1	<1		<1	<1		<1	<1		<1		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Xylenes (tot) (ug/L) (o-xylene/p-xylene)				0.35/0.2	<2	<2	<2		<2	<2		<2	<2		<2		<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2
BTEX (tot) (ug/L)				N/A	<5	<5	<5		<5	<5		<5	<5		<5		<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
C6-C9 (tot) (ug/L)				N/A	<25	<25	<25		<25	<25		<25	<25		<25		<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25
C10-C14 (tot) (ug/L)				N/A	<25	<25	25		<25	<25		<25	58		<25		<25	70		<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25
C15-C28 (tot) (ug/L)				N/A	<100	<100	290		<100	<100		<100	450		<100		<100	570		<100	<100	220	260	<100	<100	570	<100	820					
C29-C36 (tot) (ug/L)				N/A	<100	<100	<100		<100	<100		<100	<100		<100		<100	<100		<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	560
Total recoverable hydrocarbons (tot) (TRH) (ug/L)				N/A	<250	<250	320		<250	<250		<250	510		<250		<250	640		<250	<250	260	260	<250	<250	960	<250	1500					
Acenaphthene (tot) (ug/L)				N/A	<0.01	<0.01	0.093		<0.01	<0.01		<0.01	0.078		<1		<1	0.380		<1	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	1.100	<0.01	0.180				
Acenaphthylene (tot) (ug/L)				N/A	<0.01	<0.01	0.013		<0.01	<0.01		<0.01	<0.01		<1		<1	<0.01		<1	0.026	<0.01	<0.01	<0.01	<0.01	<0.01	0.081	<0.01	0.077				
Anthracene (tot) (ug/L)				0.4	<0.01	<0.01	0.019		<0.01	<0.01		<0.01	<0.01		<1		<1	0.014		<1	0.065	<0.01	<0.01	<0.01	<0.01	<0.01	0.096	0.021	0.019				
Benzo[a]pyrene (tot) (ug/L)				0.2	<0.01	<0.01	0.040		<0.01	<0.01		<0.01	<0.01		<1		<1	0.190		<1	0.190	<0.01	<0.01	<0.01	<0.01	<0.01	0.021	<0.01	<0.01				
Benzo[a]anthracene (tot) (ug/L)				N/A	<0.01	<0.01	0.036		<0.01	<0.01		<0.01	<0.01		<1		<1	<0.01		<1	0.068	<0.01	<0.01	<0.01	<0.01	<0.01	0.041	<0.01	<0.01				
Benzo[b]fluoranthene & Benzo[k]fluoranthene (tot) (ug/L)				N/A	<0.02	<0.02	0.081		<0.02	<0.02		<0.02	<0.02		<2		<2	<0.02		<2	0.280	<0.02	<0.02	<0.02	<0.02	<0.02	0.042	<0.02	<0.02				
Benzo[ghi]perylene (tot) (ug/L)				N/A	<0.01	<0.01	0.054		<0.01	<0.01		<0.01	<0.01		<1		<1	<0.01		<1	0.270	<0.01	<0.01	<0.01	<0.01	<0.01	0.018	<0.01	<0.01				
Chrysene (tot) (ug/L)				N/A	<0.01	<0.01	0.025		<0.01	<0.01		<0.01	<0.01		<1		<1	<0.01		<1	0.072	<0.01	<0.01	<0.01	<0.01	<0.01	0.071	<0.01	0.016				
Dibenz[ah]anthracene (tot) (ug/L)				N/A	<0.01	<0.01	<0.01		<0.01	<0.01		<0.01	<0.01		<1		<1	<0.01		<1	0.051	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01				
Fluoranthene (tot) (ug/L)				1.4	<0.01	<0.01	0.045		0.011	<0.01		<0.01	<0.01		<1		<1	0.011		<1	0.094	<0.01	<0.01										

Table 4: Groundwater sampling results at Bicentennial Adenia Park in May 2006 (1), November 2006 (2) and May/June 2007 (3)

Site	Alternative Guideline Reference	Alternative Guideline Value	Guideline ANZECC 2000 ¹	LOR	Bicentennial Adenia Park																	
					BCR1			BCR3			BCR4			BCR5			BCR6					
					1	2	3	1	2	3	1	2	3	1	2	3	1	2	3			
Water temperature (in situ) (deg C)			N/A		21.5	20.0	20.0	19.3	18.9	22.0	21.1	21.1	20.7	22.1	22.1	21.6						
pH (none)			6.5 - 8.5		6.51	6.24	6.65	6.57	6.52	6.55	7.05	6.91	6.72	6.67								
O - DO % (%)			N/A		7.5	9.9	70.8	2.0	29.0	14.0	7.5	9.1	83.7	11.5								
Cond comp 25 deg C (in situ) (mS/cm)			N/A		0.93	1.05	1.97	5.04	0.75	0.90	0.98	0.89	10.99	2.72								
Eh (RP, Redox) (mV)			N/A		90	212	36	85		222	-88	46		149								
Al (tot) (mg/L)			0.06		1.30	0.78	0.45	1.50	0.74	0.60	0.24	0.09	0.43	1.90	1.00	2.20	0.14	0.11	0.04			
As (tot) (mg/L)	(A)	0.05	0.013	<0.001	<0.001	0.002	0.002	0.002	<0.001	<0.001	<0.001	<0.001	0.001	0.002	<0.001	0.002	0.002	0.003	<0.001			
Cd (tot) (mg/L)			0.0002	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001			
Co (tot) (mg/L)			0.090	<0.001	<0.001	<0.001	0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001			
Cr (tot) (mg/L)			0.001	<0.001	<0.001	0.001	<0.001	0.001	<0.001	<0.001	0.001	<0.001	0.002	<0.001	0.004	<0.001	<0.001	<0.001	<0.001			
Cu (tot) (mg/L)	(A)	0.002	0.001	<0.001	0.002	0.002	0.001	<0.001	<0.001	<0.001	0.001	0.002	<0.001	0.003	<0.001	<0.001	<0.001	<0.001	<0.001			
Fe (tot) (mg/L)	(A)	1.0	0.3	<0.001	1.4	1.0	0.6	16.0	23.0	21.0	0.5	0.1	0.4	1.2	0.5	1.7	62.0	17.0	16.0			
Hg (tot) (mg/L)	(A)	0.0001	0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001			
Mn (tot) (mg/L)			1.90	<0.05	0.02	<0.05	0.02	0.24	0.27	0.25	0.02	0.03	0.03	<0.05	0.04	0.04	1.00	0.75	0.65			
Mo (tot) (mg/L)			0.034	<0.001	0.008	0.006	0.010	0.007	0.006	<0.001	<0.001	<0.001	0.003	0.003	0.002	0.001	0.001	0.001	<0.001			
Ni (tot) (mg/L)	(A)	0.015	0.011	<0.001	<0.001	0.001	<0.001	<0.001	0.002	<0.001	<0.001	<0.001	0.001	<0.001	0.002	<0.001	<0.001	<0.001	<0.001			
Pb (tot) (mg/L)	(A)	0.001	0.003	<0.001	0.003	0.001	<0.001	0.004	<0.001	0.001	<0.001	<0.001	0.006	0.003	<0.001	0.010	<0.001	<0.001	<0.001			
Se (tot) (mg/L)	(A) / (B)	0.005	0.011	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.004	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001			
Zn (tot) (mg/L)	(A)	0.005	0.008	<0.001	<0.001	0.004	0.001	0.001	<0.001	0.003	0.009	<0.001	0.018	0.016	<0.001	0.015	0.006	0.003	0.002			
Benzene (tot) (ug/L)			950.0	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1			
Toluene (tot) (ug/L)			300	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1			
Ethyl benz (tot) (ug/L)			N/A	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1			
Xylenes (tot) (ug/L) (o-xylene/p-xylene)			0.35/0.2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2			
BTEX (tot) (ug/L)			N/A	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5			
C6-C9 (tot) (ug/L)			N/A	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25			
C10-C14 (tot) (ug/L)			N/A	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25			
C15-C28 (tot) (ug/L)			N/A	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100			
C29-C36 (tot) (ug/L)			N/A	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100			
Total recoverable hydrocarbons (tot) (TRH) (ug/L)			N/A	<250	<250	<250	<250	<250	<250	<250	<250	<250	<250	<250	<250	<250	<250	<250	<250			
Acenaphthene (tot) (ug/L)			N/A	<0.01	<0.01	<0.01	<0.01	<0.01	<1	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01			
Acenaphthylene (tot) (ug/L)			N/A	<0.01	<0.01	<0.01	<0.01	<0.01	<1	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01			
Anthracene (tot) (ug/L)			0.4	<0.01	<0.01	<0.01	<0.01	<0.01	<1	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01			
Benzo[a]pyrene (tot) (ug/L)			0.2	<0.01	<0.01	<0.01	<0.01	<0.01	<1	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01			
Benzo[a]anthracene (tot) (ug/L)			N/A	<0.01	<0.01	<0.01	<0.01	<0.01	<1	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01			
Benzo[b]fluoranthene & Benzo[k]fluoranthene (tot) (ug/L)			N/A	<0.02	<0.02	<0.02	<0.02	<0.02	<2	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02			
Benzo[ghi]perylene (tot) (ug/L)			N/A	<0.01	<0.01	<0.01	<0.01	<0.01	<1	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01			
Chrysene (tot) (ug/L)			N/A	<0.01	<0.01	<0.01	<0.01	<0.01	<1	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01			
Dibenz[ah]anthracene (tot) (ug/L)			N/A	<0.01	<0.01	<0.01	<0.01	<0.01	<1	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01			
Fluoranthene (tot) (ug/L)			1.4	<0.01	<0.01	<0.01	<0.01	<0.01	<1	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01			
Fluorene (tot) (ug/L)			N/A	<0.01	<0.01	<0.01	<0.01	<0.01	<1	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01			
Indeno[1,2,3-cd]pyrene (tot) (ug/L)			N/A	<0.01	<0.01	<0.01	<0.01	<0.01	<1	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01			
Naphthalene (tot) (ug/L)			16	<0.01	<0.01	<0.01	<0.01	<0.01	<1	<0.01	<0.01	<0.01	0.061	0.013	0.016	0.016	<0.01	<0.01	<0.01			
Phenanthrene (tot) (ug/L)			2	<0.01	<0.01	<0.01	<0.01	<0.01	<1	<0.01	<0.01	<0.01	0.014	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01			
Pyrene (tot) (ug/L)			N/A	<0.01	<0.01	<0.01	<0.01	<0.01	<1	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01			
Cl (sol) (mg/L)			3000		190	170	240	210	1200	110	110	140	140	160	150	2600	410	670				
SO4 (sol) (mg/L)			N/A	<5 / <2	42	<2	18	16	8	84	13	6	5	33	6	7	200	100	83			
F (sol) (mg/L)			N/A	<0.2	<0.2	<0.2	<0.2	0.2	0.3	0.3	0.3	0.2	0.2	0.4	0.3	0.3	0.7	0.3	0.5			
Alkalinity (tot) (CaCO3) (mg/L)			N/A		43	71		470	470		220	220		250	190		400	420				
Acidity (CaCO3) (mg/L)			N/A		22	38	29	340	230	170	38	50	51	12	43	29	150	92	130			
TN (tot) (mg/L)			1.2		0.76	4.3	0.62	3.3	3.3	1.1	1.4	2	1.8	2	2.3	4.4	1.3	4.5				
NH3-N/NH4-N (sol) (mg/L)			0.08		0.083	0.2	0.19	2.0	2.3	0.76	0.43	0.57	0.7	1.0	0.71	0.76	3.1	0.094	4.0			
NOx-N (mg/L)			0.15	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.034	<0.01	0.029	<0.01	<0.01	<0.01	<0.01			
DON (sum sol org) (mg/L)			N/A	<0.025	0.65	0.85	0.35	0.82	0.67	2.1	0.67	0.78	0.83	0.68	1.3	1.5	1.0	1.1	0.39			
TP (tot) (mg/L)			0.065		0.011	0.017	0.015	0.54	0.95	0.39	0.43	0.23	0.29	0.67	0.69	0.6	0.14	0.39	0.14			
PO4-P (FRP) (mg/L)			0.04	<0.005	0.006	0.011	0.013	0.009	0.011	0.009	0.36	0.23	0.23	0.64	0.65	0.49	0.012	0.01	0.024			
DOC (sol org)(mg/L)			N/A		22	19	19	29	39	23	26	31	36	33	33	43	30	34	27			

