The characteristics and impacts of landfill leachate from Horotiu, New Zealand and Maseru, Lesotho:

A comparative study

A thesis

submitted in partial fulfilment

of the requirements

for the degree of

Master of Science in Environmental Science

at

The University of Waikato

by

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THE UNIVERSITY OF
WAIKATO
Te Whare Wānanga o Waikato

2008

Abstract

Landfills are a potential pollution threat to both ground and surface water resources. This study focuses on two landfills, the Horotiu municipal waste landfill, near Hamilton, New Zealand, and the Maseru landfill in Lesotho. The Horotiu landfill is located less than 50 metres from the Waikato River and also sits on a shallow (< lm to water table) aquifer. In Lesotho, the Maseru landfill is 4 km from a river and 2 km from a water reservoir and rests on a huge aquifer. Over 5000 people depend on groundwater in the area between the landfill and the river. The objectives of my study were to: 1. compare and contrast conditions, management, and potential environmental impacts of the Horotiu and Maseru landfills; 2. evaluate the potential for groundwater contamination as the result of leachate migration; and 3. investigate the chemical characteristics of the landfill leachates and the impacts of the landfills on groundwater quality.

The Horotiu study was based on the leachate and groundwater quality monitoring data obtained from the Hamilton City Council. Samples were collected every three months from 1991-2006 and analysed for about 30 chemical parameters. The data for the Maseru landfill consisted of groundwater quality collected by the author during July-September 2007 and borehole pumping data obtained from the Department of Water Affairs, in Lesotho.

At Horotiu results indicate that the leachate had high concentrations of: NH_4-N (630 mg/l), TOC (405 mg/l), BOD (126 mg/l), and COD (1289 mg/l), while heavy metals were in low concentrations (<0.1mg/l). Leachate quality was found to change with time and with rainfall. Groundwater samples obtained from the landfill boreholes indicated that the Horotiu landfill had an influence in the quality of groundwater. Groundwater at the down-slope side of the landfill had higher concentrations of all chemical parameters, except for NO_3-N, SO_4^{-2} and Reactive P, than the groundwater on the upstream side. The mean groundwater quality at Horotiu was within New Zealand drinking water standards though some standards were exceeded by some individual samples.

In the Maseru landfill, the borehole water had high concentrations of chemical parameters such as EC (1580 µS/cm) and Chloride (190 mg/l), compared to the national average of 250 µS/cm and 28 mg/l. The Maseru landfill groundwater quality was within the WHO drinking water standard for all analysed chemical constituents, except lead.

Groundwater beneath both landfills was influenced by leachate but the impacts are currently not at an alarming stage, for analysed chemical parameters. At Maseru introduction of landfill linings has potential to reduce the effect of leachate on groundwater.

Acknowledgments

I would like to express my deepest gratitude to my principal supervisor Dr. Megan Balks for her wise and patient guidance from the beginning to the completion of this research. I would also like to thank Dr. David Campbell for his valuable contribution to this work. Thank you guys and God bless.

My gratitude is also due to the following institutes: Hamilton City Council and Environment Waikato in New Zealand for providing information, opinion and reports for the Horotiu landfill; The Department of Water Affairs in Lesotho for the information and data on Maseru landfill; CRL Ltd, New Zealand for the educative trip around the Horotiu landfill and for the interview on leachate and groundwater monitoring.

I give thanks also to my sponsor, NZAID and my employer, Lesotho Government for giving me the opportunity to undertake this study.

Last but not least, heaps of thanks to my graceful wife, ‘Matobatsi and my magnificent son, Tobatsi for being part of my life and for supporting me during this nerve-racking period.

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Chapter 1

Introduction

1.1 Background

Management of solid waste and related environmental impacts presents a challenge to both developing and developed countries. The amount of waste generated is directly linked to the increasing population, increasing wealth and resource use. The most widely used method for disposal of municipal solid waste is landfilling, accounting for up to 95% of the total waste collected world wide (Kurniawan *et al*. 2006).

Landfilling is also generally the most economical method of disposing of municipal solid waste (Ustohalova *et al.* 2006). However, there are a number of environmental drawbacks associated with landfills which have aroused social and environmental attention in recent decades (Calvo *et al.* 2005). Amongst the drawbacks, disposal of solid waste in landfills constitutes a considerable source of groundwater pollution (Bjerg *et al.* 2003; Todd 1980).

After waste is disposed of at landfills, it undergoes a number of physical, chemical and microbiological changes. Leachate is generated when water percolates through the waste layers (Kjeldsen *et al.* 2002). When the amount of rainfall is greater than the evaporation rate, the leachate level in the landfill increases (Robinson 2005). Leachate may contain large amounts of organic and inorganic compounds (Bodzek *et al.* 2006). If leachate is not controlled, it can find its way to the surrounding soils and eventually to the groundwater.

Contamination of groundwater by landfill leachate has been reported by several authors (Chofqi *et al.* 2004; Christensen *et al.* 1994; Fatta *et al.* 1999; Jonnes-Lee & Lee 1993; Rapti-Caputo & Vaccaro 2006; van Breukelen *et al.* 2003). Contamination of groundwater by landfill leachate may eventually lead to surface water contamination because groundwater usually discharges to surface water bodies such as lakes and rivers (Freeze & Cherry 1979).

Leachate from a landfill can continue to pose a groundwater contamination problem for many years after the closure of the landfill. For instance, landfills constructed by the Romans 2000 years ago are reported by Freeze and Cherry (1979) to be still continuing to produce leachate.

Solid waste facilities consist of uncontrolled open dumps (also known as 'dilute and disperse') and sanitary engineered (also known as 'containment') landfills. Open dumps are not designed/ engineered and leachate from them freely enters both surface and groundwater bodies, thus presenting a clear environmental risk (Rosqvist & Destouni 2000). Open dumps are the more common in developing countries and were prevalent in New Zealand up to the 1980's. Sanitary landfills, such as the Horotiu landfill, are now employed in New Zealand and other countries, to minimize adverse environmental impacts. However, sanitary landfills are not without flaws and are still prone to structural failure. For this reason, Allen (2001) argues that sanitary landfills are just the 'myth of sustainability' citing uncertainty in the long-term durability and failure of hydraulic barrier liners.

The current study is focused on investigating landfill leachate at two landfill sites. The main focus will be on the Horotiu sanitary landfill which is located near Hamilton in New Zealand. The other site is an open dump solid waste facility in the Lesotho capital, Maseru. At both sites, there is acknowledgement of the potential of groundwater contamination due to migration of landfill leachate; hence both sites are equipped with groundwater monitoring networks. The networks are aimed at detecting the presence of leachate in the local groundwater and possibly surface water sources.

1.2 Objectives

Understanding both the physical and chemical properties of the landfill leachate can help in dealing with and mitigating its environmental impacts. This research is aimed at investigating the chemical composition and the movement of landfill leachates at the two sites, Horotiu and Maseru, which represent respectively, a typical modern sanitary landfill and a traditional open dump. The objectives of the study are outlined as follows:

1. To compare and contrast conditions, management, and potential environmental impacts of the Horotiu and Maseru landfills.

2. To evaluate the potential for groundwater contamination as the result of leachate migration.

3. To investigate the chemical characteristics of the landfill leachates and the impacts of the landfills on groundwater quality.

Chapter 2

Literature Review

2.1 Landfill location selection criterion

In order to select the most suitable location for a landfill, there are some measures that would normally be followed to minimise the impact of the landfill on the surrounding environment. Important factors to consider when locating a landfill include: geology, geohydrology and surface drainage. Geological investigations are carried out to locate features like dykes, faults and geological contacts (USEPA 1998).

Geohydrological investigations are undertaken to assess the aquifer system of the area, the thickness and the properties of the soil coverage in the unsaturated zone. Groundwater flow directions and head gradient are also of importance. Carrying out spring and water borehole inventories, depth to the top of aquifers and piezometric levels, water quality and permeability of rock and soil formations are also necessary (USEPA 1998). An ideal location, according to USEPA (1998), should have the following characteristics:

- No geological faults/ dykes.
- Very low permeability strata at the base of the landfill.
- Unsaturated layer of thickness more than 30 m.
- More than 1000m from the nearest surface water bodies.
- Low hydraulic conductivity of the ground.
- The nearest aquifer below the landfill should not be used for domestic purposes.
- Be located downstream of the aquifers.

2.2 Sanitary landfill design

2.2.1 Landfill Liners

Engineered sanitary landfills are designed to isolate waste from the surroundings (Hoeks *et al*, 1987), to control leachate migration from the landfill into the surrounding environment, as well as to collect leachate for treatment. This is normally achieved by installing a liner system at the base and sides of a sanitary landfill. Liners are applied on landfills to provide a barrier to minimise migration of contaminants from the containment site to groundwater. Liners are normally in the form of a compacted clay or a geomembrane (Bouazza & van Impe 1998). Figures 2.1 and 2.2 show cross-sectional views of how compacted clay and geomembrane liners may be installed to contain waste. There are several other materials that have been used as landfill liners, either individually or in combination. For example, Edil and Berthouex (1990) have investigated the performance of fly ash-sand and bentonite-sand mixtures for use as liners.

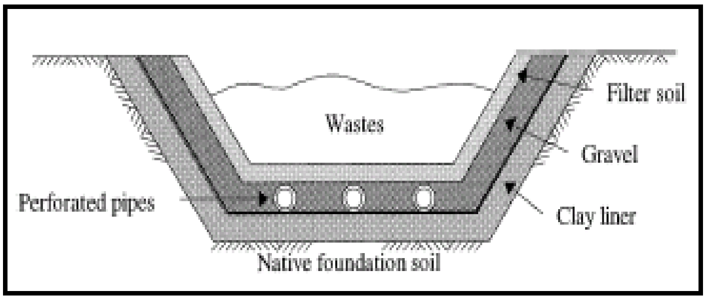

Figure 2.1 Cross-sectional view of a compacted clay liner. (source: Bouazza and van Impe 1998).

A study by Benson and Othman (1993) suggested that there is a possibility of using compacted compost derived from municipal for lining because it displays hydraulic and mechanical properties required for liners. The authors reported that compacted compost is more resistant to an increase in hydraulic conductivity, which may result from desiccation and freeze-thaw, and possesses greater shear strength than compacted clay. However, contaminants such as heavy metals were found to leach from the compacted compost (Benson and Othman 1993), which is a disadvantage for use of compacted compost for lining landfills.

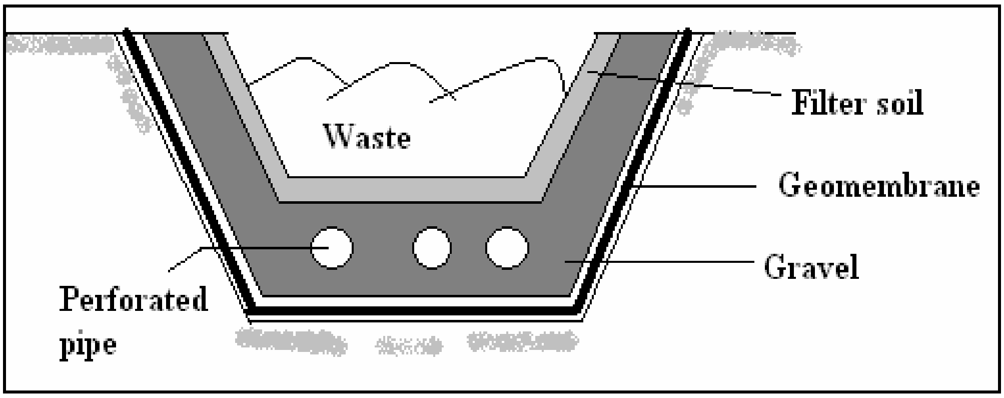

Figure 2.2 Cross-sectional view of a geomembrane liner. (after: Bouazza and van Impe, 1998).

A liner system combining two or more barrier materials has been used. This is called a composite liner system. Composite liner systems may consist of materials such as compacted clay liners (CCL), geomembrane (GM) and geosynthetic clay liners (GCL) (Bergado *et al.* 2006). Figure 2.3 shows an example of a composite liner comprising geomembrane placed over a compacted clay layer.

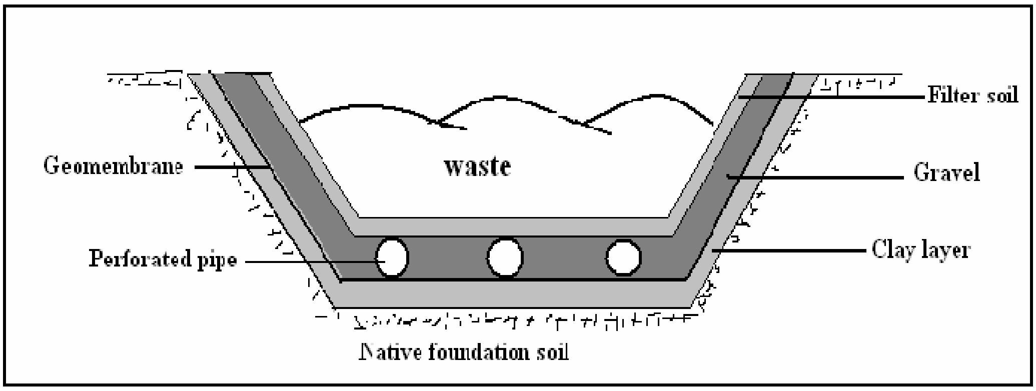

Figure 2.3 Cross-sectional view of a composite liner (after: Bouazza and van Impe 1998).

Composite liner systems are far more effective (Bouazza and van Impe 1998) than single liners used separately. Leakages from the composite liners are often orders of magnitudes less than leakage from single geomembrane and clay liners (Bouazza and van Impe 1998; *Katsumi et al.* 2001). In the CCL-GM composite system, the thickness of the clay layer should be between 0.6 and 0.9 m and the geomembrane should not be less than 1.5 mm thick (Bouazza and van Impe 1998). Katsumi *et al.* (2001) consider geomembrane and clay layer thickness of 1 mm and 0.6 m respectively, to be sufficient for composite lining.

Perforated pipes are normally incorporated in liners as a means of leachate collection. There is no global standard for designing municipal landfill liners.

2.2.2 Landfill Capping

After the end of the landfill operations, the landfill must be covered or capped. The engineered capping is done to prevent or control infiltration of precipitation, thereby minimising movement of fluids through the waste (Elshorbagy and Mohamed 2000) and therefore minimising production of leachate. The cover is also meant to prevent erosion that may lead to exposure of waste (Simon and Muller 2004). Simon and Muller (2004) suggest that a sanitary landfill soil barrier cap may consist of the following structures, from top to bottom:

- Native vegetation cover.
- 0.3 m of top soil.
- 0.3 m of subsoil.
- 0.6 m of compacted clay with permeability of not more than $1x10^{-7}$ m/s or material with equivalent specification.
- Geomembrane of thickness not less than 2.5 mm.
- 0.3 m of intermediate cover.

The covering top soil and subsoil are essential for plant growth and burrowing animals. Other types of capping materials are also being used. Didier *et al.* (2000) indicate that there is an emerging interest in the use of geosynthetic clay liners (GCLs) covers instead of soil barriers because the CCLs are efficient as hydraulic barriers and are easy to install. One of the problems with landfill cover is cracking of clay material (Sadek *et al.* 2007). Harison and Hardin (1994) suggest clays may crack because of ‘external loads’ and settlement.

Miller and Lee (1999) have reported that clay covers primarily fail in cold regions because of alternating freeze and melt incidents, leading to cracking, soil heaving and permeability increase. Freeze/thaw can cause increase of permeability in clays by as much as 100 times (Kim and Daniel 1992).

2.3 Landfill Leachate

2.3.1 Leachate generation

When solid waste is disposed of and processed at landfills, it undergoes a combination of physical, chemical and microbial processes (Christensen *et al.* 2001). These processes transform waste into various water-soluble compounds and transfer the pollutants from the refuse to the percolating water (Bjerg *et al.* 2003).

The contaminant-rich water based solution of pollutants is termed “leachate”. Landfill leachate is formed when excess water percolates through the waste layers (Christensen *et al.* 2001), thus removing the contaminant compound from the solid waste. The sources of percolating water include precipitation, irrigation, surface runoff, groundwater intrusion and the initial moisture content present within the waste (El-Fadel *et al.* 1997).

Microbial decomposition of the waste also contributes to the formation of leachate. The rate of generation of leachate in a landfill depends on a number of variables, including waste characteristics, moisture content, temperature, pH and the availability of nutrients and microbes (El-Fadel *et al.* 1997). Acton and Barker (1992) provide a summary of variables influencing the generation of leachate (Figure 2.4).

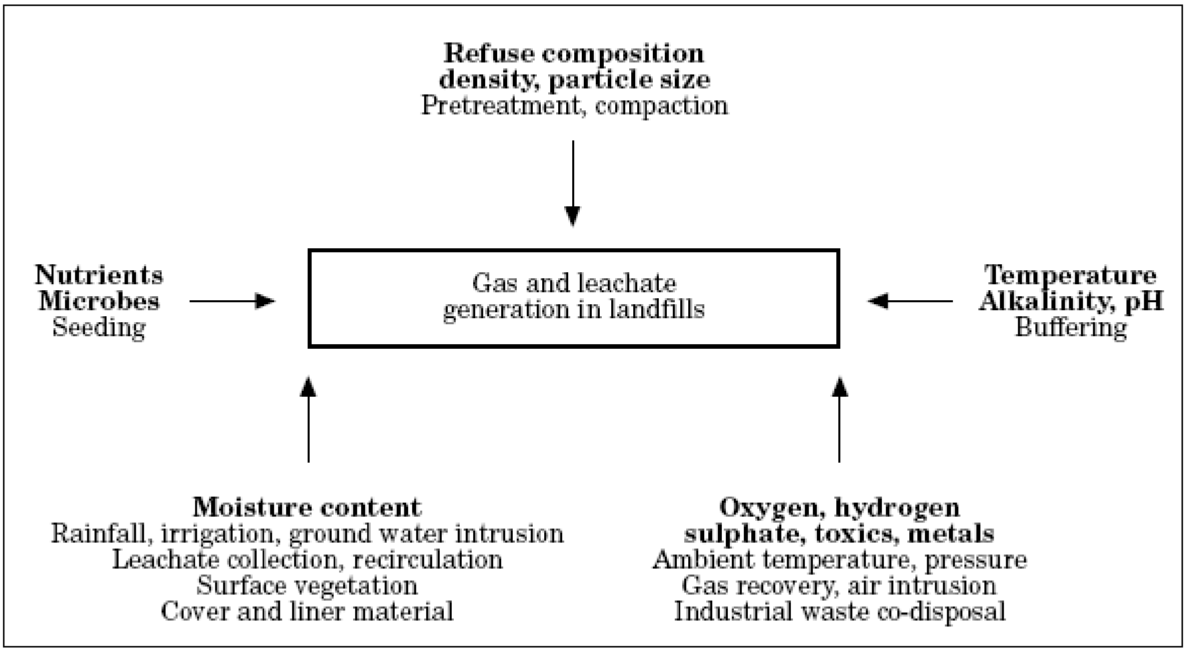

Figure 2.4 Factors influencing the generation of leachate in landfills.
(source: El Fadel *et al*. 1997)

2.3.2 Leachate Plumes

Percolation and infiltration of water, derived from precipitation, through a landfill waste will normally cause water table build-up within and below the landfill (Freeze and Cherry 1979), this is known as mounding. Bouwer (1978) suggested that up to 50% of precipitation can infiltrate to produce leachate. Mounding causes leachate to move vertically (downwards) and laterally (outwards). Figure 2.5 shows a mound under a landfill and how the leachate may flow. The vertical flow of leachate may contaminate groundwater resources especially in cases where the base of the landfill is not lined with a hydraulic barrier and also if the underlying soil profile is of highly permeable material such as gravels and coarse sand. The lateral flow normally gives rise to leachate springs at the margins of the landfill or seepage into surface water bodies (Freeze and Cherry 1979).

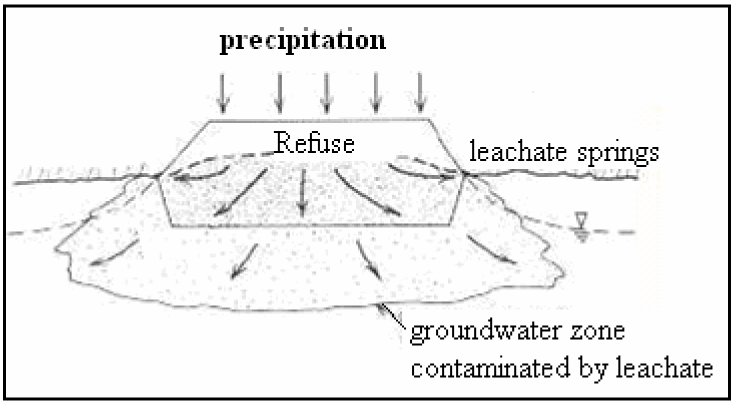

Figure 2.5 Leachate mound and movement beneath a landfill.
(source: Freeze and Cherry 1979)

The continued vertical movement of landfill leachate will eventually lead to the introduction of leachate into a previously pristine groundwater system. The entrance of leachate into pristine groundwater will normally result in a set of chemical reactions that changes the chemical composition of the groundwater (Acworth and Jorstad 2006).

The zone of groundwater influenced by leachate is known as a leachate plume. The plume normally has concentrations of various chemical constituents which are much higher than the pristine groundwater values. In one study Nicholson *et al.* (1983) reported calcium to be the dominant cation and sulphate and bicarbonate to be the dominant anions in the leachate contaminant plume with maximum concentrations of 400, 2000 and 1200 mg.l^{-1}, respectively. The authors also infer that the most highly contaminated water in the aquifer was beneath the landfill, with the total dissolved solids of about 4000 mg.l^{-1}.

Most leachate plumes usually have lengths less than 1000 m and rarely exceed 2000 m (Christensen *et al.* 2001). Kimmel and Braids (1974) observed a leachate plume extending up to 3 200 m from a landfill. Depths of plumes are normally much shorter than their lengths.

A plume of about 50 m depth was reported by Kimmel and Braids (1974) from a landfill on sand and gravel in New York, USA. Leachate plumes are normally not much wider than the landfill (Christensen *et al.* 2001).

To delineate a leachate plume several groundwater sampling points should be installed down-gradient from a landfill to obtain hydrochemical composition. The extent of contamination can be determined by hydrochemical parameters such as chlorides, sulphates and electrical conductivity (MacFarlane *et al.* 1983). MacFarlane *et al.* (1983) also used the thermal regime of groundwater to delineate a leachate plume. Figures 2.6 and 2.7 provide an example of the vertical and horizontal extent of landfill leachate plume using the chloride concentration. Other methods of delineating leachate have also been applied. For example, David *et al.* (2000) used an electromagnetic method to delineate a plume in a coastal aquifer located near Christchurch in New Zealand.

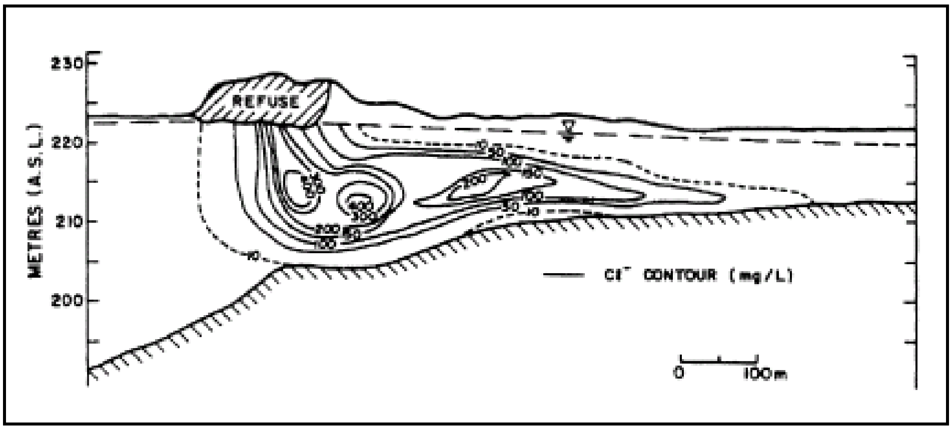

Figure 2.6 Vertical delineation of a landfill leachate plume.
(source: Christensen *et al.* 2001)

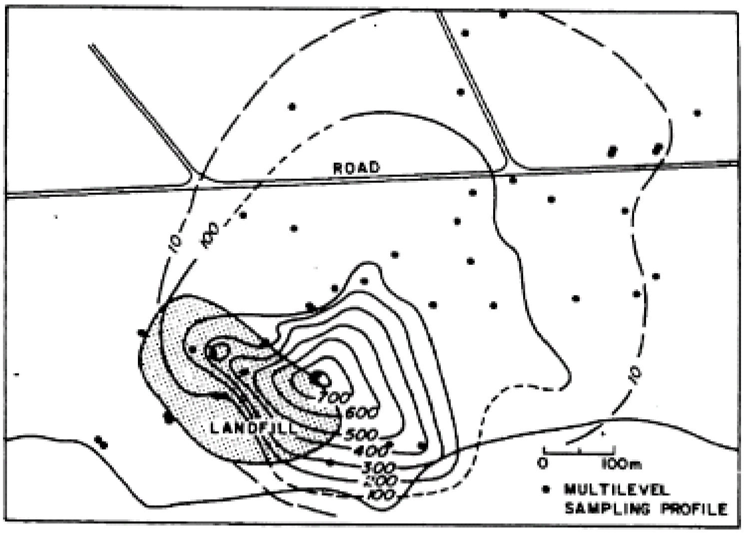

Figure 2.7 Spatial delineation of a landfill leachate plume (Source: Christensen *et al.* 2001).

2.3.3 Leachate chemical characteristics

2.3.3.1 General leachate composition

Most sanitary landfills such as the Horotiu landfill, normally receive a mixture of municipal, commercial and mixed industrial waste. These do not include hazardous, radioactive, and specific chemical wastes. Leachate generated from such landfills may be characterised on the basis of four major groups of pollutants: dissolved organic matter, inorganic macro-components, heavy metals and xenobiotic organic compounds (Christensen *et al.* 1994).

Other compounds that may be present, but in minute amounts, in leachate from landfills include: boron, arsenic, selenium, lithium, mercury and cobalt. These are regarded as of secondary importance (Christensen *et al.* 2001). Table 2.1 provides ranges of concentrations of constituents that are normally present in landfill leachate.

Variation in leachate composition has been observed by several authors (Al-Yaqout and Hamoda 2003; Bjerg *et al.* 2003; Fan *et al.* 2006; Rodriguez *et al.* 2004) to significantly depend on waste composition, waste age, landfill technology, degree of compaction, the hydrology of the site and climate.

2.3.3.2 Dissolved organic matter

The dissolved organic matter component of landfill leachate is usually expressed as chemical oxygen demand (COD), total organic carbon (TOC) or biochemical oxygen demand (BOD). At early stages of landfilling, leachate usually has high BOD (e.g. 9500 $mg.l^{-1}$) value and even higher COD (e.g. 14 000$mg.l^{-1}$) content (Kjeldsen *et al.* 2002).

Dissolved organic matter is a bulk parameter covering a wide range of organic degradation products including methane (CH_4), volatile fatty acids and some refractory compounds such as fulvic and humic-like compounds. The decomposition of organic matter gives leachate its colour: yellow, brown or black (Aziz *et al.* 2007).

Table 2.1. General composition of landfill leachate. Values are in mg/l, except pH and electrical conductivity.

Parameter	Range	References*
pH	3-6; 6.2-8.8; 7.7-8.1	h; s; p
Electrical conductivity (µS/cm)	8600-20000; 23000-26900	i; j
Total dissolved solids	2000-60000; 1000-90000	f; o
Organic matter		
Total organic carbon (TOC)	230-1565; 30-29000	n;f
Biological oxygen demand (BOD5)	520-865; 9500-80795	j; s
Chemical oxygen demand (COD)	695-767; 3950-14000	g;d
BOD5/COD ratio	0.096-0.195; 0.02-0.8	j; f
Organic nitrogen	14-2500	c
Inorganic macrocomponents		
Total phosphorus	0.1-23	c
Chloride	65-2080; 630-30000	n; l
Sulphate	29-66; <1-1000	n;l
Hydrogencarbonate	610-7320	c
Sodium	50-2821; 519-2957	l; b
Potasssium	202-1 612; 1700-1900	b; q
Ammonium-N	549-1 040; 1635-1810	g; k
Calcium	3.8-138; 2000-4000	s; h
Magnesium	73-97; 30-15000	m; q
Iron	0.0048-3.88; 500-1500	r; h
Manganese	0.05-0.42; 2.5-6.37	s; p
Silica	4.3-44; 4-70	o; f
Heavy metals		
Arsenic	0.01-1	c
Cadmium	0.018-0.023; 0.0084-0.034;0.012-0.52	k ;e; a
Chromium	0.02-1.5	m
Cobalt	0.0226-0.0537; 0.005-1.5	r; f
Copper	0.08-0.1; 0.005-10; 0.04-19.4	q; m; a
Lead	0.016-0.0208; 0.2-0.96; 0.19-1.7	r; k; a
Mercury	0.00005-0.16; 0.0012-0.002	c; q
Nickel	0.06-0.45; 18-70	n; a
Zinc	0.175-.025; 0.7-0.747	r; e

* [a]Abu-Rukah and Kofani (2001); [b]Bernard, *et al.*(1997); [c]Bjerg, *et al.*(2003); [d]Castillo, *et al*,.(2007); [e]Chofqi, *et al.*(2004); [f]Christensen, *et al.* (2001); [g]Chu, *et al.* (1994); [h]El-Fadel, *et al.* (2002); [i]Fan, *et al.*(2006); [j]Fatta, *et al.* (1999); [k]Im, *et al.* (2001); [l]Jones, *et al.* (2006); [m]Kjeldsen and Christophersen (2001); [n]Lo and Irene (1996); [o]Owen and Manning (1997); [p]Sawaittayothin and Polprasert (2007); [q]Silva, *et al.*(2004); [r]Suchecka, et al.(2006); [s]Tatsi and Zouboulis(2002).

2.3.3.3 Inorganic macro-components

Major inorganic constituents of leachate are: calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), ammonium (NH_4^+), iron (Fe), manganese (Mn), chloride (Cl^-), sulphates (SO_4^{-2}) and bicarbonates (HCO_3^-). The concentrations of most of the macro components in leachate depend on the stabilization processes in the landfill (Kjeldsen *et al.* 2002).

2.3.3.4 Heavy metals

Heavy metals include arsenic, cadmium, chromium, cobalt, copper, lead, mercury, nickel and zinc. Most heavy metals occur naturally as ores, in the environment. However, human have also produced and used heavy metals in different ways. Anthropogenic sources of heavy metals are usually deposited in landfills as refuse.

Possible sources of heavy metals in landfills are illustrated in Table 2.2. Concentrations of heavy metals in landfill leachates are normally low and do not pose a groundwater pollution problem at landfills (Bjerg *et al.* 2003). However, if present in high concentrations, heavy metals can cause leachate to be toxic (Sawaittayothin and Polprasert 2007).

Table 2.2 Common sources of heavy metals in municipal landfills

Metal	Source	References
Arsenic	Photovoltaic solar cells Optoelectronic devices Paints Dyes Soaps Textiles	Nriagu (1994), Stoeppler (2004)
Cadmium	Batteries Television components Anti-corrosive plating	Herber (2004)
Chromium	Leather products, used in tanning leather	Stoecker (2004)
Cobalt	Porcelain Soaps Paints	Schrauzer (2004)
Copper	Photovoltaic solar cells Plumbing pipes, electrical cables	Momcilovic (2004)
Lead	Spray paints Batteries	Gerhardsson (2004)
Mercury	Batteries Fluorescent lamps Color photograph paper Fireworks cosmetics	Drasch, *et al.*(2004)
Nickel	Cooking utensils Coins Jewelry Batteries Ceramics Computer components	Sunderman (2004)
Zinc	Human medicine Cosmetics Dyes Dry-cell batteries Fungicides Soaps	Peganova and Eder (2004)

2.3.3.5 Xenobiotic organic compounds (XOCs)

XOCs originate from household and industrial chemicals. These compounds include a variety of aromatic hydrocarbons, phenols and chlorinated aliphatics. A broad range of XOC concentration in landfill leachate is a result of differences in co-disposal practices, waste composition, landfill technologies, and waste age. The XOCs are chiefly associated with industrial or conventional hazardous waste, but a large number occur in municipal or household waste. Likewise paint, garden chemicals, household cleaning agents, human and veterinary medicines, motor vehicle products, waste electrical and electronic equipment and batteries, are all potential sources of xenobiotic substances (Slack *et al.*; Slack *et al.* 2007). The most common XOCs are the aromatic hydrocarbons and halogenated hydrocarbons. These pollutants are normally present in very high concentrations. However, the concentration of the XOCs in a landfill leachate decreases with time (Christensen *et al.* 2001).

2.3.4 Factors affecting leachate composition

2.3.4.1 Refuse age

Chemical composition of landfill leachate changes with time since commencement of waste disposal at a landfill. Chen (1996) showed that the variation of the BOD/COD ratio of leachate from nine landfill sites in Taiwan decreased sharply with time (Figure 2.8) then acquired a constant steady level after about a year. The author suggested that this indicates a decreasing proportion of biodegradable organics with time.

Zhao *et al.* (2000) used a three year data-set of landfill leachates to demonstrate in detail how various leachate components varied with time. Based on these data the authors derived a mathematical simulation to predict long-term concentrations of some leachate parameters. A similar technique was followed by Ozkaya *et al.* (2006), who presented a mathematical formula simulating changes in concentrations of sulfates (SO_4), chlorides (Cl^-), chemical oxygen demand (COD) and biochemical oxygen demand (BOD) with refuse age. The authors demonstrated breakthrough curves similar to those shown in Figure 2.9.

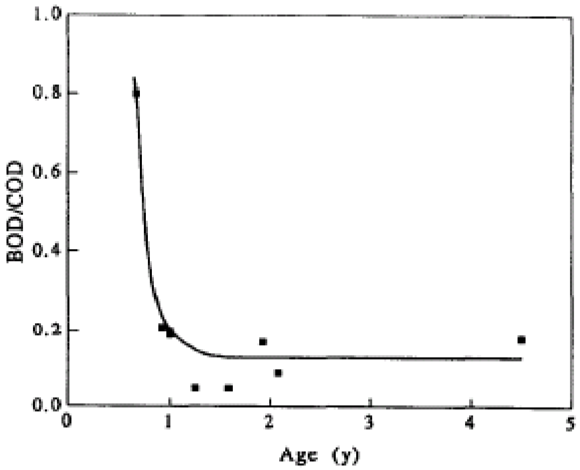

Figure 2.8 Change of BOD/COD ratio in leachate with landfill age. (After: Chen 1996)

Most leachate components are present in high concentrations at an early age, about 12 months, of landfills and decrease with landfill age (Kjeldsen *et al.* 2002; Kjeldsen and Christophersen 2001). Figure 2.9 depicts a general trend in various leachate components.

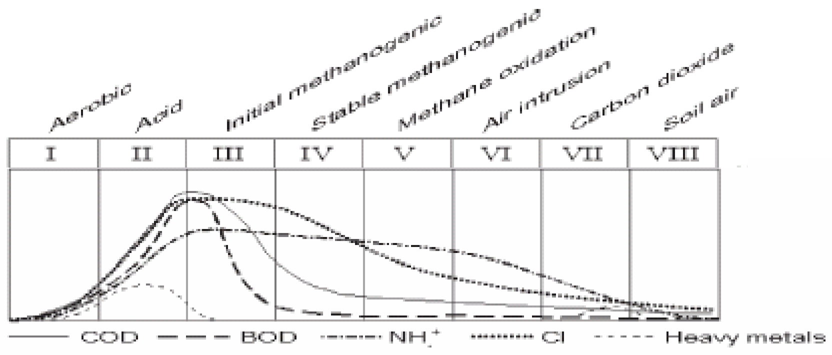

Figure 2.9 General trends in leachate quality (Source: Kjeldsen et al. 2002).

2.3.4.2 Phase of refuse decomposition

The chemical composition of leachate has been related to the phase or stage of decomposition of refuse. Farquhar and Rovers (1973) have identified four phases of waste decomposition as: i) the aerobic phase, ii) the anaerobic acid phase, iii) the initial unsteady methanogenic phase, and iv) the steady methanogenic phase.

Subsequent phases of decomposition have also been suggested based on theory and no physical evidence (Kjeldsen *et al.* 2002).

i) Aerobic phase- in this phase there is plenty of oxygen within the spaces of newly buried waste. The oxygen is quickly consumed and carbon dioxide is produced. When the refuse is covered oxygen cannot be replenished and quickly runs out. The aerobic phase lasts only for a few days. Leachate generated during this stage is mainly derived from the release of moisture during compaction of waste and precipitation percolating through the waste (Kjeldsen *et al.* 2002).

ii) *Anaerobic acid phase*- this phase takes place when the refuse is depleted of oxygen and anaerobic fermentation processes occur. Fermentation and bacterial actions upon biodegradable compounds result in the production and accumulation of acids and a decrease in pH. During this phase BOD and COD concentrations in leachate are highest. Leachate produced during the anaerobic acid phase is acidic and it enhances solubility of many compounds (Kjeldsen *et al.* 2002).

iii) *Initial unsteady methanogenic phase*- this phase is marked by occurrence of significant amounts of methane gas. The acids accumulated during the previous acid phase are transformed to methane and carbon dioxide gases by methanogenic bacteria. This is accompanied by pH increase in leachate. COD and BOD concentrations in leachate begin to decline in this phase.

iv) *Steady methanogenic phase*- Methane production is at a peak in this phase because of further transformation of accumulated acids. pH continues to increase until it reaches a steady level. During this phase BOD and COD concentrations in leachate are lowest and the ratio BOD:COD are also very low (Kjeldsen *et al.* 2002).

Concentrations of several leachate components decline during continuing decomposition of waste, for example from acid phase to methanogenic phase. The increasing pH affects the solubility of various inorganic components

(Kjeldsen *et al.* 2002). Table 2.3 shows ranges of parameters which have been observed to be significantly affected by the degree of waste decomposition.

The rate of decomposition of waste can be enhanced by addition of moisture to the refuse or by recycling leachate (Anex 1996) because moisture is a major factor for biodegradation (Wall & Zeiss 1995). Various studies (Bae *et al.* 1998; Barlaz *et al.* 1992; San & Onay 2001) have demonstrated that leachate recycling is effective in enhancing decomposition of waste, thus reducing time for leachate generation after landfill closure.

Table 2.3 Characteristics of leachate during acid and methanogenic phases. Values are in mg/l except pH. Source: Kjeldsen *et al.* (2002).

Parameter	Acid phase	Methanogenic phase
pH	4.5-7.5	7.5-9
BOD	4000-40000	20-550
COD	6000-60000	500-4500
Sulphates	70-1750	10-420
Calcium	10-2500	20-600
Magnesium	50-1150	40-350
Iron	20-2100	3-280
Manganese	0.3-65	0.03-45
Zinc	0.1-120	0.03-4

2.3.4.3 Amount of precipitation

The chemical quality of landfill leachate varies with the amount of rainfall at the landfill (Chen 1996). Chen (1996) investigated the effects of rainfall on landfill leachate composition and found that concentrations of some leachate parameters, such as TOC and conductivity, decrease with the increasing rainfall amount. The authors suggest that rainwater has a diluting effect on leachate. Figure 2.10 shows the relationship between TOC and rainfall; Figure 2.11 shows EC and rainfall. A strong correlation was obtained for the two relationships.

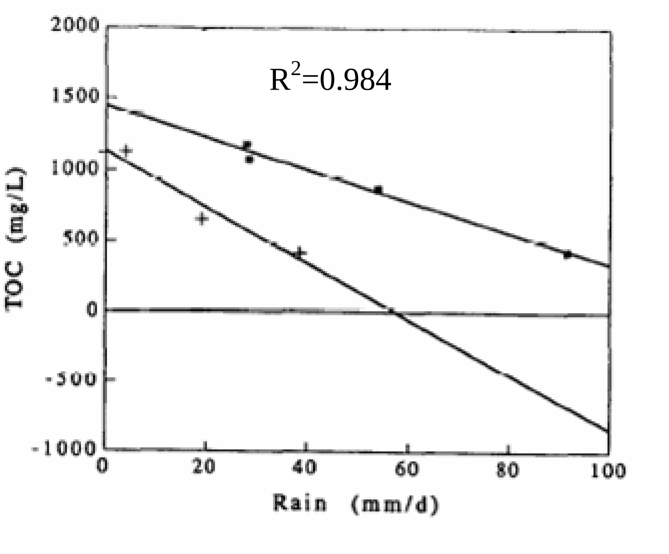

Figure 2.10 Variation of TOC concentration in leachate with the amount of rainfall. (Source: Chen 1996)

It cannot be firmly concluded that rainfall has a diluting effect on all of the leachate components. Johnson *et al.* (1999) compared the composition of leachate in dry and rainy seasons from a landfill in Switzerland. The authors observed that while concentration of some of the leachate components such as Mo, V, Mn, Zn and Cd decreased with rainfall events, others such as Al, Cu, Sb and Cr increased. According to the authors, these observations could not be attributed to the amount of rainfall alone, but also to chemical composition of the rainwater.

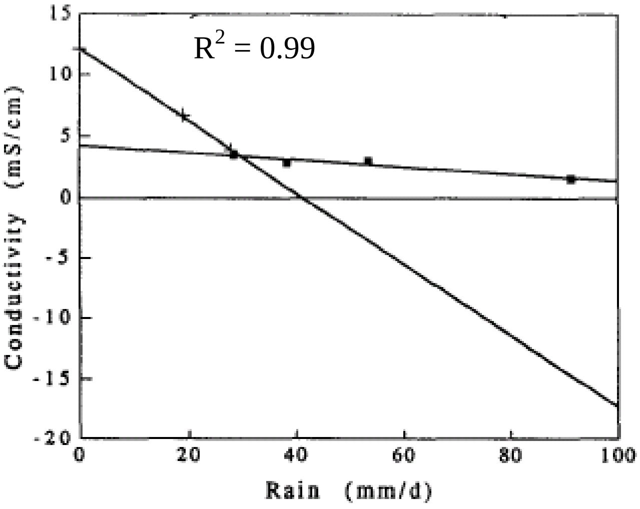

Figure 2.11 Relationship between leachate electrical conductivity and the amount of rainfall. (Source: Chen 1996)

2.3.5 Attenuation of leachate concentration in groundwater systems

Contaminants constituting landfill leachate have a tendency to be removed or reduced in concentration once they enter groundwater, with both time and distance from the landfill. The decline in concentrations of chemical components is referred to as attenuation (Miller 1980). Attenuation of contaminants in a leachate plume naturally occurs by physical, geochemical and microbial processes.

2.3.5.1 Physical attenuation

All the constituents of the leachate will be subject to physical processes, such as dilution, as the leachate enters and mixes with groundwater. Dilution is the physical interaction of the leachate flow with groundwater flow and is the only mechanism of attenuation for non-reactive chemical components of which Cl^- is the most common. Once the leachate enters groundwater, it will then be governed by the general principles of groundwater flow such as geological structure, hydraulic gradient, permeability and physical boundaries. The groundwater principles will determine the position and velocity of the leachate plume (Christensen *et al.* 2001).

The flow of leachate may differ from the flow of groundwater. The lateral spreading of the leachate plume may be enhanced by the effects of the local mounding, which takes place beneath the landfill as the leachate infiltrates into the groundwater. The lateral spreading of the leachate plume may result in the increase of the volume of contaminated groundwater, and at the same time diluting the concentration of the contaminants. Differences in the density (caused by high salt content in leachate) and viscosity of leachate and ambient groundwater may also affect the rate of plume spreading and dilution rate.

Dilution of leachate by the surrounding groundwater is mainly driven by heterogeneities of hydraulic conductivity. Thus dilution is more limited in homogeneous aquifers (Christensen *et al.* 2001).

On a similar theme MacFarlane et al (1983) suggested that dilution of the contaminant plume may also be caused by seasonal variations in groundwater flow direction.

Concentrations of colloidal or large particles present in leachate are reduced by filtration. Filtration is most effective in finer aquifer materials such as clay, and is least effective in gravels, fractured or cavernous rock aquifers (Jackson 1980). Filtration process causes leachate to have a reduction in concentration of suspended solids.

2.3.5.2 Geochemical attenuation

A number of geochemical attenuation mechanisms usually occur in leachate contaminated groundwaters. Complexation and ionic strength increase the mobility of some metals and therefore are able to migrate from the landfill (Kennel 1998).

Acid-base reactions influence solubility and mobility of most leachate constituents which normally increase with decreasing pH levels (Jackson 1980). Mobility of elements depends on the oxidation-reduction conditions. Some elements such as chromium are more mobile under oxidising conditions, while others including iron and manganese are most mobile under reducing conditions (Jackson 1980).

Large amounts of anions (e.g. carbonate, phosphate, silicate, hydroxide and sulphide) may result in precipitation of multivalent cations to form insoluble compounds. On the other hand, changes in oxygen content may reverse the precipitation process and give rise to the formation of soluble compounds. This chemical process is defined by Jackson (1980) as precipitation-dissolution.

Metal cations are usually adsorbed on the surfaces of clays or other materials and are removed from the leachate solution during the process called adsorption-desorption (Jackson 1980). The adsorption-desorption process results in reduction of concentrations of cations in the leachate. The process may be reversible and return the species into solution.

Leachate may contain volatile components. Dissolved volatile components normally attenuate by escaping into the unsaturated soil above the leachate plume. These include, for example methane (CH_4) (Barber *et al.* 1990). Sorption and degradation processes attenuate dissolved organic matter and other components of the leachate. Sorption occurs when contaminant particles attach to the solid material of the aquifer thereby reducing in concentration.

2.4.4.3 Microbial attenuation

The number of micro-organisms in uncontaminated aquifers is very low. However, when leachate, rich in dissolved organic matter, enters groundwater, the composition of the original microbial population (dominated by bacteria) of the aquifer will change dramatically. Micro-organisms are believed to be responsible for some chemical processes, such as reduction of sulfates, iron, manganese, and nitrate and degradation of dissolved organic matter and production of methane (Ludvigsen *et al.* 1998). Micro-organisms are also able to break down insoluble fats, carbohydrates, and proteins into soluble substances (Jackson 1980). Detailed attenuation action of leachate components in aquifers by micro-organisms has been discussed by Acton and Barker (1992), Albrechtsen *et al.* (1995), Hutchins *et al.* (1991) and Roling *et al.* (2001).

2.3.6 Movement of leachate

Contaminants deposited in a landfill enter aquifers by vertical infiltration, passing first through the unsaturated soil layer. Some of the contaminants constituting landfill leachate are known to be non-reactive and will not undergo reactive attenuation when they come into contact with groundwater. However, these components will move and mix with ambient groundwater according to physical mechanisms of solute transport, to the point of groundwater discharge, such as pumping wells or natural discharge zones. There are three major transport mechanisms by which leachate (solutes) can migrate in groundwater from a landfill. A number of studies on the movement of leachate in groundwater have been carried out (Dance & Reardon 1983; MacFarlane *et al.* 1983; Nicholson *et al.* 1983; Sudicky *et al.* 1983), while others such as Islam and Singhal (2002) have performed a one-dimensional transport model to simulate migration of contaminants under a landfill. Leachate can migrate from the source by the following transport mechanisms: diffusive, convective and dispersive transport (Batu 2006).

2.3.5.1 Diffusive transport

Freeze and Cherry (1979) define diffusive transport as the process whereby dissolved ionic and molecular constituents move under the influence of their kinetic activity in the direction of decreasing concentration. The ionic and molecular movement does not necessarily require any bulk hydraulic movement of water. Thus contaminants in the leachate will spread in aquifers even if the groundwater is stagnant or very slow. Batu (2006) (after Gillham and Cherry, 1982a, 1982b) indicates that diffusive transport is the dominant contaminant transport mechanism at low groundwater velocities (less than about 1.6×10^{-10} m/sec). Movement of contaminants by diffusive transport will continue until their concentration is evenly distributed. Fick's first law (Freeze & Cherry 1979) states that the rate of transfer of diffusing contaminant passing through a unit cross-sectional area is proportional to the concentration gradient. This law can be expressed as:

$$F = -D \frac{dC}{dx}$$

Where *F* is mass flux of solute per unit cross sectional area per unit time [M/L^2T]; *D* is the diffusion coefficient [L^2/T]; C is the contaminant concentration [M/L^3]; *dC/dx* is the concentration gradient (negative because contaminant migration is in the direction of decreasing concentration.

The above equation can be modified for diffusion flux in a saturated porous media as:

$$F = -\varphi D \frac{dC}{dx}$$

Where φ is the effective porosity of the aquifer (Batu 2006). Various chemical constituents have different diffusion coefficients, which are temperature-dependant; Freeze and Cherry (1979) suggest that major ions in groundwater have *D*-values in the range 1×10^{-9} to 2×10^{-9} m^2/sec at 25^oC.

2.3.5.2 Convective transport

Also known as advective transport, convective transport is the process by which dissolved solutes/contaminants are transported by the bulk motion of the moving water in an aquifer (Batu 2006). Contaminants would, under pure convection conditions, move at the same average velocity as the groundwater. Flux for convection is given by (Batu 2006):

$$F = v\varphi C = -q_x C$$

Where q_x is the Darcy velocity.

2.3.5.3 Dispersive transport

Solutes have a tendency to spread away from the general path according to convective flow. This spreading of solutes is termed dispersion (Freeze & Cherry 1979). Dispersive transport occurs as a result of mechanical mixing caused by the moving groundwater. This type of solute transport occurs by three mechanisms. One occurs in pore channels because particles travel at different velocities due to the roughness of the pore surfaces. The second mechanism is due to the difference in pore sizes along the flow paths. The last is caused by the tortuosity, branching and interconnecting of pore channels (Freeze & Cherry 1979). Dispersion in the direction of the flow is known as longitudinal dispersion, while dispersion perpendicular to the bulk flow direction is termed transverse/lateral dispersion. Longitudinal dispersion is usually dominant over lateral dispersion.

According to Batu (2006), laboratory and field experiments indicate that the dispersion flux can be represented by an equation similar to the equation for diffusive flux:

$$F = -\varphi D_m \frac{dC}{dx}$$

Where D_m is the dispersion coefficient; other symbols are as defined above.

2.4 Impacts of leachate

Leachate contains a lot of organic and inorganic compounds and heavy metals in high quantities. Most of these constituents may be toxic and can have negative impacts within both surface and groundwater environments. Impacts on the water environment can affect human, animal and plant lives.

2.4.1 Environmental impacts

During the early (or acetogenic) biodegradation phase of the landfill, the leachate is characterised by a high EC, COD, BOD, and Sodium, Chloride and ammonium contents. These constituents are toxic to aquatic life and can have serious consequences if leachate enters surface water sources (Jones *et al.* 2006).

Under aerobic conditions, ammonium contained in the leachate can be transformed by nitrification to nitrate which is assimilated by plants. When nitrate is combined with phosphate, the condition can lead to eutrophication of surface water courses (Jones *et al.* 2006). The high concentrations of ammoniacal-nitrogen (NH_3-N) can enhance algal blooms, which can deplete dissolved oxygen and have toxic impacts on aquatic life. Kurniawan *et al.* (2006) reported that at concentrations higher than 100 mg/l, NH_3-N can be highly toxic to aquatic organisms including zebrafish, freshwater fish and luminescent bacteria.

Pivato and Gaspari (2006) emphasized that the toxicity of the leachate might consistently depend on the ammonia concentration and that leachate toxicity is much lower in old landfills where ammonia had been degraded. Cheung *et al.* (1993) reported acute toxicity of landfill leachate on green algal species and that ammoniacal-nitrogen and organic compounds appear to be the leading factors affecting toxicity of leachate.

In their investigation on the toxicity of municipal landfill leachate Sang *et al.* (2006) and Schrab *et al*. (1993), reported that leachate can have genotoxic effects on plants and bacterial cells. Sang *et al.* (2006) added that exposure to leachate pollution in an aquatic environment is likely to pose a risk for generation of ‘cytogenetic damage’[1] in organisms.

Landfill leachate is also hazardous to sanitation as it contains harmful micro-organisms. Leachate may contain *E. coli* and *Streptococcus* in amounts of about 10^{-6}-10^{-7} per 100 cm^3 (Bodzek *et al.* 2006).

Although leachate comprises numerous chemical constituents in highly variable concentrations (Table 2.1), several studies (Bernard *et al.* 1997; Bila *et al.* 2005; Bloor *et al.* 2005; Bloor *et al.* 2006; Dave & Nilsson 2005; Devare & Bahadir 1994; Fent 2004; Li *et al.* 2006; Wong 1989) did not single out individual components but focused on leachate as an entity. These studies reported potential toxicity of leachate on various organisms such as algae, fish, mice, plants and bacteria.

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[1] Relating to chromosomal and genetic material.

2.4.2 Impacts on human health

Although there are many studies on toxicity and other adverse properties of leachate on the environment, reports on human health impacts of leachate are rare, if available at all. Nonetheless, various individual chemical components found in leachate are known to pose health risks and aesthetic concerns for humans if present in drinking water.

Forstnaer and Wittman (1983) have documented the impacts on human health of various heavy metals present in leachate-contaminated water and reported several case studies of heavy metal poisoning. Mercury, which is a common component in landfill leachates, is considered to be the most toxic of the metals, followed by cadmium, lead, and others (Forstner & Wittman 1983). Potential health effects caused by ingestion of high amounts of some chemical contaminants found in leachate are presented in Table 2.4.

Groundwater which is contaminated by landfill leachate may contain high quantities of organics, measured as COD, BOD or TOC. Presence of organics can cause taste and odour problems and oxygen depletion in groundwater. Chemicals comprising organics may also affect public health if the water is consumed (Jonnes-Lee & Lee 1993).

Table 2.4 Human health effects that may be caused by pollutants present in landfill leachate.

Parameter	Health effect
Arsenic	Skin damage; problems with circulatory systems; increases risks of cancer.
Organic chemicals	Cause anemia; decrease of blood platelets; increase risk of cancer and liver problems.
Cadmium	Kidney damage.
Copper	Short term exposure causes gastrointestinal distress; long term exposure can cause liver or kidney damage.
Fluoride	Pain and tenderness of the bones; can cause mottled teeth in children.
Lead	Delays mental and physical development in infants; deficits in attention span and learning abilities in children; kidney problems and high blood pressure in adults.
Mercury	Kidney damage.
Nitrates	Shortness of breath; blue-baby syndrome in infants under six months.
Chromium	Increases risk of cancer.
Zinc	Urinary tract problems.
Calcium	Urinary tract problems.

Source: World Health Organisation (2006)

2.4.3 Drinking water standards

Concentrations of leachate-derived pollutants in public groundwater sources are much lower than that of leachate because of natural attenuation of leachate, but may be considerably higher than the pristine water concentrations. At very low levels, pollutants in water supplies may not pose health problems in human.

However, elevated amounts of some pollutants in drinking water may be of health concern and they are referred to as primary contaminants USEPA (2006). Other chemicals such as chlorides, EC, potassium and sodium are not known to cause any health problems but may cause water to be of objectionable odour, colour and taste and unsuitable for domestic use. These chemicals are called secondary contaminants.

Various countries and organizations have derived standards stipulating levels of chemicals in drinking water below which there is no significant health risk. Values for secondary contaminants with aesthetic effects are not always set. Drinking water standards state maximum concentrations of chemical, radiological and microbiological components. Standards from different countries or organisations may differ according to methods used to derive them. Table 2.5 compares drinking water standards from New Zealand, European Union, United States of America and World Health Organisation for chemical contaminants that would normally be present in leachate-contaminated groundwater.

Leachates from municipal landfills contain various chemical parameters (Table 2.1) and microbiological agents in concentrations that are many times higher than the concentrations in drinking water. Landfill leachate may also be toxic to aquatic life and can be harmful if ingested by humans. The intrusion of leachate into drinking water sources can increase the concentrations of chemical components in water beyond the drinking water standards, thus, rendering the water unfit for domestic use.

Table 2.5. Drinking water standards showing allowable amounts (in mg/l) of some of the pollutants found in landfill leachate. (-) implies standards are not set.

Parameter	**NZ[(1)]**	**EU[(2)]**	**USA[(3)]**	**WHO[(4)]**
Ammonium-N	-	0.5	-	-
Arsenic	0.01	0.01	0.01	0.01
Cadmium	0.004	0.005	0.005	0.003
Chloride	-	250	-	-
Chromium	0.05	0.05	0.1	0.05
Copper	2	2	1.3	2
Electrical conductivity (µS/cm)	-	2500	-	-
Fluoride	1.5	1.5	4	1.5
Iron	-	0.2	0.3	-
Lead	0.01	0.01	0.015	0.01
Magnesium	-	-	-	-
Manganese	0.4	0.05	0.05	0.4
Mercury	0.002	0.001	0.002	0.006
Nickel	0.02	0.02	-	0.07
Nitrates	50	50	10	50
pH	-	6.5-9.5	6.5-8.5	-
Potassium	-	-	-	-
Selenium	0.01	0.01	0.05	0.01
Sodium	-	200	-	-
Sulphate	-	250	250	-
Total dissolved solids	-	-	500	-
Zinc	-	-	5	-

Sources: (1) Ministry of Health (2005); (2) Lenntech (2006); (3) USEPA (2006); (4) World Health Organisation (2006).

2.4.4 Summary

Landfilling of waste is the most economical method of dealing with refuse. Landfills therefore play an important role in maintaining environment. However, landfills pose a degree of environmental hazard. The hazards can be minimised by siting landfills in areas with low permeability, at downstream side of aquifers which are not used for domestic purposes, and at a distance from surface water bodies.

A landfill should be lined at the sides and base with impermeable liners which may consist of geomembrane, clay and filter soil. Landfills should also be capped with barriers made of: geomembrane (2.5 mm), compacted clay (0.6 m thick), subsoil (0.3 m thick) top soil (0.3 m thick) and native vegetation. Lining and capping landfills help in containing leachate and minimising the amount of precipitation percolating through the waste. Landfills should also be fitted with leachate collection systems. Even the best engineered landfills will not perfectly contain leachate, with some leaking into the ground.

