Design Optimisation of Hazardous Waste Disposal Facilities through the Application of Water Balance and Mass Transport Modelling

By

Robert Shane Turner

Student Number: 2008131746

Submitted in fulfilment of the requirements for the degree of

Master of Science

In the faculty of Natural and Agricultural Sciences
Institute for Groundwater Studies
University of the Free State
Bloemfontein
South Africa

Supervisor: Prof G.J. van Tonder

November 2011

ABSTRACT

Although the country's legislation emphasizes the importance of waste prevention, recovery and re-use, waste disposal currently forms the basis of waste management within South Africa. Due to the lack of facilities as well as the high cost of waste disposal by incineration, the most common form of organic and inorganic waste disposal in South Africa is by landfill. Waste disposal by landfill may be cost effective and is environmentally acceptable if carried out correctly and appropriately. The prime environmental media that are affected by waste disposal by landfill are typically water and air, of which ground water forms one of the major migration pathways for contaminants. Ground water is one of South Africa's major water resources and it is thus of utmost importance that the countries ground water resource be protected. The greatest threat posed by modern landfills to the ground water environment is the leachate that is generated at the base of the landfill disposal facility. This leachate consists essentially of water-soluble compounds that accumulate in association with infiltrating water as it percolates through the waste. The quality of this leachate is variable and due to the processes by which certain wastes are generated, may contain elements that could potentially have an adverse impact on the environment if the waste is not disposed of correctly. All waste is required to be assessed and appropriately disposed of, as currently formalized in the Department of Water Affairs and Forestry's, Waste Management Series, Second Edition 1998 - Minimum Requirement Documents. These documents classify waste into two classes, namely general waste and hazardous waste, according to the toxological risk that the waste poses on contaminating the environment. The Minimum Requirement Documents have proposed 10 different landfill liner designs which are required to be installed at landfill disposal facilities according to the classification of the waste. The two landfill liner designs that are suitable for hazardous waste disposal are required to entail significant leachate interception and removal systems, irrespective of the site water balance or site specific conditions and are thus often unrepresentative for the specific disposal facility. Use was made of site specific parameters, such as the required site water balance, geochemical composition and analyses of the slag, physical properties of the slag material as well as the efficiency of the layers within the liner design, to determine the most optimal liner design for the slag disposal facility investigated. Slag in an inorganic metallurgical waste that is generically produced at ferrochrome producing plants in South Africa. Slag is disposed of by means of landfill as a dry aggregate material with an average grain size of 20 mm. The risk that the slag disposal facility posed on contaminating the environment was assessed in accordance with the current environmental legislation and the optimized liner design was determined. The optimized liner design for the 50 ha slag disposal facility investigated consists of 4 layers and is capable of capturing the required volume of leachate in order to optimally protect the environment from any adverse effects caused by the leachate. The liner has thus been designed according to the Best Practicable Environmental Option norm and at the most optimal cost.

OPSOMMING

Alhoewel die land se wetgewing die belangrikheid van afval voorkoming, herwinning en hergebruik beklemtoon, vorm afvalverwydering tog tans die basis van afval bestuur in Suid-Afrika. As gevolg van die tekort aan fasiliteite tensame met die hoë koste van afvalverwydering deur verbranding, is die mees algemene vorm van organiese en anorganiese afvalverwydering in Suid Afrika deur storting. Afval beskikking deur storting kan koste doeltreffend en omgewingsvriendelik aanvaarbaar wees as dit korrek en toepaslik uitgevoer word. Die hoof omgewing media wat deur afvalverwydering beinvloed word deur storting is gewoonlik water en lug, waarvan grondwater een van die hoof migrasie roetes vir besoedeling vorm. Grondwater is een van Suid-Afrika se hoof waterbronne en dit is dus van kardinale belang dat die land se grondwater bronne beskerm word. Die grootste bedreiging wat afvalstortingsterreine vir die grondwater omgewing inhou is die uitloging van besoedelstowwe uit die bodem van die fasiliteite. Hierdie besoedelstowwe bestaan hoofsaaklik uit wateroplosbare verbindings wat versamel as die water deur die afval in die stortingsterrein syfer. Die kwaliteite van hierdie besoedelstowwe kan varieer en is afhangend van die die verskillende prosesse waartydens die afvalstowwe gegenereer word. Alle afval moet ondersoek word en mee weggedoen word deur toepaslikke riglyne te volg soos tans beskryf in die Departement van Waterwese en Bosbou se Afvalbestuur-reeks, 2de uitgawe 1998 – Minimum Vereiste Dokumente. Hierdie dokumentasie onderskei afval in twee klasse, naamlik algemene afval en gevaarlike afval, volgens die toksologisie risiko wat die afval inhou om die omgewing potensiaal nadelig te beïnvloed. Die minimum vereistes stel 10 belyningsontwerpe voor wat vereis word op grond van die klassifikasie van die betrokke afvalstof. Die twee belyningsontwerpe wat aanvaarbaar is vir gevaarlike afvalstorting vereis dat 'n komplekse en beduidenswaardige sisteem in plek gestel moet word waartydens gevaarlike besoedelingstowwe wat uit afvalstortingsterreine kan uitloog ge-onderskep en verwyder kan word. Die vereiste vir sulke komplekse belyningsontwerpe bestaan onafhanklik van die liggingspesifieke kondisies of waterbalanse van die betrokke afvalstortingsterrein en kan dus partymaal onverteenwoordigend wees vir sekere afvalstortingsterreine. Tydens die bepaling van 'n gepaste belyningsontweerpe vir slak stortingsterreine is daar gekyk na liggingspesifieke parameters, die fisiese eienskappe van die slak asook die effektiwiteit van lae binne-in die belyningsontwerp. Slak is 'n anorganiese metallurgiese afvalstof wat generies gegenereer word by ferrochroom aanlegte in Suid Afrika. Slak word in groot volumes op slak afvalstortingsterreine as droë aggregraat gestort met 'n gemiddelde korrelgrootte van 20 mm. Die risiko van potensiële omgewingskontaminasie afkomend van slak stortingsterreine was destyds ondersoek na aanleiding van die omgewingswetgewing van die tyd en die toepaslike belyningsmetode/vereiste was bepaal. Die toepaslike belyningsmetode vir die 50 ha slak stortingsterrein wat ondersoek was bestaan uit 4 lae en kan die nodige volume van besoedelstowwe wat moontlik kan uitloog, opvang, om sodoende die optimale vlak van beskerming aan die omgewing te bied teen die negatiewe impakte wat geassosieer kan word met die uitloging. Die belyningsisteem was dus ontwerp op grond van die norm van die Bes Praktiese Uitvoerbare Omgewingsbestuurs Opsie teen die mees optimale koste.

DECLARATION

I, Robert Shane Turner, the undersigned hereby declare that the work contained in this thesis report, written in fulfilment of a Master of Science (MSc) Degree in Geohydrology in the Faculty of Natural and Agricultural Sciences, Institute for Groundwater Studies at the University of the Free State is my own original work. The report has not previously in its entirety or in part been submitted by me or anyone else at any other university. I furthermore cede the copyright of the thesis in favour of the University of the Free State.

ACKNOWLEDGMENTS

I would firstly like to thank the directors of JMA Consulting (Pty) Ltd., namely; Mr Jasper Müller, Mr Jaco van der Berg and Mr Riaan Grobbelaar for granting me the opportunity to complete my studies in Geohydrology at the University of the Free State, South Africa.

I would further like to thank Mr Johan Fourie from Geostratum - Groundwater and Geochemistry Consulting for the assistance given with regards to the fundamentals of the modelling software used as well as the interpretation of the geochemical data used during this MSc research project.

I would lastly like to thank my parents, family and close friends, especially my fiancé Jessica Hofmeyr for all their continued support and prayers throughout this research project. The Lord has truly blessed me with continued strength and a wonderful support base of family and friends for which I am really grateful.

KEY WORDS

Hazardous Waste

HELP

Landfill Classification

Landfill Liner Design

Mass Transport Modelling

Minimum Requirement Documents

MODFLOW

Waste Characterization and Classification

Waste Disposal

Water Balance

TABLE OF CONTENTS

Page

TABLE OF CONTENTS

Page

TABLE OF CONTENTS

Page

TABLE OF CONTENTS

Page

LIST OF FIGURES

Page

LIST OF FIGURES

Page

LIST OF TABLES

Page

LIST OF TABLES

Page

LIST OF ACRONYMS

AEC	Acceptable Environmental Concentration
AER	Acceptable Environmental Risk
ARL	Acceptable Risk Level
ARLP	Acid Rain Leaching Procedure
AUC	Average Upper Crust
BIC	Bushveld Igneous Complex
BPEO	Best Practicable Environmental Option
DA	Disposable Allowed
DEA	Department of Environmental Affairs
DEM	Digital Elevation Model
DF	Dilution Factor
DTM	Digital Terrain Model
DWAF	Department of Water Affairs and Forestry
DWEA	Department of Water and Environmental Affairs
EC	Electrical Conductivity
EEC	Estimated Environmental Concentration
EMP	Environmental Management Plan
FML	Flexible Membrane Layer
GCG	Generalized Conjugate Gradient
GCL	Geosynthetic Clay Layer
HDPE	High Density Polyethylene
HELP	Hydrologic Evaluation of Landfill Performance
HR	Hazard Rating
IEM	Integrated Environmental Management
IMDG	International Maritime Dangerous Goods
LG	Lower Group
LOD	Limit of Detection
MAE	Mean Annual Evaporation
MAMSL	Meters Above Mean Sea Level
MAP	Mean Annual Precipitation
MAR	Mean Annual Recharge
MBC	Meters Below Collar
MBGL	Meters Below Ground Level
MG	Middle Group

LIST OF ACRONYMS

MRD	Maximum Rate of Deposition
MSc	Master of Science (Degree)
NEMA	National Environmental Management Act
NEMWA	National Environmental Management Waste Act
NWA	National Water Act
PGE’s	Platinum Group Element’s
RMS	Root Mean Square
RWMS	Rustenburg Weather Monitoring Station
SABS	South African Bureau of Standards
SANS	South African National Standard
TCLP	Toxic Characteristic Leaching Procedure
TDS	Total Dissolved Solids
UG	Upper Group
USEPA	United States Environmental Protection Agency
USGS	United State Geological Survey
WISH	Windows Interpretation System for the Hydrogeologist
XRD	X-Ray Diffraction
XRF	X-Ray Fluorescence

LIST OF ELEMENTS AND COMPOUNDS

Ag	Silver	Nb	Niobium
Al	Aluminium	NH_3	Ammonia
As	Arsenic	NH_4^+	Ammonium
Ba	Barium	Ni	Nickel
Bi	Bismuth	NO_3	Nitrate
Br	Bromide	Pb	Lead
C	Carbon	pH	pH
Ca	Calcium	Rb	Rubidium
Cd	Cadnium	S	Sulphur
Cl	Chloride	Sb	Antimony
Co	Cobolt	Sc	Scandium
CO_2	Carbon Dioxide	Se	Selenium
Cr	Chromium	Si	Silicon
Cu	Copper	Sn	Tin
F	Fluorine	SO_4	Sulphate
Fe	Iron	Sr	Strontium
Ga	Gallium	T.Alk	Total Alkalinity
Ge	Germanium	Ta	Tantalum
H_2CO_3	Carbonic Acid	Te	Tellurium
H_2O	Water	Th	Thorium
Hf	Hafnium	Tl	Thallium
Hg	Mercury	U	Uranium
I	Iodine	V	Vanadium
K	Potassium	W	Tungsten
Mg	Magnesium	Y	Yttrium
Mn	Manganese	Yb	Ytterbium
Mo	Molybdenum	Zn	Zinc
Na	Sodium	Zr	Zirconium

1 INTRODUCTION AND STUDY OBJECTIVE

Waste is regarded as any by-product, residue or material that cannot further be used in the process from which it was formed. Waste may occur in many forms, such as a solid material, as sludge, as a liquid or even a combination of the three. There are various types of waste and waste streams each with their own unique chemical composition and physical characteristics. Wastes may vary from general garden refuse and domestic waste, through to medical, chemical, mining and industrial waste. The composition of each waste material is unique and is dependent on the processes and activities from which the waste was generated.

Although legislation emphasizes the importance of waste prevention, recovery and re-use, waste disposal still forms the basis of waste management within South Africa. Waste is typically disposed of by means of landfill or incineration. Landfill is the process of dumping the waste at specified sites or excavations on the surface, whilst incineration involves the burning of the waste. Due to the lack of facilities as well as the high cost of waste disposal by incineration, the most common form of organic and inorganic waste disposal in South Africa is by landfill.

Due to processes by which certain wastes are generated, they may contain material or constituents that could potentially have an adverse impact on the environment if they are not treated or disposed of correctly. It is therefore important that the concentrations or chemical composition of each waste material be analysed and assessed in order to determine the apparent risk that it poses on impacting the environment. The assessment of the waste should indicate the risk that the waste, or certain elements in the waste, pose on potentially contaminating the environment if released from the waste material. The assessment of the waste should then be used to determine the level of protection required during its disposal.

The classification of waste is legally required, and all waste generators are obligated to assess the composition of their waste and determine the risk that the waste poses on contaminating the environment. The classification of waste in South Africa is commonly done in accordance with the Department of Water Affairs and Forestry's, Waste Management Series, Second Edition 1998 – (DWAF, 1998. Minimum Requirement Documents 1, 2 and 3).

The three Waste Management Series' Minimum Requirement Documents (DWAF, 1998) are namely*: Minimum Requirements for the Handling, Classification and Disposal of Hazardous Waste* (Document 1), *Minimum Requirements for Waste Disposal by Landfill* (Document 2) and *Minimum Requirements for the Monitoring of Water Quality and Waste Management Facilities* (Document 3).

The classification system provided in the Minimum Requirement Documents distinguishes waste into two separate classes, namely General Waste and Hazardous Waste. If it is determined that a waste poses little or no risk on contaminating the environment it is classified as General Waste. If it is however observed that certain elements in the waste pose a significant risk on contaminating the environment, the waste is classified as a Hazardous Waste.

Waste that is disposed of by landfill may be mono-disposed, in which the entire landfill site is solely used for the disposal of one type of waste, or it may be co-disposed, along with other wastes. General Wastes are typically co-disposed, whilst Hazardous Waste are more often required to be mono-disposed at the specified waste disposal facilities.

Waste that is disposed of at landfill sites is typically exposed to atmospheric conditions and is subject to precipitation, evaporation and wind etc. Precipitation falling onto the waste at a landfill disposal facility may chemically interact with the waste and potentially form a leachate. This leachate essentially consists of water and water-soluble compounds that accumulate in association with the water as it infiltrates through the waste. The quality of this leachate is variable and has the potential to migrate downwards through the waste and infiltrate into the underlying unsaturated and saturated ground water zones.

Water and air are typically the prime environmental media that are affected by waste disposal by landfill, of which ground water forms one of the major migration pathways for any contaminant. Any contaminants that enter the ground water system have the potential of migrating laterally until they are consumed by a ground water receptor, which includes rivers, dams, the ocean or users of abstracted ground water. The greatest threat posed by modern landfills to the ground water environment as well as to humans is the leachate generated at the base of the landfill disposal facility, which has the potential of infiltrating through the soils and into the underlying ground water system.

Ground water forms one of South Africa's major water resources and is used as a resource for livestock, irrigation as well as domestic purposes. Ground water is vital to the sustainability of the countries water resources and it is thus of utmost importance that the ground water resource be protected. Increasing attention has been given to the impacts on human health and the environment as a result of chemical contaminants in wastes that are incorrectly disposed of or facilities that are not properly managed.

The legislation in South Africa stipulates that all waste generators are to manage their waste, including the disposal thereof, in order to protect the environment, which includes the ground water resource, as well as the human public from the harmful effects caused by incorrect waste disposal. In order to avoid ground water pollution it is essential that significant leachate generation from landfills be managed by means of leachate interception and treatment systems.

Modern landfill waste disposal sites are as a result comprehensively engineered containment facilities, designed to minimize the impact that the disposal of solid waste has on the environment and human health. Certain landfill sites are thus commonly designed with low permeability liner systems at the base of the site which separate and isolate the waste from the underlying ground water system. The function of these liner systems is to capture and prohibit any elements or leachate generated from the waste from further infiltrating into the underlying ground water system.

Due to the toxic, chemical or physical properties of hazardous wastes, stringent technical control measures are required for the disposal thereof. Specific hazardous waste landfill disposal facilities are therefore designed to accommodate the disposal of hazardous waste in order to protect the receiving environments. Improved waste management and more stringent liner systems will inevitably result in increased costs and the Best Practicable Environmental Option (BPEO) is therefore recommended to be adopted, which aims to optimize the protection of the environment at optimal costs.

The BPEO is defined in the National Environmental Management Act 107 of 1998 as "*the option that provides the most benefit or causes the least damage to the environment as a whole, at a cost that is acceptable to society in the long term as well as the short term" (Department of Environmental Affairs, 1998).* Determining the most applicable liner system for the disposal of waste by landfill is therefore of utmost importance to optimally protect the environment at the most rational cost.

Waste that is disposed of by landfill is subject to and may be influenced by atmospheric and climatic weather conditions. Precipitation that falls onto and comes into contact with waste that has been disposed of by landfill has the potential of generating a leachate, the nature of which is dependent on the atmospheric conditions as well as the composition of the waste. As the precipitation infiltrates through the waste, it comes into contact with and may interact chemically with the waste material. The nature and degree of interaction is dependent on the chemistry of the infiltrating water, the chemical composition of the waste as well as the physical characteristics of the waste and in fact the entire waste disposal facility.

Certain wastes contain elements or material that is toxic and may have severe negative effects if consumed by humans or the environment. Such wastes need to be identified and should be disposed of at the appropriate landfill facilities. Waste disposal by landfill is environmentally acceptable if carried out correctly. Unfortunately however, if not carried out to sufficiently high standards, waste disposal by landfill has the potential to have adverse short-term or long term impacts on the environment.

It is thus vital that the chemistry of all wastes be assessed prior to the disposal thereof, to distinguish between wastes that pose a large risk on contaminating the environment and those that pose a minimal risk. Wastes or waste sites that could potentially generate leachates are to be disposed of or managed in such a manner that the leachate is intercepted and removed, before it enters the environment.

The most common method of preventing leachate generated in the waste at landfill facilities from entering the environment is by installing low permeability liner systems at the base of the landfill disposal facility. These liner systems may include a combination of semi-impermeable layers, drainage layers and drains as well as the associated leachate collection infrastructure adjacent to the landfill facility. The primary function of the liner systems is to capture and prohibit any leachate generated at the base of the landfill disposal facility from infiltrating into the underlying unsaturated zone.