Notes:

Concentrations highlighted in green exceed ANZECC & ARMCANZ (2000) guidelines by less than a factor of 10, those in purple exceed guidelines by a factor of 10 but less than a factor of 100, those in red exceed guidelines by a factor of 100

Concentrations in bold identify petroleum and PAHs measured above the limit of reporting

1 Those values in italics are cited from the Australian Government Website at http://hermes.erin.gov.au/pls/crg_public/!CRGPPUBLIC.PSTART?strAction=SearchByChemical

2 Sampling event corresponds to (1) May 2006, (2) November 2006 or (3) May/June 2007

A National Environment Protection Council 1999, *Schedule B (1) Guideline on the Investigation Levels for Soil and Groundwater*

B Department of Environmental Protection 2003, *Assessment Levels for Soil, Sediment and Water*

3.1 Physical data

Temperature

Water temperature was generally consistent in individual bores between sampling events, varying by less than one degree at all sites except BAC1 and BAC2 (Woodbridge Riverside Park), BWF1, BWF6 (Bayswater Riverside Gardens) and BCR1 (Bicentennial Adenia Park).

There was considerable variability across each site with ranges as follows;

- Woodbridge Riverside Park: 19.9 °C (CB9) – 25.9 °C (CB3)
- Bayswater Riverside Gardens: 18.3 °C (BWF1) – 21.9 °C (BWF6)
- Bicentennial Adenia Park: 18.9 °C (BCR3) – 22.1 °C (BCR6)

Conductivity

The stability of conductivity (temperature compensated to 25 °C) within the groundwater varied at individual bores across sampling occasions. The majority of samples from Woodbridge Riverside Park had a conductivity between 1.66 mS/cm and 3.66 mS/cm. However, on the third sampling occasion (May/June 2007) three sites located adjacent to the Swan River (BAC1, BAC2 and BAC4) displayed conductivities higher than 7 mS/cm. A fourth sample, CB14 which is not adjacent to the river, but is located down-gradient of the rest of the site, recorded the relatively high conductivity of 6.2 mS/cm.

A similar situation was observed at Bayswater Riverside Gardens with all sites having a groundwater conductivity within the range of 1.97 mS/cm to 3.47 mS/cm. Most sites recorded conductivity readings within 0.3 mS/cm when comparing between sampling occasions, however BWF3, adjacent to the Swan River and positioned low on the floodplain recorded a conductivity on the first sampling occasion of 2.87 mS/cm and 3.47 mS/cm in the third.

Sites at Bicentennial Adenia Park displayed relatively consistent conductivities when comparing between sampling occasions with sites varying by less than 0.3 mS/cm, except for BCR5 and BCR6 which varied substantially between the first and third sampling occasion from 1.97 mS/cm to 5.04 mS/cm and 10.99 mS/cm to 2.72 mS/cm respectively.

pH

The groundwater pH of sites was recorded in both the first and third sampling occasions. The pH of 20 of the 25 sites fell within the range indicated within the ANZECC guidelines (6.5 – 8.0) on both of these occasions. Four of the 14 sites at Woodbridge Riverside Park, and one of the six sites at Bicentennial Adenia Park recorded pH values below the lower trigger value of the ANZECC guidelines, each on the third sampling occasion. There were no pH readings below 6.2.

Redox (Eh)

Redox potential recorded in this study was highly variable within each historical waste disposal site and between sampling occasions. Of the readings taken at Woodbridge Riverside Park, all were positive except for two sites in the first sampling occasion, indicating mostly oxidising (aerobic) conditions within the aquifer. When considering only the 13 readings from the third sampling occasion, nine were within the range of 150 – 181 mV and four were within the range of 44 – 109 mV. Redox potential readings at Bayswater Riverside

Gardens ranged from 98 – 173 mV across both the first and third sampling occasions. Bicentennial Adenia Park also recorded highly variable redox potentials, ranging from -88 to +212 mV.

Dissolved oxygen

The percentage saturation of dissolved oxygen was variable when comparing between sampling sites and between sampling occasions. In the majority of samples, dissolved oxygen was measured at less than 20% saturation, however caution should be taken when interpreting these results due to the difficulty in obtaining accurate measurements of dissolved oxygen concentrations in grab samples of ground water. In particular, instances where higher oxygen concentrations were measured may be due to a flawed sampling technique and may not be representative of the *in-situ* conditions.

3.2 Metals

In general the highest concentrations of metals were detected at Woodbridge Riverside Park, followed by Bayswater Riverside Gardens and Bicentennial Adenia Park. Lead, aluminium, chromium, copper, iron and zinc were found in concentrations that exceeded the ANZECC trigger values by more than 100-fold in at least one sample and arsenic, cadmium, manganese and nickel were in concentrations that exceeded the ANZECC guidelines in several samples.

Aluminium (Al)

Aluminium was detected in all groundwater samples, frequently at levels that exceeded the ANZECC trigger value. At Woodbridge Riverside Park there were 19 instances of aluminium concentrations in excess of the trigger value. In seven of these, concentrations were between 10 and 100-fold of the trigger value, and another seven were at concentrations in excess of 100 times the trigger value.

At Bayswater Riverside Gardens there were 14 samples with concentrations of aluminium that exceeded the trigger value. Three of these contained concentrations more than 10 times that of the guideline. Of the 15 samples taken at Bicentennial Adenia Park, 14 contained aluminium concentrations in excess of the trigger value, with eight of these at more than 10 times the trigger value.

Arsenic (As)

The presence of arsenic in groundwater samples was far less common than other metals. There were three instances of arsenic concentrations at Woodbridge Riverside Park in excess of the ANZECC trigger value, one of which was more than 10 times the trigger value.

At Bayswater Riverside Gardens, arsenic was present in concentrations higher than the trigger value at one site, BWF4, on all three sampling events. No samples at Bicentennial Adenia Park contained arsenic concentrations in excess of the trigger value. Further, of the 15 samples taken, eight did not exceed the limits of reporting.

Cadmium (Cd)

There were eight instances of cadmium concentrations in excess of the ANZECC trigger value, all of which occurred at Woodbridge Riverside Park. One sample taken from CB13, exceeded the trigger value by a factor of 10. There were not detections of cadmium at either Bayswater Riverside Gardens or Bicentennial Adenia Park.

Cobalt (Co)

Cobalt was present in low concentrations in all samples taken from Woodbridge Riverside Park; 15 of the 18 taken from Bayswater Riverside Gardens and only one of the 15 samples from Bicentennial Adenia Park. No samples contained cobalt at concentrations in excess of the ANZECC trigger value.

Chromium (Cr)

The limit of reporting for chromium was equal to the ANZECC trigger value, therefore any reported concentrations exceeded the trigger value. Six samples at Woodbridge Riverside Park did not exceed the trigger value. Another 18 samples contained chromium in concentrations exceeding the ANZECC trigger value, eight of which exceeded it by a factor of 10.

Twelve of the 18 samples taken from Bayswater Riverside Gardens contained concentrations of chromium in excess of the trigger value with one of these samples exceeding it by a factor of 10. The remaining six samples were below the limit of reporting.

While the majority of the 15 samples taken from Bicentennial Adenia Park did not contain concentrations of chromium in excess of the reporting limit, four samples taken from two sites exceeded the ANZECC trigger value.

Copper (Cu)

Seventeen of the 24 samples taken at Woodbridge Riverside Park contained concentrations in excess of the ANZECC trigger value for copper. Of these, seven samples exceeded the trigger value by 10-fold but less than 100-fold and another two exceeded the value by 100-fold.

Again, there were fewer reports at both Bayswater Riverside Gardens and Bicentennial Adenia Park. There were six samples with concentrations in excess of the trigger value at Bayswater, two of them at levels more than 10-fold higher than the guideline value. There were two bores at Bayswater at which copper was not reported on any of the three sampling runs.

Four of the 15 samples at Bicentennial Adenia Park contained copper in concentrations that exceeded the ANZECC trigger value. Copper was not present above the limit of reporting on any sampling run at three of the five sites.

Iron (Fe)

Of all the samples collected from the three waste disposal sites, only one sample at Bicentennial Adenia Park contained concentrations of iron that did not exceed the ANZECC trigger values. Of the 24 samples taken at Woodbridge Riverside Gardens, eighteen contained iron in concentrations that exceed the trigger value by a factor of 10, while another four exceeded the trigger value by at least a factor of 100. One site, CB14, contained iron concentrations at 670 times that of the trigger value. When sampling this site, iron flocculate was abundant in the groundwater collected through purging of the bore (Figure 5).

Iron flocculate was also frequently evident at Bayswater Riverside Gardens. There were 12 samples containing concentrations of iron that exceeded the ANZECC trigger value by 10-fold, and the remaining six samples exceeded the trigger value by at least 100-fold. In fact, the range of iron concentrations was relatively small at the site with a minimum concentration of 5.5 mg/L and a maximum concentration of 38 mg/L.



Figure 5: Iron flocculate present in groundwater sampled from CB14

Bicentennial Adenia Park was more variable with regard to iron concentrations. There were 14 instances where ANZECC trigger values were exceeded, five of which were at concentrations in excess of 10-fold the trigger value and one at levels in excess of 100-fold the trigger value.

Mercury (Hg)

Mercury was detected only once in the sampling, at one of the boreholes drilled in 2007 at Woodbridge Riverside Park. It should be noted that the limit of reporting is significantly higher (0.0001 mg/L) than the ANZECC trigger value (0.00006 mg/L) for mercury, therefore samples in which mercury was not reported may still exceed the ANZECC trigger value.