Landfill leachate forms when precipitation runs through waste, and may contain high concentrations of chemical parameters such as TOC (29 000 mg/l), BOD (80 000 mg/l), COD (14 000 mg/l), chlorides (30 000 mg/l), nitrates (1 000mg/l) and ammonium-N (1800 mg/l). The composition of leachate is affected by the time since refuse was disposed of, the phase of decomposition and the amount of rainfall percolating into the landfill. Once leachate enters the environment it naturally degrades by physical, geochemical and microbial attenuation processes. Leachate will be transported as a plume in groundwater by three mechanisms namely: diffuse, convective and dispersive transport. A better understanding of leachate chemical composition, its movement in the subsurface level and how it naturally attenuates, will enable sound mitigation measures to minimise impact of leachate contamination on the environment.

Landfill leachate may have a negative environmental impact because of its toxicity to aquatic organisms including freshwater fish, micro-organisms and plants. Migration of leachate to surface water can also lead to algal blooms and eutrophication because of a high content of nitrates and phosphates. Leachate has been reported to have a damaging effect on chromosomal and genetic materials of some plants and bacteria. Leachate can be harmful to human being as well because it contains chemicals such as organics, and copper which can cause anaemia and kidney problems. Intrusion of leachate into drinking water sources may cause water to exceed drinking water standards and be unfit for consumption.

It is also important to know possible environmental impacts once leachate has entered the groundwater in order to take necessary precautions and remedial measures. This study will contribute towards understanding the quality and fate of landfill leachate, and thus help in the quest to maintain a safe environment for human kind and other organisms.

Chapter 3

Site Descriptions and Methods

3.1 Horotiu Landfill

3.1.1 Site history and operation

The Horotiu landfill is located at Horotiu, about 6 km north of Hamilton City (Figure 3.1). The landfill was established by the Hamilton City Council (H.C.C) in October 1985 for handling and processing Hamilton's (a city of about 100 000 people) refuse. The site is bordered on the southwest by the Waikato River. The landfill site covers a total area of about 950 000 m^2 (95 ha) (Hamilton City Council 1996). Of this area only a quarter (27 ha) has been used for waste disposal (Hamilton City Council 2005). The landfill is located on previously excavated sand mine pits whose operations occurred in the 1970s through to about the year 2000. After landfilling the land is planned to be rehabilitated and turned into pastoral land (Hamilton City Council 1996). The changing land use of the site has been summarised by Hamilton City Council (1996) follows:

Pastoral land
↓
Stripping of topsoil
↓
Recovery of sand resource
↓
Construction of landfill base
↓
Landfilling of refuse
↓
Capping of refuse
↓
Site restoration
↓
Pastoral land

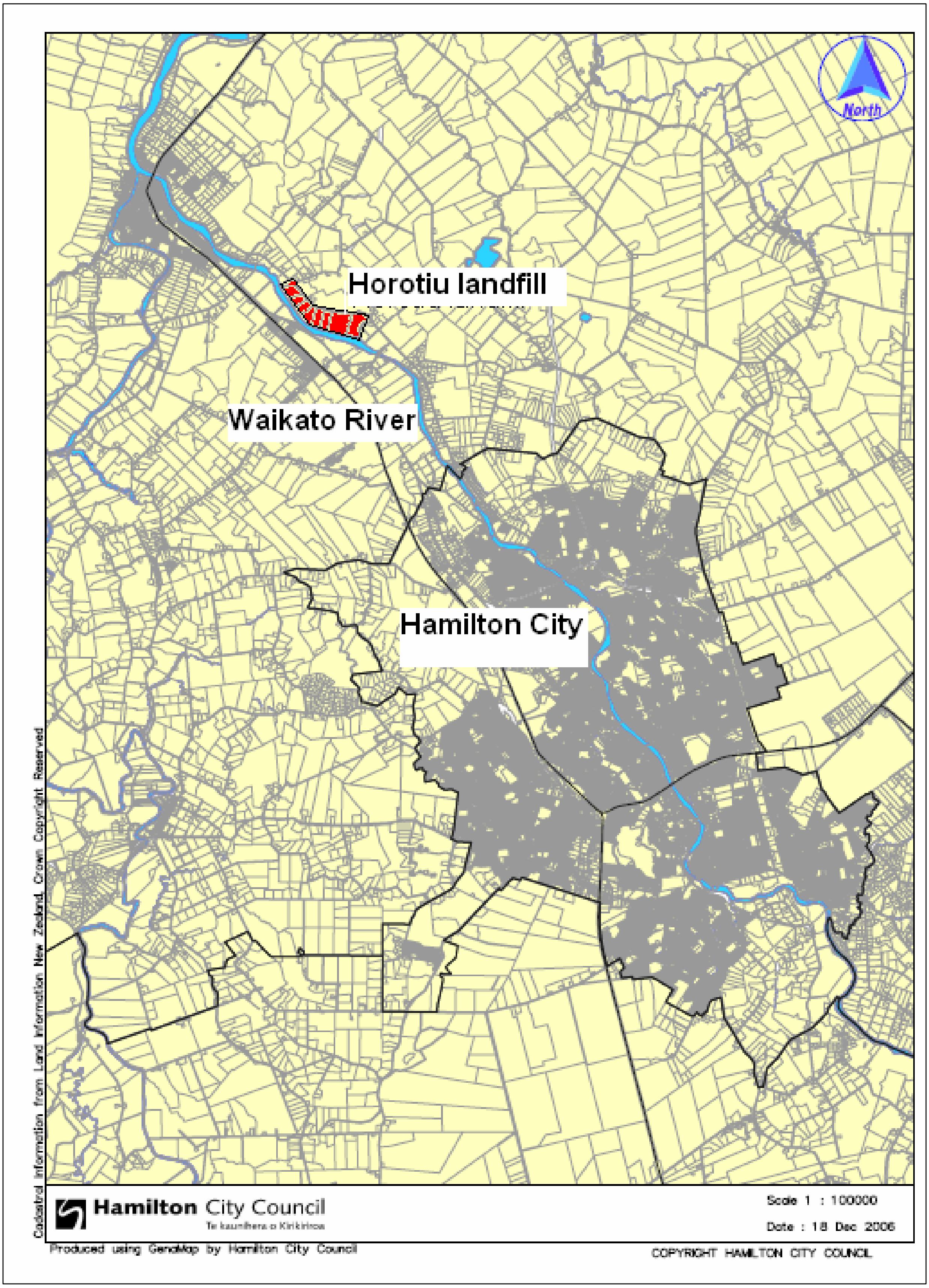


Figure 3.1 Location of the Horotiu landfill, shown in red. (Source: Hamilton City Council)

The Horotiu landfill has accepted between 50 000 and 90 000 tonnes of waste per year. The processed refuse consists of general and special wastes. General waste consists of a mixture of domestic, commercial and light industrial wastes. Special wastes are defined by Hamilton City Council (1996) as 'the waste which will be stable … and not contribute to contamination of the leachate or groundwater with persistent or intractable substances'.

With a filling rate of 95 000 tonnes/year, the landfill was originally expected to have an operation span of more than 60 years. However, due to the introduction of the Resource Management Act and subsequent application of new resource consent conditions, the landfill operations ceased at the end of 2006. The Horotiu landfill site was partitioned into 13 operation stages, with varying depths and surface areas (Table 3.1 and Figure 3.2). The total capacity of the landfill is estimated to be over 4 million tonnes.

Table 3.1 Horotiu landfill stage information (source: Hamilton City Council 2005).

Stage	Estimated area (ha)	Average depth (m)	Filling started (Month/year)	Capped (Month/year)
1	2.1	6.8	Oct-85	Mar-88
2A	1.1	6.3	Feb-87	Dec-88
2B	1.8	6.9	Feb-88	May-89
3A	1.7	8	Apr-94	Jan-01
3B	1.6	7.5	Feb-89	Oct-95
3C	2.2	7.9	Aug-90	Oct-95
5A	2.2	7.9	Sep-92	Oct-95
5B	1.6	7.9	Jun-95	Jan-06
4A	2.2		Mar-97	Jan -07
4B	2		Mar-98	Jan -07
4C	2		Mar-99	Jan -07
6	3.7		Nov-06	Jan -07

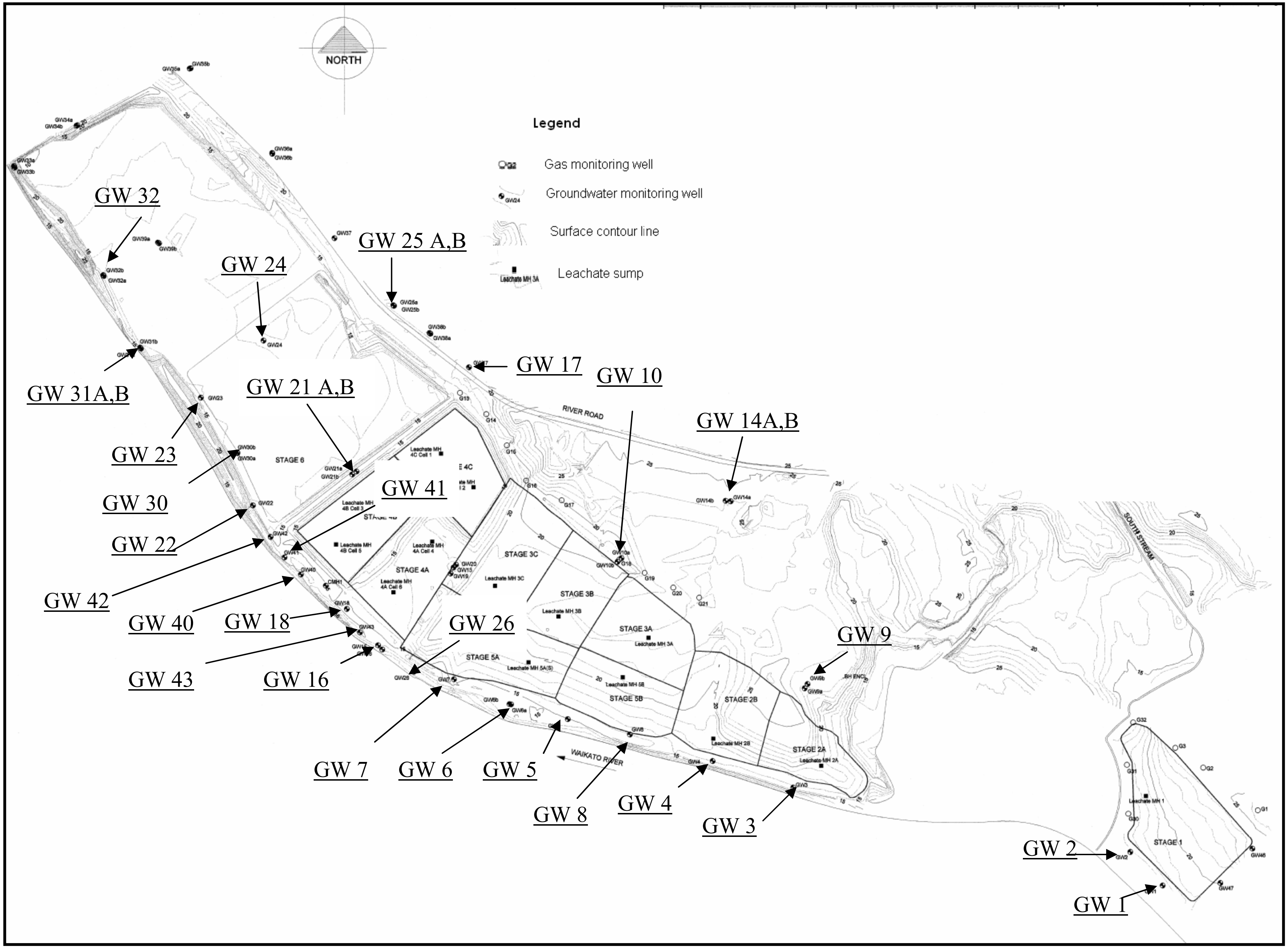


Figure 3.2 Horotiu landfill layout showing cells, monitoring wells (Gw1 – Gw43) and leachate sumps (MH 1 –MH 6). (Modified from a diagram supplied by HCC, 2005)

3.1.2 Geology and Hydrogeology

Geology at and around the Horotiu sanitary landfill is described, by Hamilton City Council (1996), to consist of Quaternary sediments, which comprise bedded clay, silts, sands and gravels of the Hinuera Formation. The Hinuera Formation overlays the Puketoka formation, which consists of pumiceous alluvium and conglomerate. Hamilton City Council (1996) reported that the landfill extends 4 to 7 metres into the Hinuera Formation materials. The Hinuera Formation has a relatively high permeability, which enables easy movement of water through it (Hamilton City Council 1996).

An unpublished report by Hamilton City Council (2003) indicates that 53 groundwater boreholes and piezometers were constructed in and around the landfill site during the period from November 1990 to April 1999. The boreholes were intended to monitor both groundwater quality and water table level. Analysis of the borehole logs revealed that there are numerous layers of low hydraulic conductivity silt and organic soils embedded within the coarse sands, causing the presence of perched water tables with high groundwater levels (Hamilton City Council. 1996).

Groundwater flow in the vicinity of the landfill is generally in a southerly direction towards the Waikato River. Groundwater level monitoring in the boreholes close to the river indicate that the groundwater levels are influenced by the levels in the Waikato River (Hamilton City Council 1996). Groundwater levels are generally close to the base of the landfill and are often less than 0.5 metres from the base of the landfill. Figure 3.3 shows the relative levels of the landfill base, river and groundwater table. The groundwater gradients range from 3.6×10^{-3} to 2.2×10^{-4} m/m at the near side of the river, and from 1.9×10^{-2} to 2.7×10^{-3} m/m at the landward side. Hydraulic conductivity tests carried out *in situ* resulted in ranges between 0.271 and 0.051 m/day, while groundwater flow velocities were found to vary between 0.0385 and 0.405 m/day (Hamilton City Council 1996).

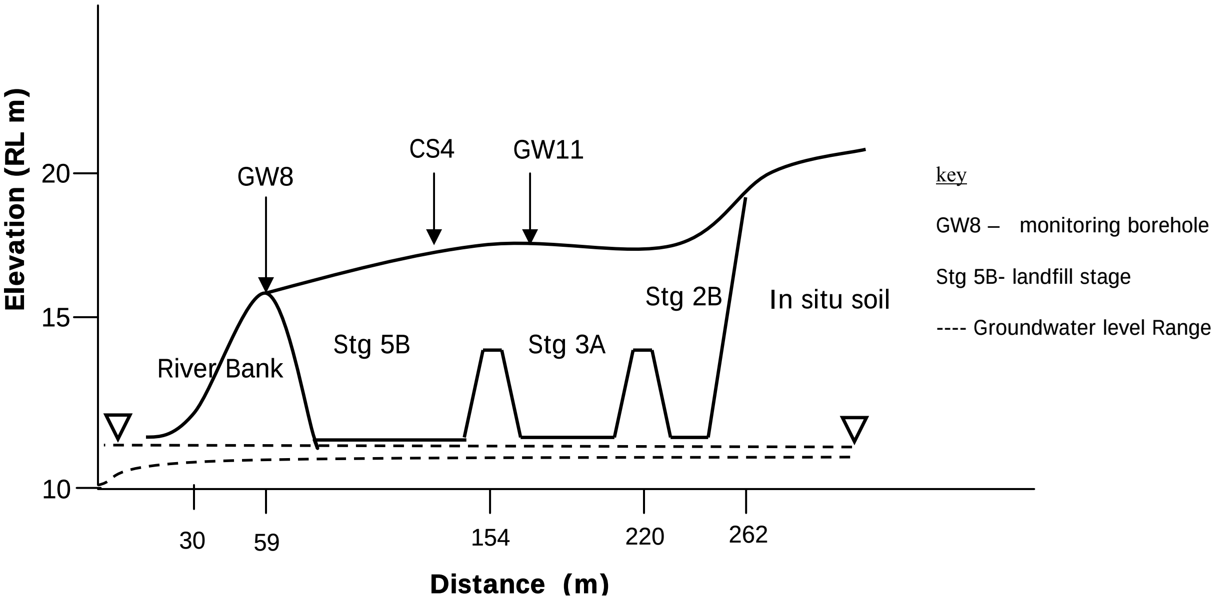


Figure 3.3 Groundwater elevations beneath the Horotiu landfill (Source: Hamilton City Council 1996).

3.1.3 Characteristics of Leachate at Horotiu

The environmental effects of the Horotiu landfill leachate on groundwater and the Waikato River depend on the quantity and contaminant load of the leachate lost from the site (Hamilton City Council 1996). According to Hamilton City Council (1996) the quantity and quality of the leachate produced from any landfill cell, at Horotiu depends on the following factors:

- "Net precipitation
- Permeability and design of landfill cap
- Drainage characteristics of the landfill
- Maintained depth of leachate
- Permeability of the base liner"

The total amount of leachate produced during 1995 was estimated to be 19 400 m^3 per annum, from five operational stages (Hamilton City Council 1996). Some fraction of the leachate may be lost to the ground if there is leakage on the landfill base liner and due to spills over the constructed liner. The amount of leachate produced from the 150 000 m^2 of filled and capped cells was 7 500 m^3 (or 50 mm) per annum and leachate from 40 000m^2 of uncapped cells was about 3 200m^3 (or 80 mm) per annum (H.C.C 2005b). The amount of leachate produced from the entire capped landfill after the cessation of filling operations is estimated to be just less than 11 000 m^3/annum (H.C.C 2005b). Leachate from the landfill is pumped into the two leachate holding basins with a combined capacity of 1530 m^3 (H.C.C 2005b) and then transported for treatment at the Hamilton wastewater treatment plant.

Landfill leachate at Horotiu has been collected and analysed for various chemical components and indicators since commencement of the filling. It is reported by Hamilton City Council (1996) that there has been a general trend of an initial peak followed by decline in parameters such as BOD and COD and that the decline has occurred after two years as the ‘leachate matures’. The composition of the Horotiu leachate is akin to leachates from other New Zealand landfills, with typical high concentrations of chlorides and heavy metals Hamilton City Council (2006).

3.2 Maseru Landfill

3.2.1 Landfill location and history

The Maseru refuse disposal facility is located about 5 km from the Maseru city centre, capital of Lesotho. The site was established in 1983 to accommodate domestic, industrial and medical waste generated from the city of about 477 600 people. The site had previously been utilized as a quarry for gravel (weathered dolerite dyke). It is therefore, in terms of operations and origin, not classified as sanitary landfill and lacks facilities such as leachate collection systems, base liner and capping mechanisms. However, the dump site had recently been equipped with a number of groundwater monitoring boreholes in recognition for its possible impact on the local groundwater resources. Maseru dump site is located upstream of several privately owned domestic boreholes and the city’s main surface water reservoir.

The Maseru landfill accommodates almost every type of waste generated in the city, including electric and electronic equipment, all sorts of batteries, dead animals, obsolete chemicals and pesticides, and garden waste (Ministry of Tourism environment and culture 1996). The waste accepted in the landfill is produced from a wide range of sources. The main sources of waste in the Maseru city are: textile industries, commercial, residential and medical institutes. There are no records of type, weight and volume of waste accommodated in the landfill (Ministry of Tourism environment and culture 1996).

3.2.2 Geology and hydrogeology

The Maseru landfill is located on a dolerite dyke intruding two geological formations, namely: Clarens and Elliot. The Clarens and Elliot formations belong to the Stormberg group. The dolerite intrusion is dissected by a very long (>10 km) and wide (up to 150 m) dolerite dyke (Figure 3.4) (Ministry of Natural Resources 1980).

The Elliot formation is made of very fine grained sediments consisting of mudstones, siltstones and sandstones. Rocks in this formation are estimated to be on average, of the thickness ranging between 150 and 200 metres (Ministry of Natural Resources 1980). Clarens formation consists of poorly bedded siltstones and sandstones. The thickness of the Clarens formation is in the range 100-200 metres (Ministry of Natural Resources 1980).

Hydrogeological investigations by Arduino *et al.* (1996) showed that dolerite dykes in Lesotho are a major geological indicator in siting productive boreholes. Boreholes drilled at dolerite dykes have yields ranging from 0.3 to 4 l/s. Thus the Maseru landfill rests on an aquifer with reasonable porosity and permeability which is a potential groundwater source. Andruino *et al.* (1996) add that contact zones between dykes and sedimentary rocks often have higher hydraulic conductivity than the surrounding parent rocks. The dyke running through the landfill may, therefore act as conduit for landfill leachate.

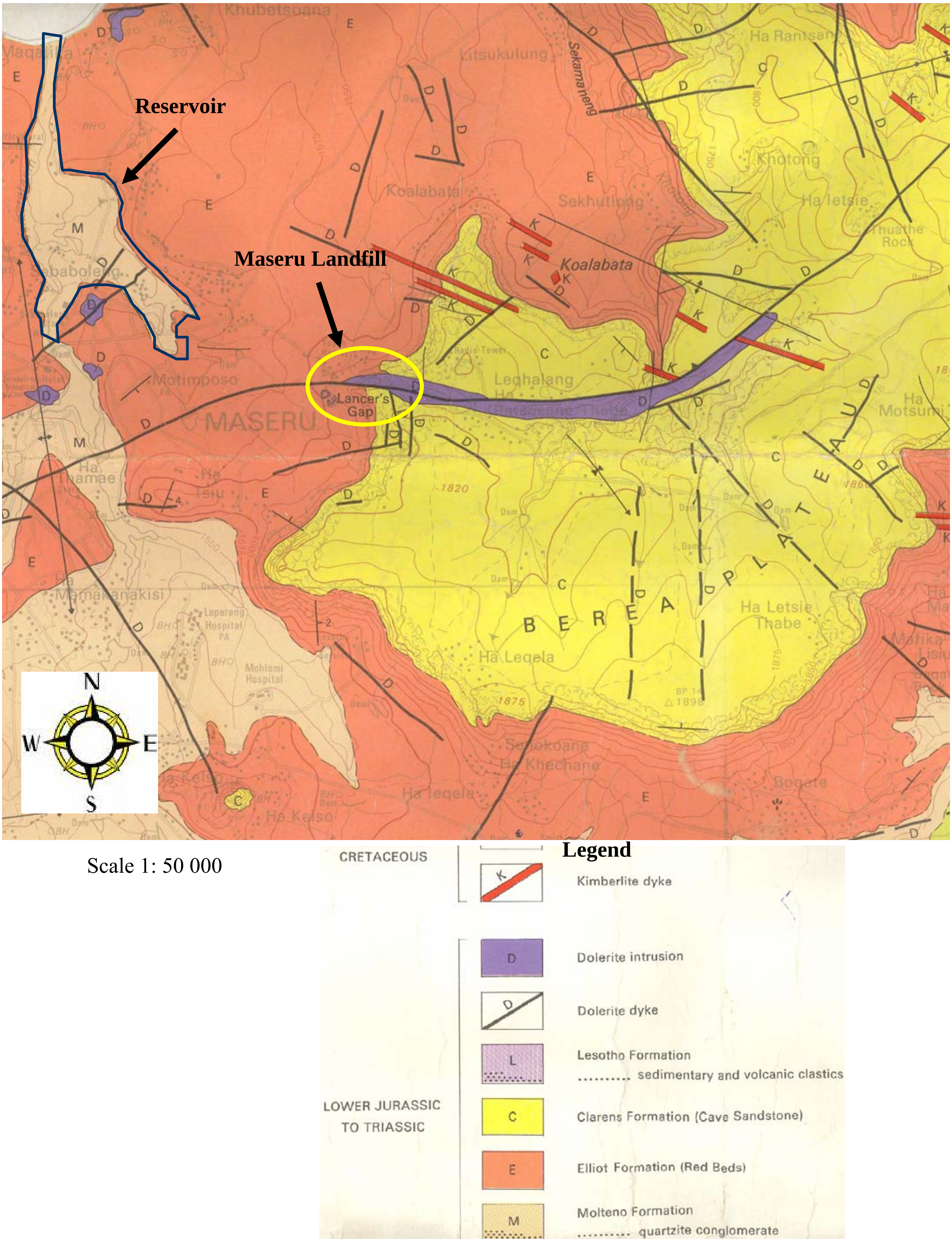


Figure 3.4 Geological map of Maseru (Source: Department of geology, Lesotho)

3.3 Methods

3.3.1 Groundwater and leachate sampling at Horotiu landfill

The Horotiu landfill is managed by the Hamilton City Council while Coal Research Energy Limited (CRL Energy Ltd) is charged with monitoring the landfill. CRL regularly collects groundwater samples from monitoring boreholes at the landfill and leachate samples from the sumps within the landfill. CRL do some field measurements for some of the chemical parameters of groundwater and leachate in situ. For more detailed chemical analysis, CRL sent samples to an analytical facility, Hill Laboratories, located in Hamilton, New Zealand. All the chemical analyses in this report were done by the Hill laboratory. Hill laboratories is an IANZ accredited chemical facility (International Accreditation New Zealand 2007).

The following account of sampling procedures and sample handling was obtained from an interview and field sampling trip with staff members from CRL in May 2007.

3.3.1.1 Sampling and measurements

A. Water level

Depths to water level measurements were obtained by CRL Ltd, by lowering a water level meter probe (Heron dipper-T meter), attached to a measuring tape, into a borehole until a buzzer was activated. Reading on the tape was recorded when the sound was heard.

B. Groundwater sampling

When obtaining groundwater samples, water in the boreholes was pumped out (CRL Ltd) to remove the stagnant water. The amount of water removed was three times the volume of water in the borehole. The volume of water to be removed was determined by the following equation:

$$V = 3\pi r^2 h$$

Where: V = required volume of water in m^3.

r = radius of the borehole in meters;

h= height of water in the borehole (depth of borehole – depth to water level) in meters.

For a known discharge, Q (m^3/sec), the time t (sec) required for removing the required volume of water was given by:

$$t = V/Q .$$

An electric submersible pump (Grundfos BTI/MP1) was used in boreholes that are accessible by vehicle and have diameters of 50 mm and above. For narrower and less accessible boreholes, a manual Teflon bailer was used to pump out the borehole water.

To be confident the stagnant water is removed from the borehole, water pH, temperature or conductivity are monitored during pumping and if not stable after the required volume of water was removed, pumping continued until stable parameter values were attained.

C. Leachate sampling

Leachate was collected from the leachate sumps at each landfill cell. The leachate was collected by turning open a stand tap. 1000 ml polyethylene jugs were used to contain the leachate samples which were then placed in various bottles (as described below).

D. Sample handling and storage

Groundwater and leachate samples were stored in bottles of different materials- polyethylene (PE), glass or plastic and volume/capacities depending on the chemical parameter to be analysed. The bottles, if not containing preservatives, were rinsed with distilled water before samples were placed in them.

Preservatives may also be utilised if necessary. Table 3.2 provides a list of preservatives and types of bottles used for storing samples intended for analyses of various chemical components.

The water samples were stored in a cooler box/ chiller at temperatures below 4° C for transport to the laboratory. The samples were then stored in a refrigerator at 4°C prior to analyses being undertaken.

Table 3.2 Types of bottles and preservatives used for various chemical parameters (Source: CRL Ltd).

Determinant	**Bottle type**	**Capacity (ml)**	**Preservative**
Inorganics	PE	250	None
BOD	PE	500	None
Phenols	PE	250	Sulphuric acid
COD	PE	250	Sulphuric acid
TKN	PE	250	Sulphuric acid
Sulphide	PE	100	Zinc Acetate
Mercury	Glass	250	Potassium dichromate
Total HMs	PE	100	Nitric acid
Acid soluble HMs	PE	100	Nitric acid
Soluble HMs	PE	50	Nitric acid (filtered)*
VOCs	Amber glass	50	None
SVOCs	Glass	500	None
TPH/OAG	Glass	250	Sulphuric acid
TOC	Glass	100	None

* Samples filtered through 0.45 um filter.

Note: BOD- Biological oxygen demand.
COD- Chemical oxygen demand.
TKN- Total Kjeldahl nitrogen.
HMs- Heavy metals.
VOCs- Volatile organic carbons.
SVOCs – Semi-volatile organic carbons.
TPH – Total petroleum hydrocarbons.
TOC- Total organic carbon.

3.3.1.2 Chemical Analyses

A. In situ measurements

Some parameters are easy to determine once samples are obtained and do not require complex analytical methods. The use of digital instrumentation with probes has enabled quick and easy measurements. Parameters such as electrical conductivity, pH, temperature and dissolved oxygen were measured immediately after collecting the water sample, using a digital electronic instrument with a multi-probe capability (WTW MultiLine P4). Probes were dipped into the sample and readings were allowed to stabilise to obtain a final reading.

B. Laboratory measurements

Groundwater and leachate samples were analysed, by Hill Laboratory for parameters including: non-metal inorganics, Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), phenols, Total Kjeldahl Nitrogen (TKN), Heavy metals (HMs), sulphide, mercury, Volatile Organic Carbons (VOCs), Semi Volatile Organic Carbons (SVOC), Total Petroleum Hydrocarbons (TPH) and Total Organic Carbon (TOC).

Various analytical methods were used by the Hill Laboratories to analyse different chemical components which could not be determined in the field and required the use of complex analytical methods and machinery (Table 3.3).

Table 3.3 Analytical methods used for various chemical determinants. (Source: Hill Laboratory technical note, 1998)

Determinant	**Method**	**Detection limit (mg/l)**
Alkalinity	APHA 2320-B	1
Chloride	APHA 4500-Cl B	0.5
Potassium	AA Flame/ICP-OES	0.02
BOD	APHA 5210 B	0.4
TOC	APHA 5210 B	0.5
Ammonium-N	Colorimetric	0.01
Nitrates-N	Cd reduction, colorimetric	0.02
COD	NAWASCO	6
Iron	AA Flame/ICP-OES/ICP-MS	0.04
Zinc	GF AA or ICP-MS	0.005
Sodium	AA Flame/ICP-OES	0.02
Calcium	AA Flame/ICP-OES	0.05
Magnesium	AA Flame/ICP-OES	0.02
Sulphate	Turbidimetric	1
Sulphide	APHA 4500-S^2-D	0.02
TKN	Acid digestion, colorimetric	0.1
DRP	NAZASCO	0.004
Aluminium	ICP-MS	0.03
Arsenic	ICP-MS	0.01
Boron	ICP-MS	0.05
Cadmium	ICP-MS	0.0005
Cobalt	ICP-MS	0.002
Chromium	ICP-MS	0.005
Copper	ICP-MS	0.005
Manganese	ICP-MS	0.005
Nickel	ICP-MS	0.01
Lead	ICP-MS	0.001
Mercury	Cold vapour AA	0.0001
Selenium	ICP-MS	0.05

Note: APHA- American public health association.

AA- Atomic absorption.

ICP- Inductively coupled plasma.

MS- Mass spectrometer.

OES- Optical emission spectrometer.

3.3.2 Groundwater Sampling at Maseru landfill

Groundwater samples were collected, stored and transported to the Water and Sewerage Authority (WASA) laboratory by the author for chemical analyses, while the borehole pumping test operations were carried out by personnel from the Department of Water Affairs in Lesotho.

3.3.2.1 Collecting groundwater Samples

Before the groundwater sample was obtained, boreholes were first purged to remove stagnant water so that the groundwater sample was representative of the *in situ* groundwater. Stagnant borehole water is known to be affected by several processes which make it to be different from the aquifer water. While water was being removed pH and EC were monitored. Removal of water was done till pH and EC were constant. Water was pumped out using an electric powered submersible pump.

3.3.2.2 Sample storage

Water samples were stored in 500ml plastic bottles and kept in an ice box and transported to the laboratory, for analysis, the same day they were obtained. The bottles were all filled to the top, so that no air was present.

3.3.2.3 Filtering

Groundwater samples were filtered using a filter with pore sizes ranging from 0.1 to 2.0 microns. All water samples were filtered before being stored.

3.3.2.4 Chemical analysis

Various analytical methods were used by the WASA laboratory for analysing the groundwater samples (Table 3.4).

3.3.2.5 Water level measurement

A probe or sensor was lowered into the borehole until a buzzer and/or light goes on. The sensor was then raised until the buzzer goes off. This level was taken as depth to water level. A Durham Geo 51690315 WLI water level indicator was used.

3.3.2.6 Borehole depth measurement

A 0.25 kg steel weight was attached to a Teflon measuring tape and lowered into a borehole until the bottom of the borehole is felt. The mark of the tape at the edge of the casing was taken as the depth of the borehole.

Table 3.4 List of methods and equipment used for water chemical analysis and added preservatives.

Determinant (units)	Equipment/Method	Preservative
Electrical Conductivity (uS/cm)	Knick Conductivity meter	-
Total dissolved solids (mg/l)	Gravimetric	Cool to 4^oC
Total suspended solid (mg/l)	Photometry	Cool to 4^oC
Temperature (^OC)	Digital/glass thermometer	-
Chloride (mg/l Cl-)	Titration with silver nitrate	Cool to 4^oC
Fluoride (mg/l F)	HACH DR/2000-Spectrophotometer	Cool to 4^oC
pH	Crison pH meter	Cool to 4^oC
Nitrate_ Nitrogen (mg/l)	HACH DR/2000-Spectrophotometer	Cool to 4^oC
Sulphate (mg/l SO_4^{2-})	HACH DR/2000-Spectrophotometer	Cool to 4^oC
Total Iron (mg/l Fe)	HACH DR/2000-Spectrophotometer	Nitric acid, pH<2
Magnesium (mg/l $CaCO_3$)	HACH DR/2000-Spectrophotometer	Nitric acid, pH<2
Calcium (mg/l)	Digital/Burette titration	Nitric acid, pH<2
Total Alkalinity (mg/l $CaCO_3$)	Digital/Burette titration, pH meter	Cool to 4^oC
Lead (mg/l)	ICP-MS	Cool to 4^oC
Zinc (mg/l)	ICP-MS	Cool to 4^oC
Potassium (mg/l)	ICP-MS	Cool to 4^oC
Sodium (mg/l)	ICP-MS	Cool to 4^oC

3.3.3 Borehole pumping test

Borehole pumping test operations were carried out by the Department of Water Affair personnel. The pumping tests were done by pumping water out of the boreholes, one at the time, using a Lowara (Z8) submersible pump. Before the tests resume, static water levels were recorded. Water levels were also measured during the test at various time intervals (Table 3.5).

Table 3.5 Time intervals for measuring water levels during pumping test

Interval (minutes)	Time since test began
1	0-10 min
2	10-20 min
5	20-60 min
10	60-120 min
20	120 min - onwards

Discharge rates were kept constant and measured every one hour by means of a 10L bucket and a stop watch. Water was conveyed by a pipe to a distance 100 metres away from the boreholes to prevent it from returning to the aquifer. Pumping tests were conducted for 72 hrs for each borehole, otherwise stopped if a borehole runs out of water.

The pumping test was analysed by comparing the rate of change of water level in a pumped borehole with time to achieve those changes, and also considering the discharge rate. Pumping tests are generally aimed at estimating aquifer hydraulic parameters, namely: Storativity, Transmissivity and hydraulic conductivity.

Pumping test results were analysed using an '*excel*' spreadsheet-based computer software '*Cooper-Jacob single well analysis*' (Halford & Kuniasky 2002). The package solves a well-known 'Cooper-Jacob' analytical groundwater flow equation:

$$s = \frac{2.30Q}{4\pi KD} \log \frac{2.25KDt}{r^2 S} \quad \text{(Kruseman \& de Ridder 1991)}$$

Where: s – drawdown [L] (i.e. static water level – dynamic water level)

K- Hydraulic conductivity [L^2/T]

D- thickness of saturated aquifer [L] (i.e. static water level – borehole depth)

t- time since test began [T]
r- radius of the borehole [L]
S- storativity [-]

The program makes time v drawdown scatter plots. From the plots best-fit line were matched on to the plot data. The program calculates the slope of the line and also using the applied pumping rate, Q, it mathematically interprets this to hydraulic conductivity, K of the pumped borehole.

Analyses of pumping test results are generally based on the following assumptions (Kruseman & de Ridder 1991):

1. "The aquifer has an infinite areal extent.
2. The aquifer is homogeneous, isotropic and of uniform thickness over the area influenced by the pumping test.
3. Prior to the test, the piezometric surface is horizontal over the area influenced by the test.
4. The aquifer is pumped at the constant discharge rate.
5. The pumped borehole penetrates the entire thickness of the aquifer and thus receives water by horizontal flow".

3.3.4 Chemical data presentation

Chemical data presentation was done by use of a software program named '*AQqa'* (Demo version) developed by RockWare Inc. (2004). The program was here used to display the groundwater chemical data on the Schoeller diagram, which shows the major ions in units of milli-equivalent per kilogram (meq/kg). The program also calculated carbonate speciation and computed the hydrogeological water types.

3.3.5 Statistical analyses

3.3.5.1 Linear correlation

To establish whether one variable (e.g. rainfall) has any influence on the other variable (e.g. concentration landfill leachate), statistical correlation analyses were carried out. Linear correlation is normally used to evaluate a linear relationship between two variables. Such relationships are quantified by a correlation coefficient, which is defined as the measure of linear association between two variables (Freedman *et al.* 1998).

Correlation coefficient ranges between 0 and 1, with 1 being a perfect correlation and 0 no correlation at all. Negative correlation occurs when the increase of one variable corresponds to a decrease in another. Correlation coefficients are here calculated using *excel* spread sheet (Microsoft office 2003) which uses the equation:

$$r(x,y)=\frac{\sum(x-\overline{x})(y-\overline{y})}{\sqrt{\sum(x-\overline{x})^2\sum(y-\overline{y})^2}}$$

Where: r is correlation coefficient
x and y are variables.

In the above equation, for example, x variable may be rainfall amount and y represents individual leachate component or x be groundwater EC, while y was groundwater level.

3.3.5.1 Student's *t*-test

Differences between the means of some chemical parameters (e.g. nitrate) of the downstream and upstream boreholes were determined by student's t-test. The test was carried out by the use of *excel* sheet (Microsoft office 2003). The formula for t is as follows (Wheater &Cook 2000):

$$t=\frac{\left|\overline{x_1}-\overline{x_2}\right|}{\sqrt{\frac{(n_1-1)s_1^2+(n_2-1)s_2^2}{(n_1+n_2-2)}*\frac{n_1+n_2}{n_1n_2}}}$$

Where: $\bar{x}_1$ and $\overline{x_2}$ are the means for upstream and down stream boreholes;

s_1^2 and s_2^2 are the variances of upstream and downstream boreholes;

n_1 and n_2 are number of upstream and down stream boreholes.

The null hypothesis stated that two means, of the parameter in question, for upstream and downstream were the same. The calculated t-value was compared to the critical t-value for a given degree of freedom. The means for the investigated parameter were regarded to be significantly different if the calculated t-value was greater than the critical t-value.

Chapter 4

Horotiu landfill leachate quality

4.1 Leachate Chemistry

4.1.1 Introduction

Horotiu landfill leachate has been collected from 16 leachate chambers (sumps) located in 12 landfill cells (Figure 4.1, Table 4.1). Leachate has been collected at six month intervals since 1997. Data sets used in this study were supplied by The Hamilton City Council (unpublished) and consist of records from 1997 until the landfill decommission at the end of 2006. The leachate samples were analysed in a commercial laboratory for: pH, electrical conductivity (EC), alkalinity, sulphates, nitrates, ammoniacal-nitrogen, total nitrogen, total organic carbon (TOC), chemical oxygen demand (COD), biochemical oxygen demand (BOD), reactive silica, selected major cations and selected heavy metals.

Table 4.1 Leachate sumps at Horotiu landfill and their locations.

Leachate sump	Stage	Filling started	Capped
1	1	Oct-85	Mar-88
2a	2A	Feb-87	Dec-88
2b	2B	Feb-88	May-89
3a	3A	Apr-94	Jan-01
3b	3B	Feb-89	Oct-95
3c	3C	Aug-90	Oct-95
4a East	4A		
4a West	4A	Mar-97	Jan-07
4b East	4B		
4b West	4B	Mar-98	Jan-07
4c North	4C		
4c South	4C	Mar-99	Jan-07
5a North	5A		
5a South	5A	Mar-92	Oct-92
5b	5B	Jun-95	Jan-06
6	6	Nov-06	Jan -07

Data from Hamilton City Council

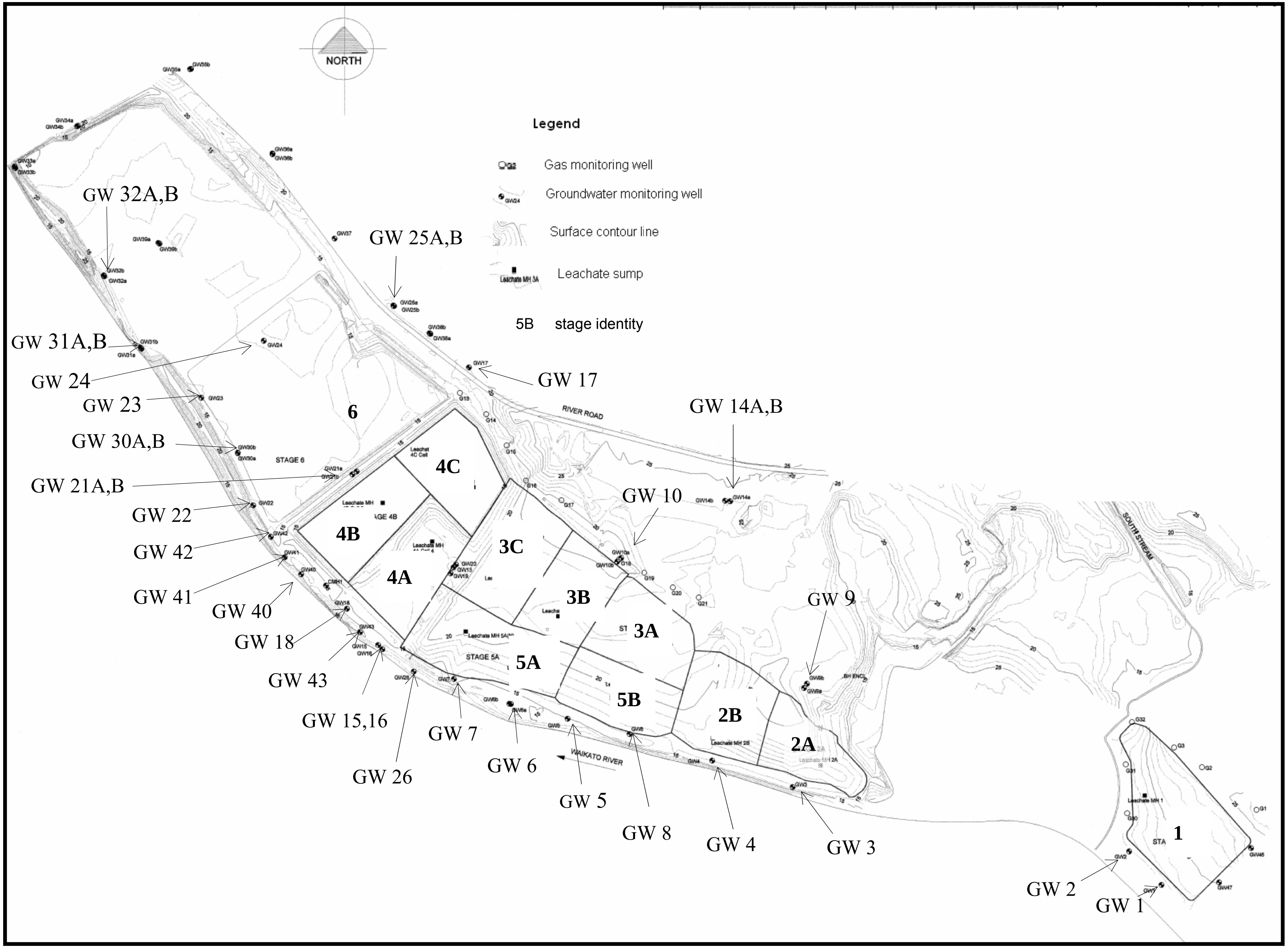


Figure 4.1 Horotiu landfill map showing landfill stages and locations of gas and groundwater monitoring wells. (Adapted from a diagram by Hamilton City Council)

4.1.2 Leachate Composition

The quality of leachate from all the landfill cells over the sampling/monitoring period is summarised in Table 4.2. Parameter averages of each of the 16 sampling sites were compared with each other to obtain range, mean, and standard deviation for the landfill as a whole. The full data-set for leachate monitoring of chemical parameters is included in Appendix 1.

The chemical composition of the leachate from the Horotiu landfill was dominated by alkalinity with the concentration range of 1500-7600 mg/l. Chlorides, ammonium, total nitrogen, major cations, TOC and BOD were relatively high (Table 4.2). Electrical conductivity was also relatively high with a maximum value of over 14000 µS/cm. Heavy metals are in low concentrations, generally below 1 mg/l. Nitrates are present only in low concentrations (mean of 2.7 mg/l) (Table 4.2).

The maximum concentrations for many parameters are considerably larger than the minimum concentrations, particularly for electrical conductivity, sulphates, chlorides, ammonium, and COD (Table 4.2).

Table 4.2. Leachate composition at the Horotiu landfill. Amalgamated data for all the leachate sources. All values are in mg/l except, pH, electrical conductivity (µS/cm) and BOD/COD.

Parameter	*Min*	*Max*	*Mean**	*S.D*
pH	6.9	7.8	7.4	0.3
Electrical Conductivity	3160	14265	8489	3381
Alkalinity	1454	7555	3718	1686
Sulphate	13	337	92	87
Chloride	186	1394	704	382
Nitrate-Nitrogen	0.2	16.0	2.7	5.2
Ammoniacal- Nitrogen	227	1270	632	316
Total Kjeldahl Nitrogen	299	1496	837	377
TOC	114	1212	405	304
BOD	14	397	126	107
COD	312	3520	1289	848
BOD/COD	0.04	0.26	0.09	0.05
Silica	31	52	40	7
Dissolved Reactive Phosphorus	0.04	11.3	2.9	3.3
Sodium	164	1133	563	309
Potassium	167	862	444	195
Calcium	108	171	135	18
Magnesium	29	73	60	13
Boron	2.3	13.0	6.3	3.2
Iron	5.8	88.8	18.0	21.7
Zinc	0.1	4.9	0.7	1.2
Aluminium	0.24	62.9	5.1	16.6
Chromium	0.01	0.71	0.19	0.23
Manganese	0.673	111	9.7	29.1
Cobalt	0.015	0.054	0.032	0.010
Nickel	0.014	0.120	0.073	0.036
Copper	0.005	0.192	0.028	0.048
Arsenic	0.012	0.703	0.164	0.190
Cadmium	0.0003	0.0055	0.0009	0.0013
Lead	0.0008	0.1199	0.0149	0.0306

*Mean of all samples from all cells from 1997 to 2006.

4.2 Temporal variations of leachate quality

Changes in chemical composition of leachate with time were assessed. In this section pH, electrical conductivity, alkalinity and concentrations of major cations and anions are compared to evaluate variations in leachate samples, over the monitoring period.

4.2.1 Leachate pH

There were no consistent changes of leachate pH over time for all landfill stages. All pH values were near neutral, with pH values ranging between 6 and 8 (Figure 4.2).

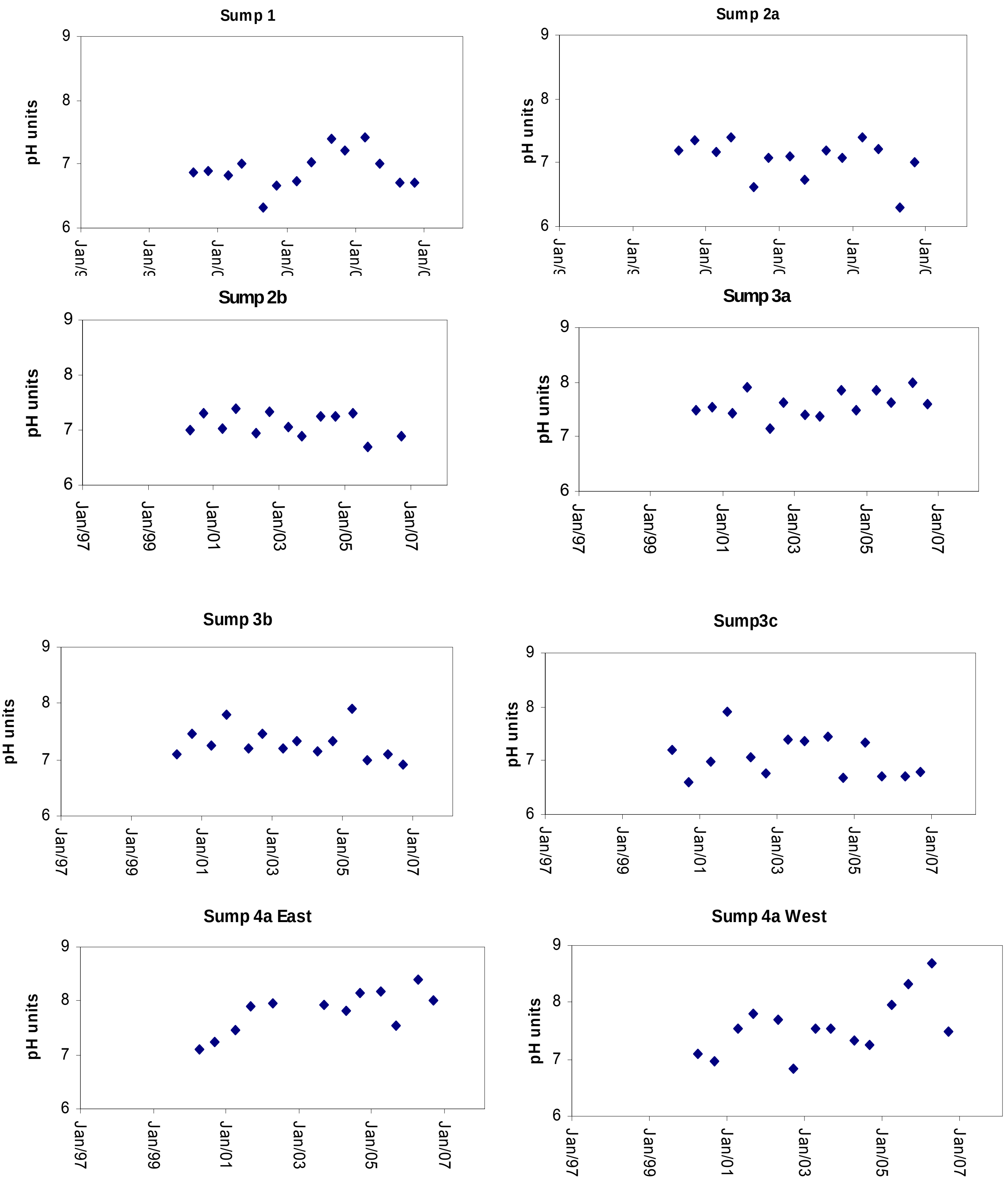


Figure 4.2 Graphs of leachate pH against time for individual leachate sample sites.

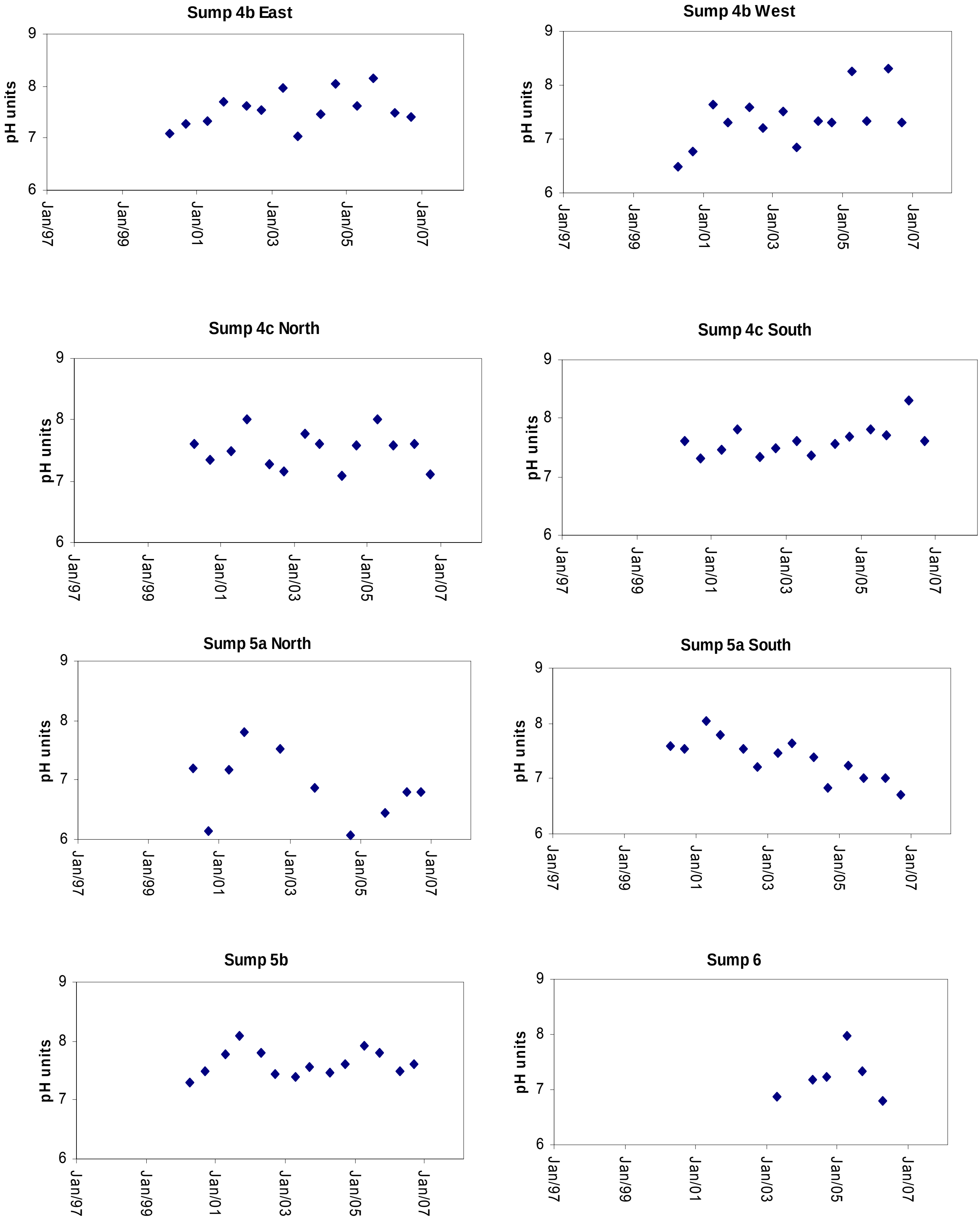


Figure 4.2 (continued) Graphs of leachate pH against time for individual leachate sample sites.

4.2.2 Electrical conductivity and alkalinity

Electrical conductivity (EC) and alkalinity were used to demonstrate temporal changes in leachate quality. E.C indicates the ability of a substance (leachate) to conduct electric current due to dissolved ions, and alkalinity is here expressed as concentration of carbonates. EC may also be used to indicate the strength or load of leachate.

Figure 4.3 presents the changes in concentrations of EC and alkalinity during the monitoring period for different landfill cells. Long-term trends of both alkalinity and EC seem to mimic each other, giving an indication of strong correlation between the two parameters. Leachate from sumps 1, 2a, 2b and 3c had relatively low concentrations, with EC less than 1000 µS/cm and alkalinity less than 5000 mg/l. Leachate from sumps 4a east, 4b east, 4c north, 4c south 5a north 5b and 6 had relatively high values of both EC and alkalinity, with at least one record of EC higher than 15 000 µS/cm and an alkalinity of over 5000 mg/l.

Leachates from individual landfill cells had varying general trends over the monitoring period. Because EC is correlated with other parameters, it can be used to generalize the overall trend of leachate strength. Electrical conductivity trends are represented by black solid lines. Figure 4.3 indicates that about 44% of leachate sources demonstrated decreasing leachate strength, 38% increasing leachate strength, and 18% showed no long term changes.

