Quantification of the Impacts of a Domestic Waste Site on a Karoo Aquifer

By

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Declaration

I, Sakhile Sibusiso Edwin Mndaweni, declare that this dissertation submitted for the degree Magister Scientiae in the Faculty of Natural and Agricultural Sciences, Department of Geohydrology, University of the Free State, Bloemfontein, South Africa, is my own work and have not been submitted to any other institution of higher education. I further declare that all sources cited are indicated in references.

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Abstract

Waste generation is a widespread phenomenon around the world, of which the majority is disposed by landfilling. In landfills, waste constitutes an integral part of the hydrological system, and thus poses a threat to down-gradient groundwater and surface water receptors. This research was undertaken with the purpose of determining the interactions between landfill and the underlying Karoo aquifer, investigating the impacts of a domestic waste landfill on the aquifer and further predicting the magnitude of future contamination.

A domestic waste landfill site at Sasol Synfuels (Secunda), located on the Karoo aquifer, was investigated in order to achieve these objectives. This site (Charlie I Landfill) has been used by the refinery to dispose of all non-hazardous/general waste produced for the past twenty years. It is not lined. There is no information available on the type and volume of waste disposed, and the impact on groundwater was not quantified.

The landfill is classified as **GMB$^+$** (i.e. producing significant amounts of leachate), with the bord-and-pillar mining method taking place underneath the site at the depths of 90-120m. This implies a lower probability of subsidence at this position. Field investigations indicate that there is a contaminant plume emanating from the landfill, which is mostly concentrated in the upper part of the soil horizon. This horizon is mainly composed of clayey loams and clay, averaging 3m in depth with a laboratory estimated maximum hydraulic conductivity of 0.0128 m/day. It is underlain by the Karoo sediments (sandstones and shales).

Regional groundwater levels have been disturbed by the presence of the landfill site, with the higher water table closer to the site and the deeper water table moving away from the site. According to the blow yields obtained, slug tests for boreholes and piezometers, as well as the pumping tests, an average K- value of 10^{-2} was obtained for the aquifer, except in regions where a dolerite sill or fractures exists. Soil and water quality analyses indicate little contamination to groundwater; while contamination is mainly concentrated

in the upper soil zone (i.e. originates from the surface leachate springs at the edge of the landfill). Modelling of the contaminant plume also indicates a slow migration of the plume to the adjacent areas.

The physical properties of soils indicate that retardation (by biochemical reactions, sorption, cation-exchange etc.) of contaminants will occur with only very small quantities reaching groundwater. The presence of leachate springs and low levels of contaminant concentrations in groundwater indicates a limited vertical movement of contaminants. Therefore, leachate produced by the landfill site does not infiltrate into the groundwater system.

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1. Introduction

1.1. General

It is a common phenomenon that all life forms convert raw materials to products of value to themselves. In this process, waste material is produced (Novella *et al.,* 1999). Waste can be described as anything or everything that has lost value to the user, thus becoming useless or undesired, and hence the need arises to discard it. Globally, the most common method for waste disposal is landfilling.

Waste disposal by landfill is the oldest form of waste handling, and it is the simplest, cheapest and most cost-effective method for this purpose. Almost 100% of generated waste in developing countries is landfilled, and there is not much difference among the developed countries (Taylor and Allen, 2004), where some of the waste is reclaimed. It is estimated that South Africa generates about 42.2 million cubic metres per annum (m^3/a) of general waste (DWAF, 1998), of which most is landfilled.

The common practice worldwide is that land with little or no economic value is used for waste disposal by landfill (Noble, 1992). Examples include old quarry sites, where waste is disposed of as an alternative to backfilling. In most of these locations, groundwater is in direct contact with waste, resulting in contamination. In the landfills, waste constitutes an integral part of the hydrological system, and poses a long-term threat to groundwater and surface water downstream. The consequences are more severe for groundwater, due to the relatively long subsurface residence times associated with it.

It is estimated that between 13% and 15% of the total water consumption in South Africa is derived from groundwater (DWAF, 2002), with the majority abstracted using boreholes from the low-yielding, shallow, weathered and/or fractured-rock aquifer systems. More than half of South Africa's land is underlain by the sediments of the Karoo Stratigraphic Sequence, characterised by fractured hard rock aquifers (Botha *et al.*, 1998). These rocks consist of sandstones, mudstones, shale and siltstones with low permeabilities, intruded by Jurassic age dolerite dykes and sills. The Karoo aquifers can be described as the most important source of potable water for many of South Africa's rural communities, with the potential to contribute significantly to the country's water budget (Woodford and Chevallier, 2002).

Although the sediment characteristics (low permeability) of the Karoo rocks inhibits the rapid and effective movement of contaminated water in terms of aquifer vulnerability, the presence of secondary permeability, dyke and sill structures may allow for preferential or focused infiltration and redistribution of contaminated water in the subsurface (Woodford and Chevallier, 2002). This in turn makes an impact assessment of the Karoo aquifers very complicated, and a need arises for site-specific investigations in order to improve knowledge on the groundwater vulnerability of the Karoo aquifer systems (Woodford and Chevallier, 2002).

1.2. Objectives

Given the problems outlined above, the objectives of the dissertation are as follows:

- To determine the interaction between domestic waste landfill and the underlying Karoo aquifers by developing an informed understanding of the geology, geohydrology, hydraulic characteristics and chemical evolution of the aquifer system,
- To investigate the impact of a domestic waste landfill on the water quality of the underlying aquifer, predicting the nature of leachate produced by domestic waste, and
- To evaluate/predict the magnitude of future contamination

A domestic waste landfill at Sasol Synfuels (Secunda) was identified to be investigated in order to achieve the above objectives.

1.3. Method of Investigation

Steps involved include:

- Development of an initial site conceptual model based on existing site information.
- Determining the mechanism by which the leachate is formed.
- Determining the chemical composition of the leachate generated at the site.
- Identifying the pathway by which possible receptors might be affected by the leachate.
- Identifying the receptors (groundwater, streams, etc.) currently affected and that may be affected by the leachate in the future.
- Determination of the feasibility of expanding this landfill site, or identification of new site after closure.

The following methods are aimed at meeting the above objectives:

- Literature and background information study on waste disposal, leachate formation and migration, and regional geohydrological controls,
- Geophysical investigation of the area,
- Drilling boreholes and installation of piezometers,
- Aquifer parameter estimation,
- Soil and water quality investigations,
- Numerical flow and mass transport modelling.

1.4.Sequence of Chapters

Chapter 2 presents a theoretical description of the processes associated with waste disposal by landfill. Laws that govern siting, operation and closure of landfills are clearly described, and all chemical processes throughout the waste degradation process, including leachate production and migration, are depicted. Chapter 3 provides a concise description of the study area, including geology and geohydrology, whilst Chapter 4 discusses the process of field data collection and analysis. Chapter 5 presents findings on the soil and water quality analyses in the vicinity of the landfill site. Chapter 6 presents a summary and interpretation of results, and a conceptualisation of the hydrogeological system of the landfill site, including numerical flow and mass transport modelling. Chapter 7 provides conclusions based on the findings.

2. Waste Disposal by Landfill

2.1 Legal Framework

2.1.1. South African Laws

Currently, the South African water resource environment is protected by several important pieces of legislation. The three most significant include:

- The Constitution of the Republic of South Africa (Act 108 of 1996), which states that *it is a fundamental right of every person to have an environment which is not detrimental to his/her health or wellbeing and to have an environment protected for the benefit of present and future generations*,
- The Environmental Conservation Act (ECA Act 73 of 1989), which governs the protection and control of the environment, and
- The National Water Act (NWA Act 36 of 1998), providing the necessary framework within which to protect, use, develop, conserve, manage and control South African water resources.

The Waste Bill (Government Gazette No. 30142, 2007) is aimed at reforming the law regulating waste management for protection from pollution and ecological degradation.

2.1.2. International Laws

Numerous regulations have been implemented all over the world, with the aim of protecting the natural environment from pollution. The European Environmental Agency (1993) is responsible for diverging information to policy-making agents and the public in order to achieve improvements and sustainable development in the European environment. In the United States, the USEPA Resource Conservation and Recovery Act (RCRA, 1976) sets a framework for waste management and focuses on currently active and future waste sites. The Comprehensive Environmental Response Compensation and Liability Act (CERCLA, 1980), also known as SUPERFUND, establishes prohibitions and requirements concerning closed and abandoned waste sites.

2.2. Waste Management

The Waste Management Series documents are published by the Department of Water Affairs and Forestry (DWAF), and used to set minimum (lowest limit to comply with) procedures, actions and information requirements for successful permit application; to provide a point of departure to achieve acceptable waste disposal practices at large; and to provide standards or specifications to be followed. These are divided into a set of six documents, only three of which are discussed here:

- Document 1: Minimum Requirements for the Handling, Classification and Disposal of Hazardous Waste
- Document 2: Minimum Requirements for Waste Disposal by Landfill
- Document 3: Minimum Requirements for Water Monitoring at Waste Management Facilities

2.2.1. Minimum Requirements for the Handling, Classification and Disposal of Hazardous Waste (DWAF, 1998)

This document provides a systematic framework for identifying hazardous waste, and classifies it accordingly, taking into consideration the risks it poses. The objectives are:

- To ensure correct identification and classification of hazardous waste,
- To keep hazardous waste from entering the environment illegally,
- To implement "cradle-to-grave" principles by means of planned waste management strategies, and
- To control hazardous waste until it is safely disposed of, by setting Minimum Requirements at crucial points in its management.

The system classifies waste into two types:

- General Waste – any waste that is not classified as hazardous, and
- Hazardous Waste – any waste that has the potential to cause adverse effects on public health and the environment due to its toxic, chemical and physical characteristics.

Furthermore, hazardous waste is classified according to a Hazard Rating (i.e. low risk is indicated by a low hazard rating, and extreme risk by a high hazard rating, e.g. H:H – high rating 1 or 2, and H:h – low rating 3 or 4). The document also provides minimum requirements for the safe treatment, handling, transportation, storage and disposal of hazardous wastes.

2.2.2. Minimum Requirements for Waste Disposal by Landfill – 3rd Edition - Draft (DWAF, 2005)

This document aims to raise the standards of waste disposal in South Africa to environmentally acceptable levels. DWAF provides guidelines and practical information to assist in compliance with the departmental policies, and a minimum framework for standards to be adhered to or deviated from. The minimum requirements are used in selection, investigation, design, authorisation, preparation, operation, closure, and monitoring at waste disposal and other waste facilities. The main objectives of the document are:

- To improve the standard of landfilling in South Africa,
- To provide guidelines for environmentally acceptable waste disposal for a wide variety of landfill sizes and types,
- To provide a framework of minimum waste disposal standards within which to work and upon which to build, and
- To provide an approach for applying minimum requirements to waste management facilities other than landfills.

The landfill is classified in terms of waste class, operation size, and the potential of leachate generation due to the difference in their setting. Graded standards are set for all aspects of landfilling. The document furthermore provides minimum requirements for site classification, site selection, authorisation, assessment and mitigation of environmental impacts, design, preparation and commissioning, operation and monitoring, remediation, closure and water quality monitoring.

2.2.3. Minimum Requirements for Water Monitoring at Waste Management Facilities – 3rd Edition - Draft (DWAF, 2005)

This document provides minimum requirements for monitoring the quality of surface and groundwater in the vicinity of waste disposal facilities. While the requirements are designed to consider the uniqueness of the South African situation concerning groundwater systems, they do not apply to hazardous waste disposal sites. The document aims to explain and provide basic information to all levels of management in terms of groundwater behaviour, reasons for monitoring, principles of risk assessment, water sampling, indicator analysis, installation of a monitoring system, monitoring of different aquifers, and advanced monitoring principles.

All the documents within the Waste Management Series promote an Integrated Environmental Management approach, as envisaged by the National Environmental Management Act (NEMA Act 107, 1998), which promotes the cooperative management of issues pertaining the environment. The objective of these documents is to ensure that the most cost-effective means are used to protect the environment and public health from the adverse impacts of waste disposal.

2.3. Waste Types

Waste can be classified into broad categories according to its origin and risk to humans and the environment (Taylor and Allen, 2004). These are:

- household waste,
- municipal solid waste (MSW),
- commercial and non-hazardous industrial waste,
- hazardous (toxic) industrial wastes,
- construction and demolition waste,
- health care wastes,
- human and animal wastes, and
- incinerator wastes.

DWAF (1998) classifies waste into two main categories - General and Hazardous - according to the risk it poses.

2.3.1. General Waste

This is any waste that is not by definition hazardous. This includes domestic, commercial, certain industrial wastes, and building rubble. Domestic waste may contain hazardous components in minute quantities (DWAF, 2005). Although general waste is not defined as hazardous, it may cause harm to the environment and human health, depending on waste composition.

2.3.2. Hazardous Waste

Hazardous waste has the potential, even in low concentrations, to have a significantly adverse effect on public health and the environment. The definition: *"an inorganic or organic element or compound that, because of its toxicological, physical, chemical or persistency properties"* indicates that such waste may exercise detrimental, acute or chronic impacts on human health and the environment; intractable means that, by virtue of its toxicity, chemical or physical characteristic, it is difficult to dispose of or treat safely. Leachate from hazardous waste may be toxic to natural bacteria, thus delaying the biodegradation of organic substances (Taylor and Allen, 2004). Hazardous wastes are further subdivided into low or moderately hazardous (H:h) and high or extremely hazardous (H:H).

2.4. Landfill Leachate

Leachate is a potentially polluting liquid generated by water or other liquids passing through waste, carrying dissolved or suspended contaminants (Novella *et al*., 1999; Taylor and Allen, 2004). Freeze and Cherry (1979) describe it as resulting from leaching by percolating water derived from rain through any waste; an exception is found in arid regions. Rainfall does not occur regularly in such regions. Fetter (2001) describes it as precipitation that infiltrates waste, mixing with liquids already present and leached compounds from solid waste. Parsons (1994) describes leachate as liquid formed when water or another liquid comes into contact with waste. It is a complex and highly variable mixture of soluble organic, inorganic and bacteriological constituents, and suspended solids in an aqueous medium. Leachate may have harmful effects on groundwater and surface water in the vicinity of a landfill site (SEPA, 2003).

2.4.1. Leachate Generation

Waste deposited in landfills becomes part on the hydrological system of that particular site (Taylor and Allen, 2004). Fluids from rainfall, groundwater and liquids generated by waste itself percolate through the waste deposit. Solid waste absorbs this excess moisture until its field capacity is reached (Novella *et al*., 1999). *Field capacity of solid waste is defined as the volume of liquid that can be absorbed by a given weight of solid waste without the release of excess water under the forces of gravity* (Novella *et al*., 1999). Infiltration from rainfall provides a transport phase for contaminants to leach and migrate from landfill. Leachate contaminates local groundwater through direct infiltration on the site.

2.4.2. Leachate Composition

Waste composition varies from country to country, and relates to human activities in the area, quantity and type of products used (Taylor and Allen, 2004). Leachate composition will vary as well. The exact composition is variable and site-specific. Table 1 indicates the composition ranges of leachates from municipal waste landfills.

2.4.3. Leachate Production

Biodegradation/biotransformation consumes oxygen (O_2), changing the redox potential of the liquid, and influencing the mobility of other constituents (Taylor and Allen, 2004). Percolating rainwater provides a degradation medium for waste. Biochemical reactions involved in waste degradation are: dissolution, hydrolysis, oxidation and reduction. These processes are influenced by micro-organisms.

Table 1: Composition of leachates from municipal solid waste landfills ranges of concentration in samples (in mg/L) (Novella et al., *1999).*

Determinand	Range	Determinand	Range
pH	6.2 - 7.4	Mg	12 - 480
COD	66 - 11600	K	20 - 650
BOD	< 2 - 8000	Ca	165 - 1150
TOC	21 - 4400	Cr	< 0.05 - 0.14
NH4 - N	5 - 730	Mn	0.32 - 26.5
Org - N	ND - 155	Fe	0.09 - 380
NO3 - N	< 0.5 - 0.49	Ni	< 0.05 - 0.16
NO2 - N	< 0.2 - 1.8	Cu	< 0.01- 0.15
Ortho - P	< 0.02 - 3.4	Zn	< 0.05 - 0.95
Cl	70 - 2777	Cd	< 0.005 - 0.01
SO4	55 - 456	Pb	< 0.05 - 0.22
Na	43 - 2500		

Mechanisms from which leachate originates are divided into three processes (Taylor and Allen, 2004);

- Hydrolysis of solid waste and biological degradation,
- Dissolution of soluble salts in waste,
- Suspension of particle matter.

2.4.3.1. Aerobic Conditions

Hydrolysis processes have a generally short duration (a few days or weeks); consequently no significant volumes of leachate are produced. Hydrolysis is not catalysed by the presence of micro-organisms (Domenico and Schwartz, 1990). Organic matter in waste under aerobic conditions is oxidised and releases carbon dioxide (CO_2), water, nitrate ($NO3^-$) and sulphates (SO_4^{2-}) in the form of amino acids, fatty acids and glycerol. Oxygen consumption and CO_2 production are the dominant processes in the very shallow part of the subsurface (Freeze and Cherry, 1979). This process is exothermic, and thus results in an elevation of temperatures from 80–90C^0 (SEPA 2003) within the waste body. CO_2 dissolves in water to produce carbonic acid (H_2CO_3), which dissociates to bicarbonate (HCO_3^-) at a neutral pH. When all the oxygen is consumed, oxidation of organic matter can still occur due to the oxidising agents NO_3^-, MnO_2, $Fe(OH)_3$ and SO_4^{2-} (Freeze and Cherry, 1979).

2.4.3.2. Anaerobic Conditions

The anaerobic phase in waste is divided into three stages (Taylor and Allen, 2004):

- Acetogenic/Acidogenic Fermentation
- Intermediate Anaerobiosis
- Methanogenic Fermentation

2.4.3.2.1. Acetogenic Fermentation

In acetogenic fermentation, a decrease in pH is observed, with a high concentration of volatile fatty acids and inorganic ions (Cl^-, SO_4^{2-}, Ca^{2+}, Mg^{2+}, and Na^+). The redox potential drops, and thus sulphates (SO_4^{2-}) are reduced to sulphides (e.g. FeS_2), with sulphides precipitating Fe, Mn and other heavy metals that are dissolved by acid fermentation. A decrease in pH due to the production of volatile fatty acids (VFA's), and high partial pressures of CO_2 with an increased concentration of anions and cations result in leaching soluble material in waste. The redox potential is reduced to <330mV, with leachate from this phase characterised by:

- High Biochemical Oxygen Demand (BOD) > 10000mg/L
- High Biochemical Oxygen Demand /Chemical Oxygen Demand (BOD/COD) ratio > 0.7
- Acidic pH (5-6), and
- Ammonia (NH_4)

2.4.3.2.2. Intermediate Anaerobiosis

During intermediate anaerobiosis, there is a gradual increase in the release of methane (CH_4) gas, accompanied by the decrease of H_2, CO_2 and volatile fatty acids (VFAs). The decrease in VFAs results in a solution with a high pH and consequent decrease in the solubility of calcium (Ca), iron (Fe), manganese (Mn) and heavy metals precipitated as sulphides. Ammonia is released, but not converted to nitrate due to the anaerobic environment.

2.4.3.2.3. Methanogenic Fermentation

Methanogenic fermentation is the final stage, with an extremely limited pH range (6-8), and a leachate character with low pH, low concentrations of volatile acids, and low TDS (indicating that the dissolution of the majority of organic components is almost complete). Methane is the dominant product (more than 50%), accompanied by NH_4 leachate. The latter is characterised by;

- Low BOD, and
- Low BOD/COD ratios.

Degradation processes convert nitrogen (N_2) to a reduced form of NH_4, while Mn and Fe are mobilised, resulting in the release of H_2S gas. Methane production indicates reducing conditions, with a redox potential in the order of -400mV. Leachate comprises dissolved organic carbon in the form of fulvic acids. The solubility of metals and organic contaminants is enhanced through complex formation by dissolved organic matter and the presence of high levels of organic carbon, respectively.

2.4.4. Leachate Migration

This is often affected by the way in which waste is disposed of (i.e. whether the site is lined or capped). The increased hydraulic head on the site promotes the downward flow to groundwater and the outward flow to the leachate margin (Taylor and Allen, 2004). Waste capping results in no water ingress and reduces leachate volume, but a more concentrated leachate is produced over time and further microbiological and biochemical reactions will be inhibited, resulting in a prolonged degradation process. Residence times for rainwater entering landfill vary from a few days to several years. The conditions in the unsaturated zone may inhibit leachate migration (liners and clay) or increased flow (through fissure and faults).

2.4.5. Leachate and Groundwater

With leachate reaching groundwater, biochemical changes occur because strongly reducing leachate mixes with mild to strongly oxidising (oxic aquifer) groundwater at the water table. A reversal of the reducing reactions results in a series of redox zones in the leachate plume adjacent to the landfill in reverse order (Taylor and Allen, 2004). Organic carbon is oxidised to CO_2 and the leachate plume undergoes a continuous transition in the direction of groundwater flow until conditions are no longer anaerobic, attaining redox potential levels identical to the background levels in an aquifer. Methane and ammonia disappear, and nitrogen in solution and sulphur are oxidised to NO_3^- and SO_4^{2-} respectively. Iron precipitates as $Fe\ (OH)_3$ and manganese remains in solution. A lateral comparison with background values will yield an indication of the presence and extent of the plume. Multiple depth sampling boreholes will indicate the vertical extent of the plume.

Taylor and Allen note that reactive constituent migration is inhibited through biochemical reactions (precipitation and volatisation) and an interaction with the aquifer matrix (adsorption, cation exchange); unreactive or conservative constituent reduction is achieved through dispersion and dilution. Exceptions occur when the contaminant is transformed to more complex/toxic compounds (e.g. the halogenation of perchloroethene (PCE) to trichloroethylene (TCE)).

2.4.6. Leachate Attenuation

Most waste disposal facilities include a leachate collection system, and provisions are made for the attenuation capacity of the underlying strata contributing to pollution control measures (this is exploited by older landfills) (Thornton e*t al.*, 2001). Heavy metals such as Cd, Cu, As, Pb and Cr^{6+}, NH_4 and NO_3^-, pose a major environmental threat to human health. Their attenuation process is attained by dilution, dispersion, sorption and biodegradation (Lee *et al.*, 2006). Attenuation allows leachate to migrate from the landfill and take advantage of the natural subsurface processes of biodegradation, filtration, sorption, and ion-exchange to attenuate contaminants (Taylor and Allen, 2004).

Taylor and Allen describe the older dilute and disperse attenuation principle that relies on passive subsurface dilution and dispersion processes (superseded by containment strategy in the 1980s). The modern attenuation approach in which an active management strategy requires *in-situ* or imported attenuation barriers to attenuate leachate. The assumption is that the underlying geology is able to moderate contaminant concentrations derived from landfill leachate to acceptable levels prior to groundwater discharge.

Lee *et al*. (2006) note that, during the field investigations at two uncontrolled sites in Korea, cation-exchange and nitrification (biological oxidation) lead to ammonium (NH_4) attenuation with NO_3^-, Cl^-, hardness, and SO_4^{2-} only attenuates by dilution. This trend has also been noted by Thornton *et al*. (2001) in their laboratory experiments. They used Acetogenic and Methanogenic leachates from the domestic waste landfills to investigate and understand the variability in leachate attenuation that may occur.

2.4.7. Leachate Containment

The leachate containment procedure requires that all liquid and gas produced by the landfill be contained and collected for treatment (Taylor and Allen, 2004). This is a form of leachate management system. The aim is to minimise the production of leachate by restricting rainwater entering the waste and preventing the migration of leachate produced by the landfill. Artificial lining systems comprise landfill liners with a leachate collection system and capping.

2.5. Contaminant Fate and Transport in the Subsurface

Since leachate that forms within landfill sites may become part of the hydrological system, it is a good exercise to examine the processes that control the fate and transport of contaminants in the subsurface. A number of processes that encourage contaminant movement and retardation in the subsurface have been identified (Boulding, 2004; Fetter, 2001; Knox *et al.,* 1993; Dominico and Schwartz, 1990; Freeze and Cherry, 1979).

These processes play a crucial role in determining the shape, size and speed of contaminant plumes; and are furthermore controlled by factors relating to aquifer materials and the characteristics of the contaminants. Novella *et al*. (1999) describe these processes by means of three general categories:

- Hydrodynamic processes – these affect contaminant transport by impacting on the flow of groundwater (advection, dispersion),
- Abiotic/Chemical processes – affecting contaminant transport by causing interactions between the contaminants and aquifer material (sorption and ion exchange) or by affecting the form of the contaminant (hydrolysis and redox reactions), and
- Biotic processes – affecting contaminant by metabolising or mineralising contaminant (biodegradation).

Table 2 provides a list of expected subsurface processes and corresponding subsurface and contaminant properties influencing these processes. Hydrodynamic processes and multiphase flow play a major role in the saturated zone of the subsurface, whilst the abiotic/chemical and biotic processes are more important for both unsaturated and saturated conditions.

Table 2: Subsurface processes and the corresponding subsurface and contaminant properties affecting the fate and transport of contaminants (Knox et al.*, 1993).*

Process	**Subsurface Property**	**Contaminant Property**	**Interactions**
Hydrodynamic Solute Transport			
Advection	Groundwater gradient, hydraulic conducivity, porosity	Independent of contaminant	
Dispersion	Dispersivity, pore water velocity	Diffusion coefficient	Dispersion coefficient
Preferential Flow	Pore size distribution, fractures, macropores		
Abiotic Solute Transport			
Adsorption	Organic content, clay content, specific surface area	Solubility, octanol-water partition coefficient Kd for inorganics	
Volatisation	Degree of saturation	Vapour presure, Henry's constant	
Ion-exchange	Cation exchange capacity, ionic strength, background ions	Valency, dipole moment	
Hydrolysis	pH, competing reactions	Hydrolysis half-life	
Precipitation/dissolution	pH, other metals	Solubility versus pH, speciation reactions	
Co-solvation	Types and fraction of other solvents present	Solubility, octanol-water partition coefficient	
Redox	pE, pH	pKa, Redox sensitivity	
Colloid transport	pH, ionic strength, flow rate, mobile particle size, aquifer and particle surface chemistry	Sorption, reactivity, speciation, solubility	Colloid Stability
Biotic			
Metabolism/co-metabolism	Microorganisms, nutrients, pH, pE (electron acceptors), trace elements	BOD, COD, degree of halogenation, etc.	
Multiphase flow	Intrinsic permeability, saturation, porosity	Solubility, volativity, density, viscousity	Relative permeability, residual saturation, wettability, interfacial tension (surface tension), capillary pressure

3. Description of the Study Area

3.1. Overview

The Charlie I waste disposal/landfill site is currently used by Sasol Synfuels (Secunda) to dispose of non-hazardous (general) waste. There is no information on the history of the site, since there is no record on the type and volume of waste disposed of. The impact of the site on groundwater has only been monitored by two boreholes since 1990, but during 2006 and 2007, additional monitoring boreholes were drilled (JMA Reports, 1998 – 2003, IGS Reports, 2004 –); to date the impact on groundwater has not been quantified.

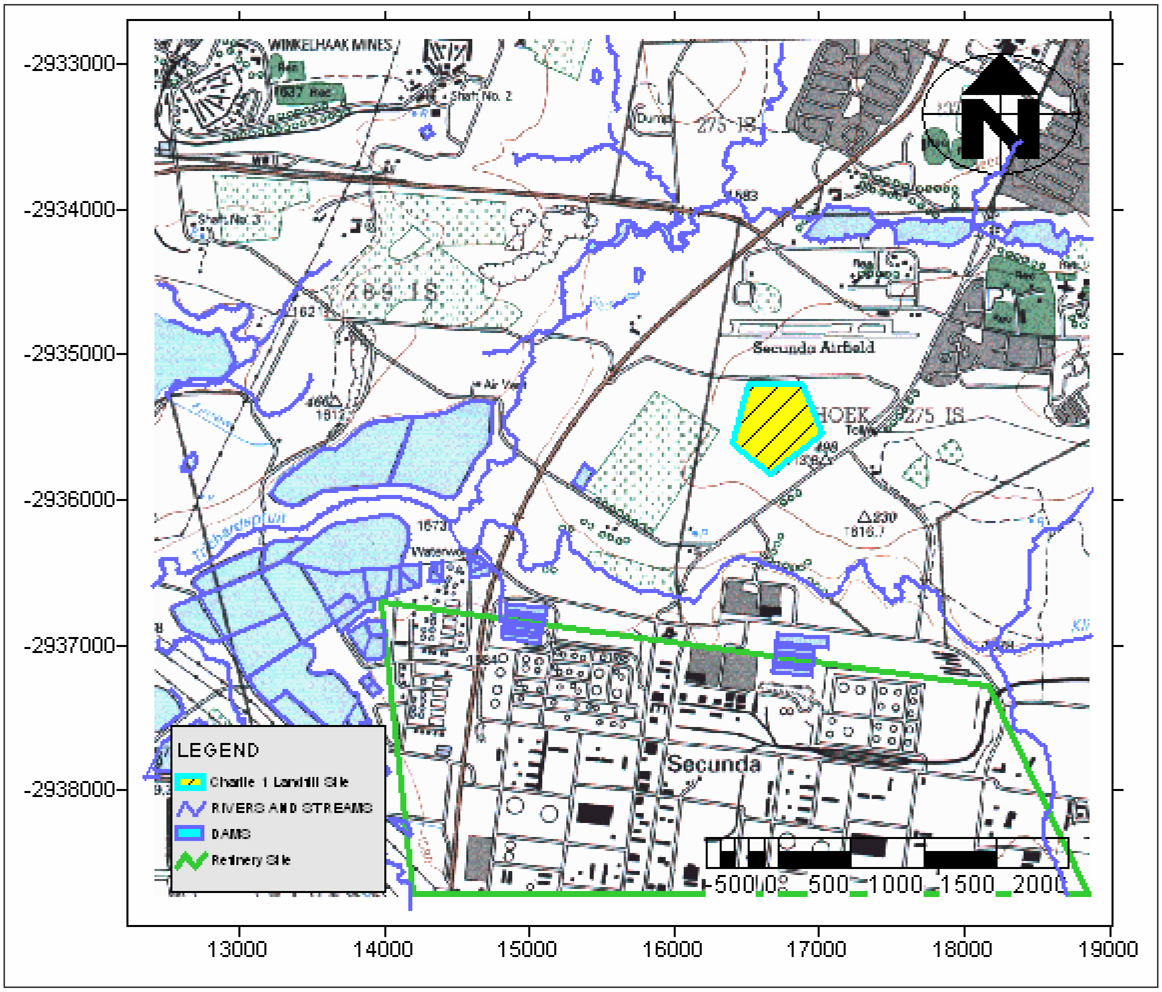

Figure 1: Locality map of the Charlie I landfill site, Sasol Synfuels, Secunda.

The landfill site is situated at 1.3 km north of the refinery site, 450 m west of the Charlie 1 main Sasol Synfuels gate (which it is named after), 960 m east of the Charlie 2 gate, and 300 m south of the Secunda Airfield (Figure 1). The possible surface water receptors are rivers and streams located northwest and south of the landfill site (Figure 1). Evidence of rock quarry activities are visible 300 m east of the site, with a pit almost completely filled with water (Figure 2). The area immediately adjacent (west) to the landfill site is used for agricultural activities (i.e. stock and crop farming).

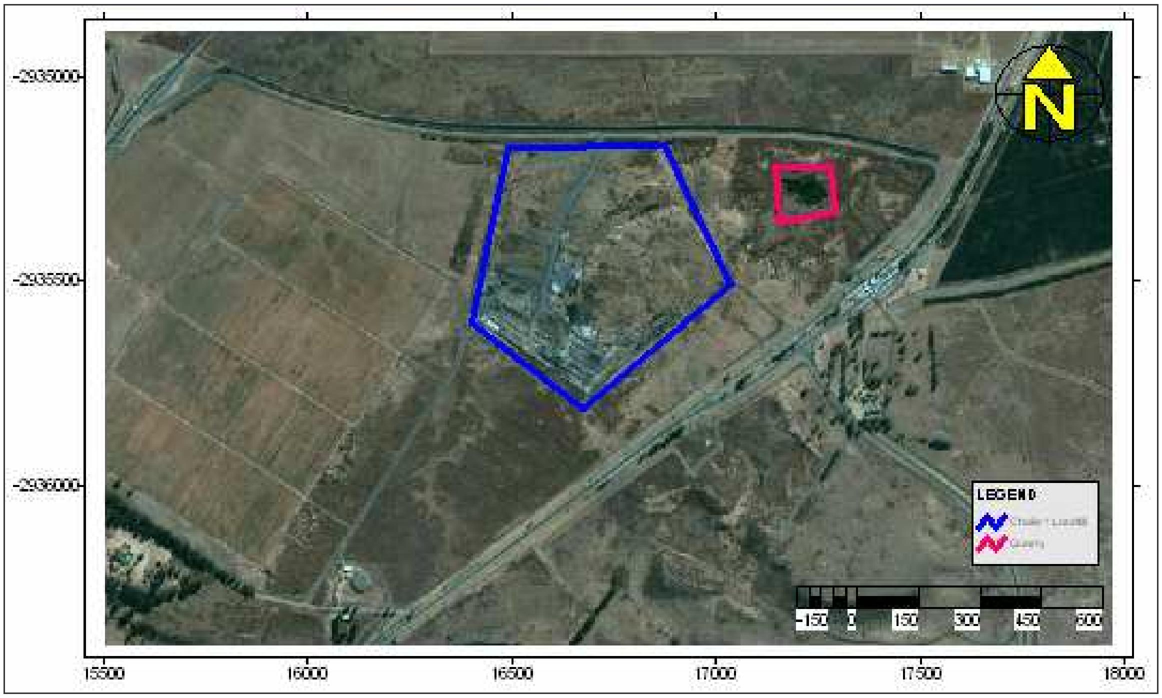

Figure 2: Air photo (Google Earth) map showing the area around the Charlie I landfill site (in blue). The red box indicates the locality of the old quarry site.

3.2. Physiography

3.2.1. Climate

The Sasol Synfuels (Secunda) area has a temperate climate; with hot summers and cool to cold winters with frost. Average maximum daily temperatures range in the vicinity of 26°C in December - January to an average minimum of 1°C in June - July (SA Weather Service).

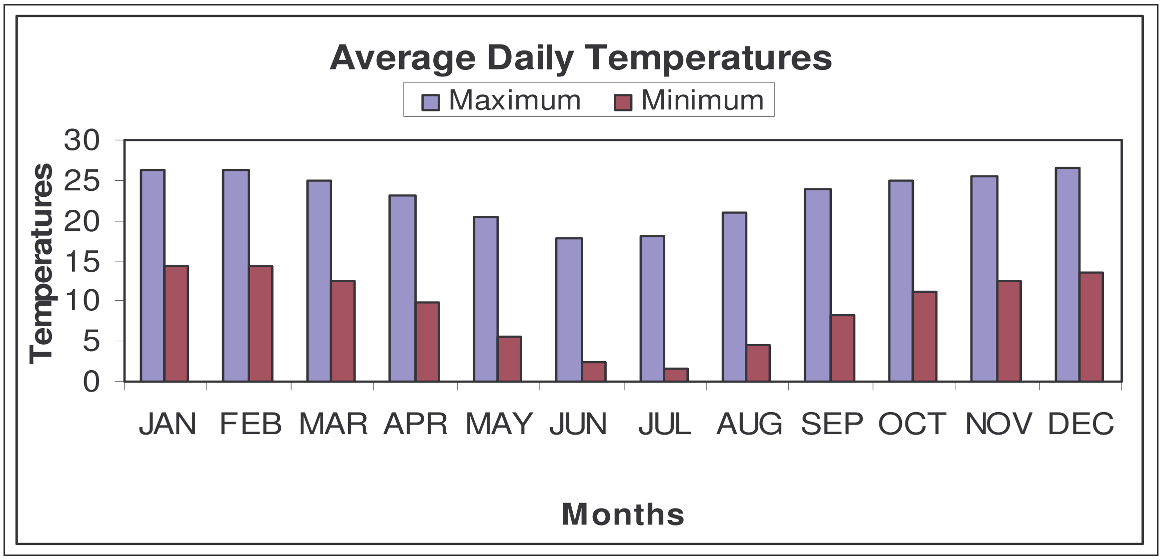

Figure 3: Average daily temperatures (Secunda: 04783303).