Manganese (Mn)

Manganese was detected in three samples at Woodbridge Riverside Park at concentrations in excess of the ANZECC trigger value, each of which were from bores constructed in 2007. Manganese was present in concentrations above trigger values in only one of the 18 samples at Bayswater Riverside Gardens and in no samples from Bicentennial Adenia Park.

Molybdenum (Mo)

Molybdenum was reported at all three disused waste disposal sites, however there were no samples containing concentrations in excess of the ANZECC trigger value.

Nickel (Ni)

There were 10 samples at Woodbridge Riverside Park that contained nickel in concentrations in excess of the ANZECC trigger value. One such sample, taken in the first sampling occasion at CB1 exceeded the value by a factor of 10. The concentration was variable at this bore, when re-sampled approximately six months later during the second sampling event, the concentration was less than the trigger value. It was not possible to re-sample this bore on the third sampling occasion in May and June 2007 due to insufficient groundwater levels.

Concentrations were generally lower at the other two locations. Five of the 18 samples from Bayswater Riverside Gardens did not exceed the limit of reporting for nickel, while the remaining 13 contained concentrations less than the ANZECC guidelines. Eleven of the 15 samples at Bicentennial Adenia Park had concentrations of nickel less than the limit of reporting while the remaining four samples did not exceed the trigger value.

Lead (Pb)

In the case of lead, the National Environment Protection Council guideline is more conservative than the ANZECC trigger value. For consistency, in Table 2, Table 3 and Table 4, the colour coding refers to instances where the ANZECC trigger value is exceeded, however it should be noted that several other samples in the results table do exceed the alternative guidelines. Like the majority of metals, lead was more frequently detected at Woodbridge Riverside Park than the other two sites; there were 14 samples at Woodbridge that exceeded the ANZECC trigger value, five of which were at levels more than 10 times the guideline value and one at a concentration which exceeded the guideline by more than 100-fold.

Of the 18 samples at Bayswater Riverside Gardens, 11 did not contain lead in concentrations above the limits of reporting and four samples exceeded the ANZECC guidelines. Eight of the 15 samples at Bicentennial Adenia Park did not contain concentrations of lead above the limit of reporting, while three samples contained concentrations that exceeded the trigger value.

Selenium (Se)

Only one sample contained selenium at concentrations above the limit of reporting. The concentration in this sample, from Woodbridge Riverside Park, did not exceed the ANZECC trigger value, nor the more conservative guideline values of the National Environment Protection Council or the Department of Environment.

Zinc (Zn)

Concentrations of zinc have been compared to the ANZECC trigger value, however it should be noted that similar to lead, the National Environment Protection Council guideline value is slightly more conservative. There are therefore some instances in the summary table of samples that are not highlighted which contain concentrations in excess of the alternative guideline.

The incidence of zinc in samples was more prevalent at Woodbridge Riverside Park than the other two waste disposal sites. Of a total 24 samples, zinc was not reported in two, and three contained levels below that of the ANZECC trigger value. The remaining 19 samples exceeded the guideline, five by at least a factor of 10 and another two by at least a factor of 100.

All samples taken from Bayswater Riverside Gardens contained concentrations of zinc above reporting limits. Ten of the 18 samples exceeded the ANZECC trigger value, but to a lesser extent than Woodbridge. Four samples from Bicentennial Adenia Park did not contain zinc above limits of reporting. Another four samples, taken from two sites, contained concentrations of zinc that exceeded the ANZECC trigger value.

3.3 Petroleum hydrocarbons and PAHs

Despite many petroleum hydrocarbons and PAHs having potential detrimental environmental effects at extremely low concentrations, there are currently no ANZECC trigger values for all but eight of those determined in this study. This deficiency in the guidelines made it impossible to determine exceedances for many of the analytes and it is possible that 'unflagged' contaminants may be present at concentrations sufficient to cause detriment to the environment. In the absence of appropriate guideline values for ecological protection, concentrations above the limit of reporting are highlighted in bold to prompt a closer review of the data. For example, the British Columbian guidelines provide criteria for many of the PAHs, i.e. phenanthrene and benzo[a]pyrene, that are lower than the concentrations reported in this study.

Of the targeted petroleum hydrocarbons and PAHs only naphthalene was present in concentrations that exceeded an ANZECC trigger value. Occurrences of other analytes within this category were far more frequent at Woodbridge Riverside Park than both Bayswater Riverside Gardens and Bicentennial Adenia Park. Some bores contained a range of hydrocarbons while others had no or minimal detections. Petroleum hydrocarbons detected across the three sites included benzene, the molecular weight fractions; C₁₀-C₁₄, C₁₅-C₂₈, C₂₉-C₃₆ and total recoverable hydrocarbons.

PAHs were sporadic. Of the 40 samples analysed over the three sampling events only 15 contained one or more of the target PAHs. Ten of these samples were obtained from Woodbridge Riverside Park, confined to 8 bores, two were collected from a single bore at Bayswater Gardens and three were collected from two bores at Bicentennial Adenia Park. Amongst these 15 samples, ten contained multiple target PAHs. Most noteworthy were bores BAC1, CB3, CB5 and CB13 at Woodbridge Riverside Park, which contained 13, 6, 12 and 14 of these analytes respectively. Six target PAHs were reported at BWF1 at Bayswater Riverside Gardens on the second sampling occasion.

For many of the PAHs the limits of reporting were substantially higher for the analysis of the second sampling event, possibly resulting in an underestimation of occurrence within samples. There were many PAHs that were detected for the first time on the third sampling occasion at concentrations below the limits of reporting applied previously.

The occurrence of individual petroleum hydrocarbons and PAHs are discussed in more detail below.

Benzene, toluene, ethylbenzene, xylenes and total BTEX

Benzene was reported in two samples at Woodbridge Riverside Park at concentrations that were substantially less than the ANZECC trigger value. The presence of benzene was not reported in any other sample. Similarly the presence of toluene, ethylbenzene and xylene was not reported at any of the historical waste disposal sites.

Unsurprisingly, the almost complete absence of each of the BTEX components was reflected in the total BTEX concentration. Total BTEX was reported in only one sample (CB13) at the Woodbridge site, as the other sample in which benzene was detected (CB3) did not exceed the limits of reporting for BTEX.

Petroleum hydrocarbon fractions C₆ - C₉, C₁₀ - C₁₄, C₁₅ - C₂₈, C₂₉ - C₃₆, and total reactive hydrocarbons (TRH)

There were no occurrences of the petroleum hydrocarbon fraction C₆-C₉ at any of the historical waste disposal sites. Of the 18 samples taken at Woodbridge Riverside Park, five contained concentrations of the petroleum hydrocarbon fraction C₁₀-C₁₄ above reporting limits. When sampling at the site which reported the highest concentration of this fraction, a strong hydrocarbon smell was noted. There were no detections at the other two historical waste disposal sites.

There were seven occurrences of the C₁₅-C₂₈ fraction at Woodbridge Riverside Park, including all sites that had reported a presence of the C₁₀-C₁₄ fraction. The C₁₅-C₂₈ fraction was reported once at Bayswater Riverside Gardens and never at Bicentennial Adenia Park.

There were less occurrences of the C₂₉-C₃₆ fraction, reported in only one sample at Woodbridge Riverside Park and one sample at Bayswater Riverside Gardens.

There were six occurrences of total recoverable hydrocarbons at Woodbridge Riverside Park and one at Bayswater Riverside Gardens, however none of these exceeded the ANZECC trigger value. The limit of reporting for any hydrocarbon fraction or total recoverable hydrocarbons was not exceeded in any sample at Bicentennial Adenia Park.

Acenaphthene

Acenaphthene was present above reporting limits in five of the Woodbridge Riverside Park samples and in two Bayswater Riverside Gardens samples. There was no such occurrence at Bicentennial Adenia Park.

Acenaphthylene

Acenaphthylene was reported in four samples at Woodbridge Riverside Park, all on the third sampling occasion. There were no reports of acenaphthylene at Bayswater Riverside Gardens or Bicentennial Adenia Park.

Anthracene

Six samples from Woodbridge Riverside Park and a single sample from Bayswater Riverside Gardens contained anthracene. There were no reports at Bicentennial Adenia Park.

Benzo[a]pyrene

There were three occurrences of Benzo[a]pyrene reported at Woodbridge Riverside Gardens, all on the third sampling occasion. It is likely that the lower limit of reporting applied on this sampling occasion may have allowed for reporting of contaminants that were previously below the limit of reporting. Although the ANZECC trigger value was not exceeded in any sample, one sample at Woodbridge Riverside Park (CB5) contained concentrations approaching this value.

The presence of benzo[a]pyrene was not reported at either Bayswater Riverside Gardens or Bicentennial Adenia Park. It is important to note that the limit of reporting was similar to the ANZECC trigger value, and in the second sampling occasion there were samples for which the limit of reporting was substantially higher. Therefore some care should be taken in the interpretation of non-reported concentrations.

Benzo[a]anthracene, benzo[b]fluoranthene and benzo[k]fluoranthene benzo[ghi]perylene, indeno[1,2,3-cd]pyrene and chrysene

The same three samples that showed the presence of Benzo[a]pyrene (ie BAC1, CB5 and CB13) at Woodbridge Riverside Park, also exceeded reporting limits for benzo[a]anthracene, benzo[b]fluoranthene and benzo[k]fluoranthene, benzo[ghi]perylene, indeno[1,2,3-cd]pyrene and chrysene. An additional sample at Woodbridge Riverside Park also contained chrysene. There were no reports of any of these analytes at either of the other two historical waste disposal sites.

Dibenz[ah]anthracene

The presence of dibenz[ah]anthracene was reported only once at Woodbridge Riverside Park.

Fluoranthene

Seven samples at Woodbridge Riverside Park and one sample at Bayswater Riverside Gardens contained concentrations of fluoranthene above the limits of reporting. None of these exceeded the ANZECC trigger value.

Fluorene

Fluorene was reported in three samples at Woodbridge Riverside Park and two samples at Bayswater Riverside Gardens.

Naphthalene

Naphthalene was reported in 11 samples at Woodbridge Riverside Park, one of which was in excess of the ANZECC trigger value. Naphthalene was reported in three samples at Bicentennial Adenia Park, however none exceeded the ANZECC trigger value. There were no reports at Bayswater Riverside Gardens.

Phenanthrene

While phenanthrene was reported at all three historic waste disposal sites it was never present in concentrations that exceeded the ANZECC trigger value. Eight samples at Woodbridge Riverside Park exceeded the limit of reporting for phenanthrene, as well as two samples at Bayswater Riverside Gardens and one sample at Bicentennial Adenia Park.

Pyrene

Pyrene was reported in six samples at Woodbridge Riverside Park and once at Bayswater Riverside Gardens. There were no reports of pyrene at Bicentennial Adenia Park.

3.4 Major ions

Alkalinity and acidity

Alkalinity and acidity vary considerably depending upon local geology, and therefore there are currently no guidelines available for this variable. Alkalinity is the total concentration of bases in water expressed as an equivalent concentration of calcium carbonate (CaCO_3). Usually these bases are bicarbonates (HCO_3^-) and carbonates (CO_3^{2-}) and that buffer the water against decreases in pH.