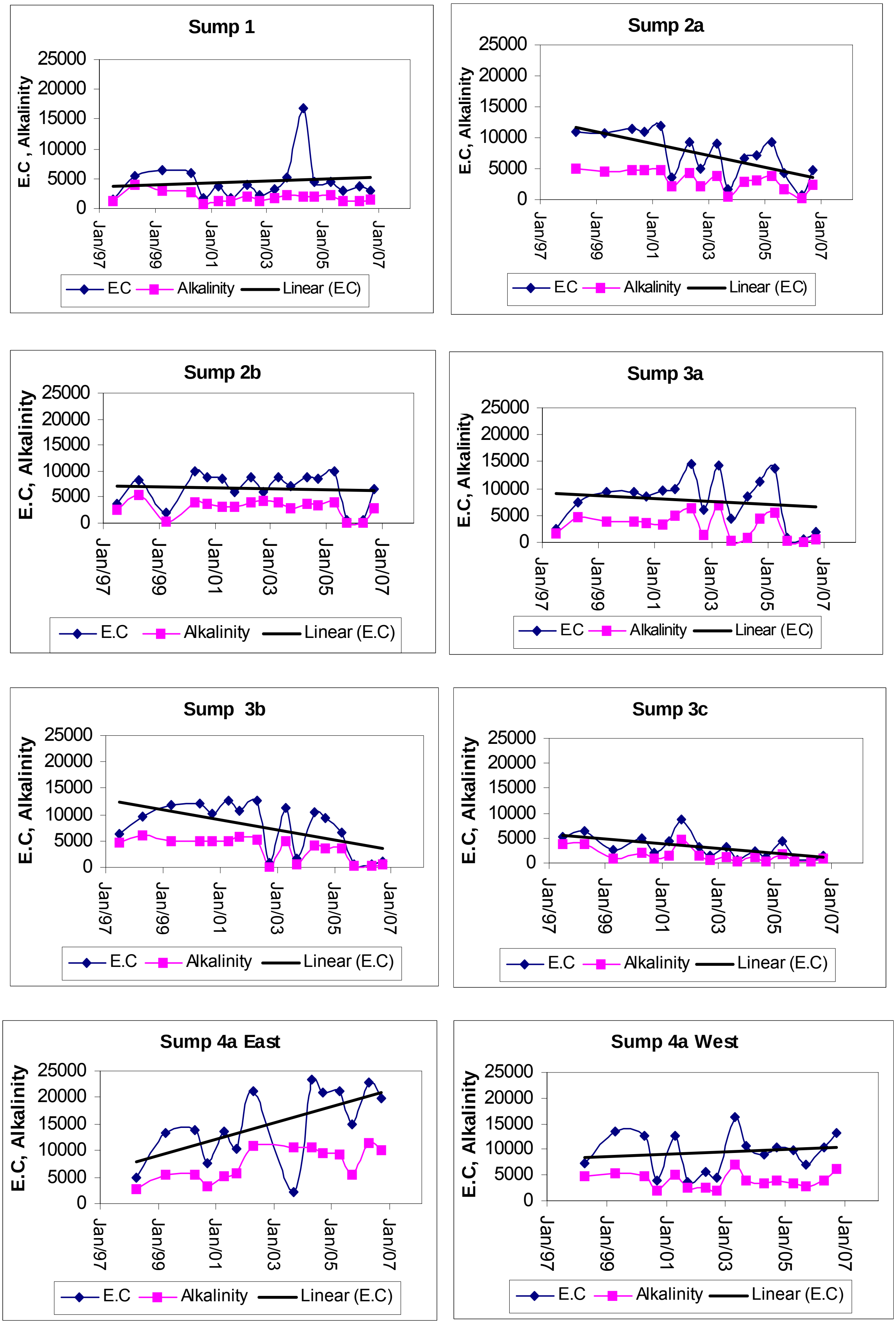
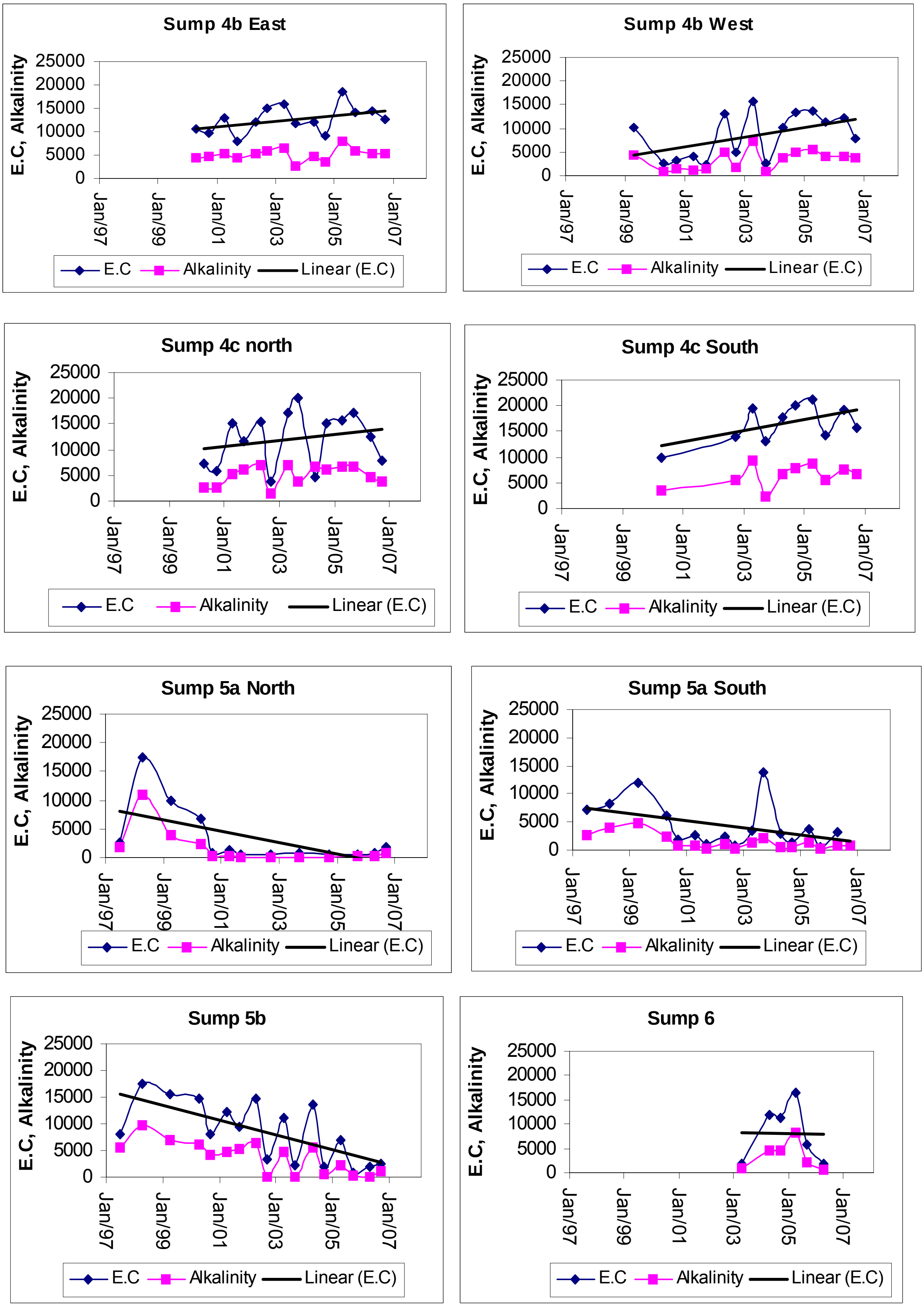


Figure 4.3 Plots of leachate EC (µS/cm) and alkalinity (mg/l) against time.



Sump 4b East

Sump 4b West

Sump 4c north

Sump 4c South

Sump 5a North

Sump 5a South

Sump 5b

Sump 6

Figure 4.3 (continued) Plots of leachate E.C (µS/cm) and alkalinity (mg/l) against time.

4.2.3 Major Anions

Anions in leachate at Horotiu landfill were dominated by Chlorides, Sulphates and Nitrate-N. Concentration of chlorides was the highest and nitrate-N the lowest for all leachate sumps (Figure 4.4). There is evidence of short-term fluctuations and long-term trends in concentrations of these parameters over the time of sampling for the leachate sources. More than 50% of leachate sources have relatively high concentrations of the anions, particularly chlorides (> 1000 mg/l).

4.2.4 Major Cations

The most abundant cations present in the Horotiu landfill leachates are sodium (Na), potassium (K), calcium (Ca) magnesium (Mg) and ammoniacal- nitrogen (NH_4-N). Temporal variations of the cations are used to convey the long-term trends of concentration of the major cations for each landfill cell (Figure 4.5, Table 4.3). Leachate from old landfill stages (i.e. 1, 2A, 2B, 3A, 3B, 3C, 5A and 5B) had decreasing concentrations of major cations, while young landfill stages (i.e. 4A, 4B,4C and 6) had leachates with increasing amounts of major cations (Figure 4.6).

All leachate samples display changes in long-term concentrations of major ions. All leachate samples are high in potassium and sodium concentrations, followed by ammoniacal-nitrogen. Calcium and magnesium have lower concentrations than the other cations. More than half of the leachates show that the concentrations of the major cations were decreasing during the period of sampling. Leachate from sump 4a east was the most loaded with the cations, while leachate from 5a north has the least concentration of the cations.

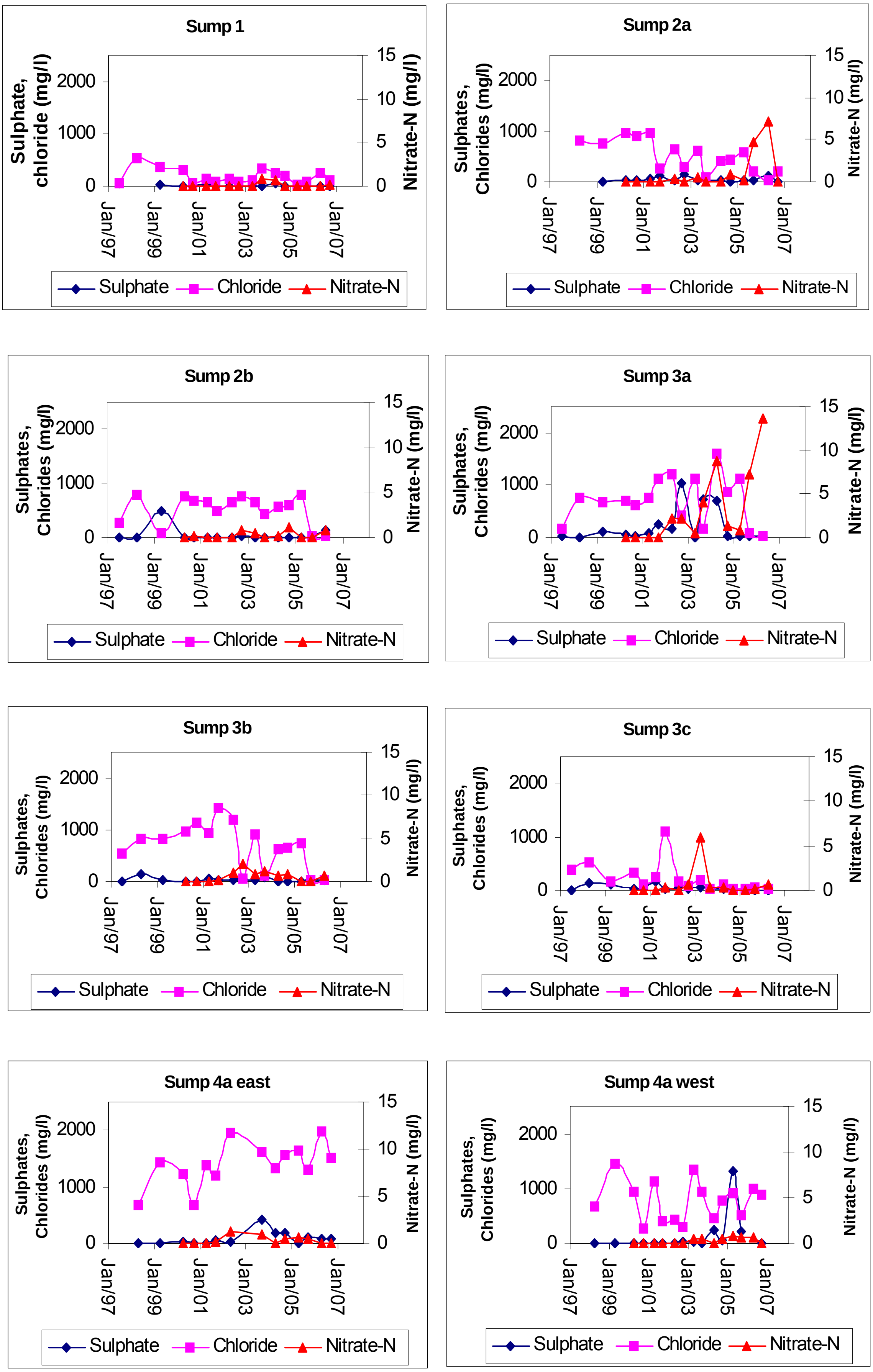


Figure 4.4 Plots of major anions against time for leachate at each landfill cell.

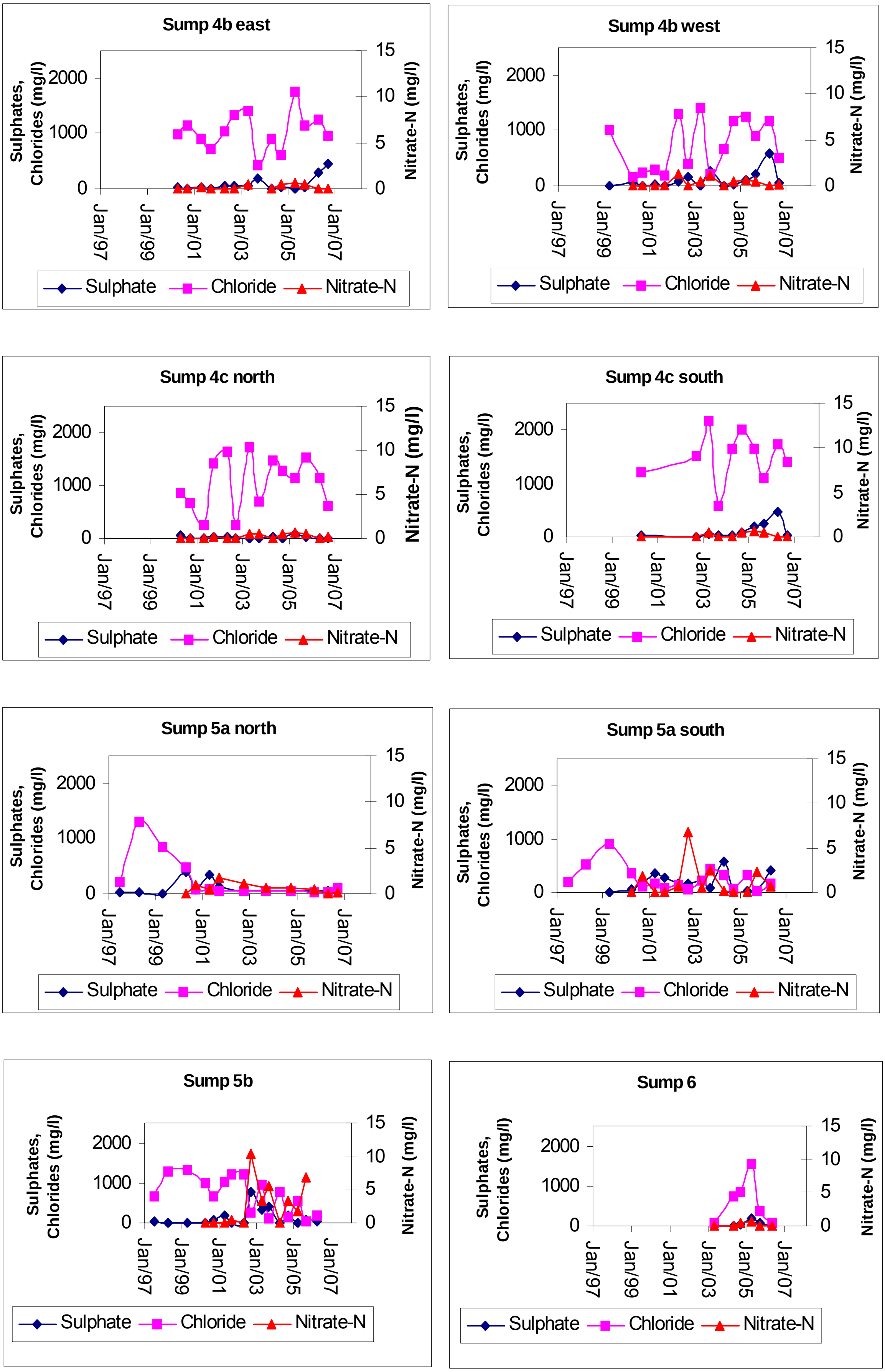


Figure 4.4(continued) Plots of major anions against time for leachate at each landfill cell.

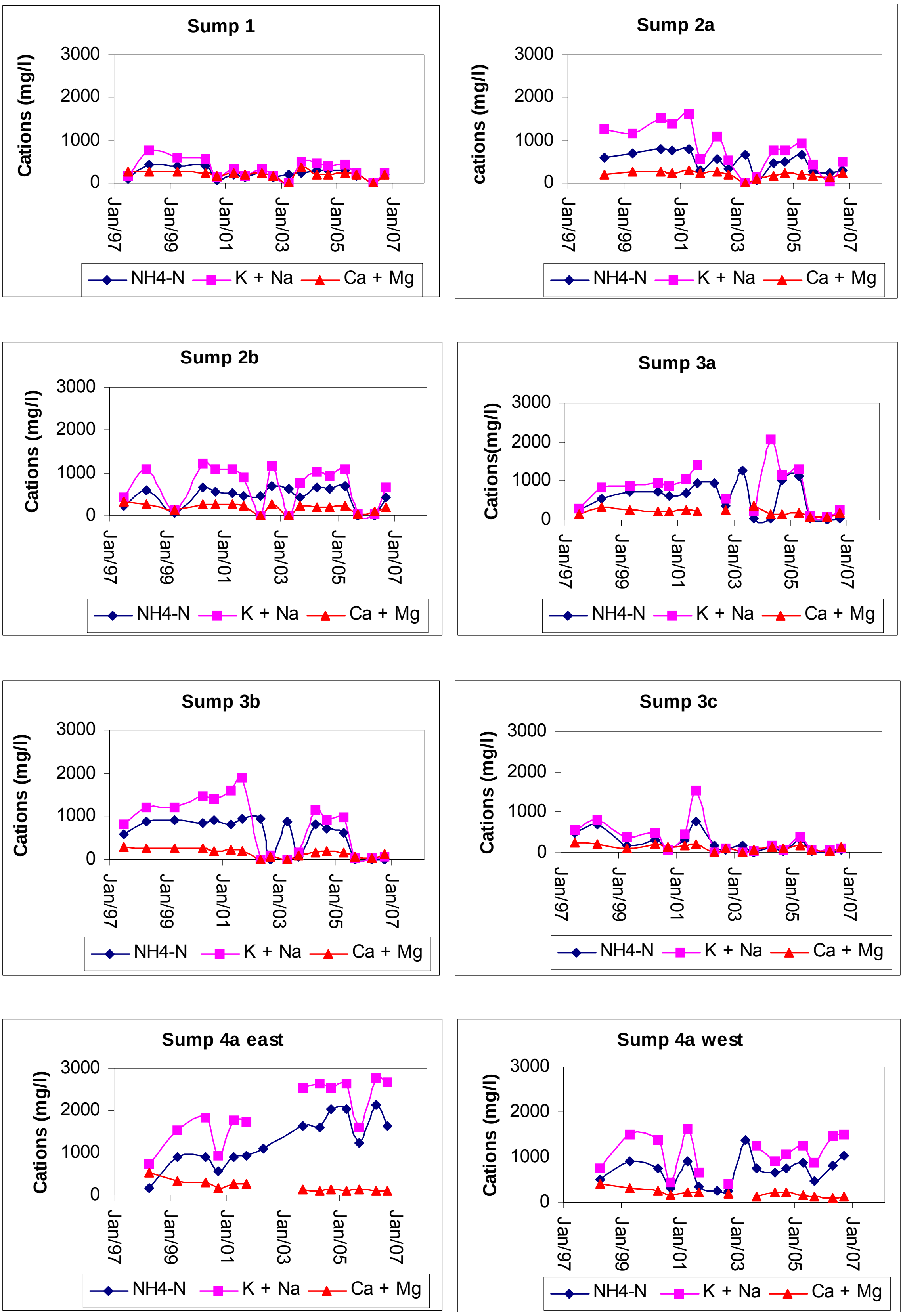


Figure 4.5 Graphs of major cations against time for each landfill cell.

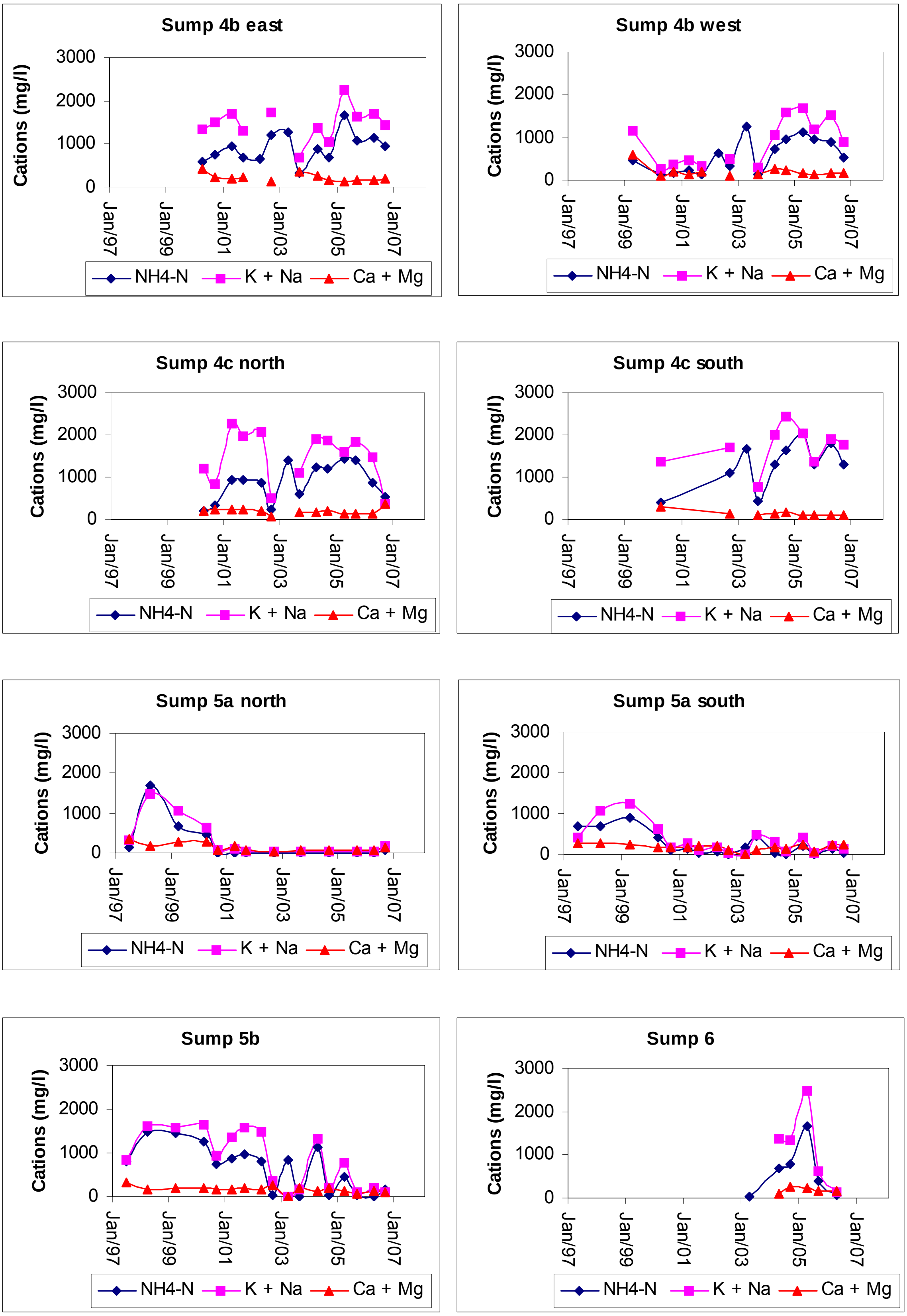


Figure 4.5 (continued) Graphs of major cations against time for each landfill cell.

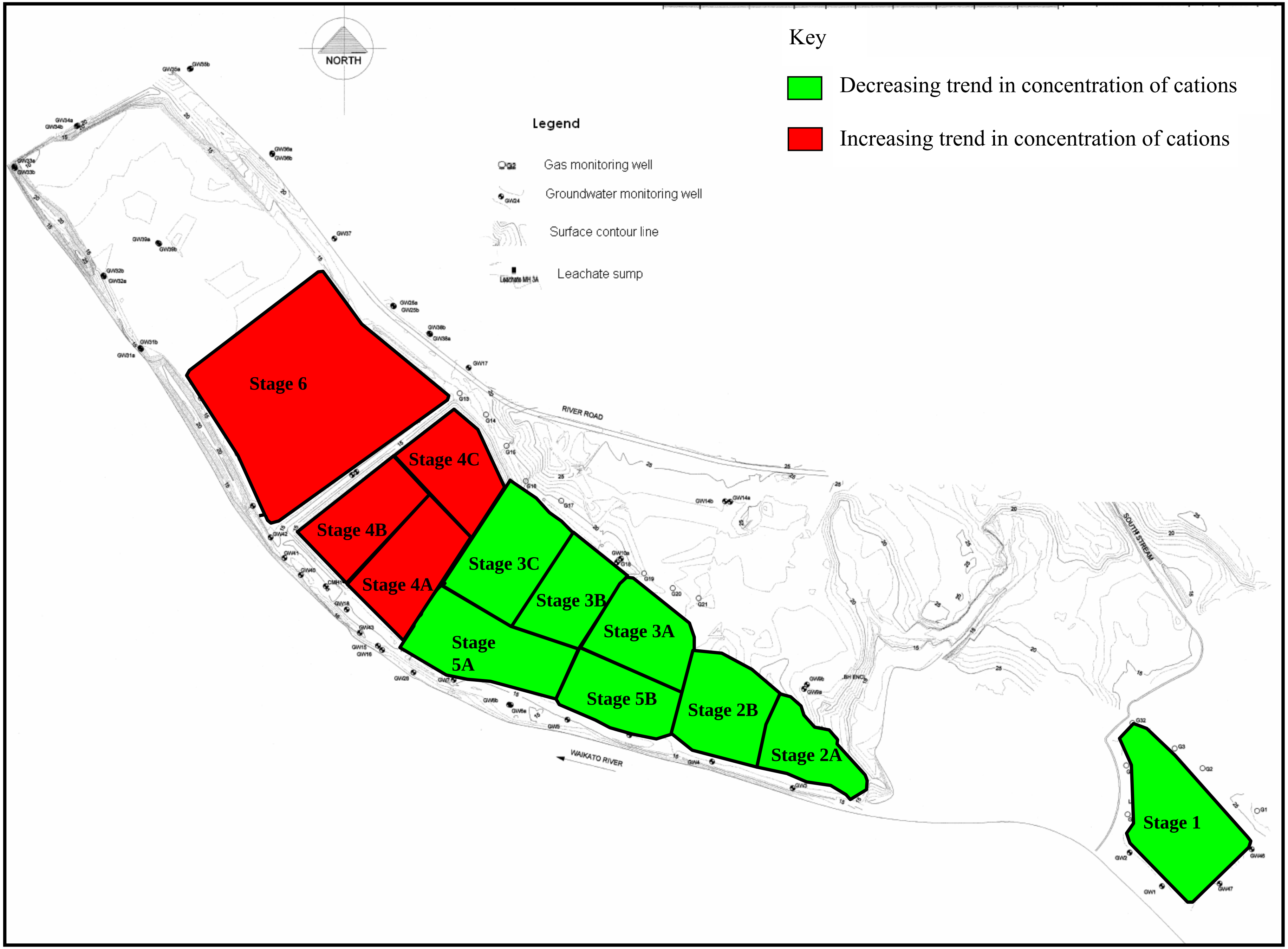


Figure 4.6 The Horotiu landfill map showing sites with major temporal trends in leachate cations.

Table 4.3 Long-term trends of total sum of the major cations for each landfill stage.

Landfill stage	Duration of filling		Trend*
	Started filling	capping	
1	Oct -85	Mar-88	▼
2A	Feb -87	Dec-88	▼
2B	Feb -88	May-89	▼
3A	Apr -94	Jan-01	▼
3B	Feb -89	Oct-95	▼
3C	Aug -90	Oct-95	▼
4A	Mar -97	Jan-07	▲
4B	Mar -98	Jan-07	▲
4C	Mar -99	Jan-07	▲
5A	Sep-92	Oct-95	▼
5B	Jan-95	Jan-06	▼
6	Nov-06	Jan-07	▲

*▲ Increasing trend
▼ Decreasing trend

4.2.5 Organic Content

The organic load of landfill leachate may be denoted by total organic carbon (TOC), chemical oxygen demand (COD) and biochemical oxygen demand (BOD). BOD:COD ratio is used to express the fraction of organics which is readily biodegradable (Wiszniowski *et al.* 2007). Temporal variations of TOC, COD, BOD and BOD: COD ratio are shown in Figure 4.7. COD was found in highest concentrations from all leachate sources, followed by TOC then BOD. Temporal variations of all the parameters are evident for both short and long-terms, though COD and TOC demonstrate higher fluctuations. For all the cells in the Horotiu landfill, BOD: COD ratio was generally decreasing throughout the sampling period and ranged between 0.4 to below 0.1 (Figure 4.7). Cells 4b east, 4b west and 4c south had the highest concentrations COD (maximum of about 3000 mg/l) and cell 4a east has highest concentration of TOC (maximum of 2400 mg/l). Cells 1 and 3c had the lowest concentrations of COD and BOD.

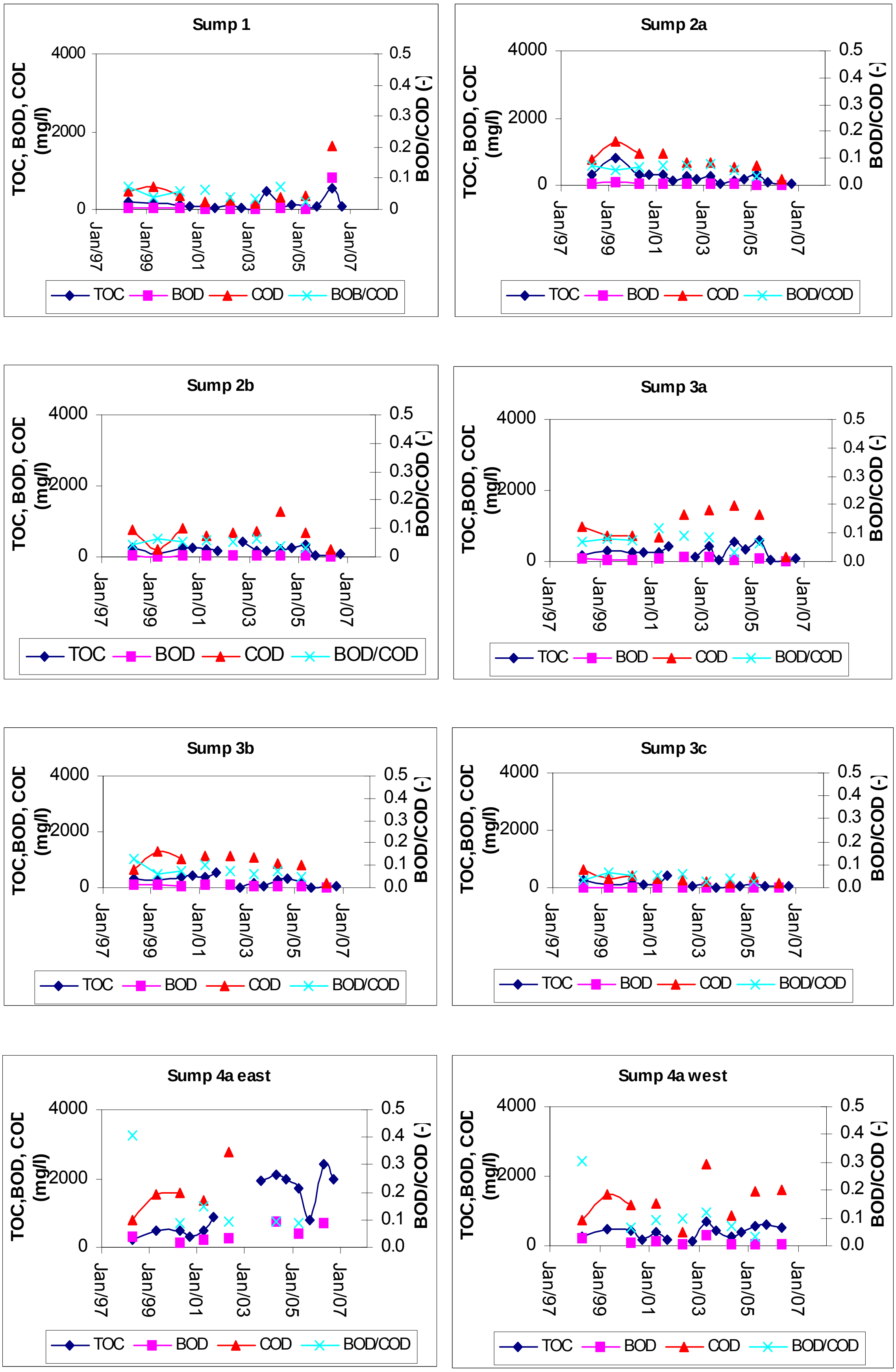


Figure 4.7 Graphs of leachate organic content versus time for each landfill cell.

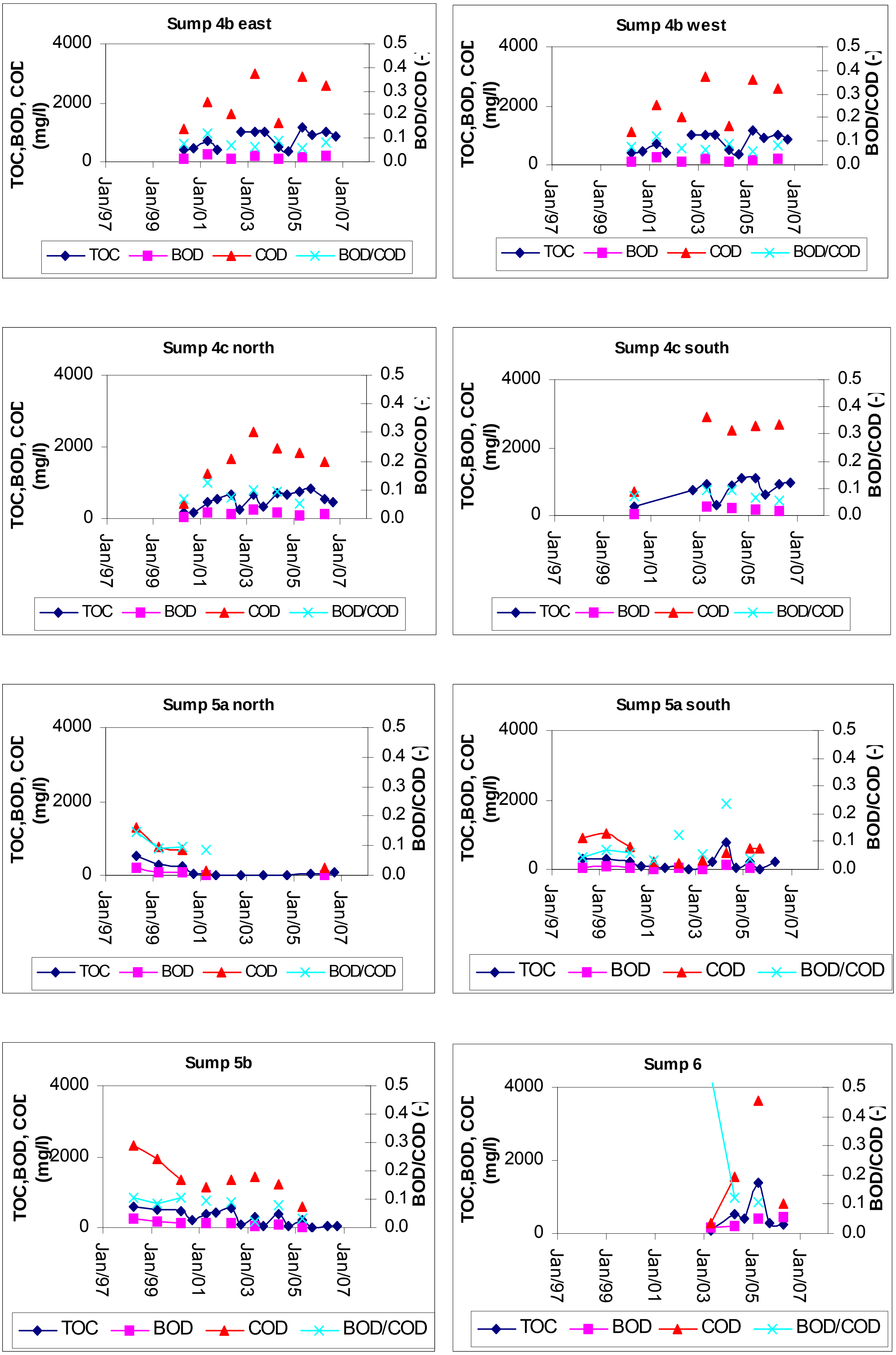


Figure 4.7 (continued) Graphs of leachate organic content versus time for each landfill cell.

4.2.6 Heavy Metals

Landfill leachate at Horotiu has been monitored for a number of heavy metals. Changes in leachate concentrations of selected heavy metals: chromium, nickel, copper, arsenic and cadmium are presented in Figure 4.8. There were no major observable short-term fluctuations and long-term trends in concentrations of the heavy metals in landfill cells: 1, 2a, 2b, 3a, 3b and 3c. Leachate from these landfill cells demonstrate very low concentrations (<< 1 mg/l) for all the heavy metals (Figure 4.8). The low concentrations are maintained from the beginning to the end of the sampling period.

Leachates from other cells display different forms of short and long term concentration changes for all the heavy metals. Landfill cells 4a east, 4a west, 4b east, 4b west, 4c north, 4c south and 6 demonstrate an increasing trend in concentration of heavy metals, more noticeably chromium, which seems to be a dominant metal. Decreasing long-term trends are observed in cells 5a north, 5a south and 5b.

Chromium and arsenic were two most abundant heavy metals in Horotiu landfill, with chromium having the highest concentrations in all the cells followed by arsenic. Of all the landfill cells, 4a east had the highest concentrations, about 2 mg/l, for both chromium and arsenic, followed by 4b east with chromium concentration of about 1 mg/l (Figure 4.8). Nickel, copper and cadmium were the lowest (< 0.5 mg/l) in all the landfill cells and did not show observable fluctuations throughout the sampling period.

There were no significant trends in heavy metal concentrations with pH in leachate (Figure 4.9) which reflects the relatively high pH values and the small range in pH variability.

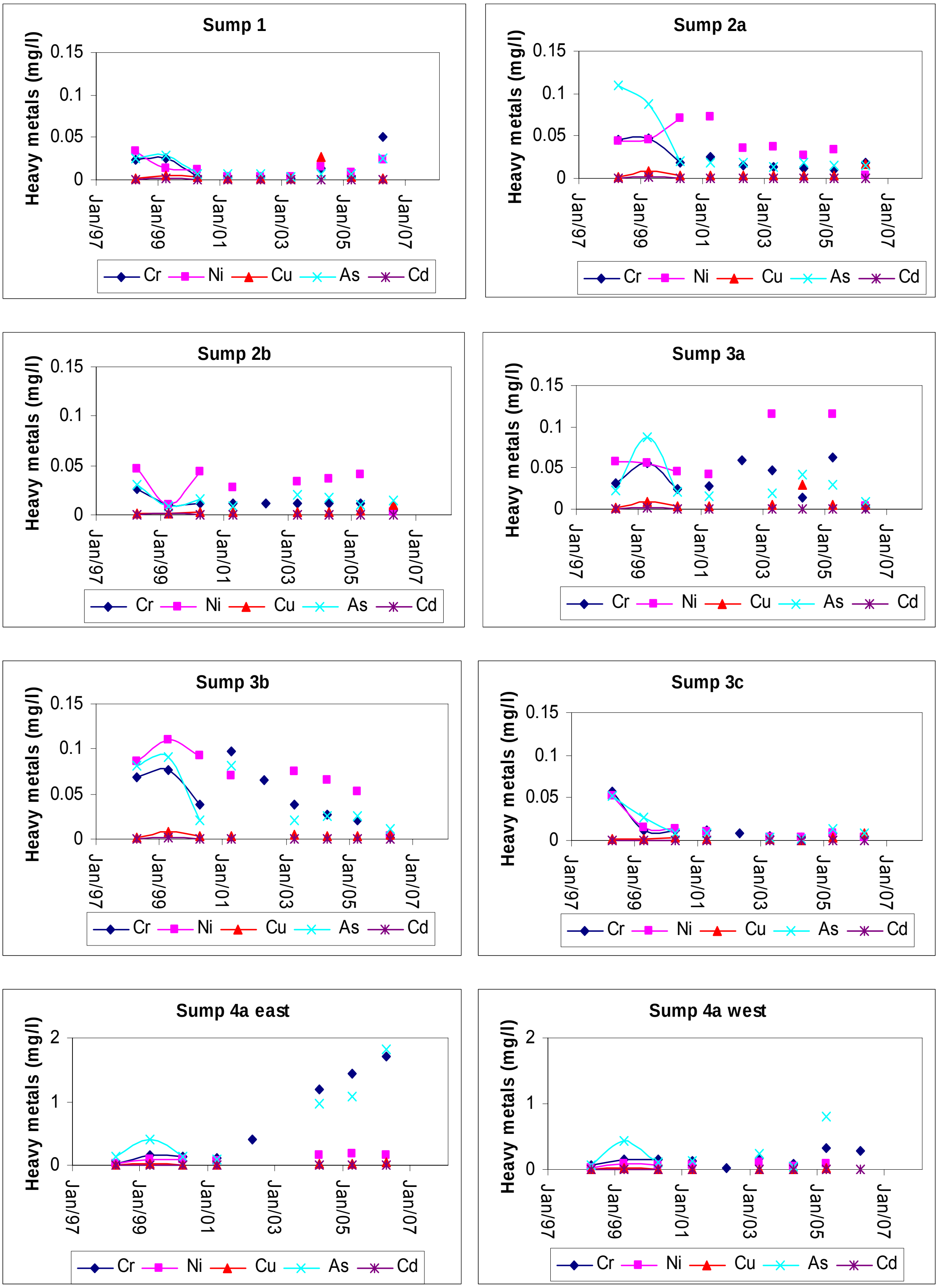


Figure 4.8 Changes of heavy metal concentration in leachate with time. Note a difference in vertical scale: Sump1– 3c and sump 4a east - 6.

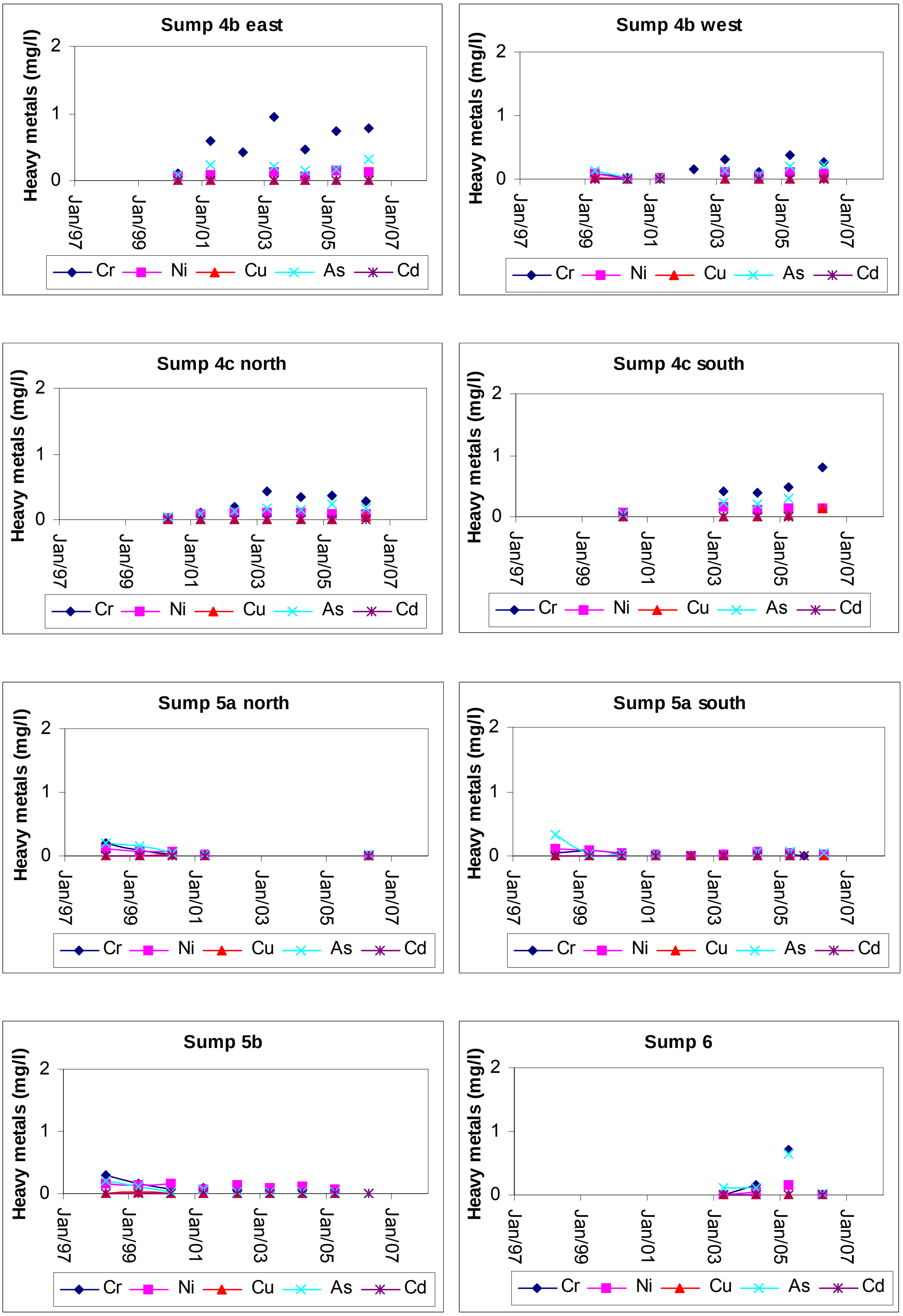


Figure 4.8(continued) Changes of heavy metal concentration in leachate with time. Note a difference in vertical scale: Sump1– 3c and sump 4a east - 6.

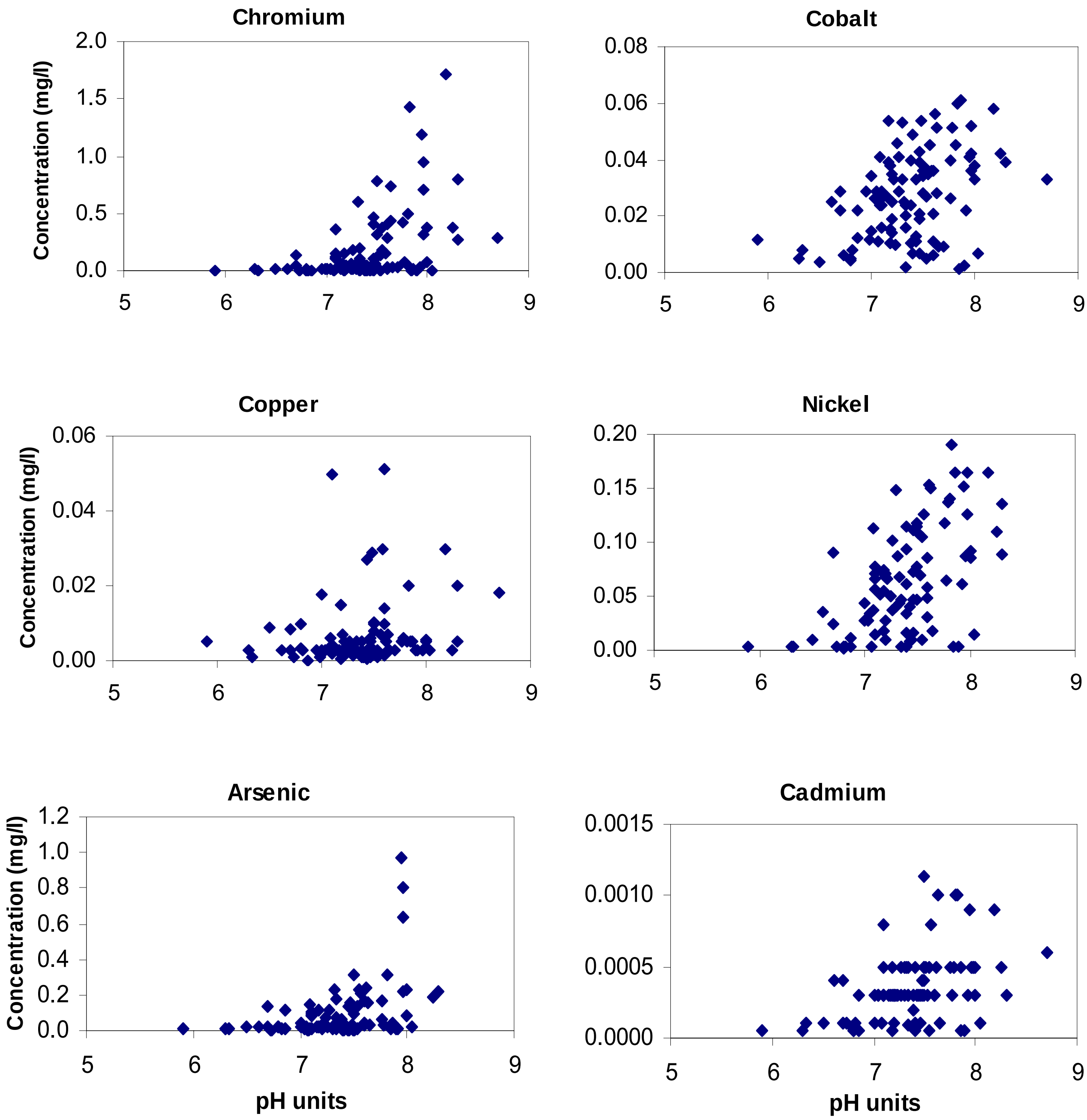


Figure 4.9 Plots of leachate pH against concentrations of heavy metals. Consolidated values for all the landfill cells.

4.3 Variation of leachate with amounts of rainfall

4.3.1 Introduction

Rainfall is perhaps the most important natural contributor to the formation of leachate. Rainfall adds quantity to leachate as rain-water percolates through the waste. The impact of rainfall may be more direct in operational cells of the landfill and to a lesser extent in completed and capped landfills. This section evaluates the influence of rainfall amounts on the chemical quality of leachate in both operational and capped cells of the Horotiu landfill.

4.3.2 Rainfall amounts and leachate quality

It has been shown in the literature that the amount of rainfall may influence the concentration of some of the leachate components (Chen 1996; Johnson *et al.* 1999). However, the causal-effect of rainfall on leachate may be a debatable subject as different relationships between rainfall and leachate have been documented.

Rainfall amount is here referred to as the total amount of rainfall in the past 30 days before leachate sample was obtained. The 30-day period was arbitrarily selected for convenience. Rainfall data for Horotiu is included in Appendix 2. Correlation coefficients for rainfall and various leachate components are shown in Table 4.4. There were more leachate components at Horotiu landfill correlating negatively with rainfall amounts than those correlating positively (Table 4.4).

It is evident that correlations of individual leachate components with rainfall amounts differ between landfill cells. Sodium was the only component which was negatively correlated with rainfall in all of the landfill cells. Negative correlations of rainfall with leachate alkalinity, chlorides, ammonium-N, potassium and magnesium occurred in 95% of the landfill cells. These negative correlations may indicate diluting effect of rainwater. The concentrations of leachate components such as electrical conductivity, total kjeldahl nitrogen, TOC, boron and cadmium decreased with increasing rainfall amounts in 90% of the landfill cells.

Other parameters correlate negatively with rainfall in more than 50 % of the landfill cells, with the exception of: copper, manganese, chromium, aluminium, zinc, iron, sulphate and BOD/COD. The concentrations of these components increased with increasing rainfall amounts in more than half of the landfill cells.

There were few incidences of strong correlations (i.e. $r > 0.7$), both positive and negative, occurring with some of the leachate component. Strong correlations are shown in bold fonts in Table 4.4.

Occurrences of negative correlations of rainfall and leachate components are ubiquitous within the various landfill cells. However, the landfill cells exhibit varying frequencies of negative correlations of different magnitudes. Cells in which the most number of leachate parameters with negative correlations are 4a east and 5a north, 87%. Cells 2b, 3a, 3b, 3c, and 4c north had between 70 and 80% of the leachate parameters varying negatively with rainfall amounts.

Cells 1, 2a, 4a west, 4b west, 4c south, 5b, and 6 had 55 to 65 % of leachate parameters increasing with decreasing rainfall amounts. The only landfill cell where the majority of parameters correlated positively with rainfall amounts is 4b east where 67 % of the parameters varied positively.

Table 4.4 Correlation coefficients (r) for rainfall amounts and leachate components at each landfill cell. (Bolded data indicate r> 0.7)

Landfill cell	*1*	*2a*	*2b*	*3a*	*3b*	*3c*	*4a East*	*4a west*
pH	-0.186	-0.334	-0.549	0.111	-0.038	-0.402	-0.370	0.340
E.C	-0.447	-0.306	-0.540	-0.494	-0.334	-0.311	-0.313	-0.212
Alkalinity	-0.444	-0.350	-0.608	-0.318	-0.292	-0.277	-0.453	-0.253
Sulphate	-0.413	0.287	0.567	-0.200	0.233	-0.073	-0.024	-0.260
Chloride	0.169	-0.167	-0.522	-0.664	-0.184	-0.090	-0.639	-0.016
Nitrate-N	-0.066	0.585	0.094	0.017	-0.097	-0.100	-0.389	0.278
NH4-N	-0.503	-0.320	-0.614	-0.294	-0.306	-0.230	-0.387	-0.188
TKN	-0.566	**0.904**	**-0.869**	-0.412	**-0.915**	-0.602	-0.665	0.009
Silica	0.649	-0.126	-0.252	-0.070	-0.284	-0.297	0.200	-0.274
DRP	-0.449	0.341	0.033	-0.467	-0.307	0.016	-0.270	-0.149
TOC	0.612	-0.171	-0.359	-0.598	-0.121	-0.046	-0.322	0.046
BOD	**0.900**	-0.264	-0.626	-0.575	-0.437	0.253	-0.299	-0.107
COD	**0.875**	-0.492	**-0.887**	**-0.913**	**-0.717**	-0.113	-0.374	0.322
BOD/COD	-0.084	0.468	**0.719**	**0.900**	0.433	0.282	0.576	0.261
Sodium	-0.218	-0.217	-0.527	-0.621	-0.202	-0.185	-0.558	-0.130
Potassium	-0.488	-0.229	-0.488	-0.564	-0.182	-0.228	-0.407	0.024
Calcium	0.267	-0.367	-0.313	0.035	-0.327	-0.552	0.190	-0.557
Magnesium	-0.362	-0.361	-0.468	-0.318	-0.204	-0.271	-0.024	-0.304
Boron	-0.501	-0.356	-0.552	0.441	-0.194	-0.218	-0.398	-0.193
Iron	0.326	0.009	0.027	-0.207	-0.113	0.355	-0.181	-0.022
Zinc	-0.445	0.545	0.491	-0.140	0.409	0.662	-0.246	0.565
Aluminium	**0.906**	**0.910**	**0.881**	0.692	**0.764**	**0.926**	**-0.733**	0.053
Chromium	**0.812**	0.520	**-0.851**	-0.516	-0.266	-0.140	**-0.702**	0.498
Manganese	**0.906**	**0.783**	**0.889**	-0.096	**0.901**	**-0.818**	0.665	-0.406
Cobalt	**0.825**	-0.458	**-0.860**	**-0.979**	**-0.807**	-0.496	**-0.873**	0.273
Nickel	0.550	-0.324	**-0.883**	**-0.881**	**-0.731**	-0.178	**-0.910**	0.446
Copper	-0.532	**0.902**	**0.845**	-0.509	0.359	**0.878**	-0.651	-0.163
Arsenic	**0.892**	-0.350	-0.139	**-0.885**	-0.121	0.356	-0.632	-0.051
Cadmium	-0.181	**-0.857**	**-0.789**	**-0.931**	**-0.899**	-0.153	**-0.794**	0.597
Lead	-0.143	-0.190	-0.537	**-0.882**	-0.245	0.513	-0.594	**0.913**

Table 4.4 (continued) Correlation coefficients (r) for rainfall amounts and leachate components at each landfill cell. (Bolded data indicate r> 0.7)

Landfill cell	*4b East*	*4b West*	*4c North*	*4c South*	*5a North*	*5a South*	*5b*	*6*
pH	-0.178	-0.028	0.191	0.250	-0.393	0.055	-0.084	0.077
E.C	-0.121	-0.252	0.174	-0.373	-0.255	0.181	-0.424	-0.281
Alkalinity	-0.281	-0.330	-0.317	-0.443	-0.270	0.100	-0.361	-0.263
Sulphate	0.131	0.613	-0.327	0.484	-0.325	0.020	0.015	0.064
Chloride	-0.068	-0.166	-0.195	-0.497	-0.268	-0.103	-0.314	-0.232
Nitrate-N	-0.150	-0.094	-0.076	-0.175	-0.039	0.190	0.103	-0.068
NH4-N	-0.180	-0.205	-0.251	-0.269	-0.256	0.221	-0.357	-0.190
TKN	-0.074	-0.092	-0.331	0.114	-0.595	-0.025	-0.071	-0.191
Silica	0.458	0.199	0.100	-0.362	-0.016	-0.072	0.237	0.032
DRP	-0.394	-0.341	-0.409	-0.282	-0.260	0.398	-0.292	-0.200
TOC	0.063	-0.185	-0.332	-0.409	-0.277	-0.351	-0.415	-0.272
BOD	0.522	-0.162	-0.123	-0.246	-0.471	**-0.848**	0.196	0.064
COD	0.334	0.074	-0.216	0.069	-0.494	0.086	0.167	-0.164
BOD/COD	0.137	0.338	0.332	-0.401	-0.416	**-0.861**	0.194	**0.720**
Sodium	-0.074	-0.147	-0.396	-0.538	-0.276	-0.124	-0.458	-0.358
Potassium	-0.126	-0.085	-0.151	-0.542	-0.264	-0.006	-0.342	-0.192
Calcium	0.001	-0.221	-0.166	0.264	-0.294	-0.145	0.047	0.051
Magnesium	0.088	-0.210	-0.066	-0.282	-0.184	-0.226	-0.369	-0.679
Boron	0.373	-0.048	-0.181	**-0.811**	-0.286	-0.230	-0.261	-0.272
Iron	0.058	0.259	0.680	**0.772**	0.050	-0.263	-0.133	0.092
Zinc	0.159	**0.715**	-0.409	-0.557	0.390	0.524	0.011	-0.567
Aluminium	0.534	-0.016	0.212	0.601	0.604	0.324	0.377	0.092
Chromium	0.280	0.145	-0.147	0.526	-0.600	0.166	0.648	0.011
Manganese	0.583	0.177	0.679	0.187	0.045	0.120	**0.908**	0.617
Cobalt	0.144	0.215	-0.105	-0.513	**-0.788**	0.325	-0.150	0.287
Nickel	0.182	0.120	-0.277	0.060	**-0.771**	-0.371	-0.138	-0.100
Copper	0.492	0.430	**0.884**	**0.882**	-0.688	**0.781**	0.445	-0.046
Arsenic	**0.743**	0.492	-0.006	-0.479	-0.600	-0.197	-0.211	0.187
Cadmium	-0.252	-0.185	**-0.740**	**-0.744**	-0.600	-0.319	**0.868**	-0.620
Lead	0.668	0.269	-0.147	**0.726**	-0.552	0.042	-0.370	-0.403

4.4 Discussion

4.4.1 Chemical composition of leachate

The chemical composition of the Horotiu landfill leachate is quite diverse. The difference between the maximum and minimum values of many parameters is huge. For example, electrical conductivity (EC) values ranges between 3 160 and 14 265 µS/cm and chloride (Cl) between 186 and 1 394 mg/l. The E.C range for the Horotiu leachate is comparable to 4 100 −10 500 µS/cm that was reported by Kylefors (2003) for a municipal landfill in Sweden. For the same landfill the Kylefors (2003) reported a Cl range of 1 390 − 4 195 mg/l which is higher than that of Horotiu. For a municipal landfill in Greece, Tatsi and Zouboulis (2002) reported higher concentration ranges for both E.C (23 000 – 35 500 µS/cm) and Cl (580 − 10 000 mg/l). Thus the E.C levels in the Horotiu leachate are not exceptional.