The unsaturated zone is that part of the earth's geological stratum, including soils and clays that occur above the ground water table. Water and any potential leachate in the unsaturated zone occur within the interstices or voids between the individual grains or host rock material along with air and other gases. Water in the unsaturated zone is under atmospheric conditions and will percolate downwards through the voids in the unsaturated zone and into the underlying saturated ground water zone under the influence of gravity. The saturated ground water zone is the part of the earth's crust that is situated beneath the ground water table or piezometric surface. The voids in the saturated zone are entirely filled with water at pressures equal to or greater than that of atmospheric pressure.

The term ground water is used to describe all subsurface water within the saturated zone, whilst subsurface water relates to water that occurs within the saturated as well as the unsaturated zones. The rate at which the subsurface water or leachate will infiltrate through the unsaturated zone is dependent on, amongst others; the viscosity of the infiltrating fluid, the degree of saturation of the unsaturated zone, the hydraulic conductivity of the unsaturated zone as well the hydraulic head of the infiltrating fluid.

Once any infiltrating subsurface water or leachate enters the saturated zone, the solutes in the water or leachate begin to migrate laterally. This lateral movement results primarily from the bulk movement or transport of water due to advection. Advection is the predominant process by which solutes are transported in the saturated ground water zone, especially in highly permeable material during which the solutes are carried along with the flowing ground water.

Contaminants within the ground water may also migrate laterally as a result of adsorption, diffusion and dispersion, although to a much smaller degree than advection. Contaminants within the saturated ground water zone will therefore primarily be transported away from the infiltration source, due to the mass movement of ground water until it is abstracted or intercepted by a surface water body.

The potential movement of leachate or contaminants, generated at the base of a landfill disposal facility, through the unsaturated and saturated ground water zones towards the ground water receptors is schematically depicted in Figure 1. The movement of surface water, subsurface water and associated contaminant flow paths are indicated by the arrows on Figure 1. The landfill disposal facility is depicted as the potential Source of contamination.

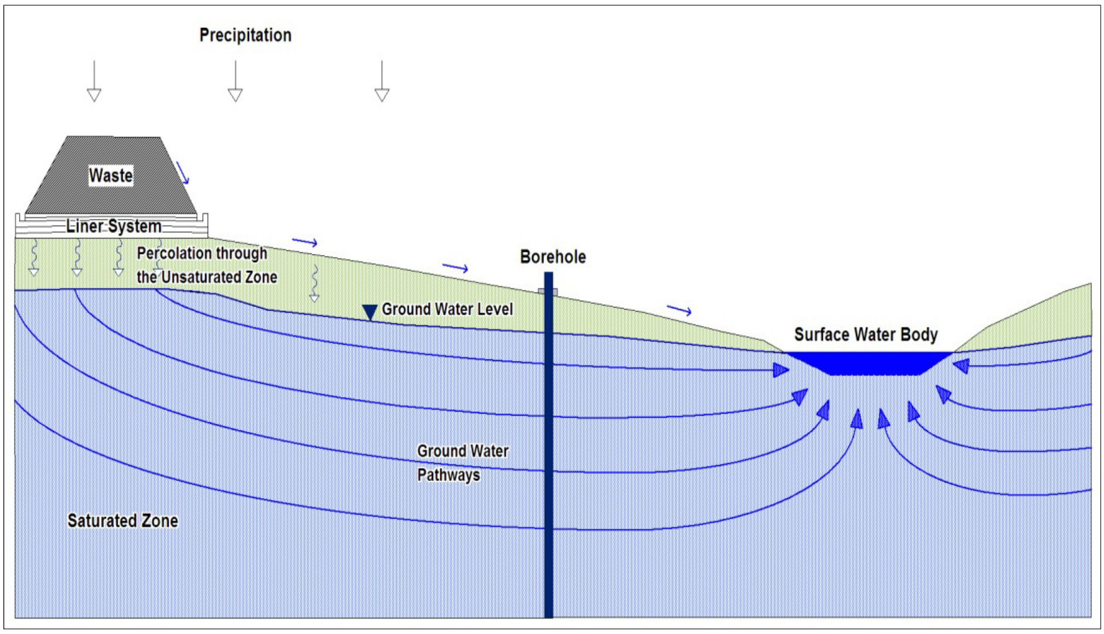


Figure 1: Schematic Surface Water and Sub-Surface Water Flow Paths

Landfill disposal facilities may be classified as point, linear or spatial sources based on their geometry and size. The landfill disposal facility that is going to be investigated during this research project is a generic slag disposal facility in South Africa. Slag is an inorganic metallurgical waste that is typically generated by Ferro-Alloy producing plants. Slag is predominantly deposited at landfill disposal facilities as a dry aggregate material with an average grain size of 20 mm (Figure 2).

Any leachate that is generated at the base of the slag disposal facility originates primarily as a result of infiltrating precipitation that comes into contact with the slag and is required to be separated from the underlying ground water zones by low permeability liner systems. The primary aim of liner systems are to intercept and prohibit any leachate generated at the base of the waste disposal facility from infiltrating into the underlying unsaturated and saturated zones. The leachate that is captured is legally required to be contained in a surface water containment facility where it is to be re-used or treated to an environmentally acceptable quality before it may be released.

The possibility that not all the leachate is captured by the liner systems does still however exist and is often related to the inappropriate liner selection or inefficient installation thereof. The effectiveness or appropriateness of the liner design and installation thereof is thus of utmost importance in order to protect the underlying ground water resource adjacent to landfill disposal facilities in South Africa.

Figure 2: Image of Deposited Slag

Both the unsaturated and saturated zones are regarded as **Pathways** and represent zones through which the leachate or contaminants may move. Certain major aquifer systems are however often regarded as **Receptors**, but not for the purpose of this research project. A **Receptor** is more commonly, classified as a downstream user of the ground water or as a surface water feature, such as a spring, river, lake, dam or the ocean. Either way, whether classified as pathways or receptors, the ground water system in South Africa is legally required to be protected. This includes the protection of the aquifer from adverse contamination caused by infiltrating leachate generated at the base of the waste deposited at landfill disposal facilities.

Waste disposal in South Africa is currently controlled and formalized through the stipulated Best Management Practices, the Environmental Management Plan (EMP) process as well as the Minimum Requirement Documents, which form part of the Waste Management Series, Second Edition, 1998 developed by the Department of Water Affairs and Forestry.

The waste management series was initiated with the aim of upgrading the standard of waste management in South Africa. The objective of the Minimum Requirement Documents is to "*set-out systematic steps to protect and prevent the degradation of the water quality and the environment as well as to improve the standard of Waste Disposal in South Africa*". The intention of the waste classification system stipulated in the Minimum Requirement Documents is to distinguish between wastes that potentially pose a large risk on contaminating the environment and those that pose a smaller risk.

The Minimum Requirement Documents set out a systematic framework of procedures that are to be followed during the identification and classification of different waste types according to their waste stream and risk that they potentially pose on contaminating the environment. Based on the classification of the waste, different requirements are set regarding the disposal thereof. The aim of the landfill disposal requirements is to ensure that wastes which are classified as potentially posing a large risk on contaminating the environment are disposed of more stringently than wastes that are classified as posing less risk of contamination.

The Minimum Requirement Documents initially classify wastes into two separate classes according to their toxological chemical properties, namely "*General Waste*" or "*Hazardous Waste*". General waste is simply referred to as waste that poses little risk to the environment whilst hazardous waste is referred to as waste that poses a significant risk on contaminating the environment.

According to the Minimum Requirement Documents the first indication that a waste could potentially be classified as being hazardous is determined from the industrial group or process from which it was generated. This classification is further verified during the geochemical analyses of the waste material, whereby the geochemistry of the waste is assessed against the SABS Code 0228 tables included in the Minimum Requirements for the Handling Classification and Disposal of Hazardous Waste (DWAF 1998). If the analyses confirm that the waste does contain hazardous substances, the generator of the waste is to register as a "*hazardous waste generator*" and is required to determine the minimum requirements associated with the disposal of the waste.

In instances where the waste is required to be treated before it may be disposed the Minimum Requirement Documents stipulate that "*the residue of the treated waste be analysed and assessed*". It is further required that the toxicity (LD_{50}), ecotoxicity (LC_{50}), carcinogenicity, mutagenicity, teratogenicity, persistence or environmental fate and estimated environmental concentration (EEC) of the hazardous waste or its residue be determined.

The Minimum requirement Documents further subdivide hazardous waste according to the risk that it poses at disposal. This classification is made according to a Hazard Rating (HR) classification system. The Hazard Rating classification of the waste is intended to provide an assessment of the risk posed by a hazardous substance in the waste and distinguish a less hazardous waste from an extremely hazardous one. A hazardous waste with a Hazard Rating of 1 represents a waste that potentially poses an "*extreme hazard*" on contaminating the environment. A waste with a Hazard Rating of 2 poses a "*high hazard*", a waste with a Hazard Rating of 3 a "*medium hazard*" and a waste with a Hazard Rating of 4 a "*low hazard*" on contaminating the environment.

Two factors are taken into account during the Hazard Rating classification system, namely the amount of the substance in the waste that can potentially enter the environment, termed the EEC and the inherent toxological hazard of the substance, termed the ecotoxicity. The ecotoxicity is the concentration of a substance at which there is the potential to harm animals, plants, ecosystems or environmental processes.

The EEC is required by the Minimum Requirement Documents to be calculated as the "*resultant concentration of hazardous substance in the body of water, should the total amount of the hazardous substance in the waste, that is disposed of on 1 hectare of landfill, leach out from the waste and into the body of water over an indefinite period of time"*. The EEC represents a worst case scenario as it assumes that the hazardous substance will leach out entirely from the waste and does not take ground water flow (advection), dispersion or diffusion into consideration

In order to determine the risk that the waste or hazardous substance in the waste pose on contaminating the environment, the Minimum Requirement Documents require that the EEC of the most hazardous substance in the waste be determined and used during the Hazard Rating calculations.

During the Hazard Rating calculations the EEC of the most hazardous substance in the waste is compared to 10% of the stipulated ecotoxicity value for that substance. 10% of the ecotoxicity value is termed the "Acceptable Risk Level" and according to the

Minimum Requirement Documents, represents the concentration "*at which the substance would cause a mortality incidence of one in three hundred thousand in an aquatic environment"*. The Acceptable Risk Level represents the concentration at which a substance is deemed to have an insignificant impact if it enters the environment.

If it is determined that the EEC of the most hazardous substance in the waste is higher than the Acceptable Risk Level, the waste is assigned the Hazard Rating of that specific hazardous substance. If the EEC is lower than the Acceptable Risk Level, a waste with a Hazard Rating of 1 remains in the same Hazard Rating, whilst wastes with Hazard Ratings of 2, 3 or 4 can be delisted and assigned lower Hazard Ratings. The Minimum Requirement Documents stipulate that tests such as the Acid Rain Leaching Procedure (ARLP) or Toxic Characteristic Leaching Procedure (TCLP) are also to be used to determine whether it is safe to delist certain hazardous wastes or not.

Hazardous wastes with Hazard Ratings of 2, 3 or 4 that have been delisted can be legally be disposed of at general waste landfills containing a leachate interception system. A waste with a Hazard Rating of 1 can only be delisted to a general waste landfill containing a leachate interception system if the EEC of the most hazardous substance in the waste is less than 10% of the Acceptable Risk Level.

The liner designs assigned to the waste class being disposed of therefore needs to be appropriately designed and efficiently installed in order to optimally protect the environment from adverse effects caused by the leachate generated during the disposal of waste. The Minimum Requirement Documents classify landfill disposal facilities according to three parameters, namely: 1) the waste type, 2) the size of the operation and 3) the site water balance. There are 10 different waste landfill designs stipulated in the Minimum Requirement Documents, 8 of which cater for general (G) waste streams and 2 of which cater for hazardous (H) waste streams.

General waste landfills are subdivided into four classes based on the size of the waste stream and operation from which it was formed. These classes are namely Communal (C) landfills, Small (S) landfills, Medium (M) landfills and Large (L) landfills. The size classification is based on the Maximum Rate of Deposition (MRD) of the waste stream. The MRD is simply the projected average annual rate of waste disposal by landfill and is expressed in tonnes per day.

Waste streams with a MRD in excess of 500 tonnes per day are classified as large landfills. Medium landfills are classified as having a MRD of between 150 and 500 tonnes per day, whilst small landfills have an MRD of between 25 and 150 tonnes per day. Landfills in which the MRD is less than 25 tonnes per day are classified as communal Landfills.

General waste landfills are further subdivided according to the risk that the wastes pose on generating a significant leachate. The Minimum Requirement Documents state that "*the potential a waste poses on generating a significant leachate is dependent on the water balance associated with the site*". This is termed the site water balance and is affected by factors such as rainfall, evaporation, moisture content of the waste and water ingress into the waste body as a result of ineffective waste disposal practices.

The Minimum Requirement Documents stipulate that the relationship between the rainfall and the evaporation, termed the climatic water balance (B), is to be calculated and used as an initial indicator as to whether the possibility for significant leachate generation exists or not. The climatic water balance is calculated by subtracting the Mean Annual Evaporation (MAE) from the Mean Annual Precipitation (MAP) and indicates whether the climate in which a landfill is situated will cause it to generate a significant leachate or not.

All general waste landfills are therefore separated into two classes based on the water balance calculations. These are namely (B^+) and (B^-) landfill classes for sites with positive and negative climatic water balances respectively. Landfills at which there is a positive water balance (B^+) are identified as sites at which it is expected that a significant leachate will be generated. Landfills at which there is a negative climatic water balance (B^-) are expected to only generate a sporadic leachate.

In order to avoid contamination of the underlying ground water system, landfills at which significant leachate generation is expected are required to be installed with liners that include leachate collection and removal systems. All B^+ sites, with the exception of communal sites, are therefore required to be installed with liners which include leachate management systems. Due to the fact that B^- landfills are expected to only produce sporadic leachates, the Minimum Requirement Documents state that these landfills do not require leachate management systems.

The proposed general waste landfills excluding communal waste landfills are listed and summarized in Table 1. The cost of the material and the installation thereof has been calculated using the March 2011 material and engineering costs for the case study, which will be used for comparative cost purposes in determining the Best Practicable Environmental Option regarding the landfill design.

It is known that these costs may vary from site to site, depending on the availability and types of soil/clay present as well as the cost of the synthetic layers, availability of machinery and contractors etc. The costs indicated have been determined specifically for the 50 ha slag disposal facility addressed in the case study.

Table 1: General Waste Landfill Classes (DWAF 1998)

Landfill	Summary	Cost per ha
$G:S:B^-$	$G:S:B^-$ liners consist of a 150 mm thick compacted, re-worked soil base preparation (G) layer implemented directly on top of the un-reworked in-situ soil.	R 500 000
$G:M:B^-$	$G:M:B^-$ liners consist of an initial 150 mm thick desiccation protection layer, underlain by two 150 mm thick compacted clay (B) layers. The bottommost B layer is further underlain by a 150 mm thick base preparation (G) layer implemented directly on top of the un-reworked in-situ soil.	R 1 300 000
$G:L:B^-$	$G:L:B^-$ liners consist of an initial 150 mm thick desiccation protection layer, underlain by three 150 mm thick compacted clay (B) layers. The bottommost B layer is further underlain by a 150 mm thick base preparation (G) layer implemented directly on top of the un-reworked in-situ soil.	R 1 450 000
$G:S:B^+$	$G:S:B^+$ liners consist of an initial 150 mm thick single-sized gravel/crushed stone leachate collection (A) layer underlain by two 150 thick mm compacted clay (B) layers. The bottommost B layer is further underlain by a 150 mm thick base preparation (G) layer implemented directly on top of the un-reworked soil.	R 1 300 000
$G:M:B^+$	$G:M:B^+$ liners consist of an initial 150 mm thick single-sized gravel/ crushed stone leachate collection (A) layer underlain by four 150 mm thick compacted clay (B) layers. The bottommost B layer is underlain by a geotextile (C) layer which covers the underlying 150 mm thick leakage detection and collection (D) layer from silting up. The D layer is underlain by a 150 mm thick B layer which is further underlain by a 150 mm thick base preparation (G) layer implemented directly on top of the un-reworked in-situ soil.	R 2 000 000
$G:L:B^+$	$G:L:B^+$ liners are the same as those stipulated for $G:M:B^+$ liners and consist of an initial 150 mm thick single-sized gravel/ crushed stone leachate collection (A) layer underlain by four 150 mm thick compacted clay (B) layers. The bottommost B layer is underlain by a geotextile (C) layer which covers the underlying 150 mm thick leakage detection and collection (D) layer from silting up. The D layer is underlain by a 150 mm thick B layer which is further underlain by a 150 mm thick base preparation (G) layer implemented directly on top of the un-reworked in-situ soil.	R 2 000 000

In situations where the climatic water balance method is incomprehensive or where site specific factors are involved, the Minimum Requirement Documents stipulate that a full, detailed site water balance calculation may be required to determine whether a site will generate a significant leachate or not.

A modelling program such as HELP (Hydrologic Evaluation of Landfill Performance) may be useful in this regard. The water balance calculations obtained from the HELP models can then be used to determine the leachate generation potential of the landfill disposal facility. HELP modelling software is extensively used as a modelling tool for water balance calculations during waste disposal by landfill and will be used for the purposes of this research project.

Because of the high risk posed by certain substances in hazardous waste, their landfill disposal facilities are required by the Minimum Requirement Documents to be conservatively lined containment facilities, regardless of the site water balance. All hazardous waste landfills are therefore required to be installed and separated from the ground water system by liner systems that include leachate management systems irrespective of the site's water balance calculations.

The Minimum Requirement Documents have proposed two types of hazardous waste landfills that are to be implemented during the disposal of solid hazardous waste. The landfill classification is based entirely on the Hazard Rating of the waste stream and does not take the size of the operation, the size of the waste stream or the site water balance calculations into account.

The two hazardous waste landfills proposed by the Minimum Requirement Documents are namely H:h landfills and H:H landfills. H:H landfills are the most conservative and stringently designed of all the landfill liners and may accommodate wastes of all four hazard ratings, whilst H:h landfills may only accept wastes that have a Hazard Rating of 3 or 4 as well as general waste.

The proposed hazardous waste landfills for solid waste disposal, listed in The Minimum Requirement Documents are listed and described in Table 2. The cost of the material and the installation thereof has been calculated using the March 2011 material and engineering costs for the case study and will be used for comparative cost purposes.