Alkalinity was highly variable in groundwater within each waste disposal site, however concentrations were generally consistent within bores. The range of measured alkalinity was

190 – 1400 mg/L at Woodbridge Riverside Park, 590 – 1200 mg/L at Bayswater Riverside Gardens and 43 – 470 mg/L at Bicentennial Adenia Park.

Similarly to alkalinity, acidity as calcium carbonate equivalents was variable within each waste disposal site, but consistent between sampling runs. Acidity ranged from 54 mg/L – 390 mg/L at Woodbridge Riverside Park, 66 – 290 mg/L at Bayswater Riverside Park and 12 – 340 mg/L at Bicentennial Adenia Park.

Fluoride

There is currently no guideline value available for fluoride. Of the 24 samples taken from Woodbridge Riverside Park, 12 failed to exceed the limit of reporting for fluoride (less than 0.2 mg/L), ten contained concentrations less than 1.0 mg/L, and two contained concentrations between 1.0 mg/L and 1.2 mg/L.

All 18 samples from Bayswater Riverside Gardens contained concentrations of fluoride between 0.2 mg/L and 0.9 mg/L. All three samples taken from BCR1 at Bicentennial Adenia Park contained concentrations of fluoride at less than the limit of reporting (less than 0.2 mg/L). The remaining nine samples from the site contained concentrations of fluoride between 0.2 mg/L and 0.7 mg/L.

Chloride and sulphate

As chloride is believed to be a conservative (i.e. unreactive) component of groundwater and surface water, the ratio of chloride to sulphate ions is often used as an indicator of possible sulphate contamination. The ratio of chloride to sulphate in seawater is relatively constant at approximately 7.2 (National Resource Management 2006). Table 5 is adapted from Davidson (1995) and lists indicative ratios of chloride to sulphate for various water sources and impact scenarios. Lower chloride to sulphate ratios can indicate an additional source of sulphate, for example from the oxidation of sulphides in acid sulphate soil or from fertiliser application (Appleyard, cited in Davidson 1995).

Table 5: Chloride to Sulphate ratios for varying degrees of groundwater pollution (adapted from Davidson 1995, p.p 91)

	Chloride/sulphate ratio	Sulphate/chloride ratio
Rainfall	~20 – 10	~0.05 – 0.1
Natural groundwater	~ 33 - 20	~ 0.03 – 0.05
Seawater impacted groundwater	~ 20	~ 0.05
Groundwater impacted by irrigated horticulture	~ 7.7 – 4.2	~ 0.13 – 0.24
Groundwater impacted by industry	~ 2.9 - <2.0	~ 0.5 - > 0.35

Chloride and sulphate concentrations for the groundwater bores are presented in Figure 6. For many samples, sulphate concentrations were below the limits of reporting and therefore appear along the y-axis. There was a broad range of chloride to sulphate ratios across all bores and all sampling occasions. For example, samples from CB5 (Woodbridge Riverside Park) and BWF5 and BWF6 (Bayswater Riverside Gardens) displayed Cl:SO₄²⁻ ratios consistent with horticulturally impacted water while BAC1 and CB14 (Woodbridge Riverside Park) were consistent with natural groundwater.

While several samples had chloride to sulphate ratios indicative of contamination, the majority of samples had ratios that were higher than would be expected for a contaminated water source.

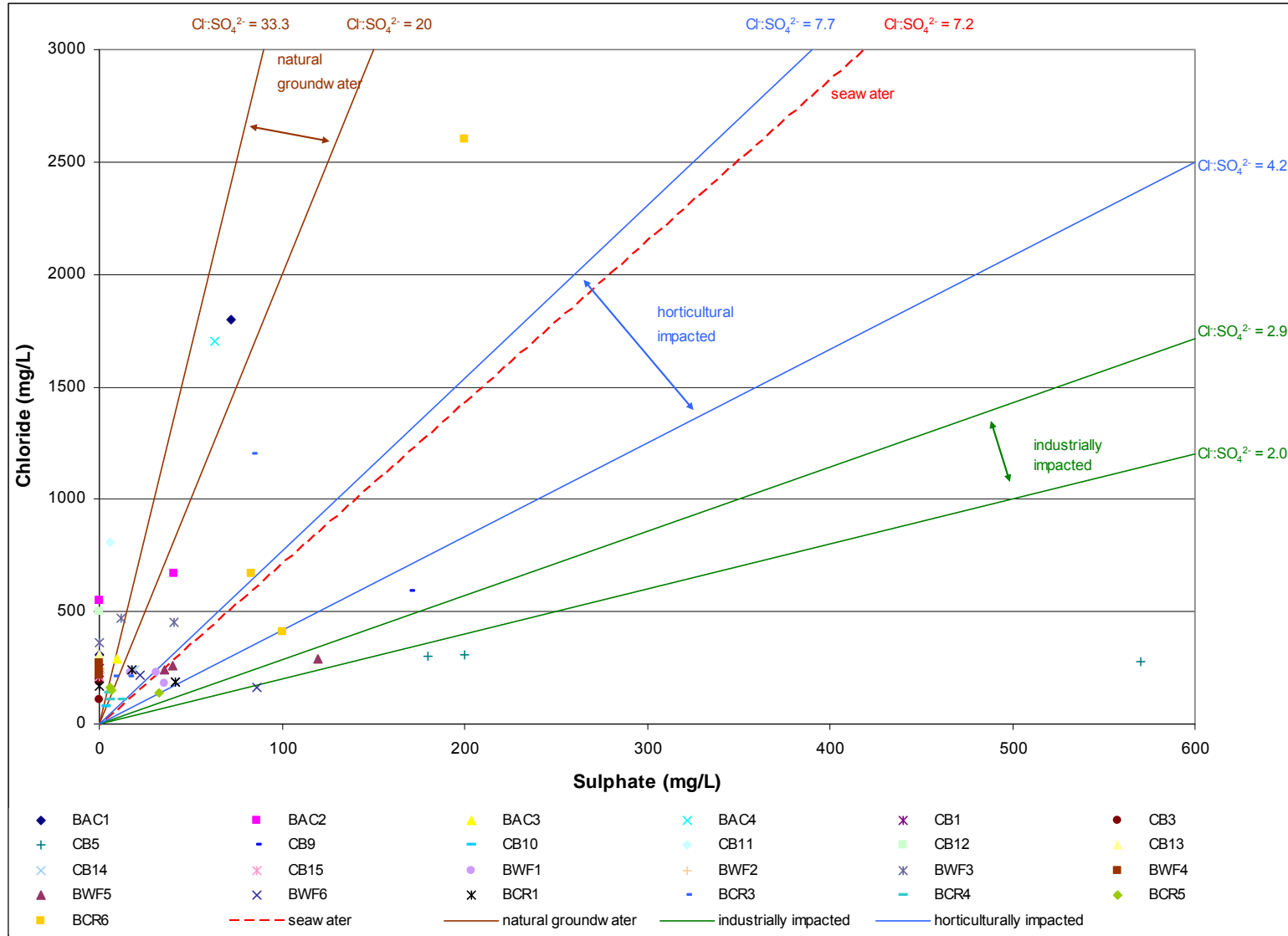


Figure 6: Chloride to sulphate ratio in groundwater sites

3.5 Nutrients

Total nitrogen

Samples were analysed for various forms of nitrogen: total nitrogen, total kjeldahl nitrogen, dissolved organic nitrogen, total oxidised nitrogen (i.e. nitrate and nitrite) and ammonia/ammonium. Total nitrogen concentrations were extremely high in the majority of groundwater samples, with only nine per cent of samples containing total nitrogen concentrations that did not exceed the ANZECC guidelines.

Of the 24 groundwater samples taken at Woodbridge Riverside Park, 22 exceeded the ANZECC total nitrogen trigger value for total nitrogen. Of those, 13 samples contained concentrations in excess of 10 times the trigger value and another six were in excess of 100 times the guidelines. The highest concentrations were consistently recorded at CB3, with a maximum concentration of 240 mg/L.

All of the 18 samples from Bayswater Riverside Gardens contained total nitrogen concentrations in excess of the ANZECC trigger value, with exactly half of those samples (at three sites) containing concentrations that were more than 10 times the ANZECC guideline. The highest nitrogen concentrations were consistently recorded at BWF4, with a maximum concentration of 53 mg/L.

In general, total nitrogen levels were lowest at Bicentennial Adenia Park. While 12 of the 15 samples exceeded the ANZECC trigger value, all of these were by less than a factor of 10. The highest total nitrogen concentration of 4.5 mg/L was recorded at BCR6, substantially less than the other two historical waste disposal sites.

Ammonia/ammonium

Concentrations of ammonia/ammonium (hereafter referred to as ammonium) exceeded the ANZECC trigger value in all samples in the study. In general, ammonium was the predominant inorganic species of nitrogen collected at all sites.

Of the 24 samples taken at Woodbridge Riverside Park, four contained ammonium in concentrations up to 10 times the ANZECC trigger value, two at levels in excess of 10 times the ANZECC trigger value and another 18 at levels in excess of 100 times the ANZECC trigger value. CB3 contained the highest concentrations on each of the three sampling occasions, with a maximum concentration of 230 mg/L.

Ammonium frequently was the predominant nitrogen species in samples from Bayswater Riverside Gardens. Eight of the 18 samples exceeded the ANZECC trigger value by 10-fold or more and the remaining 10 samples by at least a factor of 100. Again the highest concentrations were recorded at BWF4 with a maximum concentration of 38 mg/L.

Ammonium made up a large proportion of the total nitrogen content of samples collected from Bicentennial Adenia Park. As a result, all sites exceeded the ANZECC trigger value for ammonium, five in concentrations in excess of 10 times that guideline. A maximum concentration of ammonium of 4 mg/L was recorded at BCR6.

Oxidised nitrogen

With ammonium frequently contributing the majority of the total nitrogen concentration, many of the samples had relatively low concentrations of oxidised nitrogen. Only eight of the 57 sites throughout the study area exceeded the ANZECC trigger value for oxidised nitrogen with 27 of the samples not exceeding the limit of reporting.

Of the eight samples that did exceed the ANZECC trigger value, five were from sites BAC1, BAC2 and BAC3 at Woodbridge Riverside Park, all of which were adjacent to either the Swan River or Blackadder Creek. The maximum concentration recorded was 0.82 mg/L. The remaining three samples that contained oxidised nitrogen in excess of the ANZECC trigger value were from Bayswater Riverside Gardens, also with a maximum concentration of 0.82 mg/L. Only two samples from Bicentennial Adenia Park contained concentrations of oxidised nitrogen which exceeded the limit of reporting, both of which were well below the ANZECC guideline.

Dissolved organic nitrogen

Concentrations of dissolved organic nitrogen (DON) were highly variable when comparing between samples, being below the limit of reporting in one sample and representing a major portion of total nitrogen in others. There is currently no ANZECC guideline for DON, and therefore it is not highlighted in the results table even when present at concentrations that far exceeded the ANZECC guideline for total nitrogen.