The pH values of the Horotiu leachate ranged between 6.5 and 9. This pH range is slightly alkaline. Alkaline leachates are indicative of final stages (methanogenic phase) of the biochemical reactions within a landfill (Fatta *et al.* 1999). A similar pH range, 6.6 to 7.5, was documented by Deng and Englehardt (2007) for leachates from several municipal landfills aged between 5 and 10 years. Horotiu's alkalinity range (1 454 – 7 555 mg/l) is wider than a reported range (2 130 − 3 255 mg/l) (Tatsi & Zouboulis 2002).

The concentration of leachate BOD at Horotiu ranged between 14 and 397 mg/l. This range was lower than 7782- 2670 mg/l reported by Castillo *et al.* (2007), for a municipal landfill in Columbia and 520-865 mg/l reported by Fatta *et al*. (1999) for the one in Greece. The COD concentration range (312-3 520 mg/l), was comparable to 781−3 203 mg/l reported by Nivala *et al*. (2007) for a municipal landfill in the US. Similar observation was made for the leachate TOC range of 114−1212 mg/l which is akin to the range of 250 − 1040 mg/l for a municipal waste landfill reported by Fan *et al.* (2006).

The BOD/COD ratio at Horotiu was between 0.05 and 0.26. The ratio is related to the age of the landfill. According to El-Fadel *et al.* (2002) BOD/COD ratio below 0.1 indicates an old stable landfill whereas the range 0.1 − 0.5 points to a moderately stable landfill. Using the El-Fadel *et al.* (2002) notion, most of the landfill stages (1, 2A, 2B, 3A, 3B, 3C, 4B east, 4B west, 4C north, 4C south, 5A and 5B) are old and stable as they had BOD/COD ratio of less than 0.1 for most of the sampling period. Few stages (4A east, 4A west, and 6) had higher BOD/COD ratio: between 0.1 and 0.5 during the monitoring period and thus, are in the moderate stage of decomposition. The scenario concurs with the relative ages of the stages in Horotiu.

The heavy metal (boron, chromium, cobalt nickel, copper, arsenic, cadmium and lead) concentrations in leachate at Horotiu were low, compared to other parameters and were generally below 1 mg/l. The concentrations of heavy metals were similar to those reported in literature (Fan *et al.* 2006; Fatta *et al.* 1999). Low (less than 1 mg/l) concentrations of heavy metals in leachate are typical for municipal sanitary landfills, probably because of relatively high pH which decrease their solubility.

4.4.2 Variations in leachate quality

Leachate pH from older stages: 1, 2A, 2B, 3A, 3B, 3C, 5A and 5B at the Horotiu landfill did not exhibit a ‘common’ trend, often reported in the literature, which is marked by an acidic phase followed by an alkaline phase. Leachate pH has been reported to increase with age of landfill (Chen 1996; El-Fadel *et al.* 2002). Leachate pH at Horotiu was fairly stable and ranged between 6 and 9 during the 10-year monitoring period. Similarly, after analysing 12 years of data leachate quality from a lined municipal landfill in the US, Statom *et al.* (2004) also did not observe any significant temporal changes in leachate pH. However, at Horotiu minor increases in pH were observed in recently constructed stages (4A, 4B and 4C, and 6) which are still in the early phases of decomposition.

Landfill cells at Horotiu exhibit decreasing, increasing or steady trends in concentrations of various leachate parameters such as: organic contents, major ions, heavy metals and inorganic components. Literature (El-Fadel *et al.* 2002; Kjeldsen *et al.* 2002; Statom *et al.* 2004) has shown that in the initial phases of waste decomposition, leachate is normally acidic and so it is high in solubility of components such as metals, therefore making it more loaded with chemical constituents. At later phases leachate becomes alkaline and solubility of metals decreases (Kjeldsen *et al.* 2002).

Older landfill stages (1, 2A, 2B, 3A, 3B, 3C, 5A and 5B) at Horotiu generally demonstrated decreasing trends in the concentrations of major cations, alkalinity, organic content and heavy metals. This could be explained by the fact that these stages are in a stabilized phases of the landfill life. On the other hand, the newer stages had either increasing or steady trends in concentration of various parameters because they are still in the initial phase of decomposition.

Concentration of anions (sulphate, chloride and nitrates) in leachate had short-term temporal fluctuations, with great variability and there were no major long-term trends observed for most parts of the landfill. These fluctuations could have been caused by rainfall events or could be an analytical error.

Decreases in concentrations of leachate may continue for many years to very low levels. El-Fadel *et al.* (2002) showed that BOD can decrease from 10 000 to <50 mg/l and COD from 15 000 to < 1 000 mg/l, over a period of 20 years.

Changes of leachate quality with rainfall amounts cannot be generalised with a good degree of confidence. Various leachate components showed different relationships with rainfall amounts. Though most leachate parameters (including: Cobalt, Nickel, Cadmium, EC, COD and alkalinity) correlated negatively with rainfall, suggesting dilution effects, others (including: aluminium, iron and manganese) correlated positively. The scenario of contradicting responses of leachate constituents to rainfall amounts observed in Horotiu is similar to that reported by Johnson *et al*. (1999), who suggested that while rainfall had a diluting effect to some leachate parameters, it had led to an increase in some (e.g. aluminium, copper and chromium) possibly by mobilising them as it moves down through the landfill material . However, there may also be other factors and chemical reactions involved other than the physical impact of rainwater. Intrusion of Waikato river water into the landfill might also have had an impact on the quality of leachate.

All the landfill stages at Horotiu have been capped to reduce the infiltration rate of rainwater. However, the impact of capping on the quality of leachate could not be established. Capping of old landfill stages (1, 2A, 2B, 3B, 3C and 5A) was done in 1988 and 1995, prior to the commencement of leachate monitoring, while younger sites (4A, 4B, 4C, 5B and 6) were capped in 2007. Stage 3A was capped in 2001 but there was no observable difference in leachate quality before and after capping. A more obvious effect of landfill capping may be on the reduction in the amount leachate produced because of reduced infiltration of precipitation (Hudgins & Harper 1999).

4.4.3 Summary

Leachate from the Horotiu landfill had been monitored from 1997 to 2006. Monitoring data showed that Horotiu leachate had the characteristics of a typical municipal waste landfill. Younger landfill sites at Horotiu had relatively higher and increasing leachate concentrations compared to the older parts of the landfill. This is a common scenario because the load of leachate decreases with time as the waste becomes stable. Chemical constituents, such as EC, chloride, BOD and alkalinity, present in the Horotiu leachate were in lower concentrations than those reported for other countries.

Heavy metals in leachate were in low concentrations (less than 1 mg/l) and did not show significant variation with pH. Leachate had a small pH range (6.5-9). Heavy metal concentration would be expected to increase as the pH decreases.

The impact of rainfall amount on the concentration of various leachate constituents was inconclusive. There was a negative correlation between concentrations of cobalt, nickel, chloride and cadmium and rainfall amounts. Negative correlations would be expected because of the diluting effect of rainwater. However, aluminium, manganese, iron and zinc correlated positively with rainfall amounts.

Chapter 5

Horotiu Landfill Groundwater Chemistry

5.1 Introduction

The Horotiu landfill was originally equipped with a groundwater monitoring network consisting of 53 boreholes. Some of the boreholes may have either been destroyed during construction works or experienced some form of physical failure, with the effect that only 36 were comprehensively monitored.

The boreholes were constructed at varying times and locations and are of different depths (Table 5.1, Figure 5.1). The groundwater monitoring network was installed with the intention to detect and observe any impact the landfill has on the groundwater in the vicinity and underlying the landfill. Boreholes were monitored for both groundwater quality and groundwater depth. Some of the boreholes were placed to intercept groundwater which is not influenced by the landfill and they are located on the upstream side of the landfill.

Table 5.1 Details of the groundwater monitoring boreholes at Horotiu landfill.

Borehole ID	*Date of construction*	*Monitored Period*		*Depth of borehole (m)*	*Adjacent Landfill stage**
		Start	Complete		
GW1	Nov-90	1991	2006	-	1
GW2	Nov-90	1991	2006	-	1
GW3	Nov-90	1991	2006	8.7	2A
GW4	Nov-90	1991	2006	8.2	2B
GW5	Nov-90	1992	2006	7.5	5B
GW6	Apr-92	1992	2006	5.82	5A
GW7	May-92	1992	2006	7.5	5A
GW8	Oct-95	1995	2006	8.65	5B
GW9	Oct-95	1995	2006	18.3	Upstream
GW10	Sep-95	1995	2006	19	Upstream
GW11	Sep-95	1995	2002	-	-
GW13	-	1995	1996	-	4A
GW14A	Sep-96	1996	2002	16.01	Upstream
GW14B	Jun-97	2000	2006	5.5	Upstream
GW15	Oct-96	1996	2002	21.1	4A
GW16	Oct-96	1997	2006	6.4	4A
GW17	Oct-96	1996	2006	6	Upstream
GW18	Oct-96	1996	2006	18.58	4A
GW21A	Jun-97	1997	2002	20.2	4B
GW21B	Jun-97	1997	2002	7.5	4B
GW22	Jun-97	1998	2006	6.32	6
GW23	Jun-97	1997	2006	14	6
GW24	Jul-97	1997	2006	14.55	6
GW25A	Jul-97	1997	2002	13	Upstream
GW25B	Jul-97	1997	2006	9	Upstream
GW26	Jul-97	1997	2006	12.35	5A
GW27	-	1998	2000	-	
GW30A	May-98	1998	2006	14.9	6
GW30B	May-98	2000	2006	6.8	6
GW31A	May-98	1999	2006	15.35	6
GW31B	May-98	2000	2006	7	6
GW32	May-98	1999	2002	15.55	6
GW40	Apr-99	1999	2006	15	4B
GW41	Apr-99	1999	2006	15	4B
GW42	Apr-99	1999	2006	9.42	4B
GW43	Apr-99	1999	2006	9.05	4A

*Boreholes are located outside the adjacent cells.

A and B are paired boreholes at different depths; Upstream refers to a borehole position up-hill of the landfill assumed to be intercepting background groundwater.

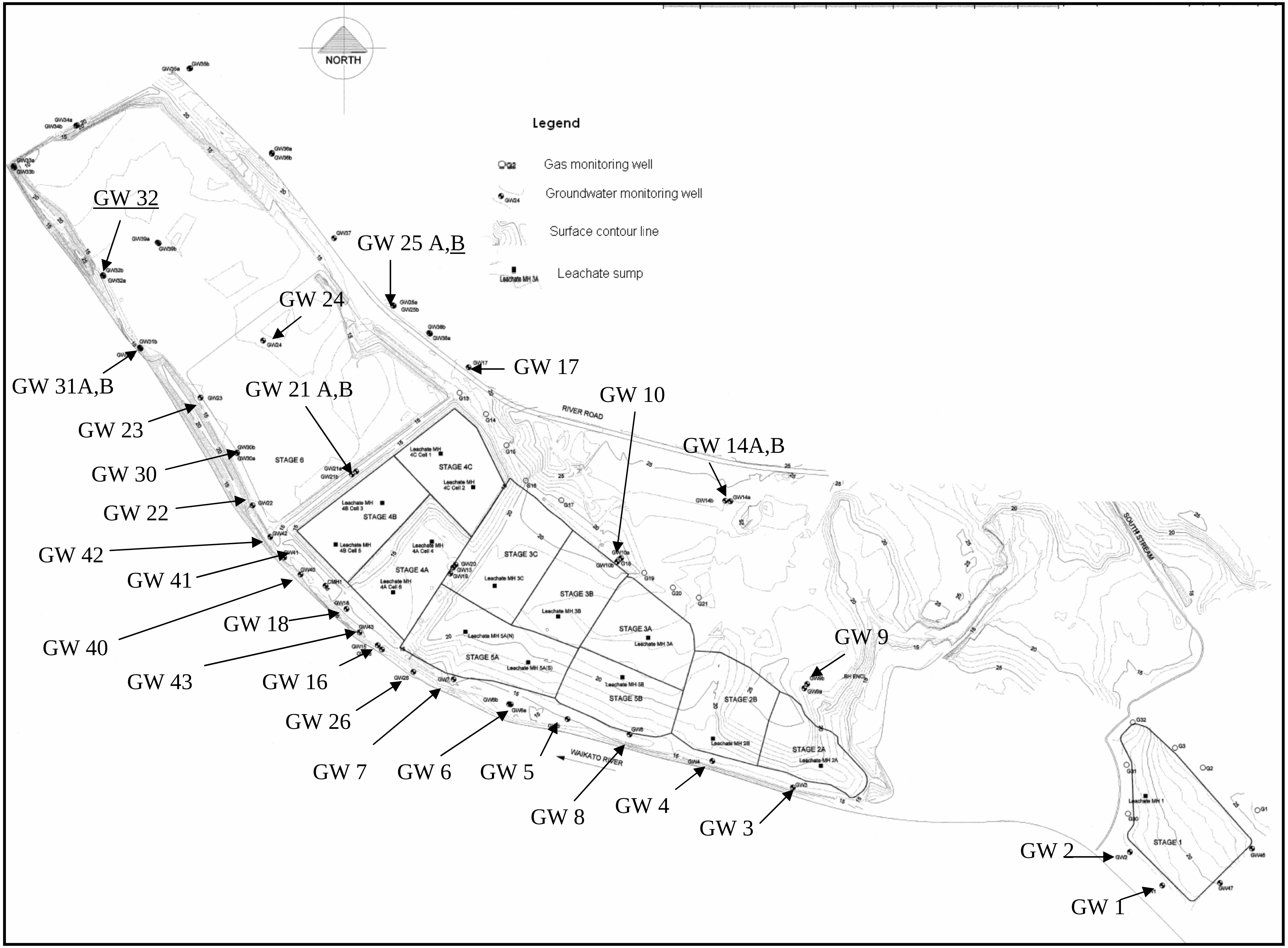


Figure 5.1. Map of the Horotiu landfill showing positions of the boreholes. (Modified from a diagram supplied by HCC)

5.2 Groundwater Chemical composition

Groundwater samples were collected at Horotiu landfill from 1991 to 2006 and analysed for chemical parameters including: electrical conductivity, pH, major anions, major cations, heavy metals and organic content. Table 5.2a presents a descriptive statistical summary (average values) of the chemical analyses for groundwater from upstream boreholes and Table 5.2b for downstream boreholes, from 1991 to 2006, together with drinking water standards. Chemistry data for individual boreholes is included in Appendix 3.

The average groundwater quality at the Horotiu landfill had low average concentrations for most of the chemical parameters (Tables 5.2a and 5.2b). Groundwater at the upstream side generally had lower concentrations of chemical parameters compared to the downstream boreholes, with the exception of heavy metals and pH, which are comparable in both parts of the landfill. A large difference in upstream and downstream borehole water quality was observed for parameters such as EC, alkalinity, chloride, ammoniacal-N and iron, where the downstream concentration are as much as three times the upstream water quality. On the other hand, upstream groundwater had significantly ($P<0.01$) higher mean amounts of sulphates (24 mg/l) than the downstream groundwater (9.1 mg/l). Similarly, the average nitrate content was significantly ($P<0.01$) higher in the upstream (3.6 mg/l) than in the downstream (0.9 mg/l) boreholes. Reactive phosphorus was also higher in the upstream boreholes, but not significantly ($P=0.35$) (Tables 5.2a and 5.2b).

For the upstream boreholes the average groundwater concentrations of all parameters, except pH, iron, lead and manganese, are within both New Zealand and European Union standards for drinking water (Table 5.2a). Chemical constituents exceeding the drinking water standards are shown in bold fonts in Tables 5.2a and 5.2b.

Table 5.2a Upstream groundwater quality at Horotiu landfill and drinking water standards. All values are in mg/l except pH and electrical conductivity (µS/cm). (-) represents unavailable or unset values. Values in bold fonts are outside drinking water standards.

	Horotiu groundwater quality*				**Drinking water standards**	
Parameter	*Average*	*Median*	*Min*	*Max*	*NZ*[1]	*EU*[2]
Electrical Conductivity	268	212	113	569	-	2500
pH	**6.2**	**6.3**	**6.0**	**6.3**	-	6.5-9.5
Alkalinity	66	32	19	228	-	-
Chloride	20.5	22.0	15.3	26.1	-	250
Ammoniacal-N	0.11	0.09	0.03	0.32	-	1
Nitrate N	3.61#	4.24	1.04	5.63	50	50
Reactive P	0.071#	0.050	0.018	0.237	-	-
Sulphate	23.7#	25.7	6.9	39.4	-	250
Boron	0.03	0.02	0.01	0.06	-	-
Calcium	15.8	12.4	4.2	36.7	-	-
Potassium	6.7	7.0	2.6	11.0	-	-
Magnesium	7.7	6.3	1.7	21.0	-	-
Sodium	19.2	16.0	12.8	34.6	-	200
Reactive Si	58.1	58.8	30.7	78.6	-	-
Zinc	0.04	0.03	0.01	0.10	-	-
Iron	**7.1**	**1.2**	0.2	**26.2**	-	0.2
Aluminium	0.08	0.07	0.02	0.14	-	-
Arsenic	0.0012	0.0012	0.0010	0.0014	-	0.01
Cadmium	0.0003	0.0003	0.0001	0.0005	-	0.005
Chromium	0.0010	0.0009	0.0004	0.0019	-	0.05
Cobalt	0.0040	0.0008	0.0002	0.0210	-	-
Copper	0.0028	0.0011	0.0007	0.0115	2.0	2.0
lead	**0.040**	**0.020**	0.0002	**0.144**	0.01	0.01
Manganese	**0.44**	**0.06**	0.005	**2.19**	0.4	0.05
Mercury	-	-	-	-	-	-
Molybdenum	-	-	-	-	-	-
Nickel	0.005	0.003	0.0003	0.019	0.02	0.02
Selenium	-	-	-	-	0.01	0.01
Strontium	-	-	-	-	-	-
Tin	-	-	-	-	-	-

Sources: [1] Ministry of Health (2005); [2] Lenntech (2006)

* Data analysed for boreholes: Gw9, Gw10, Gw14A, Gw14B, Gw17, Gw25A and Gw25B.

Values significantly higher in the upstream than in the downstream boreholes.

Table 5.2b Downstream groundwater quality at Horotiu landfill and drinking water standards. All values are in mg/l except pH and electrical conductivity (µS/cm). (-) represents unavailable or unset values. Values in bold fonts are outside drinking water standards.

	Horotiu groundwater quality*				**Drinking water standards**	
Parameter	*Average*	*Median*	*Min*	*Max*	*NZ*[1]	*EU*[2]
Electrical Conductivity	756	781	163	**3074**	-	2500
pH	6.5	6.5	**6.3**	6.7	-	6.5-9.5
Alkalinity	254	252	35	727	-	-
Chloride	85.4	55.9	16.8	**615.6**	-	250
Ammoniacal-N	**5.39**	0.58	0.01	**44.94**	-	1
Nitrate N	0.90	0.14	0.03	5.47	50	50
Reactive P	0.041	0.034	0.014	0.106	-	-
Sulphate	9.1	8.8	1.1	25.1	-	250
Boron	0.32	0.17	0.09	1.54	-	-
Calcium	42.1	34.7	6.3	91.4	-	-
Potassium	15.1	13.5	6.0	56.6	-	-
Magnesium	20.1	15.6	3.5	51.2	-	-
Sodium	59.7	38.1	16.0	**447.8**	-	200
Reactive Si	54.1	54.9	23.2	67.8	-	-
Zinc	0.03	0.02	0.01	0.11	-	-
Iron	**41.6**	**21.3**	0.1	**166.1**	-	0.2
Aluminium	5.4	2.7	0.0	23.2	-	-
Arsenic	**0.0968**	0.0200	0.0044	**0.2700**	-	0.01
Cadmium	**0.0107**	**0.0100**	0.0001	**0.0400**	-	0.005
Chromium	0.0050	0.0011	0.00010	0.0205	-	0.05
Cobalt	0.0115	0.0081	0.0009	0.0285	-	-
Copper	0.0163	0.0029	0.0007	0.0603	2.0	2.0
lead	**0.045**	**0.043**	0.0001	**0.157**	0.01	0.01
Manganese	**2.85**	**2.03**	0.04	**16.89**	0.4	0.05
Mercury	0.004	0.001	0.001	0.018	-	-
Molybdenum	0.014	0.01	0.01	0.04	-	-
Nickel	0.006	0.006	0.0005	0.016	0.02	0.02
Selenium	**0.137**	**0.2**	**0.02**	**0.3**	0.01	0.01
Strontium	0.36	0.26	0.15	0.78	-	-
Tin	0.028	0.02	0.02	0.07	-	-

Sources: [1] Ministry of Health (2005); [2] Lenntech (2006)

* Data analysed for boreholes: Gw1, Gw2, Gw3, Gw4, Gw5, Gw6, Gw7, Gw8, Gw11, Gw15, Gw16, Gw18, Gw21, Gw22, Gw23, Gw24, Gw26, Gw27, Gw30, Gw40, Gw41, Gw42 and Gw43.

The water quality from both sides of the landfill showed similar chemical composition (Figure 5.2). The proportional distribution of major ions is the same and the groundwater upstream and downstream of the landfill is dominated by bicarbonates-carbonate and sodium-potassium. The groundwater on both sides of the landfill was of the hydrogeological water type: Na-HCO_3.

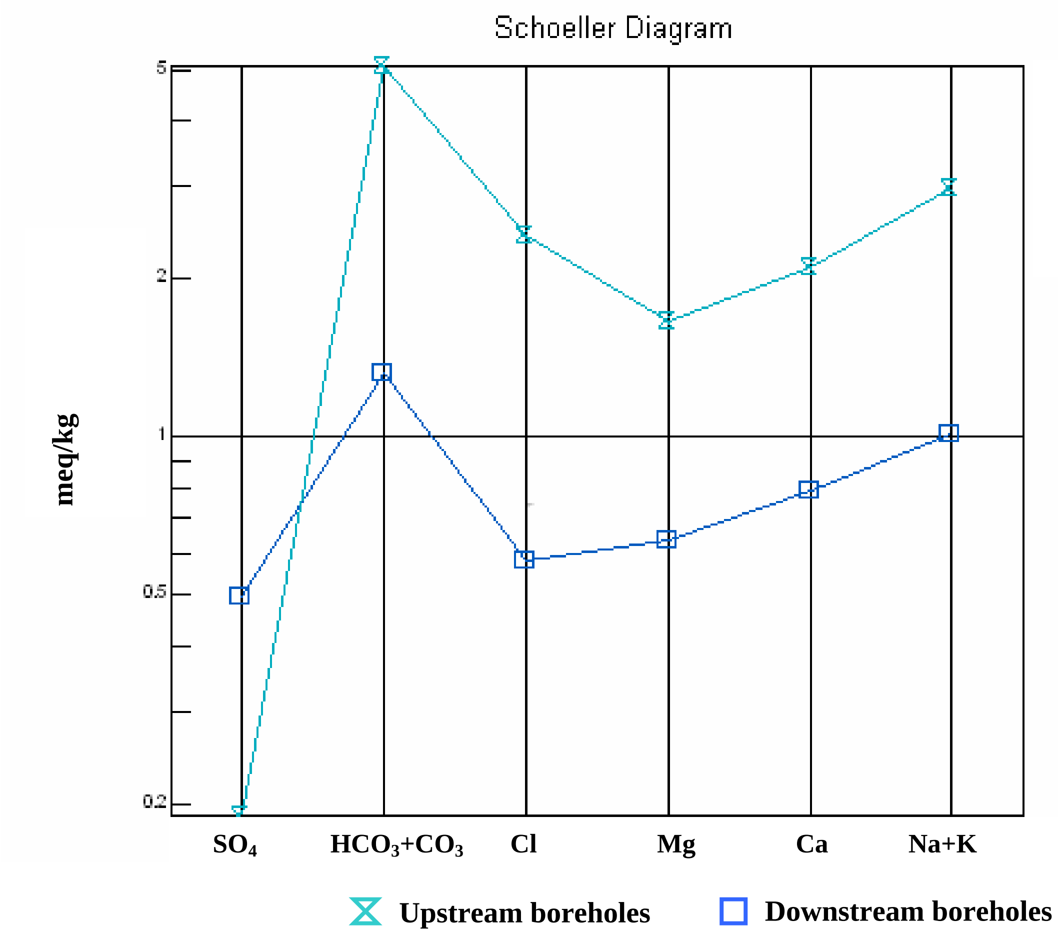


Figure 5.2 Major ions for average upstream and downstream boreholes at Horotiu landfill.

5.3 Spatial Variations

Concentration of chlorides in groundwater and the value of electrical conductivity are normally used as indicators or tracers for contamination. Median concentrations of chlorides and electrical conductivity for each borehole indicate that water quality is diverse within the vicinity of the landfill (Figure 5.3). Values in Figure 5.3 are median values of the concentrations of groundwater samples collected at three month intervals over the sampling period (1991- 2006). Boreholes in green code are on the upstream side of the landfill.

Some boreholes show higher values for both chloride concentration and electrical conductivity. Borehole GW 13 is the most loaded, with E.C over 2000 μS/cm and chloride up to 300 mg/l. It is followed by borehole GW 16, GW 26, GW 27 and GW 43 which have EC values above 1000 μS/cm and chlorides over 100 mg/l. Both E.C and chloride are below the drinking water standards for the boreholes except for chloride in GW 13 which exceeds both the European Union and New Zealand drinking water standards (Figure 5.3).

A few boreholes (e.g. GW 14A, GW14B, GW17, GW 25A, GW 25B) had relatively low values for both EC and chlorides (Figure 5.3). These boreholes are on the upstream side of the landfill and are presumed to not be influenced by landfill leachate. However, one of the upstream boreholes (GW 9) has concentration values higher than some of the downstream boreholes (Figures 5.3 and 5.4). There are also boreholes on the downstream side (e.g. Gw 21A, Gw 21B, Gw 22, Gw 23, Gw 24 and Gw 31B) with low EC. These boreholes may have had low amounts of EC because they are near to newly constructed parts of the landfill (stages 4B and 6) which have an extra HDPE lining on the base and sides.

It is evident (Figure 5.3) that there is a strong correlation between EC values and chloride concentration for all the boreholes. This correlation is statistically significant (P = 0.0002). E.C can then be mathematically expressed in terms of chloride concentration, for the entire groundwater domain at the Horotiu landfill, by the following equation:

$$EC\ (\mu S/cm) = 6.76 * Cl + 194.83\ (R^2 = 0.82)$$

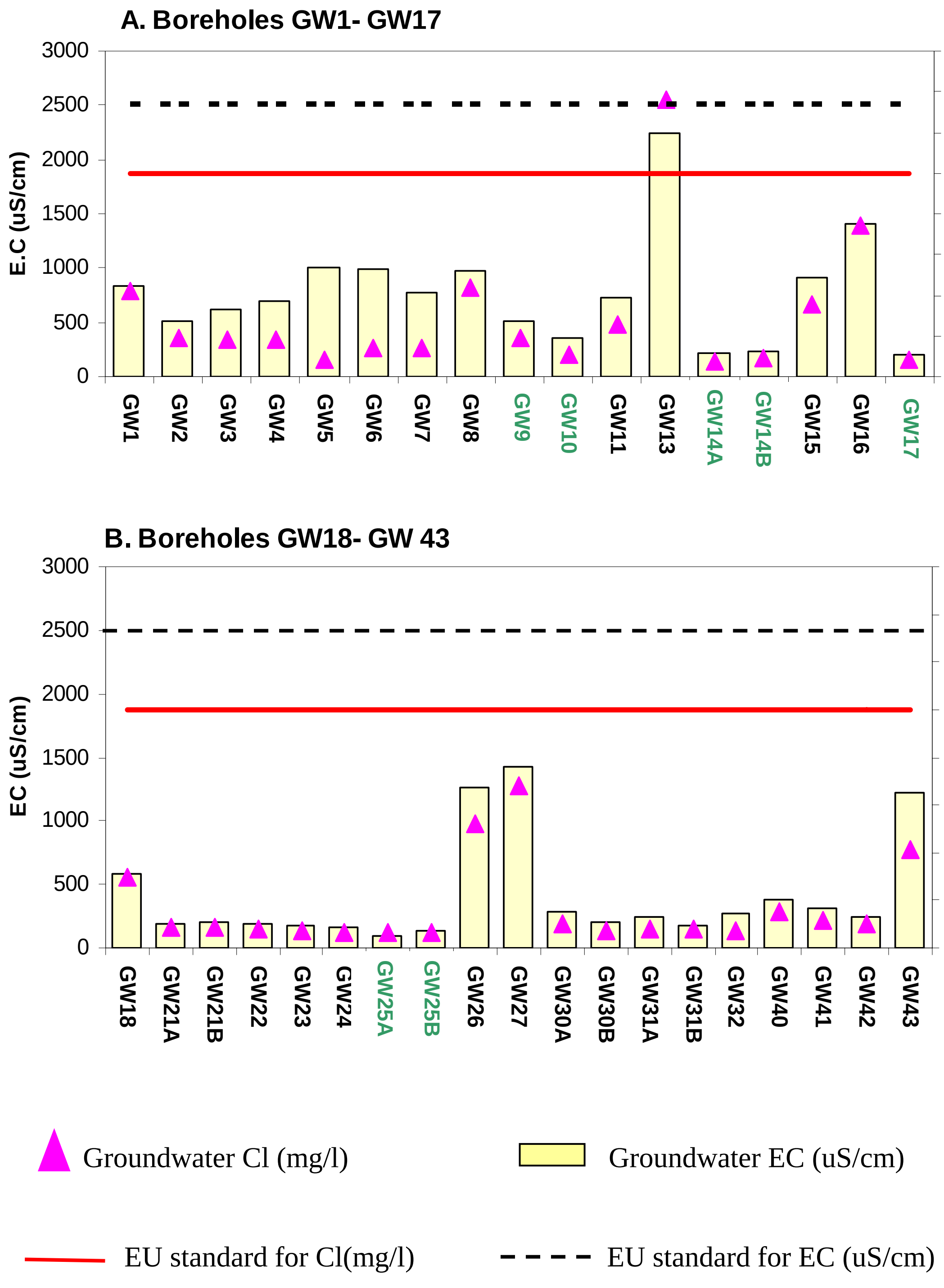


Figure 5.3 Average groundwater chloride and electrical conductivity for boreholes at Horotiu landfill. Horizontal lines represent European Union (E.U) drinking water standards. Green labels are for upstream boreholes.

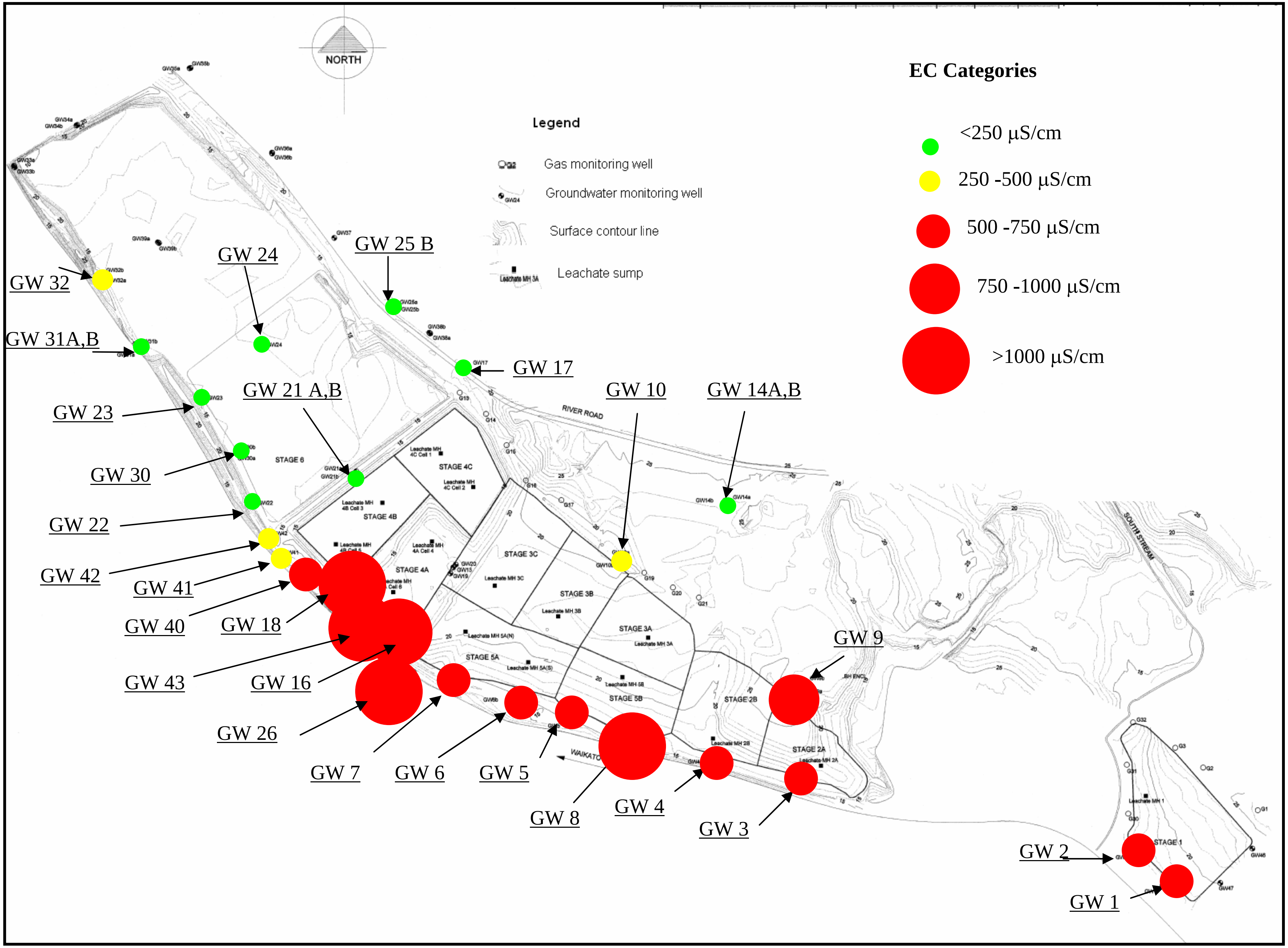


Figure 5.4 Map showing average EC values for groundwater in boreholes at the Horotiu landfill (Modified from a diagram supplied by HCC).

5.4 Temporal Variations

Changes in the quality of groundwater in the vicinity of the landfill may reflect the activities and changes in the operations on the landfill. Electrical conductivity (EC) is used as an indicator of general quality of groundwater. Figures 5.5-5.9 present trends in the groundwater EC for boreholes in the vicinity of the Horotiu landfill.

Linear and non-linear regression analyses were carried out to establish the best fit for the variation of the EC values with time. Boreholes fitted with linear models, had slopes of varying magnitudes and directions. Magnitudes of the slopes reflect a changing influence of leachate percolation in groundwater.

The boreholes with linear trends were grouped according to the magnitude of their slopes. Only two boreholes, Gw9 and Gw18, had the highest slope magnitude of EC range, 0.1 to 1µS/cm/yr (Figure 5.5). These are the boreholes which have been influenced the most by leachate percolation.

The majority of boreholes had a consistent EC values and had minor increase/ decrease ranging, from 0.001 to 0.1µS/cm/yr (Figure 5.6). Some boreholes showed an upward trend followed by a downward trend, which fits a quadratic trend (Figure 5.7). This scenario may represent a recovery in groundwater quality from leachate contamination. The scenario implies that the groundwater at these locations may have been contaminated by leachate in the past, but was then beginning to be diluted with relatively ‘clean’ incoming water. The boreholes also showed short term trends of highs and lows which appear to be seasonal.

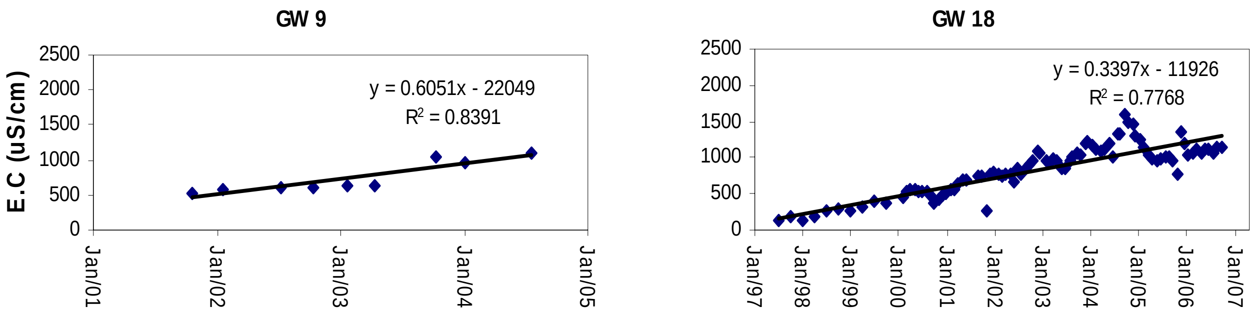


Figure 5.5 Boreholes at Horotiu landfill with rapidly increasing groundwater EC trends.

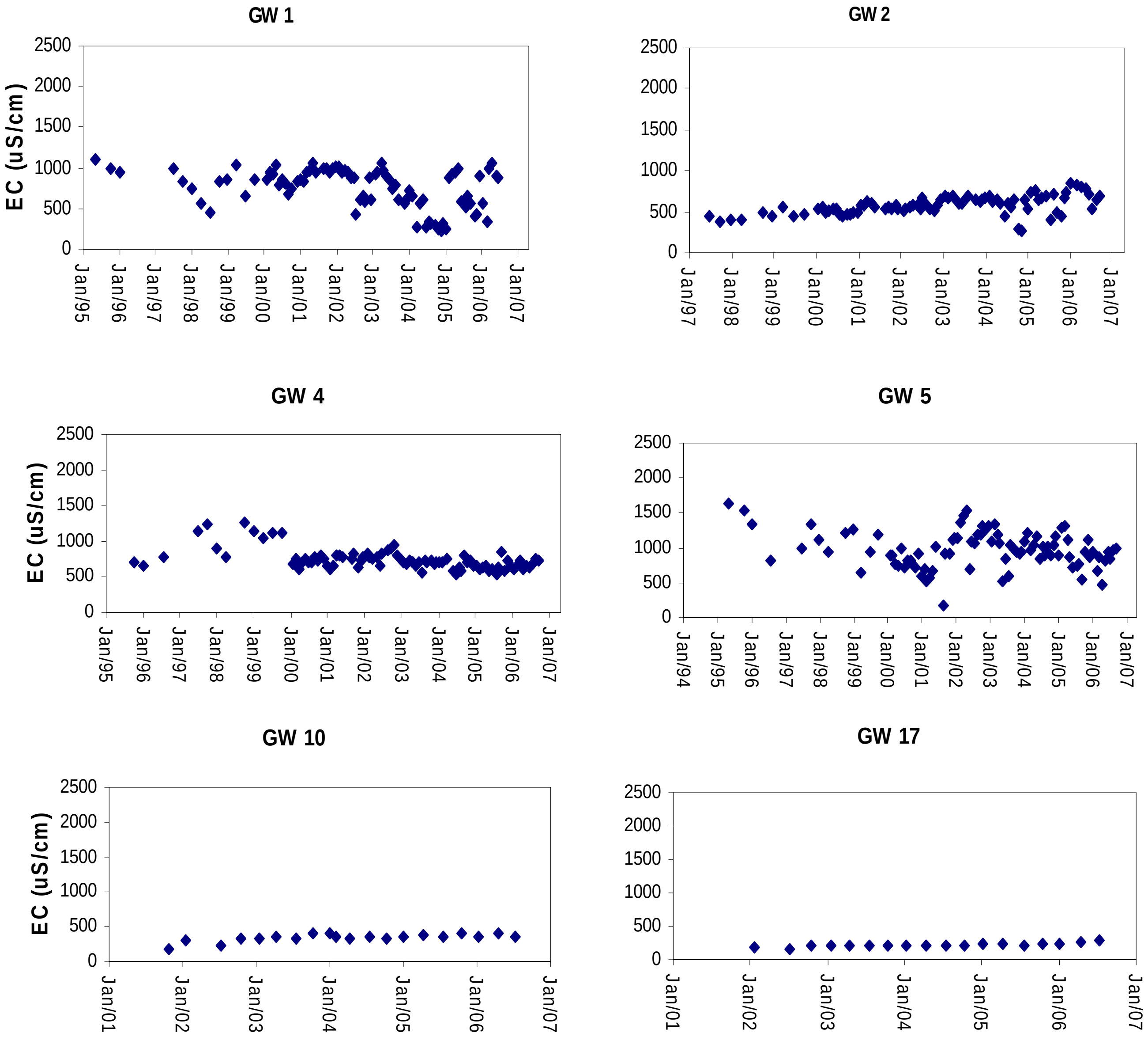


Figure 5.6 Boreholes at Horotiu landfill that showed a consistent EC.

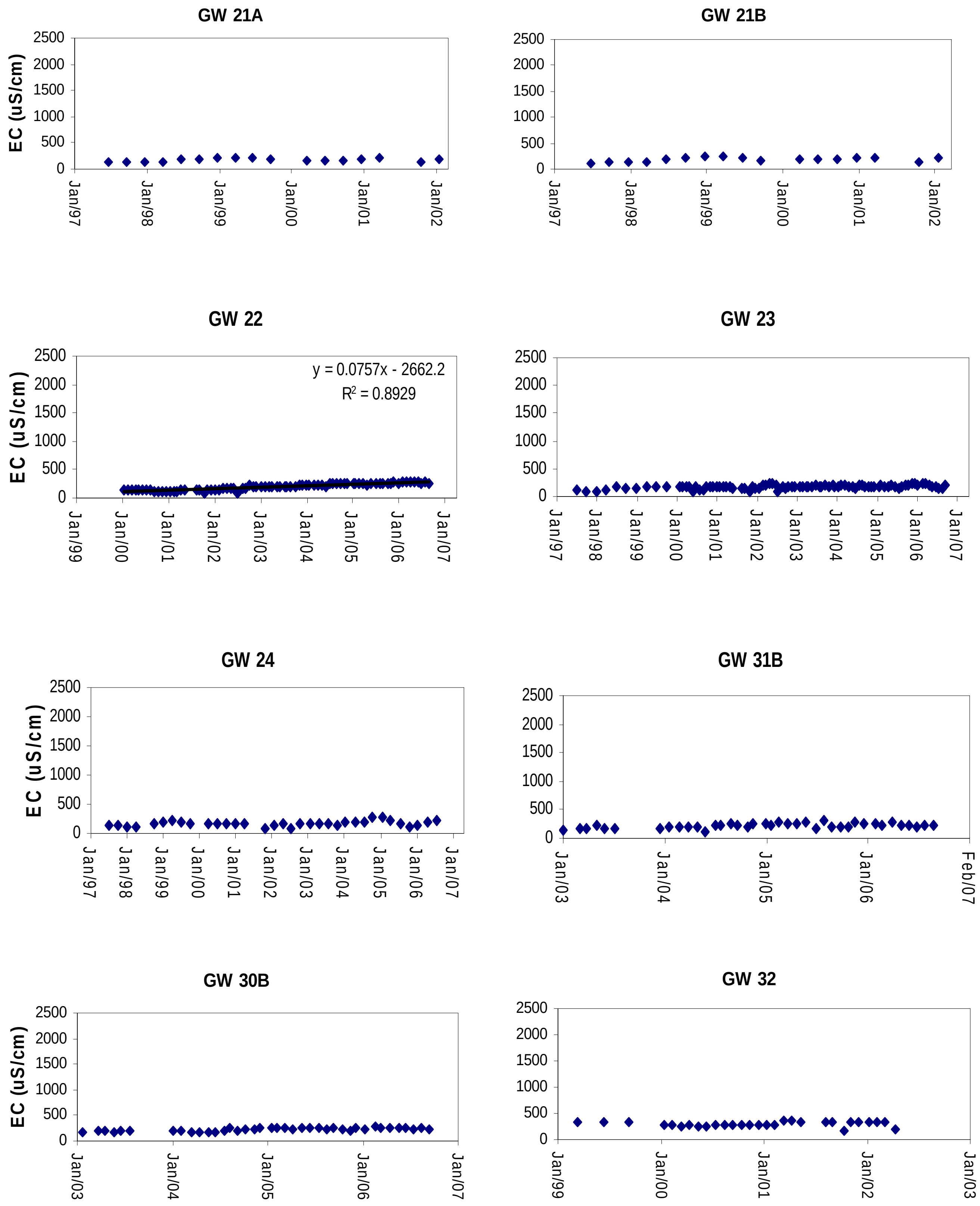


Figure 5.6 (continued) Boreholes at Horotiu landfill that showed a consistent EC.

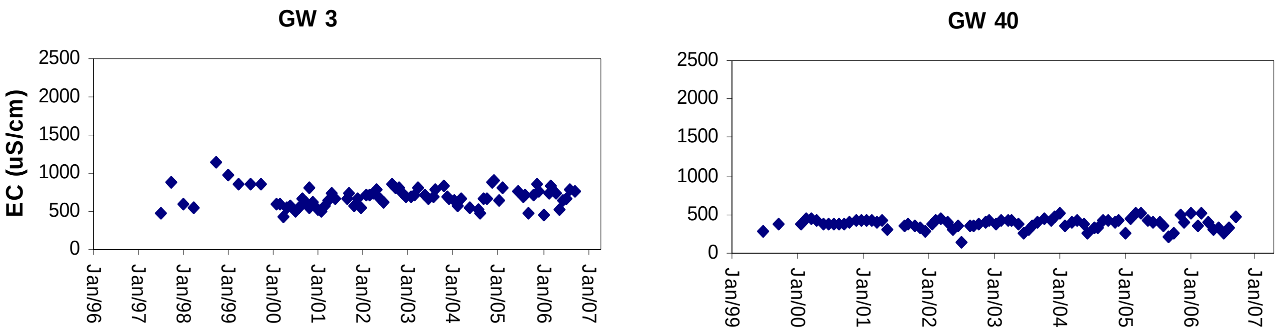


Figure 5.6 (continued) Boreholes at Horotiu landfill that showed a consistent EC.

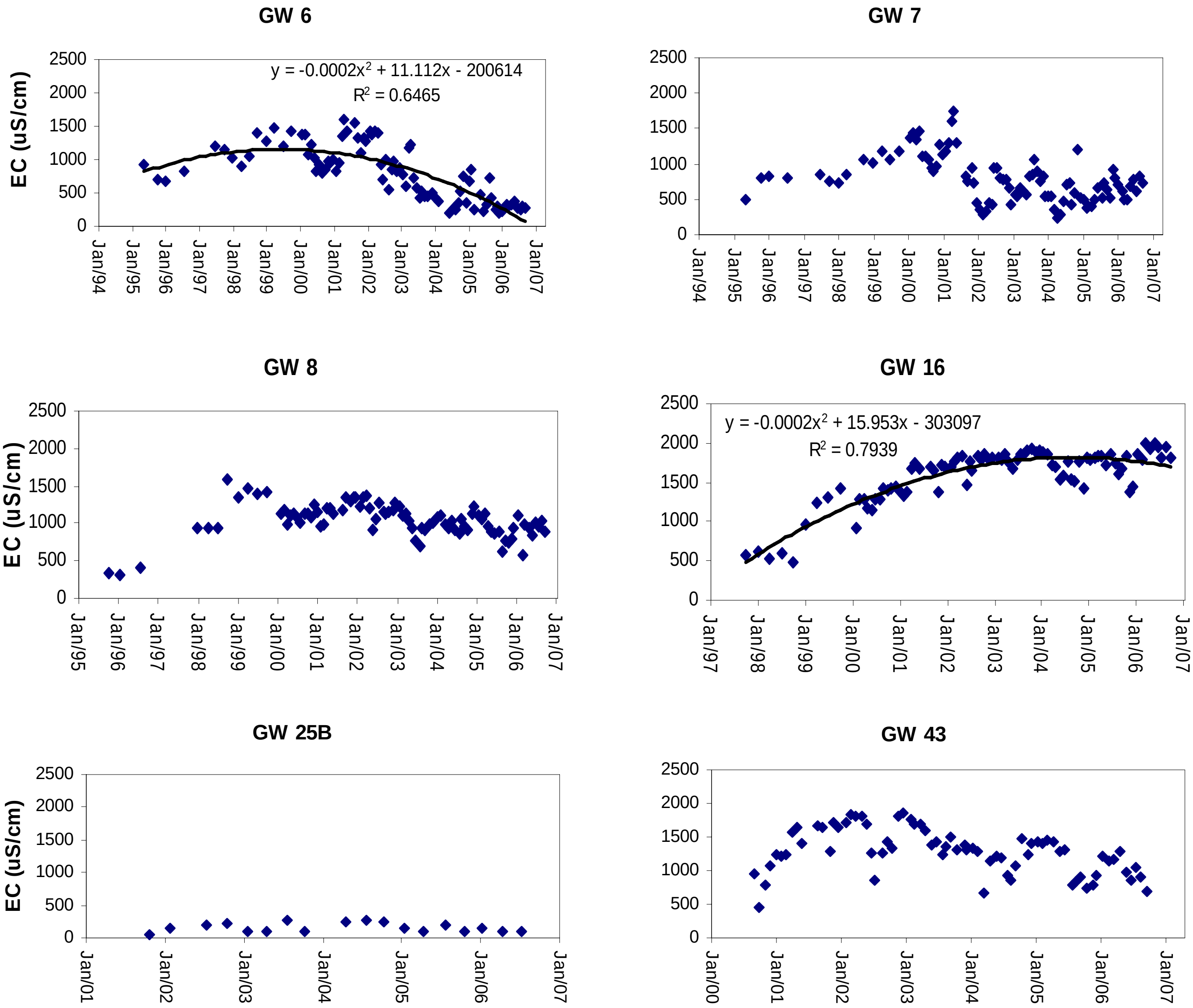


Figure 5.7 Boreholes at Horotiu landfill with quadratic groundwater EC trend.

Trend shown by Gw26 (Figure 5.8) does not fit either a linear or a quadratic trend. It is best defined by a sinusoidal type of trend, with a several highs and lows, repeating almost every two years.

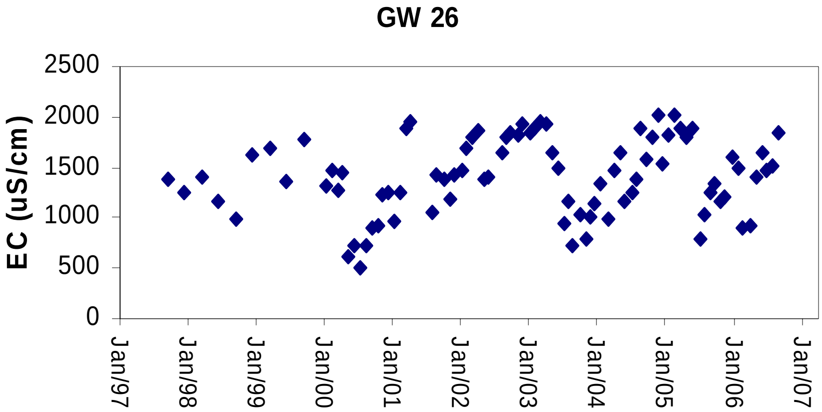


Figure 5.8 Boreholes at Horotiu landfill with polynomial groundwater EC trend.

Long-term trends in groundwater EC can be explained in terms of continuous infiltration of leachate into the groundwater domain. The long-term trends give an indication of whether groundwater quality is improving or declining, while short term fluctuations may indicate changes in activities in the landfills, such as temporary overflow of leachate and events such as rainfall and groundwater recharge/ influx.

Short and long term trends in groundwater EC can be identified from boreholes located at various positions relative the landfill. Boreholes located on the upstream side of the landfill, GW9, GW10, GW14B, GW17 and GW25B exhibit minor short and long term variations with regard to the EC levels. Amongst the upstream boreholes, GW 9 had the highest value of EC, above 500 µS/cm, while GW 14B had the lowest of less than 300 µS/cm. On the other hand, most boreholes on the downstream side showed a lot of short-term fluctuations in water quality, with relatively higher values of EC. Boreholes GW6, GW7, GW8, GW26, GW43 and GW16 had highest values of EC, (> 1500 µS/cm).

Figure 5.9 shows that boreholes (Gw1, Gw4, Gw5, Gw6, Gw7, Gw8 and Gw26) with improving water quality i.e. those with decreasing EC trends are located at the south and south western parts of the landfill. These parts of the landfill consist of relatively old stages: 1, 2B, 4A, 5A and 5B.

Boreholes located at various other part of the landfill sites had rising EC level, seemingly indicating the influence of leachate on groundwater quality. It is evident (Figure 5.9) that boreholes Gw 17, Gw 10 and Gw 9 on the upstream side of the landfill, which were assumed to not be influenced by leachate percolation, are in fact showing rising trend of electric conductivity. This could imply that leachate is affecting these boreholes.

There are some boreholes which are located at the downstream side of the landfill but which showed characteristics similar to those located upstream of the landfill. These boreholes GW42, GW32 and GW30B had low E.C values and had only minor short-term fluctuations.

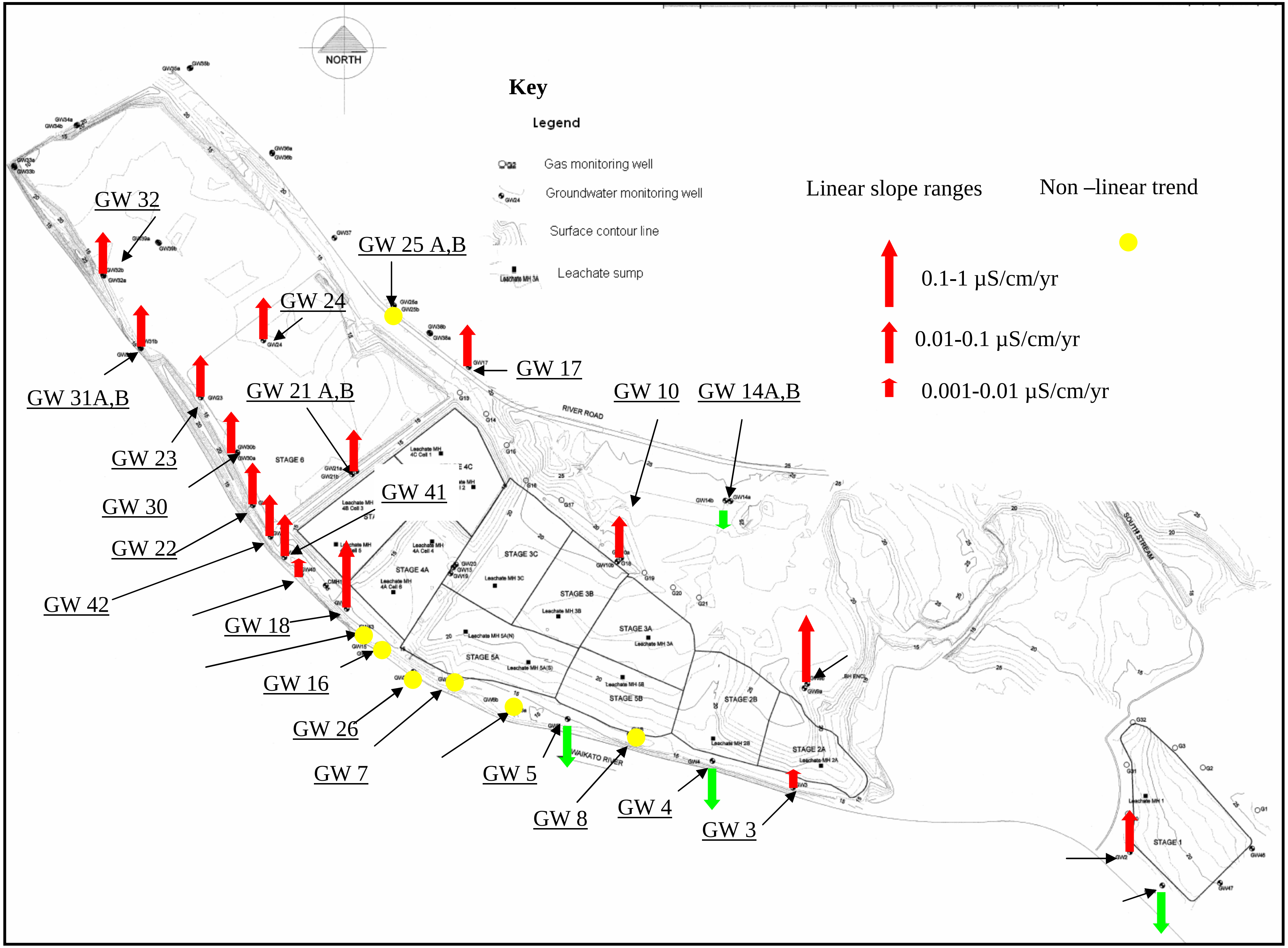


Figure 5.9 Trends of groundwater electrical conductivity. Downwards arrows represent decreasing E .C. trends (Modified from the diagram supplied by HCC).

5.5 Variation of groundwater quality with borehole water level

Short term changes in groundwater quality may be related to, among other factors, fluctuations in groundwater levels. To investigate the possible links between groundwater quality and level, time series graphs for groundwater EC and levels were plotted together (Figure 5.10). Full record of groundwater level monitoring is shown in Appendix 4.

It is observed that some boreholes (e.g. Gw1, Gw6, Gw16, Gw22, Gw23 and Gw43) had EC peaks corresponding with water level troughs on the time series plots of groundwater level and EC (Figure 5.10). High groundwater levels were apparently associating with low concentrations of EC. This relation indicates that there is a possibility of dilution effect emanating from outside the boundaries of the landfill, possibly the Waikato River or rainfall or both.

Some boreholes showed positive linear correlations (r) between groundwater levels and EC values. However, there are also some boreholes (Gw5, Gw7, Gw17, Gw18, Gw22, and Gw25B) which had negative correlation for groundwater level and groundwater EC. Linear correlation values (r) for most boreholes were less than 0.5 (Figure 5.10). This gives an indication that the relationship between the two variables is not necessarily linear. On the other hand, there are some boreholes which do not exhibit any association between groundwater level and EC, for example Gw17 (close to the river) and Gw26 (on the far side of the landfill). The association of groundwater quality with groundwater level was observed in boreholes both at the upstream (away from Waikato River) and downstream sides (near Waikato River) of the landfill.