The region is a summer (October - March) rainfall region, with 89% of rain occurring during these months. Most of the heavy rain in the region occurs in the form of thunderstorms. The average annual rainfall for the area is 740mm per annum (SA Weather Service). The mean annual evaporation (MAE) of the region is 1550mm, and the mean annual run-off (MAR) 50mm (Midgley *et al.*, 1994).

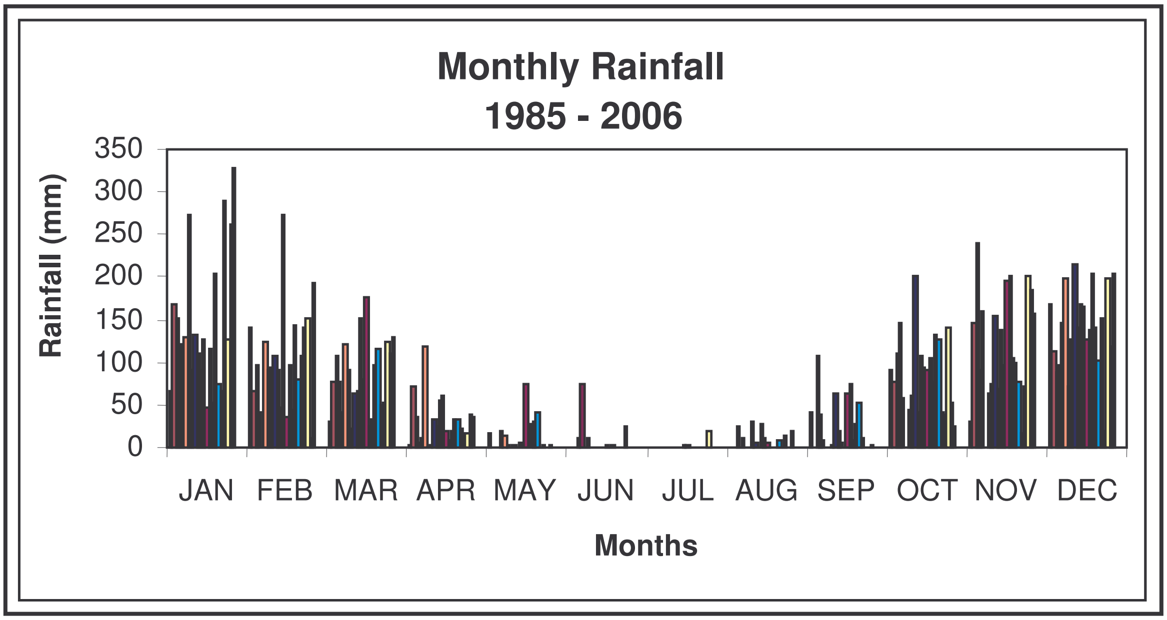

Figure 4: Monthly rainfall in mm (Secunda: 04783303).

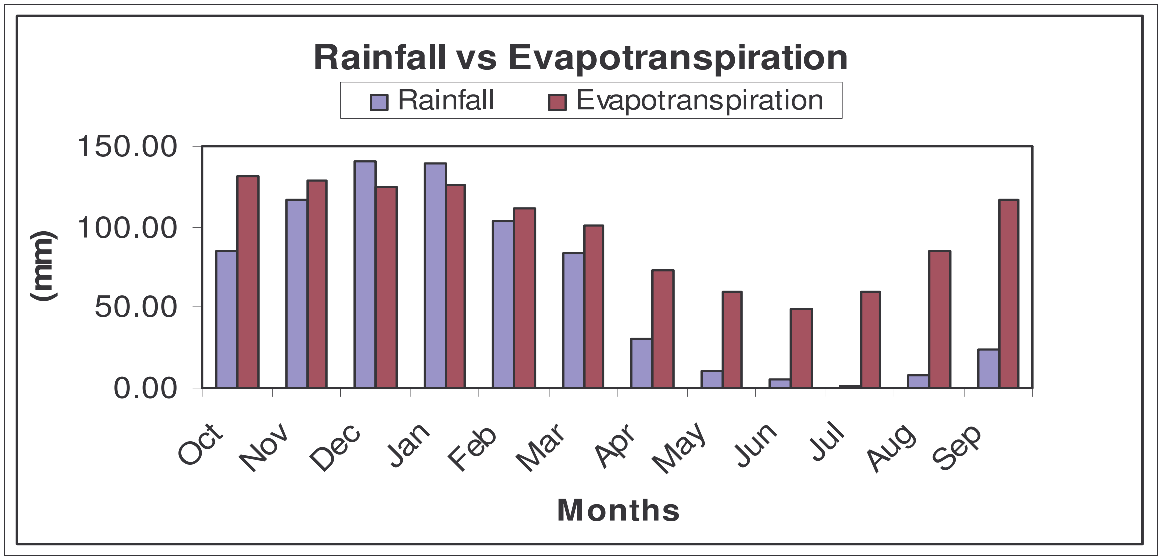

Figure 5: Plot of monthly rainfall vs. evapotranspiration in the Secunda area.

The estimated evapotranspiration for the district is 1160mm per annum. The plot of average rainfall versus evapotranspiration for the Secunda area (Figure 5) indicates higher evapotranspiration rates than rainfall during March - October, implying less leachate from the site during these months. During the high rainfall months in the region (November - February), **leachate springs are observed at the base of the landfill.**

3.2.2. Topography and Drainage

The region is characterised by gently rolling hills that are broken by drainage lines, with an average elevation of 1520-1640 metres above mean sea level. The Sasol Secunda area falls within quaternary catchment C12D in the Upper Vaal River catchment area, which forms a border with the Olifants River catchment. The landscape is characterised by low-gradient streams meandering over small alluvial plains.

The Charlie I landfill site is located between two tributaries, the Klipspruit in the south and Trichardspruit in the north-northwest (Figure 1). The general flow trend of these tributaries is towards the southwest, converging into the Grootspruit Stream, which in turn flows into the Waterval River, the major tributary of the Vaal River in the region.

Water quality monitoring has been conducted as part of the Sasol monitoring programme for these tributaries, and will be discussed in Chapter 5.

3.3. Waste Site Classification

The landfill classification system uses only waste type, size of operation and the potential for leachate generation. The objectives of this landfill classification system are (DWAF, 2005):

- To consider waste disposal situations and needs in terms of combinations of waste type, size of waste stream and potential for significant leachate generation.
- To develop landfill classes that reflect the spectrum of waste disposal needs.
- To use the landfill classes as a basis for setting graded Minimum Requirements for the cost-effective selection, investigation, design, operation and closure of landfills.

Using the classification system, landfills are grouped according to:

- the type of waste involved
- the size of the waste stream, and
- the potential for significant leachate generation.

3.3.1. Waste Type

The information provided by Millenium Waste indicates that the Charlie I landfill site can be classified as a recipient of general waste, i.e domestic, commercial, industrial waste, and building rubble (Table 3). Sandblast and insulation could indicate possible hazardous wastes. Figure 6 indicates the different wastes received by the landfill site.

Figure 6: Waste types disposed of at Charlie I landfill site.

3.3.2. Size of Waste Site

Table 3: Monthly waste loads (March 2007 – January 2008) Millemium Waste.

Type	March	April	May	June	July	August	October	November	December	January
Rubble	1205	1428	2088	1706	689	394	277	424	103	99
Soil	5054	3725	6600	4973	3379	1800	2002	2853	990	2279
Domestic	638	519	590	518	560	661	562.8	478.2	422.9	298.1
Garden	29	31	52	31	30	16	19	15.4	24	9
Sandblast/Industrial	120	129	220	285	165	71	284	386	60	95
Insulation	137	112	63	56	95	126	77.5	117.1	43.3	58.3
Monthly Total (tonnage)	7183	5944	9613	7569	4918	3068	3222.3	4273.7	1643.2	2838.4
Annual Total (tonnage)	50273									

The size classification focuses on the size of the waste stream and the consequent size of the operation. The size of operation depends on the daily rate of waste deposition. DWAF classifies landfills by means of the Maximum Rate of Deposition (MRD), expressed as tonnes/day.

$$\mathbf{MRD = (IRD)\ (1+d)^{t}}$$

IRD = initial rate of deposition of refuse on site in tonnes/day,

d = expected annual development rate (based on population growth rate),

t = year since the deposition started at **IRD,** and

MRD = maximum rate of deposition after t years.

General waste disposal sites are divided into four size categories;

- **C**ommunal (<25 tonnes/day),
- **S**mall (25 – 150 tonnes/day),
- **M**edium (150 – 500 tonnes/day), and
- **L**arge (>500tonnes/day).

Table 3 presents the monthly waste loads at the Charlie I site over 10 months, which indicates that the site can be classified as **M**edium in size.

3.3.3. Potential for Leachate Generation

The Climatic Water Balance (CWB) method has been adopted by DWAF (2005) in terms of their Minimum Requirements, as a tool to provide a basis for decisions regarding the need for leachate management systems (i.e. whether the site will produce significant leachate or not). The CWB method uses published, easily available climatic data to evaluate the leachate generating potential of a site. It also considers the major water input and moisture loss components of the balance.

$$B = R - E$$

where: **B** is the climatic water balance, (mm);

R is the rainfall, (mm); and

E is the evaporation from the landfill surface, taken as 0.7 x A-pan evaporation.

The CWB method does not attempt to quantify the volume of leachate generated by the site. This method yields a classification of **B$^+$** (indicating that an underliner and leachate collecting system are required) or **B$^-$** (indicating that no underliner or leachate collecting system is required). The rainfall and evaporation data (Section 3.3.1.) for the region show that a **B$^-$** value for the site is suggested, thus demonstrating that no significant leachate will be produced by the site. According to the DWAF landfill site classification system, the Charlie I landfill site can be classified as a **GMB$^-$** site (i.e. no liner or leachate collecting system is required).

The CWB method has its limitations. Rainfall is for example considered an average process, while rainfall does not occur as an average process in Secunda and other Highveld regions, but rather in short, sharp events that may lead to leachate. Field visits and site investigations confirm that the Charlie I landfill site does produce significant amounts of leachate, and should therefore be classified as a **GMB$^+$** landfill site (i.e. producing leachate).

Figure 7: Salt precipitation from the leachate produced by the Charlie I landfill site Sasol Synfuels – Secunda.

3.3. Geology and Geohydrology

3.3.1. General Geology

Regionally, the area is entirely underlain by rocks of the Karoo Supergroup, mainly comprising clastic sediments of the Permian age Ecca Group (SACS, 1980). In South Africa, the Ecca Group occurs between the lower late Carboniferous Dwyka Group and the upper late Permian-Middle Triassic Beaufort Group, attaining a maximum depth of about 3000m in the south (foreland), and diminishing outward. In the northern part of the Karoo Basin (Caincross, 2001), the Ecca Group is subdivided, from the bottom to Pietermaritzburg, Vryheid and Volkrust formations, conformably overlying the Dwyka tillite that represents the basal unit of the Karoo sequence.

The Secunda area forms the northern part of the Karoo Basin (the Highveld Coalfields). The area is predominantly underlain by rocks of the Vryheid formation, comprising shallow marine and fluvio-deltaic sediments (Caincross, 2001). These predominantly consist of a series of vertically stacked, upward-coarsening and upward-fining facies assemblages of interbedded sandstone, siltstone, shale, minor conglomerates and several coal seams. The depths below the surface of the coal seams are relatively shallow, with the underground workings seldom deeper than 200m.

Throughout South Africa, the Jurassic age dolerites have intruded into the Karoo Supergroup and the underlying gneissic basement in the form of horizontal to sub-horizontal transgressive sills and near-vertical dykes in the region. The dolerite sills range in thickness from 30-300m, and the dolerite dykes range from 1-50m. Most sediments in the vicinity of intrusions were recrystallised during intrusion.

Quaternary deposits are found along the rivers and streams, consisting mainly of gravels that comprise cobbles and boulders.

3.3.2. General Geohydrology in the Area

The Karoo Supergroup mainly consists of fractured-rock aquifers characterised by sediments with low permeability (Botha *et al.*, 1998). This implies that groundwater movement occurs mostly along secondary structures such as fractures, cracks and joints in the sediments. The Karoo aquifers are the most extensive type of aquifer in South Africa.

There are two distinct and superimposed groundwater systems in the Highveld Coalfields area;

- The upper weathered Ecca aquifer system, and
- The lower fractured rock Ecca aquifer system.

The upper weathered Ecca aquifer system is associated with the uppermost weathered horizon, mainly comprising weathered Ecca sediments and quaternary deposits, weathered to depths between 5-12 metres below surface (Hodgson and Krantz, 1998), and sometimes perched. This aquifer is directly recharged by rainfall infiltrating through the weathered zone until it reaches the underlying impermeable solid rock. Thereafter, groundwater movement occurs on the contact zone between the weathered part and the underlying consolidated sediments following their slope. Where barriers (dykes, sill, etc.) obstruct the flow, this water is often discharged on surface as fountains or springs. The aquifer has low yields (+/- 0.1 l/s) with shallow water tables. A significant volume of groundwater from this aquifer is discharged into surrounding rivers and streams.

Immediately below the upper weathered horizon is the lower fractured Ecca aquifer system, which is mainly composed of well-cemented sediments with little or no groundwater movement. Groundwater movement is predominantly associated with secondary structures (fractures, faults, dykes, etc.). Borehole yields in the Karoo aquifers are generally low (+/- 1 l/s), with regional flow resembling flow in the porous medium (i.e. obeying Darcy's law). These formations contain large quantities of water that cannot be readily released on a small scale.

3.4. Other Factors Influencing Vertical Migration of the Contaminant Plume

3.5.1. Overview

The DWAF (2005) minimum requirements clearly indicate that landfills should not be sited on unstable ground (e.g. fault zones, seismic zones, dolerite dykes and where sinkholes and subsidence are likely to occur).

3.5.1.1. Mining Activities

The Secunda area is located within the Highveld Coalfields, forming the Secunda Coalfield. Two mining methods have been applied extensively for coal extraction in most of South Africa's underground coal mines: Bord-and-Pillar (involving pillars of coal left in place to support the roof) and High Extraction "stooping and longwall" (up to 85% of coal extraction) (Bell *et al*., 2001).

Once the high extraction method has been applied to the coal seam, the coal seam roof will collapse, resulting in changes in the geohydrological properties of the rocks and soils overlying the workings. At shallow mines (200–300m), the collapse spreads, and is visible in the form of subsidence on surface.

3.5.1.2. Recharge into Mines

Subsidence results in reduced run-off (rainfall water percolates through the cracks/fissures to the underground workings), increased recharge, and therefore water quality deterioration (Bell *et al.*, 2001). The amount of influx has been quantified in the range of 6–11% of the annual rainfall (Hodgson and Krantz, 1998).

Furthermore, Hodgson *et al*. (2007) show that the mining method and geometry have a major impact on the control of water influx and quality in collieries. Risk values associated with each mining method are proposed as follows

- Bord-and-Pillar – low risk
- High extraction (stooping and longwall) - higher risk.

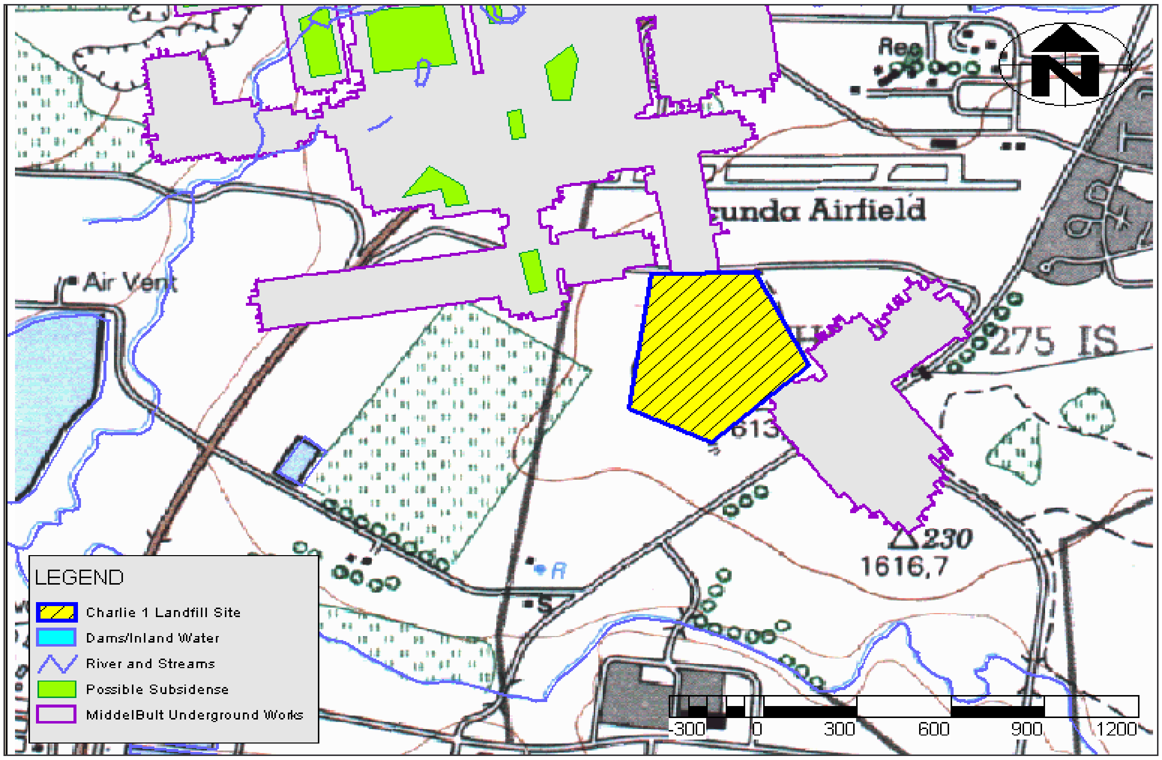

Figure 8: Underground coal mining activities in the vicinity of the Charlie I landfill site (High Extraction method area indicated in green, with grey representing Bord-and-Pillar method).

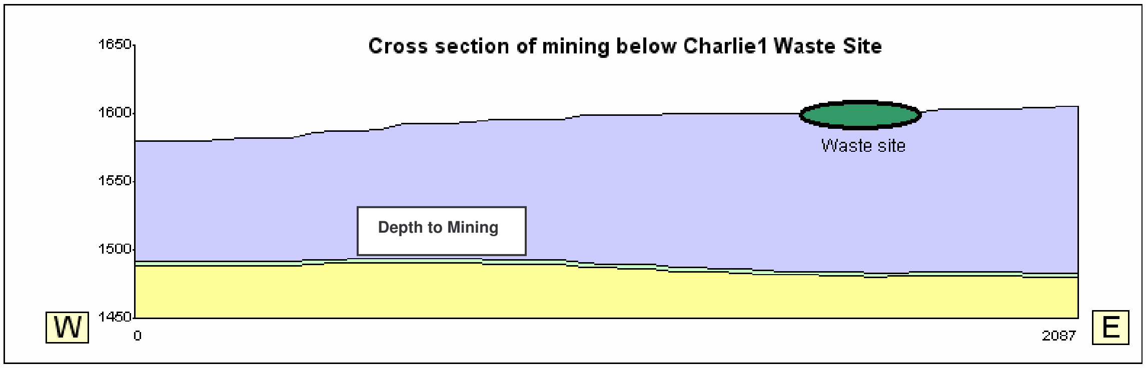

Figure 9: Cross-section (from the stream in the west to the quarry in the east) to indicate mining depth below the waste site.

The underground workings underlying the Charlie I landfill site (Figure 8) have adopted the bord-and-pillar mining method, which implies a very low probability of hanging wall collapse, resulting in subsidence. The vertical K-value for the bord-and-pillar mining method in similar geohydrological settings has been estimated at 1.02×10^{-4}m/day (Hodgson *et al.*, 2007), indicating the ease with which water moves vertically through the strata. The northwestern area of the site includes regions with adapted high extraction methods (Figure 8), posing the possibility of potentially unstable ground between the site and the surface water receptors in the northwest.

The mining depth in the area of the waste site ranges from 90-120m (Figure 9). With the low vertical K-value, lack of high extraction in the area, as well as the high clay content of the soils, movement of contaminants into the mining area will be low.

4. Field Investigations and Data Analysis

4.1. Geophysical Investigations

Geophysical techniques are useful in the assessment of the physical and chemical properties of soils, rocks and groundwater. In groundwater contamination studies, they are useful in the preliminary characterisation of soils, geologic stratigraphy and subsurface structures, and the further characterisation of the extent and direction of the contaminant plume. For the purpose of this investigation, magnetic and resistivity methods were applied.

4.1.1. Magnetic Survey

4.1.1.1. Method

The magnetic method is used to map the intensity of the Earth's magnetic field and interpret the intensity variations at different locations. The method relies on the fact that a number of minerals contain iron and nickel, thus displaying the properties of ferromagnetism. Rocks and soils containing these minerals have strong magnetic properties; and can therefore produce significant local magnetic fields. Such magnetic properties can be either remnant or induced.

Magnetic features such as dolerite dykes and sills, iron-rich layers, magnetite-rich ore bodies, mineralised faults and fault zones, behave like magnets within the earth's crust, thus adding to the earth's main magnetic field. The change observed is referred to as a magnetic anomaly, which is a property of rock.

G5 Proton magnetometer geophysical surveys were performed in the area of interest to delineate any subsurface structures. The profiles were aimed at delineating structures in areas of lower elevation (southwestern) at the site, with the decision informed by the monitoring data, indicating that groundwater flow in the region follows the topography. The motive was to identify structures that can act as conduits or pathways for leachate from the site, and further to delineate structures in the areas targeted for landfill site expansion. Nine traverse lines were conducted in the southwest region of the site (Figure 10 below).

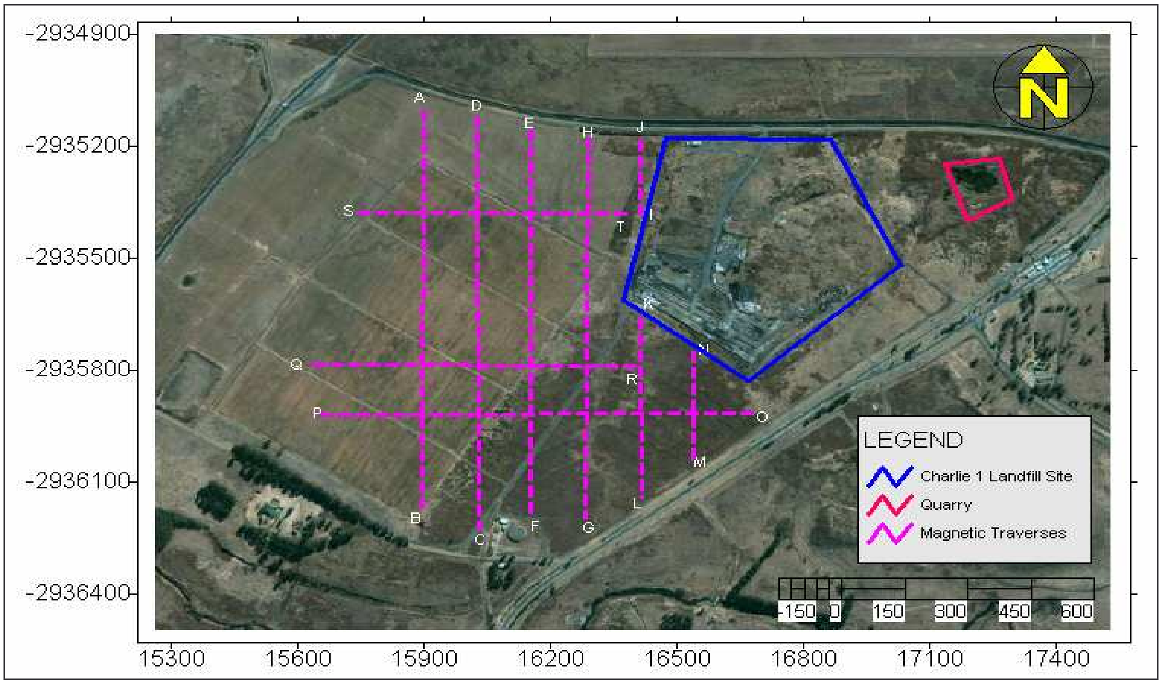

Figure 10: Position of magnetic traverse lines adjacent to the Charlie I landfill site.

4.1.1.2. Results and Interpretations

Six traverses were conducted in the north-south direction, and three in the east-west direction, forming a grid. The generally noisy nature of the data can be partly ascribed to the variations in magnetic properties of the country rock, but is also partly due to the presence of manmade noise in the form of large metal objects at surface, as well as buried infrastructure.

According to traverses O-P and C-D, a sill is encountered at the southwestern side of the terrain. This sill can also be observed in the 3D illustration of the geology in Figure 24. According to traverses A-B, C-D and S-T, no sill is encountered at the northwestern side; this is supported by the geological logs of the monitoring boreholes. It is however possible that the sill dips towards the southwest and also towards the northwest, resulting in the sill being deeper in the northwest than the southwest. This makes detection and interpretation difficult.

The results of the magnetic survey in the immediate western regions (Figure 10) of the Charlie I landfill site indicate that no major structural features were encountered in those regions. The majority of the traverse lines show no major changes in magnetic field intensity (Appendix 1), with the exception of locations with manmade features (pipes, fence, boreholes, etc.), where anomalies are observed with amplitudes of 300nT.

No magnetic traverses were conducted inside the landfill site and/or in the northeastern region of the site, as there is no possibility of expansion to the northeast.

4.1.2. Resistivity Survey

4.1.2.1. Method

Resistivity geophysical methods are based on the behaviour of electrical current in the subsurface (Van Zijl, 1985). Resistivity is reciprocal to conductivity (i.e. the higher the electrical conductivity, the lower the electrical resistivity, or vice versa). The resistivity method is widely used for groundwater exploration, but also used in groundwater pollution studies to determine the presence of zones saturated with highly conducting leachate. A two-dimensional electrical resistivity profiling method (ABEM SAS) was applied to delineate the extent of the contaminant plume along the western region of the landfill site (Figure 11).

A Wenner array electrode configuration with electrode spacing of two metres was used to obtain apparent resistivities on the site. A multi-core cable was placed in the ground, with 40 electrodes connected at two-metre equal intervals (i.e. AM=MN=NB). All electrodes were connected to the central recording system, with only four selected at a time for resistance measurement. For each measurement, a resistivity value and depth are obtained and results plotted by 2D imaging interpretation.

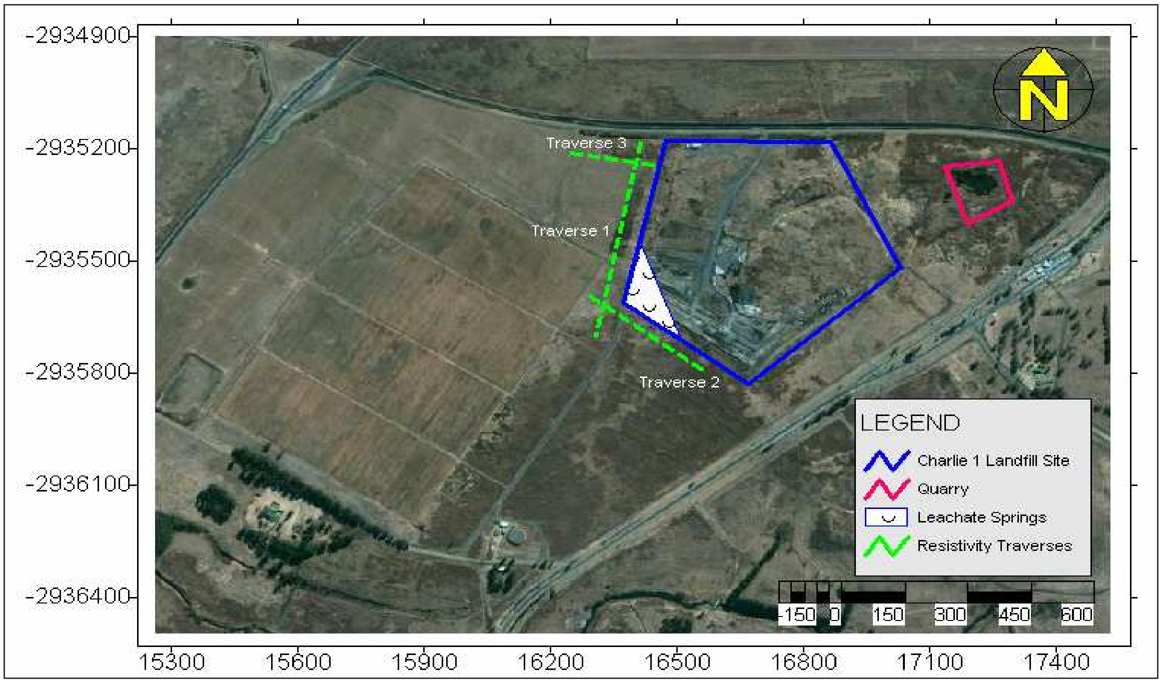

Figure 11: Position of electrical resistivity traverse lines at the Charlie I landfill site.

The method is based on the contrasts in electrical resistivity between different geological units. The electrical conductivity of a contaminant plume is generally higher (due to elevated salt content) than the surrounding groundwater conductivity; thus the spatial distribution of such a plume may be delineated by the resistivity method. Also, the presence of clays will indicate higher electrical conductivity due to the higher clay porosities.

4.1.2.2. Results and Interpretation

The results of the interpretation are displayed as the 2D electrical resistivity image of the subsurface along the line of the traverse.

4.1.2.2.1. Traverse Line 1

This traverse line was run 20m away and along the western side of the landfill (Figure 10), in a north-south direction. The 2D electrical resistivity image (Figure 12) shows the upper 3m of the profile, indicating a highly conductive zone that represents the upper soil, clay or weathered zone. Field observations during the surveys indicate that this zone is highly saturated with water (due to clays) and its highly conductive nature is attributed to the conductive nature of water and the high salt content of the leachate emanating from the landfill site, which is concentrated on this zone. Immediately below this (between 4 - 10m), is a less conductive zone, representing solid rock with low porosity (i.e. pore spaces are less filled with water). Below 10m, the conductivity of the formation increases, indicating an increase in pore spaces and water occupying those spaces; these have a lower conductivity compared to the upper 3m zone.

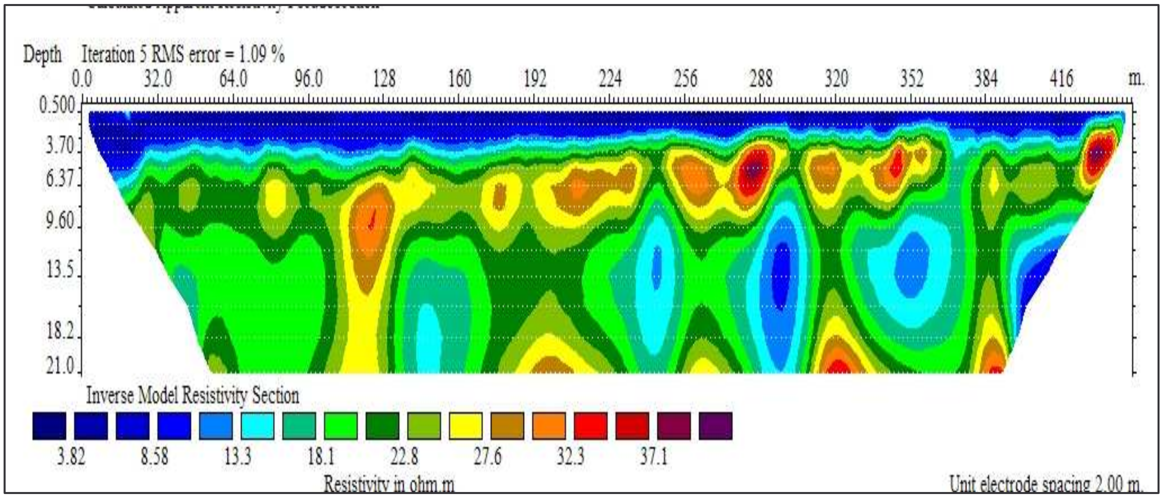

Figure 12: Resistivity profile 1.

4.1.2.2.2. Traverse Line 2

This traverse line was run 20m away, along the southern boundary of the landfill site (Figure 11) in the NW-SE direction. The traverse is characterised by highly conductive layers up to a 20m depth (Figure 13). The high conductivity at these depths may be attributed to the presence of highly conductive fluids occupying the pore spaces between the sediments.

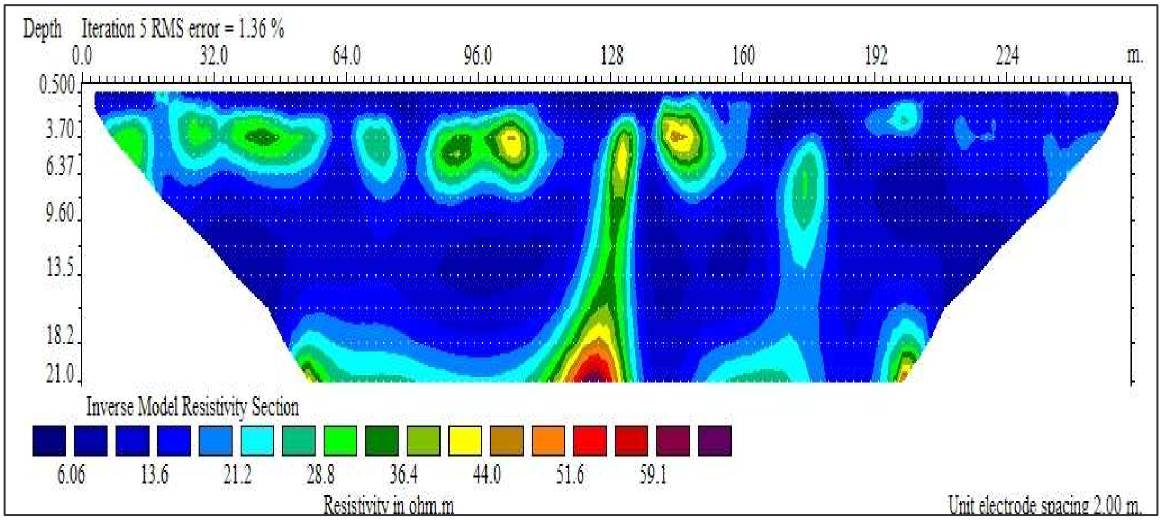

Figure 13: Resistivity profile 2.

4.1.2.2.3. Traverse Line 3

This traverse line was run on the western side of the landfill site, in an east-west direction (Figure 11). The uppermost layer (0 – 5m) is characterised by a very highly conductive unconsolidated soil/clay layer, with a high salt content. Closer to the landfill site, layers below 5m are highly conductive, compared to those further away, which are less conductive (Figure 14). This indicates the presence of a contaminant plume or high porosity formation closer to the site, which diminishes with distance.

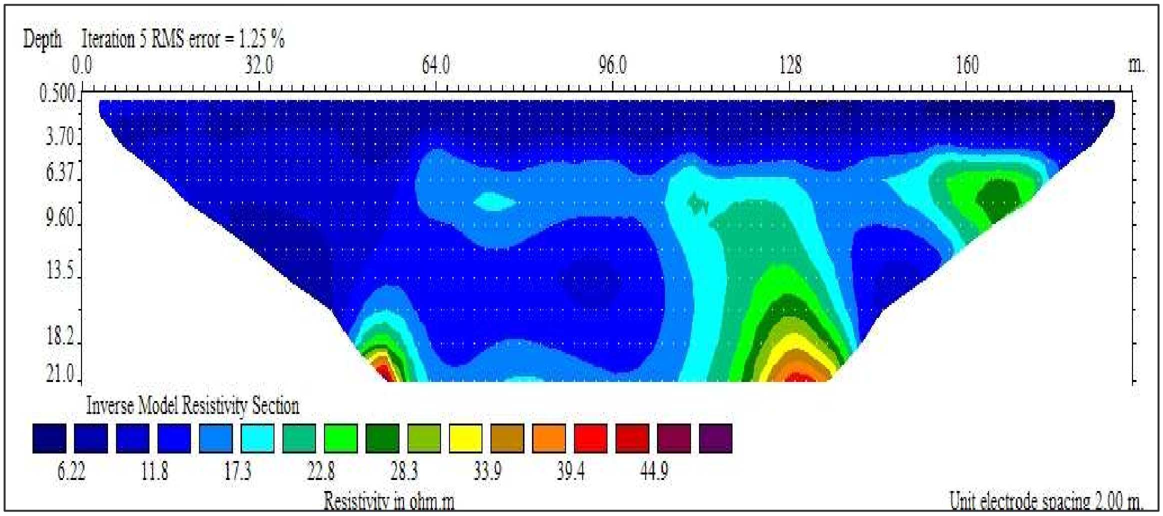

Figure 14: Resistivity profile 3.