DON was reported in all samples from Woodbridge Riverside Park. The highest concentrations were recorded at BAC2 (58 mg/L), CB13 (110 mg/L) and CB15 (100 mg/L). In each of these samples, the DON concentration was in excess of 60% of the total nitrogen concentrations.

DON concentrations were also highly variable at Bayswater Riverside Gardens. The highest concentrations of DON were at BWF2 (3.5 mg/L), BWF4 (14 mg/L) and BWF5 (9.9 mg/L). In general, the proportion of total nitrogen that could be attributed to DON concentrations was smaller at Bayswater than at Woodbridge.

The lowest DON concentrations were recorded at Bicentennial Adenia Park, with a maximum concentration recorded at BCR3 of 2.1 mg/L. It should be noted that while DON concentrations were much lower at Bicentennial Adenia Park, they still exceeded the ANZECC guideline specified for total nitrogen in several instances.

Total phosphorus

Of the 24 samples collected from Woodbridge Riverside Park, 16 contained concentrations of total phosphorus that exceeded the ANZECC trigger value. A maximum concentration of 0.45 mg/L was recorded at CB15, approximately seven times that of the trigger value.

Nine of the 18 samples from Bayswater Riverside Garden contained concentrations in excess of the trigger value, with a maximum concentration of 0.49 mg/L at BWF6.

While Bicentennial Adenia Park samples generally contained lower concentrations of most analytes relative to the other two sites, they contained the highest concentrations of total phosphorus. While one of the five bores (BCR1) did not exceed the ANZECC trigger value on any of the three sampling occasions, samples taken from the other four bores exceeded the guideline value on all occasions. Three of these samples exceeded the trigger value by more than a factor of ten with a maximum concentration of 0.95 mg/L at BCR3.

Filterable reactive phosphorus

Four of the 24 samples from Woodbridge Riverside Park contained concentrations of filterable (i.e. soluble) reactive phosphorus in excess of the ANZECC trigger value. Three of these samples were from BAC1 (i.e. all sampling occasions) and one sample, from BAC4, contained the maximum concentration of 0.17 mg/L, approximately four times the ANZECC trigger value.

While filterable reactive phosphorus was present in all samples at Bayswater Riverside Gardens, none exceeded the ANZECC trigger value. Three bores at Bicentennial Adenia Park did not exceed the trigger value on any of the sampling occasions. The remaining two sites, BCR4 and BCR5, consistently exceeded the ANZECC trigger values, the latter by a factor of greater than 10 on all three sampling occasions.

Dissolved organic carbon (DOC)

There is currently no ANZECC guideline available for DOC, however United Nations Educational Scientific and Cultural Organisation (UNESCO et al 1996) suggest that concentrations of 10 – 100 mg/L should be investigated further in surface water. As organic components of the waste disposal sites are degraded by processes within the site, dissolved organic carbon will increase in concentration in the groundwater. DOC concentrations were inconsistent at all three historical waste disposal sites with concentrations ranging from 8 - 110 mg/L, 17 - 110 mg/l and 19 - 43 mg/L at Woodbridge Riverside Park, Bayswater Riverside Gardens and Bicentennial Adenia Park respectively.

3.6 Target analytes not reported

PCBs and pesticides

PCBs and pesticides (including herbicides and organochlorine and organophosphate pesticides) were nominated as target analytes on both the second and the third sampling occasions. There were no reports of the presence of any of these analytes in any of the samples collected in the study. The list of target analytes are shown in Appendix A along with associated limits of reporting. It is important to note that the limit of reporting from NMI for organophosphate pesticides was higher than the ANZECC guidelines for those analytes.

4 Discussion

The results of this baseline study reflect the highly variable nature of disposal site waste, leachate generation and subsequent biogeochemical changes occurring within the groundwater.

The study has produced a baseline data-set which may be used to identify contaminants of concern occurring in the groundwater of historical waste disposal sites. It is known that groundwater interacts with the Swan and Canning Rivers (Westbrook et al. 2005) and as such these water bodies are considered as potential 'receiving water bodies' for the groundwater from sites adjacent to them. The trigger values of the ANZECC guidelines have been used to identify analytes present in concentrations which may result in ecological harm.

This discussion addresses physical data relative to background 'natural' levels, identifies those contaminants measured in particularly high concentrations or found extensively across sampling sites, and addresses variability in groundwater quality across the three sites. It is important to emphasise that as a leachate plume migrates, the relative concentration of contaminants detected at various points across and within the waste disposal site will change (Christensen et al. 2001). As such, hydrogeological mapping of the groundwater surface and contaminant concentrations would facilitate a greater understanding of the risk the leachate poses to receiving water bodies.

4.1 Physical data

The range of temperatures recorded across sites and sampling occasions (18.3°C – 25.9°C) was slightly greater than that which would be expected within the superficial aquifer (19 – 24 °C) (Davidson 1995). Those sites that recorded temperatures in excess of 24 °C included CB1, CB3, CB5 and CB10 at Woodbridge Riverside Park. These sites frequently registered temperatures several degrees higher than other bores in the same sampling period. The reason for elevated temperatures at these sites was not investigated in this study.

The electrical conductivity of the superficial groundwater aquifer of the Perth region generally falls in the range of 1.8 – 12 mS/cm (Davidson 1995). There were several bores that showed fluctuations in conductivity, possibly a result of interaction with the adjacent river. Variable conductivity readings may also be due to dissolution and evaporative processes occurring within the groundwater.

The pH of groundwater within the Perth region generally ranges between 4.0 and 8.0 depending on the geology on the region (Davidson 1995). In the final stages of waste disposal site stabilisation, pH is usually neutral or slightly alkaline. The pH of all samples in the study fell within the range of 6.2 – 7.3.

Most dissolved oxygen concentrations were below 20% saturation, however there were instances where higher concentrations were recorded. It is believed that dissolved oxygen concentrations reported here are higher than what would be present *in-situ*, as a result of the sampling technique through which oxygenation of the groundwater can occur while taking the measurement.

4.2 Redox environments and biodegradation

Groundwater tends towards a state of equilibrium between dissolved substances, aquifer solids and natural bacteria (Centre for Groundwater Studies 2005). As leachate percolates through waste and enters the groundwater, a complex series of reactions and processes will

determine the attenuation of each of the contaminants. Important processes at play include physical (dilution, absorption and adsorption), geochemical reduction and oxidation reactions (redox) and microbiological activity (Christensen et al. 2001). The geochemical processes that are characteristic of waste disposal site leachate are discussed in some detail in order to explain the concentrations of various key variables such as sulphate, iron, ammonium and nitrate. In addition, redox conditions will greatly influence the reactivity, mobility and toxicity of various other contaminants (Sigg n.d.).

Redox conditions will vary depending on the distance from the contaminant source, and are measured as a standard redox potential. The standard redox potential of a groundwater resource refers to the tendency of the solution to either gain or lose electrons with the introduction of a new species. In waste disposal sites, groundwater plumes of varying redox potentials will be produced as contaminants undergo transformations and the waste disposal site ages (Centre for Groundwater Studies 2005).

Within the waste disposal site, organic carbon will initially be broken down readily by aerobic respiration and denitrification. Once the system is depleted in oxygen and nitrate, reducing conditions result and denitrification occurs. If there is still organic carbon available, iron and manganese reduction (and solubilisation) may occur, followed by sulphate reduction and ultimately methane fermentation (Christensen et al 2001). As such, it would be expected that redox conditions will be more reducing the longer the waste has been degrading. In addition, more oxidising conditions should prevail at greater distances from the waste disposal site. The variability observed across waste disposal sites in the current study may not only be attributed to the heterogeneous nature of the fill but also the movement of the contaminated plume and associated biochemical processes at play.

It is inherently difficult to measure redox potential in the field, due to the presence of numerous redox couples often in dis-equilibrium (Sigg n.d.), including $\text{Fe}^{2+}/\text{Fe}^{3+}$ and $\text{SO}_4^{2-}/\text{H}_2\text{S}$. It should be noted that some redox reactions can take 1000 years to reach equilibrium. With these limitations in mind, and reference to the high degree of variability of measured redox potentials between sites and sampling occasions, caution must be taken when drawing conclusions from the redox potentials.

Redox potential was measured in the field using a Hydrolab Quanta within a representative groundwater sample. Analogous to the determination of dissolved oxygen, it is likely that this method of sampling might have resulting in some degree of oxygenation of the sample through disturbance, and an increase in the measured redox potential. Future sampling methods should endeavour to measure redox in-situ where possible, to increase the accuracy of the measurement and enable better interpretation of the biogeochemical processes occurring in the aquifer.

A slightly to moderately positive redox potential was recorded at the majority of bores across all three sites, indicative of nitrate, manganese and/or iron reduction. At lower redox potentials in the order of -200 MV (Langmuir 1997), the oxidation of organic matter involves the use of sulphate as an electron acceptor by microorganisms, thereby reducing sulphate to dissolved sulphide or gaseous hydrogen sulphide. Despite only measuring positive redox potentials, a hydrogen sulphide odour was noted at several sites and low sulphate ion concentrations were measured at many sites, suggesting that sulphate reduction was in fact occurring to some degree within the aquifer. The unexpectedly high and variable redox potentials are believed to be a result of the sampling technique as well as intra site variability due to the non-uniform nature of waste within the waste disposal site.

Sulphate ion concentrations less than 100 mg/L are considered to be consistent with natural background in the Perth region (Davidson 1995). Higher concentrations may be attributable, for example, to the oxidation of sulphides in acid sulphate soil materials (Department of Environment 2004), evaporative concentration in shallow watertables, saltwater intrusion, or contamination from fertilizers and other sulphur products. Sulphide is widely present in groundwater as hydrogen sulphide across the Perth region (Davidson 1995).

The ratio of chloride to sulphate can be used as a tool for indicating possible contamination of a water body. Due to its unreactive nature within aquifers, chloride is believed to be a conservative solute in groundwater (Christensen et al 2001). Several samples had particularly low chloride to sulphate ratios, suggesting an external source of sulphate. More commonly however, sulphate concentrations in samples were low and the ratio of chloride to sulphate was higher than that indicative of a contaminated water source. This is likely to be due to the occurrence of sulphate reduction involved in the degradation of matter in the waste disposal site, rather than a lack of sulphate contamination within the groundwater. The variability in the concentration of these species is to be expected across waste disposal sites in which the composition of the fill is not uniform and the composition of the leachate plume is likely to change as it migrates across the site.

Alkalinity and acidity as calcium carbonate are measures of the system's ability to buffer against decreases and increases in pH respectively. Often preceding the leachate front, methane gas is oxidised resulting in high levels of dissolved carbon dioxide. This may be detected by increased concentrations of alkalinity through the reaction with soils minerals to produce calcium or manganese carbonate in solution (Centre for Groundwater Studies 2005).

An important function of alkalinity in a leachate plume is its ability to form complexes and precipitates with several metal species. This has a buffering effect upon pH and prevents the formation of acidic leachate. While all of the waste disposal sites had a greater degree of alkalinity than acidity, analysis suggested they had a considerable buffering capacity against increases or decreases in pH. It is important to note here that while pH does not appear to be problematic at any of the groundwater bores, if the leachate is discharged into another environment, such as the Swan or Canning Rivers or exposed to air the situation may change dramatically. For example, there may be a loss of carbon dioxide gas with exposure of the leachate to the atmosphere which may result in a subsequent drop in pH.