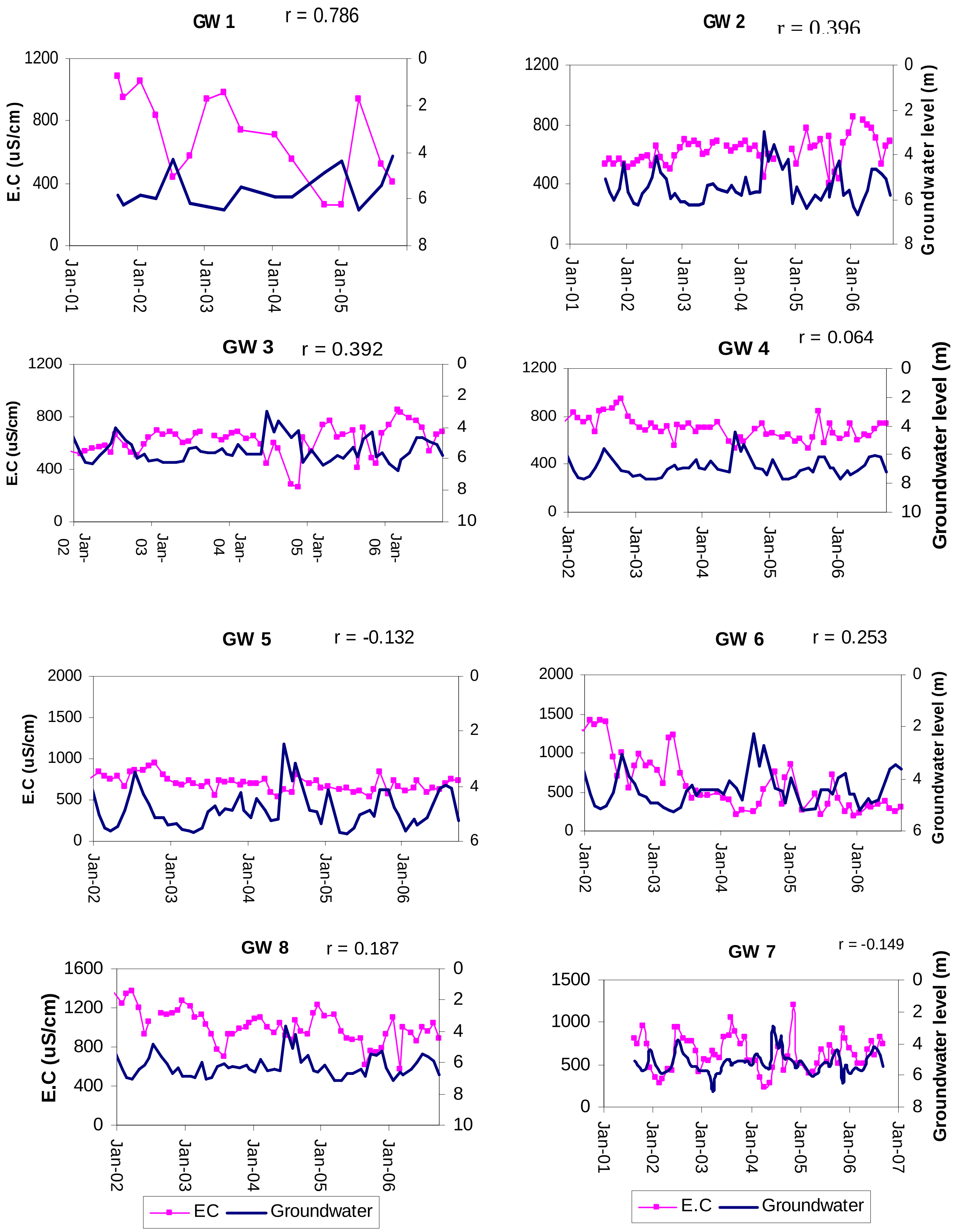


Figure 5.10 Time series plots of groundwater E.C and level at Horotiu landfill

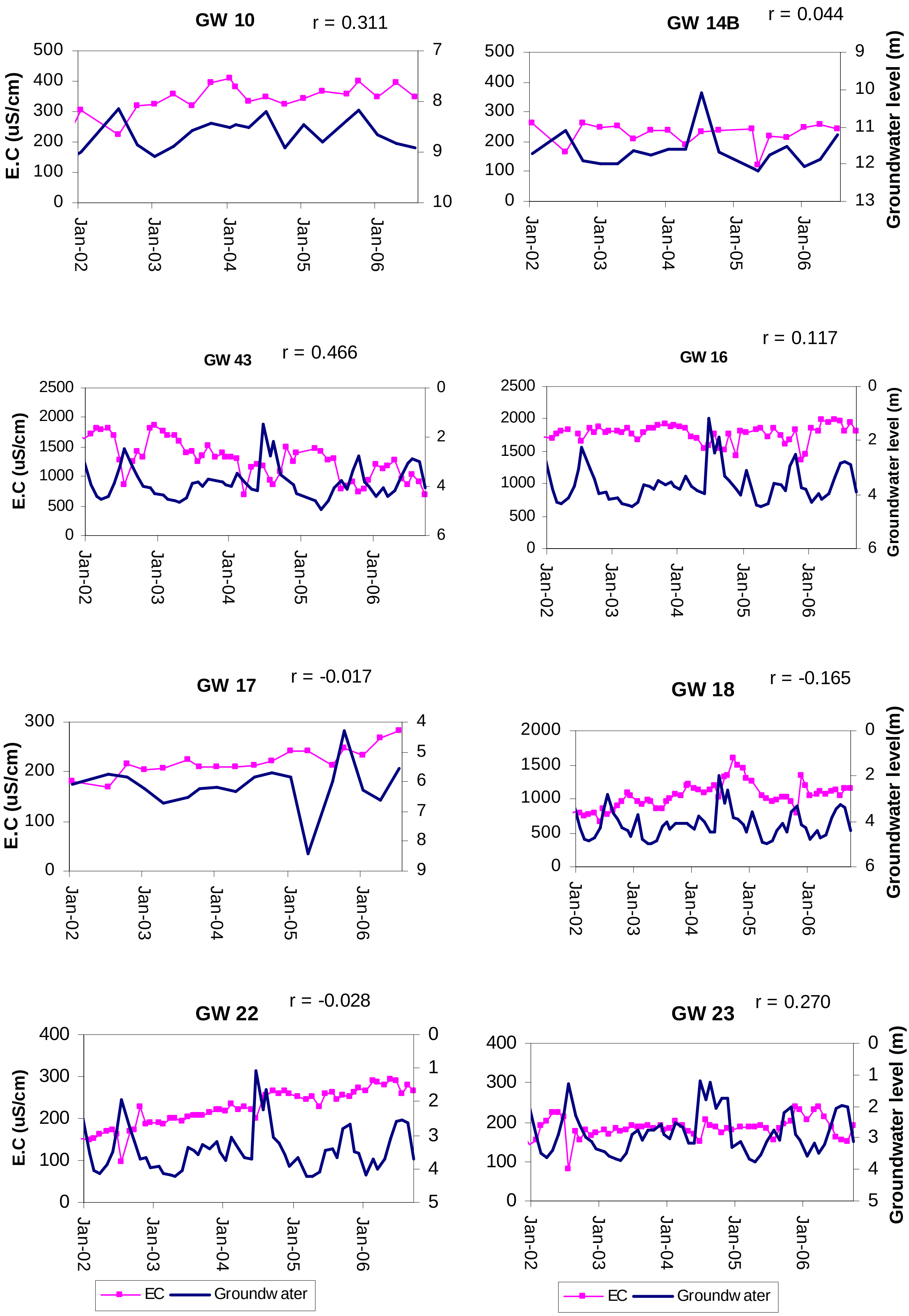


Figure 5.10 (continued) Time series plots of groundwater E.C and level at Horotiu landfill

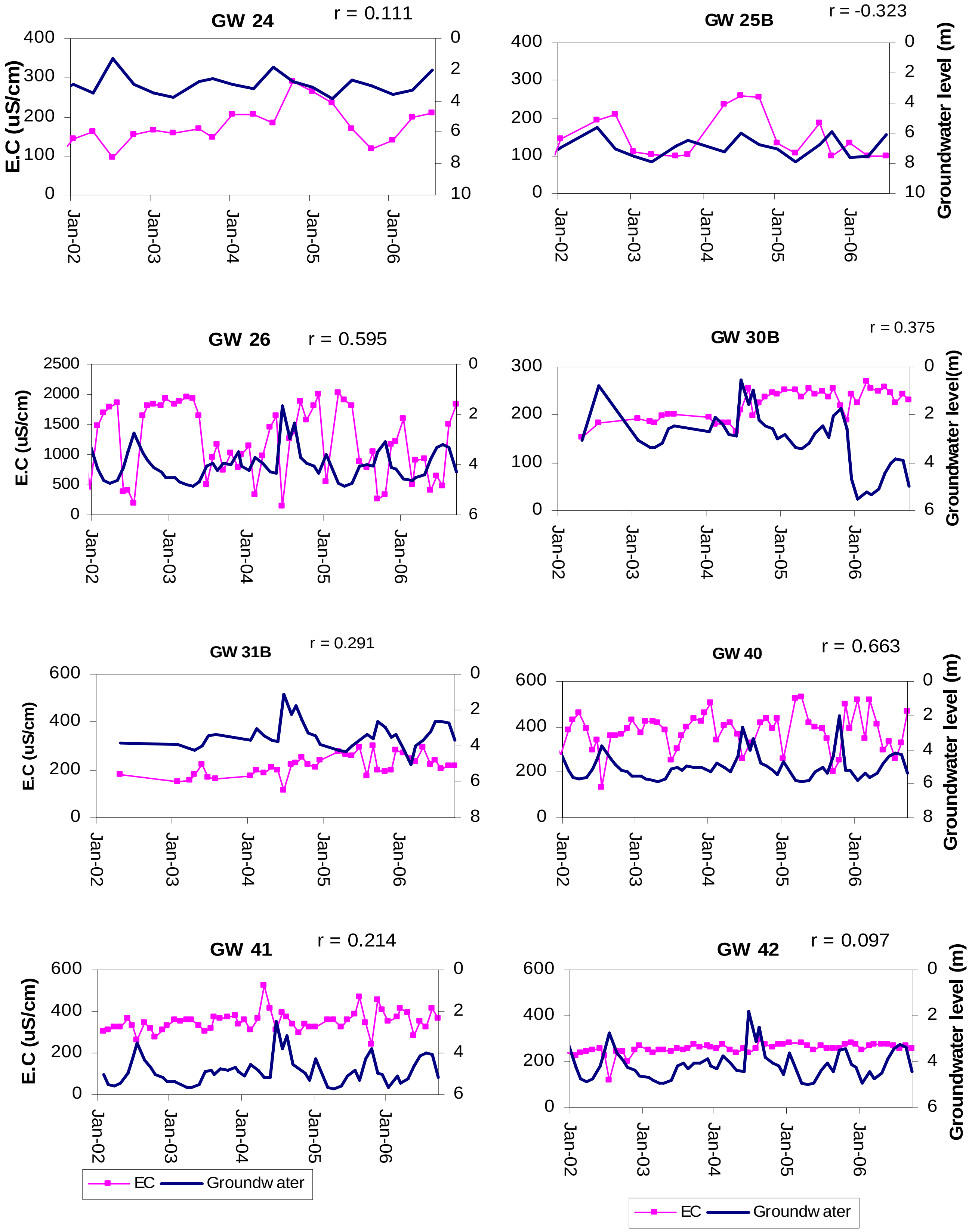


Figure 5.10 (continued) Time series plots of groundwater E.C and level at Horotiu landfill

Groundwater levels at the Horotiu landfill were strongly related to the water level of the Waikato River, giving an indication that river water might influence groundwater quality. Full record of daily average water level for Waikato River is in Appendix 5. Time series graphs for groundwater at Horotiu landfill and Waikato River levels, for arbitrarily chosen boreholes are presented in Figure 5.11. Both river water and groundwater levels are highly correlated ($R^2>0.7$, $P<0.05$).

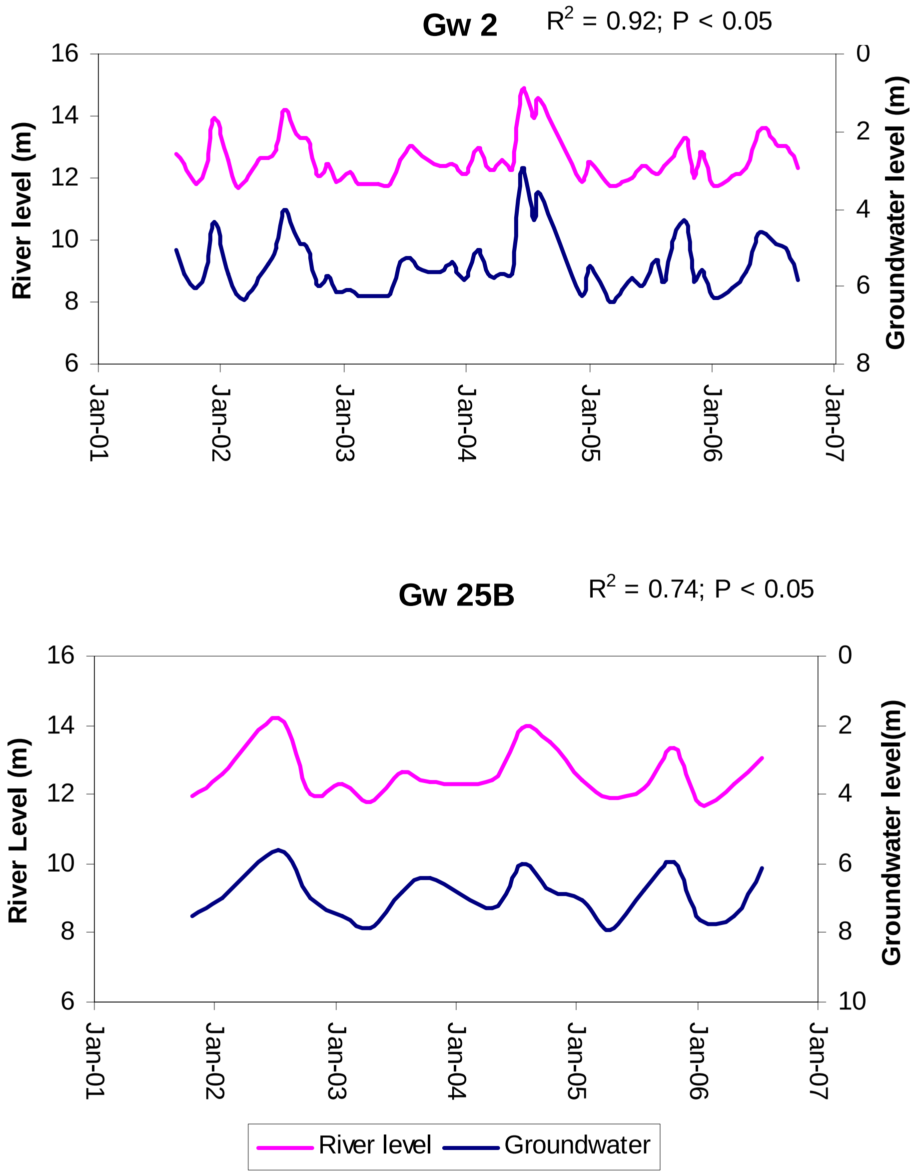
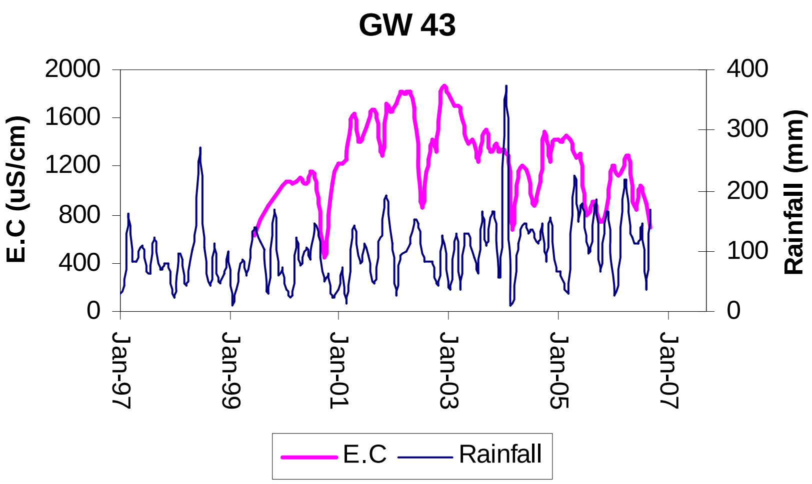


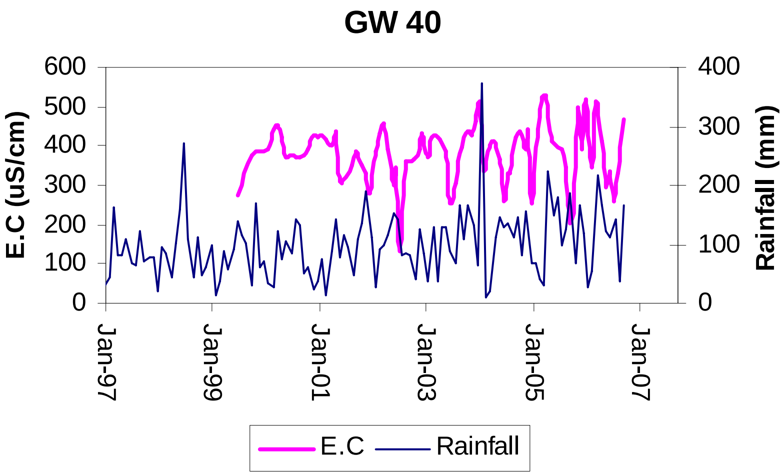
Figure 5.11 Time series plots of groundwater levels at Horotiu landfill and the Waikato river stage, with correlation coefficient and statistical significance. Gw2 is located close to the river and Gw25B is at the far side of the landfill.

5.6 Variations of Groundwater quality with amount of rainfall

It is plausible to assume that rainfall events may affect the quality of groundwater resources as portions of rainwater infiltrate into the ground and becomes part of groundwater. Comparisons of temporal variations of both groundwater quality and rainfall are likely to reveal any impact rainfall might have on the quality of groundwater. Rainfall values are the 30-day total amounts prior to sampling of groundwater. The 30-day period was arbitrarily chosen as a time rain water might take to be part of groundwater at this area.

Figure 5.12 is time series plot of the 30-day total rainfall amounts and groundwater EC of randomly selected boreholes in the vicinity of the Horotiu landfill. The time series plots (Figure 5.12) do not depict any significant association between rainfall events and the groundwater EC amounts. Peaks and troughs in rainfall do not correspond to those of EC. For instance, there are two major peaks of rainfall, one in mid-1998 and another in early 2004. These two peaks do not appear to be followed by any consistent rise or decrease in groundwater EC.





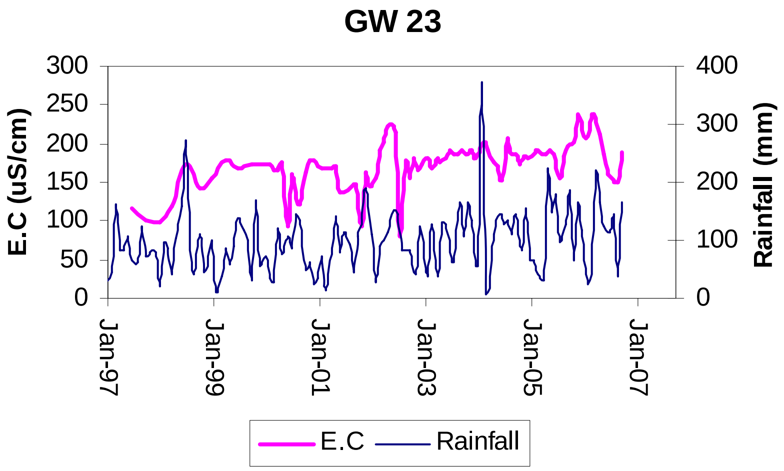
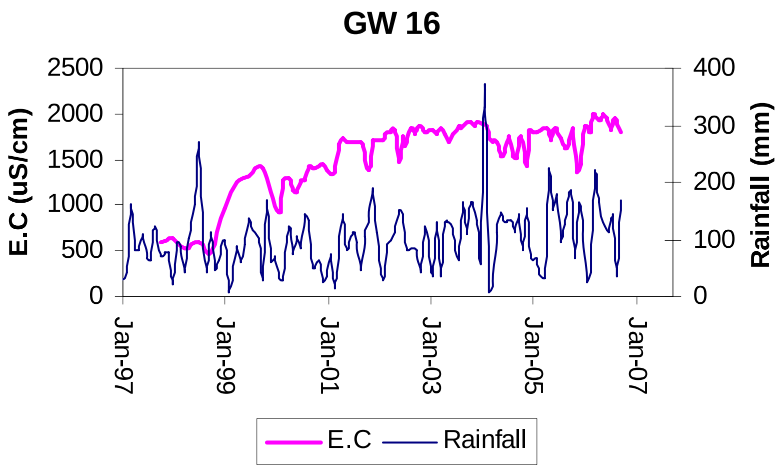
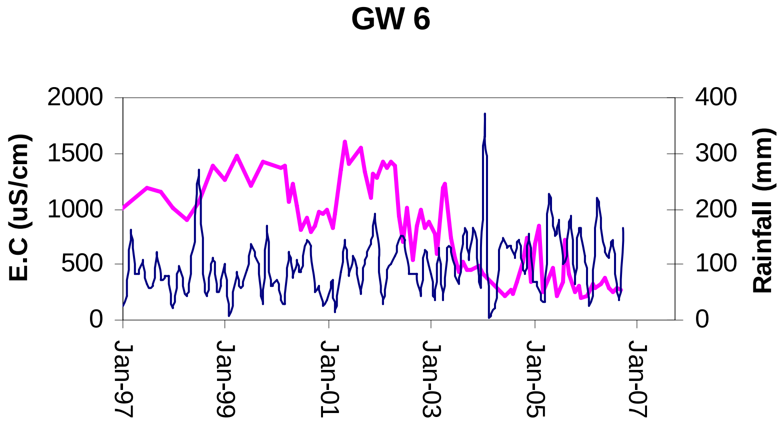


Figure 5.12Time series plots of groundwater E.C and the 30-day rainfall at the Horotiu landfill.





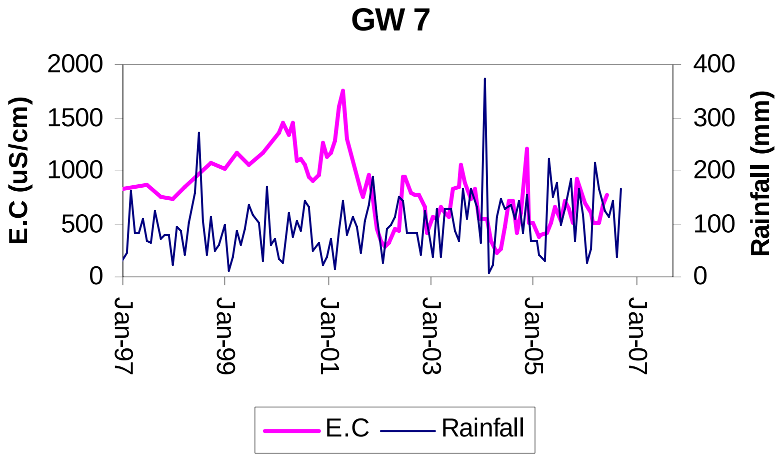


Figure 5.12 (continued) Time series plots of groundwater E.C and the 30-day rainfall at the Horotiu landfill.

There is a likelihood that rain water effects could take place in a shorter time period than 30 days, say, a week or even a day. Regression analyses were undertaken on total rainfall amounts for periods of 1 day, 7 days and 30 days prior to measuring groundwater EC and the EC values, to determine any association between the two. The statistical analyses revealed that only boreholes Gw26, Gw40 and Gw41 had significant relationship ($P<0.05$) between the 30 day rainfall and groundwater EC. Borehole Gw17 demonstrated a significant association between a 7-day rainfall and groundwater EC (Table 5.3). Rainfall event occurring a day prior to measuring groundwater EC had no impact on the groundwater EC in all boreholes.

Table 5.3 Slopes for the multiple regression analysis of groundwater EC against rainfall for 1 day, 1 week and 1 month prior to sampling groundwater ($P<0.05$).

Borehole ID	1 day	7 days	30 days
GW 17	-	1.3	-
GW 26	-	-	-6.2
GW 40	-	-	-0.73
GW 41	-	-	0.52

5.7 Landfill stages and groundwater quality

Stages at Horotiu landfill differ amongst each other in terms of construction liners, capping techniques, volume of refuse, depth and duration and dates of filling. It is therefore plausible that the landfill stages may have differing impacts on the quality of groundwater at the landfill site. To assess how the landfill stages may impact the groundwater quality, monitoring boreholes may be grouped according to the landfill stage(s) they are close (or immediately adjacent) to.

All the landfill stages were lined at the base and side with clay. In addition to a clay liner, stages 4A, 4B, 4C and 6 were also lined with geosynthetic clay liner (GCL) and high density polyethylene (HDPE) (Table 5.4). The GCL and HDPE provided a further protection against leakage of leachate through the base and sides.

Table 5.4 Horotiu landfill stage liner information (source: HCC).
(-) indicates 'not applied'

Landfill Stage	Liner			
	Clay thickness(m)	**Max. permeability K(m/s)**	**GCL**	**HDPE**
1	0.5	10^{-7}	-	-
2A	0.5	10^{-7}	-	-
2B	0.5	10^{-7}	-	-
3A	0.5	10^{-7}	-	-
3B	0.5	10^{-7}	-	-
3C	0.5	10^{-7}	-	-
5A	0.5	10^{-7}	-	-
5B	0.5	10^{-7}	-	-
4A	0.35-0.6	10^{-8}	Bentofix	2 mm
4B	0.35-0.6	10^{-8}	Bentofix	2 mm
4C	0.35-0.6	10^{-8}	Bentofix	2 mm
6	0.35	10^{-8}	Bentofix	1.5 mm

Selected boreholes are those which are likely to intercept or detect any contamination emanating from the landfill stages on the down-stream side of the landfill. Boreholes upstream of the landfill are also grouped together.

Concentration of the chemically conservative chloride ion in groundwater is used to evaluate the influence of landfill leachate on the groundwater quality. Figure 5.13 compares the temporal variations of chloride concentrations for the different groups of groundwater boreholes.

All the boreholes from the upstream group show a consistent and steady concentration in groundwater chloride. The chloride concentration for the upstream groundwater is relatively low and was below 50 mg/l for the boreholes in the group for the duration of sampling. A similar pattern and range of concentration was also observed for boreholes adjacent to landfill stages 4B and 6 (Figure 5.13).

Boreholes Gw3 in stage 2A, Gw4 in stage 2B and Gw5 in stage 5B show a long–term average concentration value similar to the background concentrations, but short-term fluctuations were also observed. Stages 2A, 2B and 5B are older parts of the landfill. The three boreholes had high concentrations, (about 150 mg/l), at the beginning of the monitoring period (1991) which then gradually declined to about 50 mg/l at end of the year 2006. This scenario suggests that the influence of leachate in landfill stages 2A, 2B and 5B lessened probably after capping.

Boreholes adjacent to landfill stages 4B and 6 had chloride concentration and trends very similar to those of background boreholes (Figure 5.13), hinting that leachate from the two stages did not percolate to contaminate groundwater. This is in accord with the fact that stage 4B, constructed in 1998, and stage 6, constructed in 2006 are the most recently constructed parts of the landfill. The two stages are therefore, more likely to be engineered to minimise the intrusion of leachate into the underlying groundwater resources.

One borehole in stage 1 (Gw1), one in stage 5B (Gw8) and all the boreholes in groups of stages 4A, 5A had chloride concentrations, 4 to 5 times higher than the value on the upstream side. Stages 5A and 5B were lined with clay only while 4A was lined with additional GCL and HDPE. Gw1 showed a lot of fluctuations throughout the sampling period, with an overall declining trend.

All boreholes in stage 4A had low chloride concentrations, at the beginning of 1997 (when filling started), which gradually increased to reach the maximum concentration in 2000 which was then maintained until the end of the monitoring period. Gw8 in stage 5B and all the boreholes of stage 5A began with low chloride concentrations which increased to a peak value and then dropped again (Figure 5.13). The concentration decline in borehole Gw8 began in the year 2000, many years before stage 5B was capped in 2006, while the decline experienced by boreholes adjacent to stage 5A took place in 2002, several years after stage 5A was capped in 1992.

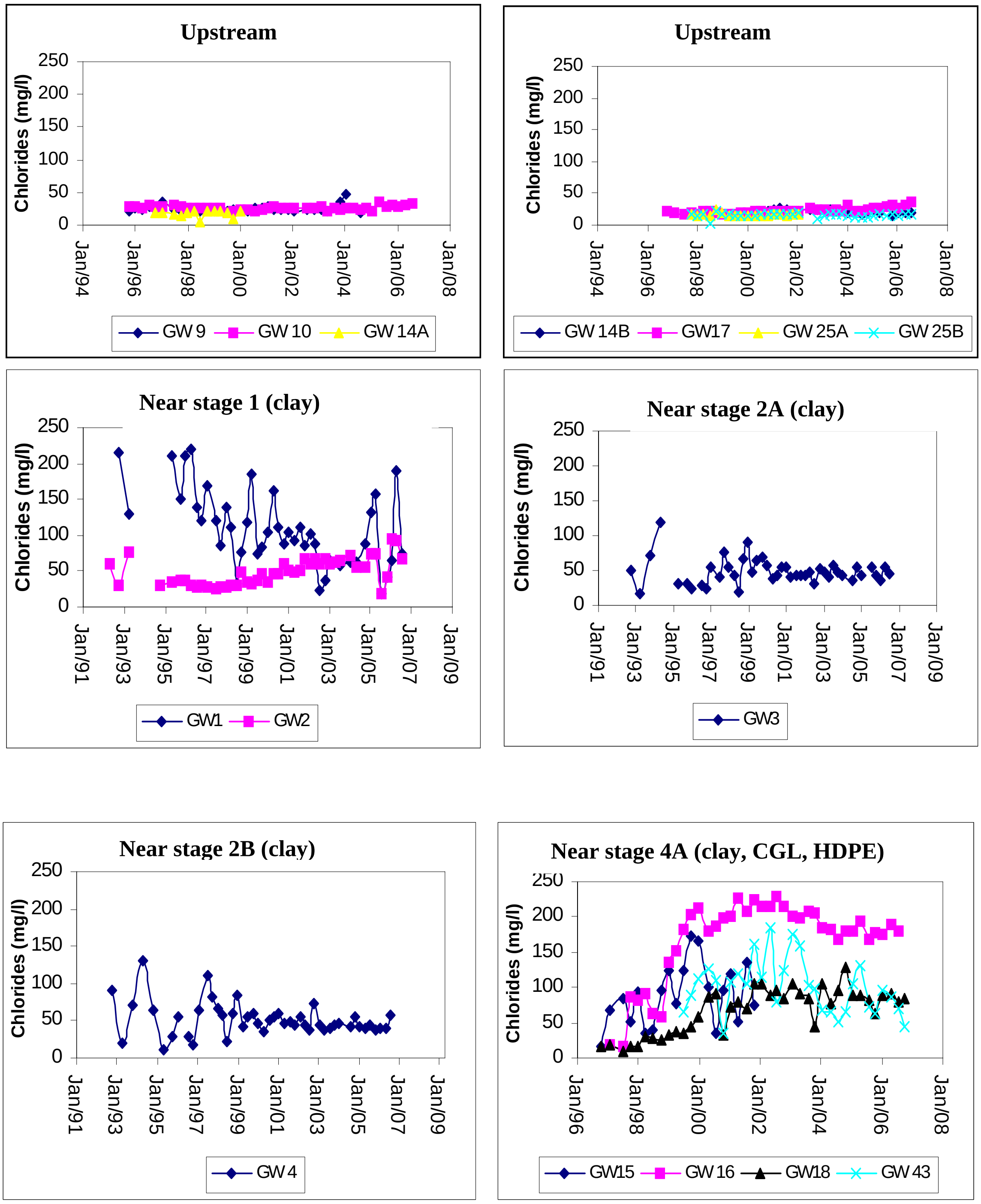
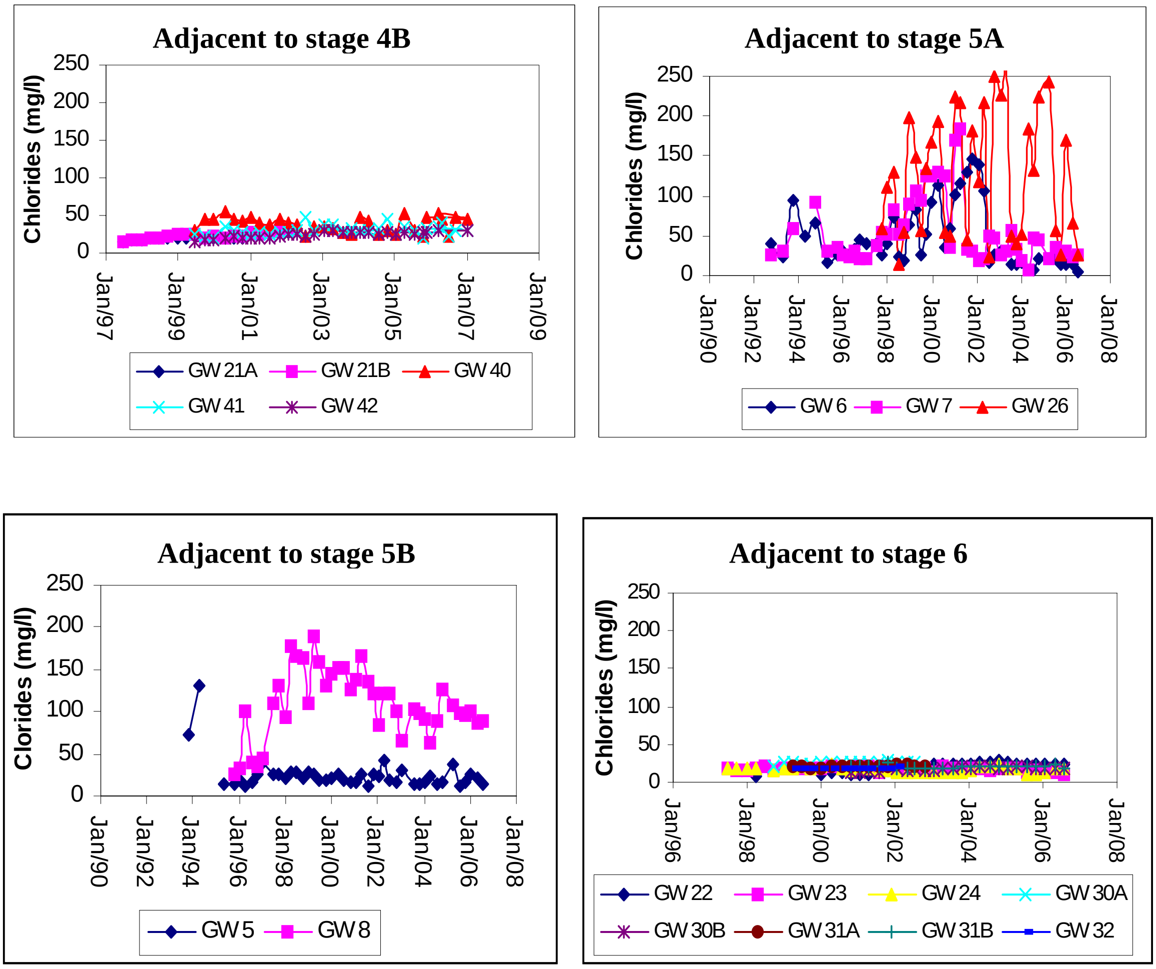


Figure 5.13 Plots of chloride concentrations versus time for groups of boreholes associated with various landfill stages at Horotiu landfill. Liner information is in parenthesis.


Adjacent to stage 4B

Adjacent to stage 5A

Adjacent to stage 5B

Adjacent to stage 6

Figure 5.13 (continued) Plots of chloride concentrations versus time for groups of boreholes associated with various landfill stages at Horotiu landfill. Liner information is in parenthesis.

5.8 Discussion

Groundwater sources at the Horotiu landfill site are currently not utilized for any purpose, may be due to concerns of contamination or simply because they are not (yet) needed and there is only a small distance between the landfill and the river. Analyses of groundwater chemical quality indicate that the average groundwater quality at the Horotiu landfill were still within the drinking water standards (New Zealand and European Union) for parameters such as nitrates, chlorides, sodium and EC. However, there were some parameters (e.g. manganese, iron, lead and pH) which were not within the drinking water standards. The concentrations of these constituents were higher (pH was lower) than the standards in both the upstream and downstream boreholes, giving an indication of their possible natural occurrence in the area. Selenium, arsenic, and cadmium were above the standards only in downstream boreholes.

The average lead content in groundwater upstream (0.04 mg/l) and downstream (0.045 mg/l) of the landfill, was higher than the average (0.015 mg/l) in landfill leachate. Similarly, average iron content in downstream boreholes (41 mg/l) was higher than average in leachate (18 mg/l), whereas the average upstream iron content was lower (7.1 mg/l). This scenario may indicate that leachate may not be the sole source of chemical parameters in groundwater on the down stream side of the landfill.

The upstream groundwater was of a better quality than the downstream groundwater. Concentrations of chemical parameters such as chloride and iron are as high as four times the concentration in the upstream groundwater. This might be because of leachate percolating into groundwater thereby introducing the chemicals. However, sulphate (23.7 mg/l), nitrates (3.61 mg/l) and reactive phosphorus (0.071 mg/l) were found to be higher in the upstream boreholes than in the downstream boreholes. These three components were present in relatively low concentrations in leachate. The average for sulphates was 92 mg/l, nitrate 2.7 mg/l and reactive phosphorus 2.9 mg/l. It is also observed that the average nitrate concentration (3.6 mg/l) for upstream boreholes was higher the average concentration in leachate.

With the ranges of pH (6.0-6.7), chloride (15-616 mg/l), sulphate (0.7-39 mg/l) and zinc (0.008-0.04 mg/l), the average groundwater quality at the Horotiu landfill is comparable to groundwater quality around the Greenmount landfill, in New Zealand, with ranges of pH (6.3-7.2 mg/l), chloride (24.5-66 mg/l), sulphate (8.6-53 mg/l) and zinc (0.02-0.07 mg/l) (Bardsley *et al.* 1992).

Concentrations of most chemical parameters in groundwater are not as high as they are in leachate. This implies that chemical constituents in leachate are attenuated by dilution, sorption or ion-exchange, as they enter groundwater domain. Landfill liners also have an attenuation effect on leachate (Bright *et al.* 2000).

Groundwater quality at Horotiu landfill varied with groundwater level, which in turn was found to be influenced by the water level in the Waikato River. Groundwater EC content at all but two sites decreased when groundwater levels were high. The river water, with EC content range of 140-181 µS/cm measured at Horotiu Bridge (Environment Waikato 2007), might simultaneously had a diluting effect on groundwater and an increase in groundwater levels.

Rainfall had no effect on groundwater quality. This could be because the landfill is designed to divert the rainwater and that rainwater does not fully percolate to reach groundwater due to low permeability landfill capping and lining. The rainfall impact would be, therefore, masked.

The groundwater EC content and hence the general groundwater quality varied with point of groundwater sampling. Background water and boreholes close to stages 6 and 4B had lower EC content than groundwater close to older parts of the landfill. These variations may have been caused by the effectiveness of the liner system at the base and sides of stages 6 and 4B. Groundwater in boreholes adjacent to stages 4B and 6 have similar trends and magnitudes for chlorides to the background groundwater. Lining of landfill at the base and sides plays a vital role in protecting groundwater against leachate percolation.

Stages 4 and 6 were lined with clay, like the others, but geosynthetic clay liner (GCL) and high-density polyethylene liner (HDPE) were also used. The HDPE have been used in modern landfills because it is resistant to aggressive leachate components (Rowe & Sangam 2002). GCL liners are reported, by Bouazza (2002) to be resistant to freezing and thawing and have ‘self-healing’ properties when punctured. GCL and DHPE liners have seemingly contributed to making the groundwater quality around stages 4 and 6 to have lower concentration of contaminants than groundwater at other sites of the landfill.

On average, groundwater at the Horotiu landfill is within the drinking water standards and is comparable to that of Greenmount landfill. However, few parameters (manganese, iron, lead and pH) are not within the standards. There was a variation of groundwater quality for upstream and downstream boreholes. Heavy metals were higher in downstream boreholes than in upstream boreholes, while sulphates, nitrates and reactive silicon were higher in upstream boreholes than in downstream boreholes. Groundwater quality at Horotiu landfill varied with Waikato River level, whereas rainfall had no obvious impact on groundwater quality.

Chapter 6

Maseru landfill groundwater quality

6.1 Introduction

The Maseru landfill is located about 5 km from the Maseru city centre. The landfill was established on the 1980’s at a site previously used as gravel quarry. The landfill was not lined at the base and sides to contain any leachate produced. It is therefore a potential source of groundwater contamination. The landfill is on the higher ground level, below which there are groundwater resources utilised by more than 5000 people for domestic purposes. The city’s surface water reservoir also lies 2 km downstream of the landfill. The mean annual rainfall in this part of the country is about 500mm and the rainy season is from October to April.

A number of boreholes were drilled at and near the landfill to intercept the local groundwater in order to detect and evaluate any contamination as a result of landfill leachate. One borehole (BH3) was drilled topographically upslope of the landfill with the aim of intercepting pristine water coming towards the landfill, while others (BH1, BH2 and BH4) were drilled in such a way as to tap groundwater affected by the landfill. A pond was also dug to capture surface water running through the refuse. Positions of the boreholes relative to the landfill and to each other are shown in cross-sectional view (Figure 6.1a) and aerial view (Figure 6.1b).

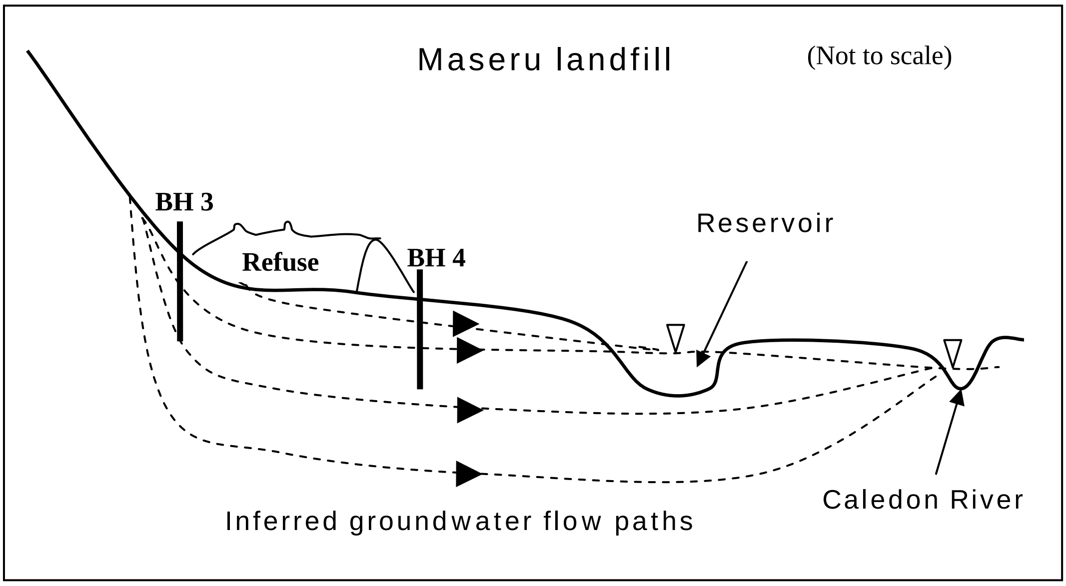


Figure 6.1a Cross-sectional view of Maseru landfill, showing relative positions of monitoring boreholes.

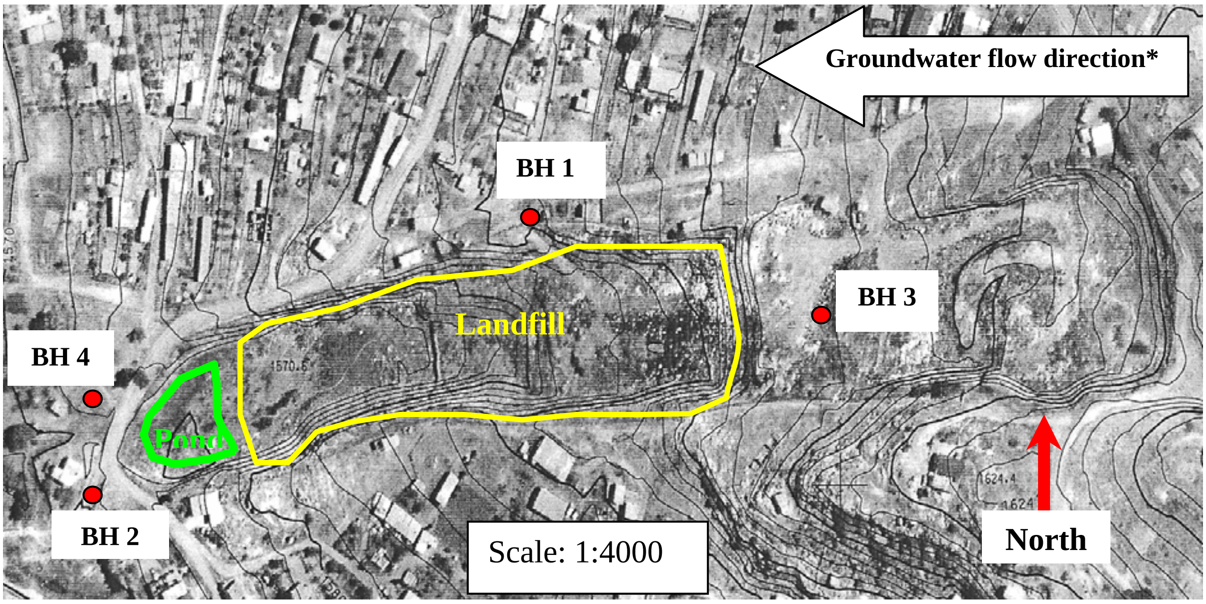


Figure 6.1b Aerial view of the Maseru landfill site (Source: Land survey and physical planning, 2000). The groundwater flow direction is assumed based on the topographic slope orientation.

6.2 Groundwater Chemistry

The concentrations of chemical parameters in all the landfill monitoring boreholes surpass those of the country's average groundwater (referred hereafter as "background water"). This indicates that boreholes at both the upstream and down stream sides of the landfill are impacted by the landfill leachate. BH4 was the most affected borehole since it had the highest concentrations of total dissolved solids (TDS), electrical conductivity (EC) and parameters such electric conductivity, total dissolved solids, nitrates, sulphates, iron, alkalinity and potassium. With the lowest content of TDS, EC and other contaminants, BH3 appeared to be the least affected borehole (Table 6.1, Figure 6.2). TDS and EC indicate the overall contaminant load of water. Considering only the analysed chemical parameters, in Table 6.1, the quality of groundwater around the landfill is still within the WHO drinking water standards, used by Lesotho, except for lead. The WHO-specified concentration for lead is 0.05 mg/l, which was exceeded also by the background water.

Table 6.1 Groundwater chemistry around the Maseru landfill. Values in mg/l, except pH and Electrical conductivity. Bold fonts exceed drinking water standards.

Parameters	BH1	BH2	BH3	BH4	Pond	Background	EU Standards
pH	7.56	7.39	7.51	6.97	6.5	7.22	6.5-9.5
TDS	755	804	362	941	473	146	-
Conductivity (µS/cm)	1430	1586	649	1869	943	250	2500
N-NO_3	11.7	11	11	11.8	11.7	0.58	50
SO_4	73	46	36	75	50	6.6	250
Fluoride	0.08	0.1	0.07	0.08	0.11	0.06	-
Total Fe	0.15	**0.99**	**0.42**	**1.23**	**0.75**	0.05	0.2
Chloride	140	191	60	83	105	28	250
Alkalinity as $CaCO_3$	210	240	233	254	207	58	-
Calcium	98	52	44	78	75	34	-
Magnesium	120	80	72	90	105	15	-
Potassium	37.5	25	19.5	39	28	8	-
Sodium	106	95	86	56	77	23	200
Lead	**0.05**	**0.05**	**0.06**	**0.05**	**0.07**	**0.05**	0.01
Zinc	0.09	0.06	0.04	0.05	0.05	0.04	-

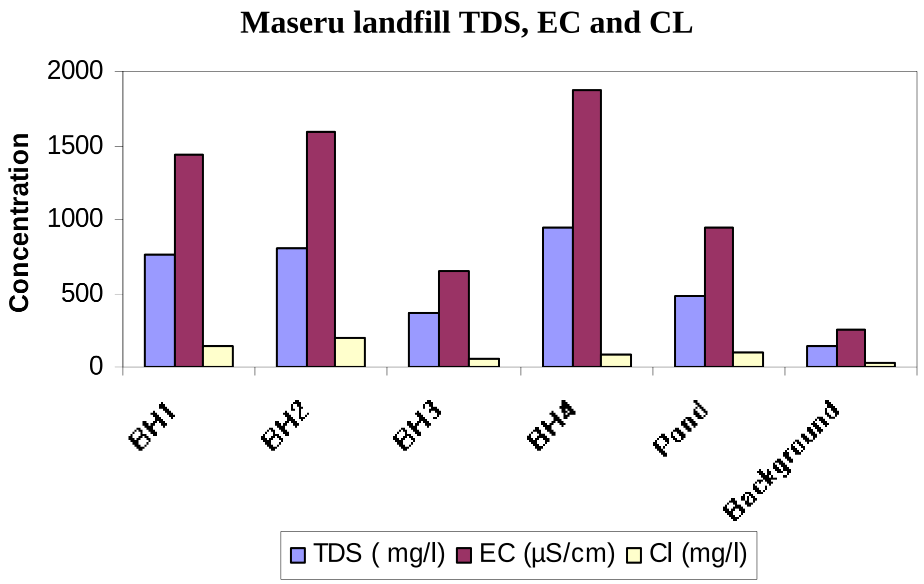


Figure 6.2 Concentration of TDS, EC and Cl at the Maseru landfill site.

There was evidence of strong statistical relationships between EC - chloride (Figure 6.3) and EC- TDS (Figure 6.4). Such relationships may be important in predicting values of unknown parameters if other parameters are measured. For instance, chloride is usually determined in a laboratory; if EC, often measured *in-situ*, is known, the chloride content can be estimated by the following equation:

$$EC = 8.38*Cl + 93 \ (R^2 = 0.96)$$

Such mathematical equations are also useful in spotting erroneous results. One point (BH4) was excluded from Figure 6.3 because it was an outlier. When BH4 is included, R2 value decreases to less than 0.5. There was also a strong relationship between EC and TDS for the Maseru landfill and the background groundwaters:

$$EC = 2*TDS – 53.5 \ (R^2 = 0.997)$$

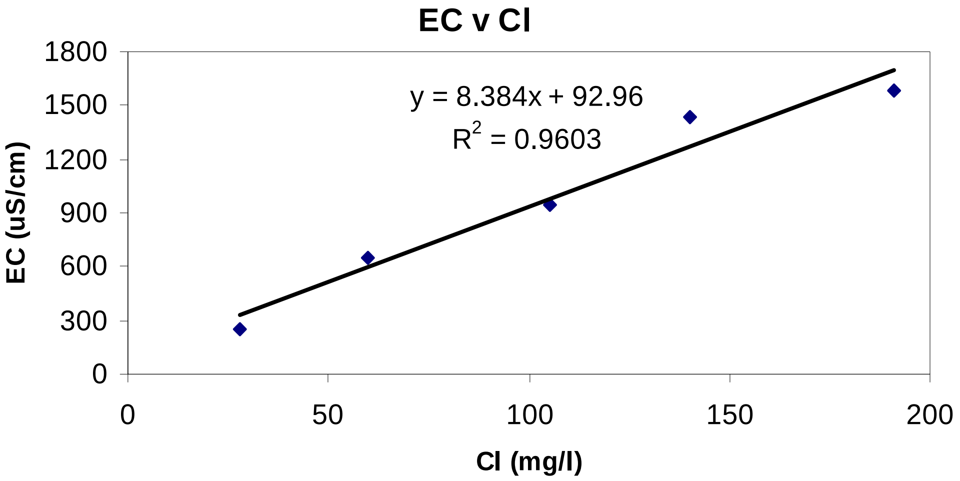


Figure 6.3 Scatter plot of electrical conductivity against chloride.

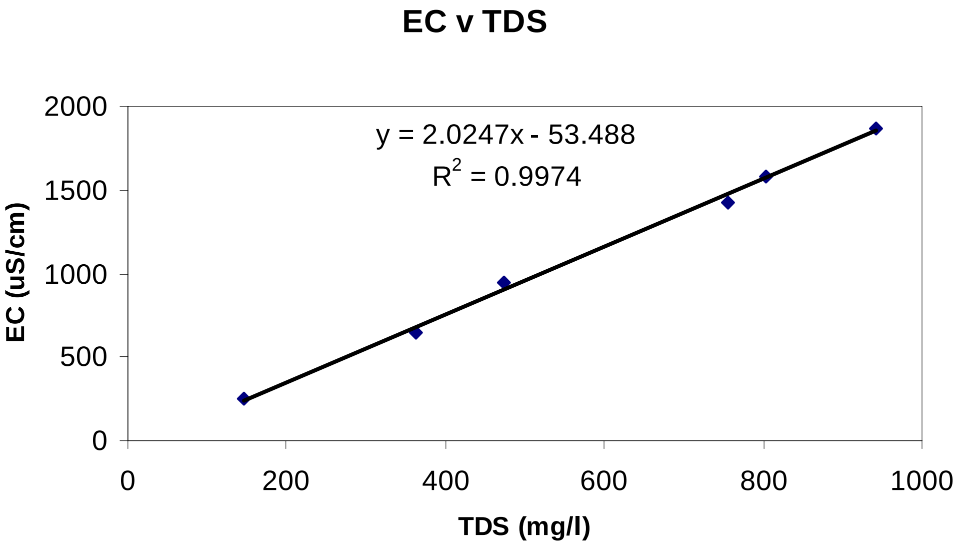


Figure 6.4 Scatter plot of electrical conductivity against total dissolved solids.

There was a minor areal variation in groundwater quality at the Maseru landfill site. Groundwater from most boreholes around the landfill was dominated by bicarbonate (HCO_3) ion as major anion and by magnesium (Mg) as a dominant cation. On the other hand, a dominant cation for the background was calcium (Ca). Groundwater at the landfill site was of a water type Mg-HCO_3, while the background water was of the type Ca- HCO_3. The quality of pond water is similar to that of the boreholes and it contained the highest amount magnesium.

Concentrations of major ions for landfill, background groundwater and the pond are depicted as Schoeller diagram (Figure 6.5).

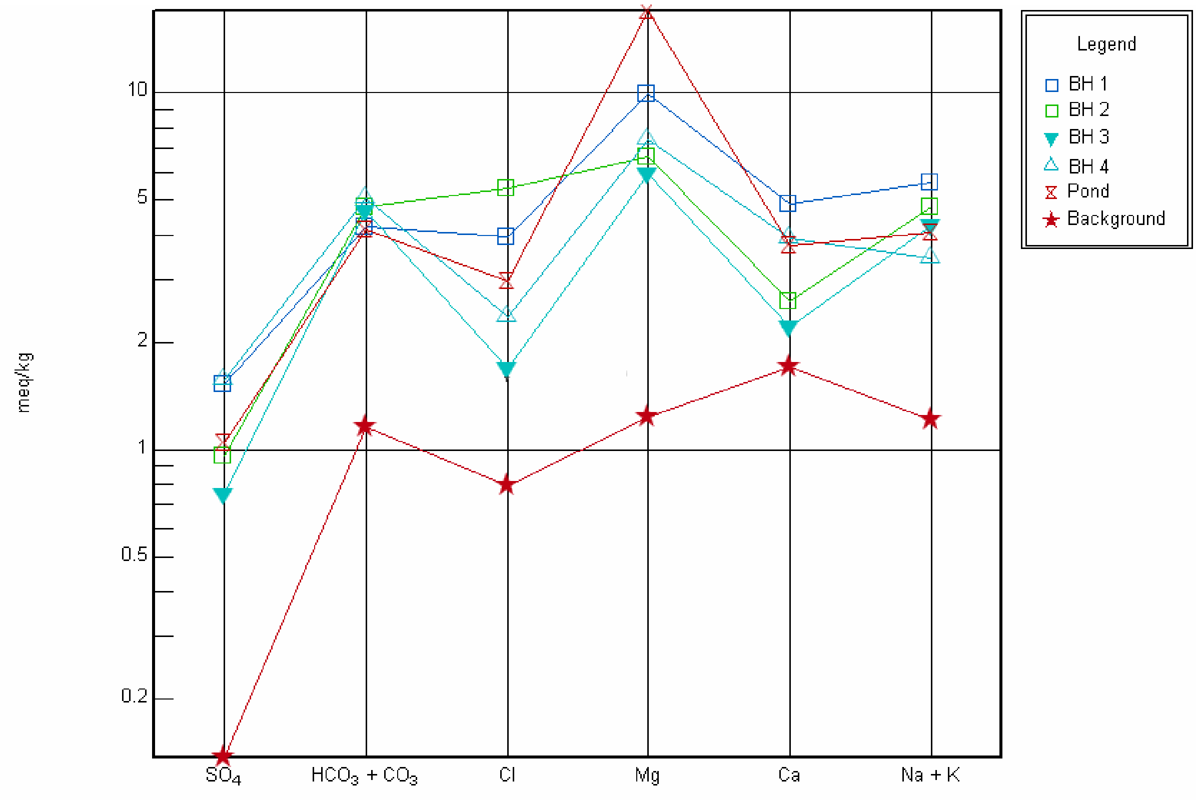


Figure 6.5 Shoeller diagram for groundwater and pond water at the Maseru landfill.