Table 2: Hazardous Waste Landfill Classes (DWAF 1998)

Landfill	Description	Cost per ha
H:h	H:h liners are relatively stringent liners and consist of an initial 150 mm thick single-sized gravel/crushed stone leachate collection (A) layer underlain by a 150 mm highly permeable soil protection (E) layer. The E layer covers and protects the underlying 1.5 mm impermeable flexible membrane layer or geotextile (F) layer. The F layer is underlain by four 150 mm compacted clay (B) layers. The bottommost B layer is underlain by a geotextile (C) layer which covers the underlying 150 mm thick leakage detection and collection (D) layer from silting up. The D layer is underlain by another 150 mm compacted clay B layer which is further underlain by a base preparation (G) layer implemented directly on top of the un-reworked in-situ soil.	R 3 000 000
H:H	H:H liners are the most stringent of the liner designs and consist of two initial 150 mm thick single-sized gravel/crushed stone leachate collection (A) layers. The bottommost A layer is layer underlain by a 150 mm highly permeable soil protection (E) layer. The E layer covers and protects the underlying 2.0 mm impermeable flexible membrane layer or geotextile (F) layer. The F layer is underlain by four 150 mm compacted clay (B) layers. The bottommost B layer is underlain by a geotextile (C) layer which covers the underlying 150 mm thick leakage detection and collection (D) layer from silting up. The D layer is underlain by another two 150 mm compacted clay B layers which are further underlain by a base preparation (G) layer implemented directly on top of the un-reworked in-situ soil.	R 4 500 000

The Department of Environmental Affairs (DEA) initiated a project in 2010 which aimed to develop a revised waste classification system that would support the move away from waste disposal by landfill towards waste management options which favour waste recovery and re-use. This revised waste classification system was also developed with the aim of addressing some of the concerns that have been raised with respect to the implementation of the waste classification system stipulated in the Minimum Requirement Documents.

The main objective thereof is to review the current hazardous waste classification system used within the country, in order to develop a refined waste classification system. This revised waste classification system is still in its draft phase and has not yet been commissioned/published. The liner options proposed in the revised waste classification system are however still addressed for future reference purposes.

The proposed liner options were developed for solid waste sites only, with the aim of superseding the landfill classes stipulated in the Minimum Requirement Documents. This classification has its own shortcomings and has proposed that the liners be selected from one of four options, instead of the ten options stipulated in the Minimum Requirement Documents. The four landfill classes proposed by the Department of Environmental Affairs are summarized in Table 3.

Table 3: Proposed Waste Landfill Classes (DEA 2010)

Landfill	Description
Class A	Class A liners are the most stringent of the newly proposed liners and consist of an initial geotextile filter layer, underlain by a 200 mm thick stone leachate collection layer. The stone leachate collection layer is underlain by a 100 mm thick silty sand protection layer or a geotextile layer of equivalent performance. This layer is then further underlain by a 2 mm HDPE geo-membrane layer, followed by four 150 mm thick compacted clay layers. The compacted clay layers are further underlain by a geotextile filter layer as well as a 150 mm leakage detection layer comprising of granular material or a geo-synthetic equivalent. This is further underlain by another 100 mm thick silty sand protection layer, a 1.5 mm thick HDPE geo-membrane layer and one 200 mm thick compacted clay layer, underlain by the 150 mm thick base preparation layer. The base preparation layer is the bottommost layer and is installed directly on top of the in-situ soils.
Class B	Class B liners consist of an initial geotextile filter layer, underlain by a 150mm thick stone leachate collection layer. The stone leachate collection layer is underlain by a 100 mm thick silty sand protection layer or a geotextile layer of equivalent performance. This layer is then further underlain by a 1.5 mm HDPE geo-membrane layer, followed by four 150 mm thick compacted clay layers. The compacted clay layers are directly underlain by a drainage and monitoring system layer. This leachate monitoring layer is installed directly above the base preparation layer, which itself is installed directly on top of the in-situ soils.
Class C	Class C liners consist of an initial 300 mm thick finger drain consisting of geotextile covered aggregate. The finger drain layer is then underlain by a 100 mm thick silty sand protection layer or a geotextile layer of equivalent performance. This layer is then further underlain by a 1.5 mm HDPE geo-membrane layer, followed by two 150 mm thick compacted clay layers. The compacted clay layers are directly underlain by a drainage and monitoring system layer that is instilled within the base preparation layer, directly on top of the in-situ soils.
Class D	Class D liners consist only of a 150 mm thick base preparation layer that is directly installed on top of the in-situ soils. These are the least stringent of the newly proposed liners and have the same requirements as stipulated for the G:S:B$^-$ landfill liners.

Each of the abovementioned landfills are selected according to the classification of the waste and or according to the size of the waste stream and do not take site specific factors fully into account. The landfill and liner options are thus selected from a series of predefined landfills that have been proposed and are often inappropriate for the specific waste disposal facility.

It is the aim of this research project is to investigate the benefits of using data that is required to be obtained in the field to design the most appropriate landfill in the most conservative and cost effective way, through the application of available water balance and mass transport modelling techniques.

Several different lining systems are investigated and various sensitivity analyses conducted for the various layer thicknesses, slopes, permeability etc within the liner designs. These analyses were carried out using the HELP modelling software to investigate and comparatively assess the predicted volumes of leachate that could potentially infiltrate through each of the different liners. The movement and concentration of the leachate in the saturated ground water zone will be assessed using mass transport modelling techniques and simulations. Visual MODFLOW will be used as the mass transport modelling software and will be used to determine and graphically illustrate the simulated lateral migration and concentrations of leachate or contaminants in the saturated ground water zone for the different landfill options.

The volume and geochemistry of the leachate that is expected to infiltrate through the different landfill options will be used as the input leachate volumes and concentrations for the mass transport model. Although it is expected that the geochemistry of the leachate will alter as it infiltrates through the unsaturated zone and into the saturated zone, it will however not be assessed for the purpose of this research project. This is a conservative calculation and will as a result represent the scenario that exists if all the leachate that passes through the liner systems enters the saturated ground water zone. The concentrations of leachates simulated in the saturated zone therefore represent the worst case scenario and assumes that all the chemicals are mobile and will remain in solution. The geochemistry of the leachate generated from the slag will however be determined, assessed and used to characterise the waste.

By following this process the landfill will be optimally designed according to the data obtained in the field, rather than using a generic allocated landfill option, which has been selected according to a set of waste classification systems. It is therefore expected that each individual landfill site will be unique and optimally designed according to the site specific factors, such as the meteorological conditions, the composition and physical properties of the waste as well as the topographical setting of the disposal facility

The project will investigate the potential generation of soluble/mobile contaminants (leachate) within the slag disposal facility, the potential quality of the leachate generated from the slag disposal facility, the degree to which the various landfill liner options can capture and remove the leachate and finally investigate the lateral migration of these contaminants within the saturated zone away from the source and towards the receptors.

The ground water flow and mass transport model has an additional benefit in that it may be used to indicate the expected contaminant migration pathways and extent, from which an optimal ground water monitoring plan may be determined and implemented prior to waste disposal. "The ability to reliably predict the rate and direction of ground water flow and contaminant transport is critical in planning and implementing ground water remediation measures" (Bear, et *al.*, 1992).

Improved waste management and more stringent liner systems will inevitably result in increased costs. The Best Practicable Environmental Option norm is therefore recommended to be adopted, which accounts for the optimal environmental protection at the optimal costs of waste management. The BPEO will used as a motivation in order to assess the benefits of optimally selecting the most comprehensive and conservative liner at the most optimal costs, using the field data that is available as well water balance and mass transport modelling techniques.

The research project will therefore ultimately determine the effectiveness of selected stipulated liner designs in capturing the leachate that may be generated at the base of the landfill disposal facility. The research project further aims to determine the Best Practicable Environmental Landfill Design Option for the slag disposal facility investigated, by means of a comparative cost assessment and in compliance with South Africa's current environmental legislation.

2 LITERATURE REVIEW

2.1 OVERVIEW OF ENVIRONMENTAL LEGISLATIONS

The management of waste remains one of the country's major environmental issues and it is thus important that the disposal thereof is properly managed. South Africa's legislation makes it clear that everyone has the right to a clean and safe environment and that any waste being disposed of should be done in such a way so that it does not affect the quality and quantity of the natural resources. Ground water in South Africa is one such resource and has a high potential of being impacted by infiltrating leachate generated at the surface.

Some of the internationally established environmental norms and phrases used in the country's constitution and legislation include: "Sustainable Development", "The Precautionary Principle", "Intergenerational Equity", "A Human Right to a Decent Environment" and "The Preventive Principle" which all indicate the need to protect the environment and conserve for future generations. Also included in the South African legislation is the philosophy of a "Risk Averse" environmental management approach, which uses the Source-Pathway-Receptor hierarchy. Each of these phrases leads to an understanding that the country's resources should be protected and managed.

Some of the country's legislation that aims to protect the natural resources include: The National Environmental Management Act; The National Environmental Management Waste Act; The National Water Act and various guidelines such as the Department of Water Affairs' Minimum Requirement Documents.

These environmental regulations and guidelines are used to motivate the actions of correct waste disposal including the assessment of potential impacts that waste disposal facilities may have on the environment, including the ground water resources, prior to the disposal thereof. The underlying objective is to raise the point that we essentially need to protect and manage the environment as well as to contain and manage any waste generated in the most optimal way.

2.1.1 The Constitution of the Republic of South Africa

The Constitution of the Republic of South Africa, (Act 108 of 1996) referred to as the "Constitution" is the supreme law of the country and incorporates a Bill of Rights (Chapter 2) in which particular environmental protection concerns are addressed. "*This Bill of Rights is a cornerstone of democracy in South Africa. It enshrines the rights of all people in our country and affirms the democratic values of human dignity, equality and freedom*", The Constitution of the Republic of South Africa.

Section 24 of the Bill of Rights states that "*everyone has the right to (a) an environment that is not harmful to his or her health or well-being, and (b) to have the environment protected, for the benefit of present and future generations, through reasonable legislative and other measures.*" It is for this reason that potential environmental impacts during waste disposal activities are to be identified, managed, mitigated and if possible remediated or removed.

The establishment and operation of waste disposal sites must therefore not violate the constitutional right of the communities living in the vicinity of the landfill disposal facility, as well as the environment as a whole. This indicates that any potential leachates generated at the landfill disposal facilities should therefore be captured, contained and removed so that it does not enter the environment.

2.1.2 The National Environmental Management Act

The National Environmental Management Act (Act 107 of 1998) ("NEMA") imposes certain environmental management duties and obligations on industrial activities and Section 2 of the NEMA refers to the National Environmental Management Principles. This section commonly serves as the general framework within which environmental management and implementation plans in South Africa are formulated and carried out. Section 2 of the NEMA is used in practice to guide the interpretation, administration and implementation of actions regarding the protection or management of the environment.

Section 2 of the NEMA gives further reference to the principles highlighting the concept of "Sustainable Development". Relevant to this research project is the principle in which negative impacts on the environment and on people's environmental rights as a result of waste disposal are to be anticipated and prevented, and where they cannot be altogether prevented, should be minimized and/or remediated. The analysis of the slag is therefore of vital importance as it will provide essential information regarding the chemical composition thereof as well as its physical attributes at disposal.

The NEMA makes provision for Integrated Environmental Management (IEM) and one of the objectives is to "*identify, predict and evaluate the actual and potential impact on the environment with a view of minimizing negative impacts, maximising benefits and promoting compliance with the principles of environmental management*" Section 2 of the NEMA.

Whilst the abovementioned provisions provide a broad outline of the legislative intent, a more direct obligation whereby the necessary implications involving the assessment and characterization of the source is found in Section 24 of the NEMA. Section 24 of the NEMA states that "*the potential consequences for or impacts on the environment of listed activities or specified activities must be considered, investigated and assessed*".

Section 24 also states that the procedures must include the investigation of "*potential consequences or impacts of alternatives to the activity on the environment and an assessment of the significance of those potential consequences or impacts, including the option of not implementing the activity should be considered*".

The assessment and characterization of the slag becomes relevant in Section 28 of the NEMA, which includes a provision known as the statutory "duty of care". The duty of care states that "*every person (or institution) that causes, has caused or may cause significant pollution or degradation of the environment must take reasonable measures to prevent such pollution or degradation from occurring, continuing or recurring*". In other words, the generator of the waste is responsible for any that the waste might have on the environment. The statutory duty of care is a general duty that finds application in addition to and over and above any legislation or specific legal obligation.

Section 28 of the NEMA also provides for a general statutory duty to take reasonable measures to prevent pollution or degradation of the natural environment, especially during disposal.

Typical landfill waste disposal facilities are more often than not subject to this statutory duty. In order to comply with its duty, industrial activities or waste generators should take reasonable measures to prevent pollution or degradation of the environment caused by their activities on the site.

The reasonable measures may include the following:

- investigate, assess and evaluate the impact on the environment;
- cease, modify or control any act, activity or process causing the pollution or degradation;
- contain or prevent the movement of pollutants or the source causing the degradation;
- eliminate any source of the pollution or degradation; or
- remediate the effects of the pollution or degradation.

The duty of care applies to industrial activities as well as mining activities insofar as these operations have an impact on the environment.

2.1.3 The National Environmental Management Waste Act

The National Environmental Management Waste Act (Act 59 of 2008) ("NEMWA") acknowledges the internationally recognised hierarchy of waste management, stating that sustainable development requires that "*waste generation is avoided, or if it cannot be avoided, that it is reduced, re-used, recycled or recovered, and as a last resort treated and/or safely disposed of*".

The NEMWA recognises that waste management practices in many areas of the country are not favourable to a healthy environment and can lead to an adverse impact thereof. It also recognises that under certain circumstances waste is a resource and the remediation thereof may offer economic opportunities.

Central to the NEMWA is the requirement of a Waste Management Licence in order to undertake certain specified Waste Management Activities. Specific waste management measures include the identification of priority wastes and measures to be prescribed for dealing with such wastes. In addition to industry waste management plans, the principle of 'extended producer responsibility' (cradle to grave principle) is also formalized in the NEMWA. In accordance with the "duty of care" principle, the "cradle to grave" principle places the responsibility, management and costs associated with the disposal of the waste on the generator thereof.

2.1.4 The National Water Act

The purpose of the National Water Act (Act 36 of 1998) ("NWA") is to ensure that the country's water resources are "*protected, developed, conserved, managed, controlled and used in a way, which takes into account, inter alia the reduction and prevention or degradation*" of the water resources in South Africa.

The prevention of pollution in terms of the NWA includes the protection of the water resources as well as the remediation of the effects that pollution may have already had on the resources. These are to be performed in terms of the provisions of Section 19 of the NWA, which states that "*an owner of land, a person in control of land or a person who occupies or uses land on which any process is or was performed or undertaken, or any other situation exists, which causes, has caused or is likely to cause pollution of a water resource, must take all reasonable measures to prevent any pollution from occurring, continuing to occur or recurring*".

Whereas section 28 of the NEMA relates to the environment in a broad sense, Section 19 of the NWA refers to water resources as statutorily defined. In terms of Section 19, a duty of care to prevent pollution and environmental degradation is imposed on the operations/companies that want to dispose of hazardous waste as well.

Information regarding the sources of impacts on the water resources is therefore essential in order to develop the legal parameters in terms from which reasonable measures can be formulated with regards to present and historical ground and surface water contamination. The legal framework for the assessment and characterization of the slag is therefore to be found in the statutory duty of care recorded in the NEMA as well as the duty to prevent pollution of water resources in the NWA.

The Department of Water Affairs published three minimum requirement documents in 1998 regarding the handling, classification, transport, disposal, and monitoring of hazardous waste as part of their "Waste Management Series". The waste management series was initiated with the aim to upgrade the standard of waste management within South Africa and to provide a system whereby waste disposal could be managed.

The first of three documents within the Waste Management Series refers to the "Minimum Requirements for the Handling, Classification and Disposal of Hazardous Waste", whilst the second refers to the "Minimum Requirements for Waste Disposal by Landfill" and the third refers to the "Minimum Requirements for the Monitoring of Water Quality and Waste Management Facilities".

Both the first and the second Minimum Requirement Documents are applicable for the purposes of this research project. The third document which refers to monitoring is equally important, but will not be looked at in great depth for the purposes of this study. It does however remain a vital part in the management and protection of the environment when it comes to waste disposal.

Through the implementation of the classification system stipulated in the "*Minimum Requirements for the Handling, Classification and Disposal of Hazardous Waste (1998)"* certain shortcomings have been identified by consultants, industrial and waste managers alike. In an attempt to address these issues, a draft 3rd Edition of the Minimum Requirements was published in 2005, but due to various reasons, the revised system was never finalised and has not been implemented.

The Department of Water and Environmental Affairs has therefore initiated a project to develop a revised waste classification system, which would support the movement away from waste disposal by landfill towards waste management options which favour waste recovery and re-use. The main aim thereof is to review the current hazardous waste classification system used within the country, in order to develop a revised waste classification system. This revised waste classification system is still in its draft phase and is yet to be commissioned/published.

2.2 MINIMUM REQUIREMENT DOCUMENTS

The Minimum Requirement Documents form part of the previous Department of Water Affairs and Forestry (DWAF) Waste Management Series and were published in 1998 with the aim of protecting the country's water resources, the environment as well as human health.

The Minimum Requirement Documents set out a systematic framework of procedures that are to be followed during the identification and classification of different waste types according to their waste stream as well as the risk that they potentially pose on contaminating the environment. The documents also stipulate various standards or "minimum requirements" that are to be adhered to during the handling, classification, disposal, treatment, monitoring and transport thereof as well.

The first document (*Document 1 - Minimum Requirements for the Handling, Classification and Disposal of Hazardous Waste*) sets out a type of waste classification system that is recommended to be used as a guideline for most waste disposal facilities in South Africa. This classification system distinguishes the waste into separate classes according to the degree of hazard that the waste poses on contaminating the environment based on the toxicity of the waste, as well as the disposal thereof.

The second document (*Document 2 - Minimum Requirements for Waste Disposal by Landfill*) deals with the disposal of waste by landfill and addresses the siting, investigation, design, operation and management of landfill sites as well the classification thereof. In the landfill classification system set out in Document 2, a landfill is classified in terms of waste class, size of operation and the potential it poses for significant leachate generation, all of which influence the risk it poses to the environment. Graded requirements for all aspects of landfilling are then set out in which the waste disposer is required to adhere to.

The third document (*Document 3 - Minimum Requirements for the Monitoring of Water Quality at Waste Management Facilities*) addressed the monitoring of the water quality at and around disposal facilities. Although ground water and surface water monitoring plays a vital role with regards to the management of waste disposal facilities, it will not be addressed for the purpose of this research project.