Traverse lines 2 and 3 indicate higher electrical conductivity values for deeper parts of the sediments/formation as compared to traverse line 1. Higher conductivity values may be due to the elevated salt content of the leachate generated by the landfill site or the property of the rock formations in these regions (clays). The former statement may hold, since most studies on landfill sites and leachates indicate that there are elevated concentrations of total dissolved solids (TDS), which are associated with landfill.

The results of the resistivity survey indicate that a contamination plume may emanate from the landfill site, which it is mostly concentrated on the upper weathered soil and/or clay zone. The depth of the plume can be estimated at greater depths closer to the landfill site, which diminish with movement away from the site. This is observed in traverse 3, with a higher electrical conductivity zone to the depths of 15m closer to the site and 7m depths away from the site (traverse 3 is the only traverse conducted perpendicular to/away from the landfill site).

4.2. Drilling

Drilling incorporates the collection of all site-related information on subsurface conditions, i.e. geology, hydrogeology and the extent of contamination with depth. Two types of drilling methods were utilised for the full site characterisation in order to obtain information about the geology (soil types, soil stratigraphy, physical and chemical properties, water quality and rock types) of the landfill site:

- Auger Drilling and
- Percussion Drilling.

Boreholes were drilled at strategic locations between the landfill site and the lower-lying streams/surface water receptors, to determine the spatial distribution of the contaminant plume.

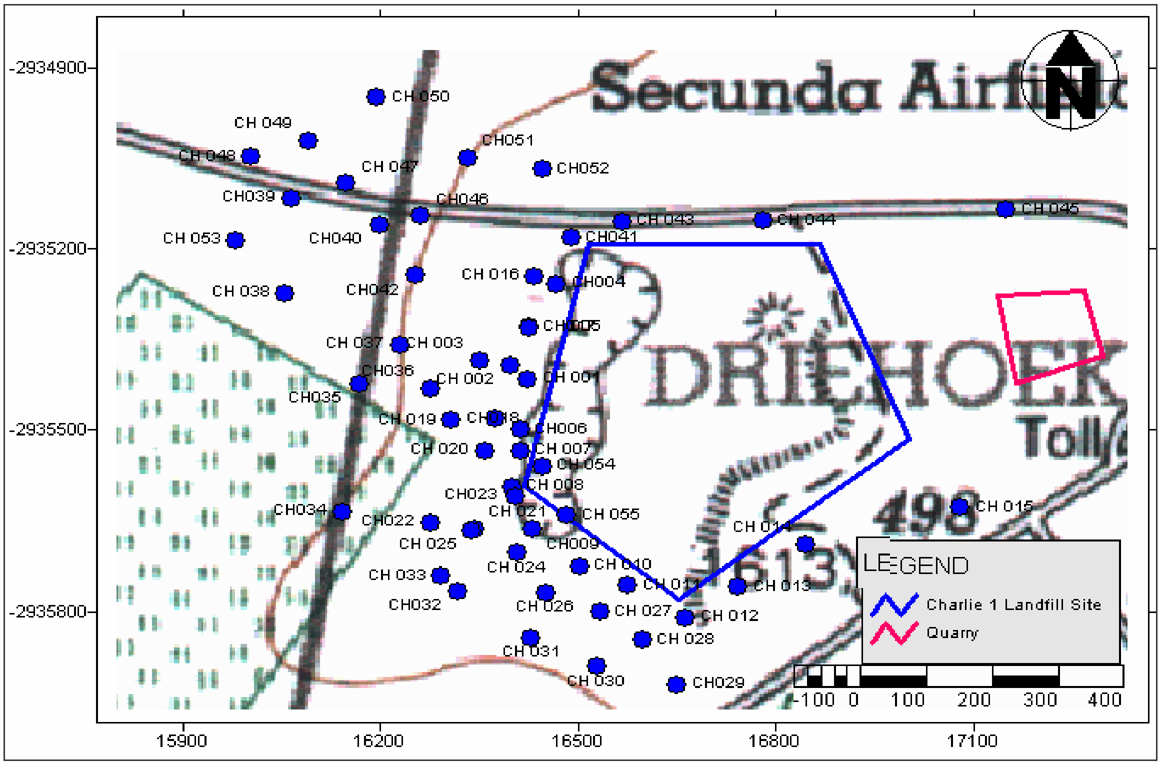

Figure 15: Position of all auger drilled holes at the Charlie 1 landfill site.

4.2.1. Auger Drilling

Fifty-five auger holes with an average depth of 3m were drilled for soil sampling and piezometer installation in order to delineate the extent of contaminant plume in areas adjacent to the landfill site (Figure 15).

Figure 16: Auger solid stem drilling at the landfill site.

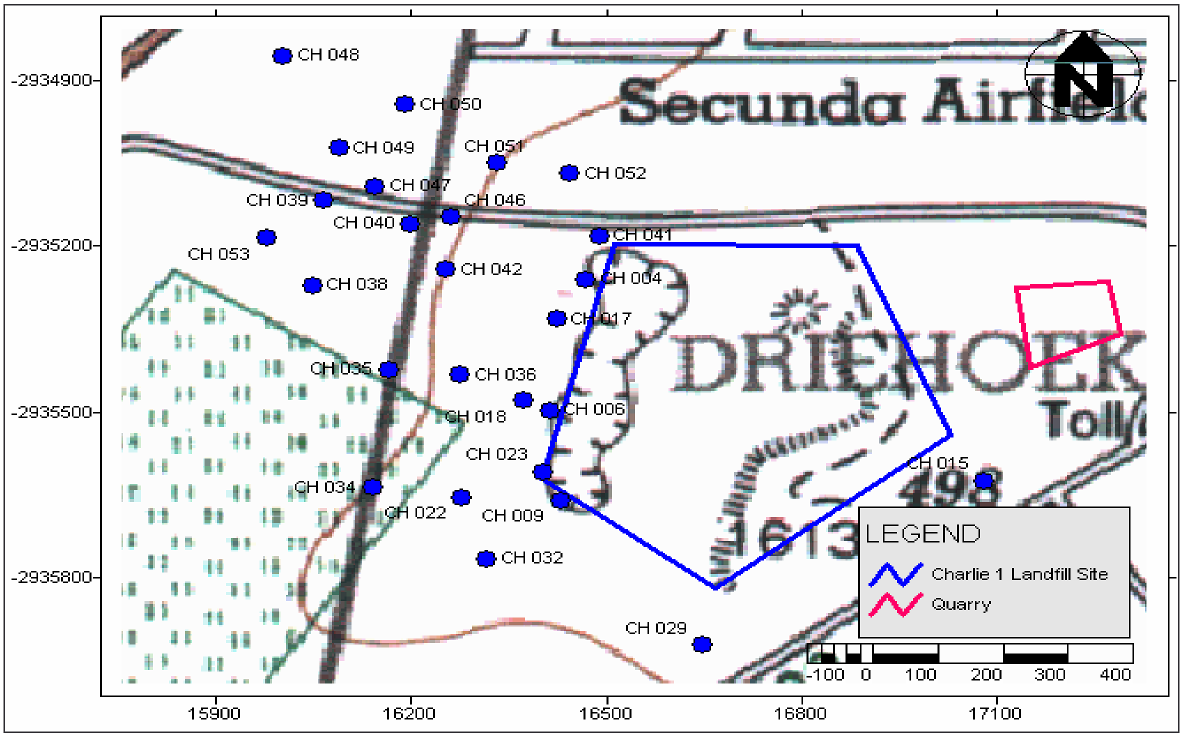

Figure 17: Position of auger holes installed with piezometers at the Charlie I landfill site.

The auger solid stem drilling (Figure 16) method was applied to enable drilling even on the hard clayey part of the unconsolidated soil, and also on the weathered horizon. Twenty-six of the auger holes were installed with piezometers for water quality sampling. Figure 17 shows the positions of auger drilled boreholes installed with piezometers at the site.

4.2.1.1. Soil Horizon

The uppermost layer in the soil horizon is mainly composed of dark brown clayey loam soil, averaging between 0.5 – 1m, with the lower part comprising yellowish brown clay (Figure 18) and resting on weathered hard rock (sandstone/shale).

4.2.1.2. Piezometer Construction

The construction of all piezometers involves the installation of a slotted HDPE pipe in the lower two metres to allow horizontal flow through the piezometer, with the upper one or two metres receiving solid pipe.

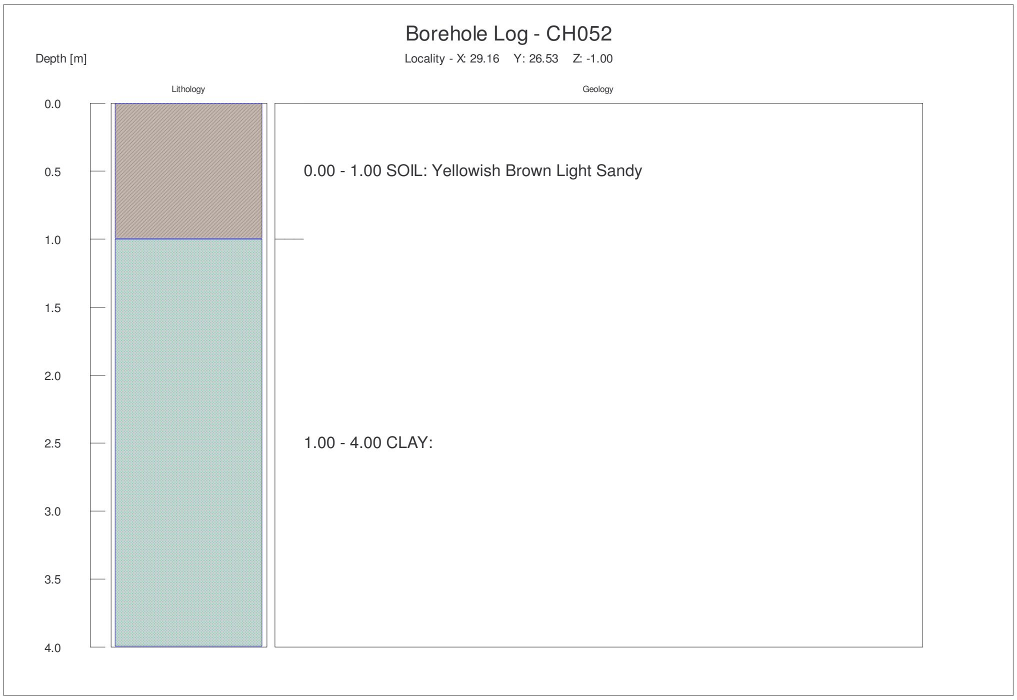

Figure 18: Typical soil profile at the Charlie I landfill site.

4.2.2. Percussion Drilling

Six previously drilled boreholes on site were supplemented with a further two pairs (shallow and deep) drilled for the current study. The shallow boreholes were drilled to 12 m, and cased with slotted casing. The deep boreholes were drilled to 30 m, with solid casing installed only in the soil and weathered part of upper formations. Figure 19 shows the positions of all the boreholes at the Charlie I landfill site.

4.2.2.1. Lithology

The general lithology obtained from borehole drilling at the site is mainly composed of alternating layers of sandstones and shales below the soil clay layer. Dolerite sill is found at the northeastern part of the site (Figure 22), intruding on the sandstone that overlies the shale layer. No geophysical surveys were conducted in the north-eastern region of the landfill site.

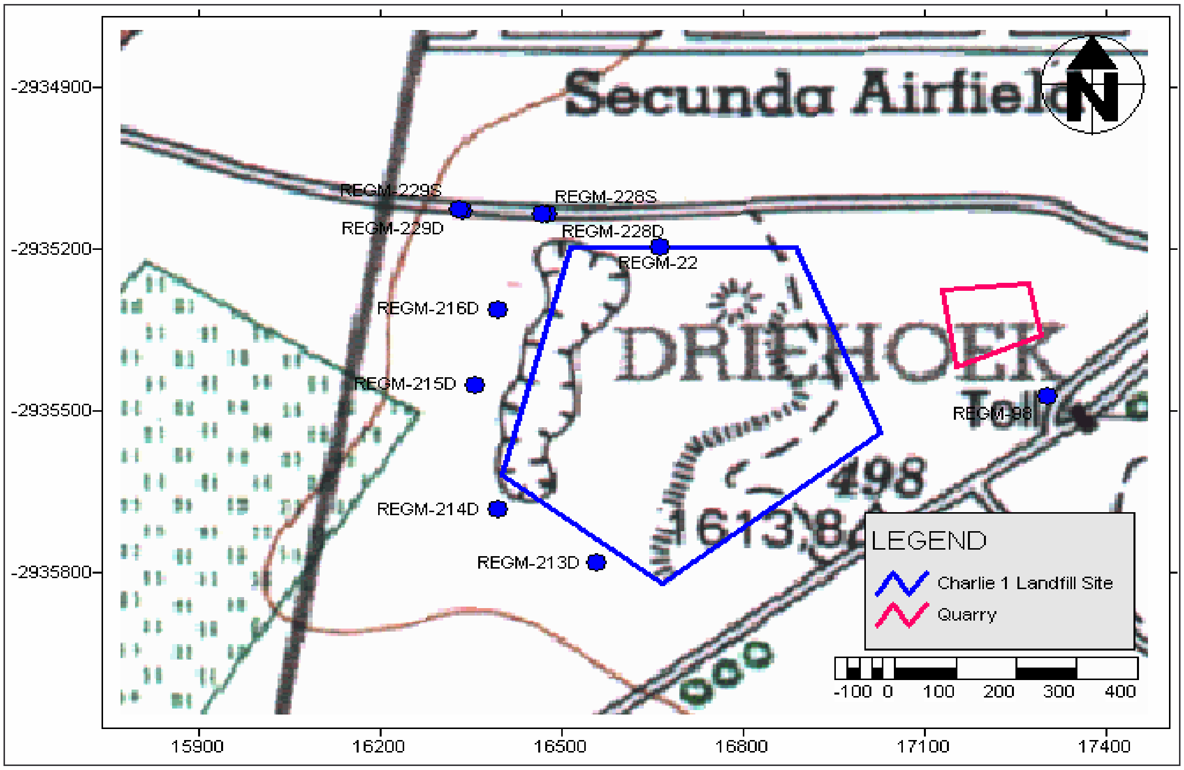

Figure 19: Position of all boreholes at the Charlie I landfill site.

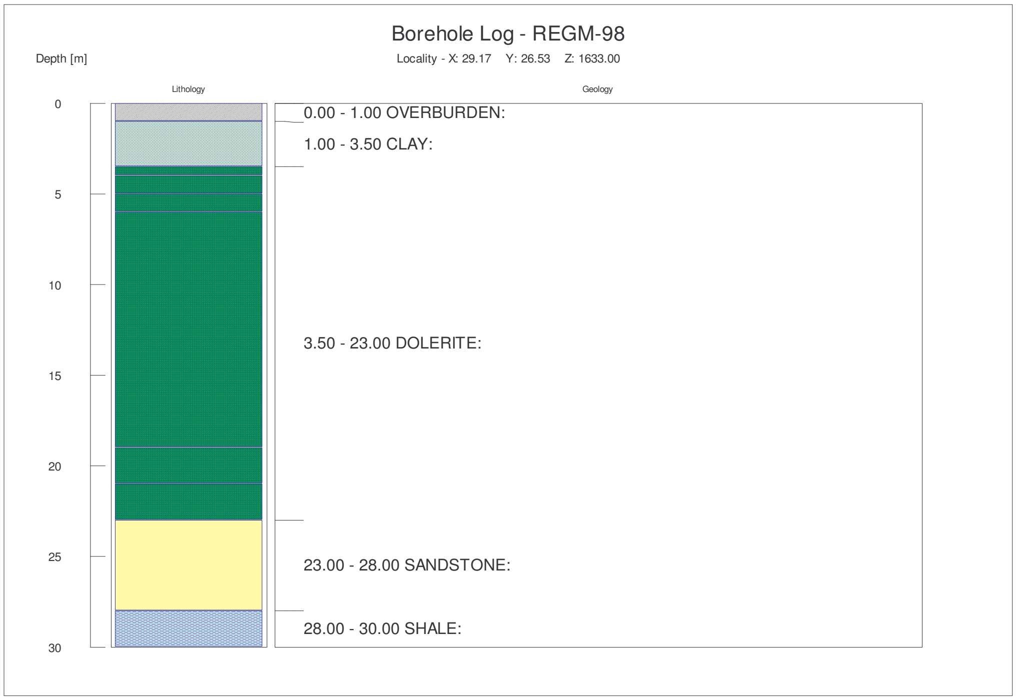

Figure 20: Typical geological log east of the site.

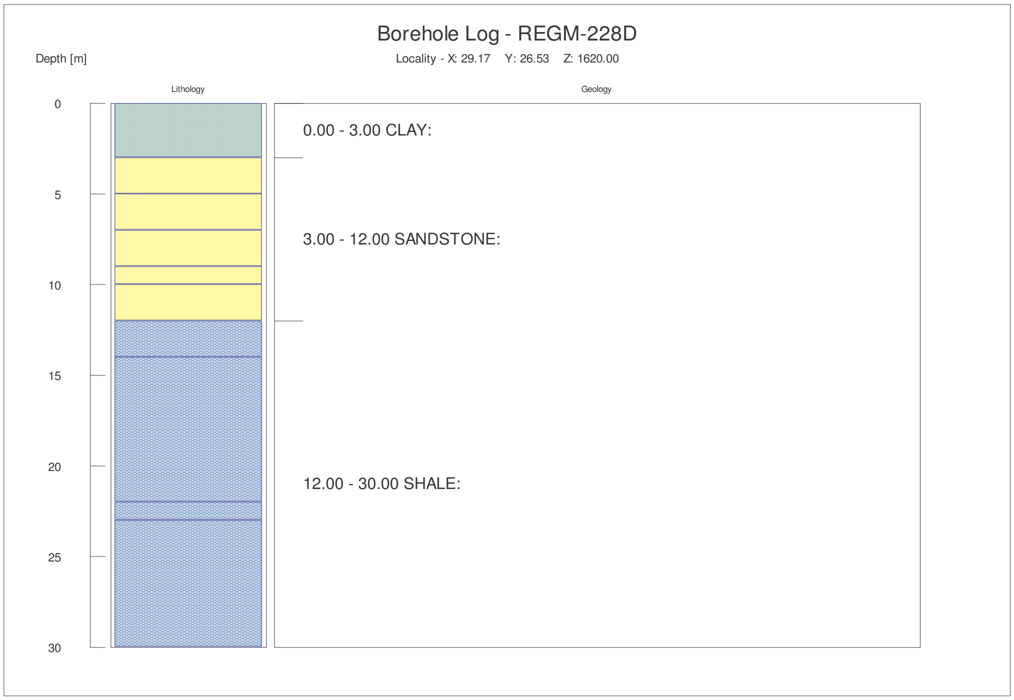

Figure 211: Typical geological log north of the site.

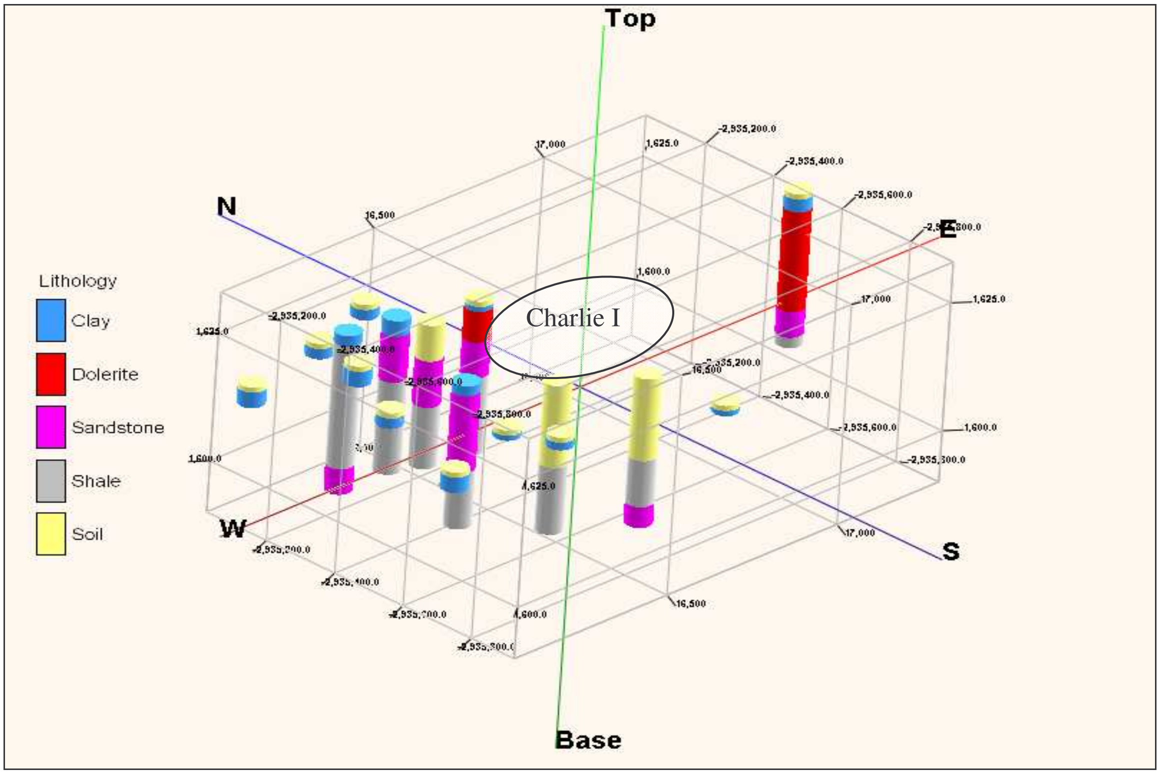

Figure 22: 3D model showing borehole distribution of the borehole logs at the Charlie I landfill site.

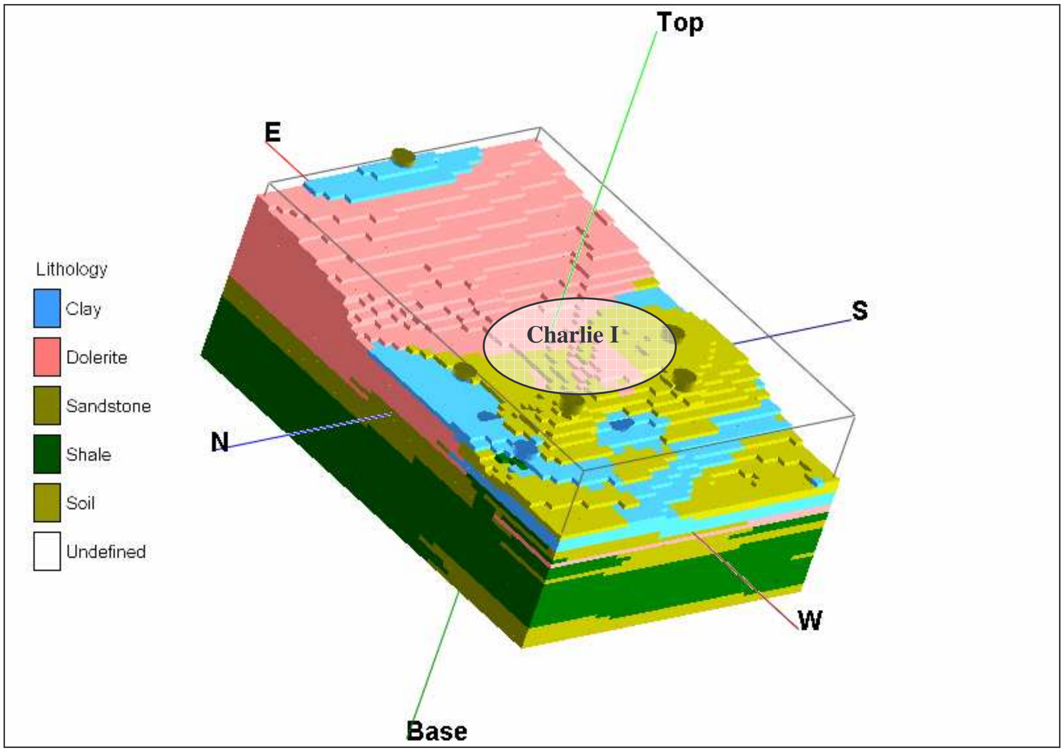

Figure 23: 3D model of the geology at the Charlie I landfill site.

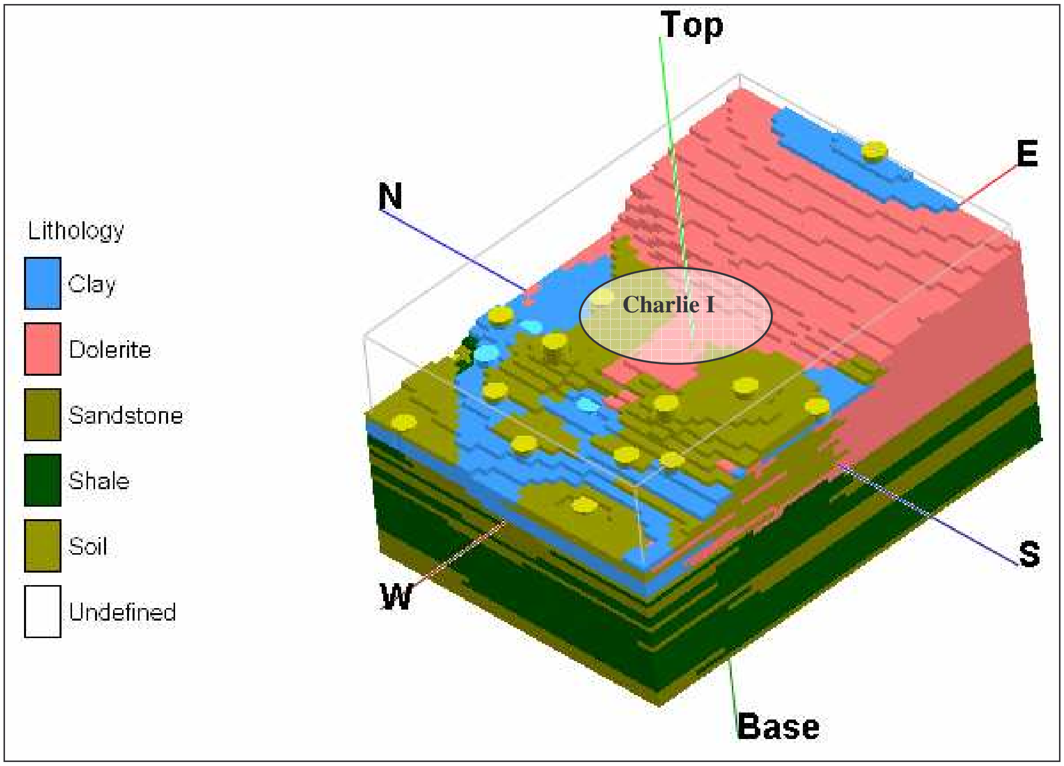

Figure 24: 3D model of the geology at the Charlie I landfill site.

3D models created by Rockworks Software (Rockware), using borehole drilling data obtained from the site, show the dolerite sill thinning towards the west (Figure 23 and Figure 23), indicating that the Charlie I landfill is located either on the contact zone between the dolerite sill and the underlying sandstone, or only on the sandstone and shale contact zone, due to a minor dip that affects the sedimentary layers.

4.2.3. Soil Analysis

4.2.3.1. Soil Texture

The average thickness of soil from the auger-drilled holes in the area is 3m. Soil was sampled to obtain information on its basic properties, and to further evaluate a wide variety of geochemical reactions. Most soil samples were disturbed during sampling, implying that changes in stress conditions, water content, soil structure mixing and segregation, and chemical changes might have occurred.

Soil samples were sent to the Glen Agricultural Institute, Department of Agriculture, Bloemfontein, for soil texture analysis. Soil texture is classified by its relative proportions of sand, silt and clay (USDA). Most of the soils on the Charlie I landfill site are clays, sandy clays, sandy clay loams and sandy loams (Figure 25). Sandy loams can be attributed to soil and sandstone mixing during sampling.

The moisture content of all soils was measured by means of the gravimetric oven drying procedure. This involves measuring the weight of the known volume of soil, and oven drying it to evaporate the water content. Water content from the soils in the area ranges from 28 – 47%. The bulk density is determined in the laboratory with the use of the above information, and found to be 0.95 – 1.3 g/cm^3; thus porosity, assuming a soil particle density of 2.65 g/cm^3 (*i.e. dominant mineralogy is quartz*), can be estimated at 0.35 – 0.49.

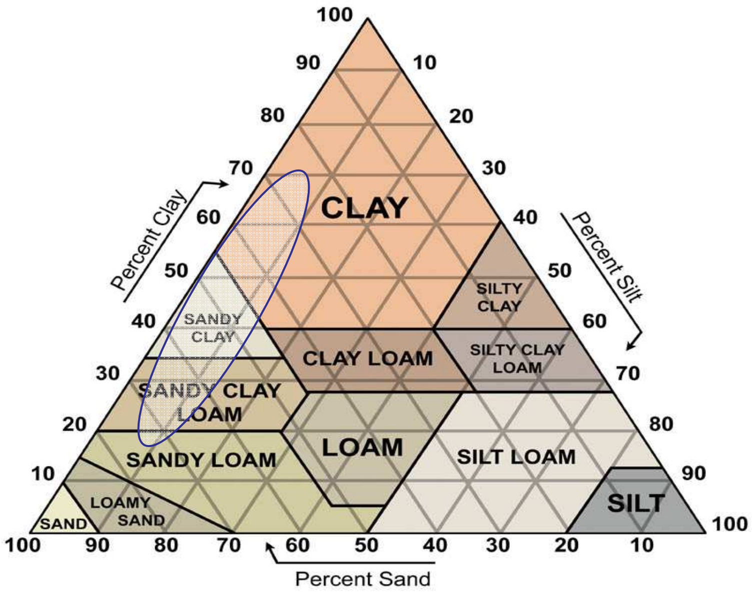

Figure 25: USDA soil classification based on grain size (Blue oval indicates zone of plotting for soils at this site).

The average organic matter from Terrattest 5.22 (Eurofins Analytico B. V., Barneveld, Netherlands) is 2.23 % dm (dry matter). The dry weight percentage (Table 4) represents the percentage of samples allowed to dry at room temperature before the tests; therefore this does not represent the dry weight percentage of fresh samples. The high percentage of fraction less than 2µm also confirms the high clay content on the soils in the region.

Table 4: Physical properties of the soil.

Sample Description	**Dry weight %(w/w)**	**Organic matter %dm**	**Fraction <2µm %(w/w) dm**
CH 036	89.4	4.5	14.5
CH 017	96	3.1	38.7
CH 009	96.6	3.7	29.3
CH 042	95.4	3.8	44.7
CH 041	95	3	37.6
CH 007	97.7	5.2	11
CH 018	95.4	3.3	20.6
CH 046	91.6	<0.5	14.5
CH 023	97.3	2.3	11.4
CH 022	97.3	3.5	25.1
CH 029	96.9	3.1	26.7
CH 054	97.2	3.2	15.9

4.2.3.2. Soil Hydraulic Conductivity (K-value)

The Soil Horizontal Hydraulic conductivity (*K*) was laboratory-determined by means of Darcy's law (Equation 1) and applying the Dupuit assumptions (Equation 2 and 3) to different soil samples (

Figure 26) from the site; it was found to average at 1.485E-5 cm/sec (i.e. 0.0128 m/d) (Table 5).

From Darcy's Law $Q = KiA$ -----------1

Therefore, $K = Q/iA$

Since, $i = (h_2 - h_1)/L$ -----------2

and $A = W(h_2 + h_1)/2$ ------3

Then, $K = \dfrac{Q\,2\,L}{W(h_2^2 - h_1^2)}$ --------4

Where K (hydraulic conductivity),
Q (discharge rate),
i (hydraulic gradient),
A (area of flow),
L (flow length), and
W (width of flow cell).

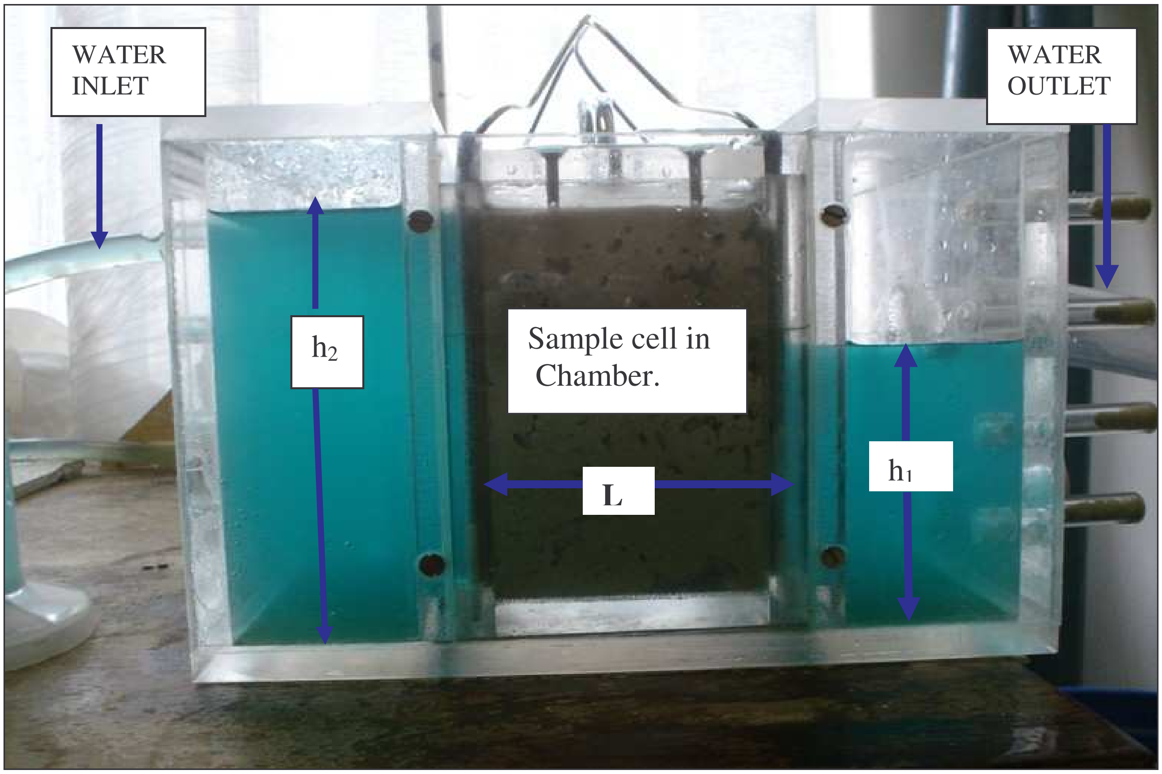

Figure 26: Phreatic Hydraulic Conductivity Apparatus. Note the height of water (h_1) in the inlet chamber; the height (h_2) in the outlet chamber; L (length of sample cell); the water inlet and water outlet tubes (Akoachere et al.*, 2007).*

The above tests were conducted in order to obtain information about hydraulic characteristics of the soil in the areas adjacent the Charlie I landfill site. During the design or assessment of any existing landfill, the hydraulic properties of soil are very important to determine the rate at which contaminated water or leachate will move downward or be retarded in the subsurface, thus quantifying the threat of groundwater contamination.

Table 5: Laboratory Determined Horizontal Hydraulic Conductivity values for soil.

Sample Name *(3m depth)*	Height h2 *(cm)*	Height h1 *(cm)*	Width W *(cm)*	Length L *(cm)*	Volume V *(cm3)*	Time t *(sec)*	Discharge Q *(cm3/sec)*	Hydraulic Conductivity K *(cm/sec)*	Hydraulic Conductivity K *(m/day)*
CH001	11.5	2.7	18.5	8.5	20	8.53E+03	2.34E-03	1.72E-05	0.015
CH009	11.3	2.6	18.5	8.5	20.2	1.52E+04	1.33E-03	1.01E-05	0.009
CH017	11.3	2.7	18.5	8.5	20	1.76E+04	1.14E-03	8.67E-06	0.008
CH023	11.3	2.5	18.5	8.5	20.1	7.13E+03	2.82E-03	2.13E-05	0.018
CH029	11.4	2.6	18.5	8.5	20	1.17E+04	1.71E-03	1.28E-05	0.011
CH036	11.4	2.7	18.5	8.5	20	7.88E+03	2.54E-03	1.90E-05	0.016
								1.48E-05	**0.0128**

The data from the soil analysis indicate that soils in the vicinity of the Charlie I landfill site have a high clay content, high porosity values (associated with clays) and low horizontal hydraulic conductivity values. These factors indicate that the transport of contaminants from the site will be retarded.