6.3 Hydrogeology of the Maseru landfill

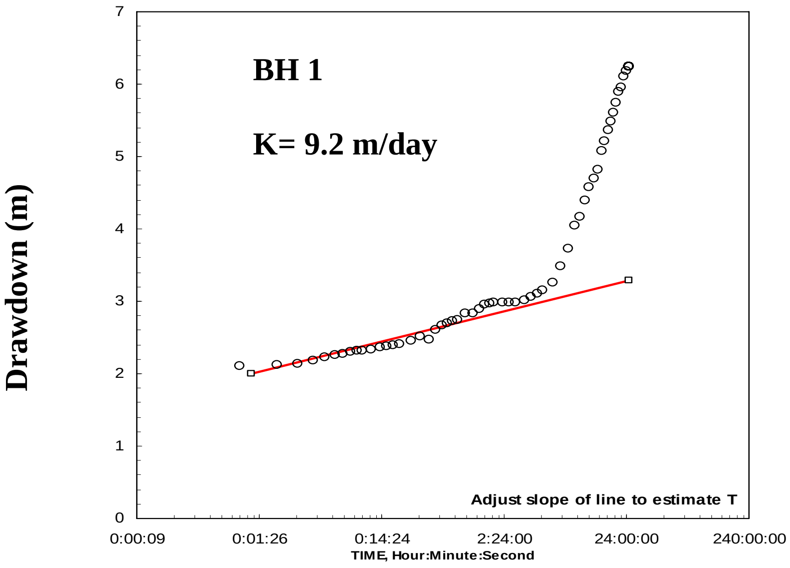
The groundwater monitoring network at the Maseru landfill consists of boreholes at an elevation ranging from 1594 to 1636 metres above mean sea level (m.s.l). The boreholes are of varying depths and cut through sandstones, mudstone and dolerite. Depths to water levels at this area range between 13.14 to 14.12 m below the ground level (Table 6.2).

Table 6.2 Borehole information at Maseru landfill.

		Borehole Summary			
Bore ID	**Elevation m.a.s.l (m)**	**Borehole Depth (m)**	**Depth to water level (m)**	**K (m/day)**	**Borehole Lithology**
BH1	1632	79	13.8	9.2	Topsoil, sandstone, dolerite, mudstone
BH2	1595	78	13.14	6.8	Topsoil, sandstone, dolerite, mudstone
BH3	1636	82	14.12	0.36	sandstone, dolerite dyke, siltstone
BH4	1594	82	13.67	5.1	Sandy soil, dolerite, sandstone, siltstone

Hydraulic properties (hydraulic constant) of the groundwater- bearing formations were estimated by analysing pumping test data undertaken on boreholes around the Maseru landfill. The raw data from borehole pumping test results are included in Appendix 6. Values of hydraulic constants (K) vary from 0.36 m/day at BH3 to 9.2 m/day at BH1, showing that the aquifer underlying the Maseru landfill is not homogeneous. Time-drawdown curves used for estimating the hydraulic conductivity are shown in Figure 6.6. The hydraulic conductivity for the boreholes decreased with time of pumping, probably due to the effect of the surrounding rocks with lower hydraulic conductivity, as the water is drawn from farther way from the dyke. For this reason K-values were estimated at earlier time to reflect the properties of the dyke-rock contact zone rather than of the relatively impervious parent sedimentary rocks.

Clay liners, such as those used at the Horotiu landfill, normally have K values ranging from 0.0009 to 0.00009 m/day. Compared to clay liners, hydraulic conductivity of the geological formation at Maseru are at least 10000 times higher. Such large values of K indicate relative ease with water would flow through the underlying ground material. These also demonstrate that leachate percolates easily escape through the base and the sides of the landfill into groundwater. There is also potential that the leachate pollutant would travel long distances within a short time.



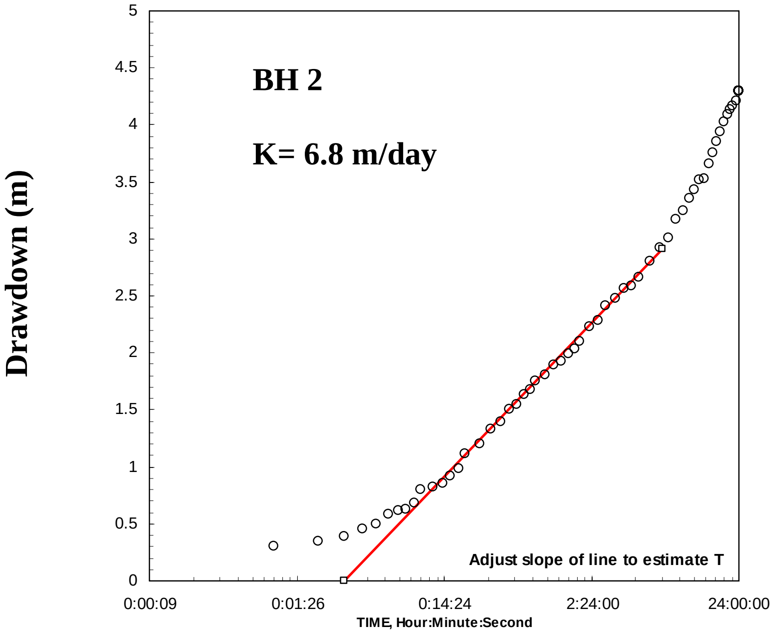
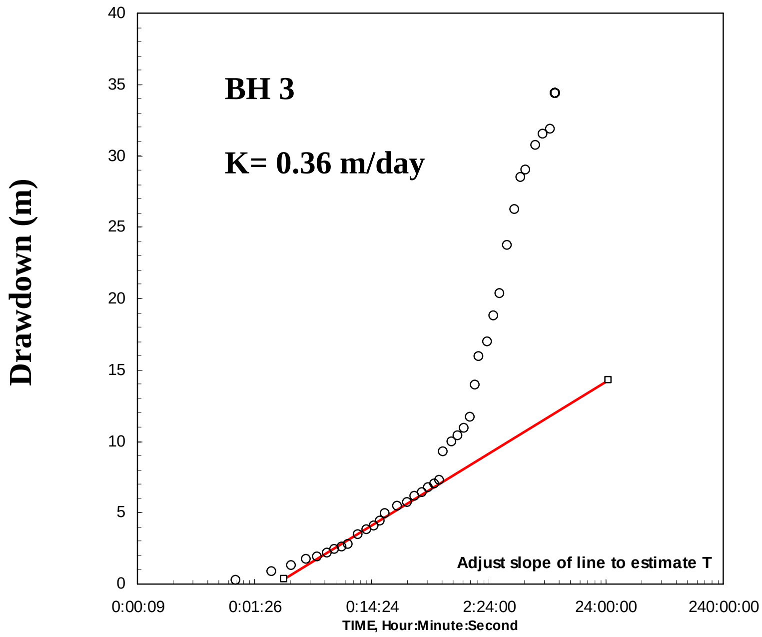


Figure 6.6 Time-drawdown curve and line of best fit for pump-test at Maseru landfill boreholes.



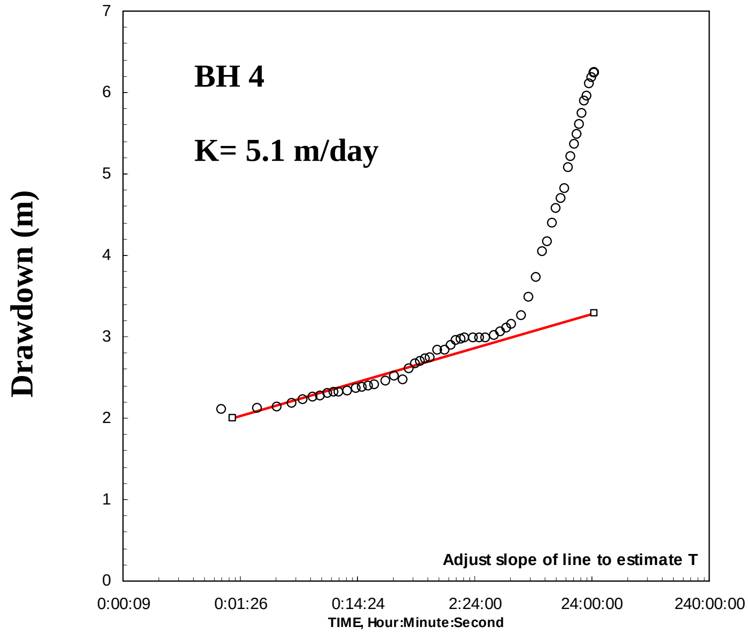


Figure 6.6 (continued) Time-drawdown curve and line of best fit for pump-test at Maseru landfill boreholes.

6.4 Discussion

Concentrations of chemical parameters in groundwater at the Maseru landfill are higher than average background. This situation preliminarily points the landfill as a source of the elevated amounts of the chemical constituents in groundwater. Groundwater at the landfill contains up to five times the amount of pollution indicators, such as chlorides, more than the average groundwater. High iron content (0.15- 1.23 mg/l) is perhaps due to metallic waste disposed of at the landfill. Compared to metallic cations, concentrations of heavy metals were low (< 0.1 mg/l). Lead content in the landfill boreholes, as well as in the background water, was higher than the drinking water standards. Higher concentrations of lead would be expected at boreholes around the landfill because leachate intrusion, but not for the background water.

Locality and nature of the Maseru landfill are far from ideal. It is located on the higher ground which is probably a groundwater recharge zone for the underlying exploitable aquifer. The landfill is not lined to contain leachate, making it easy for leachate to migrate to the groundwater system.

Pumping test results show that the landfill is on top of a geological formation with high hydraulic conductivity (0.36-9.2 m/day). Rock formations with such high conductivities enable pollutants from the landfill to migrate at a faster rate away from the landfill. However, the concentration of the leachate in groundwater would be attenuated as the groundwater moves further away from the landfill and may eventually be undetectable beyond a few kilometres from the landfill. Nonetheless, the threat of pollution at nearby boreholes is inevitable.

Chapter 7

Discussion, Summary and Conclusions, and Recommendations

7.1 Discussion

7.1.1 Introduction

Disposing of of solid waste in landfills is still regarded as the most economical method of handling waste. However, landfills are recognized as a potential source of groundwater contamination, and to a lesser extent, surface water contamination. The current study focused on two landfills, one in Horotiu, New Zealand and the other in Maseru, Lesotho. The two landfills differ in a number of ways. For instance, the Horotiu landfill was lined at the bottom and sides with various materials with low hydraulic conductivity with the aim of containing leachate whereas the Maseru landfill was not equipped with any means of protecting groundwater and the environment against leachate.

7.1.2 Leachate generation and characterisation

Landfill leachate at the Horotiu landfill had been monitored from 1997 to 2006 at three-month intervals. Horotiu leachate quality was characteristic of municipal waste landfill. Younger landfill stages (4A, 4B, 4C and 6) had relatively higher and increasing leachate concentrations than the older parts (stages 1, 2A, 2B, 3A, 3B, 3C, 5A and 5B) of the landfill. The load of leachate had been shown in literature to decrease with time, as observed with Horotiu landfill leachate. Chemical constituents, such as EC, chloride, BOD and alkalinity, present in the Horotiu leachate were in lower concentrations than those reported for other countries.

Horotiu landfill leachate had low concentrations (less than 1 mg/l) of heavy metals. The concentration of the heavy metals did not show significant variation with pH. Leachate had a small pH range (6.5-9) which remained consistent over the monitoring period.

There was a negative correlation between leachate concentrations of cobalt, nickel, chloride and cadmium with amounts of rainfall (30-day total prior to leachate sampling). Negative correlations would be expected because of the diluting effect of rainwater. However concentrations of aluminium, manganese, iron and zinc increased with increasing amounts of rainfall.

7.1.3 Groundwater composition

Analysis of groundwater chemistry data, for both the Horotiu and Maseru landfills, revealed that both landfills had an impact on the local groundwater. Concentrations of chemical components were found to be higher in groundwater adjacent to the landfills than in the background groundwater. For example, the chloride content of groundwater from the Maseru landfill monitoring boreholes was about 500% more than in the background water, while in Horotiu it was 400% higher. Chloride is an indicator of pollution because it does not readily absorb to soil and subsoil and it rarely occurs naturally in groundwater.

It is concluded that the landfills were the sources of the elevated chlorides and many other chemical parameters such as iron and sodium in groundwater. The chemical parameters of groundwater in both landfills were within the WHO and New Zealand drinking water standards, except for iron, lead, arsenic, cadmium and selenium at Horotiu and lead at Maseru.

The general groundwater qualities at Horotiu and Maseru landfills were similar. However, Horotiu groundwater had higher contents of nitrates and iron, while the Maseru groundwater was higher in EC, chlorides and alkalinity. Groundwater at both landfills had bicarbonates (HCO_3) as a dominant anion. A dominant cation for Maseru groundwater was magnesium, while in Horotiu sodium was the dominant cation. Both Maseru and Horotiu groundwater separately demonstrated strong relations between the EC and chloride contents. For Maseru, EC was about 8.4 times the chloride content and for Horotiu the EC was 6.8 times the chloride.

The electric conductivity at the Maseru landfill ranged from 649 to 1869 µS/cm, while at Horotiu the electric conductivity ranged between 713 and 3074 µS/cm. The groundwater near younger stages at Horotiu was less affected than groundwater near older landfill sites. The similarity of the extent of groundwater contamination at Horotiu and Maseru landfill undermines the fact that Horotiu landfill was lined at the bottom and side. This raises a question on the effectiveness of the landfill liners used at Horotiu.

Both landfills are sited in locations that are potentially harmful to the environment. The Horotiu landfill is on a shallow aquifer, with the water table sometimes less than 0.5 metres below the base of the landfill. It is also less than 50 metres from the Waikato River. This implies that both groundwater and the Waikato River are immediately affected by landfill leachate. The Maseru landfill is on the recharge zone of the aquifer below, polluting some of the rainwater that is replenishing the aquifer. The rock hydraulic properties at both the Maseru and Horotiu landfills are a disadvantage because the permeabilities are high, 0.36-9.2 m/day at Maseru and about 0.271 and 0.051 m/day at Horotiu (Hamilton city council 1996). Such high hydraulic conductivities would allow a rapid movement and dispersal of leachate into the groundwater, away from the landfills.

7.1.4 Potential health and environmental hazards

The groundwater qualities at the Horotiu and Maseru landfills are presently not in dire status. The situation may change with time and the groundwater quality at these sites may become critical. Unless sound rehabilitation and remediation strategies are implemented, both the Maseru and Horotiu landfills will continue to pose a threat to the environment for many years to come.

7.1.4.1 Horotiu landfill

The groundwater resources at Horotiu are currently not utilised and there is subsequently no immediate health risk involved. The leachate-contaminated groundwater enters the Waikato River with negligible risks to user because of the volume of water in the river (mean flow of $270m^3/s$) which dilutes the incoming groundwater. A significant foreseeable risk with Horotiu landfill is the potential for the river bank erosion to breach the landfill and contents of the landfill to be washed into the river. This is probably the main reason why the Horotiu landfill is now closed.

7.1.4.2 Maseru landfill

The Maseru landfill is currently in use and will continue to contaminate the local groundwater resources until the landfill is shut down and covered to prevent further leachate generation. The groundwater resources adjacent to the landfill are used by a large number of people mainly for domestic purposed. This situation puts their lives at risk of drinking high amounts of heavy metals (e.g. lead), which are linked to diseases such cancer, skin and liver problems.

7.2 Summary and conclusions

- The study focused on two solid waste landfills, one located in Horotiu New Zealand and anther in Maseru Lesotho. The Horotiu landfill takes municipal waste and some special form of industrial waste, while the Maseru landfill houses municipal, industrial and commercial wastes.

- The Horotiu landfill is located less than 50 metres from the Waikato River and is on a shallow groundwater zone (less than 0.5 m). Older stages of the Horotiu landfill were lined with clay only, while newer ones were lined with clay, geosynthetic clay (GCL) and high-dense polyethylene (HDPE) to contain leachate. The Maseru landfill is on a permeable geological formation and is also on a groundwater recharge zone for the aquifer used by thousands of people. Unlike the Horotiu landfill, the Maseru landfill was not lined to prevent leachate from entering groundwater underneath, and there is no means of collecting and monitoring the leachate.

- Boreholes were installed at both Maseru and Horotiu sites to monitor and detect any groundwater contamination as a result of leachate intrusion.

- Groundwater quality and quantity, as well as leachate quality and quantity had been regularly monitored at Horotiu landfill from 1991 to 2007. Horotiu study used the monitoring data collected at the landfill as well as design, engineering and other information about the landfill.

- At Maseru, borehole pumping test and lithology information was obtained from the existing records. Borehole pumping test data was processed by the author.

- Groundwater at Maseru was sampled by the author with chemical analysis analyses undertaken by an independent laboratory facility (WASA).

- The chemical composition of leachate at Horotiu was similar to others reported in literature. It had high amounts of chemical parameters such as electrical conductivity, chlorides and organic content. Concentrations of heavy metals were typically less than 1 mg/l.

- The quality of leachate at Horotiu landfill varied from stage to stage, with older stages having lower concentrations of many leachate parameters than younger stages. Landfill leachate also showed change in quality over time, however, pH did not change significantly over time, but remained in the range of 6 to 9.

- There was no significant correlation between the concentrations of heavy metals in leachate at Horotiu and the leachate pH.

- Chemical components in leachate at Horotiu showed an inconsistent response to rainfall amounts in various landfill stages. Concentration of the majority of parameters (e.g. cobalt, nickel, chloride and cadmium) decreased with increasing amounts of rainfall in most of the landfill stages. However, some parameters (e.g. aluminium, manganese, iron and zinc) had a positive correlation with rainfall in some landfill stages. Influence of the age of landfill stage on correlation could not be established.

- Groundwater quality at Maseru and Horotiu landfills were similar, with only minor differences in concentrations of various chemical parameters.

- Groundwater at the Maseru and Horotiu landfills had higher concentrations of chemical parameters than groundwater not affected by the landfills. However, for most chemical parameters (e.g. EC, chloride, nitrate and sulphate), groundwater quality at both landfills was within the drinking water standards. Some parameters (e.g. pH, iron, lead and manganese at Horotiu; and lead at Maseru) were not within the drinking water standards.

- Groundwater quality at Horotiu varied with groundwater water level, which in turn was found to be influenced by the water level in the Waikato River. Electrical conductivity of the groundwater decreased when the groundwater and river levels were high. The river water seemed to have a diluting effect on groundwater since it had a lower electric conductivity.

- For the recently constructed stages (Stages 4B and 6) at the Horotiu landfill, the groundwater in nearby boreholes (downstream side) had similar trends in chloride content to those of the upstream side, with low and stable concentrations. These landfill stages were lined with geosynthetic clay liner (CGL) and high-density polyethylene (HDPE) in addition to the clay liner which was applied to all the stages. However, boreholes near stage 4A, which was also lined with CGL and HDPE had higher and inconsistent chloride trends.

- The quality of groundwater beneath and around Maseru and Horotiu landfills is poor relative to the background water quality.

- Groundwater and leachate qualities at the Horotiu landfill changed with time, showing signs of improvement with time following cessation of landfilling activities and the capping of landfill stages.

- Changes in groundwater quality at Maseru landfill could not be quantified but are envisaged to worsen till the landfill shuts down.

7.3 Recommendations

The current study has offered a better understanding on the chemical characteristics of landfill leachate and how it affects the groundwater environment. Yet there is still some more investigation that needs to be done to improve our knowledge with regard to handling municipal solid waste in a manner that would not compromise the well-being if the groundwater resources. The following are recommendations for complementary research in the subject:

- The current study focused only on the chemical facet of the water quality at both Maseru and Horotiu landfills. There is a need for a further research on the microbiological and organic aspects of water quality at the two landfills in order to gain a better understanding of the characteristics of landfill leachate.

- At Maseru, further study is recommended delineate the leachate plume in order to isolate the contaminated groundwater from the exploitable clean water.

- A study to locate less vulnerable areas for future landfill sites is essential to minimise or avoid the negative impacts of landfill leachate on the environment, in both Lesotho and New Zealand.

- A combination of clay, geosynthetic clay and high-density polyethylene liners used at Horotiu landfill appeared to be effective in containing landfill leachate, such liners could be used in Lesotho for future landfills.

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Leachate quality monitoring data. All values are in mg/l, except pH, BOD: COD ratio; Conductivity in uS/cm; Ion balance in equiv./l.

					Sump 1									
Date Sampled	07/09/97	04/20/98	04/21/99	04/20/00	09/22/00	04/20/01	09/21/01	05/02/02	09/25/02	04/24/03	09/22/03	04/26/04	09/23/04	04/20/05
pH	-	-	-	6.9	6.9	6.8	7.0	6.3	6.7	6.7	7.0	7.4	7.2	7.4
Conductivity	1420	5510	6470	5900	1847	3640	1840	3960	2280	3270	5180	16940	4490	4510
Alkalinity	1200	4000	2920	2630	856	1300	1180	1980	1140	1620	2150	1940	1970	2140
Sulphate	63	-	19	9.7	3.8	24.6	1.7	1.7	3.7	8.9	3.5	53	3.5	0.5
Chloride	63	520	376	312	62	151	79	145	77.4	123	351.0	246	187	14.4
Nitrate-N	-	-	-	0.05	0.02	0.05	0.05	0.05	0.05	0.05	0.87	7	0.05	0.05
NH4-N	93	440	412	380	74	196	124	219	124	205	230	288	293	310
Reactive Silica	17	-	-	38	37	41	41	38	34.5	34.5	40.2	32.3	32.1	38.2
DRP	-	-	-	0.016	0.006	0.014	0.012	0.028	0.008	0.033	0.081	0.3	0.013	0.009
Anion Balance	-	-	-	-	18.9	-	26	-	25.1	-	53.0	-	44.7	-
Cation Balance	-	-	-	-	19		26.2		25.1	-	54.9		46.1	-
Dissolved Na	74	370	270	269	52.2	136	71	131	63.3	-	290	233	156	180
Dissolved K	87	380	310	289	69	186	100	203	102	-	200	241	236	264
Dissolved Ca	220	180	180	159	141	186	149	181	138	-	280	151	140.0	159
Dissolved Mg	28	90	78	72	23	55	33	58	32		73	59	58	63
Dissolved B	2.1	7	7.7	6.43	1.46		2.43	4.52	2.16	-	3.08	3.97	4.49	5.7
Dissolved Fe	0.06	2.2	6.8	5.7	25.1	-	42.5	21.7	39.2	-	22.4	0.51	17.7	19.5
Dissolved Zn	0.02	0.037	0.08	0.030	0.010	-	0.038	0.122	0.033	-	0.027	0.804	0.008	0.01
Total B	1.8	6.6	6.5	6.4	1.6	-	2.6	4.4	2.5		3.1	4.5	4.6	5.6
Total Fe	18.0	12	8.4	9.0	35.0	-	37	33.8	50	-	34	13.9	17.2	34.3

Total Zn	0.10	0.1	0.16	0.03	0.23	-	0.228	0.333	0.126	-	0.482	1.21	0.04	0.018
TOC	-	180	142	107	82	79.4	52.2	110	48.6	56.7	455	98.3	108	88.4
BOD		33	22	22		13		8		6		22		8
COD		460	583	368		202		217		169		304		332
BOB/COD		0.07	0.04	0.06		0.06		0.04		0.04		0.07		0.02
TKN		463	311	394		193.00		256		194		379		306
Total Anions				61.5		30.8		43.7		36.0		47.3		43.1
Total Cations				60.3		39.0		41.1		35.0		49.2		50.5
Dissolved Al		0.01	0.014	0.02		0.072		0.02		0.006		0.019		0.02
Total Al		0.37	0.046	0.06		0.813		0.481		0.05		0.186		0.056
Dissolved Cr		0.023	0.025	0.004		0.0040		0.004		0.002		0.013		0.003
Total Cr		0.012	0.012	0.007		0.005		0.004		0.005		0.016		0.008
Dissolved Mn		1	0.85	0.843		1.24		0.95		0.716		0.981		0.863
Total Mn		1.2	0.84	0.887		1.26		0.937		0.774		1.11		0.852
Dissolved Co		0.02	0.011	0.012		0.0082		0.0079		0.0063		0.0112		0.011
Total Co		0.033	0.013	0.012		0.008		0.0083		0.0071		0.0114		0.011
Dissolved Ni		0.033	0.014	0.011		0.0040		0.004		0.004		0.016		0.008
Total Ni		0.033	0.013	0.010		0.0050		0.005		0.008		0.015		0.009
Dissolved Cu		0.001	0.005	0.0		0.001		0.001		0.001		0.027		0.003
Total Cu		0.004	0.007	0.0		0.003		0.001		0.001		0.05		0.002
Dissolved As		0.026	0.028	0.007		0.007		0.006		0.003		0.006		0.007
Total As		0.021	0.01	0.007		0.010		0.009		0.005		0.015		0.01
Dissolved Cd		0.0002	0.001	0.0003		0.000		0.0001		0.0001		0.0001		0.0003
Total Cd		0.0006	0.001	0.0003		0.000		0.0001		0.0001		0.0001		0.0001
Dissolved Pb		0.0002	0.0005	0.0		0.0005		0.0003		0.0002		0.0002		0.0005
Total Pb		0.0018	0.002	0.0008		0.0043		0.0019		0.0003		0.0048		0.0004

Sump 2a														
Date Sampled	9/07/97	20/04/98	21/04/99	17/04/00	22/09/00	20/04/01	20/09/01	2/05/02	25/09/02	24/04/03	18/09/03	22/04/04	22/09/04	15/04/05	21/09/05
pH	-	-	-	7.20	7.4	7.2	7.4	6.6	7.1	7.1	6.7	7.2	7.1	7.4	7.2
Conductivity	2770	10860	10610	11470	10980	11990	3460	9240	4990	9070	1565	6660	7150	9290	4210
Alkalinity	1800	4900	4450	4800	4720	4850	2150	4250	2100	3920	585	2830	3000	3730	1770
Sulphate	310.0		13.0	33.2	27.7	46.7	128.0	36.2	155	28.8	42	24	3.2	18.3	39.3
Chloride	170	810.0	742.0	946	908	952	270	640	300	618	75	420	447	585	192
Nitrate-N	-	-	-	0.0	0.040	0.05	0.05	0.41	0.05	0.5	0.05	0.05	0.93	0.11	4.79
NH4-N	260	600	682	793	768	798	303	545	315	646	64	468	500	666	266
Reactive Silica	22.0	-		44	44	45	50	39	36.8	36.1	19.8	34.7	34.4	31.9	37.1
DRP	-	-	-	0.656	0.62	0.617	0.023	0.175	0.023	0.098	0.014	0.034	0.046	0.053	0.012
Anion Balance	-	-	-	-	121	-	53.3	-	53.7	-	14.7		72.8	-	42.0
Cation Balance	-	-	-	-	117	-	55.1	-	52.3	-	15.3		75.3	-	43.5
Dissolved Na	170	660	590	749	657	816	283	519	249	-	71	373	355	446	177
Dissolved K	180	590	570	778	714	803	271	570	282	-	68.7	382	412	483	259
Dissolved Ca	240	85	160	146	134	174	165	153	145	-	74.2	114	142	121	136
Dissolved Mg	61	110	110	110	100	123	60	96	53	-	17	67	74	74	40
Dissolved B	2.3	8.3	6.9	6.14	6.54	-	3.29	5.97	2.86	-	0.807	4.23	4.38	5.1	2.81
Dissolved Fe	1.90	2.8	3.9	1.6	4.9	-	28.4	8.0	4.7	-	22.9	7.1	12.5	1.8	1.65
Dissolved Zn	0.013	0.010	0.020	0.016	0.016	-	0.075	0.034	0.074	-	0.042	0.055	0.011	0.018	0.041
Total B	2	7.9	6.2	6.69	6.33	-	3.41	6.01	3.56	-	0.83	4.78	4.42	5.76	2.77
Total Fe	14.0	7.9	14.0	7.9	-	-	25.8	12.4	21.2	-	26.9	18.9	16.7	18.8	14.6
Total Zn	0.35	0.073	0.15	0.078	-	-	0.226	0.109	0.17	-	0.221	0.104	0.06	0.209	0.078
TOC	-	310	822	329	326	319	127	278	199	250	64	144	198	302	106
BOD	-	56	76	61	-	67	-	48	-	54	--	29		20	-
COD	-	770	1310	944	-	927	-	670	-	663	-	525	-	588	-
BOD/COD	-	0.07	0.06	0.06	-	0.07	-	0.07	-	0.08	-	0.06	-	0.03	-

TKN	-	602	639	739	-	758.00	-	708	-	655	-	587	-	673	-
Total Anions	-	-	-	123	-	125.0	-	104	-	96.4	-	68.8	-	91.4	-
Total Cations	-	-	-	125	-	132.0	-	91.8	-	97.5	-	70.9	-	91.6	-
Dissolved Al	-	0.052	0.053	0.02	-	0.03	-	0.03	-	0.02	-	0.02	-	0.02	-
Total Al	-	2.0	1.7	0.14	-	0.050	-	0.07	-	0.06	-	0.05	-	0.56	-
Dissolved Cr	-	0.046	0.047	0.019	-	0.0250	-	0.016	-	0.013	-	0.012	-	0.01	-
Total Cr	-	0.043	0.036	0.022	-	0.022	-	0.019	-	0.015	-	0.015	-	0.017	-
Dissolved Mn	-	0.18	0.76	0.417	-	0.449	-	0.485	-	0.444	-	0.781	-	0.431	-
Total Mn	-	0.19	0.75	0.471	-	0.452	-	0.498	-	0.47	-	0.901	-	0.486	-
Dissolved Co	-	0.024	0.025	0.035	-	0.0390	-	0.025	-	0.024	-	0.019	-	0.024	-
Total Co	-	0.031	0.027	0.036	-	0.037	-	0.025	-	0.026	-	0.02	-	0.028	-
Dissolved Ni	-	0.044	0.046	0.071	-	0.0730	-	0.035	-	0.037	-	0.027	-	0.034	-
Total Ni	-	0.049	0.05	0.071	-	0.0730	-	0.036	-	0.039	-	0.029	-	0.041	-
Dissolved Cu	-	0.001	0.009	0.0	-	0.003	-	0.003	-	0.003	-	0.003	-	0.003	-
Total Cu	-	0.007	0.017	0.004	--	0.006	-	0.006	-	0.014	-	0.003	-	0.005	-
Dissolved As	-	0.11	0.087	0.021	-	0.018	-	0.019	-	0.014	-	0.019	-	0.015	-
Total As	-	0.054	0.033	0.021	-	0.020	-	0.019	-	0.017	-	0.026	-	0.029	-
Dissolved Cd	-	0.0003	0.001	0.0003	-	0.000	-	0.0004	-	0.0003	-	0.0003	-	0.0003	-
Total Cd	-	0.0011	0.001	0.0011	-	0.000	-	0.0003	-	0.0003	-	0.0003	-	0.0003	-
Dissolved Pb	-	0.0004	0.0005	0.0005	-	0.0010	-	0.001	-	0.0005	-	0.0005	-	0.0005	-
Total Pb	0.008	0.0093	-	0.0026	-	0.0034	-	0.0014	-	0.0025	-	0.0046	-	-	-

sump 2b

Date Sampled	9/07/97	20/04/98	21/04/99	17/04/00	22/09/00	20/04/01	20/09/01	2/05/02	25/09/02	24/04/03	18/09/03	22/04/04	22/09/04	15/04/05	21/09/05
pH	-	-	-	7	7.3	7.04	7.4	6.95	7.32	7.05	6.88	7.26	7.24	7.3	6.69
Conductivity	3690	8100	1905	9900	8730	8630	5900	8830	6070	8870	6970	8720	8420	9910	458
Alkalinity	2500	5300	264	4040	3650	3230	3110	4010	4150	3850	2930	3720	3490	4090	134
Sulphate	3.8	4.8	499	3.5	3.3	3.1	4.3	2.2	23.8	4.8	9.3	11	4.2	9.8	32.7
Chloride	270	800	75	771	680	649	478	658	771	655	437	566	596	784	15.1
Nitrate-N				0.02	0.1	0.05	0.05	0.05	0.83	0.5	0.05	0.2	1.08	0.05	0.05
NH4-N	220	580	67	658	562	540	472	469	704	625	438	656	612	698	14.9
Reactive Silica	38	-	-	42	41	46	45	37.5	34.6	36.2	35.3	33.1	33.2	35.3	13.2
DRP	-	-	-	0.078	0.059	0.04	0.021	0.071	0.021	0.045	0.031	0.098	0.07	0.04	0.16
Anion Balance	-	-	-	-	92.2	-	75.7	-	105	-	71.1	-	86.7	-	3.79
Cation Balance	-	-	-	-	92.6	-	79.4	-	106	-	71.6	-	89.1	-	4.28
Dissolved Na	230	520	57	578	504	513	415	-	529	-	375	503	440	530	11.2
Dissolved K	190	580	80	648	571	563	462	-	609	-	384	511	497	545	22.1
Dissolved Ca	260	160	110	141	155	161	160	-	161	-	140	124	126	134	33.2
Dissolved Mg	56	100	22	107	96.7	104	85.6	-	93.5	-	78.2	88.8	86.7	88.7	3.16
Dissolved B	3.6	7.7	0.76	5.7	5.51	-	4.78	-	5.39	-	4.35	5.25	5.41	6.13	0.153
Dissolved Fe	0.35	8.7	24	5.8	6.9	-	23.2	-	47	-	22.4	2.3	1.8	1.3	6.91
Dissolved Zn	0.006	0.011	0.85	0.035	0.013	-	0.005	-	0.072	-	0.012	0.006	0.008	0.1	0.064
Total B	2.6	7.4	0.54	6.02	5.33	-	4.89	-	6.44	-	4.3	5.99	5.27	6.44	0.15
Total Fe	65	23	21	9.8	22.6	-	24.5	-	70.3	-	24	87.8	30.9	18.2	11
Total Zn	0.14	0.096	1.6	0.222	0.075	-	0.042	-	0.89	-	0.063	0.771	0.34	0.369	0.109
TOC	-	260	87	275	261	214	177	-	418	186	167	206	261	343	31.2
BOD	-	31	14	44	-	36	-	35	-	46	-	50	-	23	-
COD	-	770	213	807	-	608	-	673	-	738	-	1270	-	688	-
BOD/COD	-	0.040	0.066	0.055	-	0.059	-	0.052	-	0.062	-	0.039	-	0.033	-

TKN	-	749	71	611	-	532	-	632	-	609	-	697	-	702	-
Total Anions	-	-	-	103	-	82.9	-	98.8	-	95.5	-	90.7	-	104	-
Total Cations	-	-	-	105	-	92.4	-	87	-	101	-	95.4	-	101	-
Dissolved Al	-	0.027	0.43	0.02	-	0.02	-	0.02	-	0.02	-	0.02	-	0.03	-
Total Al	-	0.27	4.1	0.36	-	0.06	-	0.03	-	0.15	-	0.6	-	0.28	-
Dissolved Cr	-	0.026	0.01	0.011	-	0.012	-	0.012	-	0.011	-	0.011	-	0.012	-
Total Cr	-	0.02	0.013	0.013	-	0.013	-	0.011	-	0.012	-	0.019	-	0.016	-
Dissolved Mn	-	0.99	4.3	0.759	-	0.966	-	1.13	-	0.959	-	0.757	-	0.739	-
Total Mn	-	0.96	4	0.852	-	1.1	-	1.11	-	0.974	-	1.09	-	0.759	-
Dissolved Cobalt	-	0.027	0.015	0.034	-	0.026	-	0.029	-	0.029	-	0.029	-	0.033	-
Total Co	-	0.039	0.013	0.035	-	0.025	-	-	-	0.03	-	0.033	-	0.036	-
Dissolved Ni	-	0.047	0.01	0.044	-	0.027	-	-	-	0.034	-	0.037	-	0.041	-
Total Ni	-	0.052	0.012	0.045	-	0.028	-	-	-	0.035	-	0.039	-	0.045	-
Dissolved Cu	-	0.002	0.002	0.003	-	0.003	-	-	-	0.003	-	0.003	-	0.005	-
Total Cu	-	0.004	0.007	0.003	-	0.005	-	-	-	0.003	-	0.023	-	0.005	-
Dissolved As	-	0.031	0.009	0.016	-	0.009	-	-	-	0.02	-	0.018	-	0.01	-
Total As	-	0.021	0.006	0.014	-	0.013	-	-	-	0.02	-	0.052	-	0.02	-
Dissolved Cd	-	0.0004	0.001	0.0003	-	0.0003	-	-	-	0.0003	-	0.0003	-	0.0005	-
Total Cd	-	0.0015	0.001	0.0003	-	0.0003	-	-	-	0.0003	-	0.0008	-	0.0003	-
Dissolved Pb	-	0.0005	0.0005	0.0006	-	0.0006	-	-	-	0.0005	-	0.0005	-	0.001	-
Total Pb	-	0.0063	0.001	0.0031	-	0.0031	-	-	-	0.0015	-	0.0055	-	0.0069	-

Sump 3a

Date Sampled	07/09/97	04/20/98	04/21/99	04/18/00	09/22/00	04/20/01	09/20/01	05/02/02	09/25/02	04/24/03	09/17/03	04/22/04	09/22/04	04/15/05	09/21/05
pH	-	-	-	7.50	7.54	7.4	7.9	7.2	7.6	7.4	7.4	7.9	7.5	7.9	7.6
Conductivity	2390	7290	9222	9330	8430	9700	9870	14630	6100	14360	4470	8640	11300	13610	874
Alkalinity	1600	4800	3870	3780	3510	3410	5080	6260	1330	6750	310	812	4480	5450	324
Sulphate	24.0	11	120	64.3	16.9	73.8	252.0	170	1030	14	738	708	15.6	19	36.0
Chloride	170	770.0	685.0	708	623	751	1110	1220	431	1120	180	1590	875	1110	71.1
Nitrate-N	-	-	-	0.0	0.0	0.05	0.05	2.23	2.26	0.5	4.00	8.7	1.29	0.8	7.18
NH4-N	260	540	725.0	711	629	696	950	936	375	1250	30	32	997	1130	33
Reactive Silica	26.0	-	-	46	43	53	40	34.2	38.6	32.7	27.5	42.6	31.0	35	22
DRP	-	-	-	0.7	0.134	0.123	1.24	3.79	0.2	2.44	0.081	0.67	1.74	1.14	0.069
Anion Balance	-	-	-	-	88.1	-	138	-	62.0	-	29.5	-	115	-	9.75
Cation Balance	-	-	-	-	88	-	133	-	60.1	-	28.5	-	121	-	10.3
Dissolved Na	130	520	470	551	468	632	844	-	304	-	142	1210	625	727	58
Dissolved K	160	310	410	393	404	427	581	-	231	-	86	855	532	573	47
Dissolved Ca	120	220	140	135	135	151	134	-	212	-	322	88.3	80.6	109	71.7
Dissolved Mg	35	110	100	85	70	87	87	-	43	-	23	52	64	59	8
Dissolved B	2.20	16	13.000	10.2	10.2	-	7.89	-	4.64	-	3.55	19.4	8.24	7.0	1.41
Dissolved Fe	3.70	5.20	1.50	1.8	2.1	-	2.7	-	0.6	-	0.1	0.2	2.1	6.9	0.6
Dissolved Zn	0.005	0.012	0.045	0.010	0.018	-	0.29	-	0.532	-	0.169	0.145	0.049	0.12	0.044
Total B	1.6	13	10	10.9	10.1	-	8.35	-	5.47	-	3.62	22.8	7.71	7.59	1.41
Total Fe	19.0	9.1	6.7	6.6	25.0	-	15.2	-	4.5	-	0.9	5.3	11.1	12.9	2.7
Total Zn	0.068	0.11	0.071	0.043	0.102	-	1.46	-	0.81	-	0.269	0.306	0.54	0.346	0.153
TOC	-	170	289.0	235	235	245	436	-	141	426	32	572	323	609	29.8
BOD	-	67	59	56	-	81	-	123	-	125	-	53	-	83	-
COD	-	960	719	738	-	692	-	1340	-	1450	-	1590	-	1310	-
BOD/COD	-	0.070	0.082	0.076	-	0.117	-	0.092	-	0.086	-	0.033	-	0.063	-

TKN	-	619	666	654	-	707.00	-	1350	-	1290	-	91	-	1450	-
Total Anions	-	-	-	97	-	90.9	-	163	-	167	-	82.1	-	141	-
Total Cations	-	-	-	98.6	-	103.0	-	139	-	162	-	85.4	-	137	-
Dissolved Al	-	0.021	0.028	0.0	-	0	-	0.07	-	0.07	-	0.04	-	0.05	-
Total Al	-	0.28	0.12	0.05	-	0.050	-	0.15	--	1.62	--	0.39	--	0.33	--
Dissolved Cr	-	0.032	0.055	0.024	-	0.0280	-	0.059	-	0.047	-	0.014	-	0.062	-
Total Cr	-	0.032	0.04	0.027	-	0.034	-	0.066	--	0.058	--	0.033	--	0.077	--
Dissolved Mn	-	1.3	0.88	0.716	-	0.897	-	0.66	-	0.519	-	0.068	-	1.22	-
Total Mn	-	1.5	1.1	0.834	-	0.990	-	0.664	-	0.6	-	0.235	-	1.41	-
Dissolved Co	-	0.012	0.033	0.036	-	0.0330	-	0.054	-	0.049	-	0.061	-	0.054	-
Total Co	-	0.027	0.035	0.036	-	0.033	-	-	-	0.050	-	0.065	-	0.059	-
Dissolved Ni	-	0.058	0.056	0.046	-	0.0410	-	-	-	0.115	-	0.164	-	0.115	-
Total Ni	-	0.051	0.056	0.046	-	0.0430	-	-	-	0.116	-	0.180	-	0.125	-
Dissolved Cu	-	0.002	0.009	0.0	-	0.0	-	-	-	0.0	-	0.029	-	0.005	-
Total Cu	-	0.005	0.009	0.0	-	0.014	-	-	-	0.006	-	0.035	-	0.007	-
Dissolved As	-	0.023	0.087	0.021	-	0.016	-	-	-	0.02	-	0.041	-	0.03	-
Total As	-	0.031	0.027	0.023	-	0.032	-	-	-	0.029	-	0.048	-	0.042	-
Dissolved Cd	-	0.0004	0.001	0.0003	-	0.000	-	-	-	0.001	-	0.0005	-	0.0005	-
Total Cd	-	0.0009	0.001	0.0003	-	0.000	-	-	-	0.0004	-	0.0006	-	0.0005	-
Dissolved Pb	-	0.0002	0.0005	0.0	-	0.0	-	-	-	0.001	-	0.0014	-	0.001	-
Total Pb	-	0.0021	0.002	0.0005	-	0.0012	-	-	-	0.0112	-	0.0058	-	0.0051	-

Sump 3b

Date Sampled	07/09/97	04/20/98	04/21/99	04/19/00	09/22/00	04/20/01	09/20/01	05/03/02	09/25/02	04/24/03	09/17/03	04/26/04	09/22/04	04/19/05	09/21/05
pH	-	-	-	7.10	7.45	7.3	7.8	7.2	7.5	7.2	7.3	7.2	7.3	7.9	7.0
Conductivity	6340	9740	11910	12180	10100	12650	10600	12590	787	11400	1729	10340	9350	6500	492
Alkalinity	4600	6100	4950	4820	4880	5000	5760	5190	136	4940	517	4080	3580	3470	188
Sulphate	6.2	130	19	6.0	3.7	44.8	18.5	22	44	19	88	10	8.6	4.2	19.6
Chloride	550	810	813.0	980	1150	930	1420	1190	64.3	916	124	612	645	729	23.4
Nitrate-N	-	-	-	0.0	0.04	0.05	0.1	1.1	20	0.8	12.4	0.7	0.93	0.05	0.05
NH4-N	590	880	911	843	898	811	935	957	14.9	875	76	802	716	631	3.98
Reactive Silica	50	-	-	46	46	56	44	35	40	35	31	33	31	40	31
DRP	-	-	-	1	0.872	1.38	3.15	2.7	0.202	1.67	0.297	1.4	0.67	0.521	0.015
Anion Balance	-	-	-	-	130.0	-	156	-	6.87	-	16.50		90.1	-	4.82
Cation Balance	-	-	-	-	125	-	150	-	6.82	-	16.60		93.6	-	5.06
Dissolved Na	480	580	550	781	679	958	1170	-	47	-	97	599	466	478	16
Dissolved K	340	630	650	691	727	656	719	-	37	-	79	554	436	485	21
Dissolved Ca	200	150	160	152	118	140	119	-	42	-	75	87	125	110	58
Dissolved Mg	96	96	100	98.7	85.5	86.1	92.5	-	8.19	-	14	62	56	57	7
Dissolved B	7.8	8.50	7.70	8.94	7.97	-	8.46	-	0.556	-	1.0	5.9	5.7	5.2	0.19
Dissolved Fe	2.4	3.3	2.7	5.0	2.8	-	4.3	-	0.1	-	0.5	4.8	5.8	2.2	1.26
Dissolved Zn	0.04	0.032	0.24	0.020	0.014	-	0.07	-	0.071	-	0.034	0.010	0.021	0.022	0.029
Total B	5.7	8.1	6.7	9.2	7.73	-	9.08	-	0.656	-	1.03	6.54	5.57	6.08	0.189
Total Fe	16.0	7.9	32	7.0	10.4	-	6.2	-	0.31	-	1.08	9.3	21.6	10.3	10.6
Total Zn	0.69	0.12	0.45	0.111	0.038	-	0.26	-	0.085	-	0.045	0.041	1.17	0.349	0.082
TOC	-	300	289.0	367	420	400	541	-	18.4	162	39.8	292	323	231	17.2
BOD	-	84	83	80		115	-	87	-	68		64		36	-

COD	-	640	1310	1030	-	1140	-	1150	-	1070	-	855	-	799	-
BOD/COD	-	0.13	0.063	0.077	-	0.100	-	0.075	-	0.063	-	0.074	-	0.045	-
TKN	-	970	939	858	-	816.00	-	1010	-	884	-	1130	-	634	-
Total Anions	-			124	-	127.0	-	138	-	125	-	99.1	-	90.1	-
Total Cations	--			128	--	131.0	--	141	--	129	--	107	--	88.5	--
Dissolved Al	-	0.048	0.027	0.03	-	0.06	-	0.09	-	0.05	-	0.03	-	0.03	-
Total Al	--	0.6	1.1	0.08	--	0.320	--	0.5	--	0.3	--	0.13	--	0.47	--
Dissolved Cr	-	0.069	0.077	0.039	-	0.0980	-	0.066	-	0.038	-	0.027	-	0.02	-
Total Cr	-	0.044	0.036	0.04	-	0.106	-	0.072	-	0.043	-	0.031	-	0.026	-
Dissolved Mn	-	1.5	1.4	1.27	-	0.897	-	0.837	-	0.826	-	0.752	-	0.859	-
Total Mn	-	1.8	2.2	1.43	-	1.01	-	0.879	-	0.834	-	0.875	-	987	-
Dissolved Cobalt	-	0.038	0.041	0.037	-	0.0290	-	0.046	-	0.038	-	0.033	-	0.027	-
Total Co	-	0.051	0.05	0.037	-	0.030	-	-	-	0.037	-	0.035	-	0.03	-
Dissolved Ni	-	0.086	0.11	0.092	-	0.0710	-	-	-	0.075	-	0.066	-	0.052	-
Total Ni	-	0.085	0.099	0.092	-	0.0770	-	-	-	0.078	-	0.067	-	0.058	-
Dissolved Cu	-	0.002	0.008	0.0	-	0.0	-	-	-	0.0	-	0.0	-	0.003	-
Total Cu	-	0.004	0.017	0.0	-	0.022	-	-	-	0.022	-	0.003	-	0.004	-
Dissolved As	-	0.082	0.091	0.02	-	0.081	-	-	-	0.02	-	0.025	-	0.025	-
Total As	-	0.031	0.056	0.022	-	0.097	-	-	-	0.028	-	0.025	-	0.036	-
Dissolved Cd	-	0.0003	0.001	0.0003	-	0.000	-	-	-	0.000	-	0.000	-	0.0003	-
Total Cd	-	0.0014	0.001	0.0003	-	0.0003	-	-	-	0.000	-	0.000	-	0.0003	-
Dissolved Pb	-	0.0003	0.0005	0.0010	-	0.0012	-	-	-	0.001	-	0.0006	-	0.0005	-
Total Pb	-	0.0011	0.005	0.0065	-	0.0051	-	-	-	0.0029	-	0.0017	-	0.0031	-

Sump 3c															
Date Sampled	**07/09/97**	**04/20/98**	**04/21/99**	**04/19/00**	**09/22/00**	**04/20/01**	**09/20/01**	**05/03/02**	**09/25/02**	**04/24/03**	**09/17/03**	**04/26/04**	**09/22/04**	**04/18/05**	**09/21/05**
pH	-	-	-	7.2	6.6	7.0	7.9	7.1	6.8	7.4	7.4	7.4	6.7	7.3	6.7
Conductivity	5240	6530	2530	4880	1930	4410	8770	3310	1365	3130	706	2360	1245	4350	904
Alkalinity	3700	3900	1010	1990	911	1430	4530	1490	542	1280	180	1020	378	1870	340
Sulphate	6	130	110	34.8	22.7	174	19	49.1	13.8	64.0	14.2	18.0	5.7	4.3	7.1
Chloride	380	510	175	328	118	250	1090	168	70.3	189	19.2	103	34.3	18.3	48.6
Nitrate-N	-	-	-	0.0	0.0	0.05	0.3	0.05	0.6	5.88	0.35	0.4	0.05	0.05	0.19
NH4-N	480	710	175	298	105	297	768	163	57.5	183	9.1	134	42.1	302	42.8
Reactive Silica	35	-	-	42	45	38	40	37	42	33	14	32	17	27	18
DRP	-	-	-	0.400	0.010	0.125	0.726	0.056	0.011	0.046	0.066	0.015	0.005	0.02	0.112
Anion Balance	-	-	-	-	22.0	-	122	-	13.1	-	4.5		8.65		8.34
Cation Balance	-	-	-	-	21	-	124	-	12.8	-	4.6		11.1		8.76
Dissolved Na	320	330	140	239	77	193	942	-	41.2	-	12.0	78.4	32.5	181	32.1
Dissolved K	240.0	470	230.0	253	84	250	602	-	47.9	-	15.1	107	52.5	215	41
Dissolved Ca	170	140	85	164	119	135	130	-	86	-	50	109	78	155	50
Dissolved Mg	85.00	54	20	42	21	33	77	-	14	-	4.5	17.9	10.3	29.2	6.46
Dissolved B	9.4	4.8	1.6	2.88	0.92	-	6.79	-	0.498	-	0.106	1.14	0.431	2.1	0.415
Dissolved Fe	1.80	4.50	3.80	0.8	20.4	-	9.6	-	9.19	-	4.07	0.27	14.8	9.2	7.17
Dissolved Zn	0.079	0.011	0.019	0.012	0.036	-	0.056	-	0.014	-	0.044	0.041	0.026	0.015	0.059
Total B	8.7	4.2	1.2	2.9	0.9	-	7.14	-	0.567	-	0.106	1.27	0.437	2.17	0.441
Total Fe	11.0	7.1	5.8	3.6	25.1	-	13.7	-	15.4	-	5.5	13.5	16.6	11.5	14.2
Total Zn	0.570	0.077	0.11	0.058	0.069	-	0.2	-	0.030	-	0.051	0.092	0.063	0.143	0.097
TOC	-	250	129.0	134	122	113.0	445.0	-	46	90.0	24	57	35.5	119	39.1
BOD	-	21	20	21	-	18	-	15	-	5	-	6	-	10	-
COD	-	640	291	422	-	329	-	245	-	213	-	153	-	343	-
BOD/COD	-	0.03	0.07	0.05	-	0.05	-	0.06	-	0.02	-	0.04	-	0.03	-

TKN	-	619	147	335	-	297.00	-	219	-	182	-	2000	-	314	-
Total Anions	-	-	-	49.8	-	39.3	-	35.5	-	32.7	-	23.8	-	38	-
Total Cations	-	-	-	49.8	-	45.7	-	31.4	-	33.6	-	22.6	-	45.4	-
Dissolved Al	-	0.073	0.1	0.03	-	0.029	-	0.041	-	0.012	-	0.004	-	0.02	-
Total Al	--	0.55	0.72	0.340	--	0.063	--	0.306	--	0.15	--	0.55	--	0.202	--
Dissolved Cr	-	0.058	0.012	0.012	-	0.0120	-	0.008	-	0.005	-	0.003	-	0.009	-
Total Cr	--	0.038	0.013	0.015	--	0.012	--	0.009	--	0.007	--	0.004	--	0.011	--
Dissolved Mn	-	1.6	0.83	1.73	-	1.72	-	2.5	-	1.49	-	2.02	-	1.55	-
Total Mn	-	1.9	0.85	1.99	-	1.72	-	2.63	-	1.49	-	2.45	-	1.6	-
Dissolved Cobalt	-	0.032	0.009	0.016	-	0.0139	-	0.0114	-	0.0109	-	0.0067	-	0.013	-
Total Co	-	0.044	0.01	0.017	-	0.0137	-	-	-	0.0114	-	0.007	-	0.0132	-
Dissolved Ni	-	0.053	0.015	0.014	-	0.0100	-	-	-	0.004	-	0.003	-	0.009	-
Total Ni	-	0.055	0.015	0.015	-	0.0110	-	-	-	0.005	-	0.002	-	0.011	-
Dissolved Cu	-	0.001	0.002	0.0	-	0.0	-	-	-	0.0	-	0.0	-	0.003	-
Total Cu	-	0.004	0.006	0.0	-	0.003	-	-	-	0.003	-	0.002	-	0.003	-
Dissolved As	-	0.052	0.027	0.008	-	0.009	-	-	-	0.003	-	0.002	-	0.013	-
Total As	-	0.017	0.019	0.010	-	0.010	-	-	-	0.006	-	0.007	-	0.015	-
Dissolved Cd	-	0.0002	0.0003	0.000	-	0.000	-	-	-	0.000	-	0.000	-	0.0003	-
Total Cd	-	0.0012	0.001	0.000	-	0.000	-	-	-	0.000	-	0.000	-	0.0001	-
Dissolved Pb	-	0.0002	0.0005	0.0	-	0	-	-	-	0.000	-	0.000	-	0.0005	-
Total Pb	-	0.0007	0.001	0.0007	-	0.0004	-	-	-	0.0009	-	0.0006	-	0.001	-

Sump 4a East

Date Sampled	04/20/98	04/21/99	04/18/00	09/22/00	04/20/01	09/21/01	05/03/02	09/18/03	04/26/04	09/22/04	04/19/05	09/21/05
pH	-	-	7.1	7.25	7.46	7.9	7.95	7.94	7.83	8.16	8.18	7.55
Conductivity	4890	13320	13830	7480	13480	10400	21300	2250	23400	20900	21100	14880
Alkalinity	2800	5350	5560	3330	5250	5800	10800	10500	10600	9550	9230	5560
Sulphate	0.4	1	24.5	7.2	6.6	40.7	25.3	420	194	194	9	92
Chloride	690	1430	1230	670	1390	1200	1960	1620	1330	1560	1650	1300
Nitrate-N	-	-	0.02	0.03	0.05	0.1	1.28	1	0.05	0.5	0.7	0.5
NH4-N	160	887	906	560	893	935	1090	1640	1600	2050	2050	1240
Reactive Silica	-	-	65	50	40	70	40.3	60.7	10.8	66	32.9	31.6
DRP	-	-	0.9	2.39	8.34	3.5	12.9	18.7	21.4	22.2	18	5.08
Anion Balance	-	-	-	85.6	-	151	-	266	-	239	-	150
Cation Balance	-	-	-	83.2	-	146	-	214	-	243	-	152
Dissolved Na	570	970	1130	489	1100	1000	-	1360	1420	1320	1460	867
Dissolved K	160	580	714	446	676	735	-	1160	1210	1210	1180	721
Dissolved Ca	410	200	187	127	175	164	-	69	55.5	71.4	61	82.2
Dissolved Mg	120	140	120	50.4	106	97	-	53	47.9	52.1	47.4	35.8
Dissolved B	8.1	29	15.8	8.22	-	13.9	-	9.1	11.9	12.5	13.9	8.44
Dissolved Fe	32	2	4.2	1.6	-	1.5	-	1.7	1.5	2.5	2.5	8.2
Dissolved Zn	0.008	0.049	0.117	0.045	-	0.11	-	0.38	0.47	0.47	0.35	0.05
Total B	9.3	19	17.1	7.96	-	15.2	-	10.8	13.8	12.6	16.5	8.03
Total Fe	59	8.3	12.4	4.2	-	5.1	-	4	4.4	2.9	3.1	9.4
Total Zn	0.065	0.24	0.665	0.394	-	1.11	-	1.52	1.47	2.98	0.51	0.325
TOC	220	489	486	325	463	873	-	1920	2110	1960	1730	787
BOD	320		135	-	201	-	263	-	766	-	410	-
COD	790	1520	1570	-	1360	-	2770	-	8020	-	4550	-
BOD/COD	0.41		0.09	-	0.15	-	0.09	-	0.10	-	0.09	-

TKN	94	819	1050	-	892	-	2010	-	2570	-	2260	-
Total Anions	-	-	146	-	144	-	272	-	254	-	231	-
Total Cations	-	-	151	-	147	-	187	-	214	-	247	-
Dissolved Al	0.048	0.057	0.09	-	0.08	-	0.41	-	1.36	-	1.74	-
Total Al	0.31	0.13	0.24	--	0.1	--	0.64	--	2.71	--	2.54	--
Dissolved Cr	0.033	0.16	0.134	-	0.115	-	0.406	-	1.19	-	1.43	-
Total Cr	0.04	0.12	0.142	--	0.121	--	0.427	--	1.68	--	1.47	--
Dissolved Mn	6.5	1	1.34	-	0.989	-	0.436	-	0.502	-	0.43	-
Total Mn	6.8	1.3	1.49	-	1.03	-	0.483	-	0.672	-	0.419	-
Dissolved Cobalt	0.0041	0.016	0.022	-	0.024	-	0.039	-	0.041	-	0.06	-
Total Co	0.028	0.015	0.024	-	0.025	-	-	-	0.056	-	0.064	-
Dissolved Ni	0.022	0.091	0.091	-	0.077	-	-	-	0.151	-	0.19	-
Total Ni	0.028	0.093	0.094	-	0.077	-	-	-	0.173	-	0.197	-
Dissolved Cu	0.002	0.018	0.004	-	0.005	-	-	-	0.02	-	0.03	-
Total Cu	0.008	0.019	0.013	-	0.011	-	-	-	0.143	-	0.058	-
Dissolved As	0.14	0.41	0.135	-	0.09	-	-	-	0.97	-	1.07	-
Total As	0.13	0.12	0.172	-	0.1	-	-	-	1.46	-	1.19	-
Dissolved Cd	0.0004	0.0003	0.0004	-	0.0005	-	-	-	0.0009	-	0.001	-
Total Cd	0.0012	0.001	0.0006	-	0.0005	-	-	-	0.0031	-	0.0013	-
Dissolved Pb	0.0004	0.0005	0.0035	-	0.002	-	-	-	0.015	-	0.013	-
Total Pb	0.0024	0.006	0.014	-	0.008	-	-	-	0.054	-	0.021	-