2.2.1 Waste Characterization and Classification

In order for waste to be properly managed, its composition, concentration and quantity are to be determined by means of accurate and appropriate analyses. The analyses of the waste should identify the inorganic and organic constituents present in the waste, including their concentrations, toxological hazard and impact that they may have on contaminating the environment. The impact that the waste may have on the environment should also be assessed and closely characterized in conjunction with the nature and vulnerability of the receiving environment.

The Minimum Requirement Documents use the concentrations of the hazardous substances to determine the classification of the waste. Some of the methods that can be used to determine the constituents in the waste include Atomic Absorption Spectroscopy, Atomic Emission Spectroscopy, X-ray Diffraction, X-Ray Fluorescence and Ion Chromatography.

2.2.1.1 Waste Classes

The Minimum Requirement Documents classify two types of wastes according to their toxological properties as well as the risk that they potentially pose on contaminating the environment. These are namely: "*General Waste*" which poses little risk on contaminating the environment and "*Hazardous Waste*", which poses a much larger risk on contaminating the environment. The Minimum Requirement Documents define hazardous waste as "*waste that has the potential, even in low concentrations, to have a significant adverse effect on the public health and the environment because of its inherent toxicological, chemical and physical characteristics".* General Waste refers to *"any waste that does not fall within the definition of Hazardous Waste*" (Department of Water Affairs & Forestry, 1998. Waste Management Series. Minimum Requirements for the Handling, Classification and Disposal of Hazardous Waste).

This general classification of hazardous waste is fairly broad and has therefore been further subdivided according to the Minimum Requirement Documents. This subdivision is based on the risk that the waste poses on contaminating the environment at disposal and is made according to a Hazard Rating (HR) classification system.

The South African legislation has stipulated that the most practical method of identifying and classifying a hazardous waste is by:

- Providing a list of industries and processes which are identified as possible hazardous waste generators.
- Providing a list of substances against which the concentrations in the waste can be compared.
- Providing a degree of hazard approach which determines whether a waste is hazardous or not, as well as to differentiate between the degree of hazard associated with different disposal methods and sites.

- Using the "*acceptably low risk*" approach to allow for the delisting or reclassification of hazardous wastes to less hazardous wastes or even general waste if it can be shown that the risk posed to the environment is acceptably low.

The objective of the classification system is to distinguish between hazardous and general waste, determine the single most hazardous property of the waste as well as the degree of hazard posed by the hazardous waste, and provides the foundation on which the Minimum Requirement Documents' hazardous waste classification system was developed.

The "Precautionary Principle" has been applied during the Minimum Requirement Documents' waste classification system and stipulates that "*all waste is required to be regarded as being a hazardous waste until it is proven otherwise*".

2.2.1.2 Classification of Hazardous Waste

According to the Minimum Requirement Documents the first indication that a waste could potentially be classified as being hazardous is determined from the industrial group or process from which it was generated. This classification is further verified during the geochemical analyses of the waste material, whereby the geochemistry of the waste is assessed against the Hazardous Waste Classification Tables listed in the Minimum Requirement for the Handling Classification and Disposal of Hazardous Waste document (Document 1). The Hazardous Waste Classification Tables are derived from the SABS Code 0228.

The SABS Code 0228 is further derived from the International Maritime Dangerous Goods (IMDG) Code and forms the basis of the Minimum Requirement Documents' hazardous waste classification system. The IMDG Code was adopted by South Africa in 1986 and is used to provide a uniform and internationally acceptable system for the classification of hazardous substances.

Once the composition and geochemistry of a waste have been determined it is compared to the SABS Code 0228, Basel Convention and Waste Classification Tables. If any of the substances or characteristics of the waste are listed in the tables, it is confirmed that the waste is a hazardous waste and the generator thereof is to register as a "*hazardous waste generator*". The waste generator is then further required to determine the minimum requirements associated with the disposal of the waste.

The Minimum Requirement Documents' waste classification system is broken down into the following steps:

- Identify if the waste or waste stream is 'probably' hazardous or not based on the process of waste generation. The processes and activities that are likely to produce hazardous waste have been grouped into eleven industrial groups.
- Test and analyse the waste to determine the substances, compounds, properties, concentrations and characteristics of the waste.
- Once the concentrations and characteristics of a waste have been determined, they are compared to the Waste Classification Tables derived from the South African Bureau of Standards (SABS) Code 0228 ("*The Identification and Classification of Dangerous Substances and Goods*") Tables. The dangerous goods listed in the SABS Code 0228 are classified into nine classes, namely:
    - Class 1: Explosives,
    - Class 2: Gases,
    - Class 3: Flammable Liquids,
    - Class 4: Flammable Solids,
    - Class 5: Oxidizing Substances,
    - Class 6: Toxic and Infectious Substances,
    - Class 7: Radioactive Substances,
    - Class 8: Corrosive Substances and
    - Class 9: Miscellaneous Dangerous Substances.
- Confirm that the waste is hazardous, by classifying the most dangerous substance in the waste against the 9 sequential SABS Code 0228 classes.
- If any of the variable concentrations in the waste are listed in and exceed concentrations stipulated in the SABS Code 0228 tables, then the waste is classified as a hazardous waste. It should however be noted that the substances included in SABS Code 0228 tables are mostly organic substances and do not comprehensively cover the inorganic substances.
- Determine the minimum requirements that are required for the disposal of the waste by landfill according to the classification thereof. All wastes or residues of waste are required to be classified according to Class 6 (Toxic and

Infectious Substances) of the SABS Code 0228. It is at this stage that the waste is assigned a Hazard Rating. The waste is assigned a Hazard Rating based on the toxicity of the waste, which is used to determine the minimum requirements required regarding the treatment and disposal thereof.

- It is often required that a waste be treated before it can be disposed of. In such instances the Minimum Requirement Documents stipulate that the residue of the treated waste be analysed.
- The acute mammalian toxicity (LD_{50}), ecotoxicity (LC_{50}), carcinogenicity, mutagenicity, teratogenicity, persistence or environmental fate and estimated environmental concentration (EEC) of the waste or its residue are required to be determined as well. The LC_{50} is the concentration at which a substance "*would kill 50% of specific warm and cold water fish and invertebrate species if it was disposed of directly into a body of water*". The LD_{50} indicates the dosage that would statistically kill 50% of the mammals concerned and is expressed per kg body mass. The Minimum Requirement Documents state that "*due to the nature (fact) that the aquatic environment is more sensitive than man or mammals to contamination and pollution, if it is proved that it (aquatic environment) is not at risk, then it is assumed that man and mammals will not be at risk either*".
- Use the EEC to provide an exposure level against which the calculated concentrations in the waste are compared. In this approach, chemical compounds are regarded as being hazardous if they occur at concentrations above the given EEC threshold concentrations. The EEC is used as one of the factors to determine the Hazard rating of the waste.

The Minimum Requirement Documents stipulate that waste generators are allowed to perform further tests such Acid Rain Leaching Procedure or Toxicity Characteristic Leaching Procedure tests to identify whether or not the waste should be regarded as non-hazardous or of a less hazardous nature and be delisted from the original hazardous waste class.

2.2.1.3 Hazard Rating

The Hazard Rating classification system is intended to provide an assessment of the risk posed by the waste or substance in the waste to man and the environment as a result of the disposal thereof. The objectives of the Hazard Rating classification system are to indicate the degree of risk posed by a waste and hence the degree of care required to contain it at its disposal site. This includes the classification of hazardous waste landfills at which hazardous waste is to be disposed of as well as the amount of a hazardous substance that can be disposed of at a particular waste site before it begins to pose a risk on contaminating the environment.

The Hazard Rating classification system separates the hazardous waste into four distinct classes according to the risk that the waste poses at disposal. According to the Minimum Requirement Documents a hazardous waste with a Hazard Rating of 1 represents a waste that potentially poses an "*extreme hazard*" on contaminating the environment. A waste with a Hazard Rating of 2 poses a "*high hazard*", a waste with a Hazard Rating of 3 a "*medium hazard*" and a waste with a Hazard Rating of 4 a "*low hazard*" on contaminating the environment. The four classes are ranked according a logarithmic scale, where class 1 is predicted to be ten times more hazardous than class 2 and 1000 times more hazardous than class 4 for example.

Only two of the factors which are required to be determined are taken into account during the Hazard Rating classification system, namely the amount of the substance in the waste that can potentially enter the environment (EEC) and the inherent toxological hazard of the substance (ecotoxicity). The EEC represents the exposure of a hazardous substance in the waste, should it entirely enter the environment, whilst the ecotoxicity is the concentration of a substance at which there is the potential to harm animals, plants, ecosystems or environmental processes.

During the Hazard Rating calculations the EEC of the most hazardous substance in the waste is compared to 10% of the stipulated ecotoxicity value for that substance termed the Acceptable Risk Level. According to the Minimum Requirement Documents, the Acceptable Risk Level represents "*the concentration at which the substance would cause a mortality incidence of one in three hundred thousand in an aquatic environment*". The Acceptable Risk Level therefore represents the concentration at which a substance is expected to have little adverse impact if it enters the environment.

The environmental pathway of a substance generated from the waste disposal facility is usually through water. The EEC is therefore calculated as the resultant concentration of a hazardous substance in a body of water, should the total amount of the hazardous substance in the waste that is disposed of on 1 hectare (ha) of landfill, leach out from the waste and into the underlying body of water over an indefinite period of time.

The EEC represents an unrealistic worst case scenario as it assumes that all of the hazardous substances will leach out entirely from the waste and enter the environment. The EEC does not take ground water flow (advection), dispersion or diffusion into consideration either. In order to determine the most conservative risk that the waste or hazardous substance in the waste pose on contaminating the environment, the Minimum Requirement Documents require that the EEC of the most hazardous substance in the waste be determined and used during the Hazard Rating calculations.

The Minimum Requirement Documents state that the “safest” way of calculating the EEC would be “*to use a model in which an amount of contaminant is introduced in total into a body of water*”, as water is seen as the major pathway for the movement of contaminants. The EEC is thus determined using the total concentration of a hazardous substance in an aquatic environment and is expressed as:

EEC (ppb) = dose (g/ha/month) x 0.66.

The dose indicates the amount of the substance in the waste that is disposed of per hectare of landfill. The factor of 0.66 has been statistically derived from the ratio of the substance in a weight of an underground body of water. If there is more than one hazardous substance in the waste then there will be more than one EEC for that waste. In these situations, the EEC of the most hazardous substance in the waste will be used to determine the Hazard Rating.
The Hazard Rating is then in turn used to determine the class of landfill at which the hazardous waste is to be disposed of. An H:h landfill for example, may only accept hazardous wastes with a Hazard Rating of 3 or 4, whilst an H:H landfill may accept hazardous waste of all four classes.

Where the classification of the waste falls below a Hazard Rating of 4, the degree of hazard posed by the waste is considered low enough to allow the waste to be disposed of at a General Waste landfill containing a leachate interception system.

The Minimum Requirement Documents use the EEC to calculate that Hazard Rating of the waste, using the following five steps:

- Calculate how much waste is produced per month.
- Calculate the EEC and determine the most hazardous substance.
- Look at literature for the LC_{50} values for the specific substances.
- Calculate the Acceptable Risk Level (0.1 x LC_{50}) of the specific substance.
- Compare the EEC to the Acceptable Risk Level and determine the Hazard Rating of the waste.

If the EEC is higher than Acceptable Risk Level for the most hazardous substance, then the waste is assigned the Hazard Rating of that specific hazardous substance.

2.2.1.4 Estimated Environmental Concentration

The EEC, in addition to the calculation of the Hazard Rating, is used to determine the amount of waste that may be disposed of at a specific landfill within an acceptable risk (Total Load), determine the maximum amount of a given hazardous substance in the waste that can be disposed of at a landfill site and whether a waste, that is initially regarded as hazardous waste can be delisted to and disposed of as general waste.

Total Load

The Total Load is defined in the Minimum Requirement Documents as the "*capacity of the hazardous waste landfill to safely store/accept a certain substance*" and is calculated by multiplying the allowed monthly volume per hectare by a factor of 100. The total load capacity of a landfill is influenced by the inherent hazardness of the waste, the mobility (leachability) of the waste as well as the landfill design including its leachate interception system.

Delisting

Delisting refers to the situation where a hazardous compound moves from a specific risk group to a lower risk or "no-risk" group. It does, however, not become a non-hazardous waste, but the associated risk posed by the waste declines to a risk that is more acceptable.

Since a single substance can determine the Hazard Rating of the waste, treatment thereof can be used to reduce the hazardousness of the substance. Treatment of a specific contaminant in the waste may for example affect the leachability and hence the mobility of certain constituents of concern in the waste. Once the single most hazardous substance in the waste has been treated, the next most hazardous substance may be used to determine the hazard rating, and so on.

The EEC can therefore be used to prove that certain substances in the waste, because of their low mobility, are of a less hazardous nature than initially indicated. If the EEC is lower than the Acceptable Risk Level, a waste with a Hazard Rating of 1 remains in the same Hazard Rating, whilst wastes with Hazard Ratings of 2, 3 or 4 can be delisted and assigned lower Hazard Ratings. Due to the presence of carcinogens and teratogens in Hazard Rating 1 wastes, wastes in this group can only delist when the EEC is less than 10% of the Acceptable Risk Level.

Hazardous wastes with Hazard Ratings of 2, 3 or 4 that have been delisted can be legally disposed of at general waste landfills containing a leachate interception system. A waste with a Hazard Rating of 1 can only be delisted to a general waste landfill containing a leachate collection layer if the EEC of the most hazardous substance in the waste is less than 10% of the Acceptable Risk Level. The landfills for the different waste classes are therefore to be appropriately designed in order to optimally protect the environment from harmful effects, caused by the disposal of waste, in the most cost effective way.

A summary of the use of the EEC and ecotoxicity (LC_{50}) to determine whether a waste may be delisted or not as well as to determine the relevant waste landfill classification associated with the disposal thereof is summarized in the table below:

If EEC:	Risk (Y/N)	Landfill Classification
> 0.10 x LC_{50}	Yes	Remains in Hazard Rating and landfill class
< 0.10 x LC_{50} (for HR1)	Yes	HR1 waste still falls within H:H landfill class
< 0.10 x LC_{50}	No	HR2, HR3 and HR4 waste can be delisted and disposed of at $G:B^+$ landfill sites
< 0.01 x LC_{50}	No	All HR wastes can delist to $G:B^+$ landfill sites

There may be instances where it is considered that the hazard rating based on the EEC is too conservative and that Toxicity Characteristic Leaching Procedure or Acid Rain Leaching Procedure tests are to be used to affirm the calculated EEC values, or to verify whether it is safe to delist the hazardous waste to a lower rating or not.

2.2.2 Leachability Tests

Tests such as the Toxicity Characteristic Leaching Procedure (TCLP) or the Acid Rain Leaching Procedure (ARLP) are carried out in order to determine the leachability or mobility of the waste and are used to determine the amount of a hazardous substance that will leach out of the waste under acidic conditions. The TCLP test was developed by the United States of America's Environmental Protection Agency (USEPA: Method 1311) to measure the ability of a substance to leach from the waste into the environment. The TCLP test is used where wastes are co-disposed with domestic waste or other hazardous wastes containing organic matter that may generate organic acids. The Acid Rain Test is used when inorganic wastes are mono-disposed of at a specific site and no organic acids would therefore be expected to be generated at these sites.

The ARLP test is based on the fact that carbon dioxide (CO_2) dissolves in rain water (H_2O) to form carbonic acid (H_2CO_3), which could possibly mobilize organic and/or inorganic materials in the waste. The test is therefore conducted by extracting a sample of waste with a saturated solution of carbonic acid at a pH of between 3.6 and 3.8. Slag is mono-disposed and the assumption is made that the slag dump will form a permanent feature and will not be re-worked in the short term. The ARLP Test is thus the more appropriate of the two tests with regards to the slag landfill disposal facility.

The Minimum Requirement Documents stipulate that there are two further methods for classifying the waste, namely a "*fixed scenario approach*" and a "s*ite specific approach*". The fixed scenario approach is very stringent and is usually associated with the "worst case" classification of the waste. For the site specific approach, site specific data such as the local meteorology, waste properties, lining designs, geological properties etc. are used to assess the seepage volume from the waste sites, adsorption in the unsaturated zone, dilution in the saturated zone and transport modelling of the aquifer, providing a more quantitative and realistic assessment of the risk associated with the waste disposal facility. This is of utmost importance regarding the optimal management and duty of care taken with regards to waste disposal by landfill.

The site specific assessment can be conducted using available numerical, flow and mass transport modelling software and could potentially be a useful tool in the optimisation of the landfill design for waste disposal by landfill. This is highlighted by the fact that the Hazard Rating classification system and disposal of hazardous waste does not take all the site specific factors into account during the sub-classification of the hazardous waste.

2.2.3 Disposal of Hazardous Waste

Once the hazardous waste has been identified, classified and assigned the final Hazard Rating it is required to be safely disposed of. The objective of hazardous waste disposal facilities are to ensure that any adverse impacts on the environment resulting from the hazardous waste are minimized by preventing contaminants from leaching into the environment and to ensure that the hazardous waste is disposed of in accordance with the class and Hazard Rating of waste.

Hazardous waste may be disposed of by landfill or by incineration, but due to the lack of facilities and the high costs of incineration the most common method of hazardous waste disposal is by landfill. The second of the Minimum Requirement Documents deals with waste disposal by landfill and one of the aims of this document is to "*provide guidelines for environmentally acceptable waste disposal for numerous landfill sizes and types*".

After the final Hazard Rating of the hazardous waste has been determined, the Minimum Requirement Documents set out certain guidelines regarding the disposal thereof. Hazardous waste may only be disposed of at a landfill that is specifically designed for the disposal of hazardous waste.

According to the Minimum Requirement Documents, the flow of leachate through the liner of a hazardous waste landfill is estimated to be around 5%, with 95% of the leachate being absorbed permanently in the waste or captured by the leachate interception system, included in the liner systems. Landfills that can accept hazardous waste are classified as H:H and H:h landfills.

H:H landfills can accept all wastes that are permitted to be landfilled, whilst H:h landfills, which are not as stringently designed as H:H landfills may only accept hazardous wastes with a hazard rating of 3 or 4, as well as general wastes.

2.2.4 Waste Disposal by Landfill

The disposal of waste by landfill is the practice of depositing waste material on the earth's surface, whether it is the filling up of excavations or the mounding of waste at the surface. According to the Minimum Requirement Documents "*it is estimated that in excess of 95% of the waste generated in South Africa is disposed of by landfill*".