4.3. Water Levels

4.3.1. Water Levels

As part of a groundwater monitoring programme, water levels from all boreholes were measured. Figure 27 shows the water level depth fluctuations with time at the Charlie I landfill site, with all boreholes indicating similar regional trends in groundwater level fluctuation.

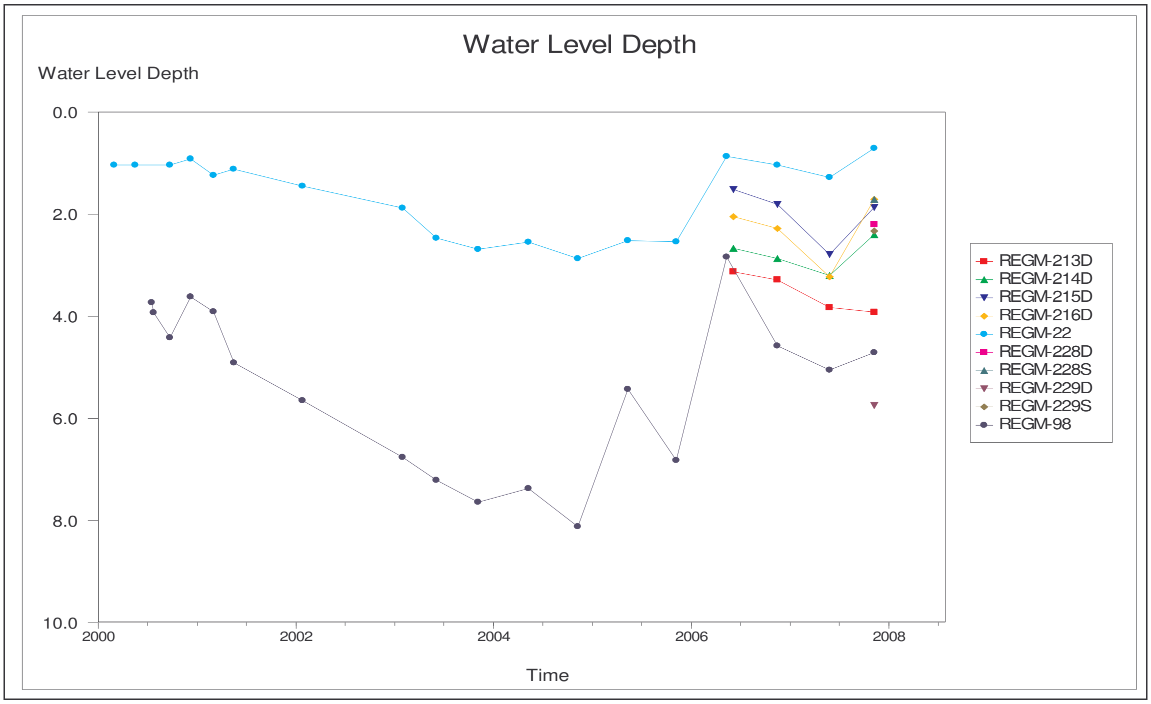

Figure 27: Plot of borehole water levels vs. time.

Borehole REGM 98 is located upgradient from the landfill site, REGM 213D and REGM 229D have deeper water levels (4 - 5 mbgl), (Figure 27) compared to the rest of the boreholes nearby. Boreholes REGM 214D, 215D, 216D, 228D, 228S and 229S show higher water levels (1 mbgl) in the vicinity of the landfill site, which could be due to the high water table associated with landfill sites.

Figure 28 shows the spatial distribution of water levels in the Charlie I landfill area, with almost all boreholes and piezometers located in close proximity to the landfill site. This indicates elevated water levels that progressively diminish with distance. Data from monitoring boreholes at about a 1 km radius from the landfill site have deeper water levels, with an elevation of up to 10 mbgl.

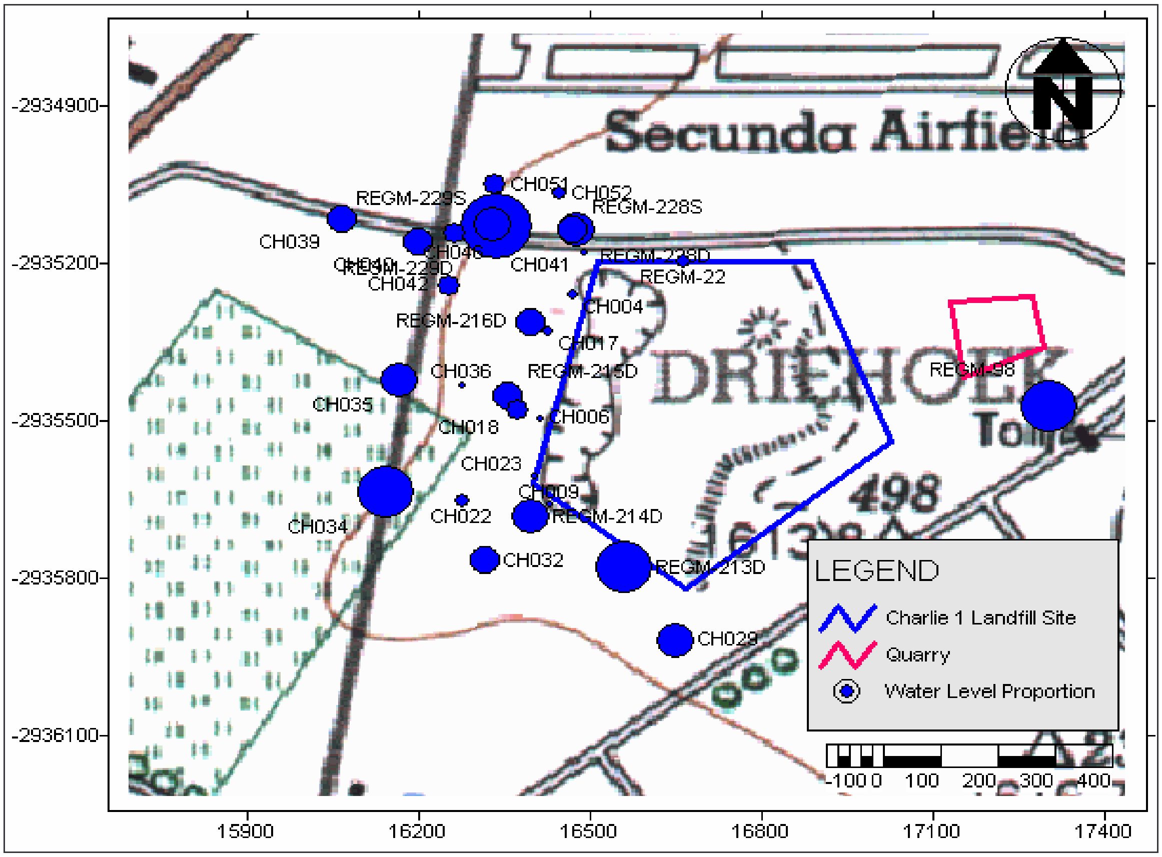

Figure 28: Spatial water level depth distribution of boreholes and piezometers.

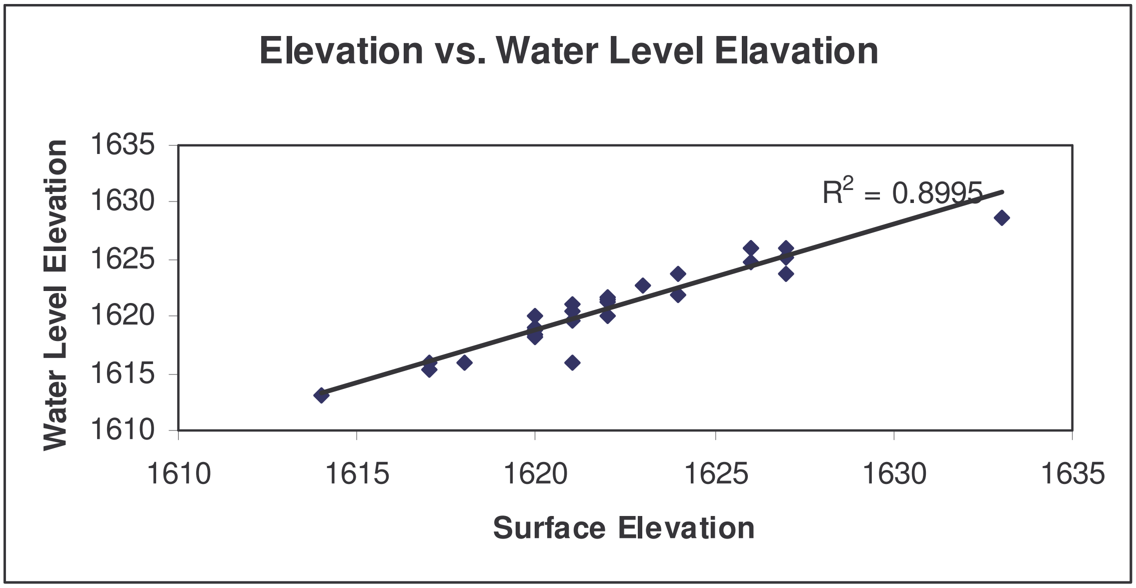

Figure 29: Plot of water levels vs. topography from the boreholes and piesometers.

Table 6 below shows the water levels of boreholes and piezometers at the Charlie I landfill site. A plot of topography versus water level elevations for boreholes and piezometers was created to obtain a mathematical relationship; thus a linear relationship is established, with an R^2 value of 0.8995 (Figure 29).

4.3.2. Groundwater Flow Direction

Since groundwater elevation follows topography, groundwater flows along the site drainage pattern (i.e. northwest at the north of the site and southwest at the west and south of the site). Figure 30 and Figure 31 present 2D contoured groundwater elevation (Bayesian interpolation) illustrations, showing the groundwater flow direction, and 3D visualisations (Rockworks software) showing the groundwater level elevations at the landfill site compared to the southern side, deepening with distance towards the southwest.

Table 6: Measured water levels at the Charlie I landfill site (07-11-2007)

SiteName	Y Coord	X Coord	Elevation	Water Level	Water Level Elevation
REGM-22	-26.52669	29.16717	1608	0	1608.00
REGM-98	-26.52917	29.17361	1616	4.26	1611.74
REGM-213D	-26.53196	29.16614	1608	3.27	1604.73
REGM-214D	-26.53107	29.16451	1604	1.77	1602.23
REGM-215D	-26.52900	29.16411	1603	1.15	1601.85
REGM-216D	-26.52773	29.16450	1601	0.94	1600.06
REGM-228D	-26.52614	29.16530	1601	1.635	1599.37
REGM-228S	-26.52614	29.16523	1601	1.06	1599.94
REGM-229D	-26.52608	29.16391	1599	5.04	1593.96
REGM-229S	-26.52607	29.16385	1599	1.79	1597.21
CH 004	-26.52725	29.16523	1604	0.24	1603.76
CH 006	-26.52940	29.16468	1607	0.20	1606.81
CH 009	-26.53088	29.16486	1605	0.00	1605.00
CH 017	-26.52789	29.16481	1604	0.46	1603.54
CH 018	-26.52923	29.16428	1603	1.28	1601.72
CH 022	-26.53081	29.16332	1603	0.60	1602.40
CH 023	-26.53040	29.16459	1606	0.00	1606.00
CH 029	-26.53322	29.16705	1604	2.48	1601.52
CH 032	-26.53182	29.16372	1603	1.88	1601.12
CH 036	-26.52881	29.16330	1601	3.84	1597.16
CH 039	-26.52597	29.16119	1601	2.47	1598.53
CH 040	-26.52636	29.16254	1600	0.22	1599.78
CH 041	-26.52655	29.16544	1596	1.98	1594.02
CH 042	-26.52710	29.16307	1599	1.62	1597.39
CH 046	-26.52622	29.16316	1604	0.00	1604.00
CH 051	-26.52536	29.16387	1601	1.28	1599.72
CH 052	-26.52551	29.16500	1597	1.02	1595.98

Figure 30 shows water level elevation contours following the surface topography with the levels flattening out towards the landfill site. **The indication is that the water level conditions are impacted by the landfill site, with a high water table; therefore the natural conditions no longer exist.**

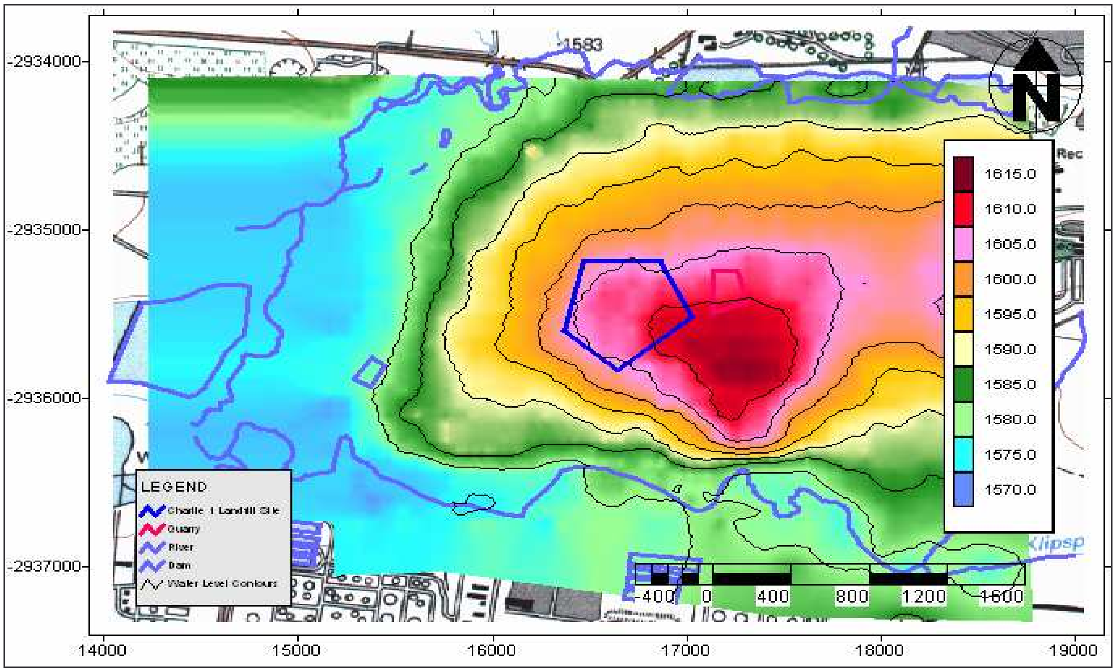

Figure 30: Bayesian Interpolated groundwater elevation contours at the Charlie I landfill site (WISH software).

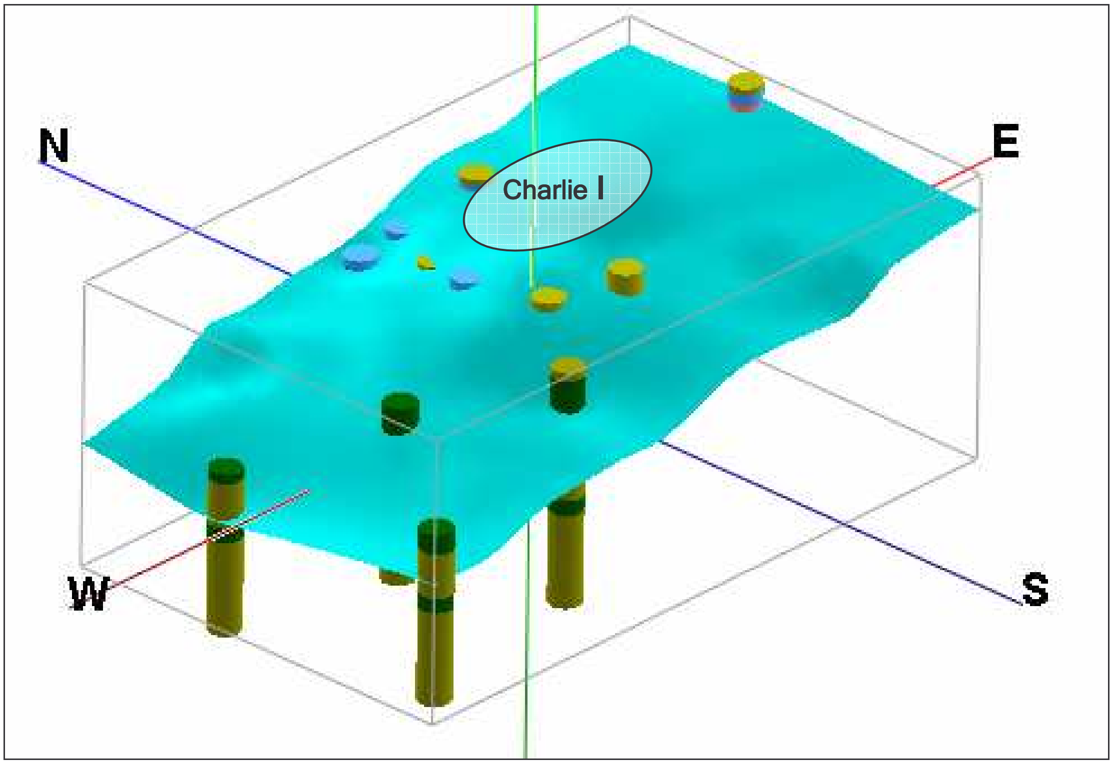

Figure 31: 3D model of water levels at the Charlie I landfill site (Oval shape represents position of Charlie I Landfill).

4.4. Aquifer Testing

4.4.1. Blow Yields

No information was available for the initial blow yields of the two boreholes (REGM 22 and 98) used for groundwater monitoring at the landfill site. From the eight recently drilled boreholes at the site, only two recorded blow yields during drilling. REGM 214 and REGM 228D yielded 1000 L/h at 24m and 2000 L/h at 29m, respectively. The initial blow yield for a borehole could provide an early estimate of the transmissivity (Van Tonder *et al.*, 2002).

$$T\ (m^2/d) = 5 \times Q \qquad \text{where Q is in L/s.}$$

Therefore, from the blow yield information, the initial assumptions of the transmissivity values for the region are in the range of 1.4 – 2.75 m^2/day.

4.4.2. Slug Test

Prior to the pump test, slug tests were performed on all boreholes and piezometers to estimate hydraulic conductivity. The slug test is applicable for the *in-situ* determination of the saturated hydraulic conductivity in unconfined and confined aquifers, and is applied in partially to fully penetrating boreholes to determine horizontal hydraulic conductivity.

This method consists of inserting (falling head) or removing (rising head) a slug of water instantaneously and measuring the recovery of the water in the borehole (Freeze and Cherry, 1979). The analysis was made with the Bouwer-Rice (1976) method in the FC-programme (Van Tonder *et al.*, 2002), and based on the equation below.

$$K = \frac{r_c^2 \ln (R_e/r_w)}{2d} \frac{1}{t} \ln \frac{h_0}{h_t}$$

Where:

r_c = radius of the unscreened part of the borehole where the head is rising

r_w = horizontal distance from the borehole centre to the undisturbed aquifer

R_e = Radial distance over which the difference in head h_0 is dissipated in the flow system of the aquifer

d = length of the borehole screen or open section of the borehole

h_0 = head in the borehole at time t_0

h_t = head in the borehole at time t

4.4.2.1. Slug test results for Boreholes

Table 7 shows the estimated hydraulic conductivities (K-values) from all boreholes on the Charlie I landfill site. The average horizontal hydraulic conductivity in the immediate vicinity of the borehole or piezometer was estimated with the above equation. Boreholes REGM 22, 98 and 229D indicate higher hydraulic conductivities compared to the other boreholes. The higher K-value at REGM 22 is influenced by its locality (i.e. the presence of surface run-off (Figure 32) from the landfill at the borehole position); these could change the initial borehole construction conditions. REGM 22 is the only borehole with high contaminant levels emanating from the landfill site (Chapter 5).

Figure 32: REGM 22.

The higher K-value obtained at Borehole REGM 98 is explained by the drilling logs (Section 4.2.2.1.). The borehole was drilled through the weathered dolerite sill. It should be noted that the contact zone between the dolerite dyke/sill and the country rock (i.e. sediments) provides a preferential flow path for groundwater; therefore this will yield higher hydraulic conductivity values.

Table 7: Hydraulic conductivity determined from boreholes.

BH No.	**K-value (m/d)**
REGM 22	0.263
REGM 98	0.142
REGM213D	0.003
REGM 214D	0.007
REGM 215D	0.018
REGM 216D	0.012
REGM 228S	0.021
REGM 228D	0.018
REGM 229S	0.007
REGM 229D	0.078

4.4.2.2. Slug test results for Piezometers

Table 8 shows hydraulic conductivities (K-values) obtained from the slug test data from all piezometers containing water analysed by the Bouwer-Rice (1976) method in the FC-programme. The K-values represent the horizontal hydraulic conductivity values for the soils at these positions. Comparing these values and the laboratory K-values (Section 4.2.3.2.) for soils, there is a similarity that indicates a higher hydraulic conductivity due to soil disturbance during sampling.

Table 8: Hydraulic conductivity from piezometer boreholes.

Piezometer No	**K-value (m/d)**
CH 006	0.023
CH 009	0.031
CH 017	0.02
CH 023	0.018
CH 029	0.00008
CH 036	0.005
CH 039	0.017
CH 041	0.003
CH 042	0.002
CH 046	0.00002
CH 052	0.012

4.4.3. Pumping Test

Constant rate discharge tests were performed to determine the transmissivity of the aquifer; thus information with regard to the hydraulic properties of the groundwater system. Constant discharge tests were performed on Boreholes REGM 98, REGM 214, REGM 216 and REGM 228D. The transmissivity (T-values) were estimated by means of the Cooper-Jacob (1946) method, as discussed by Kruseman and De Ridder (2000), with S-values obtained by RPTSOLV software (Verwey *et al.*, 1995). Table 9 shows the T-values and S-values from the boreholes tested at the Charlie I landfill site.

Table 9: Transmissivity and Storativity values.

Borehole Number	**T-value (m^2/day)**	**S-value**
REGM 98	1.4	1.12E-3
REGM 214D	1.0	1.99E-4
REGM 216D	1.3	9.79E-5
REGM 228D	1.0	2.24E-5

4.4.3.1. Diagnostic Plots

From the pump test data for Borehole REGM 98, linear flow conditions can be observed from early times for both the log-log plot and the square root of time plot (Figure 33), indicating a fractured aquifer system. From the borehole logs, this can be attributed to horizontal flow along the dolerite sill.

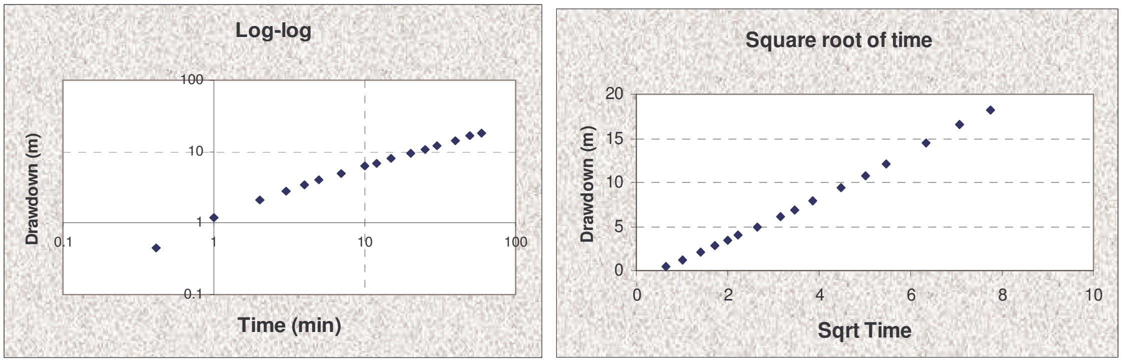

Figure 33: Log-log and square root of time plots for REGM 98.

4.4.4. Aquifer Testing Discussion

Analyses of the aquifer testing data indicate that the Charlie I landfill area has two aquifer systems, as discussed in Section 3.4.2. The upper system is characterised by soils and weathered Karoo sediments. The hydraulic conductivity (K-values) obtained from all boreholes, excluding REGM 22, 98 and 229D, shows no distinction between the K-values obtained from the piezometers (i.e. soil horizon). This indicates that the K-values in these boreholes derive from the upper aquifer system.

All tested boreholes have a low transmissivity (T-value) of approximately 1.3 m^2/day, but with different storativity values (S-value). The difference in the storativity values signifies that these boreholes do not withdraw water from the same aquifer, indicating the presence of more than one aquifer system in the region. The transmissivity values represent the T-values for both aquifers (i.e. the upper and the deeper aquifer systems), also taking into consideration the K-values obtained.

According to the blow yields obtained, slug tests for boreholes and piezometers, as well as the pumping tests (transmissivity value of 1.3 m^2/d in a 30m deep aquifer), an average K- value of 10^{-2} was obtained for the aquifer. The exceptions in the values for boreholes REGM-98 within the weathered portion of the dolerite sill to the east of the site and REGM-229D are due to the presence of fractures, which were not encountered in the other boreholes.

5. Soil and Water Quality Analysis

5.1. Soil Quality Testing

The Auger drilling gave rise to a number of soil samples requiring analysis, but only twelve soil samples were strategically selected in the vicinity of the Charlie I landfill site and sent for Terrattest 5.22 (Eurofins Analytico Environment, B. V., Barneveld, The Netherlands) chemical analyses for trace metals and organic contaminants tests. The tests detect the nature and extent of the presence of more than 200 environmental contaminating substances in soil and groundwater samples, which is very important for a comprehensive study on the impacts of landfills. All samples were sampled downgradient of the landfill site, except CH054, sampled inside the waste. Only the first top metre of the soil horizon from the samples was selected for analysis.

5.1.1. Trace Metals

Almost all the analysis results indicate elevated but not higher than allowable concentration levels of trace metals (Table *10*), compared to the standards in soils from the Dutch soil quality guidelines (Guidelines for land use) (Appendix 3). The empty spaces indicate no detection.

Table 10: Trace metals in soil (in mgkg^{-1}) (compared to Dutch Soil Quality Guidelines).

Sample Description	**As**	**Ba**	**Be**	**Cr**	**Co**	**Cu**	**Hg**	**Pb**	**Mo**	**Ni**	**Sn**	**V**	**Zn**
Optimum	29	200		100	20	36	0.3	85	10	35			140
Action	55	625		380	240	190	10	530	200	210			720
CH 036	6	610		130	59	67		12	3.9	140		150	68
CH 017	5	260		210	70	52		20		59		160	52
CH 009	3	320		120	36	57		8		73		130	55
CH 042	6	260	1	200	71	59		21	14	66		150	61
CH 041	4	260		180	40	50		12		78		120	53
CH 007	28	240		390	63	140	0.24	110	67	180	8	110	180
CH 018	5	390		160	58	60		12		95		160	58
CH 046	5	430	1	200	55	64		17		110		140	60
CH 023	4	480		78	43	41	0.16	10	1.6	80		85	52
CH 022	4	110		150	21	34		11		40		120	41
CH 029	3	200		89	25	60		6		50		120	56
CH 054	9	340		180	28	100	7.5	53	18	90	8	98	210

Only sample CH 007 has a higher than maximum allowable concentration of chromium (Cr), and was collected from the region most affected by leachate springs run-off (contamination canal). All samples recorded have elevated concentration levels of Ba, Cr, Co, Cu, Pb, and Ni. Sample CH 054 represents a background sample collected from the Charlie I landfill site, and has higher than optimum concentration levels of all trace metals, excluding only As and Pb. The conclusion is that all the areas of sampling are affected by contaminants from the landfill.

5.1.2. Organic Compounds

From the twelve samples submitted for Terrattest 5.22, only eight tested positive for organic contaminants. Samples CH036, CH007 and CH023 detected concentrations of the greatest number of different organic compounds (Table 11), although most of these were found below maximum allowable concentration levels. These samples were taken close to or where the surface water emanates as leachate from the landfill runs.

The low levels of detection for most of the organic compounds in soils are likely due to either evaporation or the downward migration of contaminants. The former is most probably the case, given the properties of most organic compounds and since most of leachate is discharged as surface water run-off at the boundaries of the landfill site. It will therefore evaporate faster into the atmosphere, given the evaporation rate (1550mm) for the region. The presence of pesticides in most samples could be due to the agricultural activity in the vicinity of the landfill site (irrigation).

Table 11: Organic compounds (in mgkg^{-1}) (compared to Dutch Soil Quality Guidelines).

Organic Compound	**CH 036**	**CH 009**	**CH 042**	**CH 041**	**CH 007**	**CH 046**	**CH 023**	**CH 054**
m,p-Xylene								0.1
Xylenes (sum)								0.1
Phenol					0.02			0.48
o-Cresol					0.01			
p-Cresol					0.02			
Cresols (sum)					0.03			
Naphtalene	0.01		0.02		0.05		0.02	0.03
Fluorene					0.01			
Phenanthrene	0.04		0.02		0.16		0.03	0.03
Anthracene					0.04			
Fluorathene	0.04				0.23		0.02	0.05
Pyrene	0.05				0.2		0.02	0.04
Benzo(a)anthracene	0.04				0.14		0.02	0.03
Chrysene	0.09				0.24		0.04	0.03
Benzo(b)fluoranthrene	0.13				0.33		0.05	0.06
Benzo(k)fluranthrene	0.02				0.07		0.01	0.01
Benzo(a)pyrene	0.04				0.1		0.02	0.02
Dibenzo(ah)anthracene	0.01				0.03			
Benzo(ghi)perylene	0.06				0.15		0.03	0.03
Indeno(123cd)pyrene	0.04				0.12		0.02	0.02
PAH 10 VROM (sum)	0.4		0.04		1.3		0.19	0.26
PAH 16 EPA (sum)	0.6		0.04		1.9		0.27	0.35
1,4-Dichlorobenzene		0.03	0.06		0.01			0.03
Dichlorobenzene		0.03	0.06		0.01			0.03
4,4-DDE	0.004	0.013	0.008	0.002	0.01	0.001		
4,4-DDT						0.009		
4,4-DDD + 2,4-DDT						0.002		
2,4-DDD					0.002			
DDT/DDE/DDD (sum)	0.004	0.013	0.008	0.002	0.012	0.012		
Biphenyl					0.007			
Dibenzofurane					0.04			0.01
TPH (C22-C30)					26			
TPH (C30-C40)					37			
TPH (sum C10-C40)					77			
Di-n-butylphtalate								0.7
Phtalates								0.7

5.2. Hydrochemical Borehole Logging

A YSI multi-parameter Sonde probe was used to obtain geochemical profiles for all the boreholes, measuring electrical conductivity (EC), Temperature (T), Oxidation Reduction Potential (ORP) and pH with depth. These profiles are obtained *in situ* and changes in any of the above parameters with depth will indicate changes in aquifer conditions, i.e. hydraulic (fracture) and/or chemical (contaminant plume) conditions.

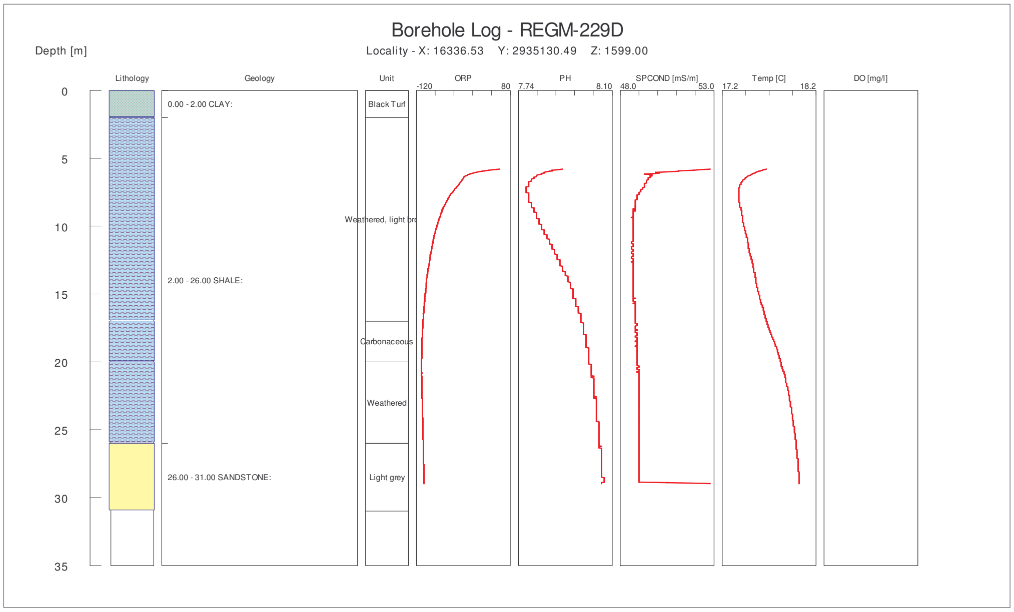

Figure 34: Multi-parameter profile for Borehole REGM 229D.

Appendix 2 illustrates the geochemical logging data from the boreholes. The conclusion is that, as demonstrated by the profile (Figure 34), the aquifer conditions change with depth. The ORP from most of the boreholes changes from positive values at the top to negative with depth. The implication is that the reducing conditions increase with depth, which indicates contamination in the lower parts of boreholes; however, water quality testing could not confirm contamination.

5.3. Water Quality

5.3.1. Surface Water Quality

Precipitation and seepage water into a landfill, together with any liquid waste, result in extraction of water-soluble compounds from the waste, and the subsequent formation of leachate. The leachate at the site seeps out as leachate springs on the southwestern edges (Figure 35). This runs off into a contaminated canal. The rate of production is dependent on rainfall. During dry winter months, less leachate is discharged by the site; thus salt precipitation takes place on the perimeter of the site. However, the smaller contaminated canal that is more observable during rainfall months continues to flow at a diminished rate (Figure 35).

Figure 35: Seepage flow (contaminated canal) from leachate springs west of the Charlie I landfill site.

The implication is that there is another source of regular water supply to the landfill site. The eastern region of the Charlie I landfill has been excavated to form a quarry, but is currently undergoing rehabilitation to the backfill the pit (Figure 35). In higher rainfall periods, water flows from the quarry to the waste site. The fact that waste has a higher permeability than the associated sediments results in further mounding of the water table within this waste site during summer.

Figure 36: Quarry undergoing rehabilitation at the eastern side of the landfill site.

Leachate samples were collected at three different positions at leachate springs along the edges of the landfill site. Surface water from the quarry located upgradient to the west of the landfill site and the rivers downgradient were sampled (Figure 37). These samples were analysed for all major ions, and one leachate sample sent for a Terrattest 5.22, analysing for organic compounds and trace metals. All samples were analysed for major ion chemistry at the Institute for Groundwater Studies laboratory, using a spectrophotometer (NH_4, COD), ion chromatograph (anions) and Inductively Coupled Plasma Atom Emission Spectrophotometer (cations).