4.3 Metals

As metal concentrations measured in this study are from unfiltered samples, metals bound to particulate matter will be dissolved when acidified during the sample preparation for chemical analysis. As such, total metal concentrations reported in this study are the highest concentrations that could possibly become bioavailable, and are likely to be an over-estimate of dissolved metal concentrations. Instances where the measured concentrations exceed the trigger values should therefore not be interpreted as necessarily indicating ecological harm, but rather highlight that further investigation is appropriate. On the other hand, if trigger values are not exceeded by total concentrations then the threat to the ecosystem is low. The determination of total metals was considered appropriate in a baseline surveillance study of this type, however future targeted studies might focus on dissolved metals to assess likely impacts of groundwater leachates on organisms in the receiving environments.

Several metals were found in high concentrations in the study relative to the ANZECC trigger values. In particular, lead, aluminium, chromium, copper, iron and zinc were found in concentrations that exceeded the ANZECC trigger values at all three historical waste disposal sites and by more than a 100-fold in at least one bore at Woodbridge Riverside Park. Cadmium and nickel were in concentrations that exceeded the ANZECC guidelines in several bores at Woodbridge Riverside Park. In addition, arsenic and manganese were in concentrations that exceeded the ANZECC trigger values at Bayswater Riverside Gardens and Woodbridge Riverside Park.

It is difficult to interpret the occurrence of iron in bores as relatively high concentrations of manganese and iron are naturally present in Perth groundwater (Hirschberg 1992). Within the Perth region, dissolved iron is present in concentrations ranging from less than 1 mg/L to greater than 50 mg/L. There are numerous natural causes for iron concentrations at the upper end of this range, including reactions involving the titanium-iron oxide mineral ilmenite (Baxter, cited in Davidson 1995), pyrite (iron sulfide) and discharge from the Leederville aquifer (Davision 1995).

The ANZECC trigger value for iron of 0.3 mg/L is substantially lower than the naturally recorded range within Perth groundwater, so some of the concentrations measured in the study are likely to reflect natural background conditions although they exceed the trigger values. Exceptionally high concentrations detected in the study might be attributed to the reaction of iron oxides contained naturally in the soil within waste disposal site leachate. It is also possible that material containing high concentrations of iron may be a component of the waste itself.

Considering the redox chemistry of the waste disposal sites, it would be expected that both soluble iron and manganese would be present in elevated concentrations as found in the current study. Insoluble iron and manganese oxides act readily as electron acceptors during the breakdown of organic contaminants, upon which their reduced forms are water soluble and therefore able to migrate within groundwater. When exposed again to an aerobic environment, such as inside a bore casing, iron(II) readily oxidises and precipitates as iron(III) hydroxide as illustrated previously in Figure 5. Due to the propensity of iron to convert between its iron oxide and reduced Fe(II) state, a naturally high concentration of iron oxides may result in 'redox buffering' retarding the migration of reduced leachate (Christensen et al 2001).

Aluminium was also present in concentrations well in excess of ANZECC trigger values. Similarly to iron, a substantial portion may be attributed to natural geological sources in addition to that contained in the fill itself.

While metal concentrations can be highly variable within waste disposal site leachate, in general, soluble heavy metals were measured in comparatively low concentrations at waste disposal sites in the literature (Christensen et al 2001). Total concentrations of heavy metals at Woodbridge Riverside Park were substantially higher than those measured at the other two sites for all heavy metals except cadmium (Table 6). Further, chromium, copper, lead and zinc were found in at least one sample at concentrations that exceeded the ANZECC guidelines by at least 100 times. It must be reiterated here that the study measured total, rather than soluble metal concentrations, and as a result, over-estimate the fraction that will be bioavailable.

Table 6: *Maximum total heavy metals concentrations (mg/L) recorded at each site*

	Woodbridge	Bayswater	Bicentennial	ANZECC (2000)
Cadmium	0.013	0.016	0.004	0.0002
Nickel	0.36	0.0094	0.002	0.011
Zinc	5.5	0.07	0.018	0.008
Copper	0.2	0.016	0.003	0.0014
Lead	0.5	0.019	0.01	0.0034
Chromium	0.19	0.016	0.004	0.001

It is evident that further investigation is required to evaluate the risk to the Swan and Canning Rivers posed by inflow of groundwater containing these metals. Priorities include: lead, aluminium, chromium, copper, iron and zinc and possibly to a lesser extent, arsenic, cadmium, manganese and nickel.

4.4 Petroleum and polycyclic aromatic hydrocarbons

Hydrocarbons released into the environment in a waste disposal site will undergo complex biodegradation processes including evaporation, leaching (dissolution), oxidation and microbiological degradation (Christensen et al 2001). The primary factor in the biodegradation of hydrocarbons is the molecular structure of the contaminant (Peters & Moldowan 1993; Fisher et al. 2001). The nature and concentrations of hydrocarbons present in groundwater affected by waste disposal site leachate is dependent upon initial concentrations within the fill, the degree to which degradation processes have altered the hydrocarbons and their migration through the aquifer. For example, the monocyclic compounds benzene, toluene, ethylbenzene and the xylene isomers, collectively referred to as BTEX are more water soluble than saturated hydrocarbons and PAHs and are therefore more easily leached from the fill material and transported through the aquifer (Gieg & Sufliya 2002).

Of the BTEX components, only benzene was present above the limit of reporting. This could be due to a greater concentration of benzene present within the waste or the faster rate of degradation of toluene, ethylbenzene and xylene under anaerobic conditions such as those encountered in the aquifer (Christensen et al 2001).

Petroleum hydrocarbons in the C₁₀-C₁₄ and C₁₅-C₂₈ fractions were more frequently reported than those of lesser or greater molecular weight. These fractions are most abundant in petroleum fluids such as crude oil and distillate (diesel). Lower molecular weight hydrocarbons (C₆-C₉, including BTEX) are also components of crude oil, but are more commonly associated with lighter petroleum fractions such as gasoline in which they are major components. Being more volatile makes these hydrocarbons more susceptible to biodegradation processes than the other fractions determined in the study. Higher molecular weight fractions (C₂₈₊) are less abundant in crude oil, are more difficult to detect and their very low water solubility limits the concentration at which they are likely to be reported in groundwater.

Of the 25 petroleum hydrocarbons and PAHs targeted in this study, only eight had ANZECC trigger values. It must be reiterated that the ANZECC guidelines are devised to be applied to surface water, and while other guideline documents specific to groundwater are based on these trigger values (National Environment Protection Council 1999; Department of Environment 2003c), comparison of concentrations measured in groundwater samples to trigger values in this study have been made cautiously.

The 15 PAHs analysed in the current study are among the 17 identified as the greatest concern with regard to potential exposure to humans (DoH 2004) and are known to be toxic to aquatic life (Connel 2000). Of these PAHs for which trigger values are available, naphthalene was present in one sample at Woodbridge Riverside Park at 31 µg/L, in excess of the ANZECC trigger value of 16 µg/L. Like many aromatic hydrocarbons, naphthalene has known aquatic toxicity; for example Black et al. (1983) recorded a chronic toxicity effect over 27 days at a concentration of 11 µg/L in rainbow trout. In the absence of trigger values many of the other PAHs, have not been highlighted. However, even at very low concentrations they may still pose an ecological risk. The British Columbia approved water quality guidelines (2006) were considered for petroleum hydrocarbons and PAHs for which no ANZECC guideline was available. Of these, phenanthrene and benzo[a]pyrene were present in concentrations at Woodbridge Riverside Park that exceeded the British Columbia guidelines (in three samples). There were no such instances at Bayswater Riverside Gardens or Bicentennial Adenia Park.

There is a limited understanding of how petroleum hydrocarbons and PAHs behave within leachate plumes and how they are affected by the major biogeochemical reactions at play (Christensen et al 2001). Toxicity testing of waste disposal site leachate may assist in assessing the ecological risk of low concentration organic contaminants in groundwater. It should be noted however, that the toxicity of inorganic species such as ammonium, present in much larger concentrations in the bores investigated may predominate over trace amounts of hydrocarbons (Christensen et al. 2001). Ammonium will, however, oxidise in a receiving water body to less toxic forms, while hydrocarbons may be more persistent within the environment.

4.5 Nutrients

Groundwater samples collected from all three historical waste disposal sites reported total nitrogen concentrations far in excess of ANZECC guidelines. Samples from Woodbridge Riverside Park were substantially higher in total nitrogen than Bayswater Riverside Gardens, which had higher concentrations than Adenia Bicentennial Park. In general high total nitrogen concentrations were attributable to high concentrations of ammonium and in some instances, dissolved organic nitrogen.

Ammonium is commonly used as a pollution indicator at waste disposal sites, with concentrations above 0.5 mg/L indicating possible groundwater contamination from leachate (Hirschberg 1992). While the maximum concentrations of ammonium recorded at Woodbridge Riverside Park (230 mg/L), Bayswater Riverside Gardens (46 mg/L) and Bicentennial Adenia Park (4 mg/L) were notably high, they fell within the range typical for waste disposal site concentrations of 0 – 1250 mg/L (Arigala et al. from Wakida & Lerner 2005).

The majority of ammonium is likely to have originated from the anaerobic decomposition of waste. Other sources of ammonium may include the disposal of bulk liquid wastes at the waste disposal sites or contamination from current or past use of septic systems in neighbouring residential areas. The three sites have now been converted to recreational parks and while fertiliser application may contribute to elevated concentrations of ammonium within topsoil, seepage to the groundwater is unlikely.

The high concentrations of ammonium reported in the study, particularly at Woodbridge Riverside Park and Bayswater Riverside Gardens is of particular concern. The United States Environmental Protection Agency investigated the acute toxicity of ammonium to 32

freshwater and 17 marine species from which average ammonium toxicity values of 2.79 mg/L and 1.76 mg/L were determined respectively (Randell & Tsui 2002). These concentrations are substantially less than those recorded within many of the sampling bores at these sites.

Although the concentrations of total oxidised nitrogen (nitrate and nitrite) in the groundwater were much lower, there were some bores in which the ANZECC trigger value was exceeded. High oxidised nitrogen concentrations were recorded at sites adjacent to the Swan River and Blackadder Creek at Woodbridge Riverside Park.

It is unlikely that the leachate plume is the source of oxidised nitrogen, as oxygen would have been consumed during the aerobic degradation of waste materials many years prior (Christensen et al. 2001). The presence of oxidised species may instead be due to interactions between the relatively aerobic waters of the adjacent river or creek and the groundwater which would produce a more oxidising groundwater environment and affect the biogeochemistry of the system (Westbrook et al 2005). Other bores containing high levels of oxidised nitrogen are likely to be either external to the waste disposal site leachate plume or intercepting the groundwater at a level unaffected by the leachate plume.