Landfilling is environmentally acceptable if it is carried out correctly and appropriately. Incorrect landfill classification or inappropriate disposal practices will inevitably result in environmental degradation and it is thus vital the most optimal landfill be designed for each individual waste that is generated.

The disposal of waste by landfill is currently regulated by the Minimum Requirement Documents and is based on the Integrated Environmental Management approach. This approach promotes: 1) "*the proactive control of pollution, by integrating environmental aspects into the planning of developments*" (Department of Environmental Affairs: The Integrated Environmental management Procedure, 1992), 2) the preventative principle as well as 3) the Best Practicable Environmental Option. The aim of the BPEO in this instance is to determine the landfill option that will provide the most benefit and least damage to the environment as whole, both in the long and short term, at a practically acceptable cost.

The objective of the landfill disposal requirements is to ensure that wastes which are classified as potentially posing a large risk on contaminating the environment are disposed of more stringently than wastes that are classified as posing less risk of contamination. Due to the chemical or toxic risk that certain substances in hazardous wastes pose on the environment, the hazardous waste liner options are designed more stringently than the liner options designed for the general waste disposal facilities. It is inevitable that the more stringent the liner design, the more expensive the material is as well as the costs involved with the construction thereof.

2.2.5 Landfill Classification

Due to the fact that landfills differ from one another in terms of size, type of waste and potential threat to the environment, a graded classification system has been included in the Minimum Requirement Documents, whereby landfills are differentiated. The Minimum requirement Documents indicate that "*to ensure practical and affordable environmental protection, graded requirements are applied to the different classes of landfill*". The landfill disposal facilities are as a result classified according to three parameters, namely the type of waste, the size of the waste stream and the potential for significant leachate generation based on the site water balance.

It should be noted that the Minimum Requirement Documents do not take the site specific parameters into consideration during the landfill classification system and state that "*such factors are addressed during the site selection, investigation and environmental impact assessment, where any critical factor would be identified*". These impacts would only be identified after the original landfill has been classified and selected after which a comprehensive re-classification process would be required.

The first landfill classification is made between landfill sites that are suitable for general waste disposal only or for hazardous waste disposal. General waste typically includes domestic, commercial, certain industrial wastes and builders rubble, whilst inorganic, oily waste, organic, putrescible, high volume/low hazard or certain miscellaneous wastes are regarded as being potentially hazardous.

All waste is therefore required to be analysed, classified and then disposed of at the allocated landfill site according to its classification. There are 10 different waste landfills that have been designed, 8 of which cater for general waste streams and only 2 of which cater for hazardous waste streams.

2.2.5.1 <u>General Waste Landfills (G)</u>

General waste may be may disposed of on any permitted landfill, according to the size of its waste stream and the potential that the waste poses on generating a leachate of significant quantity.

Size of Waste Stream

General waste landfills are subdivided into four classes based on the size of the waste stream and operation from which it was formed. These classes are namely Communal (C) landfills, Small (S) landfills, Medium (M) landfills and Large (L) landfills. The size classification is based on the Maximum Rate of Deposition (MRD) of the waste stream. The MRD is simply the projected average annual rate of waste disposal by landfill and is expressed in tonnes per day.

Waste streams with a MRD in excess of 500 tonnes per day are classified as Large Landfills. Medium Landfills are classified as having a MRD of between 150 and 500 tonnes per day, whilst Small Landfills have an MRD of between 25 and 150 tonnes per day. Landfills in which the MRD is less than 25 tonnes per day are classified as Communal Landfills.

Potential for Leachate Generation

General Waste Landfills may produce a leachate with an undesirably high contamination potential and are thus further subdivided according to the risk that the waste poses on generating a significant leachate. The Minimum Requirement Documents state that "*any landfill has the capacity to generate sporadic leachate in excessively wet weather conditions, and that it is only necessary to install leachate management systems when leachate generation could have an adverse impact on the environment*". A distinction is thus also made between general wastes that are expected to generate a sporadic leachate and those that are expected to generate a significant leachate.

The potential that a waste poses on generating a significant leachate is dependent on the water balance associated with the landfill site. The site water balance is influenced by factors such as rainfall, evaporation, moisture content of the waste as well as water ingress into the waste body as a result of insufficient waste disposal practices. As ambient climate conditions are the major uncontrollable cause of significant leachate generation at a landfill, the Minimum Requirement Documents stipulate that a "Climatic Water Balance" is to be calculated and used as an initial indicator as to whether the possibility for significant leachate generation at a landfill site exists or not.

The climatic water balance indicates whether the climate in which a landfill is located will potentially cause it to generate a significant leachate or not. The climatic water balance is not a detailed water balance and is a very coarse way of determining whether a significant leachate could potentially be generated or not. It is only thereafter that site specific factors, such as the moisture content in the waste, etc. are taken into consideration.

The stipulated climatic water balance (B) is calculated using the two climatic components of the full water balance, namely the recorded mean annual precipitation or rainfall (R) and the mean annual evaporation (E) from a soil surface. The climatic water balance is defined by the following equation:

B (mm) = R (mm) – E (mm)

The rainfall data is simply recorded throughout the year on a daily basis, whilst the evaporation data is calculated using either the A-pan or S-pan methods. The evaporation values used in the Minimum Requirement Documents are taken as 70% of the A-Pan evaporation or as 88% of the S-Pan evaporation figures.

The Minimum Requirement Documents state that "*the factor of 0.70 was determined by examining all the predications of available soil evaporation formulae. A factor of 0.70 x A-Pan evaporation gives a result that is very close to the predications of most of the soil evaporation formulae*". The factor of 0.88 applied to S-Pan evaporation results, simply gives values equivalent to those of 0.70 x A-Pan figures.

To allow for the effects of extreme weather conditions, the climatic water balance is calculated for the wet season of the wettest year on record, and then recalculated for successively drier years. It should be noted that, this procedure may give problems, as evaporation records for very wet seasons are sometimes incomplete, due to evaporation pans or rain gauges that overflow. In such instances average values are assigned and do therefore not in fact represent the storm events.

The Minimum Requirement Documents stipulate that the water balance calculation be repeated until it is established whether B is positive for less than one in every five years (<20%) or positive for more than one in every five years (>20%).

If B is positive for less than one in every five years the Minimum Requirement Documents state that there should be no significant leachate generation on account of the climate, and the site is classified as a (B^-) landfill. If the minimum requirements are met and only dry waste is to be disposed of, no leachate management system should be necessary.

If B is positive for more than one in every five years the Minimum Requirement Documents state that a significant leachate is expected to be generated and the site is classified as a (B^+) landfill, indicating that a leachate management system is required.

The cut-off point between expected sporadic leachate generation and significant leachate generation is where B is positive for more than one in every five years, or 20% of the time for which data is available. This calculation is conservative in that it ignores surface water runoff and assumes that all precipitation falling onto the landfill will infiltrate into the waste. It ignores any moisture storage capacity of the waste and cover and does not take rainfall events in which the precipitation exceeds the evaporation into consideration either.

According to the Minimum Requirement Documents, all B^- landfills are not expected to generate a significant leachate and are therefore not required to be installed with leachate interception and management systems. All B^+ landfills are expected to generate a significant leachate and with the exception of communal landfills are required to be installed with leachate interception and management systems. Significant leachate generation may be seasonal or continuous throughout the year and may result from the moisture content of the waste or as a result of the climate.

In situations where the climatic water balance method is incomprehensive or where site specific factors are involved, the Minimum Requirement Documents state that a full, detailed site water balance calculation may be required to determine whether a site will generate a significant leachate or not. A modelling program such as HELP may be useful in this regard.

Based on the type of the waste, the size of the waste stream as well as the climatic water balance, the Minimum Requirement Documents stipulate 8 separate landfill classes, namely: $G:C:B^-$, $G:C:B^+$, $G:S:B^-$, $G:M:B^-$, $G:L:B^-$, $G:SB^+$, $G:M:B^+$ and $G:L:B^+$.

2.2.5.2 Hazardous Waste Landfills (H)

Because of the apparent risk posed by hazardous waste, the Minimum Requirement Documents state that these landfills should be viewed as "*conservatively lined containment sites, regardless of the site water balance*". The classification of hazardous waste landfills is therefore based solely on the hazard rating of the waste and does not take the climatic water balance or site specific factors into account.

According to the Minimum Requirement Documents, all hazardous waste landfills are required to have leachate management systems included in their liner systems, regardless of the site water balance. This is in stark contrast to the classification of the liner design associated with general waste landfills, which are amongst others classified in terms of their potential to generate a leachate.

The Minimum Requirement Documents have specified two specific landfill classes associated with the disposal of hazardous waste and are classified entirely according to the Hazard Rating (HR) of the waste. The two Hazardous waste Landfills stipulated in the Minimum Requirement Documents are namely **H:H** and **H:h** landfills.

H:H landfills can accept wastes of all four hazard ratings, whilst H:h landfills can only accept wastes with hazard ratings of 3 or 4 as well as general wastes.

2.2.6 Landfill Design

The design of a landfill should essentially be based on the outcome of the site investigation and should effectively reduce the risk posed by the waste on contaminating the environment to an acceptable level. The design should in particular minimize the risk of water pollution by leachate run-off and infiltration by effectively capturing and removing the leachate generated within the waste. The general objective of the landfill design should be to provide the most cost effective and environmentally acceptable waste disposal containment facility. Every liner system is made up of a series of elements and layers and varies according to the class of the landfill.

There are two stages in the landfill design process according to the Minimum Requirement Documents, namely the "*conceptual landfill design*" and the "*technical landfill design*". The conceptual landfill design addresses the principles of the intended design, but does not include any of the detailed specifications. The technical landfill design is based upon the conceptual design and "*includes detailed specifications of the construction materials, soils, waste, measurements, procedures as well as technical drawings*". The technical design quantifies all the necessary aspects of the conceptual design and simulates/predicts the future performance of the landfill as well. Landfill classes at which no liners are required only need a conceptual design in order to be permitted.

The Minimum Requirement Documents explicitly state that a "*mandatory physical separation between the waste body and the ground water regimes is fundamental to all (landfill) designs*". The documents also state that because of the potential toxicity associated with leachates, (B^+) waste sites require leachate management systems which involve the construction of liners. Similarly adopting the "Precautionary Principle", the documents require minimal liners at (B^-) landfills. These are however implemented to detect the presence of leachate rather than manage it. In the case of hazardous waste sites, the Minimum Requirement Documents state, however, that a substantial liner and leachate management system is to be implemented, regardless of the climatic water balance and thus the potential to generate a leachate.

If clay/soil is used in the liner system, the Minimum Requirement Documents state that "*it may not have particle sizes exceeding 25mm, needs to have a low permeability and should be constructed so that it does not permit more than a specified maximum rate of flow of leachate through its layers*". Because the liner systems are usually designed at a time where only laboratory tests are available, the expected flow rates through the liners are based on the calculated permeability coefficients measured in the laboratory.

The maximum permissible outflow rates through the clay layers, for the different landfill classes, as stipulated in the Minimum Requirement Documents are:

G:B landfills:	0.30 m/year;	»	8.22×10^{-4} m/day	»	9.51×10^{-7} cm/s
H:h landfills:	0.10 m/year;	»	2.74×10^{-4} m/day	»	3.17×10^{-7} cm/s
H:H landfills:	0.03 m/year.	»	8.22×10^{-5} m/day	»	9.51×10^{-8} cm/s

The semi-impermeable layers within H:h and H:H landfills are indicated to consist of a combination of clay and geo-membrane layers. The clay components of the liners must fully meet the above maximum outflow rates and must be shown to comply with these prior to the installation of the geo-membranes.

In all landfills the base must be sloped so that any leachate generated, even sporadic leachate is transported to a control point via drains and sumps. The landfills at which significant leachate generation is expected are required to have leachate management systems including leachate interception, removal and treatment systems, in place.

Leachate interception is usually achieved using a graded underliner and drains which lead to a collection point or sump. Depending on soil quality, the underliner may be an engineered low permeability natural soil or clay liner, a geo-membrane liner, or a combination of the two.

The leachate interception system comprises of drains, bunds or trenches covered by the leachate interception layer. The systems are equipped with suitable drains or collection pipes that direct the gravity flow of leachate to the relevant collection points or sumps, from which it can be collected for treatment. The collected leachate is required to be contained and/or treated to a quality standard that complies with the relevant legislative standards before it may be released into the environment.

The liner design for leachate ponds/dams at hazardous waste disposal sites must be the same as the liner design for a hazardous waste lagoon. In the case of leachate ponds at $G:B^+$ sites, these must be lined to the same specifications as the landfill liner, excluding the leachate collection layer, but with an additional 2 mm thick geo-membrane liner, laid directly on the surface of the uppermost clay layer. The liners required to be installed for the leachate collection ponds/dams are however not investigated for the purpose of this research project.

The Minimum Requirement Documents graphically illustrate and define the specifications that need to be adhered to for each of the landfill liner classes. A description of the individual landfill liner designs as required by the Minimum Requirement Documents, are individually discussed below. These include the $G:S:B^-$, $G:M:B^-$, $G:L:B^-$, $G:S:B^+$, $G:M:B^+$, $G:L:B^+$, H:h and H:H landfill classes.

2.2.6.1 G:S:B⁻ Landfills

Small general waste landfills at which sporadic or insignificant leachate generation is expected (G:S:B⁻ landfills) are required to be installed with liners that compose of a 150 mm thick base preparation (G) layer. The G layer is the only layer required and is constructed directly on top of the in-situ soil and is illustrated in Figure 3.

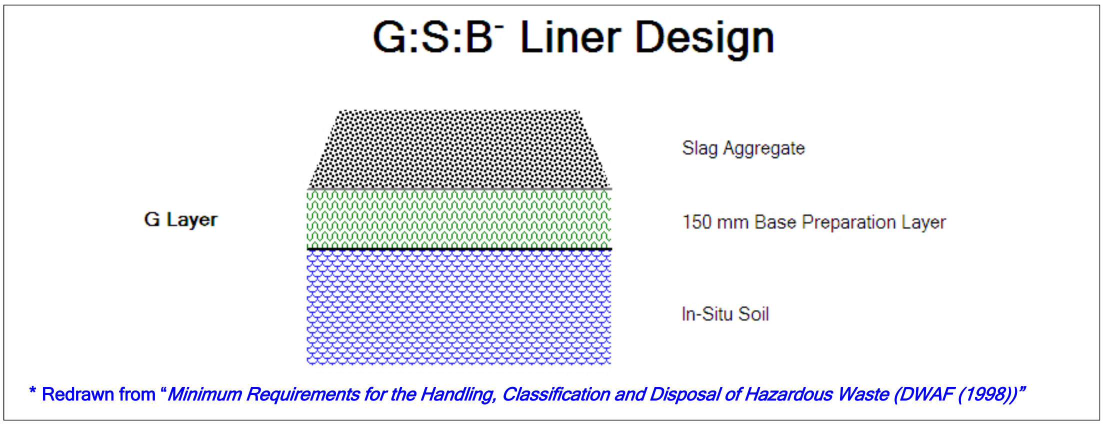


Figure 3: G:S:B⁻ Landfill Liner Design

The G layer, as stipulated in the Minimum Requirement Documents is a base preparation layer that consists of compacted, reworked in-situ soil with a minimum thickness of 150 mm and is required to be compacted to the specified compaction standards.

The compaction standard for the G layer is the same as those for the B layer (150 mm thick clay layer) used in other specified liner options. Where the permeability's of a G layer can be proven to be the same as that of a B layer it may replace the lowest B layer. The installation of a B layer is more expensive than that of a G layer, and by doing so, the cost of the liner is reduced.

The surface of the G layer must be graded towards a central channel on the down gradient side of the landfill facility, from which sporadic leachate can be collected if present. The central channel of all landfills is required to contain a prism of A-layer material that forms the leachate collector or finger drain. The minimum gradient of the G layer must be 2% for G:S:B⁻ landfills. The liner installation cost for 1 ha of a G:S:B⁻ landfill, using the March 2011 material and engineering costs is estimated to cost R 500,000/ha.

2.2.6.2 G:M:B⁻ Landfills

Medium sized general waste landfills at which sporadic or insignificant leachate generation is expected (G:M:B^- landfills) are required to be installed with liners that compose of an initial O layer, two B layers as well as a G layer. The liner is required to be at least 600 mm thick and is graphically illustrated in Figure 4.

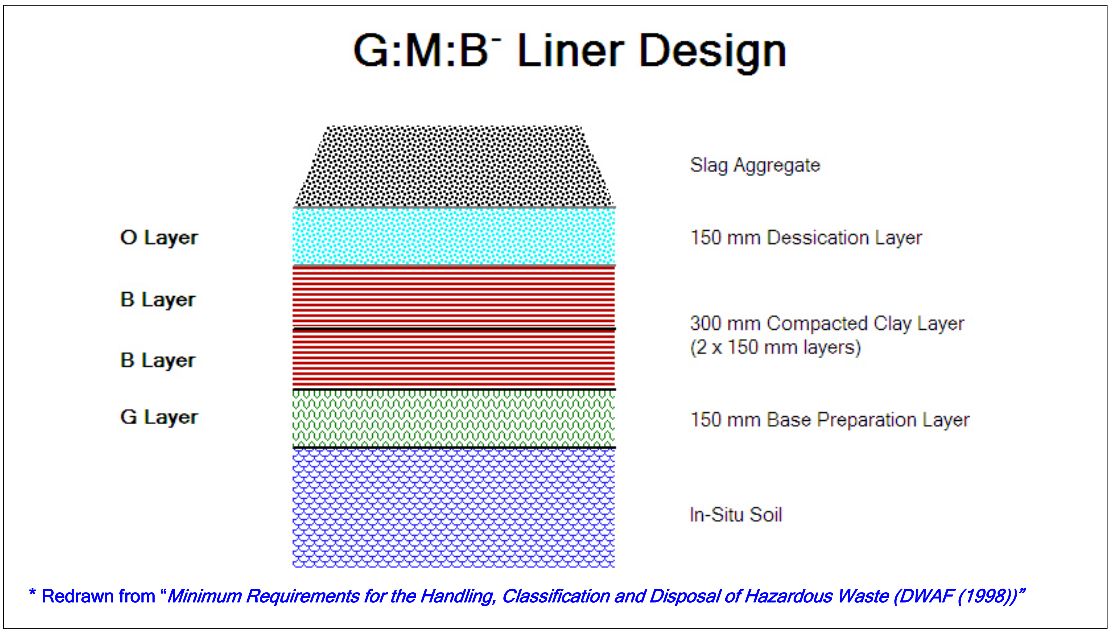


Figure 4: G:M:B^- Landfill Liner Design

The O layer is a 150 mm thick desiccation protection layer that consists of soil, gravel, rubble or other similar material. The O layer completely covers the B layer and protects it from desiccation and cracking until the waste is disposed. The O layer may often be required to be thicker, based on the site specific parameters.