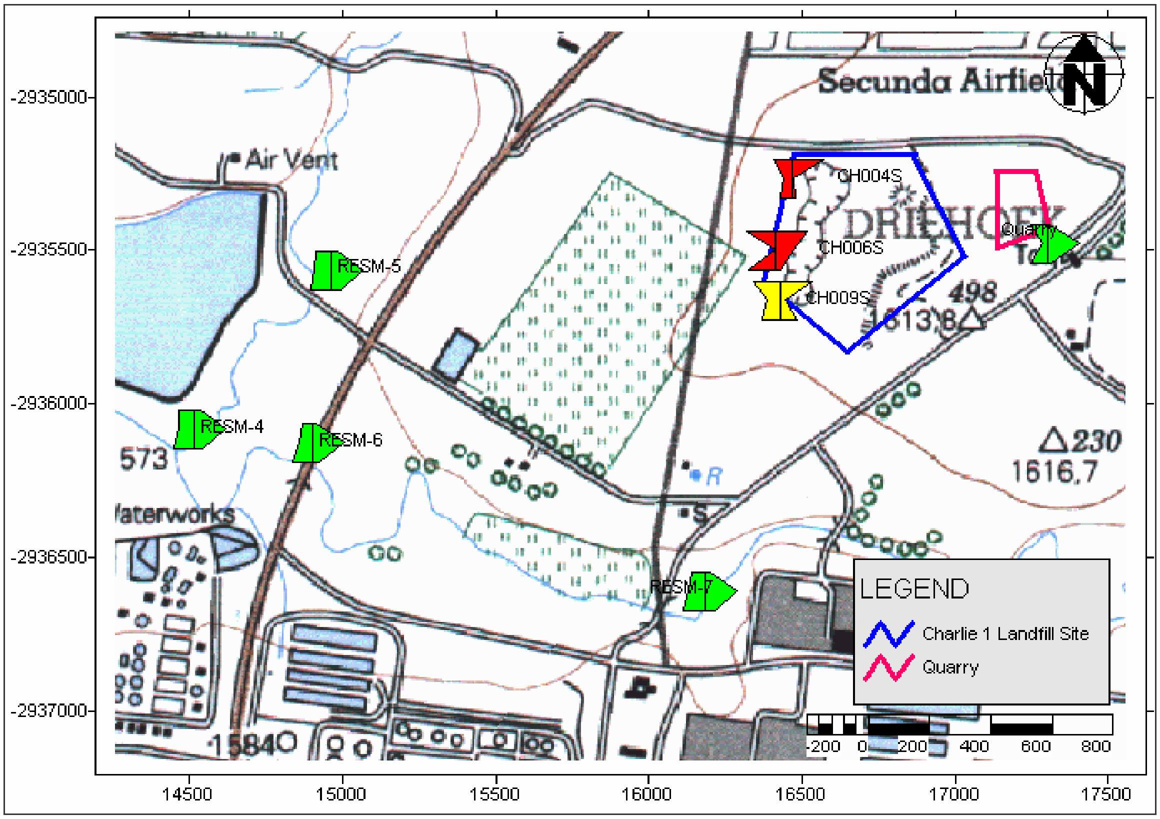

Figure 37: Position of leachate and surface water sampling points (Electrical Conductivity) – Stiff diagrams used.

The chemistry data were interpreted by means of the WISH software package (Lukas, 2008) for water quality standards and plotting specialised diagrams. *Table 12* shows the results of the chemical analyses of all samples. The compliance criteria used for major ion chemistry analysis is the **SANS 241:2005**; trace metals analysis is done according to the **World Health Organization (WHO) Drinking Water Quality Guidelines (2006). The USEPA Federal Drinking Water Standards (2003)** are used for the organic analysis. The major ion samples are classified as (SANS 241:2005):

Class I – acceptable

Class II - allowable (colour coded yellow)

Above – not allowable (colour coded **red**)

Table 12: Major ions (in mg/L, EC in mS/m) (compares to SANS 241:2005)

SiteName	pH	EC	Ca	Mg	Na	K	Palk	Malk	Cl	SO4	NO3(N)	F	Al	Fe	Mn	NH4
CH004S	7.54	686.00	335.41	271.33	824.37	30.43	0.00	216.00	2118.00	302.22	0.23	1.81	0.01	0.06	0.02	0.15
CH006S	8.43	680.00	43.70	479.92	970.65	17.59	45.80	1417.00	1636.00	373.06	0.34	3.56	0.29	0.07	0.01	0.42
CH009S	7.77	332.00	203.15	152.06	415.01	22.17	0.00	208.00	765.00	562.14	0.03	2.13	0.03	0.08	0.03	0.14
Quarry	8.84	70.00	23.93	40.11	70.58	11.52	21.40	308.00	20.22	41.53	0.03	1.01	0.21	0.05	0.01	0.22
RESM-4	7.83	59.10	40.66	35.85	34.76	3.78	0.00	169.00	20.12	121.65	0.15	0.35	0.09	0.06	0.01	0.21
RESM-5	7.59	38.30	30.91	18.50	20.64	3.40	0.00	135.00	16.79	35.54	0.20	0.33	0.08	0.05	0.01	0.16
RESM-6	7.21	40.30	26.28	24.69	23.23	3.27	0.00	107.00	11.96	86.32	0.36	0.32	0.34	0.37	0.02	0.10
RESM-7	7.32	40.10	24.57	23.88	23.06	3.28	0.00	109.00	11.95	79.86	0.34	0.31	0.34	0.34	0.02	0.13

5.3.1.1. Major Ion Chemistry

All three leachate samples show higher concentrations of electrical conductivity (EC), Mg, Na, F, Cl, and SO_4 (*Table 12*), as compared to the background surface water concentrations (i.e. Quarry). Furthermore, the leachate quality exhibits low contents of NO_3^-, NH_4, Mn, Fe and higher SO_4^{2-}, indicating that the early stages of waste degradation are in process (i.e. aerobic conditions still dominates). The quality of the samples from the streams downgradient from the site indicates no signs of receiving leachate.

Stiff diagrams provide an instant visual distinction between water from different sources and also indicate water pollution. The Stiff diagrams (Figure 38) below indicate a vast difference in water quality (different signatures) collected in the region. This indicates that there are different types of leachate produced by the landfill depending on the area and the type of waste leached. The leachate samples show very dissimilar ion concentrations when compared to the surface water samples.

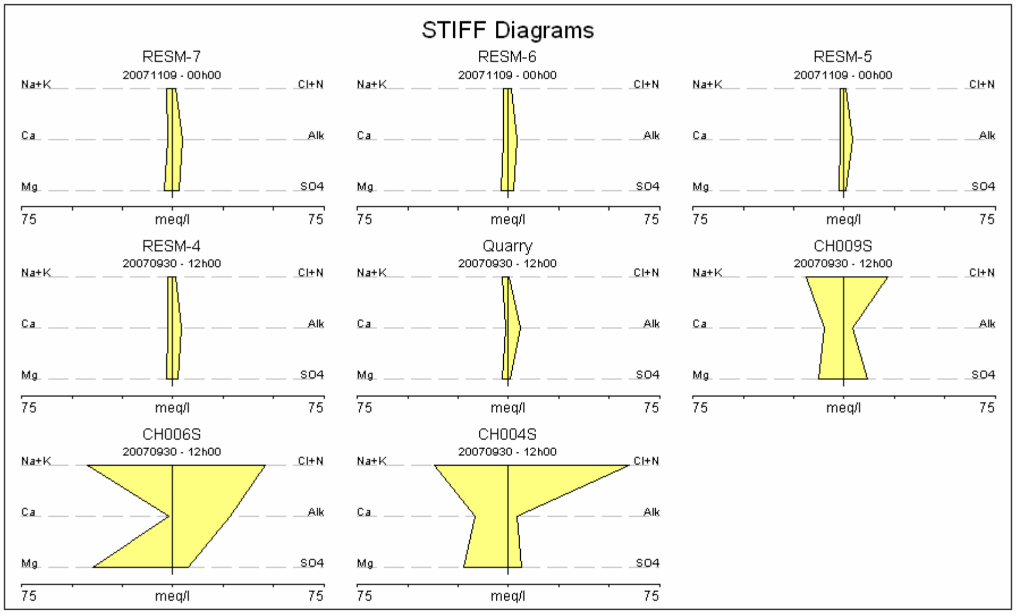

Figure 38: Stiff diagrams for leachate and surface water.

Specialised plots (i.e. Piper and Durov diagrams) present water quality data. In these diagrams, the percentages of major ions are plotted against each other and projected into a diamond field to represent the composition of water with respect to both cations and anions. A Piper diagram was used to classify the water type by plotting the percentages of major cations (Ca, Mg, Na and K) and anions (Cl, SO_4 and HCO_3+CO_3) as two points in a trilinear diagram.

From the Piper diagram (Figure 39), it is clear that the waters plot in regions where the normal groundwater composition has changed, with CH004S and CH009S plotting on the Cl+SO_4 facies and CH006S plotting on the Cl+SO_4, HCO_3 facies. Other surface water samples plot on the HCO_3 facies, indicating no major changes in natural character, and therefore no influence by the landfill site.

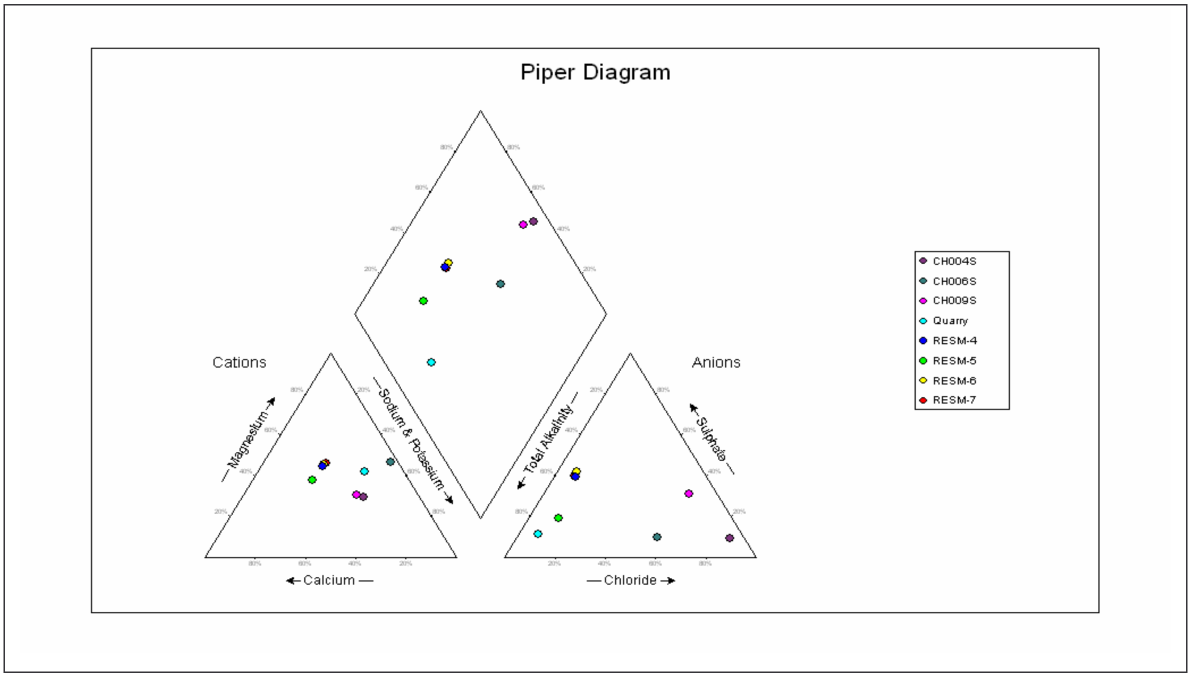

Figure 399: Piper diagrams for leachate and surface water.

The Durov diagram (Figure 40) show CH004S, CH006S and CH009S with high electrical conductivity values that indicate water contamination.

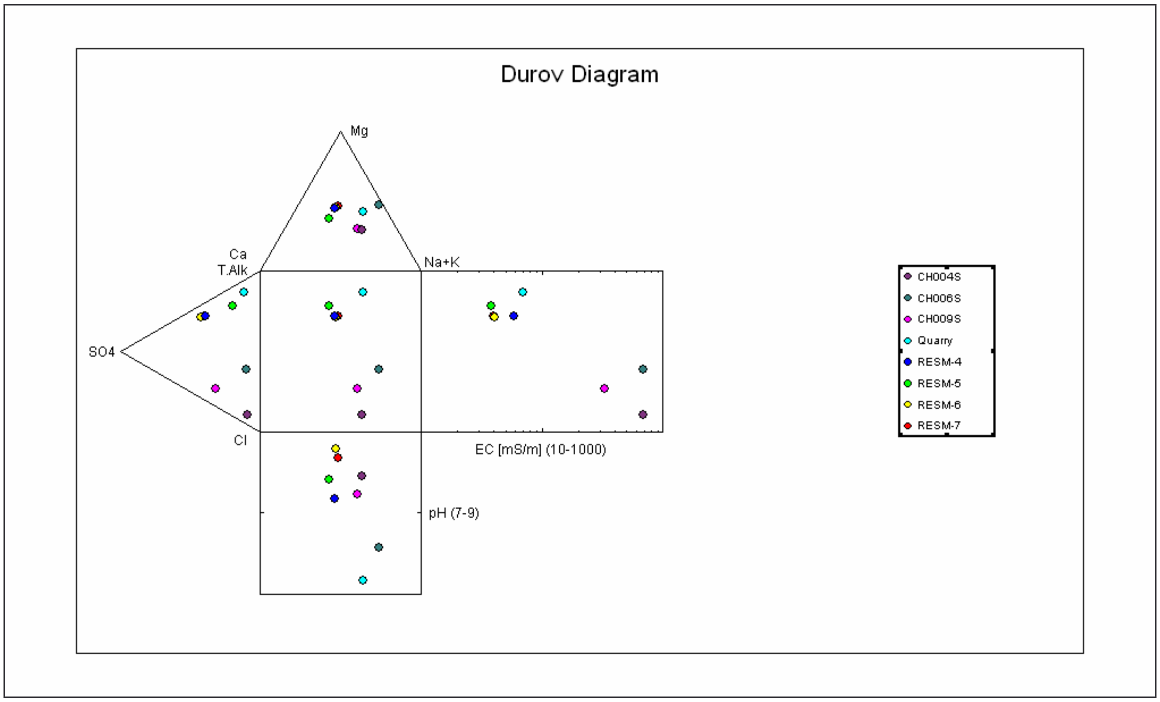

Figure 40: Durov diagram for leachate and surface water.

5.3.1.2. Trace Metals

The presence of trace metals in groundwater is a cause for great concern in terms of their health implications. In nature, trace metals are the result of mineral and soil weathering, while higher input is associated with human activities. All boreholes, three piezometer samples and two leachate samples, were analysed for Terrattest 5.22 trace metals and organic compounds analysis.

Table 13: Trace metals (in µg/L) WHO (2006)

Number	**As**	**Ba**	**Cr**	**Co**	**Cu**	**Hg**	**Mo**	**Ni**	**Se**	**V**	**Zn**
Guideline Value	10	700	50		2000	6	70	70	10		3000
CH54	0.007	0.41	0.004	0.17	0.017	0.0003	0.032	0.23	0.016	0.005	1.2
CH007S	0.014	0.12	0.002	0.015	0.021		2.2	0.2		0.063	0.015

Waste Sample CH054 was analysed and leached using the TCLP (ASTM – 1311) method. The CH007S leachate sample was collected from the leachate springs. All the trace metals tested in these leachate samples (Table 13) were within the prescribed World Health Organisation water quality (WHO, 2006) standards.

5.3.1.3. Organic Compounds

The concentration and nature of soluble organic and inorganic substances in leachate are dependent on the stage of waste degradation/decomposition. Table 14 shows the concentrations of tested organic contaminants from the leachate samples. Low concentrations (USEPA Water Quality Standards) of organic contaminants were detected in leachate samples.

Table 14: Organic Compounds (in µg/L) USEPA (2003)

Organic Compound	Guideline Value	CH054	CH007S
Benzene	5		0.2
Ethylbenzene	700		0.4
Toluene	1000	0.3	0.2
m,p-Xylene			0.1
Xylenes (sum)	10000		0.1
Styrene	100		0.4
Trichloromethane		15	
Trichloroethene	5	1.3	0.16
Bromodichloromethane	100		5.7

5.3.2. Groundwater Quality

Groundwater water quality has been monitored on the landfill site using boreholes REGM 98 (representing the background/ambient contions) and REGM 22, with the latter showing high incidents of groundwater contamination (higher electrical conductivity over the monitored period, Figure 41). It should be noted that REGM 22 is located in the path of the surface water run-off from the Charlie I landfill; this could be the main reason for its higher concentration of major ions.

5.3.2.1. Major Ion Chemistry

Table 15 shows the major ion chemistry of the boreholes at the Charlie I landfill site, with the values in red representing parameter concentrations exceeding the recommended value, and yellow representing allowable concentrations. The major ion chemistry indicates limited vertical movement of leachate into the groundwater system.

Table 15: Borehole major ions (in mg/L, EC in mS/m) (compare to SANS 241:2005)

SiteName	pH	EC	TDS	Ca	Mg	Na	K	Malk	Cl	SO4	NO3(N)	F	Al	Fe	Mn	NH4
REGM-22	7.69	223.00	1781.79	236.63	150.31	108.31	9.88	256.00	408.00	544.41	4.71	2.93	0.07	0.11	1.01	0.08
REGM-98	7.70	119.00	928.24	131.24	62.40	48.75	10.38	525.00	8.77	140.11	0.25	0.31	0.00	0.09	0.00	0.07
REGM-213D	8.15	88.30	621.94	67.42	45.17	63.99	4.28	340.00	74.00	25.44	0.02	0.20	0.01	0.16	0.18	0.28
REGM-214D	8.12	130.00	841.77	79.22	44.88	133.79	6.40	335.00	189.00	45.94	1.04	0.34	0.01	0.16	0.07	0.73
REGM-215D	7.62	78.20	554.89	65.15	43.23	45.12	3.26	338.00	41.77	16.61	0.02	0.27	0.01	0.12	0.43	0.21
REGM-216D	8.09	54.40	382.19	37.41	25.09	40.97	4.37	227.00	34.54	7.12	0.61	0.22	0.01	0.08	0.16	1.70
REGM-228D	8.08	60.50	467.56	39.09	29.41	60.67	8.48	296.00	29.94	2.66	0.08	0.16	0.03	0.10	0.03	0.23
REGM-228S	8.16	80.50	584.46	42.43	31.10	98.95	1.84	276.00	32.04	99.00	0.28	0.47	0.02	0.24	0.09	0.47
REGM-229D	8.19	52.50	394.54	31.57	23.81	51.56	5.88	268.00	12.01	0.68	0.02	0.21	0.02	0.14	0.03	0.30
REGM-229S	8.18	43.30	306.52	28.17	17.14	33.92	3.86	181.00	8.89	32.24	0.04	0.23	0.01	0.19	0.01	0.40

Figure 42 shows plot SO_4 concentrations over time for all the boreholes at the site, with REGM 22 demonstrating variable concentrations over time. The graph indicates fluctuating trends of higher SO_4 concentrations, thus indicating that leachate is released in pulses by the landfill. This variation may be climatically controlled (due to rainfall occurring as an event rather than on a continuous basis).

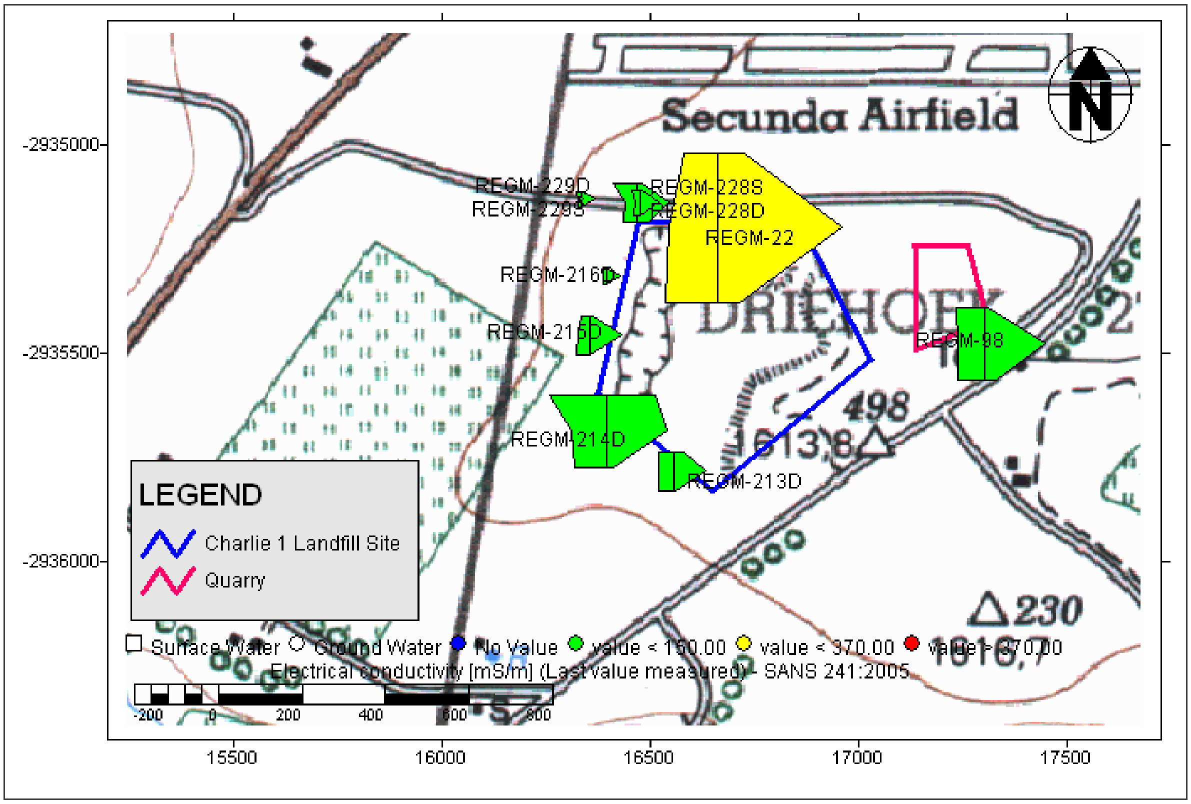

Figure 41: Position of all tested boreholes (Electrical Conductivity).

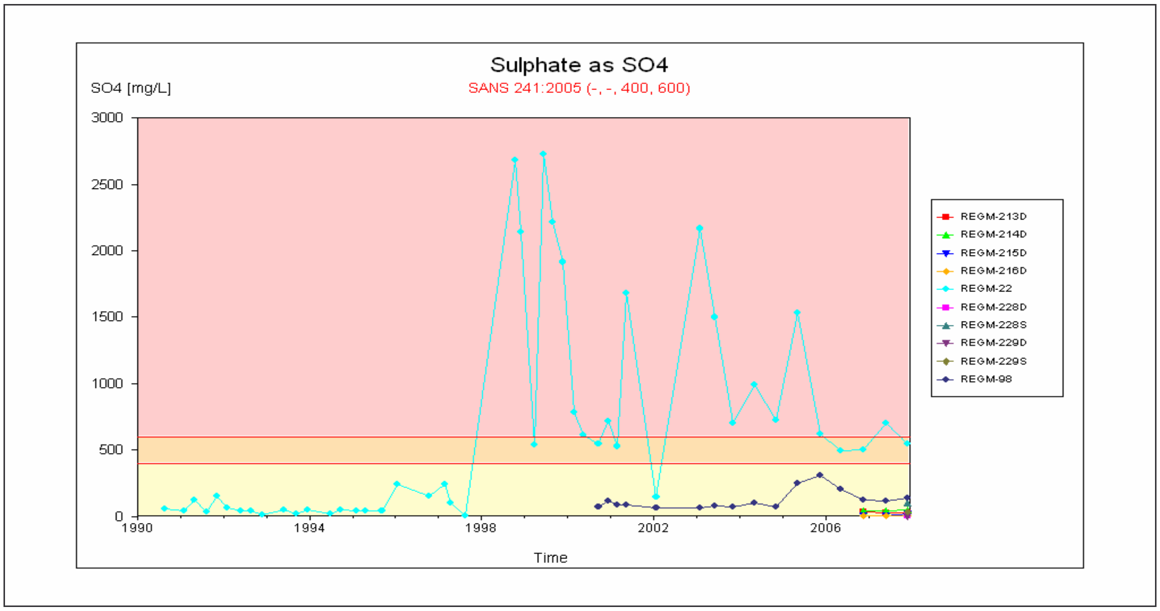

Figure 42: SO_4 Concentration vs. Time graph for all boreholes at Charlie I landfill site.

Further contouring of electrical conductivity (Figure 43) shows that only Borehole REGM 22 has been contaminated with leachate.

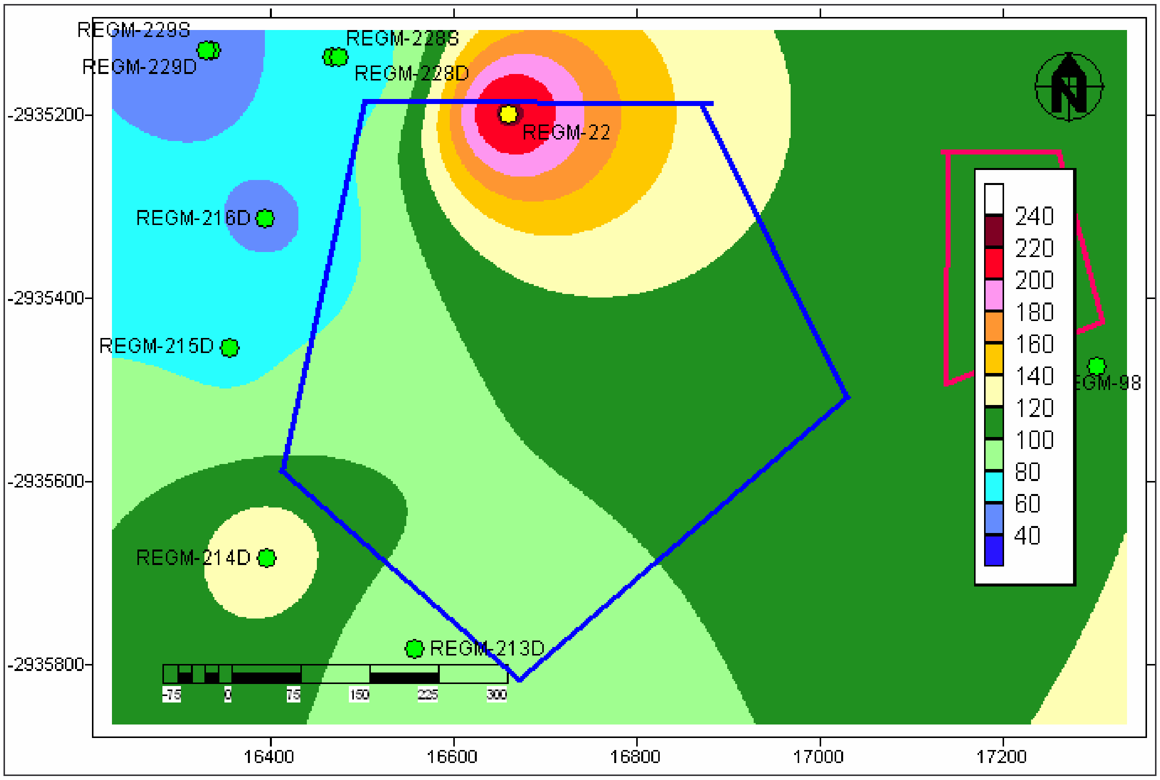

Figure 43: Observed electrical conductivity contours for all boreholes.

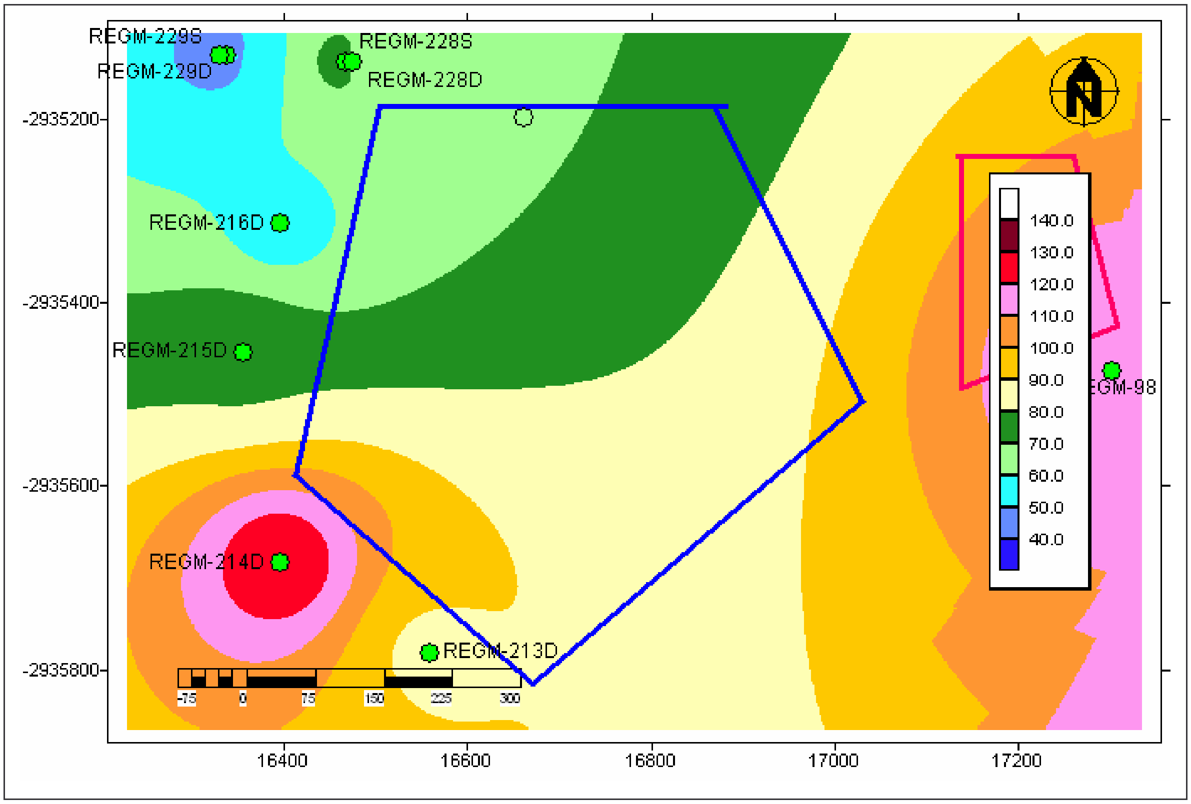

Figure 44: Observed electrical conductivity contours for all boreholes, excluding REGM 22

Figure 44 shows contouring of all the boreholes at the site, excluding REGM 22, indicating an elevated electrical conductivity value for Borehole REGM 214D in the southwestern region of the site, and REGM 98 upgradient to the east of the site.

The Piper diagram (Figure 45) shows all boreholes plotting between the Ca+Mg-Na+K facies and HCO_3-Cl+SO_4 facies. Changes occur within Borehole REGM 22, which changes to SO_4-HCO_3 due to a change in composition. The Durov diagram (Figure 46) shows REGM 22 with high electrical conductivity and SO_4 values indicative of water contamination. The Stiff diagrams (Figure 48) below indicate a close relationship (similar) of the water quality in the boreholes, with the exception of REGM 22 and REGM 213. The latter has elevated Na+K and Cl concentrations, but REGM 22 has a completely different signature.

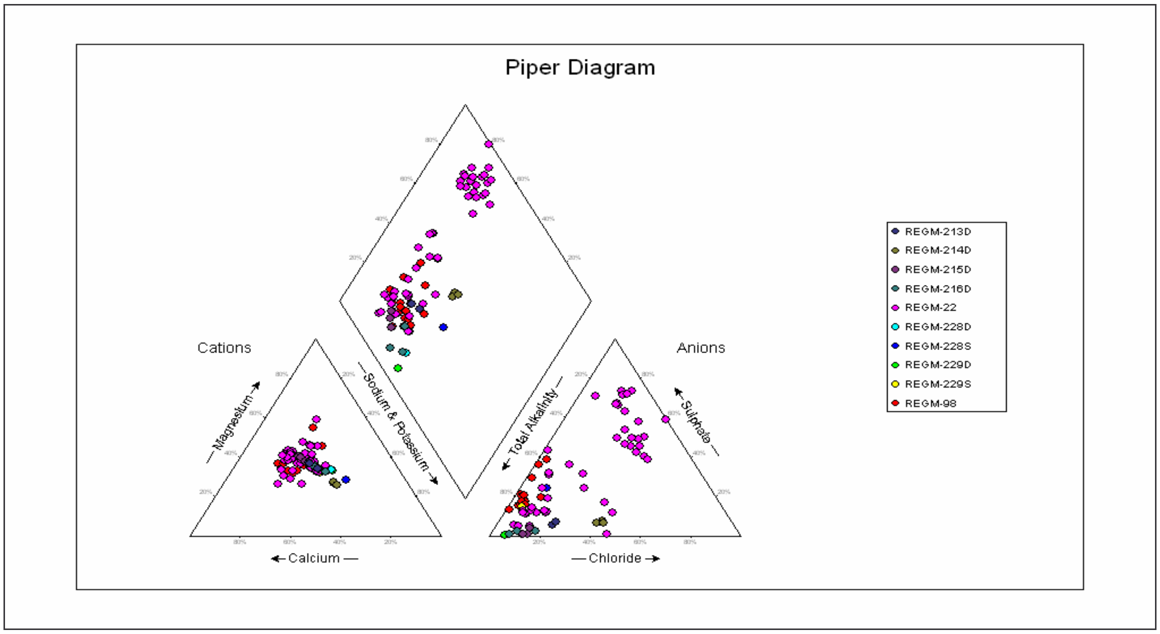

Figure 45: Piper diagrams for all boreholes.

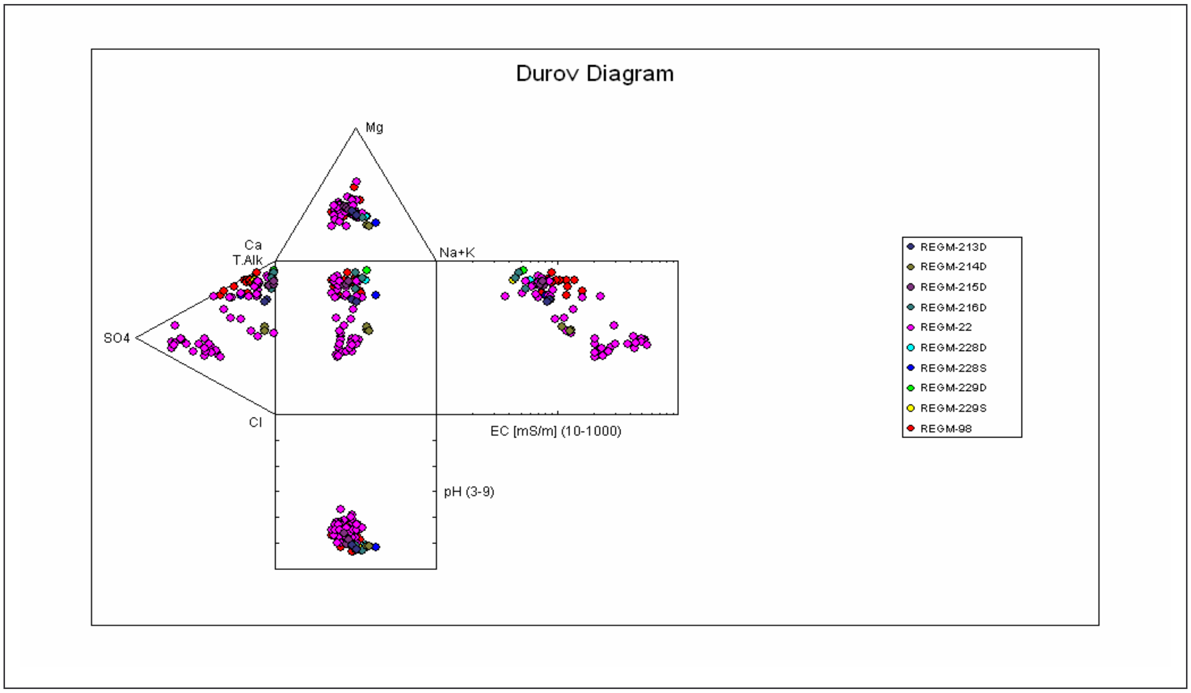

Figure 46: Durov diagram for all boreholes.