Phosphorus concentrations are typically less than 0.1 mg/L in Perth groundwater (Davidson 1995). Anthropogenic sources of phosphorus, including sewage in unsewered areas (i.e. from septic tanks and leach drains), can be retained in the soil matrix as phosphate by binding to anions such as iron. As a result, concentrations of phosphorus should be low in the superficial aquifer until the soil adsorption capacity has been exceeded, upon which, rapid increases in soluble phosphorus concentrations would be expected. Alternatively leachate plumes with low redox potential can promote the desorption of phosphate and an increase in soluble iron present in the groundwater.

As phosphate frequently binds to particulate matter in bores, filterable reactive phosphate is a more useful indicator of contamination of groundwater by phosphorous than total phosphorus concentration. The ANZECC trigger value for filterable reactive phosphorus was exceeded in two bores at Woodbridge Riverside Park, however the highest concentrations were reported at Bicentennial Adenia Park with concentrations exceeding guidelines by more than 10-fold. Alternatively, the ANZECC guidelines for filterable reactive phosphorus were not exceeded in any of the bores at Bayswater Riverside Park.

4.6 Analytes failing to exceed the limit of reporting in any sample

There were no reported occurrences of PCBs or pesticides (including herbicides and organochlorine and organophosphate pesticides), although it is not uncommon for these contaminants to be detected in leachate. Their apparent absence may be due to the type of waste disposed at the site, or their attenuation to concentrations below the sensitivity of the analysis through various degradation processes. In particular, little is known about the degradation of pesticides in waste disposal site leachate plumes (Christensen et al. 2001).

These instances where analytes do not exceed the limits of reporting should therefore be interpreted with caution. It is recommended that these analytes be included in future studies and analytical chemistry techniques with higher sensitivity be used.

4.7 Interactions with the Swan and Canning Rivers

Little is known of the hydrological interactions between the groundwater of the three historical waste disposal sites and the receiving water bodies, namely, the Swan and Canning Rivers. Further studies to investigate groundwater flow path are therefore recommended in any follow up work. It is important to note that the presence of contaminants and their mobility in a groundwater system is highly dependent on the biogeochemistry of that system. For example, a highly reducing environment such as those investigated here might contain high concentrations of ammonium, however if that water was to enter an aerobic environment such as a river, oxidation is likely to occur converting the nitrogen into the less toxic nitrate form. As such, when investigating the interaction of a contaminated groundwater plume with surface water, changes in the contaminant species must be considered.

5 Conclusions and recommendations

The study showed that groundwater at all three historical waste disposal sites was contaminated to some degree according to definition of the Department of Environment and Conservation (Department of Environment and Conservation n.d.(b)). The extent and type of pollutants present is dependant on the type of waste, waste disposal site age and size and biogeochemical reactions occurring within the aquifer. The leachate creates a series of redox zones which control the degradation of organic waste and the concentration and attenuation of contaminants. Sulphate, nitrate, iron, manganese and ammonium are particularly important in these oxidation and reduction reactions.

Contaminants occurring in groundwater in the study that may pose potential ecological risk to the Swan and Canning estuaries include:

- metals, such as lead, aluminium, chromium, copper, iron and zinc and possibly to a lesser extent, arsenic, cadmium, manganese and nickel
- polycyclic aromatic hydrocarbons, naphthalene and several other hydrocarbons for which ANZECC guideline values are currently unavailable
- nutrients, primarily ammonium, dissolved organic nitrogen and filterable reactive phosphorus.

Polychlorinated biphenyls, herbicides and organochlorine and organophosphate pesticides were not reported as present at any of the groundwater bores at the historical waste disposal sites.

Woodbridge Riverside Park was identified as the highest priority of the three waste disposal sites due to the greatest number of instances where the ANZECC guidelines were exceeded, and the most frequent reports of petroleum and aromatic hydrocarbons. On this basis, Bayswater Riverside Gardens appears to be more contaminated than Bicentennial Adenia Park. The range of contaminants present in the groundwater reflects anecdotal reports of the types of fill deposited in each site; Woodbridge receiving waste from a broad range of residential and industrial sources and Adenia receiving primarily green and inert waste.

Due to their close proximity, it is likely that contaminated groundwater from the waste disposal sites will discharge, or is currently discharging, to the Swan and Canning Rivers. The potential impact upon the Swan Canning estuary is the subject of further studies (e.g. Nice 2009). However, it is also recommended that the groundwater surface and contaminated zones of the leachate plume are mapped to determine the passage and flow rates through the sites. In addition, further investigations are required to determine the zones of interaction between the groundwater and the adjacent water and bed sediments of the Swan Canning system.

Understanding the rate of this process would require:

- mapping the groundwater surface using bore logs
- determining the rates and pathways of groundwater flow through the waste disposal site with consideration to local shallow geology and groundwater levels across the site
- performing spatial analysis of the contaminated leachate plume including zones of redox potential and high concentration zones of contaminants
- developing an understanding of the biogeochemistry occurring within the waste disposal site

- determining the zones of interaction with water and bed sediments of the Swan-Canning estuary.

These more in-depth investigations should focus initially at Woodbridge Riverside Park due to the greater degree of contamination detected in the study. The City of Swan is actively investigating this historical waste disposal site further as part of long term planning for the site. Should a contaminant plume be found that reaches the waters of the Swan-Canning estuary, then follow up sampling of the receiving environment may be required.

Appendix A - Analytes that failed to exceed the limit of reporting in any sample

Analyte	Category	Limit of reporting
2,4,5-T (tot) (µg/L)	OC herbicide	<1
2,4,5-TP (tot) {Silvex} (µg/L)	OC herbicide	<1
2,4-D (tot) (µg/L)	OC herbicide	<1
2,4-DB (tot) (µg/L)	OC herbicide	<1
Aldrin (tot) (µg/L)	OC insecticide	<0.01
Bromophos-ethyl (tot) (µg/L)	OP insecticide	<0.1
Chlordane (tot) {Tech; $\alpha+\gamma$ } (µg/L)	OP insecticide	<0.01
Chlorfenvinphos (tot) (µg/L)	OP insecticide	<0.1
Chlorpyrifos (tot) (µg/L)	OP insecticide	<0.1
Chlorpyrifos-methyl (tot) (µg/L)	OP insecticide	<0.1
DDD-p,p (tot) (µg/L)	OC insecticide	<0.01
DDE-p,p (tot) (µg/L)	OC insecticide	<0.01
DDT-p,p (tot) (µg/L)	OC insecticide	<0.01
Diazinon (tot) (µg/L)	OP insecticide	<0.1
Dicamba (tot) (µg/L)	OC herbicide	<1
Dichloroprop (tot) {2,4-DP} (µg/L)	OC herbicide	<1
Dieldrin (tot) (µg/L)	OC insecticide	<0.01
Diuron (tot) {Dichlorfenidim} (µg/L)	OC herbicide	<0.1
Endosulfan sulfate (tot) (µg/L)	OC insecticide	<0.01
Endosulfan-a (tot) (µg/L)	OC insecticide	<0.01
Endosulfan-b (tot) (µg/L)	OC insecticide	<0.01
Endrin (tot) (µg/L)	OC insecticide	<0.01
Ethion (tot) (µg/L)	OP insecticide	<0.1
Fenchlorphos (tot) (µg/L)	OP insecticide	<0.1
Fenitrothion (tot) (µg/L)	OP insecticide	<0.1
HCH (BHC) α,β,δ (tot) (µg/L)	OC insecticide	<0.01
HCH (BHC) γ (tot) {Lindane} (µg/L)	OC insecticide	<0.01
Heptachlor (tot) (µg/L)	OC insecticide	<0.01
Heptachlor epoxide (tot) (µg/L)	OC insecticide	<0.01
Hexachlorobenzene (tot) {HCB} (µg/L)	OC insecticide	<0.01
MCPA (tot) (µg/L)	OC herbicide	<1
MCPP (tot) {Mecoprop} (µg/L)	OC herbicide	<1
Malathion (tot) (µg/L)	OP insecticide	<0.1
Methoxychlor (tot) (µg/L)	OC insecticide	<0.01
Metolachlor (tot) (µg/L)	OC herbicide	<0.1
Mevinphos (tot) {Phosdrin} (µg/L)	OP insecticide	<0.1
OCs (tot) (µg/L)	OC pesticide	<0.1

OPs (tot) (µg/L)	OP pesticide	<1
Parathion (tot) {Ethyl par.} (µg/L)	OP insectide	<0.1
Parathion-methyl (tot) (µg/L)	OP insectide	<0.1
Tetrachlorvinphos (tot) (µg/L)	OP insectide	<0.1
Arochlor 1016 (tot) (µg/L)	PCB	<0.01 / <0.1
Arochlor 1221 (tot) (µg/L)	PCB	<0.01 / <0.1
Arochlor 1232 (tot) (µg/L)	PCB	<0.01 / <0.1
Arochlor 1242 (tot) (µg/L)	PCB	<0.01 / <0.1
Arochlor 1248 (tot) (µg/L)	PCB	<0.01 / <0.1
Arochlor 1254 (tot) (µg/L)	PCB	<0.01 / <0.1
Arochlor 1260 (tot) (µg/L)	PCB	<0.01 / <0.1
Atrazine (µg/L)	herbicide	<0.1
Hexazinone (tot) (µg/L)	herbicide	<0.1
Metribuzin (tot) (µg/L)	herbicide	<0.1
Molinate (tot) (µg/L)	herbicide	<0.1
PCB (tot) (µg/L)	herbicide	<0.1 / <1
Prometryn (tot) (µg/L)	herbicide	<0.1
Simazine (tot) (µg/L)	herbicide	<0.1
Triclopyr (tot) (µg/L)	herbicide	<1
Trifluralin (tot) (µg/L)	herbicide	<0.1

Glossary and acronyms

Acid sulphate materials	Acid sulphate materials are naturally occurring soils, sediments and peat that contain iron sulphides. When exposed to the atmosphere through lowering of the watertable or excavation, oxygen reacts with the iron sulphides in the soil. This oxidation reaction results in the production of sulphuric acid which can cause a breakdown of the soil structure releasing metals, precipitates and nutrients with potentially adverse environmental impacts.
Acute toxicity	Inducing harmful effects in an organism through a single or short-term exposure.
ANZECC	Australian and New Zealand Environment and Conservation Council
ARMCANZ	Agriculture and Resource Management Council of Australia and New Zealand
Background Concentrations	Naturally occurring ambient concentrations in the local areas of a site.
Bioavailable	The fraction of the contaminant in the surrounding environment that can be taken up by organisms
BTEX	Benzene, toluene, ethylbenzene and isomers of xylene
Catchment	The area of land which intercepts rainfall and contributes the collected water to surface water or groundwater
Contaminant	A substance which has the potential to present a risk of harm to human or environmental health.
Contaminated	As defined in the Contaminated Sites Act 2003, contamination refers to having a substance present on land, water or site above background concentrations and at high enough concentrations such that it presents, or has potential to present, a risk of harm to human health, the environment or any environmental value.
Contamination	As defined by the DEC "Contamination is deemed present if there are specific substances recorded above recommended concentrations, as listed in the DEC Guideline, <i>Assessment levels for soils, sediment and water</i>
DEC	Department of Environment and Conservation (formed on 1 July 2006 from the amalgamation of the Department of Environment and the Department of Conservation and Land Management)
DO	Dissolved oxygen
DOC	Dissolved organic carbon
DoE	Department of Environment
DoW	Department of Water
Ecotoxicology	The study of the toxic effects of chemicals upon ecosystems and indicator organisms