Each of the two B layers comprises of 150 mm thick compacted clay layers. The infiltration fluxes through each of the B layers are required to not exceed 0.3 m/year. The surface of the B layers must be graded towards the leachate collection drains at a minimum gradient of 2%. The interface between the two B layers must be slightly course in order to assist the bonding of the two layers together.

The Minimum Requirement Documents state that B layers may be replaced by a synthetic geo-membrane, a Geo-synthetic Clay Liner (GCL) or a composite liner, at the discretion of the Department of Water Affairs.

The two B layers are underlain by a 150 mm thick G layer. The properties and installation requirements of the G layer as the same as those stipulated for G:S:B⁻ landfills. The G layer is the first layer to be constructed and may be placed directly on top of the in-situ soil at the landfill disposal site. The liner installation cost for 1 ha of a G:M:B⁻ landfill, using the March 2011 material and engineering costs is estimated to cost R 1,300,000/ha.

2.2.6.3 G:L:B⁻ Landfills

Large sized general waste landfills at which sporadic or insignificant leachate generation is expected (G:L:B⁻ landfills) are required to be installed with liners that compose of an initial O layer, three B layers as well as a G layer. The liner is required to be at least 750 mm thick and is graphically illustrated in Figure 5.

Each of the individual layers stipulated in the G:L:B⁻ landfill liner have the same construction and installation requirements as those stipulated for the G:M:B⁻ landfill liner. The difference between the G:L:B⁻ and the and the G:M:B⁻ liner is the number of B layers included in the design.

The O layer forms the desiccation layer and protects the underlying B layers from desiccation and cracking prior to waste disposal. The O layer is required to be at least 150 mm thick and is underlain by three separate B layers.

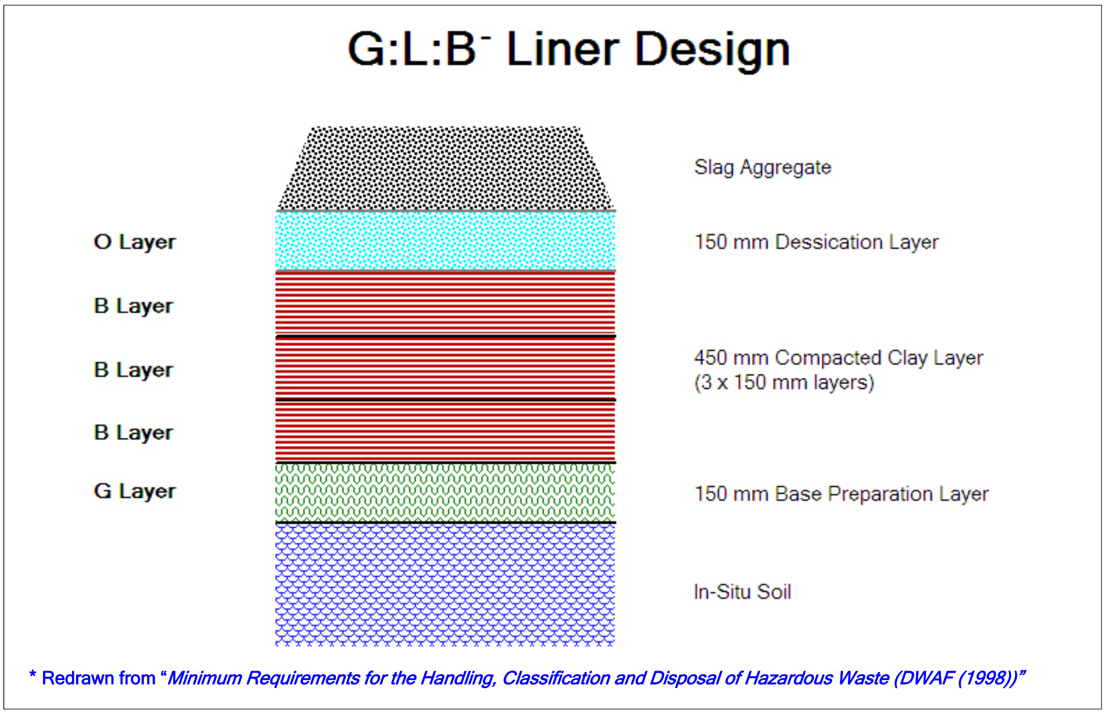


Figure 5: G:L:B^- Landfill Liner Design

Each of the B layers are required to be at least 150 mm thick with the infiltration flux through each of the B layers required to be less than 0.3 m/year. The interfaces between the B layers stipulated in the G:L:B^- liner are required to be course and have a minimum gradient of 2%.

The B layers are underlain by the base preparation G layer. The G layer is required to be at least 150 mm thick and is required to have the same compaction standards as the B layers. The liner installation cost for 1 ha of a G:L:B^- landfill, using the March 2011 material and engineering costs is estimated to cost R 1,450,000/ha.

2.2.6.4 G:S:B^+ Landfills

Small general waste landfills at which significant leachate generation is expected (G:S:B^+ landfills) are required to be installed with liners that are able to intercept and effectively remove the leachate generated from the landfill. G:S:B^+ landfill liners consist of an A layer, two B layers as well as a G layer. The liner is required to be at least 600 mm thick and is graphically illustrated in Figure 6.

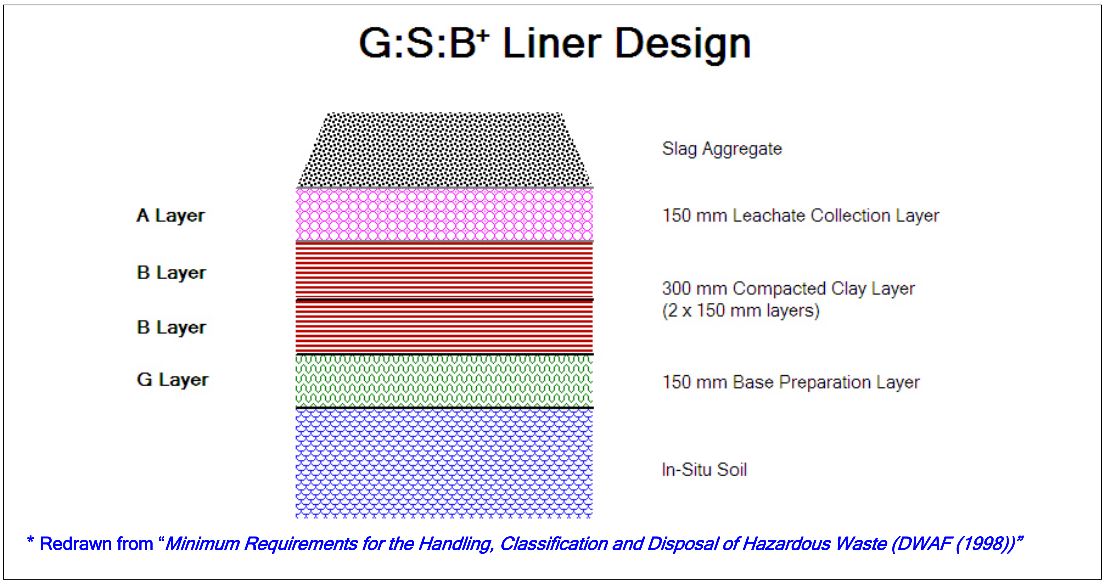


Figure 6: G:S:B$^+$ Landfill Liner Design

The A layer acts as a leachate collection layer and forms the uppermost layer specified for G:S:B$^+$ landfill liners. The A layer is required to be at least 150 mm thick and consists of single-sized gravel or crushed stones with a diameter of between 38mm and 55 mm. It is important to note that this is similar to the average size of the slag material that is deposited by landfill.

The A layer is underlain by two separate compacted clay B layers. Each of the B layers is required to be at least 150 mm thick with the infiltration flux through each of the B layers required to be less than 0.3 m/year. The surface of the clay layers are required to be coarse and are to be graded towards the leachate collection drain or sumps at a minimum gradient of 2%.

The B layers are underlain by a base preparation G layer that is constructed directly on top of the in-situ soil at the landfill. The G layer consists of compacted and reworked in-situ soil and is required to have a minimum thickness of 150 mm. The liner installation cost for 1 ha of a G:S:B$^+$ landfill, using the March 2011 material and engineering costs is estimated to cost R 1,300,000/ha.

2.2.6.5 G:M:B$^+$ and G:L:B$^+$ Landfills

Medium as well as large general waste landfills at which a significant leachate generation is expected (G:M:B$^+$ and G:L:B$^+$ landfills) have the same stipulated liner designs. The landfill liner design is required to intercept and effectively remove the leachate generated from the landfill.

G:M:B+ and G:L:B+ landfill liners consist of an A layer, five B layers, a geotextile C layer as well as a G layer. The liner is required to be at least 1200 mm thick and is graphically illustrated in Figure 7.

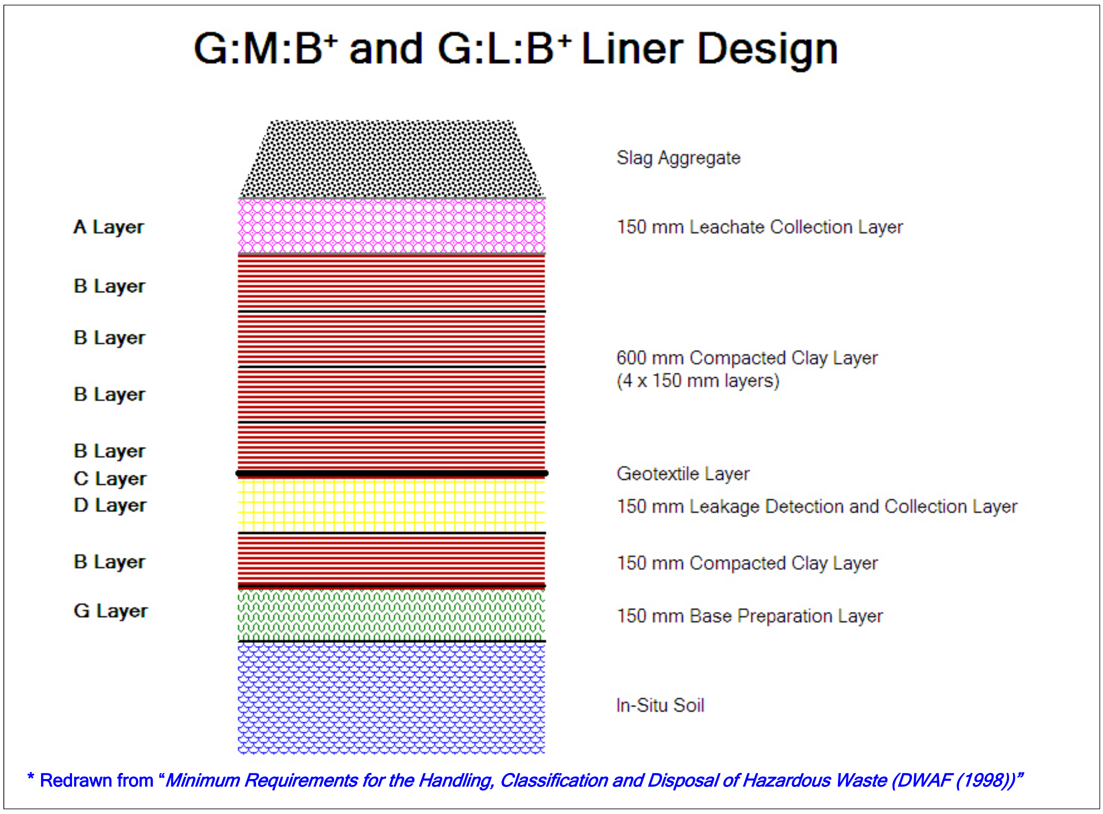


Figure 7: G:M:B+ and G:L:B+ Landfill Liner Design

The G:M:B+ and G:L:B+ landfill liner consists of 9 individual layers. The uppermost layer is the A leachate collection layer. The A layer is required to be at least 150 mm thick and comprises of single sized gravel or crushed stone with a diameter of between 38 mm and 50 mm.

The A layer is underlain by four continuous compacted clay B layers. The interface between each of the B layers is required to be course in order to assist the layers in bonding together. The surfaces of the B layers are required to be graded towards the leachate collection drain or sumps with a minimum gradient of 2%.

The four B layers are underlain by a geotextile C layer. The C layer is a geotextile layer that is commonly laid on top of the D layer to protect it from contamination or silting up due to fine material from above.

The C layer as well the four B layers form semi-impermeable layers and are installed with aim of prohibiting significant leachate from passing through the layers. These semi-impermeable layers are underlain by a more permeable D layer.

The D layer forms the leakage detection and collection layer and is installed below the C layer and on top of a B layer. The D layer is required to have a minimum thickness of 150 mm and consist of single-sized gravel or crushed stone with a diameter of between 38 mm and 50 mm.

The B layer underlying the D layer has the same specs as those installed above the B layer. This B layer forms an additional semi-impermeable layer with the aim of preventing leachate from passing through it. All leachate that enters the D layer is therefore required to drain out along the D layer into the leachate collection drains and sumps.

The B layer is further underlain by a base preparation G layer consisting of compacted and reworked in-situ soil. The G layer is constructed directly on top of the in-situ soils at the disposal facility and is required to be at least 150 mm thick. The liner design for $G:M:B^+$ and $G:L:B^+$ landfills is relatively conservative and quite comprehensive. The liner installation cost for 1 ha of a $G:M:B^+$ or $G:L:B^+$ landfill, using the March 2011 material and engineering costs is estimated to cost R 2,000,000/ha.

2.2.6.6 H:h Landfills

H:h landfills are landfills that can accept hazardous wastes with Hazard Ratings of 3 or 4 as well as general waste. Due to the toxicity and apparent adverse risk associated with hazardous waste, the Minimum Requirement Documents state that these landfills are required to be conservatively designed containment facilities.

H:h landfill liners are required to be designed with leachate collection and removal layers, regardless of the water balance calculations. These liners consists of 11 separate layers, namely an A layer, an E layer, a F layer, five B layers, a C layer, a D layer as well as a G layer. The liner is required to be at least 1350 mm thick and is graphically illustrated in Figure 8.

The uppermost layer in the H:h liner consists of a leachate collection A layer. The A layer is required to be at least 150 mm thick and consists of single sized gravel or crushed stone with a diameter of between 38 mm and 50 mm.

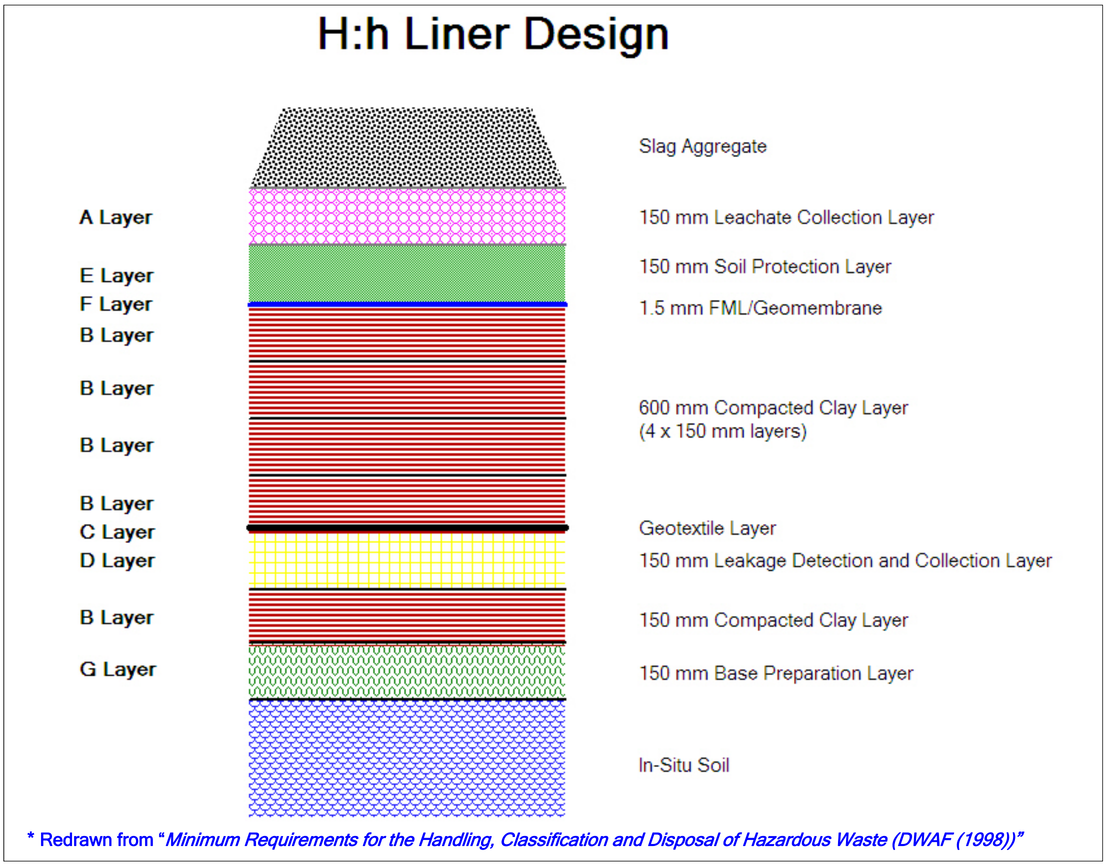


Figure 8: H:h Landfill Liner Design

The highly permeable A layer is underlain by a more impermeable, soil protection E layer with a minimum thickness of 150 mm. The E layer consists of fine to medium sand or suitable material and protects the underlying F layer from being damaged by the course A layer or other overlying material.

The F layer is a thin geo-membrane or flexible membrane layer (FML). The F is intended to form an impermeable layer and is required to be installed directly on top of a semi-impermeable compacted clay B layer. The F layer is underlain by four B layers in H:h landfill liners, which are required to be compacted to a degree at which the infiltration flux through each of the clay layers does not exceed 0.1 m/year.

The four B layers are each required to be at least 150 mm thick and are sloped at a minimum gradient of 5% to towards a leachate collection drain or sumps. The three interfaces between the B layers are required to be course and desiccated in order to ensure that the layers bonded together properly.