The variations observed in the Durov diagram (i.e. high SO_4^{2-} associated with high electrical conductivity, Figure 46) for Borehole REGM 22 are connected to the dilution of leachate by either groundwater or rainfall. Figure 47 shows a Durov diagram for REGM 22 and leachate samples, indicating a clear distinction between the leachate samples with high Cl concentrations and the borehole sample with elevated concentrations of SO_4^{2-}. The high SO_4^{2-} can be due to the ash used on roads in this region (Figure 46)

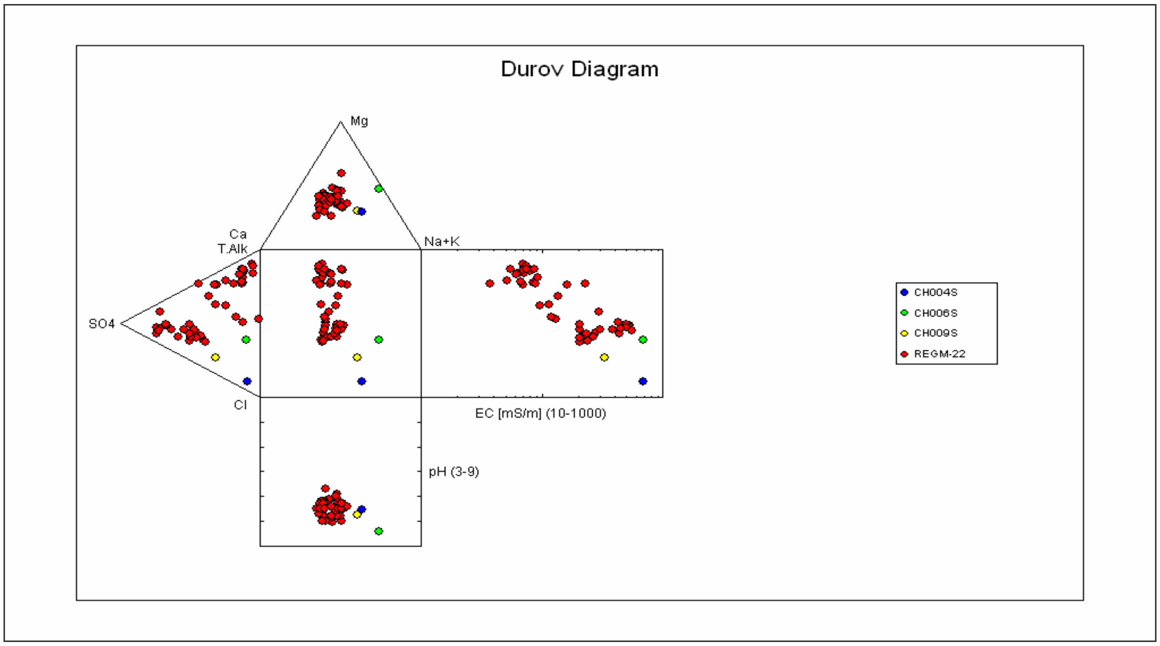

Figure 47: Durov diagram for Borehole REGM 22 and leachate samples.

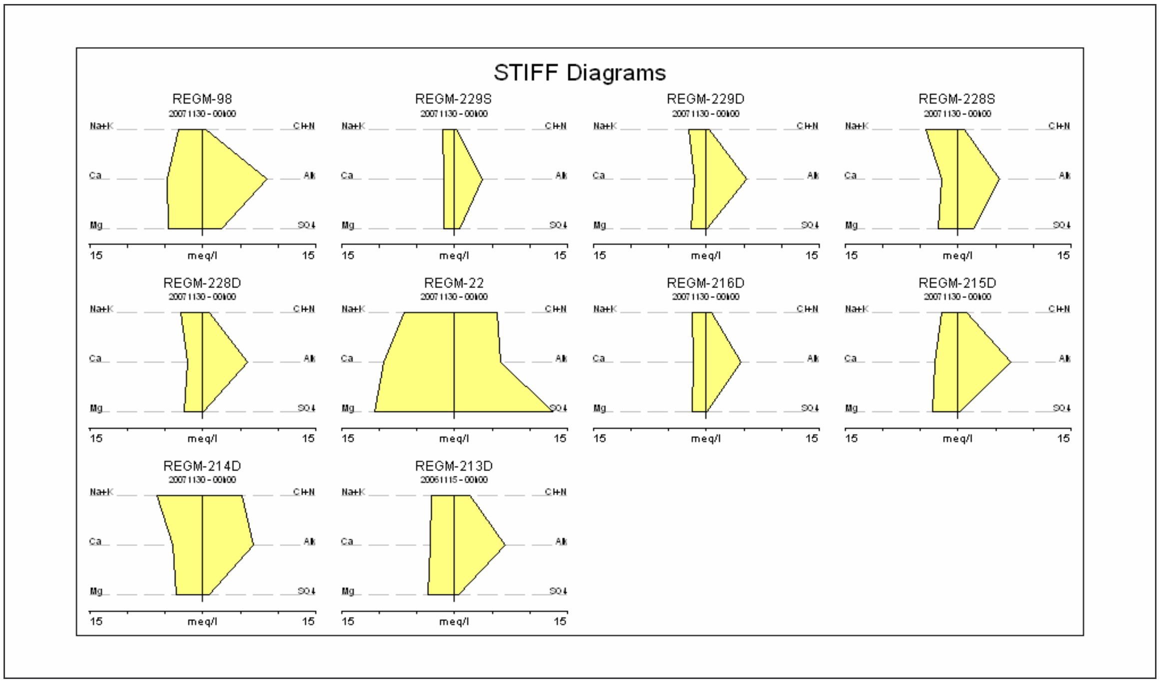

Figure 48: Stiff diagrams for all boreholes.

5.3.2.2. Trace Metals

Unlike the leachate samples, the boreholes detected very low concentrations of trace metals (Table 16), with most of these found in Borehole REGM 22. This indicates, as with the major ions, that this is the only borehole impacted by landfill activities.

Table 16: Boreholes trace metals (in µg/L) WHO (2006).

Number	**Ba**	**Co**	**Mo**	**Ni**	**V**
Guideline Value	700		70	70	
REGM-22	0.041	0.006	0.012	0.045	0.008
REGM-213	0.087			0.012	
REGM-214	0.11			0.005	

5.3.2.3. Organic Compounds

The presence of organic contaminants can be observed in almost all boreholes, and are within the USEPA drinking standards, with the exception of REGM 213 and REGM 214, both with high concentrations of trichloroethylene (TCE), a dense non-aqueous phase liquid (DNAPL). Table 17 shows the organic compounds found in groundwater at the Charlie I landfill site. The origin of the TCE could not be confirmed by the Waste Site Records.

The major ion and trace metal chemistry indicate that there is less migration of the contaminants into the subsurface (i.e. into the groundwater system). This could not be established for organic contaminants. This is influenced by the presence of DNAPLs below the water table (TCE, PCBs, etc.).

Studies on the fate and transport of DNAPLs in the subsurface indicate that their migration is not a function of groundwater transport (advection, dispersion, etc.) mechanisms, but rather a function of physical properties, geological structures and gravity (i.e. TCE passes through an intact flexible membrane landfill liner and clay, and is easily transported to the underlying groundwater system).

Table 17: Borehole organic compounds (in µg/L) USEPA (2003).

Organic Compound	Guideline Value	REGM 215	REGM 216	REGM 229	REGM 22	REGM 213	REGM 214
Benzene	5	0.2			0.1	0.2	0.2
Ethylbenzene	700	0.2		0.2	0.3	0.4	0.3
Toluene	1000	0.2	0.3	0.2	0.2	0.4	0.4
o-Xylene						0.1	0.2
m,p-Xylene						0.2	0.3
Xylenes (sum)	10000					0.4	0.4
Styrene	100					0.4	0.3
1,2,4-Trimethylbenzene						0.1	0.2
Tetrachloromethane					0.1		
Trichloroethene (TCE)	5	0.13	2.7	0.34	0.33	11	11
Bromodichloromethane	100	2					5.3
Dibromochloromethane		0.4					
Trichlorobenzenes (sum)	70					0.14	
PCB138				0.02			
PCB153				0.01			
PCB180				0.01			
PCB (6) (sum)	0.5			0.04			
PCB (7) (sum)	0.5			0.04			

5.3.3. Piezometer Water Quality

Twenty water samples were collected from shallow piezometers at different locations downgradient from the site (Figure 49), and analysed for major ion chemistry. All samples from piezometers in close proximity to the landfill site, indicate high electrical conductivity values in contrast to the piezometers sampled further away (Figure 49). The high electrical conductivity values indicate the presence of contaminants at the upper part of the soil horizon.

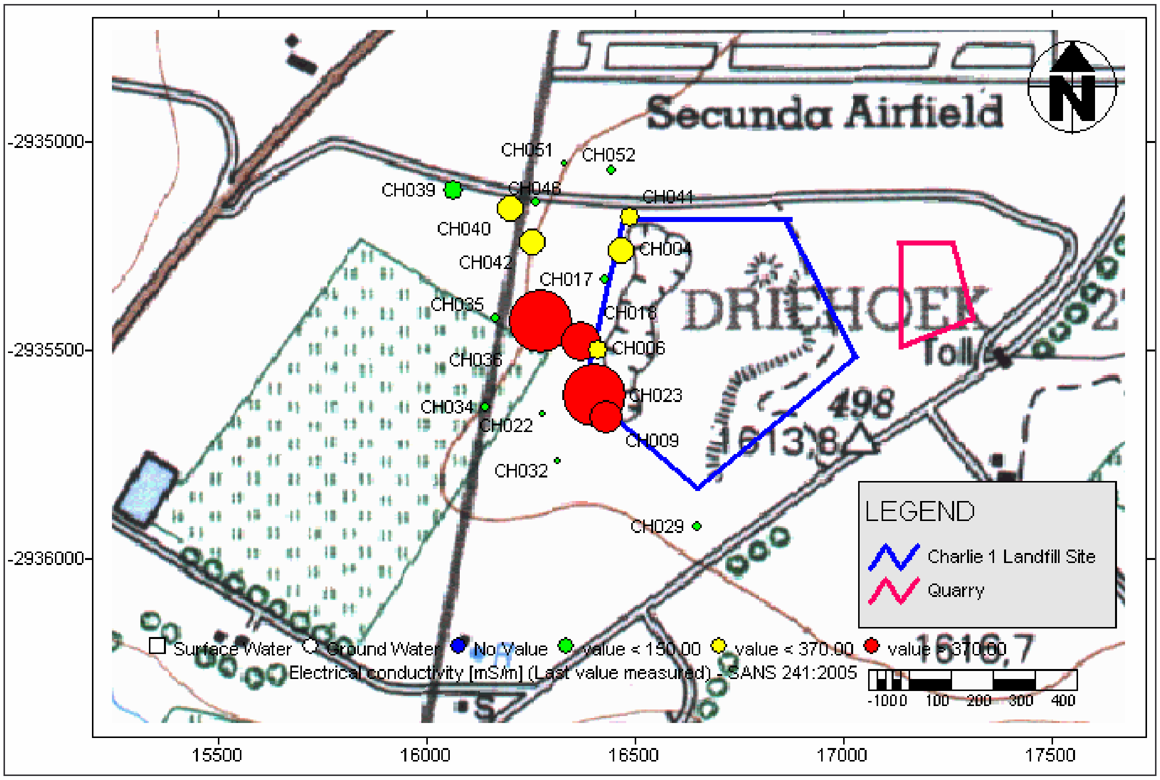

Figure 49: Positions of all tested piezometers (Electrical Conductivity).

5.3.3.1. *Major Ion Chemistry*

The chemical analysis of water samples from piezometers (Table 18) indicates that eleven piezometers have been contaminated by landfill activities. The level of contamination differs according to piezometer locality. Most of the piezometers located along the surface water run-off paths from the landfill reflect high concentrations of EC, Ca, Mg, Cl and SO_4. Piezometers CH022, CH029, CH032, CH034 and CH035, all located at the southwest of the landfill site, show high concentrations of Al, Fe and Mn, indicating a different type of waste at this part of the landfill.

Contouring chloride concentrations from all piezometers (Figure 50) indicates high chloride values in the area where leachate from the leachate springs at the sides of the landfill site flows as surface run-off. Water quality analyses from all piezometers indicate that the quality in each piezometer is influenced by the surface run-off, since the piezometer located outside these flow zones show low concentration levels of the analysed contaminants.

Table 18: Piezometers major ions (in mg/L, EC in mS/m) SANS 241:2005.

SiteName	pH	EC	Ca	Mg	Na	K	Malk	Cl	SO4	NO3(N)	F	Al	Fe	Mn	NH4
CH004	7.66	240.00	215.78	103.57	151.64	20.53	111.00	707.00	152.78	0.68	0.44	0.06	0.10	0.04	0.09
CH006	7.24	193.00	166.52	91.85	155.13	2.08	394.00	401.80	75.86	0.13	0.52	0.03	0.07	0.04	0.95
CH009	7.33	382.00	342.73	210.78	350.36	1.84	1047.00	745.00	405.49	0.11	2.02	0.24	0.16	14.38	1.17
CH017	7.04	68.30	53.57	29.47	32.48	6.30	70.20	134.00	38.33	3.21	0.21	0.10	0.08	0.02	0.07
CH018	7.66	416.00	278.64	159.32	504.12	0.58	331.00	1245.00	204.42	0.09	0.70	0.02	0.07	0.29	0.10
CH022	6.62	31.30	17.53	8.93	22.89	10.85	58.00	25.43	55.03	0.13	0.53	0.78	1.36	5.22	1.57
CH023	7.78	777.00	519.12	282.46	1150.45	17.78	309.00	1478.00	2406.00	2.54	2.10	0.12	0.07	0.04	0.17
CH029	7.26	60.30	22.05	12.62	105.60	1.22	250.00	23.87	25.98	0.08	1.30	0.57	0.49	0.43	1.03
CH032	6.73	17.30	10.60	4.87	44.69	3.42	242.00	8.13	8.27	0.22	0.28	2.88	2.99	0.41	1.14
CH034	7.63	53.10	52.48	24.35	40.02	16.23	283.00	25.42	8.55	0.15	3.14	1.37	4.61	4.83	1.21
CH035	7.12	50.40	164.64	70.28	84.46	12.14	739.00	26.43	3.24	0.02	1.27	0.33	2.56	16.14	0.92
CH036	7.83	654.00	248.73	209.27	1152.83	30.86	859.00	1304.00	1307.90	1.54	2.96	0.22	0.07	0.02	0.55
CH039	7.69	146.00	181.23	54.90	43.24	2.18	218.00	243.63	116.24	12.81	0.22	0.08	0.05	0.01	0.04
CH040	7.39	225.00	298.74	86.03	74.45	4.69	73.50	483.32	510.83	0.66	0.31	0.07	0.07	0.01	0.08
CH041	7.54	175.00	135.04	71.11	115.58	10.59	251.00	305.43	171.62	0.04	0.38	0.02	0.06	0.02	0.89
CH042	7.69	245.00	164.13	64.94	285.96	17.21	145.00	499.73	402.01	10.55	1.12	0.15	0.12	0.03	0.27
CH046	7.60	56.70	68.63	25.32	11.28	3.56	133.00	16.60	144.84	0.24	0.42	0.03	0.06	0.01	0.18
CH051	7.28	30.10	30.99	7.95	8.76	1.25	55.00	3.40	67.00	3.82	0.34	0.03	0.05	0.01	0.08
CH052	7.72	58.80	44.62	10.09	60.57	0.29	154.00	15.56	115.00	1.29	0.34	0.06	0.07	0.12	0.11

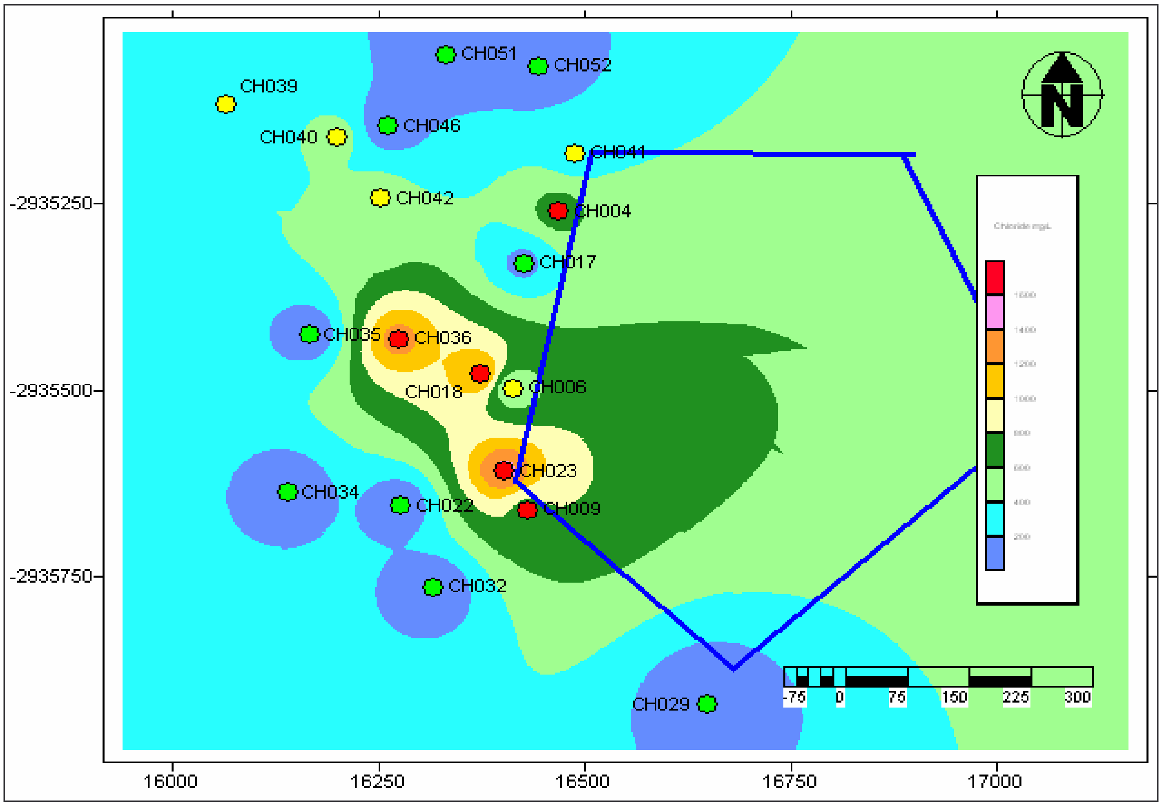

Figure 50: Observed Chloride plume from surface and piezometer samples.

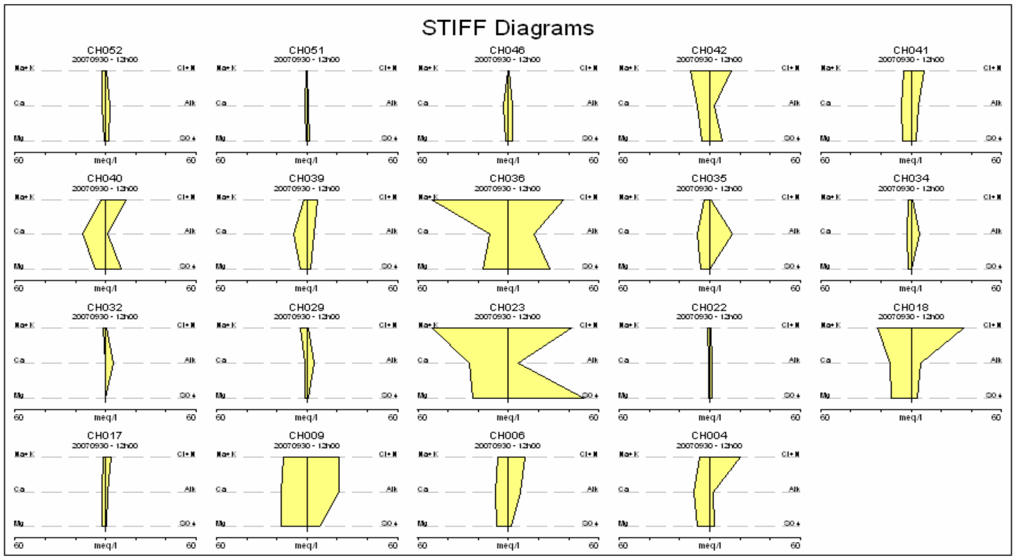

Figure 51: Stiff diagrams for all piezometers.

The Stiff diagrams (Figure 51) show the vast difference in piezometer water quality, thus demonstrating that different types of leachate have impacted the piezometer water quality. The Durov diagram (Figure 52) indicates that piezometer samples can be grouped into two groups with respect to the electrical conductivity, contaminated (with high EC) and uncontaminated (with low EC) samples.

The position of the contaminated group is illustrated clearly in Figure 49. Most of the contaminated piezometers are located in close proximity to the contaminated canal west of the landfill site. The canal runs on the surface in the northwest direction for approximately 200m and then disappears. Piezometers CH040 and CH042, located further in northwest of the canal, indicate a contaminated plume, while the other piezometers in that region detect no plume. The implication is that the plume is migrating further to the northwest in the subsurface (this may be enhanced by the presence of an underground pipeline in this region, detected to a small extent by magnetic survey), and could not be detected further. High extraction mining methods have been applied in the area (Figure 50 and also Figure 8); therefore the vertical migration of the plume is a possibility. No further movement in the horizontal direction (Figure 50) has been observed.

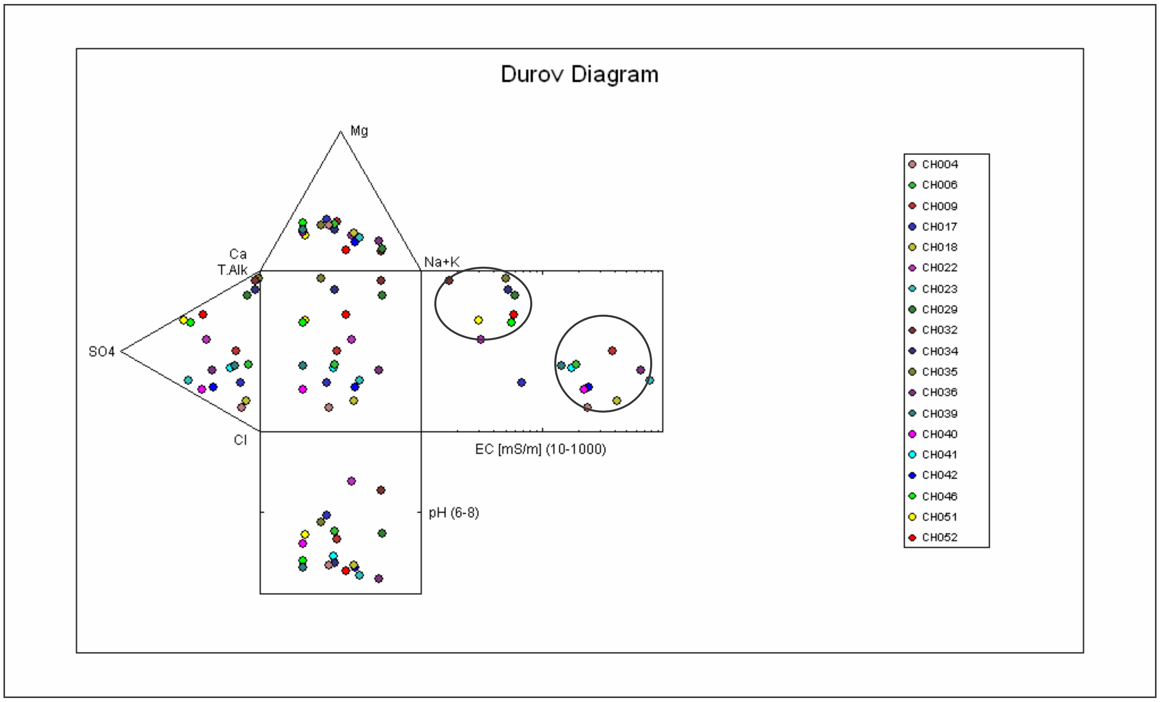

Figure 52: Durov diagram for all piezometers.

5.3.3.2. Trace Metals

Three samples from the piezometer were sent for a Terrattest 5.22 tracer metal and organic analysis (Table 19). Similarly to the boreholes, low concentrations of trace metals were detected (within the World Health Organisation (WHO) water quality standards, 2006), with the exception of the high Mercury (Hg) concentrations in CH023 at the immediate boundary of the landfill site.

Table 19: Piezometers trace metals (in µg/L) WHO (2006).

Number	**As**	**Ba**	**Cr**	**Co**	**Cu**	**Hg**	**Pb**	**Mo**	**Ni**	**Se**	**V**	**Zn**
Guideline Value	10	700	50		2000	6		70	70	10		3000
CH006		0.5		0.011			0.008	0.007	0.037		0.009	
CH017		0.46		0.007	0.005				0.11		0.012	0.012
CH023	0.006	0.069	0.003	0.008	0.037	0.1		1.8	0.14	0.047	0.026	0.014

5.3.3.4. Organic Compounds

Sample CH006 detected most of the organic contaminants (Table 20), but at acceptable concentrations compared to other sampled piezometers. The exception is the Trichloroethylene (TCE) detected in all three piezometers, and the high concentrations (i.e. above the USEPA standards) in sample CH006.

Table 20: Piezometers organic compounds (in µg/L) USEPA (2003).

Organic Compound	**Guideline Value**	**CH006**	**CH017**	**CH023**
Ethylbenzene	700	0.1		
Toluene	1000	0.2	0.2	0.2
Trichloroethene (TCE)	5	12	4.6	0.15
cis 1,2-Dichloroethylene		0.22		
1,1-Dichloroethane		0.19		
Pentachlorobenzene		0.007		
2,4/2,5-Dichlorophenol		0.02		
Dichlorophenols		0.02		
PCB52		0.02		
PCB101		0.01		
PCB118		0.02		
PCB138		0.01		
PCB153		0.01		
PCB (6) (sum)	0.5	0.06		
PCB (7) (sum)	0.5	0.08		

From the water quality analysis in the piezometers and the groundwater, as well as the soil analysis, it is clear that contamination originates from the surface leachate. The pollution is limited to the areas where this leachate occurs.

- The leachate quality of the surface water indicates early stages of the waste degradation process are taking place (i.e aerobic conditions still dominate). Different types of leachate are produced by the landfill, depending on the area and the type of waste involved.

- The groundwater and piezometer chemistry indicate limited vertical movement of leachate into the groundwater system, in close proximity to the landfill. However, the presence of high coal mining extraction zones at the northwest of the site and the subsequent disappearance of the contaminant plume in the piezometers of that region suggest vertical migration.
- Slightly elevated electrical conductivity values for Borehole REGM 214D in the southwestern region indicate the movement of groundwater towards the southwest; this corresponds with the topography contours.
- Trichloroethylene (TCE), a dense non-aqueous phase liquid (DNAPL), was detected in REGM 213 and REGM 214. The origin of the TCE could not be confirmed by the Waste Site Records.

6. Numerical Modelling of the Charlie I Landfill Site

6.1. Overview

A **model** is a pattern, plan, representation (especially in miniature), or description designed to show the main object or workings of an object, system, or concept (http://en.wikipedia.org/wiki/Model). Generally, models can be simply described as an approximation of an actual system and can either be physical (sand tank, column experiment, etc.) or mathematical (analytical, numerical, etc.). These are used as an idealised representation of the characteristics of a real system in order to understand the system's behaviour and/or predict future behaviour.

The use of numerical models has become widespread in the study of groundwater to investigate a wide variety of hydrogeologic conditions. Numerical models are useful for a visual description of hydrogeological processes taking place at the site and furthermore to predict the future behaviour of the groundwater system. They can also be applied to both complex and simple groundwater problems and can predict the transport of contaminants for risk evaluation (Anderson and Woessner, 1992).

Groundwater flow models describe the flow and transport processes by means of mathematical equations based on simplifying hypotheses that involve aquifer geometry, flow direction, sediment anisotropy or heterogeneity, contaminant transport mechanisms, and chemical reactions (Anderson and Woessner, 1992). For the Charlie I landfill site, the purpose of a groundwater flow and transport simulation model is to compute the concentration of a dissolved chemical species in an aquifer at any specified time and place. Steps involved include model conceptualisation, selection of computer code, model design, model calibration, model validation, prediction and results presentation (Anderson and Woessner, 1992).

6.2. Conceptualisation of the Groundwater System

In every model, the system under investigation is represented by a conceptual model. A conceptual model includes designing and constructing equivalent but simplified conditions for a real-world problem, which are acceptable in terms of the objectives of the modelling and associated management problems. Transferring the real-world situation into an equivalent model system allows the user to solve the problem with existing software; this is a crucial step in groundwater modelling. The following information is required for a conceptual model:

- The known geological and geohydrological features and characteristics of the area.
- The static water levels/piezometric heads of the study area.
- The effects of the geology and geohydrology on the boundary of the study area.
- A description of the processes and interactions that will influence the movement of groundwater within the study area, and
- Any simplifying assumptions necessary for the development of a numerical model and the selection of a suitable numerical code.

6.2.1. Charlie I Landfill Site Description

An important consideration is that the application of numerical simulation models to groundwater problems involves both art and science (Anderson and Woessner, 1992).

6.2.1.1. Physiography

The Charlie I landfill site is located in a relatively flat area, bounded by the Trichardspruit tributary in the north-northwest and the Klipspruit tributary in the south, flowing in an east-west direction and converging to become one streamFigure 53. The area forms a topographic high (1601 mamsl) to the two tributaries in the north and south (1572 – 1585 mamsl). Figure 54 shows north-south (A-B) and west-east (C-D) cross-sections for the Charlie I landfill site, with the two tributaries as boundaries.

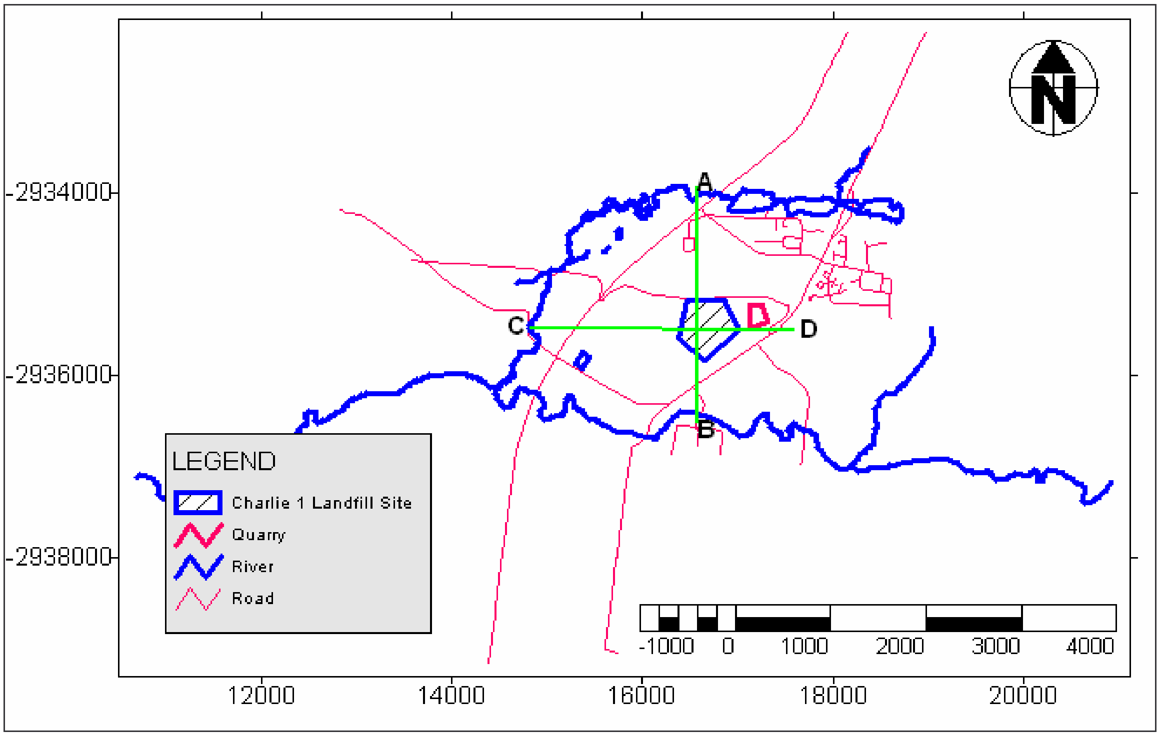

Figure 53: Plan view showing position of Charlie I landfill site bounded by the two tributaries (A-B and C-D are cross-section lines).

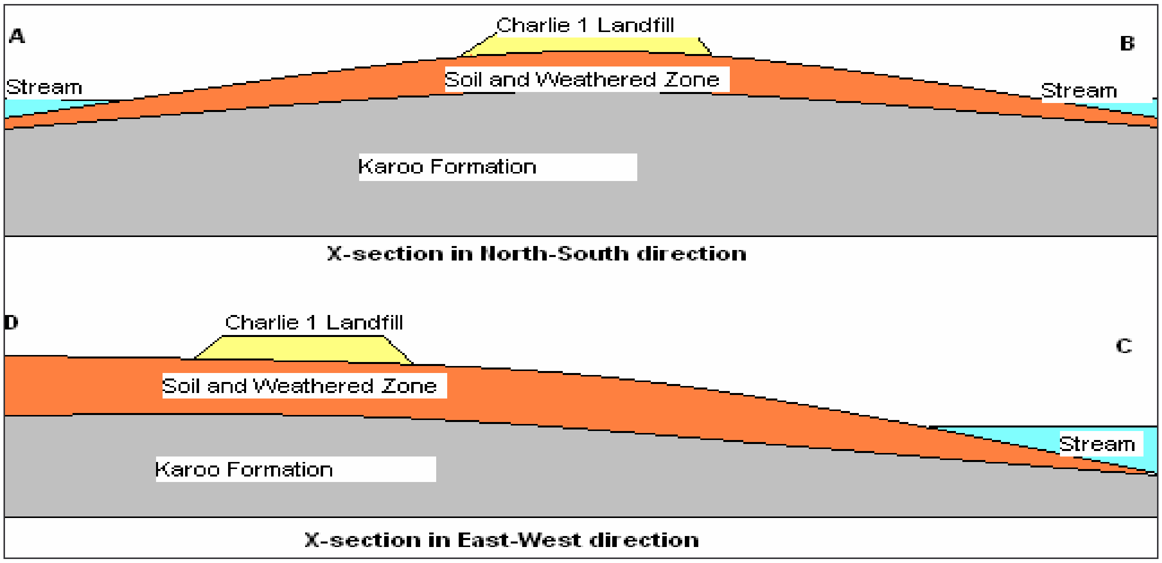

Figure 54: Cross-section of the locality of Charlie I Landfill site (not to scale).

6.2.1.2. Local Geology

The area is wholly underlain by sedimentary rocks of the Karoo Stratigraphic Sequence comprising of sandstones and shale intruded by the dolerite sills. The stratigraphy of the site is mainly composed of the top soil layers with varying thicknesses between 2 - 5 m, comprising mostly sandy loamy clays (Section 4.2.2.), overlying either shales (Figure 55) in the western region, or sandstones and dolerite to the east of the site. The dolerite sill to the east of the site has been formerly mined in the form of a quarry.

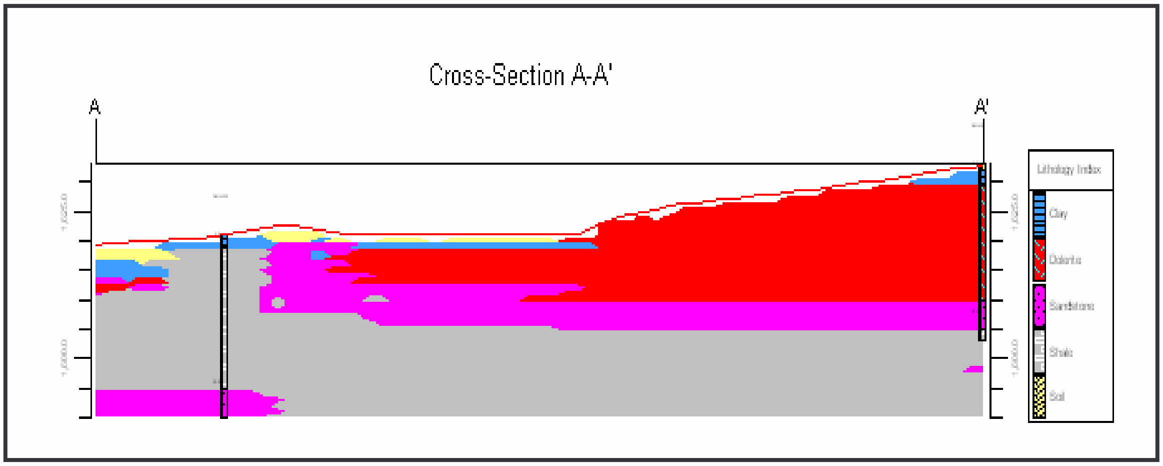

Figure 55: East (A') – West (A) Geological Cross-Section at Charlie I landfill site, created by Rockworks Software using existing borehole information.

6.2.1.3. Local Geohydrology

The Charlie I landfill site displays a disturbed hydrological system, with shallow water levels close to the site and deeper water levels with distance. The elevated water levels close to the site indicate the absence of the unsaturated zone in close proximity and underneath the landfill site. All boreholes recorded elevated water levels, except for REGM 98, 213D and 229D, with deeper water levels. Monitoring Boreholes REGM 23, 24, 25 and 26, located far away from the landfill site, also have deeper water levels. This trend is also observed with piezometers; all piezometers are located far from the site having recorded absence of water levels compared to the piezometers close to the site. The conclusion is that the regional hydraulic head has been disturbed by the presence of the landfill; therefore the hydraulic head closer to the landfill was elevated.