Estuary	Partially enclosed coastal body of water, having an open connection with the ocean, where freshwater from inland is mixed with saltwater from the sea
Filterable	Able to pass through a filter paper with pore size of 45 µm
FRP	Filterable reactive phosphorus
Hardness	Measure of calcium and magnesium concentrations in water
Hydrocarbon	Organic compounds composed of carbon and hydrogen atoms.
Hydrogeology	The study of groundwater
Inorganic	Not containing carbon.
Ions	Electrically charged particles. Many chemicals are present as ions when dissolved in water.
Landfill	In relation to the legal disposal of contaminated material, a landfill is a site used for the disposal of solid material by burial in the ground
Leachate	Water that percolates through the waste disposal site and becomes contaminated
Leaching	The removal of contaminants by water percolating through soil
Limit of reporting	The lowest concentration at which a contaminant may be reported by a laboratory for a given sample matrix and analytical method
Mini-piezometers	Mini-piezometers monitor shallow groundwater conditions in the stream or lake bed, typically at depths of less than 2 meters. The basic construction is a small-diameter pipe stoppered at the base with slots to allow entry of groundwater into the bore.
NNCP	Non-Nutrient Contaminants Program.
OC Pesticide	Organochlorine pesticide.
OP Pesticide	Organophosphorus pesticide.
Oxidation	A reaction in which an atom, molecule or ion loses electrons.
PAH	Polycyclic aromatic hydrocarbon
PCB	Polychlorinated biphenyl
pH	A measure of acidity, neutrality or alkalinity of an aqueous solution, defined as the negative logarithm of the hydrogen ion concentration. Measured on a logarithmic scale of 1 to 14, in which an acidic solution has a pH less than 7 and an alkaline solution has a pH greater than 7.
Reduction	A reaction in which an atom, molecule or ion gains electrons
River	A large natural stream of water emptying into an ocean, lake, or other body of water and usually fed along its course by converging tributaries
SAP	Sampling and Analysis Plan

Sediment	Loose particles of sand, clay, silt and other substances that settle at the bottom of a body of water. Sediment can be derived from the erosion of soil or from the decomposition of plants and animals.
Spatial	Relating to space
Subcatchment	Distinct drainage areas that form components of the overall catchment for a river or other body of water.
Temporal	Relating to, or limited by time
TOC	Total organic carbon
TPH	Total petroleum hydrocarbons
TRH	Total recoverable hydrocarbons
Trigger level	The concentrations (or loads) of the key performance indicators measured for the ecosystem, below which there exists a low risk that adverse biological (ecological) effects will occur. They indicate a risk of impact if exceeded and should 'trigger' some action, either further ecosystem specific investigations or implementation of management/remedial actions.

References

- ANZECC & ARMCANZ 2000, *Australian and New Zealand guidelines for fresh and marine water quality*, Australia and New Zealand Environment and Conservation Council & Agriculture and Resource Management Council of Australia and New Zealand.
- Appleyard, SJ 1992, *Estimated nutrient loads discharged into the Swan Canning Estuary from groundwater*, Hydrogeology Report No. 1992/20, Western Australian Geological Survey, Perth.
- Black, JA, Birge, WJ, Westerman, AG & Francis, PC 1983 'Comparative aquatic toxicity of aromatic hydrocarbons', *Toxicological Sciences*, vol. 3, no. 5, pp. 353 – 358.
- Centre for Groundwater Studies 2005, 'Groundwater quality – how has this been influenced by human development?' in *Getting to Know Groundwater and Surfacewater*, Centre for Groundwater Studies, Adelaide.
- Christensen, TH, Kjeldsen, P, Bjerg, PL, Jensen, DL, Christensen, JB, Baun A, Albrechtsen HJ & Heron G 2001, 'Biogeochemistry of landfill leachate plumes', *Applied Geochemistry*, vol 16, pp. 659 – 718.
- Christenson, SC & Cozzarelli, IM 2003, *The Norman Landfill Environmental Research Site: What happens to the waste in landfills?* Retrieved April 15, 2007 from <http://pubs.usgs.gov/fs/fs-040-03>.
- Connel, DW 2000 'Occurance and effects of petroleum hydrocarbons on Australia's marine environment', in LP Zann & D Sutton (eds) *State of the marine environment report for Australia: pollution – technical annex 2*, Great Barrier Reef Marine Park Authority, Townsville.
- Davidson, W A. 1995, *Hydrogeology and groundwater resources of the Perth region, Western Australia*, Western Australia Geological Survey, Bulletin 142.
- Department of Health 2004 *Information fact sheet on polycyclic aromatic hydrocarbons (PAHs)*, Government of South Australia, Adelaide.
- Department of Environment and Conservation n.d.(a) *How to access information on contaminated sites in Western Australia*, Government of Western Australia, Retrieved February 1, 2008, from www.dec.wa.gov.au/contaminatedsites
- Department of Environment and Conservation n.d.(b) *Site classifications – what do they mean?*, Government of Western Australia, Retrieved February 1, 2008, from www.dec.wa.gov.au/contaminatedsites
- Department of Environment and Conservation n.d.(c), *Contaminated sites*, Government of Western Australia, retrieved February 1, 2008, from http://portal.environment.wa.gov.au/portal/page?_pageid=53,34343&_dad=portal&_schema=PORTAL
- Department of Environment 2003a, *Summary report on water and sediment quality in Brookdale drain*, Department of Environment, Government of Western Australia.
- Department of Environment 2003b, *Assessment of water, sediment and fish quality in the Bayswater Drains and adjacent Swan River*, Department of Environment, Government of Western Australia.

- Department of Environment 2003c, *Assessment levels for soil, sediment and water, draft for public comment*, Department of Environment, Government of Western Australia, retrieved April 31, 2007, from http://portal.environment.wa.gov.au/pls/portal/docs/PAGE/DOE_ADMIN/GUIDELINE_REPOSITORY/ASSESSMENT%20LEVELS%20FOR%20SOIL,%20SEDIMENT%20AND%20WATER.PDF
- Department of Environment 2004, *Guidance for groundwater management in urban areas on acid sulphate soils*, Department of Environment, Government of Western Australia.
- Department of Water 2007, *Sampling and analysis plan: SG-NONNUTGRW groundwater assessment*, Department of Water, Government of Western Australia.
- Foulsham, G, Nice, HE, Fisher, S, Mueller J, Bartkow, M, Komorova, T, 2009, *A baseline study of organic contaminants in the Swan and Canning catchment drainage system using passive sampling devices*, Water Science Technical Series Report No.5, Department of Water, Western Australia.
- Gieg, LM & Suflita, JM 2002, 'Detection of anaerobic metabolites of saturated and aromatic hydrocarbons in petroleum-contaminated aquifers', *Environ. Sci. Technol.*, vol. 36, p.p. 3755 – 3762.
- Hirschberg, KJ 1992, *Municipal waste disposal in Perth and its impacts on groundwater quality*, Hydrogeology Report No. 1992/20, Western Australian Geological Survey, Perth.
- Langmuir, D 1997, *Aqueous environmental geochemistry*, Prentice Hall Inc, New Jersey.
- Ministry of Environment 2006, *British Columbia approved water quality guidelines*, Ministry of Environment, Government of British Columbia, retrieved January 2008, from http://www.env.gov.bc.ca/wat/wq/BCguidelines/approv_wq_guide/approved.html.
- National chemical reference guide – standards in the Australian environment* n.d. Retrieved April 31, 2007 from http://hermes.erin.gov.au/pls/crg_public!/CRGPPUBLIC.PSTART?strAction=SearchByChemical (for arsenic, cobalt, iron, molybdenum and selenium)
- National Environment Protection Council 1999, *Schedule B (1) Guideline on the investigation levels for soil and groundwater*, Retrieved April 31, 2007, from www.ephc.gov.au/pdf/cs/cs_01_inv_levels.pdf.
- Natural Resource Management 2006, *Estuarine, coastal and marine habitat integrity: pH*. [Brochure] National Resource Management, Australian Government.
- Nice, HE 2009, *A baseline study of contaminants in the sediments of the Swan and Canning estuaries*, Water Science Technical Series Report No.6, Department of Water, Western Australia.
- Nice, HE, Grassi, M, Foulsham, G, Morgan, B, Evans, SJ, Robb, M 2009, *A baseline study of contaminants in the Swan and Canning catchment drainage system*, Water Science Technical Series Report No.3, Department of Water, Western Australia.
- Peters, KE & Moldowan, JM 1993, *The biomarker guide: interpreting molecular fossils in petroleum and ancient sediments*, Prentice Hall, Inglewood Cliffs, New Jersey.
- Randall, DJ & Tsui, TKN 2002, 'Ammonium toxicity in fish', *Marine Pollution Bulletin*, vol. 45, no. 1-12, pp. 17-23.

- Sigg, L 'Redox potential measurements in natural waters: significance, concepts and problems' in Schuring et al (eds) *Redox: fundamentals, processes and applications*. Retrieved May 31, 2007, www.geochemie.uni-bremen.de/downloads/redox/chapter01.pdf.
- Stockholm Convention (2005) *Ridding the world of POPs: a guide to the stockholm convention on persistent organic pollutants*, United Nations Environment Programme. Retrieved May 10, 2007, www.pops.int.
- Swan River Trust (1999a) *Swan-Canning cleanup program – action plan*, Swan River Trust, Perth.
- Swan River Trust (1999b) *Swan-Canning Cleanup Program: Contaminants in the Swan-Canning Rivers and estuary: a supporting document to the Swan-Canning Cleanup Program Action Plan*, Swan River Trust, Perth.
- Total Petroleum Hydrocarbon Criteria Working Group 1998, *Analysis of petroleum hydrocarbons in environmental media*, Amherst Scientific Publishers, Massachusetts.
- UNESCO, WHO & ENED 1996, *Water quality assessment: a guide to the use of biota, sediments, and water in environmental monitoring*, 2nd edn, ed. DV Chapman, Spon Press, United States.
- Wakida, FT & Lerner, DN 2005, Non-agricultural sources of groundwater nitrate: a review and case study, *Water Research*, vol. 39, pp. 3-16.
- Westbrook, SJ, Rayner, JL, Davis, GB, Clement, TP, Bjerg, PL & Fisher, SJ 2005, 'Interaction between shallow groundwater, saline surface water and contaminant discharge at seasonally and tidally forced estuarine boundary', *Journal of Hydrology*, vol 302, pp. 255 – 269.

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Department of Water

168 St Georges Terrace, Perth, Western Australia
PO Box K822 Perth Western Australia 6842
Phone: (08) 6364 7600
Fax: (08) 6364 7601
www.water.wa.gov.au