The B layers are underlain by a geotextile C layer. The C layer is simply installed to protect the underlying D layer from contamination or silting up by fine material from above. The D layer is a leakage detection and collection layer with a minimum thickness of 150 mm. The D layer consists of single sized gravel or crushed stone with a diameter of between 38 mm and 50 mm and forms a highly permeable drainage layer. All leachate captured by the D layer is to be drained horizontally towards the leachate collection drains or sumps.

The D layer is underlain by a semi-impermeable B layer, which aims to prohibit any possible leachate from infiltrating further through the liner. The B layer consists of compacted clay and is underlain by a base preparation G layer. The G layer consists of compacted and reworked in-situ soil with a minimum thickness of 150 mm. The G layer is to be constructed with the same compaction standards as the B layer. The G layer is the first layer to be installed and is constructed directly on top of the in-situ soils at H:h landfill sites.

The liner design for H:h landfills are conservative and comprehensive due to the apparent toxicity of certain substances included in the hazardous waste. The liner installation cost for 1 ha of an H:h landfill, using the March 2011 material and engineering costs is estimated to cost R 3,000,000/ha.

2.2.6.7 H:H Landfills

H:H landfills are those that can accept all hazardous and general wastes and are as a result the most conservatively designed containment facilities associated with the disposal of waste by landfill.

H:H landfill liners are required to be designed with leachate collection and removal layers, regardless of the water balance calculations. These liners consists of 13 separate layers, namely two A layers, an E layer, a F layer, six B layers, a C layer, a D layer as well as a G layer. The liner is required to be at least 1650 mm thick and is graphically illustrated in Figure 9.

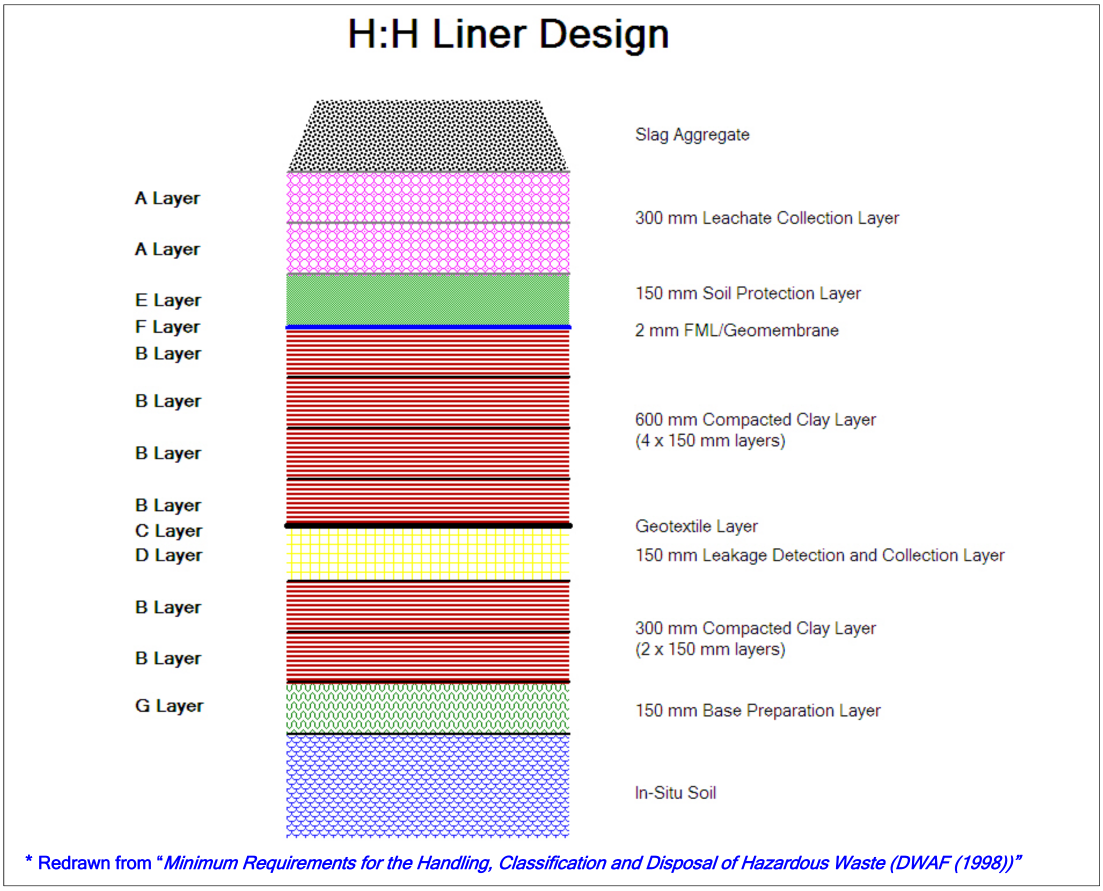


Figure 9: H:H Landfill Liner Design

The top of the H:H landfill liner consists of two separate A layers, each with a minimum thickness of 150 mm. The layers are highly permeable layers and consist of single sized gravel or crushed stone with a diameter of between 38 mm and 50 mm. The A layers form the initial leachate collection and drainage layer.

The A layers are underlain by a soil protection E layer with a minimum thickness of 150 mm. The E layer consists of fine to medium sand or suitable material and protects the underlying F layer from being damaged by the course A layer or other overlying material.

The F layer is a thin geo-membrane or flexible membrane layer (FML) and is intended to form an impermeable layer. The F layer proposed for H:H liners is required to be at least 2 mm thick and is required to be installed directly on top of four semi-impermeable compacted clay B layers, that are required to be compacted to a degree at which the infiltration flux through each of the clay layers does not exceed 0.03 m/year.

The four B layers are each required to be at least 150 mm thick and are required to be sloped at a minimum gradient of 5% to towards a leachate collection drain or sumps. The three interfaces between the B layers are required to be course and desiccated in order to ensure that the layers bond together properly.

The B layers are underlain by a geotextile C layer. The C layer is simply installed to protect the underlying D layer from contamination or silting up by fine material from above. The D layer is a leakage detection and collection layer with a minimum thickness of 150 mm. The D layer consists of single sized gravel or crushed stone with a diameter of between 38 mm and 50 mm and forms a highly permeable drainage layer. All water captured by the D layer is to be drained horizontally towards the leachate collection drains or sumps.

The D layer is underlain by two semi-impermeable B layers. These two B layers aim to prohibit any possible leachate from infiltrating further through the liner. The B layers consist of compacted clay and are underlain by a base preparation G layer. The G layer consists of compacted and reworked in-situ soil with a minimum thickness of 150 mm. The G layer is to be constructed at the same compaction standards as the B layer. The G layer is the first layer to be installed and is constructed directly on top of the in-situ soils at H:H landfill sites.

The liner design for H:H landfills are the most conservative and comprehensive of the liner designs due to the toxicity of certain substances included in the hazardous waste. The liner installation cost for 1 ha of a H:H landfill, using the March 2011 material and engineering costs is as a result the most expensive and is estimated to cost R 4,500,000/ha.

3 CONCEPTUAL CASE STUDY

The data used in the conceptual case study was obtained during several field investigations conducted at and adjacent to various ferrochrome industries within the North-West Province of South Africa. Due to the nature of the ferro-alloy producing industries within South Africa, their localities and distribution are typically located in proximity to the extent of the Bushveld Igneous Complex. Although the case study is a generic study and not representative of any specific site, site specific geohydrological data has been obtained in the field as it will be used to representatively quantify the geohydrological environment in support of the ground water modelling assessment.

3.1 GENERIC PROCESS DESCRIPTION

A ferrochrome producing plant consists generically of arc furnaces, pelletizing plants, beneficiation/recovery plants as well as the associated waste management facilities, which include slimes dams, slimes dam return water dams as well as slag disposal facilities. The final ferrochrome product is a silver grey metal alloy that consists of between 48 - 52% chromium (Cr), 7 – 8% carbon (C), 3 – 5% silicon (Si) and between 35 - 37% iron (Fe).

The raw materials used in the process include: chrome ore which is predominantly obtained from the UG-2 and LG-6 chromitite layers of the Rustenburg Layered Suite, reductants and fluxing agents. The reductants used in the process include coal, coke, char and anthracite, whilst the fluxes include dolomite, limestone and quartz. Clean and/or recycled water is used in the process as well. The plants use the UG-2, LG-6 or a UG-2/LG-6 concentrate blend as raw material to produce agglomerate ore in the form of pellets and/or blocks.

The UG-2 and LG-6 material is firstly dried, milled, pelletized and sintered at the pelletizing plants. During the pelletizing process the UG-2 and LG-6 material is loaded into a feed hopper and is conveyed to a vibratory screen where the larger material and host rock is removed. The remaining ore is then fed into a rotary drier where coal is used to generate heat to dry the material. The large dried UG-2 and LG-6 material is then conveyed to a storage bin.

The intermediate and small particles are sucked into cyclones and separated. The intermediate particles are discharged onto a conveyor belt towards storage bins whilst the small particles are captured in scrubbers and are sent to a pug mill. From the storage bins the large and medium sized UG-2 and LG-6 material is fed into a ball mill, where the material is ground with a ball media to a very fine size. This finely ground material is blown through an airlift into a holding bin from where it is fed into the pug mill as well.

In the pug mill the UG-2 and LG-6 material is mixed with a sodium silicate binder, and then conveyed to a pelletizing drum. In the pelletizing drum the mixed material is lifted up by the drum and then cut back with a cutter bar so that the material rolls down again. This action leads to the production of the pellets. The pellets are sprayed with water and fall onto a roller screen where the smaller pellets fall through the screen and are recycled back into the pelletizing drum. The large pellets are conveyed over the roller on towards the baking section.

In the semi-sintering baking zone the wet pellets are dried with by the heat generated from the oxidation of coal with air in a fluid bed reactor. Once dried, the pellets are conveyed to a stockpile as raw material for the furnaces, where the ferrochrome product is produced. Three distinct types of waste are generically generated during the production of ferrochrome, namely off gasses, slimes and slag.

At the furnaces, the ore is fed to the smelters where it is combined with the reductants and heated via high voltage carbon electrodes. The furnaces are continually filled with raw material in order to keep the electrodes submerged. The carbon in the raw materials, in combination with the heat, allows the furnace to produce reduced, or metallic, ferrochrome metal. The fluxes serve as a cleaning agent in that they react with the impurities within the metallic pool to form a molten slag material that floats to the top of the relatively heavier liquid metal.

As soon as enough melt is produced in the furnace, both metal and slag is removed via a tapping process. During the tapping process a hole is drilled into the melted material and an oxygen lance is inserted, which results in the flow of melt down to the skimmer block. Both products are tapped from the same hole.

The slag is tapped first and then the metal flows along with the slag. The metal flows underneath the slag due to its higher density. The metal is then separated from the slag by a skimmer block. The slag is diverted into the slag bay and the heavy metal stream flows below the carbon skimmer block into sand pans to form ingots.

After sufficient cooling the metal ingots are crushed and the quality of the ferrochrome is upgraded by a magnetic separation process. The slag generated by the furnaces is temporally stored on stockpiles at Metal Recovery Plants, where it is retreated and crushed allowing ferrochrome entrapped in the slag to be recovered. The recovered metals are stockpiled along with the metal from the furnaces for delivery to the market. After crushing and magnetic separation, the slag is then disposed of at the slag disposal facility as a solid waste.

3.2 REGIONAL SETTING

The regional setting of the research project's study area is described with reference to available published maps and associated information as well as the information generated during the various field investigative programmes. The regional geohydrological setting of the study area is discussed with reference to the regional topography, meteorology, surface drainage, geology, geohydrology and historical mining, all of which will have an influence on the geohydrological parameters of the study area.

3.2.1 Regional Topography

The study area is located within the north-eastern region of the North-West Province of South Africa, in which several ferro-alloy producing plants are located. The topography of the eastern region of the province is highly variable and ranges in altitude from 1000 meters above mean sea level (mamsl) to 1800 mamsl. The regional topography of the North-West Province is indicated spatially on Figure 10.

Figure 10 is the published 3D Image of the Environmental Potential Atlas for the North West Province series, supplied by the Department of Environmental Affairs and Tourism (2000).

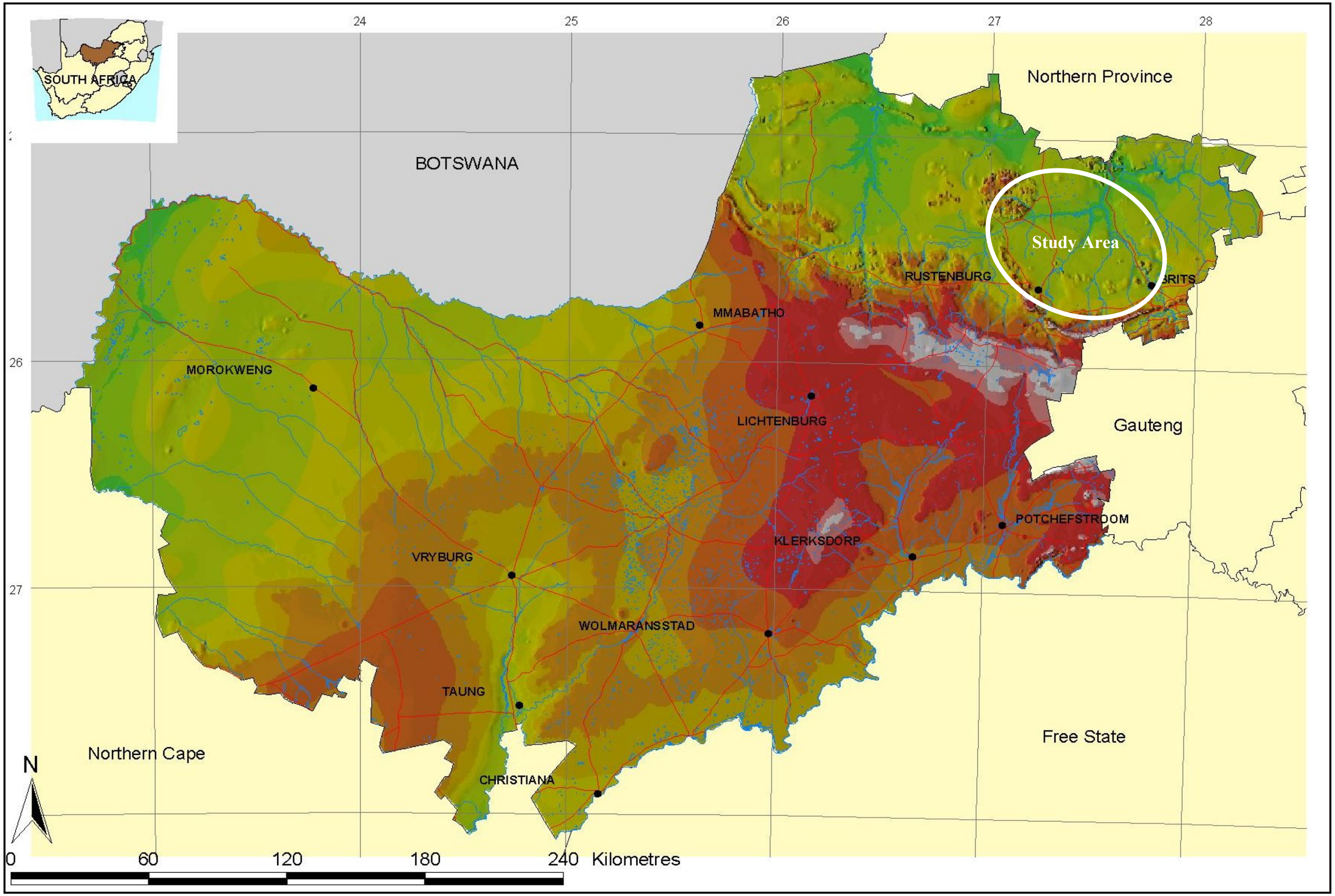


Figure 10: Surface Topography of the North West Province

** (3D Image of the Environmental Potential Atlas for the North West Province series, supplied by the Department of Environmental Affairs and Tourism, 2000).*

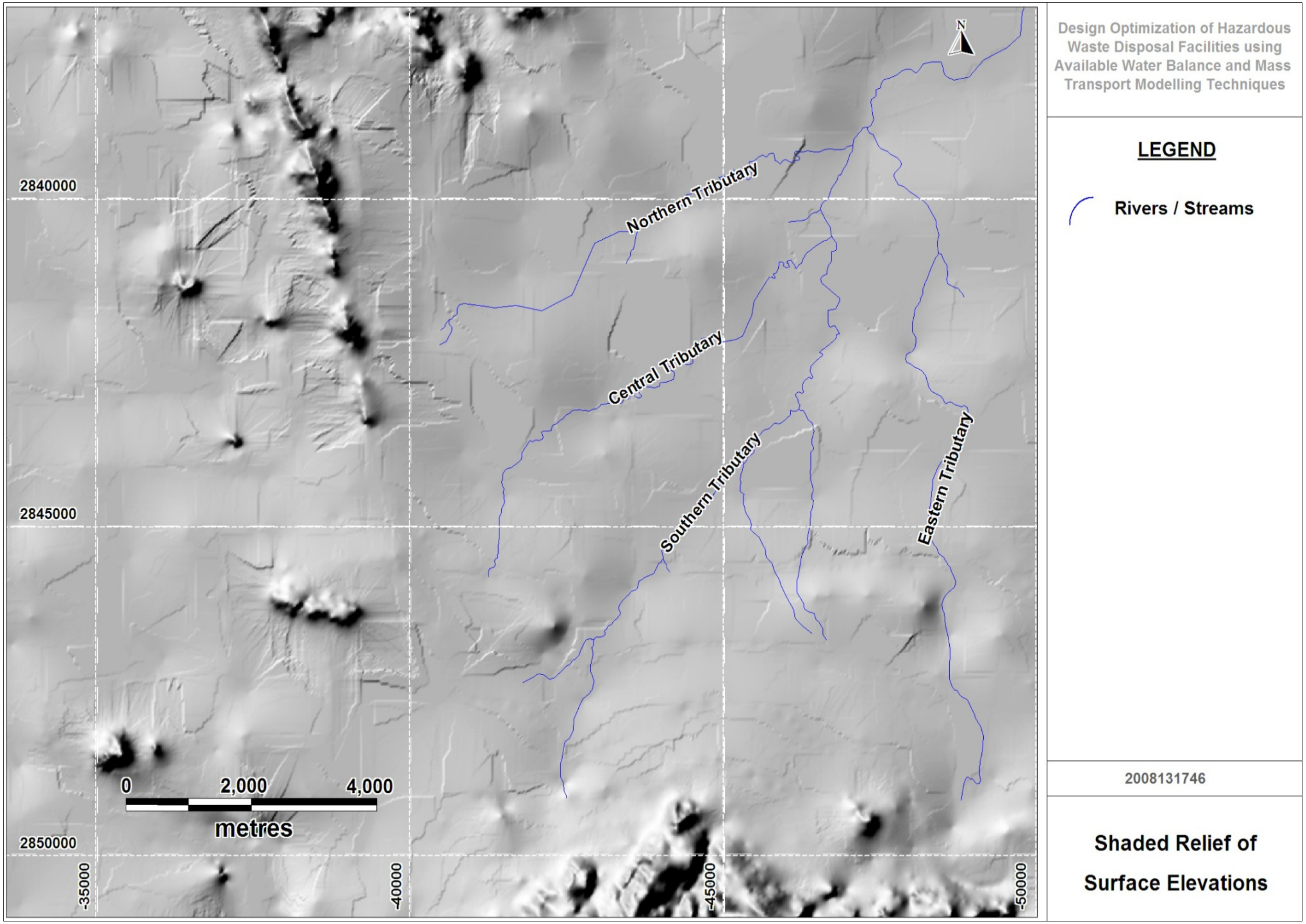


Figure 11: Shaded Relief Map of the Surface Topography within the Study Area

The eastern region of the North-West Province gives rise to two dominant topographical features, namely the Magaliesberg Mountain Range of the Transvaal Sequence as well as the Pilanesberg Complex, remnants of an ancient volcano.