Test results (Section 4.4.) and soil analyses indicate that the upper aquifer system in the soil and weathered zone has an average hydraulic conductivity K-value of 0.0128 m/day, while the lower fractured aquifer system has a higher hydraulic conductivity value

(Section 4.4.2.1.). The transmissivity T-values obtained from the pump test indicate a low transmissivity value of 1.3 m^2/day, representing the T-value for the whole formation. The groundwater flow direction follows the topography (Section 4.3.1) in the direction of the drainage.

6.2.2. Proposed Charlie I Landfill Site Hydrogeological Conceptual Model

The hydrogeological conceptual model is based on the available data, with the main objective to promote a qualitative understanding of the site in terms of hydrology and hydrogeology. From the data analysis, the following site conceptual model could be constructed:

Seepage water flows from the northeast of the site along the dolerite sill in the direction of drainage, and mixes with waste. Since waste will have a higher hydraulic conductivity than the bottom clay layer, only horizontal flow is observed on the site (resulting in leachate springs on the western region of the landfill site). The water quality analyses of Boreholes REGM 215D and 216D indicate that there is an absence of leachate within the groundwater in this region.

The soil and water quality analyses of piezometers in this region indicate the substantial presence of leachate in the upper soil zone. **The conclusion is that the hydraulic properties of the underlying sediments are such that infiltration is limited. Consequently, the leachate formed at the Charlie I landfill site is largely discharged as surface seepage.**

The recharge in the Charlie I landfill site was determined by means of recharge maps for the area (Vegter, 1995). The chloride method could not be used in this instance, due to the higher chloride values derived from the landfill resulting in a very low recharge estimation.

Aquifer testing and geologic composition indicate the presence of two shallow aquifer systems on the site:

- To the northeast, the profile isassociated with a shallow weathered dolerite sill.
- The weathered, clayey profile in the southwest (low K-values) is associated with landfill with no secondary structures. The dolerite sill dips towards the west and the northwest; in the northwest the borehole logs do not confirm the presence of dolerite, in line with the magnetometer data.
- Borehole REGM 98 is in contact with the dolerite sill and has recorded higher K-values than the other boreholes on the site. Groundwater flow is associated with the contact zone of dolerite and sandstone. Sandstone forms a confined aquifer, bounded at the top by the dolerite sill and at the bottom by the shale horizon. This contact zone between sandstone and the dolerite might be located on the landfill site; the possibility a groundwater discharge zone at that region should be expected; the position of the landfill site hinders conclusions on the presence of this discharge zone; for the sake of the investigation, this will therefore be disregarded.

The correlation between the resistivity data at the south of the landfill site and the borehole logs (REGM 213 and 214) shows that the soil layer is deeper or more weathered in this region than in other areas of the site. Water quality analyses of the drilled boreholes in the region indicate relatively low concentrations of major and/or minor ion and trace metals, with limited changes compared with the background REGM 98, although significant changes can be observed with respect to organic compounds. The presence of elevated TCE associated with other organic compounds demonstrates that there is a downward migration of the contaminant plume in the region. The observed higher electrical conductivity obtained from resistivity surveys may also be associated with the presence of more saline fluids within the pore spaces in the region.

Rainfall water, seepage water along the dolerite sill, and water derived from the landfill processes mix with waste, resulting in an elevation of water levels inside the landfill site and areas in its close proximity. Soluble ions are leached from waste by water, resulting in leachate formation. Since the landfill has a higher hydraulic conductivity than the underlying soil layer, the resulting fluids discharge as leachate springs, with a high concentration of the dissolved solids on the boundary of the landfill site. The leachate discharge is dependent on rainfall (i.e. it increases during high rainfall seasons, and limited flow is observed during dry seasons). The migration rate is limited by the underlying soil layer with high clay content. The presence of secondary structures (e.g. fissures, cracks) results in vertical downward migration of compounds such as DNAPLs.

6.3. Numerical Modelling

Numerical models are approximations that describe real systems or processes by means of mathematical equations; they are not exact descriptions of the actual system. For the Charlie I landfill site, a groundwater flow simulation model was created to be used as the flow field for particle tracking and solute transport simulation, in order to identify the pathways and receptors for leachate derived from the site. This exercise can assist in the identification of contamination sources and provide estimates of the time, magnitude and location of the contaminant occurrence/plume.

6.3.1. Modelling Software Selection

A modular three-dimensional finite difference groundwater flow model (MODFLOW), developed by United States Geological Survey (USGS), in the PMWIN programme, has been adopted for simulating the saturated groundwater flow in the vicinity of the Charlie 1 landfill site, and to predict future contaminant loading at the site. MODFLOW is simple to use (especially for USGS codes), widely used internationally, can simulate steady- and transient-state flow in an irregularly shaped flow system in which the aquifer layers can be either confined, unconfined, or both confined and unconfined, and is mathematically efficient.

The simulation model (MODFLOW) used in this modelling study is based on three-dimensional groundwater flow and can be described by the following equation:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t}$$

Where,

- K_{xx}, K_{yy} and K_{zz} = hydraulic conductivity along the x,y and z coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity (L/T),
- h = potentiomatric head (L)
- W = volumetric flux per unit volume and represent sources and/or sinks of water (1/T)
- S_s = specific storage (1/L), and
- t = time (T)

The K and S_s are allowed to be heterogeneous and anisotropic. This equation describes non-equilibrium groundwater flow.

6.3.2. Assumptions and Limitations

For the appropriate model development of an aquifer system, certain assumptions are necessary. The following assumptions were made to develop the model:

- The aquifer system can be represented by a simplified system, consisting of one layer. The geometry and thickness of this layer are obtained from geological and hydrogeological data collected in the field,
- The hydraulic conductivity (K-values), transmissivity (T-values) and storativity were measured from the field data,
- The dispersivity values were estimated from the literature (Spitz and Moreno, 1996),
- Recharge was derived from the literature (Vegter, 1995),

- Rivers are treated as Dirichlet boundaries,
- The Karoo formation is represented as one layer (i.e. fractures and/or stratification were not taken into consideration), and
- There are no groundwater extraction/abstraction zones.

6.3.3. Model Input Parameters

The quality of a groundwater numerical model output depends largely on the quality of the data used for input into the model.

6.3.3.1. Discretisation

A grid network was constructed for the area with number of columns (230 x 20m) and number of rows (167 x 20m), with the X_0Y_0= (14320, -2933821), X_1Y_1= (14320, -2937085) and X_2Y_2= (18852, -2933821). The network extends over a larger area, covering the two streams at the north and south of the site, converging in the east to form one stream. The model network extends over a larger area than the area under investigation, to ensure that the model boundaries do not affect simulated results.

6.3.3.2. Layers and layer construction

A one-layer system was constructed for the model, with the top of the layer represented by the ground surface (topography) and the bottom assigned at 1500 mamsl. This layer is formed by a confined aquifer (type 0) and comprises the Karoo system with user-defined transmissivity values.

6.3.3.2.1. Boundary Conditions

A model boundary is the interface between the model area and the surrounding environment. Boundaries in groundwater models can be specified as:

- Dirichlet (also known as constant head or constant concentration) boundary conditions
- Neuman (or specified flux) boundary conditions

- Cauchy (or a combination of Dirichlet and Neuman) boundary conditions

A constant head (Dirichlet) boundary was defined for the rivers in the north and south of the Charlie I landfill site and the other locations over the rivers were assigned as inactive cells.

6.3.3.2.2. Initial Hydraulic Heads

Point values for geohydrological parameters (e.g. T, S and water levels) are obtained from boreholes, which are usually sparsely spread over an area of interest. To obtain estimates for these parameters at points where no boreholes exist, an interpolation technique must be used. Usually Kriging is used for the interpolation of T- and S-values at unknown points of interest. Because the water level in an aquifer usually tends to mimic the topography, this extra information could be used for interpolation at unknown points (with the method of Bayesian estimation or co-Kriging, where other information is used as qualified guesses for water levels).

The data for x, y, z and water levels are provided for each borehole at the Charlie I landfill site, and a plot of topography vs. water levels (Section 4.3.1.) yields a straight line, indicating a good correlation. Since the correlation is good, a Bayesian estimation is achieved using Tripol and estimations could be made of areas where no information on water levels is available. The initial hydraulic heads for the model simulation used the actual water levels measured in the area, combined with Bayesian Interpolation and applied to the model area using the Field Interpolator function in PMWIN.

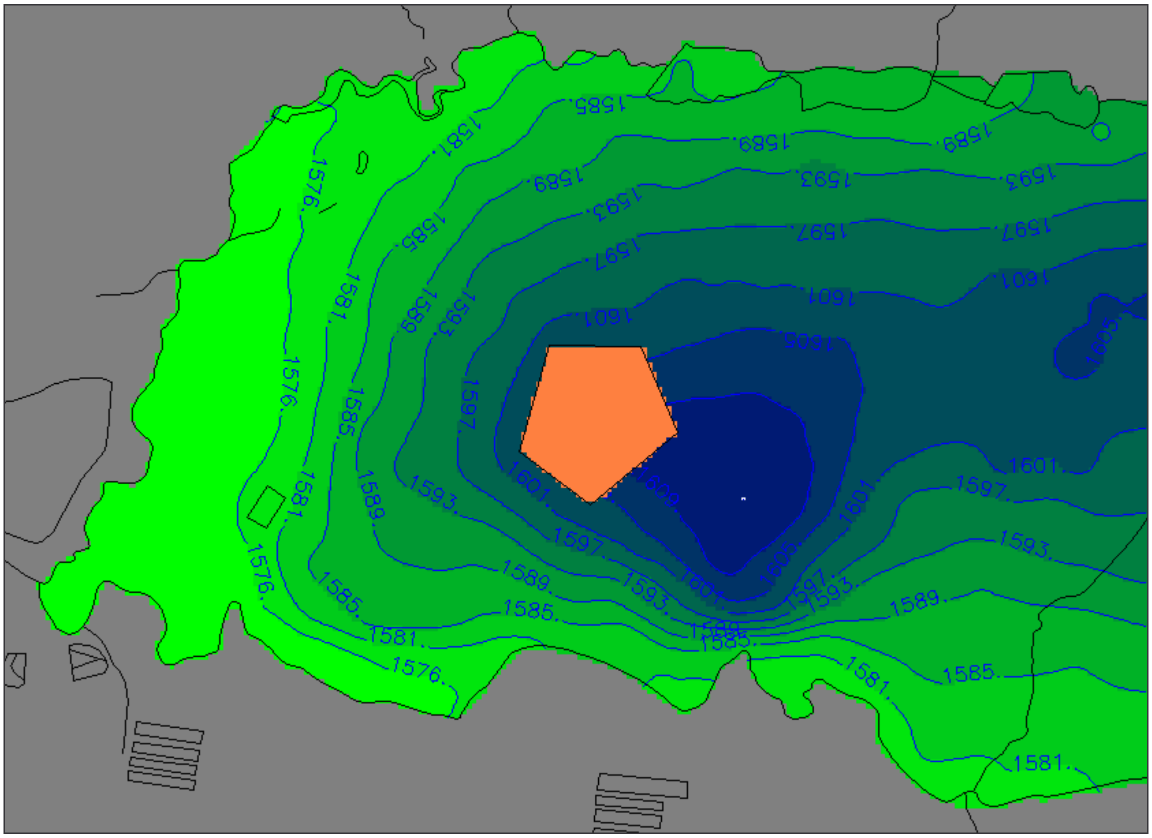

Figure 56: Interpolated Initial Starting Heads.

6.3.3.2.3. Aquifer Parameters

The model demands that each aquifer parameter be defined according to the type of aquifer system that each layer represents. It should be noted that MODFLOW uses the assigned parameters according to the layer types (i.e. type 0 - confined and type 2 - confined/unconfined uses constant transmissivity throughout the modelling process and the type 1-unconfined and type 3 - unconfined/confined uses the hydraulic conductivity with transmissivity values that vary, depending on the saturated thickness of the aquifer, (Chiang and Kinzelbach, 1998).

A value of 1.3 m^2/d for transmissivity, obtained from the pumping test analysis, was initially assigned to a layer representing the modelled aquifer. The initial horizontal was assigned at 0.013 m/day.

6.3.3.3. Mass Transport Parameters and Modelling

Mass transport modelling refers to the simulation of water contamination or pollution plume due to deteriorating water quality in response to man's disturbance of the natural conditions. The MT3DMS Mass Transport model package in the PMWIN modelling programme was used to simulate the movement of pollutants from the source. The initial input requirements are the initial contaminant concentration, transmissivity values, porosity values, longitudinal and transverse dispersivities and the hydraulic heads in the aquifer over time.

An initial concentration of 100% was assigned for the Charlie I landfill site (since the landfill contains different waste types, any contaminant concentration at any time and space can be estimated using its initial concentration in waste). One of the biggest uncertainties encountered during the transport modelling of pollutants is the kinematic/effective porosity of the aquifer. An effective porosity value of 0.02 was assigned to the model.

A transmissivity value of 1.3 m^2/d was utilised during mass transport modelling, and a longitudinal dispersivity value of 50 m for simulation (Spitz and Moreno, 1996). Bear and Verruijt (1992) estimate the average transverse dispersivity to be 10 to 20 times smaller than the longitudinal dispersivity; therefore a transverse dispersivity value of 4 m was used for the model. Hydraulic heads were assigned as constant heads throughout the mass transport simulation. The results of the mass transport model are shown in the figures below.

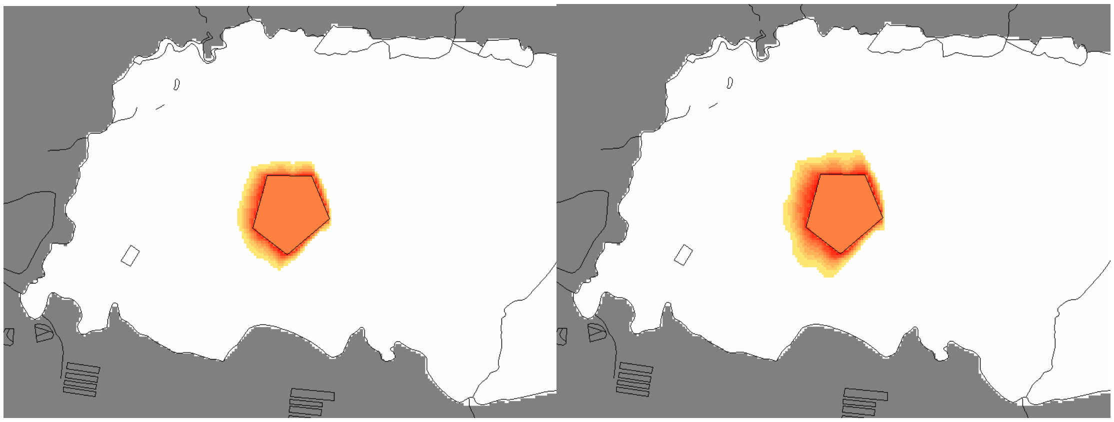

Figure 57: Plume development after twenty years (left) and forty years (right).

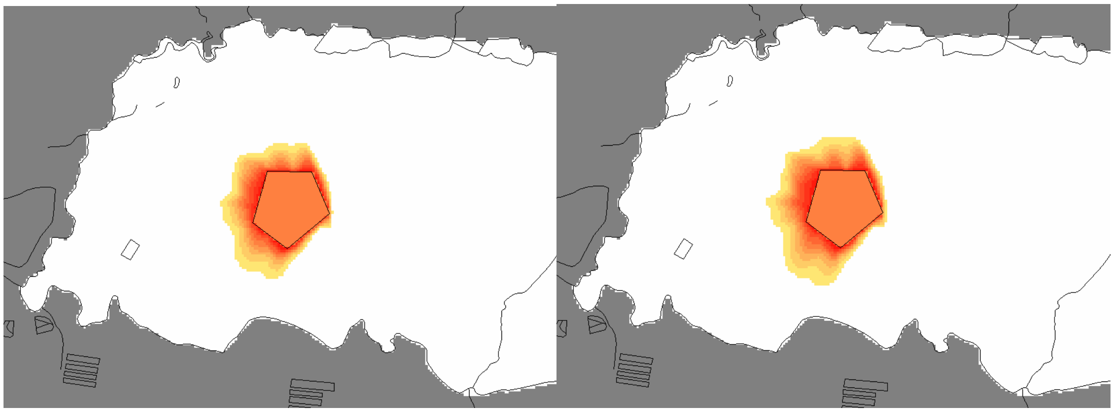

Figure 58: Plume development after sixty years (left) and eighty years (right).

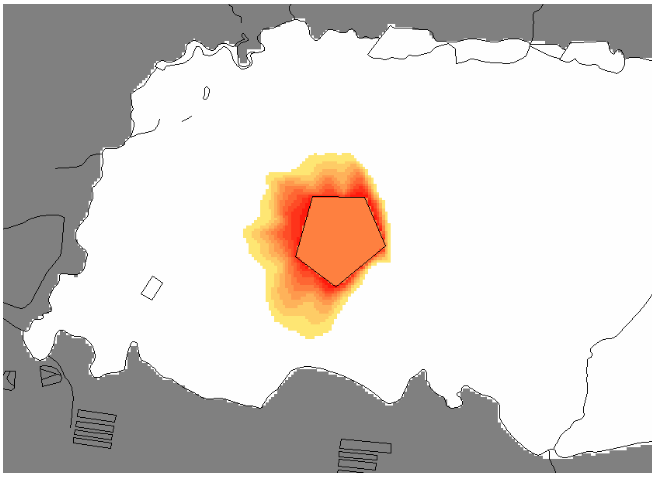

Figure 59: Plume development after one hundred years (right).

Figure 57, Figure 58 and Figure 59 show the simulated plume development from the Charlie I landfill site over the period from year 20 to year 100, with the first two plumes indicating years 20 and 40 and thereafter year 60, 80 and 100, respectively. The lateral movement is very slow, with no pollution reaching the two streams after one hundred years. The developed simulated plume after twenty years is representative of the current plume developments at the landfill site, with the plume more concentrated in the immediate vicinity of the site.

7. Conclusions and Recommendations

7.1. Conclusions

The primary objectives of the study were to determine the interactions between the domestic landfill site and the aquifer below, and also to investigate the current impacts of the site on the underlying aquifer, thus enabling a prediction of the degree of future contamination. The above objectives have been achieved by applying various field and laboratory experiments to assemble and evaluate information from the site in terms of its geological, geohydrological, and chemical properties.

The Charlie I landfill site is located near the main gate at Sasol Synfuels-Secunda and covers a pentagonal structured area of 25 ha. The site has been mainly used for disposing of the general waste generated by Sasol at the refinery plant. There are no historical records for waste disposal at the site, but it is estimated that the site has been in operation for almost twenty years. The results provide the findings of the study, based on the initial objectives.

7.2. Results

- **Site Classification**

The Charlie I landfill site has been classified as a **GMB$^+$** landfill site (i.e. receiving **G**eneral waste, **M**edium size and with positive climatic water balance **B$^+$,** producing significant amount of leachate), based on the field observations. The reason for this is that the waste field capacity of the landfill site having been reached. Any rain water infiltrating the site will result in leachate springs at the side of the landfill.

- **Soil Properties**

The average soil thickness in the area is 3m, containing between 30 – 70% clay (i.e. sandy clays), with the estimated upper limits of hydraulic conductivity values (estimated from laboratory at K-value = 0.0128 m/d) indicating that contaminant transport from the site will be retarded by soils.

- **Geology**

The Charlie I landfill site is located either on the contact zone between the dolerite sill and the underlying sandstone, or only on the sandstone and shale contact zone, due to minor dip that affects the sedimentary layers.

- **Water Levels**

A higher water table is observed due to the presence of the landfill site, indicating that landfill site has impacted on the natural water level conditions on site.

- **Aquifer Parameters**

The initial estimates of transmissivity values obtained from the blow yields for the region are in the range of 1.4 – 2.75 m^2/day. The horizontal hydraulic conductivity (K-values) obtained for boreholes and piezometers show similar values, with the exception of REGM 98 and REGM 229D, which have higher K-values; this indicates the presence of fractures or weathering. The transmissivity (T-value) of 1.3 m^2/day in all the tested boreholes represents the T-value for the formation. Varying storativity (S-values) signifies that water is not withdrawn from the same aquifer.

- **Soil Quality**

All soil samples indicate higher than allowable concentrations of trace metals in the soils and eight samples tested positive for organic compounds. Samples CH036, CH007 and CH023 indicated the most organic compounds, which is attributed to their locality with respect to the contaminated canal (i.e. seepage flow).

- **Leachate Quality**

The leachate quality exhibits low contents of NO_3^-, NH_4, Mn, Fe and higher SO_4^{2-}, indicating that neither early nor later stages of general waste degradation processes are taking place. This indicates a different type of waste to general waste. The Stiff diagrams indicated that the site produces different types of leachates, depending on the area type of waste leached. All the trace metals in the leachate samples were within the prescribed

World Health Organisation (WHO, 2006) Volume I drinking water quality standards. Low organic contaminants were detected.

- **Groundwater Quality**

Down-the-hole geochemical borehole logging results indicate changes in the oxidation reduction potentials (ORP) and in aquifer conditions with depth. Borehole REGM 22 is located in the path of the northern contaminated canal, indicating a higher concentration of major ions. Contouring of electrical conductivity show that the borehole has been contaminated with leachate. REGM 22 is the only borehole with trace metals, and as in the case of the other major ions, indicates it as the only borehole impacted by leachate from the site. It may also be influenced by the ash filling of the adjacent road.

Organic contaminants are detected at very low concentrations in most of the boreholes, with exception of TCE at REGM 213 and 214. The major ion and trace metal chemistry indicates that there is limited migration of the contaminant plume into the deeper aquifer, although organic contaminants indicate possible vertical contaminant plume migration. This is dependent on the properties of the contaminant (e.g. DNAPL's). The origin of the TCE could not be confirmed by the Waste Site Records.

- **Piezometer Water Quality**

The water quality of the piezometers located close to/along the contaminated canal (seepage flow) paths from the landfill, reflects high concentrations of EC, Ca, Mg, Cl and SO_4, indicating surface water rather than groundwater contamination.

Water quality analyses have shown that the Charlie I landfill site produces significant amounts of leachate. The quality of leachate indicates that the landfill site is neither undergoing early nor late stages of general waste degradation. This conclusion is based on the water quality data obtained during the rainfall season in the Secunda region; rain water percolating through the waste would have an impact on the quality of leachate produced. The quality of leachate and the stage of waste degradation period are not well represented by these samples. The different concentrations of contaminants in the leachate reflect the diversified nature of the waste.

Most of contaminants have been detected in samples from areas in the vicinity of the regions where leachate from the leachate springs at the boundaries of the landfill site run off as contamination canal (seepage flow), with very minimal detection in the groundwater (borehole) samples, except for organic contaminants. Organic contaminants were detected at very low concentrations (i.e. allowable) in all samples, with the exception of TCE. In the region to the south of the landfill site, high levels of Al, Mn and Fe were detected in the piezometers; these ions have also been detected in the seepage stream south of the site.

- **Modelling Results**

The model illustrated very slow lateral contaminant migration to the western part of the landfill site, with less than 500 m of movement over 100 years.

7.3. Discussion

The Climatic Water Balance (CWB) method indicated that the Charlie I landfill site is **GMB$^-$** (the site will not produce significant amounts of leachate). This limits the method, since information obtained during the field investigation indicate that the site is **GMB$^+$** (produces significant amounts of leachate). The conclusion is that this method does not hold for all sites, and it is dependent on the field capacity of the waste (i.e. whether it has been reached or not).

Other factors that might contribute to the waste reaching its field capacity is an increased head of the landscape, with the flow of water from the high-lying east (mainly dominated by dolerite sill), as well as the water-filled quarry to the east, result in seepage from the waste site even in drier periods. This results in the elevated water levels observed at the site.

The physical properties of soils in the area adjacent to the site indicate a high clay content; therefore retardation (by biochemical reactions, sorption, cation-exchange etc.) of contaminants will occur, with only very small quantities reaching the groundwater. Observation of leachate springs at the sides of the landfill and low levels of contaminant concentrations in the groundwater samples indicates that little movement of the contaminant plume occurs in the vertical direction. The conclusion, based on field and laboratory investigations, indicates that leachate produced by the landfill site, due to the high clay content of the underlying soil horizon, will not infiltrate into the groundwater system, but is discharged as seepage water (i.e. leachate springs) at the sides of the landfill. The presence of TCE in the groundwater is mainly due to the contaminant's physical properties compared with the soil physical properties that will affect its transport mechanism in the subsurface. The landfill site should also have little effect on the water in the underlying mining areas (except in the high extraction area, where small quantities of leachate may infiltrate into the mine workings) due to the dominant lateral movement of the leachate in the upper soil zone, the small vertical K-value and the clayey nature of the soil, increasing the retardation process, but further investigations should focus on areas where high extraction methods are applied.

The soil quality (in terms of land use: Dutch Guidelines) shows higher than optimum, but lower than action concentrations of trace metals; indicating that the leachate from the landfill site has a pH that is close to neutral, and metals have therefore not been leached and transported from the landfill. The leachate quality shows high concentrations of Cl^-, SO_4^{2-}, Ca^{2+}, Mg^{2+}, and Na^+ ions, with very low NO_3^- and NH_4, indicating an increase in reducing conditions; and therefore intermediate stages of waste degradation. The water quality of REGM 22 indicates a reversal in reducing conditions as leachate enters the oxic aquifer, with increased NO_3^- and SO_4^{2-}, indicating that leachate mixes with groundwater, and that the redox potential that is similar to REGM 98 (background value). The conclusion is that the waste has not undergone all the stages of waste degradation.

Groundwater modelling indicates that pollution from the Charlie I landfill site will not reach surface receptors over a period of 100 years. The conclusions is that the landfill site poses a low risk to surface and groundwater resources in the region.

7.4. Recommendations

- Leachate from the site will be decreased by the rehabilitation of the upgradient quarry. The area must be shaped to channel run-off away from the waste site.
- Cut-off trenches must be constructed downgradient from the site. This will minimise the influence of leachate on groundwater pollution; this study has indicated that most of the contamination results from leachate springs.
- A detailed historical inventory of the waste, and especially organics dumped at the site, should be traced. This will enable the researcher to determine the origin of organic pollution, and especially TCE.
- Future expansion of the waste site should preferably be to the west. There are no geological structures to enhance the movement of leachate downwards towards the mining area. The sill is also much deeper in this area and dips towards the north. The sill should be intact due to the bord-and-pillar mining, and would also act as a barrier to any vertical movement of contaminated groundwater.

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9. Appendix 1: Geophysical Surveys

9.1. Appendix 1: Magnetic Survey

Traverse A-B

This traverse runs in the north-south direction parallel to the landfill site. The traverse indicates no change in magnetic character along this line, thus implying no major structures encountered in the area.

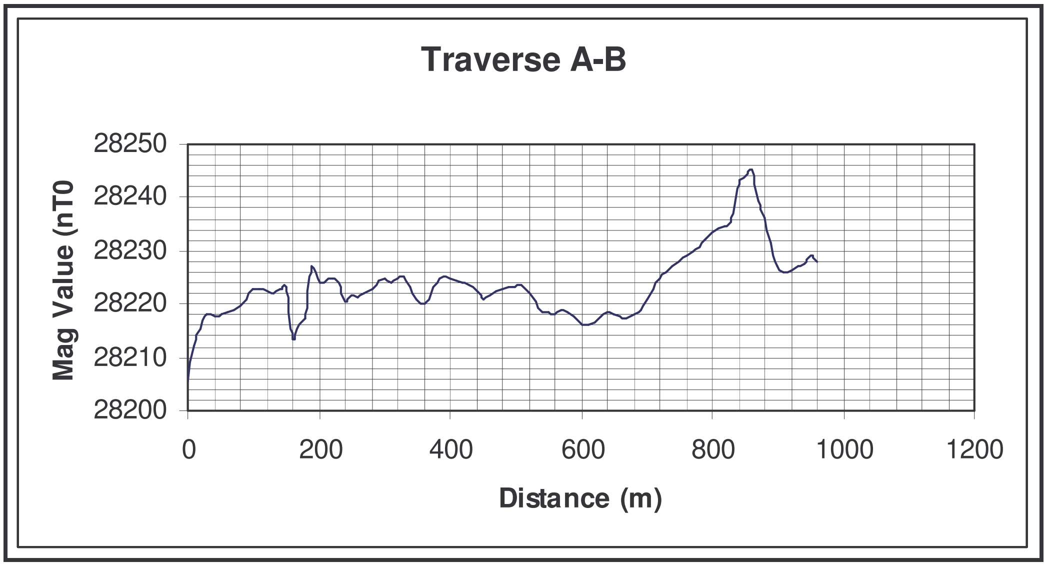

Figure 60: Magnetic traverse A-B.

Traverse C-D

The traverse runs parallel to the landfill site in the south-north direction. There are no major structures encountered on this line, but gradual change in magnetic character of the area.

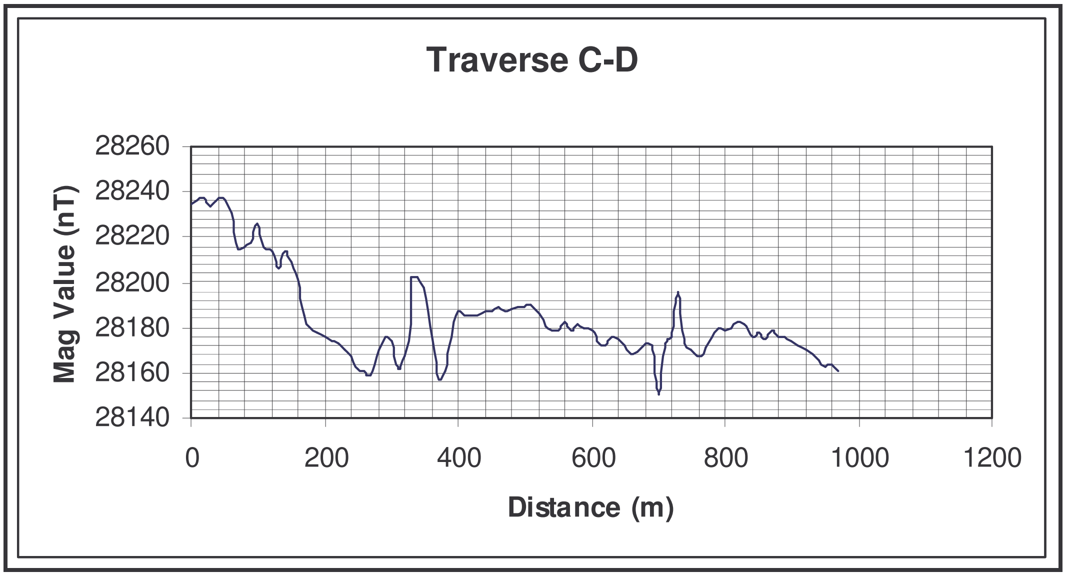

Figure 61: Magnetic traverse C-D.

Traverse E-F

This runs in the north-south direction. The erratic change in the magnetic properties at station 560 – 640m indicates the presence of pipeline at that position.

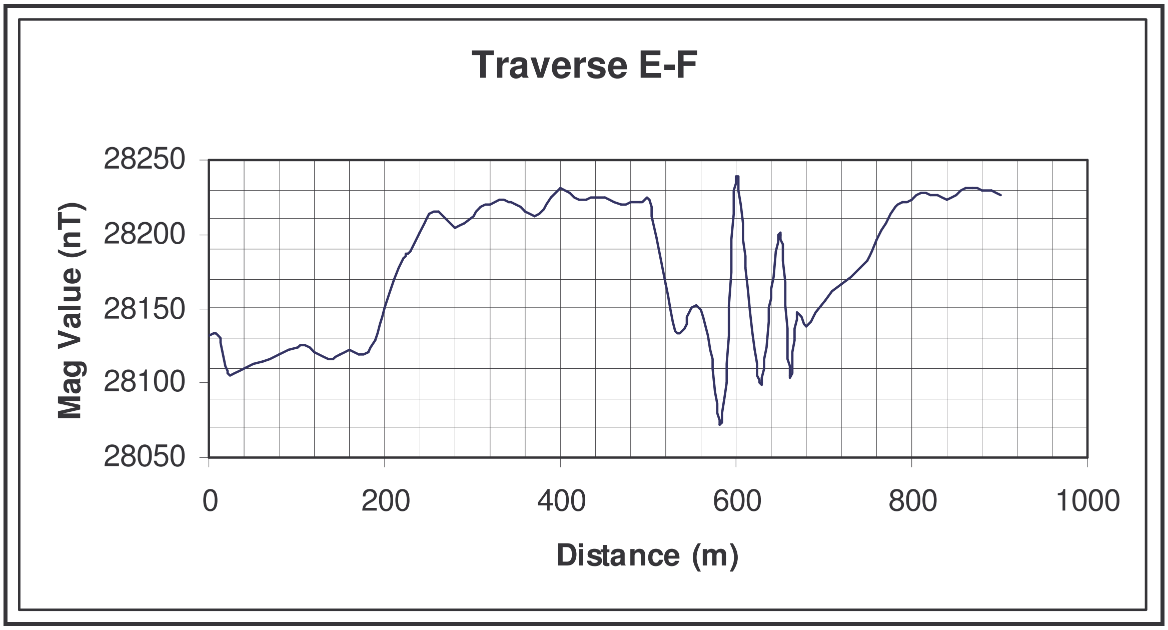

Figure 62: Magnetic traverse E-F.

Traverse G-H

Traverse in south – north direction, has no major in magnetic characteristic, but the change (decrease) in areas magnetic field at 590 – 610 is due to the presence of wire fence in that region.

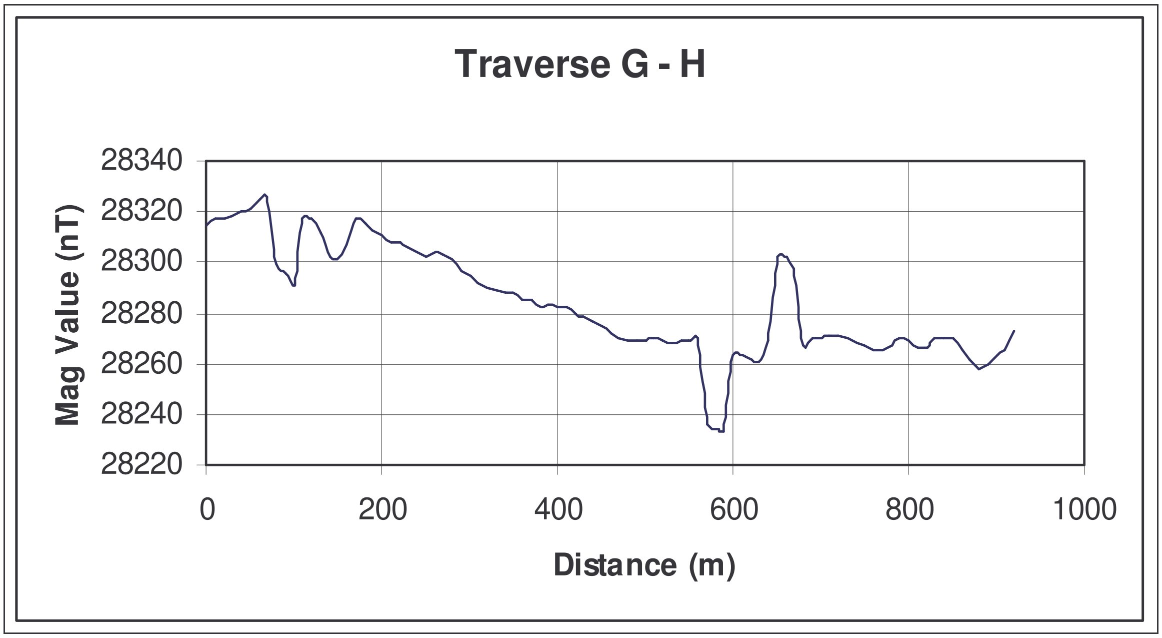

Figure 63: Magnetic traverse G-H.

Traverse I-J

The traverse is run parallel to the landfill site in the north-south direction, next to the boreholes REGM216. A change in magnetic properties is observed at 280 – 340m. This can attributed to the borehole casing in the vicinity.