Sump 4a West

Date Sampled	04/20/98	04/21/99	04/18/00	09/22/00	04/20/01	09/21/01	05/03/02	09/25/02	04/24/03	09/18/03	04/26/04	09/22/04	04/19/05	09/21/05
pH			7.1	7.0	7.5	7.8	7.7	6.8	7.6	7.6	7.3	7.2	8.0	8.3
Conductivity	7220	13500	12610	4030	12580	3710	5660	4450	16240	10630	9110	10400	9860	7070
Alkalinity	4900	5310	4640	1920	4930	2430	2480	1880	7050	4010	3510	3990	3250	2740
Sulphate	0.4	1	5.5	7.5	4.5	0.5	1.9	21.1	23	12.4	246	59	1320	203
Chloride	680	1450	936	278	1130	393	420	299	1340	953	466	781	916	504
Nitrate-N			0.0	0.0	0.05	0.05	0.05	0.1	0.5	0.53	0.05	0.50	0.8	0.70
NH4-N	510	894	754	297	920	351	245	247	1370	746	662	763	884	472
Reactive Silica			47	41	65	42	32	35	37	28	36	34	34	33
DRP			0.4	0.025	1.73	0.957	3.45	0.023	10.6	5.92	4.27	0.31	2.21	3.29
Anion Balance				46.4		59.7		46.5		107		103		73.2
Cation Balance				46		61.1		42.2		107		106		70.9
Dissolved Na	480	930	770	230	984	373		213		807	515	607	710	407
Dissolved K	260	570	593	215	652	277		180		447	400	461	544	483
Dissolved Ca	290	170	157	120	135	179		160		87	171	173	128	99
Dissolved Mg	120	140	92	29	81	45		28		38	51	60	38	24
Dissolved B	20	17	10.8	4.18		5.28		2.58		4.5	4.5	7.1	7.3	4.9
Dissolved Fe	11.0	2.1	5.8	11.3		2.6		12.4		4.1	0.5	6.3	6.3	3.9
Dissolved Zn	0.01	0.05	0.045	0.033		0.005		0.020		0.044	0.046	0.046	0.05	0.345
Total B	21	12	13.6	4.3		5.47		3.33		4.4	5.0	7.2	8.7	5.0
Total Fe	17.0	7.8	8.1	14.6		21.3		16.6		5.2	4.3	14.5	8.4	5.2
Total Zn	0.22	0.25	0.158	0.115		0.158		0.06		0.13	0.182	0.36	0.099	0.610
TOC	260	470	433	163	396	177		113	691	438	257	374	574	627
BOD	230		75		110		38		285		63		47	
COD	760	1490	1180		1220		399		2340		868		1560	
BOD/COD	0.30		0.06		0.09		0.10		0.12		0.07		0.03	

TKN	456	732	734		948.00		384		1450		700		943	
Total Anions			119		131.0		61.6		179		88.3		118	
Total Cations			118		139.0		50.3		180		92.7		118	
Dissolved Al	0.033	0.056	0.04		0.07		0.02		1.15		0.09		0.12	
Total Al	0.24	0.099	0.08		0.110		0.060		0.72		0.22		0.27	
Dissolved Cr	0.069	0.16	0.147		0.132		0.030		0.180		0.084		0.316	
Total Cr	0.071	0.12	0.148		0.134		0.032		0.29		0.094		0.353	
Dissolved Mn	2	0.96	1.14		0.844		1.78		0.626		1.39		0.717	
Total Mn	2.5	1.4	1.15		0.888		1.9		1.08		1.57		0.762	
Dissolved Cobalt	0.0037		0.016		0.0270		0.0090		0.035		0.020		0.042	
Total Co	0.035	0.015	0.02		0.027				0.039		0.020		0.045	
Dissolved Ni	0.032	0.092	0.066		0.0690				0.105		0.043		0.087	
Total Ni	0.038	0.1	0.079		0.0720				0.109		0.041		0.096	
Dissolved Cu	0.003	0.017	0.003		0.0				0.0		0.0		0.018	
Total Cu	0.01	0.016	0.005		0.006				0.015		0.003		0.045	
Dissolved As	0.067	0.44	0.100		0.134				0.23		0.041		0.8	
Total As	0.065	0.18	0.124		0.145				0.40		0.049		0.969	
Dissolved Cd	0.0005	0.0003	0.0003		0.000				0.001		0.000		0.0005	
Total Cd	0.0014	0.001	0.0004		0.0004				0.001		0.000		0.0003	
Dissolved Pb	0.0004	0.0005	0.0015		0.0020				0.002		0.001		0.001	
Total Pb	0.0081	0.005	0.007		0.0046				0.009		0.0012		0.0031	

Sump 4b East

Date Sampled	04/19/00	09/22/00	04/20/01	09/21/01	05/03/02	09/25/02	04/24/03	09/18/03	04/26/04	09/22/04	04/20/05	09/21/05
pH	7.1	7.3	7.3	7.7	7.6	7.6	8.0	7.0	7.5	8.0	7.6	8.2
Conductivity	10680	9840	12990	8060	11940	14910	15780	140	12130	9100	18480	14160
Alkalinity	4320	4620	5370	4320	5310	5790	6540	2720	4750	3660	8030	5850
Sulphate	37.6	2.2	38.0	1.8	48.0	52.9	43	183	13	39	7	35
Chloride	997	1150	909	725	1030	1320	1420	417	910	599	1750	1150
Nitrate-N	0.0	0.0	0.1	0.05	0.05	0.1	0.5	6.10	0.05	0.50	0.7	0.50
NH4-N	603	756	961	697	642	1220	1270	311	891	685	1650	1070
Reactive Silica	57	54	74	49	38	47	49	41	41	37	37	42
DRP	0.6	2.970	7.60	3.47	7.90	9.2	12.40	3.56	7.43	3.37	11.70	9.20
Anion Balance		125.0	-	107	-	154	-	70.4	-	90.8	-	150
Cation Balance		123	-	110	-	155	-	66.8	-	95.0	-	145
Dissolved Na	794	918	892	762	-	896	-	388	779	580	1320	858
Dissolved K	548	596	806	552	-	816	-	282	590	457	940	786
Dissolved Ca	290	128	142	149	-	86	-	310	211	98	86	126
Dissolved Mg	121	85	64	65	-	42	-	60	60	51	57	53
Dissolved B	7.3	11.70	-	11.8	-	7.0	-	4.2	5.2	5.0	7.2	8.2
Dissolved Fe	4.9	4.5	-	5.3	-	4.6	-	1.2	1.1	2.3	5.3	2.7
Dissolved Zn	0.068	0.085	-	0.096	-	0.175	-	0.055	0.054	0.047	0.09	0.14
Total B	7.4	11.8	-	11.8	-	9.6	-	4.5	5.6	4.7	9.5	8.0
Total Fe	4.5	4.9	-	7.3	-	8.1	-	21.6	1.7	2.8	9.6	3.3
Total Zn	0.157	0.149	--	0.298	-	0.42	-	1.66	0.15	0.13	0.22	0.245
TOC	383	437	724	419.0	-	1020	1020	1010	524	341	1170	896
BOD	82	-	241	-	113	-	192	-	121	-	163	-

COD	1090	-	2020	-	1600	-	2980	-	1320	-	2910	-
BOD/COD	0.08	-	0.12	-	0.07	-	0.06	-	0.09	-	0.06	-
TKN	584	-	1020.00	-	932	-	1260	-	971	-	1930	-
Total Anions	115	-	134.0	-	136.0	-	172	-	121	-	210	-
Total Cations	116	--	141.0	--	110.0	--	186	--	128	--	208	--
Dissolved Al	0.08	-	0.72	-	0.39	-	0.77	-	0.37	-	0.45	-
Total Al	0.09	--	0.940	--	0.630	--	0.79	--	0.55	--	4.27	--
Dissolved Cr	0.103	-	0.595	-	0.431	-	0.949	-	0.468	-	0.73	-
Total Cr	0.108	-	0.698	-	0.458	-	0.877	-	0.486	-	0.831	-
Dissolved Mn	2.86	-	1.75	-	1.14	-	1.05	-	1.63	-	1.04	-
Total Mn	3.09	-	1.83	-	1.2	-	0.944	-	1.87	-	1.17	-
Dissolved Cobalt	0.026	-	0.0250	-	0.0280	-	0.036	-	0.019	-	0.051	-
Total Co	0.026	-	0.028	-	-	-	0.036	-	0.019	-	0.057	-
Dissolved Ni	0.056	-	0.0870	-	-	-	0.126	-	0.072	-	0.15	-
Total Ni	0.056	-	0.0890	-	-	-	0.121	-	0.071	-	0.162	-
Dissolved Cu	0.003	-	0.007	-	-	-	0.006	-	0.003	-	0.01	-
Total Cu	0.006	-	0.042	-	-	-	0.014	-	0.009	-	0.012	-
Dissolved As	0.088	-	0.230	-	-	-	0.22	-	0.153	-	0.16	-
Total As	0.086	-	0.280	-	-	-	0.25	-	0.14	-	0.19	-
Dissolved Cd	0.0003	-	0.001	-	-	-	0.001	-	0.0004	-	0.001	-
Total Cd	0.0003	-	0.0005	-	-	-	0.001	-	0.0006	-	0.001	-
Dissolved Pb	0.0014	-	0.0100	-	-	-	0.006	-	0.0028	-	0.005	-
Total Pb	0.004		0.0250	-	-	-	0.011	-	0.006		0.013	-

Sump 4b west

Date Sampled	04/21/99	04/19/00	09/22/00	04/20/01	09/21/01	05/03/02	09/25/02	04/24/03	09/18/03	04/26/04	09/22/04	04/19/05	09/21/05
pH		6.5	6.78	7.7	7.3	7.6	7.2	7.5	6.9	7.3	7.3	8.3	7.3
Conductivity	10120	2560	3130	3990	2310	13070	5000	15600	2690	10050	13380	13800	11220
Alkalinity	4300	965	1490	1300	1400	4950	1760	7140	893	3890	4880	5410	4050
Sulphate	1	61.1	3.2	39.6	2.3	85.4	162	5.0	263	11.0	21	110	213
Chloride	1020	158	227	291	190	1310	397	1410	202	664	1170	1240	909
Nitrate-N	-	0.0	0.02	0.05	0.05	1135	0.1	0.5	1.08	0.05	0.50	0.7	0.50
NH4-N	478	128	165	235	123	623	324	1240	119	719	952	1130	969
Reactive Silica	--	28	38	39	40	28	26	34	27	29	34	32	34
DRP	-	0.4	0	0.376	0.014	1.44	0.535	6.42	0.04	1.3	2.05	6.96	3.17
Anion Balance	-	-	36	-	33.4	-	49.8	-	29.8	-	131	-	111
Cation Balance	-	-	35.6	-	33	-	47	-	25.8	-	139	-	118
Dissolved Na	710	125	165	252	195	-	273	-	167	606	920	968	632
Dissolved K	450	130	188	220	135	-	237	-	119	447	650	722	563
Dissolved Ca	380	77.8	160	104	163	-	80.8	-	104	191	167	107	83.4
Dissolved Mg	200	24	39.8	34	43	-	22	-	23	61	72	51	34
Dissolved B	17.0	1.24	2.46	-	1.78	-	2.37	-	2.01	5.42	9.43	8.9	6.65
Dissolved Fe	2.2	10.0	17	-	15.5	-	3.99	-	0.30	4.9	7.5	0.8	6.9
Dissolved Zn	0.02	0.007	0	-	0.023	-	0.011	-	0.028	0.017	0.041	0.02	0.021
Total B	12.0	1.28	2.60	-	1.88	-	3.21	-	2.09	6.08	8.75	10.2	6.13

Total Fe	7.6	6.4	18.4	-	27.6	-	7.8	-	9.4	8.6	10.5	2.2	8.6
Total Zn	0.089	0.187	0.2	-	1.31	-	0.09	-	0.37	0.054	0.32	0.08	0.095
TOC	266	67	141	112.0	105	-	185	610	67.7	299	542	772	541
BOD	98	24	-	27	-	32	-	171	-	63	-	83	-
COD	903	290	-	349	-	1250	-	2000	-	929	-	1800	-
BOD/COD	0.11	0.082	-	0.078	-	0.026	-	0.086	-	0.068	-	0.046	-
TKN	478	142	-	231.00	-	971	-	1240	-	757	-	1220	-
Total Anions		25	--	35.0	--	138.0	--	183	--	96.8	--	145	--
Total Cations		24.1	-	41.5	-	110.0	-	175	-	104	-	151	-
Dissolved Al	0.052	0.02	--	0.031	--	0.070	--	0.20	--	0.06	--	0.25	--
Total Al	0.22	0.74	-	0.088	-	0.420	-	0.21	-	0.19	-	0.32	-
Dissolved Cr	0.093	0.013	-	0.0230	-	0.1480	-	0.322	-	0.110	-	0.37	-
Total Cr	0.072	0.014	-	0.025	-	0.168	-	0.320	-	0.127	-	0.380	-
Dissolved Mn	3.8	1.66	-	2.13	-	0.548	-	0.807	-	1.79	-	0.591	-
Total Mn	3.8	1.88	-	2.16	-	0.647	-	0.733	-	2.06	-	0.589	-
Dissolved Cobalt	0.011	0.0037	-	0.0089	-	0.036	-	0.037	-	0.016	-	0.042	-
Total Co	0.011	0.0043	-	0.0087	-	-	-	0.036	-	0.017	-	0.043	-
Dissolved Ni	0.095	0.009	-	0.0170	-	-	-	0.108	-	0.047	-	0.109	-
Total Ni	0.11	0.01	-	0.0180	-	-	-	0.109	-	0.047	-	0.109	-
Dissolved Cu	0.013	0.003	-	0.030	-	-	-	0.0	-	0.0	-	0.005	-
Total Cu	0.014	0.008	-	0.057	-	-	-	0.007	-	0.003	-	0.006	-
Dissolved As	0.14	0.022	-	0.033	-	-	-	0.13	-	0.068	-	0.19	-
Total As	0.05	0.022	-	0.048	-	-	-	0.14	-	0.079	-	0.22	-
Dissolved Cd	0.0003	0.0001	-	0.0001	-	-	-	0.001	-	0.000	-	0.0005	-
Total Cd	0.001	0.0001	-	0.0002	-	-	-	0.0005	-	0.0003	-	0.0004	-
Dissolved Pb	0.0005	0.0005	-	0.0015	-	-	-	0.001	-	0.001	-	0.001	-
Total Pb	0.002	0.006	-	0.0033	-	-	-	0.005	-	0.0014	-	0.001	-

Sump 4c North

Date Sampled	**04/20/00**	**09/22/00**	**04/20/01**	**09/21/01**	**05/03/02**	**09/25/02**	**04/24/03**	**09/18/03**	**04/27/04**	**09/22/04**	**04/19/05**	**09/21/05**
pH	7.6	7.34	7.5	8.0	7.3	7.2	7.8	7.6	7.1	7.6	8.0	7.6
Conductivity	7270	5740	15030	11500	15449	3880	17100	20100	4650	15080	15590	17020
Alkalinity	2620	2650	5240	5990	6850	1510	6950	3660	6550	6050	6670	6690
Sulphate	65.3	1.5	11.0	18.3	19.4	9.5	13	12.7	18	5	81	21
Chloride	854	674	256	1410	1630	258	1730	682	1480	1280	1140	1520
Nitrate-N	0.0	0.0	0.05	0.1	0.05	0.1	0.5	0.49	0.05	0.50	0.7	0.50
NH4-N	185	317	940	921	877	219	1390	603	1240	1190	1430	1390
Reactive Silica	46	41	38	43	37	17	36	31	34	35	34	31
DRP	0.152	0.022	2.88	3.11	4.99	0.692	7.65	2.73	8.09	6.89	8.14	9.85
Anion Balance		72.0		160		37.6		92.8		157		177
Cation Balance		70		152		38.1		93.8		164		173
Dissolved Na	1020	533	1560	1210	1220	321		675	1180	1110	943	1040
Dissolved K	192	314	708	752	853	165		411	732	753	662	809
Dissolved Ca	100	132	132	123	122	56		126	94	123	98	94
Dissolved Mg	91	107	118	95	93	17		54	58	66	50	41
Dissolved B	3.42	4.51		8.65	11.10	1.74		4.36	7.35	6.56	6.1	7.59
Dissolved Fe	5.6	11.1		4.6	5.7	1.4		4.8	6.3	6.7	3.3	6.6
Dissolved Zn	0.130	0.009		0.07	0.090	0.071		0.038	0.060	0.044	0.07	0.05
Total B	3.35	4.5		8.84	10.90	2.19		4.3	7.92	6.34	7.13	7.08
Total Fe	5.8	13.4		5.6	5.2	4.2		7.1	6.9	8.6	7.6	7.6
Total Zn	0.135	0.026		0.24	0.110	0.33		0.125	0.09	0.20	0.22	0.165
TOC	154	161	457	540	671	262	673	345	716	651	752	851
BOD	29		154		124		242		180		97	
COD	430		1240		1670		2400		1970		1830	
BOD/COD	0.07		0.12		0.07		0.10		0.09		0.05	
TKN	204		968.00		1300		1410		1550		1470	
Total Anions	77.9		112.0		183.0		188		173		167	

Total Cations	75.3		170.0		151.0		195		168		169	
Dissolved Al	0.04		0.11		0.13		0.38		0.22		0.37	
Total Al	0.05		0.150		0.160		0.70		0.39		0.67	
Dissolved Cr	0.017		0.1130		0.1850		0.421		0.354		0.37	
Total Cr	0.019		0.123		0.192		0.479		0.383		0.431	
Dissolved Mn	1.42		1.31		0.942		1.19		0.999		0.998	
Total Mn	1.42		1.41		0.886		1.26		1.08		1.16	
Dissolved Cobalt	0.006		0.0280		0.0410		0.040		0.041		0.033	
Total Co	0.006		0.030		0.040		0.042		0.040		0.037	
Dissolved Ni	0.031		0.0780		0.101		0.118		0.113		0.092	
Total Ni	0.031		0.0830		0.099		0.119		0.113		0.102	
Dissolved Cu	0.003		0.0		0.0		0.006		0.005		0.01	
Total Cu	0.003		0.025		0.006		0.013		0.009		0.066	
Dissolved As	0.039		0.090		0.120		0.17		0.150		0.23	
Total As	0.036		0.110		0.140		0.202		0.15		0.28	
Dissolved Cd	0.0003		0.001		0.001		0.001		0.0008		0.0005	
Total Cd	0.0003		0.0005		0.0005		0.0007		0.0009		0.0005	
Dissolved Pb	0.0015		0.0030		0.003		0.003		0.002		0.002	
Total Pb	0.002		0.0070		0.004		0.0066		0.004		0.009	

Sump 4c South

Date Sampled	**04/18/00**	**09/22/00**	**04/20/01**	**09/21/01**	**05/03/02**	**09/25/02**	**04/24/03**	**09/18/03**	**04/26/04**	**09/22/04**	**04/19/05**	**09/21/05**
pH	7.6	7.32	7.5	7.8	7.3	7.5	7.6	7.4	7.6	7.7	7.8	7.7
Conductivity	10010	2860	9120	10200	12500	14090	19590	13010	17860	20200	21200	14120
Alkalinity	3410	1470	3120	5310	5610	5400	9180	2350	6790	7780	8790	5470
Sulphate	21	1.1	9.1	1.5	2.4	9.8	46	29.2	33	96	184	250
Chloride	1210	183	794	1310	1160	1500	2160	567	1660	2000	1640	1090
Nitrate-N	0.0	0.0	0.05	0.05	0.05	0.1	0.5	0.05	0.05	0.50	0.6	0.50
NH4-N	412	103	577	822	709	1110	1680	440	1310	1650	2050	1300
Reactive Silica	49	36	28	41	40	38	40	24	40	39	28	30
DRP	0.4	0.110	0.834	2.94	5.11	5.2	9.29	3.7	11.3	11.8	10.8	6.78

Anion Balance		34.5		143		150		63.6		214		145
Cation Balance		35		141		151		64.9		216		148
Dissolved Na	978	134	737	1140	801	1030		493	1250	1460	1230	778
Dissolved K	379	159	519	695	565	671		272	766	979	802	574
Dissolved Ca	145	273	178	160	169	93		64	68	90	56	76
Dissolved Mg	164	39	81	86	68	54		22	49	66	42	36
Dissolved B	7.15	1.40		10.1	10.50	6.5		2.8	9.85	9.86	7.4	5.85
Dissolved Fe	5.6	12.2		4.8	4.30	3.8		3.5	3.0	6.5	1.8	7.9
Dissolved Zn	0.028	0.057		0.06	0.100	0.171		0.037	0.150	0.110	0.12	0.12
Total B	7.66	1.5		10.1	11.30	8.06		2.84	10.6	10.1	8.62	5.18
Total Fe	10.4	14.7		5.6	5.1	5.6		5	4.1	8.7	3.6	9.8
Total Zn	0.039	0.779		0.207	0.19	0.34		0.11	0.28	0.23	0.22	0.204
TOC	242	197	326	507	565	726	930	305	870	1090	1090	617
BOD	48		108		109		267		231		177	
COD	685		934		1410		2910		2510		2620	
BOD/COD	0.07		0.12		0.08		0.09		0.09		0.07	
TKN	437		604.00		1040		1720		1520		2600	
Total Anions	103		85.0		145.0		245		183		226	
Total Cations	103		102.0		114.0		241		175		227	
Dissolved Al	0.02		0.11		0.11		0.28		0.26		0.44	
Total Al	0.03		0.150		0.210		0.31		0.51		0.74	
Dissolved Cr	0.029		0.1080		0.1960		0.407		0.381		0.49	
Total Cr	0.033		0.113		0.214		0.413		0.422		0.56	
Dissolved Mn	1.29		1.99		1.47		0.655		0.571		0.48	
Total Mn	1.49		2.05		1.53		0.602		0.622		0.528	
Dissolved Cobalt	0.011		0.0210		0.0240		0.056		0.045		0.045	
Total Co	0.012		0.021		0.024		0.056		0.046		0.05	
Dissolved Ni	0.058		0.0460		0.067		0.153		0.126		0.14	
Total Ni	0.061		0.0540		0.069		0.150		0.118		0.149	
Dissolved Cu	0.003		0.0		0.0		0.007		0.005		0.02	
Total Cu	0.003		0.009		0.012		0.010		0.013		0.026	

Dissolved As	0.045		0.134		0.180		0.24		0.210		0.31	
Total As	0.063		0.146		0.190		0.27		0.21		0.37	
Dissolved Cd	0.0003		0.000		0.001		0.001		0.0008		0.001	
Total Cd	0.0003		0.0005		0.0005		0.0010		0.0011		0.0007	
Dissolved Pb	0.0014		0.0029		0.003		0.002		0.006		0.005	
Total Pb	0.002		0.0077		0.007		0.006		0.011		0.009	

Sump 5a North

Date Sampled	**07/09/97**	**04/20/98**	**04/21/99**	**04/19/00**	**09/22/00**	**04/20/01**	**09/20/01**	**09/25/02**	**09/17/03**	**09/22/04**	**09/21/05**
pH				7.2	6.13	7.18	7.8	7.52	6.86	6.07	6.45
Conductivity	2670	17330	9900	6880	702	1238	614	584	672	524	442
Alkalinity	1800	11000	3940	2420	164	184	98	77	85	127	132
Sulphate	39	26	3	409	83.4	351	135	60.1	66.3	49.9	40.9
Chloride	210	1300	851	466	74.7	75.6	59.7	56	43.6	43.3	32.9
Nitrate-N				0.02	0.96	0.51	1.78	11.3	6.01	0.62	0.52
NH4-N	140	1700	661	465	2.17	9.3	4.48	3.51	0.28	0.03	0.94
Reactive Silica	33			50	54	1	40	48.6	39.5	48.3	48
DRP				0.7	0.012	0.027	0.025	0.1	0.032	0.012	0.009
Anion Balance					7.19		6.59	5.19	4.73	4.84	4.44
Cation Balance					6.9		6.48	4.37	4.37	4.66	4.46
Dissolved Na	200	820	580	346	37.5	57.3	33.1	25.1	19.4	19.7	15.6
Dissolved K	110	660	470	296	15.9	31.3	18	18.6	14	16.7	17.2
Dissolved Ca	270	88	160	222	62	153	65.7	37.2	47.1	43.1	48
Dissolved Mg	85	100	110	55.9	19	19.5	11.9	8.4	9.14	12.3	9.35
Dissolved B	4.1	13	18	3.47	0.089		0.152	0.141	0.108	0.075	0.085
Dissolved Fe	6.9	3.6	1	3.5	1.56		0.17	0.07	1.19	6.05	3.08
Dissolved Zn	0.079	0.056	0.019	0.1	0.091		0.034	0.022	0.106	0.041	0.044
Total B	3.2	11	12	3.73	0.094		0.162	0.175	0.11	0.08	0.081
Total Fe	34	9.7	3.7	4.5	7.12		1.55	0.47	1.62	9.32	61.6
Total Zn	1.2	0.39	0.15	0.317	0.173		0.17	0.041	0.109	0.045	0.606

TOC		510	270	226	26.3	44.1	12.6	12.4	11.8	13.7	42.9
BOD		190	69	65		10					
COD		1300	769	683		118					
BOD/COD		0.15	0.09	0.10		0.08					
TKN		1990	658	481		13.6					
Total Anions				70		13.2					
Total Cations				71.6		13.2					
Dissolved Al		0.27	0.041	0.08		0.021					
Total Al		4.9	0.56	0.82		0.104					
Dissolved Cr		0.21	0.1	0.026		0.002					
Total Cr		0.2	0.06	0.032		0.0059					
Dissolved Mn		1.1	0.86	1.35		2.04					
Total Mn		1.3	0.78	1.61		2.13					
Dissolved Cobalt		0.037	0.016	0.025		0.0101					
Total Co		0.049	0.016	0.027		0.0109					
Dissolved Ni		0.12	0.061	0.068		0.0183					
Total Ni		0.13	0.059	0.073		0.0212					
Dissolved Cu		0.002	0.009	0.015		0.0031					
Total Cu		0.02	0.013	0.068		0.0113					
Dissolved As		0.21	0.16	0.036		0.018					
Total As		0.086	0.041	0.037		0.023					
Dissolved Cd		0.0004	0.0003	0.0003		0.00005					
Total Cd		0.0014	0.001	0.0003		0.00005					
Dissolved Pb		0.001	0.0005	0.0017		0.0002					
Total Pb		0.0081	0.005	0.0026		0.0011					

Sump 5a South														
Date Sampled	**07/09/97**	**04/20/98**	**04/21/99**	**04/19/00**	**09/22/00**	**04/20/01**	**09/20/01**	**05/03/02**	**09/25/02**	**04/24/03**	**09/17/03**	**04/26/04**	**09/22/04**	**04/18/05**
pH				7.6	7.55	8.0	7.8	7.5	7.2	7.5	7.6	7.4	6.8	7.2
Conductivity	7280	8290	11860	6100	1970	2780	1160	2360	818	3350	13740	2880	1223	3760
Alkalinity	2700	3900	4900	2400	819	785	388	985	141	1260	2250	461	462	1340
Sulphate	1500	1600	8	58	184.0	369	284	154	152	227	91	586	55	15
Chloride	200	530	918	367	114	153	75	126	63.1	220	427	316	48.9	341
Nitrate-N				0.0	1.8	0.08	0.05	0.7	6.69	0.50	2.50	0.20	0.05	0.05
NH4-N	690	700	899	428	102	144	30	67	3.47	162	451	37	14.8	210
Reactive Silica	34.0			51	49	71	39	42	35.2	39.9	39.7	52.9	50.4	56.9
DRP				2	0.221	0.190	0.013	0.071	0.033	0.042	4.23	0.281	0.017	0.011
Anion Balance					23.6		15.8		8.24		59.2		11.7	
Cation Balance					22		16.2		7.03		55.5		11.8	
Dissolved Na	210	540	570	339	85	144	58	93	29.4		279	210	45.2	253
Dissolved K	210	520	660	271	75	121	37	63	15.2		197	115	33.1	178
Dissolved Ca	180	160	160	134	136	134	173	184	88		88	166	127	192
Dissolved Mg	85.00	100	92	41.4	22	36.3	18.9	34.1	8.87		20.6	18.8	18.1	37.8
Dissolved B	3.0	6.9	9.8	4.06	1.31		0.784	1.48	0.286		1.69	2.15	0.46	1.89
Dissolved Fe	1.9	3.2	1.8	1.8	0.3		10.7	0.2	0.1		2.3	0.1	4.2	8.1
Dissolved Zn	0.019	0.03	0.015	0.014	0.049		0.01	0.049	0.130		0.080	0.102	0.087	0.017
Total B	2.1	5.9	7.1	4.23	1.3		0.787	1.61	0.338		1.78	3.10	0.44	1.95
Total Fe	19	8.1	12	1.7	7.2		24.7	3.2	0.5		3.6	1130	27	23
Total Zn	0.16	0.05	0.067	0.025	0.134		0.199	0.091	0.147		0.15	69.4	0.930	0.514
TOC		310	306	221	65	99.4	55.7	76.0	21.3	62.8	214	762	40.2	206
BOD		42	71	38		8		23		14		117		24
COD		920	1030	656		232		183		267		494		598
BOD/COD		0.05	0.07	0.06		0.03		0.13		0.05		0.24		0.04
TKN		825	911	462		148.00		97.1		150		184		195

Total Anions				59.5		28		27		36.2		30.3		36.8
Total Cations				62.4		29.3		22.4		38.0		24.5		43.5
Dissolved Al		0.32	0.031	0.05		0.039		0.006		0.009		0.045		0.15
Total Al		6.5	0.56	0.1		0.190		0.053		0.165		553		4.64
Dissolved Cr		0.053	0.09	0.031		0.0070		0.0030		0.007		0.006		0.014
Total Cr		0.043	0.037	0.031		0.007		0.004		0.011		0.921		0.023
Dissolved Mn		1.5	1.5	0.69		0.37		1.26		1.72		0.197		1.58
Total Mn		1.7	1.8	0.75		0.401		1.340		1.60		17.0		1.61
Dissolved Cobalt		0.055		0.021		0.0066		0.0046		0.0069		0.0104		0.01
Total Co		0.07	0.045	0.021		0.007		0.005		0.0070		0.303		0.011
Dissolved Ni		0.11	0.097	0.048		0.0140		0.010		0.016		0.062		0.05
Total Ni		0.12	0.091	0.047		0.0160		0.011		0.017		0.673		0.056
Dissolved Cu		0.006	0.008	0.003		0.001		0.001		0.001		0.002		0.003
Total Cu		0.012	0.011	0.003		0.005		0.002		0.003		1.66		0.016
Dissolved As		0.32	0.031	0.029		0.022		0.006		0.005		0.063		0.07
Total As		0.12	0.56	0.027		0.027		0.007		0.013		1.23		0.093
Dissolved Cd		0.0004	0.0003	0.0003		0.000		0.000		0.0001		0.0002		0.0003
Total Cd		0.0015	0.001	0.0003		0.000		0.000		0.0001		0.0457		0.0004
Dissolved Pb		0.0003	0.0005	0.0006		0		0		0.0002		0.0002		0.0005
Total Pb		0.0016	0.003	0.0008		0.0008		0.0003		0.0017		1.06		0.0093

Sump 5b

Date Sampled	**07/09/97**	**04/20/98**	**04/21/99**	**04/17/00**	**09/22/00**	**04/20/01**	**09/20/01**	**05/03/02**	**09/25/02**	**04/24/03**	**09/17/03**	**04/26/04**	**09/22/04**	**04/15/05**	**09/21/05**
pH				7.3	7.49	7.77	8.1	7.79	7.43	7.39	7.57	7.47	7.6	7.9	7.8
Conductivity	7930	17450	15650	14610	8070	12330	9310	14670	3270	11200	2290	13550	2060	6860	884
Alkalinity	5500	9700	6820	6240	4260	4740	5340	6430	101	4810	138	5450	649	2290	241
Sulphate	30	13	13	10.4	67.9	168	15.1	9.1	756	343	394	13	167	14.8	55.7
Chloride	650	1300	1310	1010	668	1040	1210	1210	240	970	127	767	152	550	53.6
Nitrate-N				0.02	0.03	0.05	0.5	0.05	104	32.3	54.6	0.05	3.4	1.78	6.75
NH4-N	820	1500	1440	1270	746	879	983	803	45.7	850	5.98	1130	46.7	438	28.9

Reactive Silica	35			51	50	42	40	31.8	40.6	32.8	43.9	29.7	43.4	32.1	27.7
DRP				3	2.54	0.866	2.59	3.83	0.208	1.07	0.178	3.74	0.044	0.851	0.033
Anion Balance					105		141		32		18.4		21.0		7.97
Cation Balance					97.4		141		29.9		17		20.3		8.13
Dissolved Na	460	880	840	903	508	808	972	825	206		104	767	115	443	45.1
Dissolved K	390	730	740	746	438	542	620	643	146		50.5	559	78.9	317	36.3
Dissolved Ca	190	71	110	97.1	105	105	115	81.8	239		180	66.2	153	97.7	47.3
Dissolved Mg	140	83	93	93	65.5	69.9	80.7	87.3	24		21.4	67.5	28.7	44.7	9.81
Dissolved B	8.6	18	18	12.2	10.3		8.64	11.5	2.54		1.07	8.66	1.38	5.79	0.602
Dissolved Fe	3.8	1.1	3.2	5	3.8		3.4	3.7	0.31		0.05	2.3	0.1	1.4	0.2
Dissolved Zn	0.003	0.07	0.11	0.09	0.035		0.09	0.03	0.115		0.103	0.027	0.050	0.10	0.026
Total B	7.8	15	13	13.1	10.1		9.15	12.3	3.01		1.08	10	1.38	6.7	0.606
Total Fe	27	4.6	6.7	9.7	4.7		6.1	7.5	2.8		0.5	8	0.97	2.8	1.5
Total Zn	0.36	0.23	0.25	0.39	0.049		0.27	0.07	0.27		0.179	0.08	0.089	0.166	0.220
TOC		610	522	478	228	392	435	545	96.7	284	23.5	389	35.0	205	19.2
BOD		240	166	141		109		119		31		95		19	
COD		2300	1950	1360		1150		1330		1420		1220		607	
BOD/COD		0.10	0.09	0.10		0.09		0.09		0.02		0.08		0.03	
TKN		1700	1370	1380		940		1270		866		1230		456	
Total Anions				154		128		163		133		131		61.7	
Total Cations				162		123		121		125		137		67.3	
Dissolved Al		0.4	0.12	0.07		0.09		0.04		0.04		0.03		0.08	
Total Al		3.3	0.16	0.4		3.13		0.08		3.08		0.15		0.39	
Dissolved Cr		0.29	0.15	0.058		0.08		0.055		0.038		0.04		0.025	
Total Cr		0.24	0.11	0.067		0.11		0.06		0.091		0.049		0.029	
Dissolved Mn		0.37	0.73	0.62		0.605		0.511		0.746		0.362		0.379	
Total Mn		0.43	0.67	0.71		0.814		0.555		1.32		0.489		0.427	
Dissolved Cobalt		0.057		0.053		0.026		0.051		0.04		0.043		0.022	
Total Co		0.067	0.059	0.055		0.033		0.051		0.042		0.046		0.025	
Dissolved Ni		0.17	0.14	0.148		0.065		0.137		0.094		0.111		0.061	
Total Ni		0.19	0.14	0.154		0.084		0.14		0.097		0.12		0.066	

Dissolved Cu		0.005	0.023	0.005		0.006		0.005		0.005		0.003		0.008	
Total Cu		0.025	0.019	0.006		0.021		0.005		0.036		0.004		0.011	
Dissolved As		0.21	0.12	0.02		0.067		0.03		0.024		0.018		0.012	
Total As		0.059	0.16	0.03		0.1		0.03		0.055		0.02		0.015	
Dissolved Cd		0.0004	0.0003	0.0003		0.0003		0.0005		0.0003		0.0003		0.0003	
Total Cd		0.0019	0.001	0.0005		0.0003		0.0005		0.0006		0.0003		0.0003	
Dissolved Pb		0.002	0.0005	0.003		0.001		0.002		0.0005		0.001		0.0009	
Total Pb		0.013	0.002	0.011		0.0073		0.004		0.0172		0.0038		0.0024	

Sump 6

Date Sampled	**04/24/03**	**04/26/04**	**09/23/04**	**04/19/05**	**09/21/05**
pH	6.9	7.2	7.2	8.0	7.3
Conductivity	1949	11790	11140	16560	5770
Alkalinity	867	4550	4550	8150	2220
Sulphate	1	13	29	189	56.4
Chloride	67	753	842	1540	370
Nitrate-N	0.05	0.05	0.50	0.7	0.05
NH4-N	17.5	671	786	1650	378
Reactive Silica	76.2	38.5	42.5	42.7	45.3
DRP	0.019	2.6	1.80	12.5	2.62
Anion Balance			115		56.1
Cation Balance			119		57.4
Dissolved Na		783	675	1190	283
Dissolved K		588.0	672	1300	328
Dissolved Ca			189	134	133
Dissolved Mg		105	83.3	78.4	35.1
Dissolved B		5.30	5.15	8.26	2.56
Dissolved Fe		2.7	5.6	0.6	4.3
Dissolved Zn		0.284	0.028	0.16	0.067
Total B		6.24	4.95	10.7	2.47

Total Fe		4.6	7.9	1.8	6.6
Total Zn		0.977	0.22	0.42	0.190
TOC	83.9	517	397	1370	292
BOD	161	195		398	
COD	298	1560		3650	
BOD/COD	0.540	0.125		0.109	
TKN	22.7	789		1880	
Total Anions	19.3	112.0		211	
Total Cations	21.4	117		216	
Dissolved Al	0.016	0.13		1.00	
Total Al	0.046	0.26		1.73	
Dissolved Cr	0.002	0.145		0.708	
Total Cr	0.0021	0.168		0.759	
Dissolved Mn	11.0	2.63		1.19	
Total Mn	10.3	3.43		1.22	
Dissolved Cobalt	0.0218	0.015		0.052	
Total Co	0.0223	0.018		0.057	
Dissolved Ni	0.0039	0.055		0.164	
Total Ni	0.0046	0.063		0.180	
Dissolved Cu	0.001	0.003		0.010	
Total Cu	0.0007	0.016		0.031	
Dissolved As	0.120	0.113		0.640	
Total As	0.123	0.176		0.740	
Dissolved Cd	0.000	0.0005		0.0005	
Total Cd	0.0001	0.0009		0.0008	
Dissolved Pb	0.000	0.0040		0.006	
Total Pb	0.0002	0.0136		0.015	

Daily rainfall amounts from Ruakura meteorological station. Source: National Institute for Water and Atmosphere research (NIWA).

	1996											
Date	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1											0	9.6
2											1.2	14.8
3											8.4	0
4											0.4	10.2
5											1	0
6											0	0
7											0	0
8											0	0
9											0	0
10											0	0
11											0	0
12											11	0
13											7.8	0
14											11.6	13.6
15											0	8
16											1.4	0
17											0	6.4
18											0	0
19											9.2	0
20											2.8	1.4
21											0.8	5.2
22											0	4
23											2.2	0
24											0	0
25											0.4	0
26										0	0	0
27										4.8	0	0
28										1	0	0
29										0	12.6	0
30										1.8	1.2	12
31										0		33.2

1997												
Date	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1	0.2	0	0.4	0	0	29	12.2	4	0	9.2	0	3.8
2	0.6	0	8	0	0	34.6	13.4	3.8	0	0.2	0	5.4
3	15.6	0.2	24.2	0	0	13.6	0	0	3.8	0	0	6.8
4	0	5.8	1	0	0	1.4	0.2	0	1.2	0	0	11.8
5	2	9	0	0	0	0.2	0	0	2.6	6.8	0	0
6	0	0	7	0.2	0	0	0	0	0.2	8.2	0	0.6
7	0	0	3.4	1	0	0	0	0	0	1	1.8	0
8	0	0	46	0.2	0	0	0	0	0	0.8	1.6	0
9	0	0	3.6	35.4	0	0	0	0	0	0	9.4	0.2
10	0	0	0	1.4	0	0.2	0.4	0	1.8	0	3	0
11	2.2	0	0	0.2	0	2.6	14	0	27.8	0.2	0	0
12	1.4	3.2	15.8	0.2	0	3.6	2.8	13.2	0.2	0	0	0
13	0	0.4	0	0	0	0	0	0	0.6	0.2	13	0
14	0	0	0	16.6	0.4	0	9.6	2.6	0	0.2	0.2	0
15	0	0	0	0	0	0	0	2.4	0	18.8	0	0
16	0	0	0	0.8	0.4	0	0	4	0	0	8	0
17	0	0	0	1	0	0	0	0	0	0.8	17.6	19.2
18	2.2	0	0	0.6	0	14	1.2	0	2.2	0.6	3.2	0
19	1.6	22.6	0	0	0	1.6	0.2	1.2	2.2	7.6	0	0
20	1	0	0	13.4	0	0	0	4.2	0	13.2	0.2	0
21	0	0	0	1	0	0	0	5	0	1	6.8	18.4
22	0	0	8.6	0	0	0.4	0.2	0	0	1.6	0	0
23	0	0	10.4	0	0	0	0.2	1	15.8	0.2	0	0
24	0	2.2	34.2	8	53.4	1.4	0.4	0.8	19.6	0.2	0	0.4
25	0	0	0	0	13.8	4.8	0	0	6.6	0	0	0
26	0	0.2	0	0.2	0	0	0	0	0	0	1.8	10
27	0	0	0	0	2	0.2	0	8.4	0	0.2	0	0
28	0	0	0	1.4	0	0	0	11.4	27.2	0	0	0
29	0		0	0	0	0	0	1	0	0	4.4	2
30	0		0	0	0	0.8	0	0	11.2	0	7.6	0
31	0		0		12.4		11.8	0		0		0

1998												
Date	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1	0	0	0	0	0	0	4.4	2.6	0	7	0	0.6
2	0	0	0	2.8	1	0.2	32.4	1.2	1	0	0	0
3	0	0	0	5.8	0	7.6	5.4	0	0.2	0.4	9	0
4	0	0	0	3.4	0	0	0	0	0.8	0	9.2	45.8
5	0	0	0	5	0	0	0	0	0	5.8	0	2.6
6	0	0	0	0	0	0	0	0	0	0	0	0
7	0.4	0	0	0	1	0.6	0	0	11.8	0	0	1
8	1.2	0.4	0	0	20.6	43	0	0	1	0	0	1
9	0	0	0	1.6	0	18.6	18.8	0	0.4	0.2	0	0
10	0	0	0	5	5	16.4	31.2	2.6	0	0	0	0.4
11	0	0.8	25.8	0	1.2	0.2	34.8	49.6	0.6	2.2	0	1

Date	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
12	0	0	18.4	0	7.8	0	16.2	1	0.2	14.6	0	0
13	0.8	0	9.6	0	0	2	0	3.6	0	13.4	0	0
14	0	3.8	18.6	0	4.4	16.8	0.8	6.8	0	4	0	0
15	0	0	7.8	3.6	0	2.4	63.2	10.2	2.2	7.8	0	0
16	0	0	1.8	0	0	0	10	0	2	8.6	0	0
17	3.6	0	0	0	0	0	0	1	12.2	0	0	0
18	0	0	0	0.4	0	31.2	0	0	4.6	0	0	0
19	0	7	2	0	0	0.2	0	4	0	0	0	9.4
20	0	0	0	0	0	7.8	0	0	0	0	0	0
21	3.6	1.6	0	0	0	0	0	5.6	0	10.6	0	0
22	2	49.2	0	0	0	0	0.4	0	0	2.6	0	0
23	0	0	0	0	15.6	0	0	0	0	7	4.2	0
24	0	31.4	0	2	15.4	0	31.4	0	0	3.4	0.2	0
25	0.4	1.4	0	0	0.6	0	7.6	0	0	0	0	0
26	0	0.2	0	0	19	9.8	1.8	0	0	2	0.8	0
27	0	0	0	0	10.6	3.4	6.4	0.2	3.4	0	0	0
28	0.6	0	0	8	0	0	0	15.2	1.4	0	0	0
29	1.2		0	4.8	0	0	0	0	0	21.8	11.2	0
30	0		2.2	0	0	0	6.2	2.2	1	0.2	14.2	0
31	7.8		0.2		0		0	1.4		0		0

1999

Date	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	0	0.2	0	13.6	13	0	0	0	0	0	0	0
2	0	0	0	0	0	8.4	0	0	0.4	0	0	0
3	0.8	0	0	0	0	2.4	1.4	24.8	0	0	0	0
4	0	0	0	0	0	0.2	9.4	0.4	0	0	0	0
5	0	0	0	0	0.2	15.6	1.2	23.4	0	0	15.6	0
6	0	0	6.8	0.2	0.2	0	0	5.8	0	0	3.6	0
7	0	0	14.8	21.8	0.2	0	0	0.2	0	0	11.6	0
8	0	0	9.4	0.2	0	0	0	0	16	0.2	9	7.2
9	0	0	4.6	17.4	0	6.4	1	0	1.2	13	22.4	0
10	0	0	0	0	1	0.8	0	0	0	0	0.8	0
11	0	0	0	0	0	0	0	0	0	0	33.2	0
12	0	0	0	0	0	0	0	6.8	0	0	2.8	6
13	0	0	0	0	0	14.6	0	9	0.8	1	2.4	14
14	0.6	0	0	0	0.6	0.8	0.2	3.6	33.6	0	0	3.8
15	6.2	0	0	2	4.8	1.2	0	0	0.8	1.6	0	0.8
16	14.6	0	1	5.8	4	19.2	9	22	4.2	0	0	0
17	13.2	0	0	19.2	26	16.4	14.8	5.6	19.4	0	0	0
18	34.6	0	0	6	0	0.6	11.6	3.2	0	0	0	0
19	0	0	0	0	0	3.4	29.4	0	0	0	8	0
20	0	0	0	0	0	0	7.4	0	11.4	0	0	10.8
21	0	0.2	0	0	0	0	9.8	1.4	7.8	0.2	0	0
22	26.8	0	0	0	0	0	3.8	6.4	0.4	3.6	1	3.4
23	2.6	0	0	0	0	0	0	3	0	0	0	0
24	0	1.8	0.6	1.4	0	0	24.6	0.8	0.2	0	0	0
25	0	0	0.6	0	0	0	0	0.2	0	0.4	2	0
26	0	8.6	0	0	0	0	6.4	0	0	0	10.8	13.4
27	0	1.4	0	0	2	0	7.6	0	4.8	0	0	0.2
28	0	0	0	0	0.6	0	0	0	0.4	1.6	35.8	0
29	0		0	0	2	0	0	0	0	8	10	0
30	0		0	0	0	0	0	0	0	0	0.6	0
31	0.2		0		4.6		0	0		0		0

2000												
Date	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1	4.2	0.8	0	0	0	7.2	0	0	4.8	2.4	0.6	0
2	2.4	0	12.6	0	0	6.8	2	0	0.8	10	0	0
3	2	0	0.2	0	0	5.2	1.8	0	0.4	12.4	0	0
4	0.4	0	0	0	0	21.8	1.4	7.4	0	1	0	5.2
5	5.6	0	0	4.4	0	16.6	0	0.8	4.2	1.8	32.2	0.8
6	0	0	0	1.8	0	0	0.2	0	19	0	7.8	0
7	0	0	0	3.2	0	3.8	0	0	10.4	0	0	0
8	0	0	0	5.2	17.6	5.4	0	0	19.2	0	1.8	12.4
9	0	0	0.4	18	4.8	0	0	0	0	0	7.8	0
10	0.8	0	0	41.4	0	0	0	0	7.2	3	0	1.2
11	17	0	0	0.6	0	3.4	0	14.6	1.4	2.6	0	0.6
12	0	0	0	0	12.6	2.2	0	7.4	0	22.8	0	10.4
13	0	0	0	0	1.8	0.4	0	0	0	3	0	10.6
14	0	0.6	3	0	2.4	0	0	0	7	0.2	0	0
15	0	2	9.2	0	3.2	0	0	0	0	0	0	0
16	0	0.4	0	0	2.6	0	0	0	0	0.4	0	0
17	0	2	0	0	4.4	0	0	0	0	0	0	0
18	0	0	0	0	0	0.2	0	14.4	0	0	0	0
19	0	0.2	0	0	0	0	0.6	7.4	0	0	0.8	0
20	5.2	0	0	8	3.8	0	8.6	0.8	1	0	1.2	0
21	0	0	0	0.2	1.8	0	8.4	0	1.2	0	0.8	0
22	0	0	0	4	0	0	0.4	0	0	0	6.6	0
23	0	0.2	4.8	0	0	0	11.6	0.4	0	0	1.6	0
24	0	0	0	3.4	0	0	0.4	0	0	0	0	0
25	4.2	0	0	19.2	0	0	0	0	0	0	0	3.8
26	16.2	0	0	0	0	0	21.8	2.8	8.8	0	1.2	0.2
27	0.2	0	0	0	0	0	16.2	4.4	0	0	0	2.6
28	0	0	0	0	0	3	25.8	1.2	0	0	0	0
29	0	0	0	0	0	11.4	10.4	0.2	0	0	6.8	18.8
30	2.2		1.2	0	7.6	1	0.2	1.6	9.4	3.2	0	12.2
31	7.4		0.4		16.8		0	19.6		2.6		9.8

2001												
Date	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1	3.4	0	0	0	0	0	0	0.2	2.4	0	11.6	4.4
2	0.6	0	0	0.2	0.6	1.4	0	0	0.4	0	10.6	17
3	0.6	0	0	32	35.6	0	0	0	0	0	0	3.2
4	0	0	0	0.4	4.4	0	0	0	0	0	7.2	4
5	0	0	0	0	3.6	0	0	0	21.8	0	18.4	0
6	0	0	0	0.4	0.4	0	0	0.4	0	0	0	21.4
7	0	0	0	0	13.4	0	0	0	0.2	5	0.4	2.6
8	6	9	0	0	0.2	3	0	3.4	9.6	0	9.8	9.8
9	2.2	0.2	42	0	0	0	0	1.6	0	0.2	0.2	28.4
10	0	0	20.4	0	0	3.8	0	0	0	1.4	0	0
11	1.6	0.2	0	0.4	6.2	8.4	0	1.2	0	8.8	13	5.8
12	5.4	45	0	0	2.2	0	0	3.8	0	0	0	4.6

Date	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
13	0.6	17	0	36.2	0.8	0	0	0	0	0	0.6	3.6
14	0.6	0	0	0.4	0	0	0	2	0	0	14	0
15	0.2	0	0.8	0	0	0	5.8	0.4	0	4.4	4.8	0
16	0.6	5.4	0	0	0	0	18.8	0	0.2	7.8	0	2.8
17	1	8	0	0	0	5	22.4	0	3	0.4	0	0
18	0	23.4	0	0	0	3.6	14	0	0	0	0	11.2
19	0	0	0	0.2	0.8	0.4	12.8	4.6	0	0	0	8.4
20	0	0	0	0	7.6	0	11	5	0	2	0	10.8
21	0	0.2	0	0	0.6	0	0	4.8	0	0.6	0	16.2
22	0	0	0	0.6	8.8	0	0.2	8.4	0.2	10.2	3.8	0
23	0	36.8	0	0	3.8	0	0	3.6	0.2	2.6	27.2	0
24	0	12.6	0	0	0.6	0.2	0	0.4	0	0	6.4	8.4
25	0.2	0	0	0	2.4	3.8	0	5.8	0.2	0.2	6.4	4.8
26	0.2	0	0	0	15.4	4.8	0	3.2	0	0	0	0
27	4.8	0	0	0	5	0	0	6.4	0	2	0	0.4
28	0	0	0	0	0	4	0	0	0	1.4	0	23
29	0		13.2	0	0	1.4	0	0	0	18.8	0	11
30	0		0.8	0	14.8	0	4	0.2	0	0.6	0	6
31	0		0		9.6		0.8	0.4		0		0

2002												
Date	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1	0	0	0	7	0	0	0.2	0	0	0.2	0	0
2	0	0.4	41.4	1.2	0.4	4	3	0	0	0	5.8	0.2
3	0	0	4.8	0	0.2	1.2	9.2	0	0	0	0.8	0
4	0	0	0	0	0.4	0	1.8	8.2	1	1	0	0
5	4.2	0	0.2	0	0	0	19.6	1.4	0	0	0.2	0
6	0.6	9	0	2.6	0	0.4	12.4	0.6	0.6	0	12.4	0
7	9.8	0	0	7.4	0	0	2	0.2	0	0	3.6	7.8
8	0	0	0	4	0.8	0	11.2	3.8	0.8	0	1.2	28.8
9	0.2	0	0	0.4	0	1.2	12.4	15	0.4	0	0.2	3.2
10	14	0	0	0	0	8.2	2.6	0.8	0	0	12.6	0
11	2	0	0	0	0	3.2	3.8	0	2.4	0	4.6	2.2
12	7.6	1.4	0	0	0	1.2	6.8	0	14	0	5.8	0.2
13	7.8	6.2	0	0	0	6.2	4.4	4.4	0.4	13	2.8	33.4
14	1	0	0	0	0	0.4	0	0.6	1.6	0.2	0	0
15	8.2	0	11.2	0	0	5.2	0	20	0	0	0	0.6
16	1.6	0	0	0	0	10.8	0	6.8	0	2	0.6	0
17	0.4	0	2.8	0	0	0	0	2.6	0	12.6	3	0
18	0	0	5.4	0	0	5.4	0.6	2	0	0	9.2	5.8
19	30.8	0	1	0	0	8	0	1.6	4	2.8	2.4	11.8
20	0	0	0	0	0	1.2	0.8	0.4	5.4	0.2	3.6	8
21	6	0.8	0	0	0.2	45	0.2	0	11.2	0.2	0	0.2
22	0	0	0	0	4.4	0.4	0	0	0.4	1.2	0	0
23	0	2.4	0	0	14	5	20.4	1	0.2	0.8	0	0
24	0	1.2	0	0.8	22.8	6.4	0.2	0	0	0	1.2	0
25	0	0.2	0	0.2	2.6	0	0.2	15.4	3.2	0	0	0
26	0	0	0	9.2	7.8	0	0	1.8	0.2	13.4	0	5.8
27	0	0	0	8.4	3.8	0.4	0	0.6	9	2.8	0	0
28	0	0	0	0.8	7.4	0	0	0	0	7.2	5.8	0
29	0		0	4	14.8	4.6	0	0	6.2	7.6	0	0
30	0		0	1	3.2	0.4	0	0	14.4	4.4	3.6	0
31	0		28.2		0.4		0	0		1.8		0

2003												
Date	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1	0	0	0.4	5.4	0.4	0	4	5.2	0	13.4	0.2	0.2
2	0	0	0	0	0	0.2	3.6	1.6	20	4	9.6	0
3	0	0	13.2	0	9	0.2	0.2	0	3	0.4	1.2	0
4	0	0	2.2	0	0.2	0	10	0	3.2	17.2	14.6	0
5	0	0	0	0	1.2	1.2	7	0	16.8	1.2	0.8	0
6	1.8	0	0	8.6	0	16.2	0.4	0	6.8	1.6	0	0
7	0.2	0	0	10.6	0	11.6	0.2	0	0	0	0	6
8	0	0	1.8	0.4	0	0	2.6	0.2	5.4	0	0	0
9	2	0	0	0	0	27	0	0	0	0	1.6	8.8
10	73.4	0	0	0	0.6	1.8	0	0	0	3.2	0	18.8
11	13	0	14.4	0	1.8	0	13.2	0.2	0	0.4	0	12.6
12	0	0	43.2	0	11.4	0	1	0.2	2.8	24	0.4	10.6
13	0	0	0	0	0.2	0	0	0	0	4.2	0	10.2
14	1.4	0	0	0	0	0	0	0	12.4	2	6.6	8.8
15	0	1.2	0.2	0	0	0	0	0	2.6	0	8.4	2.2
16	0	0	1	0	0.2	30.2	0.8	8.2	10.4	0	0.2	0
17	0	0	0	0	0	14	5.4	2	0.8	0	0	0
18	0	0	6.8	0	0	10	1.2	2.4	17.2	0	0	0
19	0	0.2	0	0	0	5.2	0	0	4	0	0	0
20	0	6	0	0	9.6	0.2	0.2	0.2	4.2	0	0	0
21	1	1	0	11	4.8	2.2	0	3.2	5.8	0	0	0.4
22	0	3.2	0	10	13.8	0.4	0	0	4	0	0	13.8
23	2.6	0	0.2	0	1.4	1	0	5.8	0	0	6.8	1.6
24	0.6	2.4	0.2	0	16.6	3	0	7.2	3.4	0	9.6	9.2
25	6.8	4.6	0	0	11.6	4.8	0	0	0	0	0	3.6
26	0.2	0.6	0	0	0.2	0	0	0	0.2	0	32	0.4
27	0	9.4	6.4	0.4	0.2	0	0	0	1.2	0	25.6	0
28	0.2	16	6.4	0	0.4	0	0.4	8.8	1.4	2	3	0
29	0		17	0	0	9.2	20.2	0.4	19.6	3.8	0.4	24
30	0		1.2	0	1.6	7.6	0.4	1.8	1.4	0	0	10.4
31	0		9		3.2		0	2.8		7.4		0.8

2004												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	0	27.4	0	0	0.8	2.2	0	0	0	7.2	0	8
2	0	51.8	0.8	0.2	23.2	0	8.4	0	12.8	0	0.6	4
3	0	18.4	13.2	1.2	4.2	2	2.8	0	0.8	0	0	0.2
4	0	1.6	0	0	3.8	0.2	1.4	0	0	0	0	0
5	0	20	0	1	0	25.4	0	14	1	8.6	0	16.8
6	0	0	0	0.8	27.2	3.8	10.8	9.6	1.6	3.8	0	2
7	1.6	0	0	5.6	1.2	2.6	2	6.2	0	0	0	0.4
8	9	0	0	0	0	0	8.8	13.8	0	29	0	0
9	0	0.8	0	2.2	0.2	0	0	14.8	0	6.6	0	0
10	0	0	0	0.8	0	0	0	2.2	0	0.2	0	0.4
11	0	3.2	0.6	0.4	0	0	0	5.4	0	0	0	1.8
12	0	0.4	0	0.2	0	2.6	0	9.2	0	0	0	0
13	0	0	0	0	15	0	0	2.4	0.8	0	2.2	1
14	0	0.2	0	0	0.4	0.2	0	1.2	36.8	0	2.6	0

Date	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
15	1.4	0	0	0	1.4	0	4.2	1.4	2	0	33.4	0
16	0.2	0	0	0	0	0.2	2.6	4.6	0.4	0	5.2	10.8
17	0	4.8	0.6	0.2	0	12.6	19.2	0.2	5.6	4.8	6.4	1.2
18	0	0.4	0.4	0	0	3	0.6	1.4	0.4	9	0.4	11
19	0	0	0	0	0	30.4	0	0	1.4	3.8	0	2.6
20	8.8	25	0	0	0	6	0	0	0.2	2.8	0	0
21	16	4.6	0.2	0	0.2	10.8	1.6	0	0.2	3.2	0	0.4
22	0	0.2	0	0	6.4	13.2	0.4	0.6	0.4	0	0	13.6
23	2.2	0	0	0	11	7.4	1.6	8.6	0	0	0	6.6
24	0	4.6	0	0	0	0.2	0	0.4	0.4	2.8	10.2	11.8
25	0	0	0	0	0	0	0	0	10	23.4	0	1.6
26	0	0	0	1.8	0	0	0	0	8	1.2	6	0
27	0	0	0	1	0	0.2	8.2	0	0	13	1.2	0
28	0	23	0.8	2.8	0	3.8	10.8	0.2	2.4	0	1.4	0
29	0	60.8	0	4.8	15.2	0	5.2	0	7.2	0	0	0
30	0		0	0.4	2.8	0	0.4	0	0	15	2	7.8
31	10		0		3.2		0	0		0		19.4

2005												
Date	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1	10.2	0	0	0	1.6	27.8	0	16.6	0	0.4	0	0
2	2.4	0	0	1.6	4.6	2.4	0	12	0	14.8	0	0
3	0	1	0	0.2	44.8	3.4	0	0.2	0	11.4	0	0
4	0	0	0.6	0	16	2	0	0	0	9.8	0	0
5	0	4.4	0	0	0	1	0	0.2	0	3.6	0	0.6
6	5	0	0	0	0	0	0.4	0	1.4	5.6	0	9.4
7	8.2	0.2	3.4	0	0	0	1	1.6	1.2	17.4	2.2	11.2
8	9	0	0	0	0	0	2.4	13.8	0	16.2	4.8	2.2
9	0	0	0	0	0.4	0	6.4	0.2	0.2	6.4	0	0.6
10	6.2	0	0.8	16.4	0	0.4	1.8	7.2	0.8	30.4	0	0.4
11	11	0	0.8	0	0	0.2	1	0.8	0	5.8	0	5
12	0	25	0	0.2	0.6	0.2	13.6	5.8	0	1.6	0	0
13	0	0.2	0	0	0	0	0.2	2.4	0	2.4	2.2	0
14	0	0	0	0	0	0	0.2	0.2	0	1.8	6.6	4.2
15	0	9	0	0	0.2	0	13.2	0.2	9.6	5.6	6	0
16	0	0	0.2	0	4.6	0	4	0	0.6	0	0	0.8
17	0	0	0	0	7	0	27.8	0.2	20.8	0	0	9.8
18	0.4	0	0	0	23	1.4	21	0	39.2	0	0.2	57.2
19	0	0	0	0	5.4	11.2	10.4	0.2	19.6	0	0	0.4
20	0	0	0	0	0	0.2	0.2	0	5.8	0.4	0	18.8
21	0	0	0	3.8	0	0.4	0	0	0.2	21.2	0	4.8
22	0	0	0	0	3.2	12.6	0	0	2.2	5	8.2	7.4
23	0	0	2.6	0	7.8	0.2	0	0	14.6	0	0.8	2.2
24	0	0.2	0	1.6	0.4	9.8	2.6	22.8	0	0	0	4.4
25	0	0	12.8	0	0	22.6	0.2	1.8	0	0	0	0
26	2.6	0	1.6	0	0.4	2.6	0.4	0	0	0	18.2	1.2
27	0	0	11.8	5.2	3.8	0	1.8	0	0	0	10	0.4
28	0	7.8	1	0	4.2	0	2.8	0	2.8	0	0	0
29	0		8.4	0	6.6	0.8	9.8	0	2.2	0	0	9.2
30	0		5.8	0	27	0.2	0	0	0	0	0	1.4
31	0		0		5		0.4	0		0		1

2006												
Date	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1	0	3.8	0	1.6	1.8	0	0.2	2.6	0	0.2	0	10.2
2	0	12.6	0.6	3	0	0	0	3.8	0	23.8	0	0
3	7	0	0.4	16.2	8.8	0	0	5.6	0.4	22.4	0	0
4	0.8	0	1.2	10.8	6	12.8	3.6	1.4	1.8	3	0	0
5	1	0	0	0.6	8.6	12	4.8	0	0	0	0	4
6	13	0	0.2	0	5.2	0	3.6	25.8	0.6	0	0	0
7	2.2	1.2	3.2	0.6	0	0	10.8	32.6	0	0	0.8	0
8	0	0	3.6	20	0	0.2	3	5.2	0	1.8	21.4	0
9	0	7.4	3.4	5.8	2.8	1.2	0.2	0.2	0	0	12	15.2
10	0	0	0	16.2	8.8	0.2	0	0.2	19.2	6	7.8	5.2
11	0	12.6	0	5.6	0.6	0	0.2	2.4	0	0.6	0.2	0
12	3.2	0	14	3.4	16.8	6	7.6	0.4	0	0	0	0
13	0	0.2	1	0	5.8	17.4	25	9.6	0	0	3.8	0
14	0	0	0	0.2	0.2	0.4	0	7.6	0.4	0	0	0
15	0	2	0	0	5.8	2.8	1.8	0.8	0.4	1	7	0
16	0	0	0	0	0	1	0	0	0.4	7.4	0.2	0.4
17	0	0	0	0	0	7.8	0	0	0.6	2.2	6.6	0
18	0	0	0	2	0	7.2	0	0	0	0	0	3.4
19	1.6	0	0	13.8	0	23.2	2	0.2	0	0	16	3.8
20	10	0	0	1	0	1	34.2	0	2	3	0.6	8
21	0	0	0	0	0	0	4.4	0.6	0	0	0	1
22	0	0	0.6	0	0	8.8	0	3.8	0	0	0	1
23	0	0	24.4	0.6	2.6	3	0	0.8	0.2	9.2	0	0
24	4.4	0	6.2	0	10	0	1.4	0.4	0	17.6	0	2.2
25	38.4	0	0	25.8	14.4	0	0	9.2	0	2	2.8	0.4
26	23.6	0	0	5.6	0.6	0	0	0	0	0	0	0.2
27	0	0	9.8	0.4	19.6	0	0	8.8	0	0	2.2	0
28	0	0.6	7.6	28.4	0.2	0.2	0	0	0	0.2	2.2	2.2
29	0		0.8	10.4	3.8	0	0	0	0	2	0	0
30	0		0	11.8	0.8	0	0.2	0	0	14.6	1.6	0.2
31	0		0		0		4	0		0.2		0

Appendix 3 Groundwater chemistry data, average for individual upstream and downstream boreholes. Values in mg/l, except EC (uS/cm)

	Upstream Boreholes						
Parameter	**GW9**	**GW 10**	**GW14A**	**14B**	**GW17**	**GW 25A**	**GW25B**
Conductivity	569.3	380.8	211.5	248.2	200.1	112.7	151.1
Alkalinity	227.1	100.1	38.9	31.9	20.1	18.7	23.5
Chloride	24.7	26.1	17.0	22.0	22.2	16.2	15.3
Ammoniacal-N	0.07	0.14	0.09	0.08	0.02	0.02	0.21
Nitrate N	0.68	3.81	5.20	5.63	4.84	1.23	3.10
Reactive P	0.05	0.03	0.24	0.07	0.02	0.03	0.07
Sulphate	26.0	39.4	25.2	28.9	25.7	6.9	13.6
TOC	12.1	18.1	3.1	6.6	1.8	1.1	7.3
Boron	0.04	0.06	0.02	0.02	0.02	0.02	0.02
Calcium	36.6	26.5	14.1	12.4	8.8	4.2	7.6
Potassium	11.0	9.5	7.0	7.2	4.7	2.6	4.7
Magnesium	20.9	10.0	5.6	6.4	6.3	1.7	2.7
Sodium	34.4	24.5	15.0	18.1	16.0	13.7	12.8
Reactive Si	74.8	68.6	30.7	78.6	45.8	50.0	58.8
Zinc	0.06	0.03	0.08	0.10	0.02	0.01	0.01
pH	6.3	6.3	6.3	6.3	6.2	6.0	6.2
Iron	26.7	11.2	10.1	1.2	0.2	0.3	0.3
Aluminium	0.12	0.135	-	-	-	0.029	0.025
Arsenic	-	-	-	-	-	0.0010	0.0013
Cadmium	-	-	-	-	-	0.0001	0.0001
Chromium	0.0013	0.0007	0.0008	-	0.001	0.0008	0.0014
Cobalt	0.0210	0.0012	0.0009	-	0.0004	0.0002	0.0007
Copper	0.0115	0.0016	0.0015	-	0.0007	0.0005	0.0007
lead	0.1440	0.0556	0.0175	-	0.0220	0.0004	0.0002
Manganese	2.1917	0.3033	0.0840	-	0.0365	0.0049	0.0288
Mercury	-	-	-	-	-	-	-
Molybdenum	-	-	-	-	-	-	-

Parameter	**GW9**	**GW 10**	**GW14A**	**14B**	**GW17**	**GW 25A**	**GW25B**
Selenium	0.019	0.004	0.001	-	0.001	0.001	0.005
Strontium	-	-	-	-	-	-	-
Tin	-	-	-	-	-	-	-
TKN	-	-	-	-	-	0.54	2.9
BOD	-	-	-	-	-	1	1.47
COD	-	-	-	-	-	12.6	99.4

Downstream Boreholes

Parameter	**Gw 1**	**Gw 2**	**Gw 3**	**Gw 4**	**Gw 5**	**Gw 6**	**Gw 7**	**Gw 8**	**Gw11**	**Gw 15**	**Gw 16**	**Gw 18**	**Gw 21A**	**Gw 21B**
Conductivity	785	517	629	790	999	936	793	1003	781	876	1346	661	178	194
pH	6.4	6.5	6.4	6.5	6.4	6.3	6.4	6.6	6.7	6.7	6.5	6.3	6.5	6.5
Alkalinity	252	199	241	286	350	401	333	340	315	368	477	236	50	53
Chloride	142.2	55.9	48.5	57.6	25.3	51.4	56.1	110.9	63.2	88.0	167.0	64.9	21.7	22.6
Ammoniacal-N	3.68	0.66	4.98	5.33	26.08	4.89	6.90	2.69	21.35	0.37	1.18	0.09	0.05	0.02
Nitrate N	4.85	0.15	0.08	0.04	0.08	5.47	0.64	0.41	0.03	0.04	0.06	2.59	0.04	0.14
Reactive P	0.039	0.054	0.106	0.061	0.052	0.087	0.024	0.052	0.019	0.032	0.049	0.017	0.014	0.021
Sulphate	8.9	3.1	2.0	1.3	6.2	25.1	11.8	2.9	1.1	8.8	1.5	10.4	8.5	13.7
Boron	1.54	0.24	0.11	0.15	0.09	0.26	0.15	0.24	0.79	0.29	0.58	0.17	0.13	0.13
Calcium	39.7	34.5	29.7	34.7	69.8	70.9	80.1	54.9	27.4	67.5	87.8	43.6	6.3	8.2
Potassium	19.0	11.4	15.4	15.4	12.1	13.5	14.7	19.8	25.3	14.0	24.1	13.1	6.0	6.5
Magnesium	19.1	15.7	13.4	16.8	8.7	27.7	12.1	28.0	15.6	43.9	48.3	29.7	4.1	4.9
Sodium	89.8	38.1	37.7	38.2	35.1	38.1	30.3	80.3	55.4	45.9	110.8	39.8	20.6	21.7

Parameter	**Gw1**	**Gw2**	**Gw3**	**Gw4**	**Gw5**	**Gw6**	**Gw7**	**Gw8**	**Gw11**	**Gw15**	**Gw16**	**Gw18**	**Gw21A**	**Gw 21B**
Reactive Si	61.4	63.9	63.4	53.2	23.2	39.7	61.5	59.8	63.5	47.4	58.5	45.6	51.2	49.1
Zinc	0.04	0.04	0.03	0.05	0.03	0.11	0.04	0.02	0.03	0.01	0.08	0.02	0.01	0.03
Iron	21.3	21.4	58.3	81.7	130.7	87.9	48.8	55.9	18.9	78.9	56.3	11.4	4.3	0.1
Aluminium	8.1	8.6	2.3	2.7	23.2	3.1	11.5	0.1	0.4	-	-		-	-
Arsenic	0.0170	0.0080	0.2070	0.1000	0.2700	0.2400	0.0200	-	-	-	-	-	-	-
Cadmium	0.0100	0.0060	0.0400	0.0100	0.0100	0.0100	0.0100	-	-	-	-	-	-	-
Chromium	0.0108	0.0205	0.0008	0.0024	0.0198	0.0055	0.0024	0.0005	-	0.0010	0.0001	0.0000	-	-
Cobalt	0.0092	0.0009	0.0213	0.0285	0.0274	0.0180	0.0247	0.0081	-	0.0034	0.0035	0.0027	-	-
Copper	0.0453	0.0603	0.0269	0.0171	0.0238	0.0029	0.0275	0.0007	-	0.0015	0.0012	0.0025	-	-
lead	0.014	0.075	0.072	0.031	0.050	0.032	0.157	0.048	0.045	0.052	0.041	0.005	-	-
Manganese	1.20	2.23	2.27	6.43	16.89	2.69	2.20	-	2.03	0.33	0.53	0.20	-	-
Mercury	0.018	0.001	0.003	0.001	0.001	0.001	0.004	-	-	-	-	-	-	-
Molybdenum	0.01	0.01	0.04	0.01	0.01	0.01	0.01	-	-	-	-	-	-	-
Nickel	0.007	0.006	0.010	0.007	0.016	0.006	0.009	-	0.009	0.001	0.000	0.003	-	-
Selenium	0.2	0.02	0.02	0.02	0.3	0.2	0.2	-	-	-	-	-	-	-
Strontium	0.78	0.29	0.24	0.22	0.49	-	0.15	-	-	-	-	-	-	-
Tin	0.02	0.02	0.07	0.02	0.02	-	0.02	-	-	-	-	-	-	-

Downstream Boreholes (continued)

Parameter	**Gw 22**	**Gw 23**	**Gw 24**	**Gw 26**	**Gw 27**	**Gw 40**	**Gw 41**	**Gw 42**	**Gw 43**
Conductivity	180	163	170	1206	3074	373	321	233	1169
pH	6.4	6.5	6.6	6.4	-	6.4	6.3	6.3	6.6
Alkalinity	50	35	43	391	727	108	90	63	437
Chloride	18.8	17.7	16.8	126.8	615.6	37.2	30.0	23.9	103.2
Ammoniacal-N	0.04	0.03	0.03	0.58	44.94	0.02	0.03	0.01	0.09
Nitrate N	0.06	0.67	0.55	0.04	0.03	2.31	2.14	0.23	0.03
Reactive P	0.016	0.034	0.050	0.080	0.049	0.017	0.031	0.017	0.029
Sulphate	7.6	15.1	13.7	2.8	4.6	15.6	20.2	14.9	9.7
Boron	0.09	0.09	0.09	0.36	0.99	0.19	0.16	0.15	0.29
Calcium	7.0	6.8	7.9	69.3	79.5	21.7	18.2	10.8	91.4
Potassium	6.0	6.2	6.1	16.6	56.6	10.6	9.8	8.3	16.9
Magnesium	4.8	3.5	4.2	32.4	47.5	12.5	10.6	7.1	51.2
Sodium	17.4	16.0	16.3	60.5	447.8	30.5	25.0	21.5	56.6
Reactive Si	60.7	47.6	49.7	50.8	46.2	58.6	65.5	67.8	54.9
Zinc	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.02
Iron	2.2	0.8	0.1	166.1	-	0.9	0.3	0.9	67.1
Aluminium	0.0	0.0	-	-	-	-	-	-	-
Arsenic	0.0044	0.0044	-	-	-	-	-	-	-
Cadmium	0.0001	0.0001	-	-	-	-	-	-	-
Chromium	0.0011	0.0006	-	-	-	-	-	-	-
Cobalt	0.0011	0.0010	-	-	-	-	-	-	-
Copper	0.0010	0.0016	-	-	-	-	-	-	-
lead	0.000	0.001	-	-	-	-	-	-	-
Manganese	0.06	0.04	-	-	-	-	-	-	-
Mercury	-	-	-	-	-	-	-	-	-

Parameter									
Molybdenum	-	-	-	-	-	-	-	-	-
Nickel	0.004	0.003	-	-	-	-	-	-	-
Selenium	-	-	-	-	-	-	-	-	-
Strontium	-	-	-	-	-	-	-	-	-
Tin	-	-	-	-	-	-	-	-	-

Depth to groundwater level for boreholes at Horotiu landfill.

	Depth to groundwater level (m)				
Date	**GW 2**	**GW3**	**GW 4**	**GW5**	**GW 6**
28-Aug-01	5.06	5.06	6.66	-	4.27
21-Sep-01	5.67	5.67	7.25	-	4.7
30-Oct-01	6.02	6.02	7.53	5.48	5.02
27-Nov-01	5.53	5.53	6.99	4.95	4.54
20-Dec-01	4.33	4.33	5.93	3.88	3.6
31-Jan-02	5.66	5.66	7.12	5.04	4.6
25-Feb-02	6.21	6.21	7.63	5.53	5.04
26-Mar-02	6.28	6.28	7.68	5.62	5.14
30-Apr-02	5.78	5.78	7.51	5.44	5.04
31-May-02	5.42	5.42	6.9	4.9	4.5
26-Jun-02	5.03	5.03	6.35	4.2	3.8
18-Jul-02	4.04	4.04	5.61	3.46	3.08
29-Aug-02	4.81	4.81	6.39	4.27	3.89
25-Sep-02	5.07	5.07	6.7	4.64	4.18
24-Oct-02	5.98	5.98	7.14	5.12	4.56
26-Nov-02	5.74	5.74	7.18	5.13	4.7
17-Dec-02	6.12	6.12	7.5	5.42	4.94
29-Jan-03	6.09	6.09	7.36	5.34	4.94
24-Feb-03	6.22	6.22	7.65	5.57	5.1
31-Mar-03	6.22	6.22	7.69	5.65	5.21
24-Apr-03	6.26	6.26	7.71	5.66	5.25
28-May-03	6.18	6.18	7.58	5.54	5.1
27-Jun-03	5.36	5.36	6.98	4.91	4.48
29-Jul-03	5.28	5.28	6.73	4.7	4.23
19-Aug-03	5.54	5.54	7.05	5.01	4.63
22-Sep-03	5.61	5.61	6.89	4.84	4.4
23-Oct-03	5.65	5.65	6.92	4.86	4.39
30-Nov-03	5.37	5.37	6.31	4.24	-
16-Dec-03	5.66	5.66	6.96	4.9	4.43
13-Jan-04	5.8	5.8	7.04	5.16	4.58
13-Feb-04	5.05	5.05	6.46	4.42	4.05
22-Mar-04	5.74	5.74	6.98	4.9	4.34
27-Apr-04	5.69	5.69	-	5.23	4.79
27-May-04	5.67	5.67	7.19	5.17	-
23-Jun-04	2.95	2.95	4.39	2.46	2.27
29-Jul-04	4.3	4.3	5.8	3.79	3.5
18-Aug-04	3.59	3.59	5.26	3.15	2.73
20-Oct-04	4.65	4.65	6.88	4.87	4.36
22-Nov-04	4.23	4.23	6.98	4.92	4.49
13-Dec-04	6.19	6.19	7.44	5.35	4.93
17-Jan-05	5.48	5.48	6.36	4.14	3.97
16-Mar-05	6.38	6.38	7.73	5.66	5.19
20-Apr-05	6.11	6.11	7.69	5.71	-
19-May-05	5.8	5.8	7.54	5.52	5.17
20-Jun-05	6	6	7.08	5.04	4.41

	Depth to groundwater level (m)				
Date	**GW 2**	**GW3**	**GW 4**	**GW5**	**GW 6**
01-Aug-05	5.3	5.3	6.96	4.88	-
23-Aug-05	5.89	5.89	7.24	5.1	4.43
21-Sep-05	4.76	4.76	6.16	4.15	4.57
27-Oct-05	4.32	4.32	6.14	4.1	3.98
23-Nov-05	5.85	5.85	6.92	4.78	3.78
14-Dec-05	5.59	5.59	6.96	5.01	4.56
18-Jan-06	6.32	6.32	7.73	5.6	4.58
27-Feb-06	6.72	6.72	7.11	5.19	5.23
16-Mar-06	6.05	6.05	7.4	5.39	4.75
26-Apr-06	5.6	5.6	7.13	5.14	4.93
31-May-06	4.67	4.67	6.7	4.64	4.82
26-Jun-06	4.64	4.64	6.19	4.08	4.09
25-Jul-06	4.9	4.9	6.1	3.98	3.65
28-Aug-06	5.1	5.1	6.18	4.09	3.47
26-Sep-06	5.82	5.82	7.18	5.26	3.61

Depth to groundwater level (m)

Date	GW 16	Gw 18	Gw 22	GW 23	GW 26	Gw 40	GW 41	GW 42	GW 43
28-Aug-01	3.32	4.05	-	-	3.84	4.84	-	3.92	3.61
19-Sep-01	3.83	4.33	-	-	4.26	5.31	-	4.38	4.03
01-Nov-01	4.18	4.75	3.99	3.44	4.6	5.63	-	4.74	4.38
27-Nov-01	3.8	4.28	3.55	2.96	4.15	5.21	-	4.25	3.97
21-Dec-01	2.67	3.31	2.43	2	3.18	4.17	-	3.24	2.94
30-Jan-02	3.78	4.28	3.53	2.99	4.17	5.23	5.02	4.28	3.96
26-Feb-02	4.26	4.77	4.05	3.5	4.63	5.66	5.49	4.76	4.44
26-Mar-02	4.36	4.86	4.15	3.61	4.75	5.75	5.59	4.87	4.53
29-Apr-02	4.15	4.74	3.9	3.4	4.63	5.66	5.46	4.75	4.4
31-May-02	3.72	4.26	3.5	2.9	4.12	5.16	4.94	4.18	3.9
25-Jun-02	3.06	3.56	2.8	2.19	3.49	4.51	4.28	3.53	3.2
17-Jul-02	2.24	2.84	1.94	1.3	2.74	3.75	3.52	2.78	2.45
29-Aug-02	3.05	3.64	2.81	2.31	3.52	4.54	4.33	3.6	3.26
24-Sep-02	3.44	3.9	3.2	2.62	3.8	4.89	4.67	3.91	3.58
21-Oct-02	3.96	4.26	3.69	2.97	4.14	5.23	5.06	4.26	4.02
26-Nov-02	3.89	4.41	3.68	3.14	4.28	5.34	5.14	4.4	4.08
17-Dec-02	4.19	4.64	3.95	3.33	4.52	5.54	5.36	4.63	4.3
30-Jan-03	4.13	3.68	3.93	3.43	4.54	5.57	5.38	4.66	4.33
24-Feb-03	4.32	4.8	4.12	3.57	4.69	5.7	5.53	4.82	4.5
31-Mar-03	4.37	4.95	4.17	3.68	4.8	5.84	5.65	4.94	4.59
23-Apr-03	4.43	4.97	4.21	3.7	4.84	5.88	5.68	4.96	4.65
28-May-03	4.28	4.82	4.06	3.47	4.71	5.71	5.52	4.8	4.48
27-Jun-03	3.63	4.21	3.38	2.89	4.06	5.13	4.9	4.16	3.87
01-Aug-03	3.68	4.05	3.45	2.76	3.96	5.08	4.86	4.06	3.8
19-Aug-03	3.8	4.36	3.57	3.07	4.22	5.25	5.06	4.32	4.01
18-Sep-03	3.5	4.11	3.28	2.77	3.94	4.99	4.79	4.04	3.73
22-Oct-03	3.64	4.07	3.41	2.74	3.98	5.09	4.86	4.08	3.79

		Depth to groundwater level (m)							
Date	**GW 16**	**Gw 18**	**Gw 22**	**GW 23**	**GW 26**	**Gw 40**	**GW 41**	**GW 42**	**GW 43**
30-Nov-03	3.55	4.06	3.2	2.59	3.49	5.08	4.66	3.88	3.82
15-Dec-03	3.71	4.17	3.49	2.91	4.07	5.15	4.93	4.2	3.93
14-Jan-04	3.81	4.34	3.75	3.03	4.2	5.3	5.13	4.34	4.01
13-Feb-04	3.34	3.79	3.07	2.52	3.71	4.77	4.56	3.78	3.49
22-Mar-04	3.72	4.05	3.42	2.68	3.97	5.08	4.85	4.08	3.82
23-Apr-04	3.88	4.44	3.65	3.15	4.29	5.34	5.14	4.4	4.1
27-May-04	3.98	4.45	3.71	3.18	4.36	4.37	5.19	4.44	4.15
23-Jun-04	1.18	1.99	1.08	1.19	1.66	2.69	2.51	1.84	1.45
29-Jul-04	2.48	3.19	2.23	1.81	2.98	4.02	3.81	3.1	2.77
16-Aug-04	1.88	2.63	1.63	1.24	2.34	3.39	3.19	2.49	2.16
17-Sep-04	3.33	3.85	3.06	2.05	3.71	4.81	4.58	3.83	3.53
18-Oct-04	3.46	3.87	3.23	1.74	3.92	4.97	4.78	4.06	3.69
22-Nov-04	3.78	4.12	3.56	1.76	4.04	5.18	4.99	4.18	3.96
15-Dec-04	4.02	4.46	3.92	3.3	4.35	5.5	5.33	4.59	4.31
17-Jan-05	3.12	3.58	3.68	3.14	3.61	4.72	4.31	3.63	
15-Mar-05	4.4	4.89	4.21	3.67	4.76	5.81	5.65	4.93	4.59
14-Apr-05	4.44	4.97	4.22	3.77	4.87	5.89	5.7	4.97	4.96
18-May-05	4.34	4.87	4.1	3.52	4.77	5.79	5.6	4.93	4.58
22-Jun-05	3.6	4.38	3.46	3.1	4.08	5.31	5.1	4.35	4.05
29-Jul-05	3.64	4.11	3.4	2.77	4.01	5.08	4.85	4.07	3.79
24-Aug-05	3.87	4.47	3.65	3.06	4.06	5.37	5.29	4.44	4.13
20-Sep-05	2.95	3.55	2.79	2.19	3.49	4.41	4.25	3.53	3.36
20-Oct-05	2.53	3.33	2.68	2.01	3.07	2.05	3.82	3.42	2.79
22-Nov-05	3.75	4.17	3.51	2.9	4.1	5.18	4.98	4.14	3.84
14-Dec-05	3.79	4.29	3.55	3.07	4.18	5.2	5.06	4.28	3.99
17-Jan-06	4.26	4.76	4.17	3.6	4.59	5.82	5.64	4.92	4.42
27-Feb-06	3.95	4.4	3.69	3.17	4.65	5.37	5.12	4.44	4.05
16-Mar-06	4.17	4.74	4	3.47	4.52	5.63	5.45	4.72	4.43
26-Apr-06	3.94	4.59	3.71	3.19	4.42	5.41	5.21	4.5	4.18
29-May-06	3.37	3.82	3.11	2.54	3.76	4.84	4.61	3.85	3.53
26-Jun-06	2.83	3.45	2.6	2.06	3.32	4.35	4.14	3.42	3.05
24-Jul-06	2.78	3.24	2.53	1.98	3.22	4.19	4.01	3.27	2.89
24-Aug-06	2.88	3.37	2.62	2	3.32	4.32	4.1	3.36	2.99
25-Sep-06	3.9	4.38	3.71	3.12	4.27	5.37	5.18	4.42	4.03

Depth to groundwater level (m)

Date	GW1
21-Sep-01	5.85
30-Oct-01	6.24
31-Jan-02	5.84
30-Apr-02	5.97
18-Jul-02	4.28
24-Oct-02	6.16
29-Jan-03	6.33
24-Apr-03	6.49
29-Jul-03	5.5
13-Jan-04	5.89
27-Apr-04	5.93
20-Oct-04	4.87
17-Jan-05	4.37
20-Apr-05	6.5
01-Aug-05	5.42
27-Oct-05	4.15

Date	GW24
31-Oct-01	3.45
30-Jan-02	2.97
30-Apr-02	3.5
18-Jul-02	1.3
21-Oct-02	2.89
30-Jan-03	3.45
23-Apr-03	3.72
01-Aug-03	2.71
23-Oct-03	2.58
14-Jan-04	2.95
23-Apr-04	3.19
29-Jul-04	1.88
18-Oct-04	2.78
26-Jan-05	3.12
18-Apr-05	3.81
27-Jul-05	2.7
26-Oct-05	3.01
17-Jan-06	3.61
26-Apr-06	3.34
24-Jul-06	1.99

Date	GW10
31-Oct-01	9.23
29-Jan-02	8.99
18-Jul-02	8.15
24-Oct-02	8.86
30-Jan-03	9.09
23-Apr-03	8.88
30-Jul-03	8.56
23-Oct-03	8.43
14-Jan-04	8.5
13-Feb-04	8.47
23-Apr-04	8.52
29-Jul-04	8.19
19-Oct-04	8.91
14-Jan-05	8.46
18-Apr-05	8.8
01-Aug-05	8.37
27-Oct-05	8.17
17-Jan-06	8.67
26-Apr-06	8.83
25-Jul-06	8.91

Date	GW14 B
29-Jan-02	11.73
18-Jul-02	11.11
24-Oct-02	11.9
30-Jan-03	11.98
23-Apr-03	11.99
30-Jul-03	11.63
23-Oct-03	11.77
14-Jan-04	11.62
23-Apr-04	11.61
29-Jul-04	10.09
19-Oct-04	11.69
15-Apr-05	12.1
19-May-05	12.2
29-Jul-05	11.74
27-Oct-05	11.51
18-Jan-06	12.06
26-Apr-06	11.88
24-Jul-06	11.23

Date	GW 17
31-Jan-02	6.11
18-Jul-02	5.76
24-Oct-02	5.85
30-Jan-03	6.22
23-Apr-03	6.7
01-Aug-03	6.51
23-Oct-03	6.22
16-Jan-04	6.2
26-Apr-04	6.32
29-Jul-04	5.84
19-Oct-04	5.71
17-Jan-05	5.85
20-Apr-05	8.42
01-Aug-05	6.01
27-Oct-05	4.31
18-Jan-06	6.27
26-Apr-06	6.6
25-Jul-06	5.53

Date	GW 25B
01-Nov-01	7.51
31-Jan-02	6.98
18-Jul-02	5.59
24-Oct-02	7
30-Jan-03	7.54
23-Apr-03	7.87
01-Aug-03	6.81
23-Oct-03	6.44
26-Apr-04	7.28
29-Jul-04	6.04
19-Oct-04	6.74
26-Jan-05	7.03
20-Apr-05	7.92
01-Aug-05	6.76
27-Oct-05	5.95
18-Jan-06	7.65
26-Apr-06	7.5
25-Jul-06	6.14

Date	GW9
31-Oct-01	10.25
29-Jan-02	10.23
17-Jul-02	9.87
21-Oct-02	10.15
29-Jan-03	10.2
23-Apr-03	10.3
22-Oct-03	10.13
13-Jan-04	10.11
29-Jul-04	9.8

Date	Gw 15
28-Aug-01	3.35
19-Sep-01	3.74
01-Nov-01	4.07
27-Nov-01	3.63
21-Dec-01	2.65
30-Jan-02	3.65
26-Feb-02	4.09
26-Mar-02	4.2

Depth to groundwater level (m)		
Date	GW 30B	GW31 B
30-Apr-02	3.08	3.82
18-Jul-02	0.79	-
30-Jan-03	3.07	3.92
31-Mar-03	3.36	4.19
23-Apr-03	3.37	4.23
28-May-03	3.17	4.03
27-Jun-03	2.56	3.45
01-Aug-03	2.45	3.39
14-Jan-04	2.69	3.65
13-Feb-04	2.11	3.07
22-Mar-04	2.38	3.4
23-Apr-04	2.83	3.64
27-May-04	2.86	3.73
23-Jun-04	0.56	1.12
29-Jul-04	1.54	2.27
16-Aug-04	0.93	1.74
17-Sep-04	2.2	2.58
18-Oct-04	2.46	3.27
22-Nov-04	2.55	3.47
13-Dec-04	3	3.91
26-Jan-05	2.81	-
16-Mar-05	3.34	4.2
18-Apr-05	3.44	4.3
20-May-05	3.19	3.99
20-Jun-05	2.76	3.71
27-Jul-05	2.44	3.36
23-Aug-05	2.94	3.63
20-Sep-05	2.02	2.66
26-Oct-05	1.71	2.93
22-Nov-05	2.56	3.48
14-Dec-05	4.7	3.38
18-Jan-06	5.49	4.15
27-Feb-06	5.24	5
21-Mar-06	5.34	4.03
26-Apr-06	5.1	3.69
29-May-06	4.42	3.16
26-Jun-06	4	2.64
24-Jul-06	3.84	2.66
24-Aug-06	3.91	2.68
25-Sep-06	4.98	3.71

Daily mean levels (m) for Waikato River at Hamilton Traffic Bridge.

			Year	2001								
Date	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
					River level (m)							
1	11.88	12.49	12.72	11.91	12.07	13.70	12.33	12.39	12.54	11.82	11.93	11.93
2	11.81	12.63	12.42	12.21	12.35	13.07	12.38	12.55	11.99	11.77	11.92	11.88
3	12.05	11.93	12.21	12.67	12.59	12.35	12.79	12.53	12.52	11.76	11.96	12.09
4	12.07	11.75	12.34	12.45	12.59	12.76	12.35	12.36	13.17	11.99	12.30	12.10
5	12.25	12.10	12.36	12.55	12.15	13.20	12.08	12.03	13.07	12.47	12.38	12.16
6	11.94	12.01	12.77	12.55	12.09	13.29	12.30	12.17	12.54	12.15	12.44	12.19
7	11.92	12.28	12.23	12.09	12.38	13.57	12.05	12.30	12.42	11.91	12.44	12.36
8	12.50	12.35	12.45	11.89	12.37	13.08	11.84	12.60	12.66	12.08	12.26	12.69
9	12.27	12.36	12.92	12.61	12.56	12.51	12.14	12.42	12.03	12.66	12.06	12.74
10	12.43	12.40	12.63	12.23	12.84	12.22	12.20	12.16	12.12	12.29	12.06	13.17
11	12.57	12.11	11.94	12.54	12.42	12.66	12.47	11.93	12.49	12.06	11.82	13.71
12	12.45	12.73	12.10	12.57	12.13	13.39	12.65	11.88	12.59	12.19	11.80	13.08
13	11.97	12.74	12.28	12.24	12.21	13.37	12.17	11.89	12.44	11.93	11.98	12.57
14	12.05	12.55	12.43	11.92	12.21	12.86	12.05	12.01	12.45	11.94	12.13	12.88
15	12.32	12.40	12.48	11.87	12.60	12.60	11.94	12.41	12.28	11.91	12.17	12.97
16	12.33	12.56	12.20	11.84	12.44	12.08	12.22	12.28	11.99	11.88	11.90	13.27
17	12.48	12.07	12.08	12.35	12.45	11.83	12.59	12.14	12.24	11.86	11.86	13.28
18	12.37	11.94	11.74	12.37	12.66	12.35	12.51	11.88	12.25	11.84	11.84	13.91
19	12.54	11.99	12.06	12.41	12.21	13.01	12.94	11.81	12.40	11.77	11.89	13.93
20	12.36	12.52	12.71	12.56	11.85	13.11	13.12	12.16	12.57	11.76	12.34	13.92
21	11.98	12.42	12.62	12.03	11.92	12.90	12.72	12.15	12.44	11.81	12.40	13.67
22	12.34	12.54	12.69	12.02	12.65	12.92	12.30	12.14	12.35	11.81	12.99	13.49
23	12.70	12.95	12.71	12.38	13.03	12.14	12.48	12.11	12.09	11.85	12.86	12.89
24	12.51	12.70	12.00	12.50	12.56	11.97	12.67	12.42	12.12	11.94	12.27	13.52
25	12.63	11.94	11.78	12.00	12.59	12.82	12.79	12.44	12.44	12.32	12.22	13.28
26	12.50	12.26	12.16	12.28	12.65	12.85	12.70	12.29	12.02	12.36	12.66	12.65
27	12.22	12.61	12.88	12.30	12.64	12.49	12.38	12.45	11.86	12.07	12.36	13.12
28	12.07	12.71	12.63	11.93	13.19	12.82	11.86	12.75	11.87	11.99	12.03	13.44
29	11.94		12.54	11.74	13.41	12.72	11.82	12.76	11.82	11.91	12.13	13.50
30	12.33		12.26	11.98	13.58	12.36	12.16	12.77	11.84	11.82	11.91	13.31
31	12.37		12.08		13.66		12.48	12.86		11.78		12.70

				Year	2002							
Date	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
					Level (m)							
1	12.97	12.32	11.83	11.79	12.38	12.37	12.82	13.33	12.63	12.71	12.97	12.35
2	12.95	11.92	12.22	11.95	12.17	12.29	13.43	13.36	12.63	12.92	12.68	11.96
3	12.70	11.73	11.79	12.38	12.16	11.97	13.65	13.37	13.33	13.13	12.48	11.82
4	12.72	11.83	11.76	12.25	11.96	12.24	13.51	12.83	13.44	13.09	12.92	11.80
5	12.30	12.04	12.00	12.22	11.84	12.69	13.87	13.31	12.64	12.60	13.13	11.79
6	12.43	12.38	12.01	12.74	11.82	12.55	14.70	13.15	12.59	12.50	13.45	11.80
7	12.55	13.44	11.81	12.23	12.17	12.65	14.74	13.42	12.36	12.71	13.20	11.83
8	12.23	12.25	11.83	12.28	12.05	12.13	14.85	13.05	12.49	12.63	12.73	11.91
9	12.42	11.83	11.77	12.17	11.81	12.21	14.62	13.33	12.78	12.76	12.31	11.86
10	12.60	11.72	11.75	12.19	12.03	12.14	14.97	13.30	12.94	12.72	12.15	12.02
11	12.46	12.03	12.10	12.30	12.20	12.38	15.16	12.92	12.91	12.53	12.23	11.95
12	12.12	11.99	12.46	11.99	11.80	12.44	14.86	13.14	13.14	12.01	12.89	11.81
13	11.88	11.86	11.97	11.92	11.78	12.66	14.12	12.70	13.21	12.24	13.06	11.92
14	12.48	11.89	12.23	11.76	11.78	12.48	13.38	12.73	13.28	12.72	13.12	11.83
Date	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec

15	13.15	11.85	12.37	11.78	12.19	12.32	13.87	12.82	13.07	13.41	12.57	11.88
16	12.95	11.85	12.12	11.91	11.96	12.73	14.15	12.77	12.95	12.68	11.94	11.81
17	12.59	11.78	11.79	11.77	11.85	12.93	14.14	12.87	13.13	12.85	11.96	11.87
18	12.76	11.77	12.06	11.89	11.74	12.84	14.21	12.91	13.35	12.37	12.35	11.97
19	12.60	11.91	11.80	12.05	11.75	13.30	13.96	13.21	13.25	12.34	12.59	12.10
20	12.09	12.30	11.76	11.80	11.72	13.66	14.04	13.54	13.31	12.47	12.87	12.16
21	12.49	12.70	11.92	11.73	11.74	13.93	13.54	13.58	13.35	11.80	12.71	11.93
22	13.12	12.02	11.83	11.74	11.79	14.15	13.76	14.08	12.64	11.80	12.30	11.89
23	12.90	12.02	11.89	11.76	11.87	12.67	13.58	13.65	12.68	11.90	12.02	11.78
24	12.67	11.73	11.75	12.17	12.16	12.58	14.03	13.16	12.97	12.03	11.95	11.77
25	12.78	11.77	11.76	12.15	11.93	12.84	14.13	12.20	13.25	11.96	12.13	11.75
26	13.07	12.08	11.93	12.17	12.01	12.91	13.56	13.11	13.59	11.96	12.47	11.77
27	12.25	12.56	12.41	12.24	12.01	12.81	13.81	13.49	13.31	12.06	12.54	11.76
28	12.17	12.18	12.38	12.03	12.97	12.62	13.65	13.12	12.83	12.16	12.65	11.77
29	12.42		12.07	12.20	13.43	12.50	13.75	13.37	13.12	12.12	12.74	11.75
30	12.56		11.76	12.58	13.50	12.33	13.32	13.56	13.02	11.92	12.94	11.73
31	12.57		11.82		12.64		13.50	13.06		12.33		11.84

					Year	**2003**						
Date	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1	11.71	12.24	12.17	11.77	11.77	11.78	12.57	12.67	11.84	13.21	12.62	12.47
2	11.72	12.05	11.81	11.79	11.77	11.77	12.77	12.41	12.49	12.82	12.52	12.42
3	11.75	11.97	11.93	11.79	11.76	11.78	12.86	12.39	12.88	13.28	12.80	12.25
4	11.72	11.84	12.06	11.78	11.73	11.76	13.07	12.38	12.63	13.95	12.85	12.43
5	11.73	12.36	11.91	11.73	11.75	11.79	12.91	12.32	12.74	12.56	12.79	12.42
6	11.95	12.30	11.97	11.86	11.75	12.27	12.57	12.65	12.58	13.29	13.20	12.19
7	12.05	12.26	12.08	11.94	11.76	12.31	12.87	12.37	12.33	13.44	12.91	11.97
8	12.04	12.29	11.79	11.81	11.77	12.15	12.85	12.34	12.76	13.06	12.17	11.87
9	12.24	12.36	11.76	11.80	11.78	12.20	13.29	12.12	12.84	13.23	12.22	12.50
10	13.23	12.70	11.79	11.78	11.75	12.97	13.43	11.90	12.77	12.70	12.81	12.64
11	12.33	12.74	12.21	11.74	11.73	12.70	13.21	12.44	12.87	12.42	12.84	13.28
12	12.03	12.88	12.13	11.75	11.76	12.54	12.92	12.57	12.61	13.11	12.76	12.43
13	11.90	12.50	11.87	11.78	11.75	12.44	12.90	12.68	12.37	13.08	12.64	12.36
14	11.94	12.20	12.00	12.18	11.75	12.35	13.32	12.64	12.18	13.03	12.45	12.24
15	12.24	11.84	12.14	12.26	11.78	12.31	13.19	12.65	12.27	13.00	12.73	12.29
16	12.31	11.79	11.76	12.10	11.75	12.96	13.52	12.39	12.77	12.93	12.58	12.23
17	12.26	11.81	11.88	11.99	11.71	13.08	12.80	11.95	12.59	12.40	12.30	12.35
18	12.45	11.77	11.92	11.86	11.74	13.29	12.96	12.45	12.56	12.53	12.34	12.45
19	11.91	11.88	11.83	11.81	11.75	12.79	13.00	12.82	12.25	12.43	12.68	12.20
20	12.08	12.03	11.84	11.82	11.77	12.21	12.85	13.15	12.18	11.90	12.20	12.12
21	12.20	12.09	12.02	11.85	11.79	12.52	13.22	13.08	12.08	12.41	12.14	12.37
22	12.34	11.96	11.87	11.81	12.12	12.41	13.89	13.73	12.32	12.48	12.05	11.91
23	12.40	11.77	11.79	11.78	12.08	12.00	13.55	13.05	12.53	12.38	12.09	12.07
24	12.54	11.79	11.76	11.78	11.92	12.45	12.58	12.44	12.63	12.49	12.26	12.16
25	11.98	11.85	11.75	11.79	11.85	12.48	12.49	11.90	11.97	12.28	12.54	12.17
26	11.77	11.92	11.74	11.82	11.81	12.47	12.46	11.77	12.13	12.37	12.78	12.04
27	11.92	12.07	11.79	11.85	11.77	12.60	12.35	11.75	12.28	12.35	12.96	12.74
28	11.84	12.20	11.81	11.85	11.78	12.17	12.77	11.82	12.32	13.04	13.13	12.59
29	12.16		11.77	11.77	11.80	12.02	13.05	11.81	13.10	13.11	12.99	13.02
30	12.28		11.80	11.77	11.78	12.01	12.83	11.90	13.20	13.24	12.44	13.21
31	12.17		11.81		11.78		12.64	11.75		12.67		13.56

					Year	2004						
Date	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
					Level	**(m)**						
1	13.12	11.84	15.93	12.71	12.60	12.71	14.10	13.92	13.85	12.71	13.23	12.30
2	12.74	12.55	15.29	12.32	12.72	12.45	14.02	13.98	13.95	12.39	13.54	12.53
3	12.69	13.98	15.61	12.13	12.35	12.49	14.21	14.09	14.04	12.47	13.37	12.43
4	12.89	13.49	15.56	11.94	12.36	12.74	14.02	14.06	13.37	12.70	13.38	12.74
5	12.89	13.54	15.20	12.30	12.30	12.54	14.11	14.45	12.01	12.53	13.46	12.84
6	12.57	13.29	14.94	12.55	12.29	12.71	13.95	13.89	12.63	12.33	13.52	12.75
7	12.55	12.76	14.24	12.73	12.31	12.72	14.11	14.00	13.61	12.66	13.08	11.95
8	12.66	12.96	14.10	12.81	11.86	12.70	13.80	14.51	13.59	13.10	13.03	11.78
9	12.99	13.44	13.99	12.08	11.87	13.21	13.93	14.59	13.35	13.31	12.70	11.92
10	13.27	13.35	13.53	12.01	12.03	13.25	14.08	14.55	13.29	12.56	12.76	11.95
11	12.64	13.03	13.59	12.06	12.05	13.13	13.46	14.50	12.40	12.82	13.09	12.23
12	12.52	13.35	13.67	11.86	12.39	13.03	13.47	14.42	12.38	12.49	12.75	11.76
13	12.10	12.97	13.12	12.43	12.44	12.76	13.46	14.28	13.05	12.71	12.65	11.95
14	12.44	13.26	12.82	12.46	12.03	13.05	13.53	13.97	12.93	12.86	12.83	12.30
15	12.49	13.34	13.43	12.43	11.86	13.20	13.46	13.58	12.80	12.45	12.93	12.53
16	12.18	13.73	13.34	12.59	11.77	12.97	13.22	14.59	12.89	12.52	12.80	12.63
17	12.25	13.54	13.24	12.37	12.23	12.92	13.52	14.79	12.91	12.36	12.78	12.32
18	11.83	13.23	13.10	11.95	12.56	13.80	13.91	14.49	12.68	12.99	12.82	12.26
19	11.97	13.51	13.11	12.11	12.44	13.52	14.05	14.10	12.54	13.52	13.11	12.30
20	11.87	13.45	12.56	12.24	12.32	13.71	13.98	13.83	12.86	13.24	12.76	12.25
21	12.01	13.96	11.94	12.24	12.49	14.19	13.81	13.79	12.75	13.19	12.32	12.70
22	12.12	14.82	12.28	12.46	12.25	14.56	13.85	13.65	12.68	12.69	12.48	12.94
23	12.15	14.69	12.87	12.45	12.26	14.86	13.62	13.77	12.80	12.97	12.60	12.69
24	11.87	14.25	13.06	12.30	12.31	14.46	13.39	13.52	12.66	12.86	12.65	12.25
25	11.77	13.53	13.16	12.34	12.57	14.64	13.60	13.53	12.25	13.12	12.66	12.24
26	11.78	13.96	12.82	12.44	12.60	14.35	13.72	13.69	12.19	13.09	12.62	11.97
27	11.91	13.74	12.13	12.55	12.29	14.23	13.63	13.27	12.50	13.28	12.53	12.04
28	12.40	13.88	12.04	12.52	12.52	13.92	14.03	13.48	12.75	12.87	11.98	12.22
29	12.28	15.70	12.27	12.71	12.56	14.40	13.91	12.93	12.92	13.27	11.87	12.90
30	12.35		12.45	12.77	12.30	14.68	13.95	13.17	12.87	13.64	12.26	12.61
31	12.07		12.63		12.49		13.58	13.28		13.20		12.96

					Year	2005						
Date	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
					Level (m)							
1	12.69	12.74	12.26	11.98	11.72	12.45	13.09	12.16	12.25	12.15	13.39	12.33
2	12.34	12.96	12.24	11.72	11.76	12.58	13.03	12.87	12.24	12.18	13.11	12.38
3	12.71	12.60	11.94	11.67	12.02	12.94	12.44	12.69	11.96	13.03	12.90	12.25
4	13.14	12.83	12.14	11.76	12.34	12.78	12.80	12.59	11.86	12.83	13.07	11.99
5	13.16	12.41	11.76	11.81	11.96	12.23	13.03	12.73	11.77	13.90	12.69	12.09
6	13.64	11.90	11.75	11.95	11.79	12.08	12.46	12.06	12.13	13.73	12.59	12.64
7	13.66	12.32	11.92	11.81	11.72	12.75	12.61	12.09	12.01	13.66	12.70	13.22
8	13.73	12.54	11.84	12.00	11.71	13.00	12.27	12.31	11.83	13.72	12.15	12.58
9	13.38	12.65	11.80	11.86	11.76	13.22	11.89	12.74	11.93	13.22	12.66	12.73
10	13.70	12.71	11.86	11.71	11.76	12.86	11.87	12.97	12.17	13.88	13.51	12.43
11	13.63	12.79	11.83	11.72	11.85	12.34	12.38	12.81	11.79	14.14	12.58	12.50
12	13.38	12.53	11.78	11.78	11.89	12.27	12.97	13.07	11.81	13.92	12.50	12.53
13	13.55	12.32	11.73	11.78	11.86	12.40	12.68	12.33	11.90	13.73	12.48	12.65
14	13.03	12.58	11.74	11.81	11.67	12.45	12.67	11.91	11.89	13.75	12.73	12.84
15	12.28	12.37	11.72	11.86	11.70	12.66	12.82	11.91	11.99	13.52	12.70	13.00
16	12.44	12.50	11.71	11.77	11.90	12.59	12.23	11.82	11.99	13.47	12.70	12.44
17	12.49	12.40	11.86	11.76	12.24	12.78	12.43	12.06	12.17	13.83	12.85	12.07
18	12.34	12.30	12.27	11.80	12.06	12.73	12.99	12.27	13.06	13.53	12.91	12.40
19	12.52	12.02	12.34	12.11	12.03	12.22	12.98	12.19	13.81	13.79	12.51	12.51
20	12.46	11.89	11.83	11.89	11.85	12.36	12.58	11.92	13.13	13.81	12.77	12.03
21	12.30	12.80	11.78	11.97	11.78	12.73	12.73	11.79	12.72	13.81	12.70	11.97
22	12.27	12.52	11.95	11.92	11.73	12.76	12.77	11.86	12.72	13.66	12.47	11.98
23	11.97	12.64	12.22	11.74	11.76	12.53	12.14	12.41	12.66	13.38	12.03	12.17
24	12.01	12.51	12.15	11.77	11.82	12.81	12.04	12.39	12.03	13.68	11.92	12.01
25	12.29	12.31	11.78	11.73	11.94	12.72	12.45	12.27	12.00	13.74	12.21	11.86
26	12.41	12.24	11.74	11.75	12.08	12.54	12.62	12.41	12.41	13.41	12.38	11.77
27	12.55	12.16	11.76	12.19	12.19	12.96	12.27	12.08	11.93	13.32	12.39	11.79
28	12.52	12.56	11.75	12.02	11.90	12.70	12.23	11.92	12.23	13.55	12.11	11.75
29	12.52		11.92	12.33	11.75	12.71	12.52	11.93	12.31	13.47	12.45	11.90
30	12.38		12.03	11.85	12.19	12.77	12.24	12.30	12.32	13.13	12.30	11.78
31	11.84		12.14		12.59		11.98	12.05		13.49		11.80

					Year	**2006**						
Date	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
					Level (m)							
1	11.78	12.80	12.29	11.76	13.37	12.91	12.73	12.97	13.25	11.91	12.74	12.58
2	11.78	12.87	12.04	11.78	13.66	13.46	12.11	13.13	12.90	12.72	12.48	12.47
3	11.77	13.43	12.36	11.84	13.64	12.98	12.75	13.02	12.74	12.63	12.51	11.94
4	11.76	12.86	12.17	11.98	13.12	13.47	12.94	13.00	12.74	12.69	12.59	12.43
5	11.79	12.66	12.07	12.15	13.17	13.07	13.10	12.79	12.94	12.85	12.37	13.06
6	11.74	12.95	12.04	12.29	13.12	13.11	12.74	13.26	13.16	12.59	12.58	13.10
7	11.73	12.58	12.57	12.03	13.12	13.59	12.80	14.42	13.11	12.34	12.75	13.29
8	11.78	12.57	12.49	11.84	12.83	13.48	12.26	15.02	13.13	12.12	12.78	12.86
9	11.87	12.56	12.41	11.80	13.38	13.38	12.01	14.51	13.08	12.39	12.98	12.97
10	12.04	12.27	12.24	11.83	13.28	13.19	12.37	14.06	12.02	12.86	12.62	12.88
11	12.00	13.00	11.96	11.93	13.13	13.25	12.84	14.13	12.06	13.30	12.31	12.80
12	12.03	13.96	11.79	12.00	13.44	12.96	12.79	14.21	12.76	13.09	12.33	12.88
13	11.93	13.92	12.09	11.88	13.35	13.73	13.06	14.03	12.97	12.97	12.40	13.07
14	11.80	13.85	12.61	11.86	13.07	13.56	13.57	14.06	13.13	12.59	12.36	12.94
15	11.79	13.96	12.34	11.83	13.21	13.84	13.15	14.10	12.85	12.26	12.43	13.02
16	11.75	13.73	12.09	11.82	13.49	13.82	12.15	14.03	12.42	12.71	12.29	12.58
17	11.75	13.62	12.55	11.72	13.39	13.09	12.67	13.50	12.62	13.12	12.90	12.32
18	11.75	12.77	12.36	11.82	13.18	13.36	13.09	13.55	12.85	12.82	12.57	12.25
19	11.79	12.04	11.77	11.79	13.36	13.71	13.52	13.12	12.63	12.66	12.16	12.64
20	11.95	12.50	11.97	12.61	13.07	13.74	13.95	13.40	12.86	12.96	12.12	13.11
21	11.82	12.91	12.39	12.83	12.43	13.27	13.77	13.70	12.56	12.42	12.26	12.19
22	11.76	12.58	12.73	12.32	13.12	13.83	13.48	13.65	12.62	12.00	12.76	12.09
23	12.07	12.72	12.46	12.12	13.02	13.94	13.35	13.74	12.11	12.51	12.91	12.01
24	12.28	12.45	12.38	12.65	13.19	13.46	13.10	13.37	11.96	12.86	13.01	11.97
25	12.57	12.15	11.93	12.53	13.41	13.00	13.08	13.34	12.46	12.74	12.42	11.75
26	12.51	11.94	12.26	12.29	13.42	13.63	13.38	13.18	12.32	12.40	12.17	11.73
27	12.62	12.28	12.26	12.55	13.07	13.53	13.38	12.86	12.08	12.38	12.84	11.72
28	11.98	11.97	12.22	13.21	12.58	13.44	13.68	12.95	12.21	12.62	13.02	11.77
29	11.80		12.28	13.01	12.72	13.33	13.17	13.03	12.00	12.66	12.88	11.75
30	12.27		12.31	12.84	13.33	13.64	13.24	13.16	12.01	12.59	12.98	11.73
31	12.71		11.87		13.49		13.28	13.24		12.96		11.75

Pumping test data for boreholes at the Maseru landfill is presented below. Boreholes were pumped at the rate of 3 litres per second. Values are depth to groundwater during the pumping of each borehole, one after the other.

Depth to water level during pumping

Time (min)	BH1	BH2	BH3	BH4
0	15.1	27.08	38.48	44.96
1	15.4	32.8	41.15	47.07
2	15.45	33.07	41.38	47.08
3	15.49	34.1	41.99	47.09
4	15.55	35.51	42.48	47.14
5	15.6	36.22	42.86	47.18
6	15.68	37.02	43.09	47.22
7	15.72	38.08	43.32	47.24
8	15.73	38.6	43.57	47.27
9	15.78	38.96	43.79	47.28
10	15.9	39.12	43.95	47.28
12	15.92	39.64	44.64	47.3
14	15.95	39.75	44.97	47.33
16	16.02	39.86	45.26	47.34
18	16.09	40	45.54	47.35
20	16.21	40.15	46.08	47.37
25	16.3	40.35	46.62	47.42
30	16.43	40.4	46.87	47.47
35	16.5	40.46	47.26	47.43
40	16.6	40.57	47.58	47.57
45	16.65	40.68	47.87	47.63
50	16.73	40.77	48.15	47.65
55	16.78	40.79	48.43	47.68
60	16.85	40.88	50.4	47.7
70	16.91	41.19	51.15	47.79
80	16.99	41.33	51.56	47.8
90	17.03	41.42	52.06	47.85
100	17.09	41.45	52.83	47.92
110	17.14	41.5	55.1	47.93
120	17.2	41.52	57.07	47.94
140	17.33	41.58	58.1	47.94
160	17.38	41.65	59.9	47.94
180	17.51	41.78	61.53	47.94
210	17.58	42.76	64.84	47.97
240	17.66	42.85	67.41	48.02
270	17.69	42.88	69.61	48.06
300	17.76	42.88	70.16	48.11
360	17.9	42.98	71.85	48.22
420	18.02	43.1	72.7	48.45
480	18.11	43.16	73.02	48.68
540	18.27	43.52	75.5	49

Time (min)	BH1	BH2	BH3	BH4
600	18.35	44.3	-	49.12
660	18.45	44.4	-	49.36
720	18.53	44.45	-	49.53
780	18.62	44.49	-	49.66
840	18.63	44.66	-	49.78
900	18.76	45.9	-	50.03
960	18.85	46.08	-	50.17
1020	18.95	46.35	-	50.33
1080	19.04	46.42	-	50.45
1140	19.13	46.45	-	50.57
1200	19.19	46.51	-	50.7
1260	19.23	46.55	-	50.85
1320	19.27	46.64	-	50.92
1380	19.31	46.66	-	51.06
1440	19.4	46.67	-	51.14
1500	-	-	-	51.2