Figure 64: Magnetic traverse I-J.

Traverse K-L

Continual of the line of traverse I –J, south of the landfill site show no changes in the areas magnetic field.

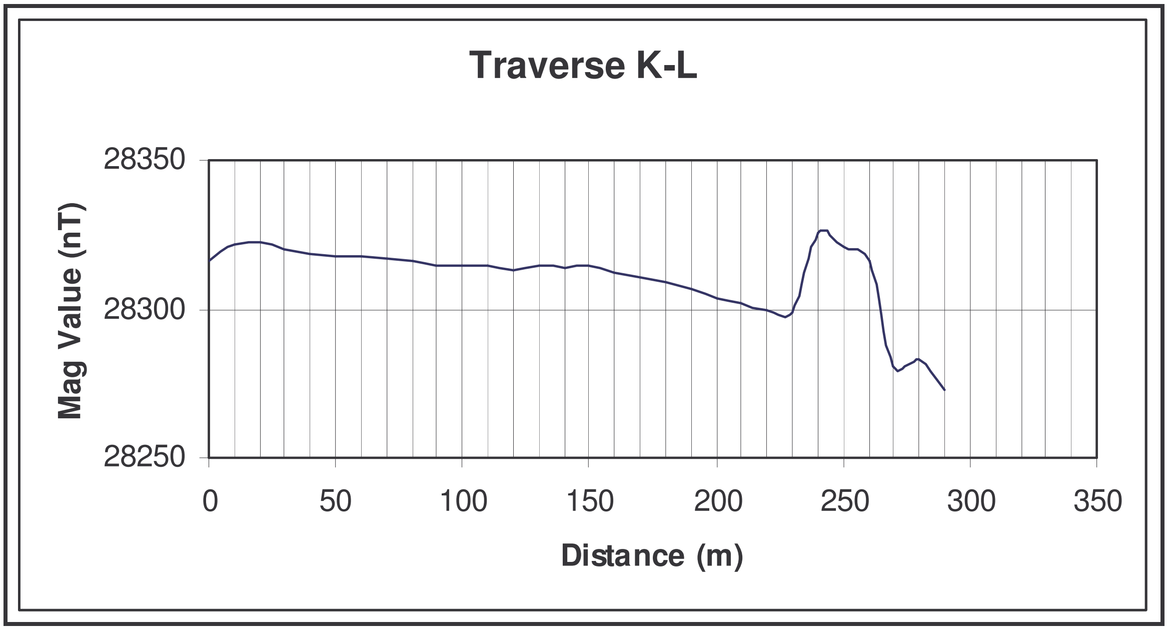

Figure 65: Magnetic traverse K-L.

Traverse M-N

The traverse runs in the west-east direction in the south of the landfill. Presence of the pipeline is observed at 440-480m resulting in increased magnetic field at that region.

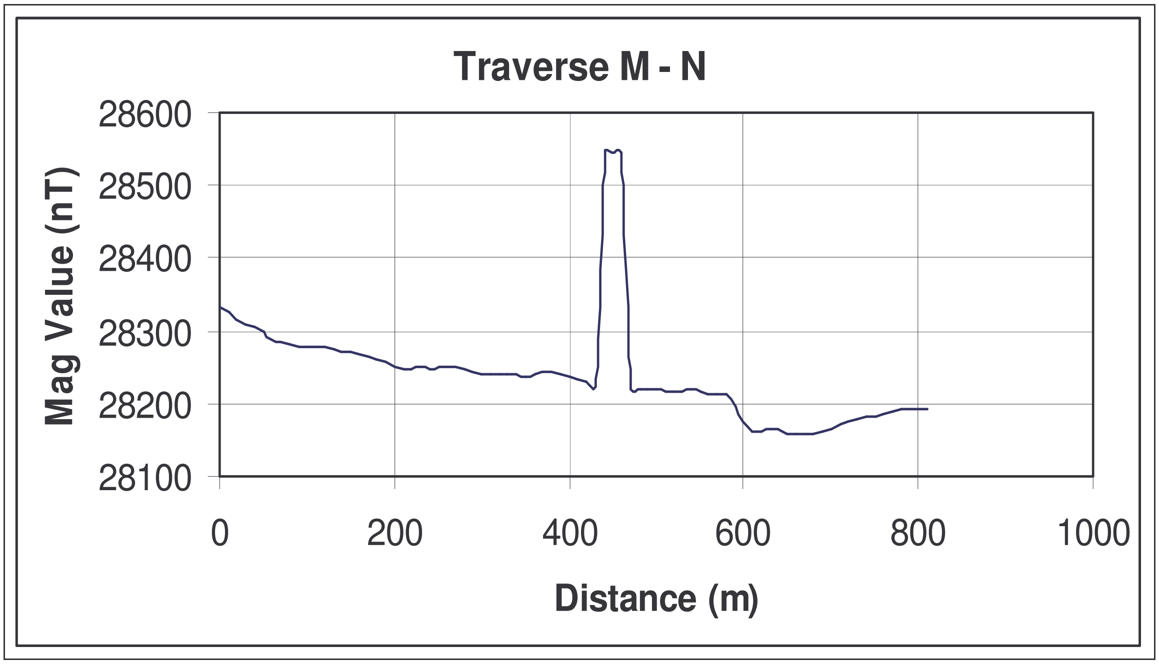

Figure 66: Magnetic traverse M-N.

Traverse O-P

The traverse line shows no changes in magnetic field, thus there are no structures along this line indicating uniform strata.

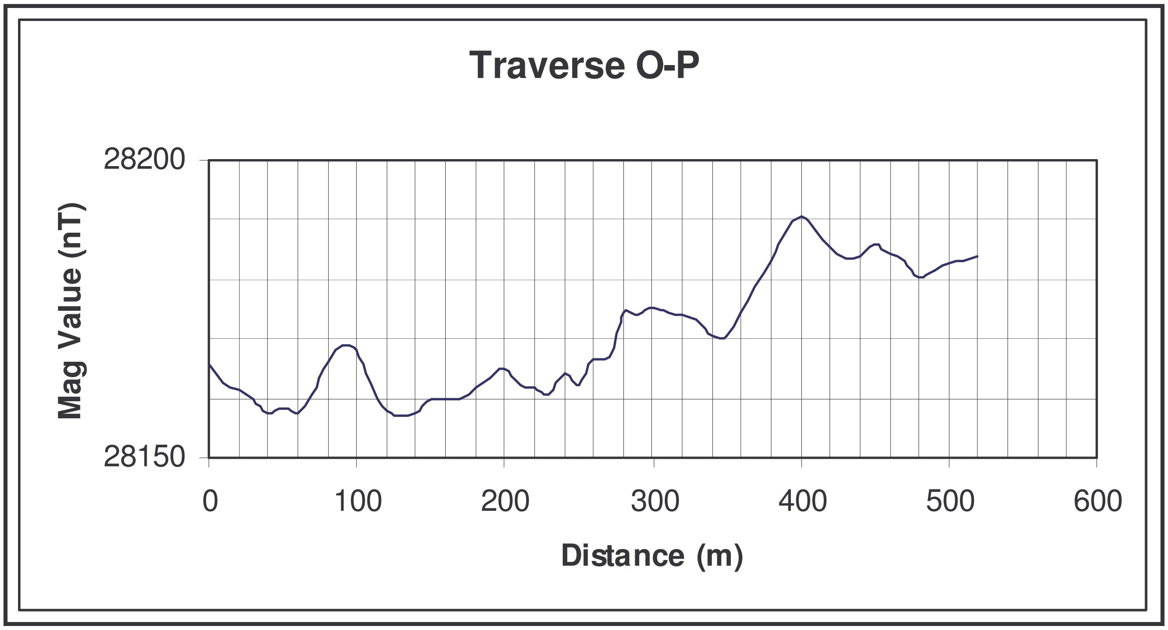

Figure 67: Magnetic traverse O-P.

Traverse S-T

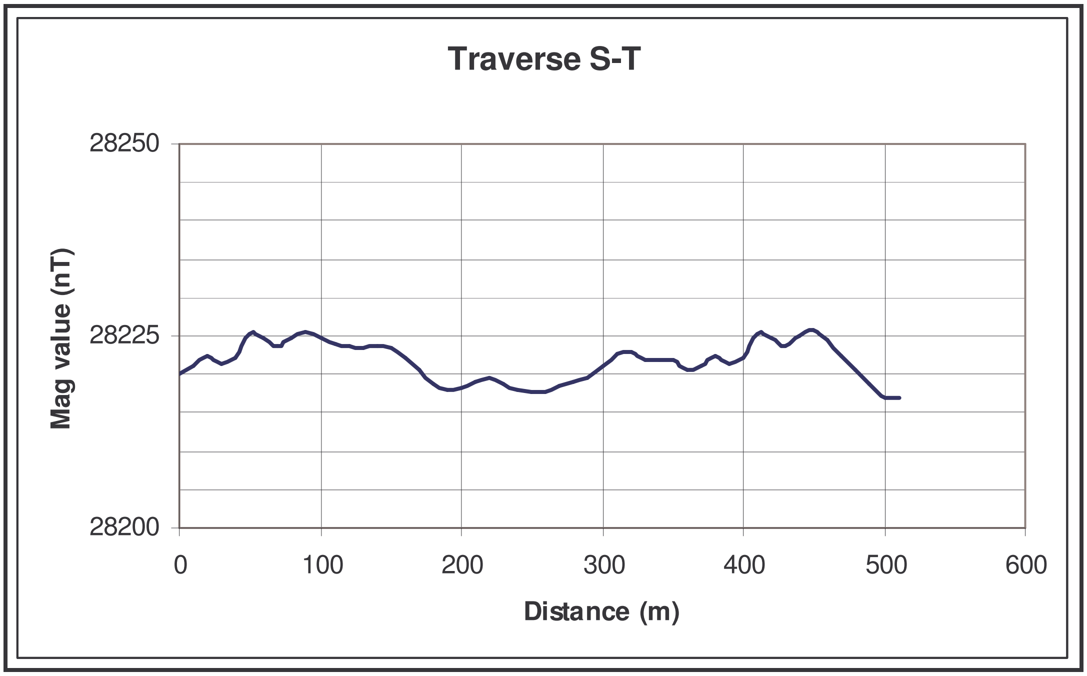

Figure 68: Magnetic traverse S-T.

10. Appendix 2: Borehole Logs and Geochemical Profiles

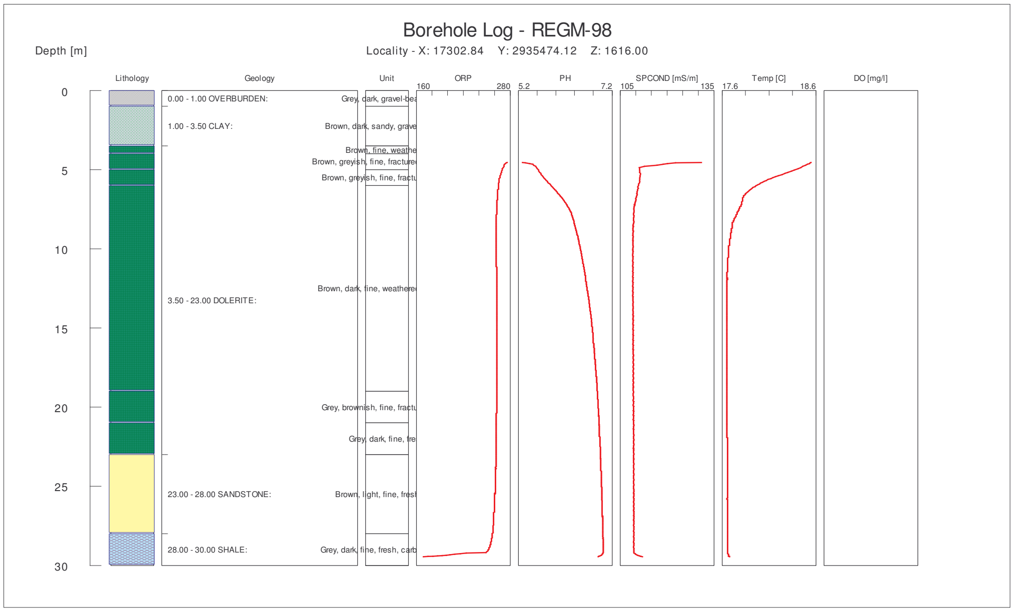

Figure 69: Geological and geochemical log of REGM 98.

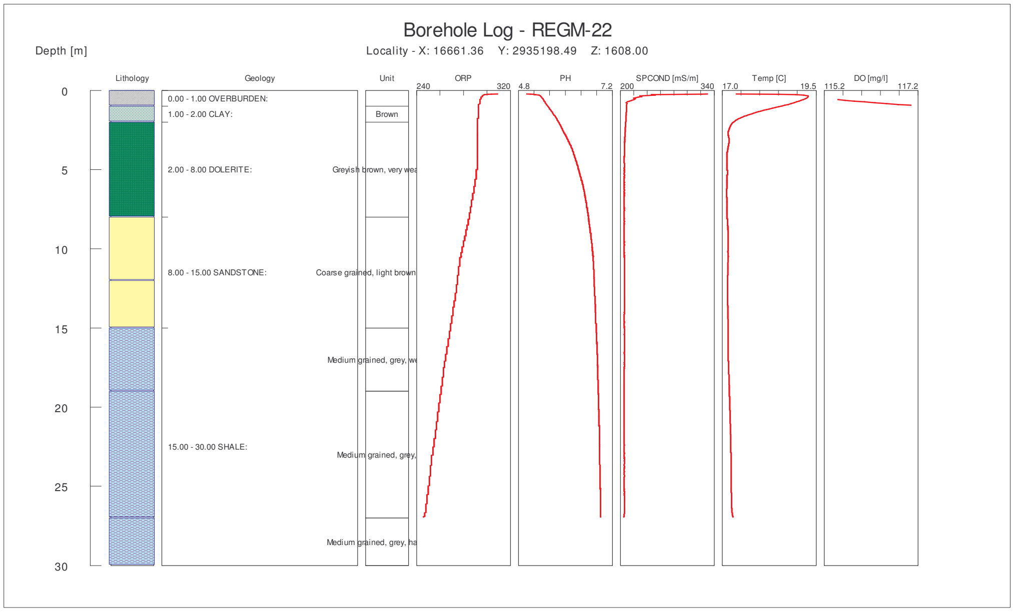

Figure 70: Geological and geochemical log of REGM 22.

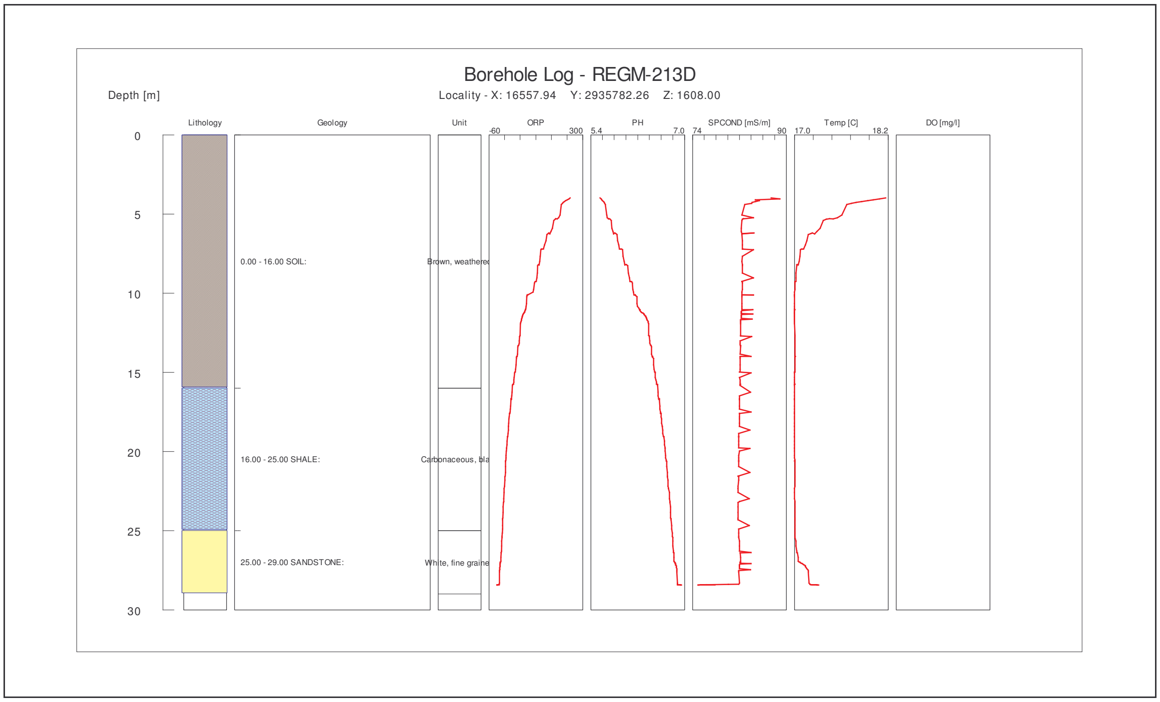

Figure 71: Geological and geochemical log of REGM 213.

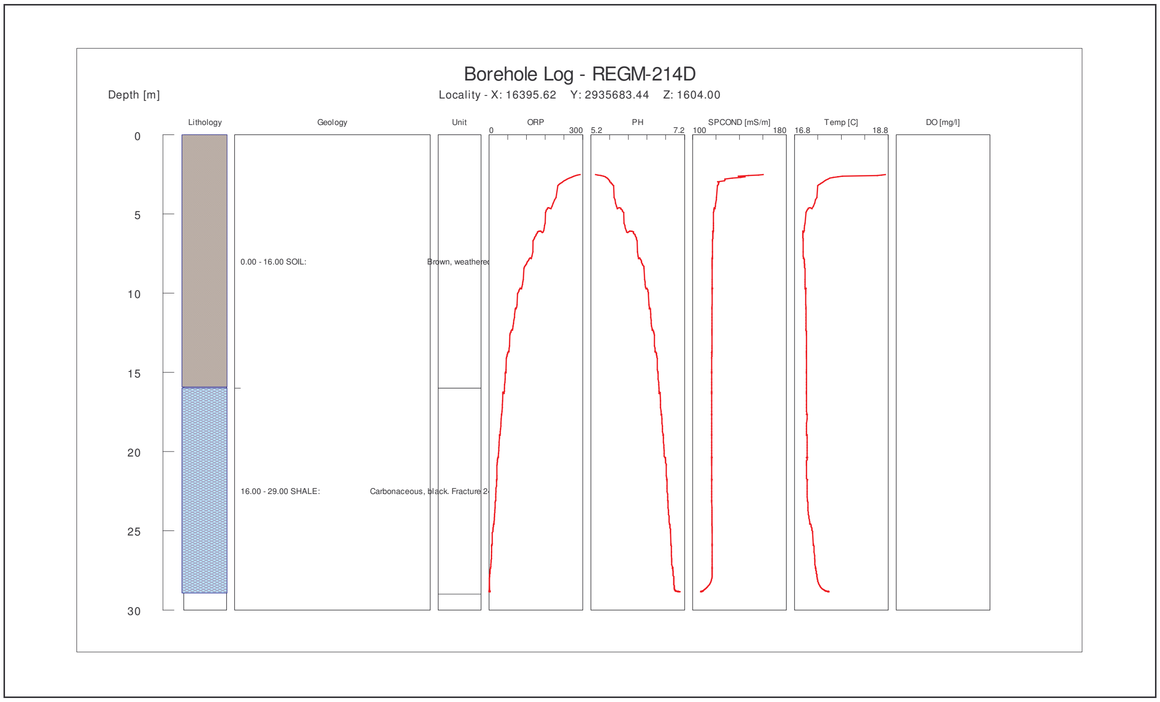

Figure 72: Geological and geochemical log of REGM 214.

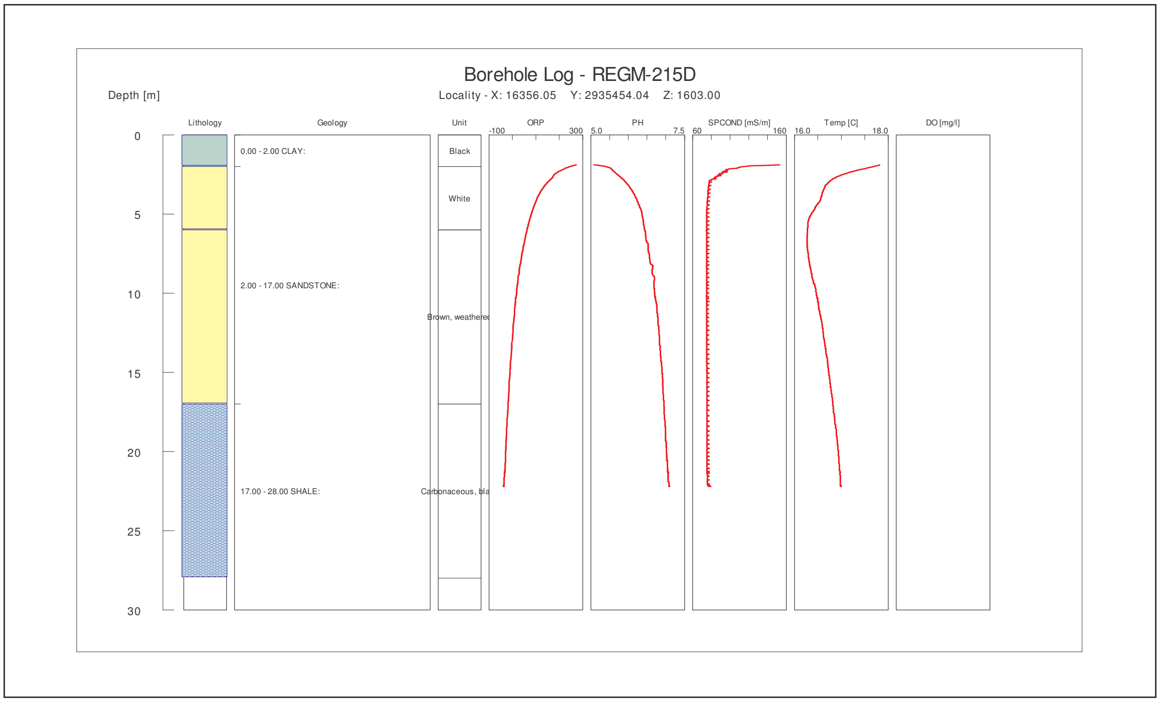

Figure 73: Geological and geochemical log of REGM 215.

Figure 74: Geological and geochemical log of REGM 216.

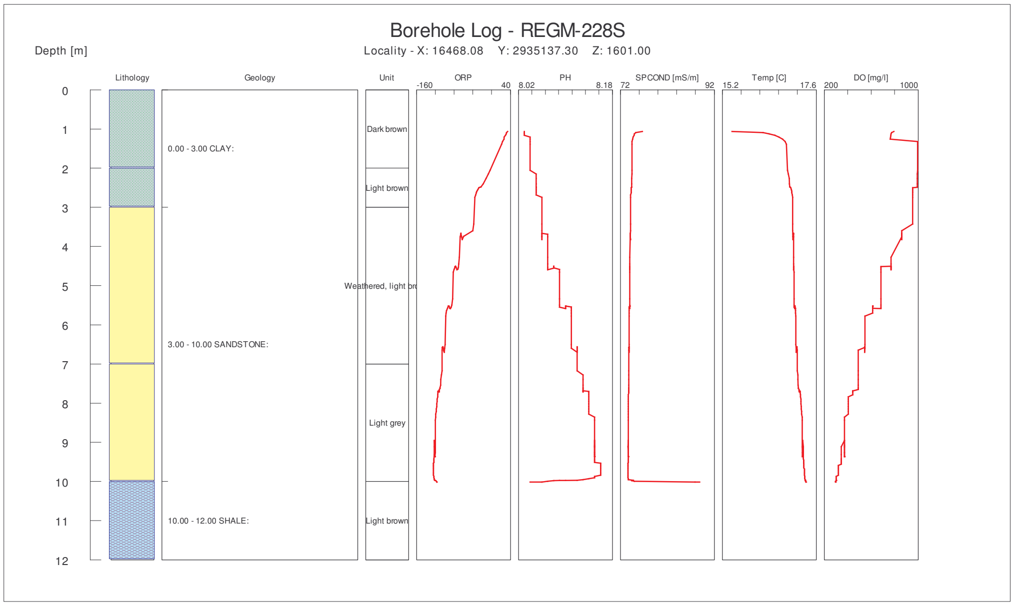

Figure 75: Geological and geochemical log of REGM228S.

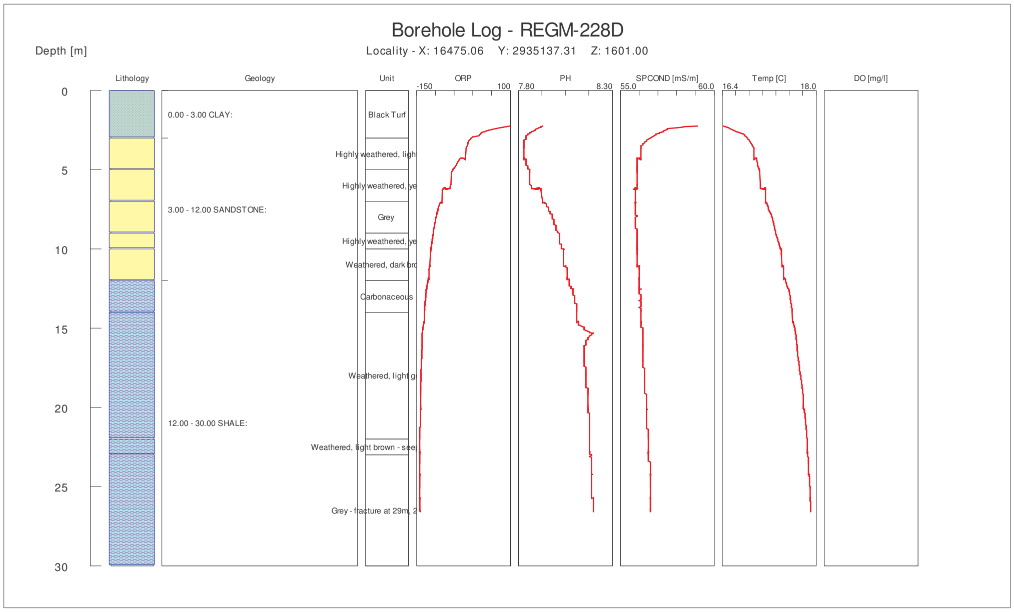

Figure 76: Geological and geochemical log of REGM 228D.

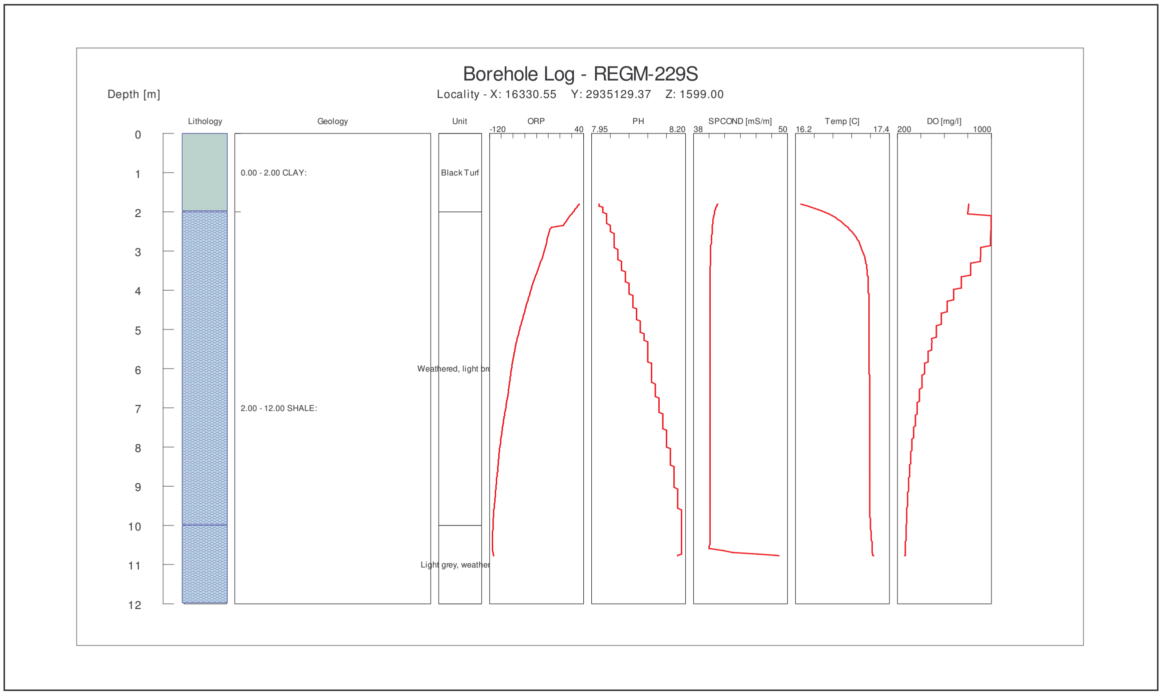

Figure 77: Geological and geochemical log of REGM 229S.

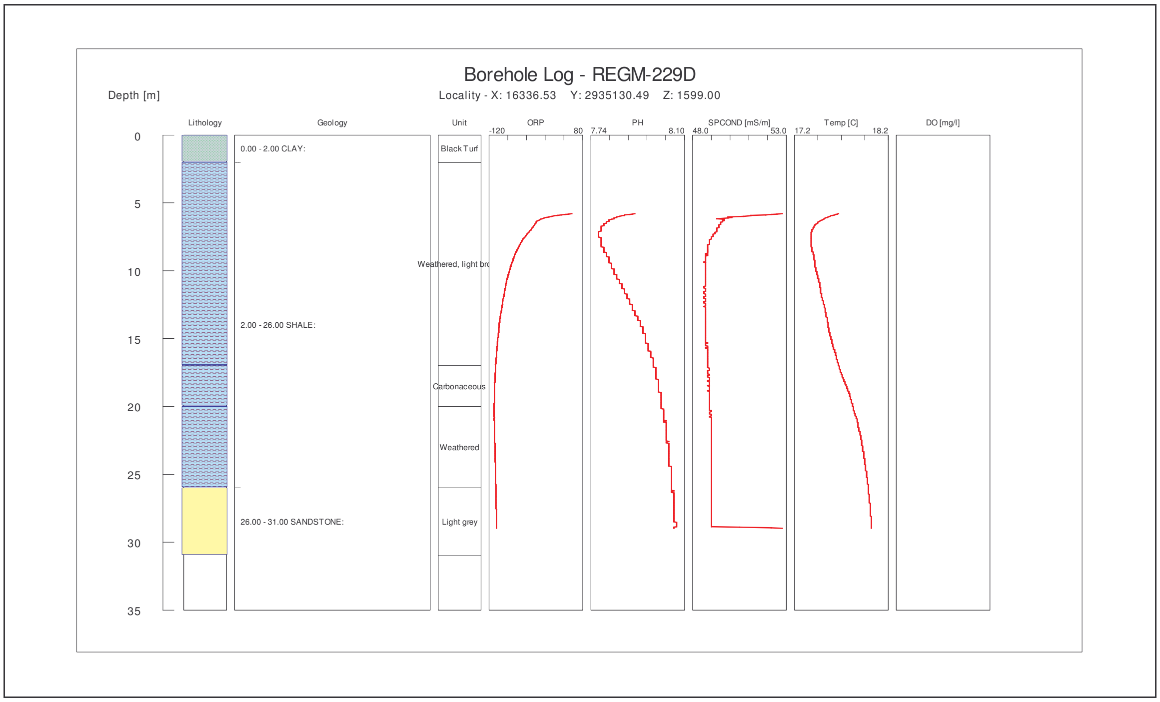

Figure 78: Geological and geochemical log of REGM 229D.

11. Appendix 3: Soil and Water Quality Guidelines

11.1. Appendix 3.1: Dutch Guidelines

Contaminant	**Soil Sediment** (mg/kg dry weight)		**Groundwater** (µg/l)	
Metals	optimum	action	optimum	action
Arsenic	29	55	10	60
Barium	200	625	50	625
Cadmium	0.8	12	0.4	6
Chromium	100	380	1	30
Cobalt	20	240	20	100
Copper	36	190	15	75
Lead	85	530	15	75
Molybdenum	10	200	5	300
Nickel	35	210	15	75
Mercury	0.3	10	0.05	0.3
Zinc	140	720	65	800
Cyanides	optimum	action	optimum	action
Free	1	20	5	1500
Complex (pH<5) (1)	5	650	10	1500
Complex (pH>5) (1)	5	50	10	1500
Thiocyanate	-	-	20	1500
Aromatics	optimum	action	optimum	action
Benzene	0.05[d]	2	0.2	30
Ethylbenzene	0.05[d]	50	0.2	150

Phenol	0.05[d]	40	0.2	2000
Toluene	0.05[d]	130	0.2	1000
Xylene	0.05[d]	25	0.2	70
Cresol	-	5[d]	-	200
Catechin	-	20	-	1250
Resorein	-	10	-	600
Hydroquinone	-	10	-	800
Polycyclic Aromatic Hydrocarbons (PAH)	optimum	action	optimum	action
Anthracene	-	-	0.02	5
Benzo(a)pyrene	- -	-	0.001	0.5
Fluoroanthrene	- -	-	0.005	1
Naphtalene	-	-	0.1	70
Phenanthrene	-	-	0.03	5
Benzo(a)anthracene	-	-	0.002	0.5
Chrysene	-	-	0.002	0.05
Benzo(a)fluoranthrene	-	-	0.003	0.5
Benzo(k)fluoranthrene	-	-	0.001	0.05
Benzo(g,h,i)perylene	-	-	0.0002	0.05
Indenol(1,2,3-c,d)pyrene	- -	-	0.0004	0.05
Total PAH (2) (10)	1	40	-	-
Chlorinated Hydrocarbons	optimum	action	optimum	action
1,2 Dichloroethane	-	4	0.01[d]	400
Dichloromethane	[d]	20	0.01[d]	1000

Tetrachloromethane	0.001	1	0.01[d]	10
Tetrachloroethane	0.01	4	0.01[d]	40
Trichloromethane	0.001	10	0.01[d]	400
Trichloroethene	0.001	60	0.01[d]	500
Vinylchloride	-	0.1	-	0.7
Monochlorobenzene	[d]	-	0.01[d]	180
Dichlorobenzol (total)	0.01	-	0.01[d]	50
Trichlorobenzol (total)	0.01	-	0.01[d]	10
Tetrachlorobenzol (total)	0.01	-	0.01[d]	2.5
Pentachlorobenzene	0.0035	-	0.01[d]	1
Hexachlorobenzene	0.0025	-	0.01[d]	0.5
Chlorobenzenes (3) (10)	-	30	-	-
Monochlorophenol	0.0025	-	0.25	100
Dichlorophenol	0.003	-	0.08	30
Trichlorophenol	0.001	-	0.025	10
Tetrachlorophenol	0.001	-	0.01	10
Pentachlorophenol	0.002	5	0.02	3
Chlorophenols (total) (4) (10)	-	10	-	-
Chloronapthylene	-	10	-	6
PolyChloroBiphenyls (total)(5) (10)	0.02	1	0.01	0.01[d]
Pesticides	optimum	action	optimum	action
DDT/DDD/DDE (total) (6)	0.0025	4	[d]	0.01
Aldrin	0.0025	-	[d]	-

Dieldrin	0.0005	-	0.02ng/l	-
Endrin	0.001	[d]	-	-
Drins (total)	-	4	-	0.1
alpha HCH	0.0025	-	[d]	-
beta HCH	0.001	-	[d]	-
gamma HCH	0.05 µg/l	-	0.2 ng/l	-
HCH combined (7)	-	2	-	1
Carbaryl	-	5	0.01[d]	0.1
Carbofuran	-	2	0.01[d]	0.1
Maneb	-	35	[d]	0.1
Atrazin	0.05 µg/l	6	0.0075	150
Miscellaneous	optimum	action	optimum	action
Tetrahydrofuran	0.1	0.4	0.5	1
Pyridine	0.1	1	0.5	3
Tetrahydrothiophene	0.1	90	0.5	30
Cyclohexanone	0.1	270	0.5	15000
Styrene	0.1	100	0.5	300
Mineral Oil (9)	50	5000	50	600
Phthalates (total)	0.1	60	0.5	5