The topography within the study area is however relatively flat, ranging in elevation between 1100 mamsl and 1400 mamsl with an average elevation of 1170 mamsl. There is a distinct north-south trending geological lineament along the western region of the study area which manifests on surface as an elevated alignment of hills and ridges, ranging in elevation from 1330 mamsl to 1200 mamsl. Figure 11 is a shaded relief map indicating the surface topography of the study area. The shaded relief map was created using Surfer 8 and used the Kriging method to interpolate the DEM surface elevation data obtained for the study area.

The topography within the study area becomes progressively flatter and lower towards the north-east, with the dominant surface drainage in a northerly to north-easterly direction. The presence of numerous slag dumps, slimes dams, quarries and mine dumps have altered the relatively flat topography which makes up the central parts of the study area. These surface activities have also altered the surface drainage patterns of the rivers as well as the natural discharge volumes of these rivers.

Of particular significance to the study area are the following localized surface topographical features:

- The linear geological feature along the west of the study area manifesting as a well-defined surface water topographical divide.
- The Northern Tributary which flows from the south-west to the north-east across the north of the study area.
- The Central tributary flows in a north-easterly direction into the main Southern Tributary channel.
- The Southern Tributary which flows from the south-west to the north-east across the south and east of the study area.
- The Eastern Tributary which flows from the south to the north in the far eastern extremity of the study area.

3.2.2 Regional Meteorology

The regional meteorology is discussed with reference to the meteorological data obtained primarily from the Rustenburg Weather Monitoring Station (RWMS). The climate across the study area is temperate and fairly uniform with an average annual temperature of 18.4°C as indicated in Table 4. Maximum temperatures are often associated with hot humid weather during the summer months, whilst overnight negative minimum temperatures are often observed during the winter months.

Table 4: Average Maximum and Minimum Temperatures
(Rustenburg Weather Station from 1997-2007)

Year	Maximum (°C)	Minimum (°C)	Average (°C)
1997	36.6	0.2	18.4
1998	36.7	-1.4	19.1
1999	37.0	0.0	18.8
2000	34.2	-4.5	17.2
2001	36.9	-2.0	18.5
2002	36.8	-1.5	18.7
2003	37.3	-2.1	19.2
2004	34.7	-2.5	18.0
2005	36.5	-0.4	18.5
2006	35.9	-1.2	17.3
2007	36.6	-1.9	19.1
Average	36.3	-1.6	18.4

The study area has a typical Highveld Type climate, characterized by hot summer months between October and March and cold winters from June through to August. The average monthly temperatures recorded at the Rustenburg Weather Monitoring Station are displayed on Figure 12 and graphically illustrate this trend.

The rainfall within the study area is highly seasonal and occurs predominantly in the form of late afternoon showers, as a result of the high humidity, during the summer months. The winter months are characterized by dry and cold weather as a result of the cold fronts which pass over the country, bringing in cold air from the Antarctic.

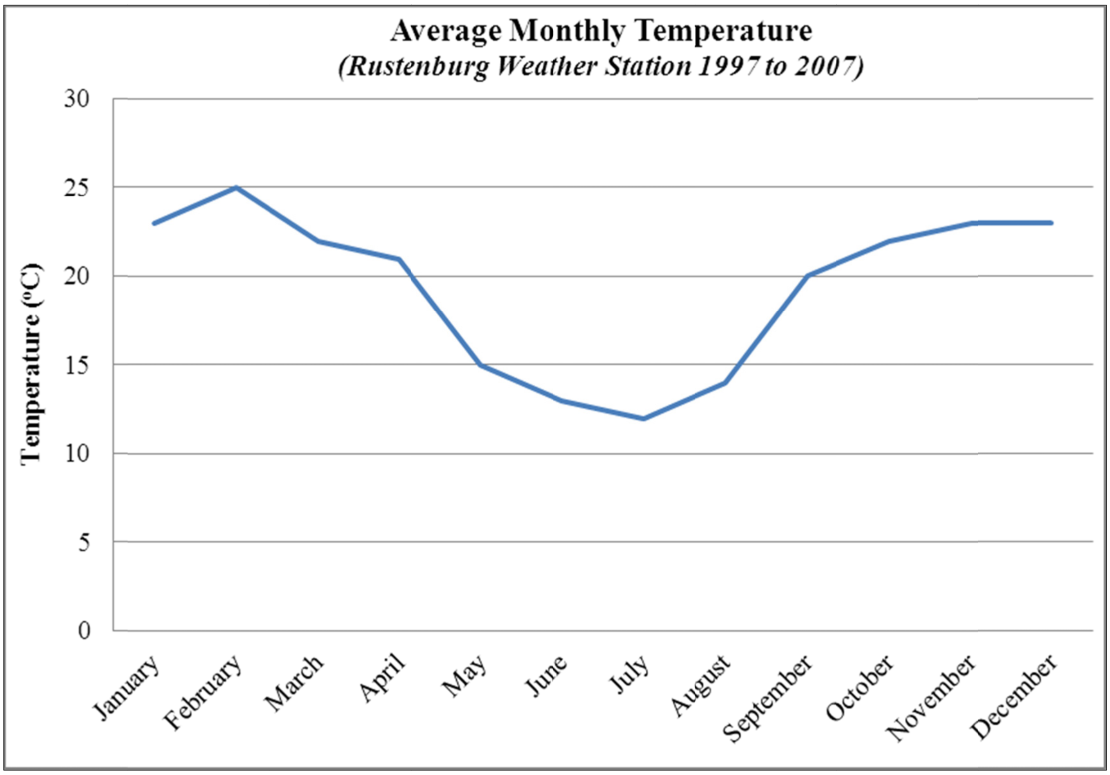


Figure 12: Average Monthly Temperatures (Rustenburg Weather Station 1997 - 2007)

Whilst gentle soaking rains do occur the rainfall within the study area is characterized by isolated thunderstorms. Although these thunderstorms are brief, they are often intense and are associated with thunder, lightning and occasional hail. The average monthly rainfall recorded at the Rustenburg Weather Monitoring Station from 1997 to 2007 is indicated in Table 5.

Table 5: Average Monthly Rainfall Distribution
(Rustenburg Weather Station from 1997 - 2007)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
mm	121	82	62	52	19	5	4	5	14	59	101	97	**621**
%	19.5	13.2	9.9	8.4	3.1	0.8	0.6	0.8	2.3	9.5	16.3	15.6	**100**

Table 5 indicates that the mean annual precipitation (MAP) as recorded at the Rustenburg Weather Monitoring Station is 621 mm/annum. Most of the rain falls during the summer months of October through to March (84.0%). The winter months (June to August) only account for 2.2% of the average annual rainfall as indicated in Table 5 and on Figure 13.

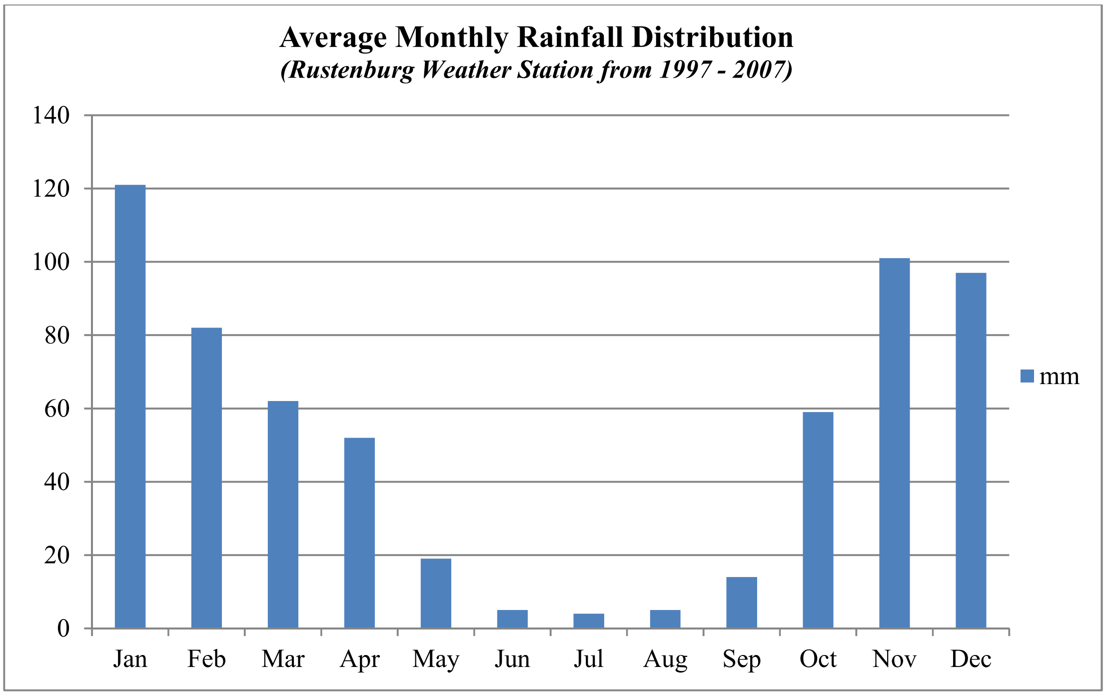


Figure 13: Average Monthly Rainfall Distribution (Rustenburg Weather Station 1997 to 2007)

In accordance with the rainfall patterns, the relative humidity is highest during the summer months (48%) and lowest during the winter months (28%). The annual average solar radiation is 221 W/m^2 and is highest during the summer (up to 1457 W/m^2) and lowest during the winter months.

In contrast to the rainfall patterns, the annual evaporation has much less seasonal variation with only 60% of the evaporation taking place during the same 6 month summer period. The average Mean Annual Evaporation (MAE) recorded at the Rustenburg Weather Monitoring Station exceeds 2000 mm/annum, which is more than three times the MAP recorded at the same station. According to the Minimum Requirement Documents this indicates that the slag disposal facility is not expected to generate a significant leachate.

The study area is dominated by moderate easterly to south-easterly winds of 3 m/s during the summer and by gentle to light south-westerly to westerly winds (1.5 m/s) during the winter months. The average annual wind speed is 1.48 m/s with the highest average wind speeds recorded during August (4 m/s).

3.2.3 Regional Surface Drainage

The study area falls within the western region of a quaternary sub-catchment area, located in the North West Province. The sub-catchment drains in a north to north-easterly direction into a Surface Water Dam, with a capacity in excess of 10 Million m^3. The sub-catchment covers a surface area of 864 km^2 and has a mean annual runoff of 86,410,000 m^3/annum. This constitutes only 3.62% of the mean annual run-off of the primary (Limpopo) catchment area.

The Southern Tributary, Northern Tributary and Eastern Tributary are the three major surface water drainage bodies within the study area and are delineated on Figure 14. The natural courses of these non-perennial surface water drainage systems have been altered to varying degrees as a result of surface activities in the study area. The dams that have been built within the sub-catchment area are primarily used for with agricultural, industrial as well as mining practices.

The Southern Tributary has two major sources which both fall within the sub-catchment area. The Central Tributary forms the one of the sources of the Southern Tributary system and flows in a north-easterly direction into the main Southern Tributary drainage body. The predominant catchment area of the Southern Tributary is located across the southern region of the study area.

The Northern Tributary occurs to the north of the study area and flows in an easterly direction, until it flows into the Southern Tributary within the study area. The Southern Tributary then continues to flow in a north-north-easterly direction until it flows into the Eastern Tributary. The natural course of the Northern Tributary has been largely influenced by the mining activities to the north of the study area.

The Eastern Tributary's source occurs to the south-east of the study area and drains in a northerly direction into a surface water dam to the north of the study area. The Eastern Tributary is the most dominant of the surface water drainage bodies in the study area and is required to serve all the recognised user groups including domestic, agricultural, recreational and industrial activities.

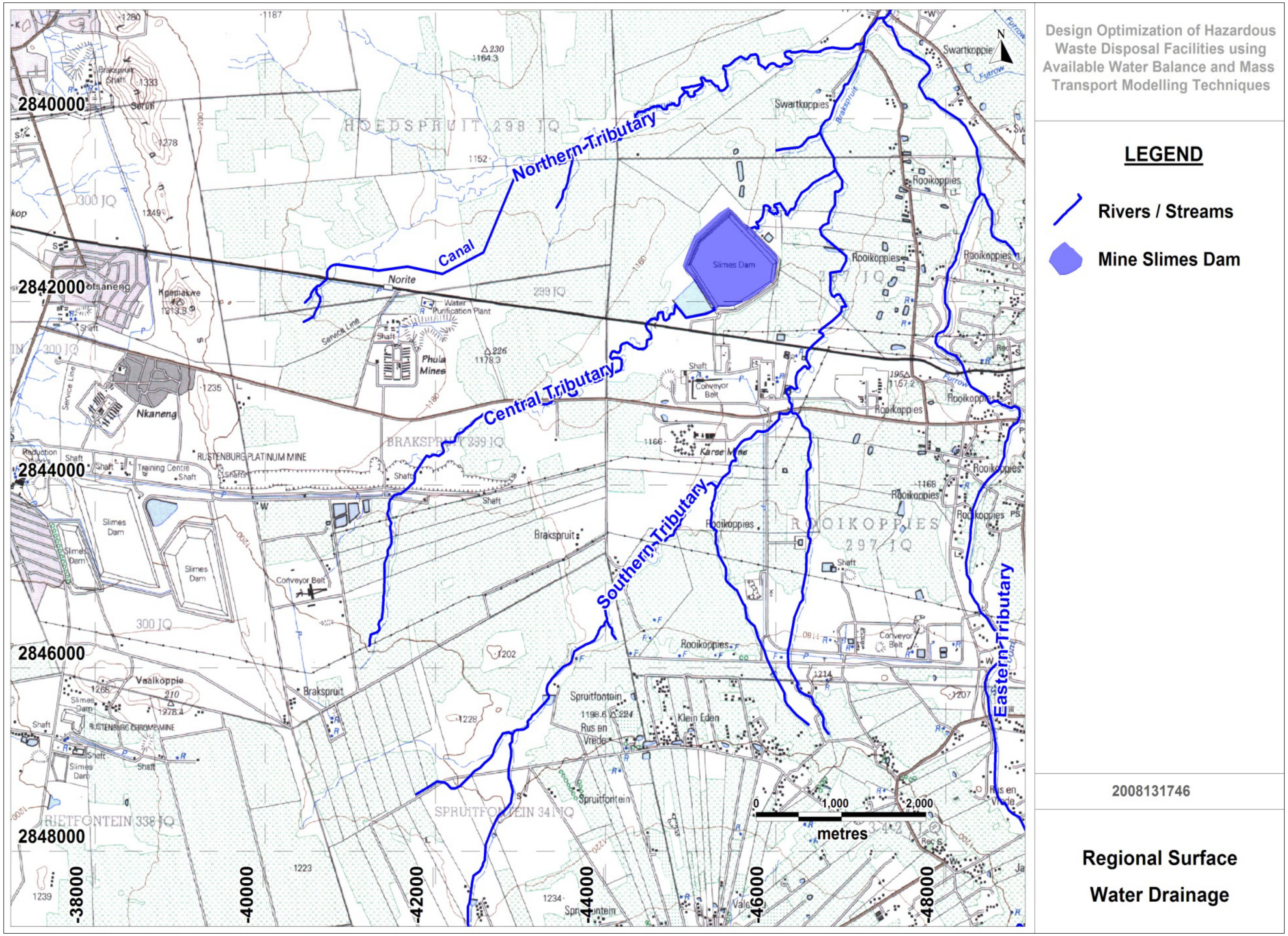


Figure 14: Regional Surface Drainage

Two of the major surface water drainage bodies form constant head boundaries for the study area. The Southern Tributary forms the southern and eastern lateral aquifer boundary, whilst the Northern Tributary forms the northern lateral aquifer boundary for the study area.

3.2.4 Regional Geology

The occurrence and movement of ground water, as well as the ground water quality are functions of the geological host rock in which the ground water occurs, including the alteration thereof as a result of human activities. The aim of the regional geological section is thus not intended to elaborate on the geological attributes of the area, but rather to set the scene for the geohydrological discussion.

The study area is predominantly underlain by norites and anorthosites of the mafic to ultramafic Bushveld Igneous Complex (BIC) which dip at an angle of 10^{o} to the north. The Bushveld Igneous Complex hosts the Rustenburg Layered Suite, which has been largely mined for chromium, platinum and the associated platinum group elements (PGE's).

The resistant meta-arenaceous quartzites and of the Pretoria Group outcrop to the south of the study area and give rise to the Magaliesberg Mountain Range. Numerous faults, some of which contain intruded material traverse the study area as well. The faults are predominantly dextral faults, many of which have later been intruded by dykes.

The majority of the dykes have north-north-west trending strikes and form part of the Pilanesberg Age dyke swarm. These dykes are light, coarse grained intrusive syenite dykes with an intermediate composition. The second major group of dykes found within the study area have north-west trending strikes and form part of the Waterberg Age dyke swarm. These dykes are dark, medium grained intrusive dolerite dykes with a basic composition.

The extent of the ore reef sub-outcrops, faults and associated dykes within the study area are indicated on Figure 15. The orthophoto's depicted in Figure 15 are clipped areas of the published 1:10 000 Orthophoto Images, Sheet 2527CB – Photo 18, 19, 23 and 23 (Chief Directorate: Surveys and Mapping (2004)).

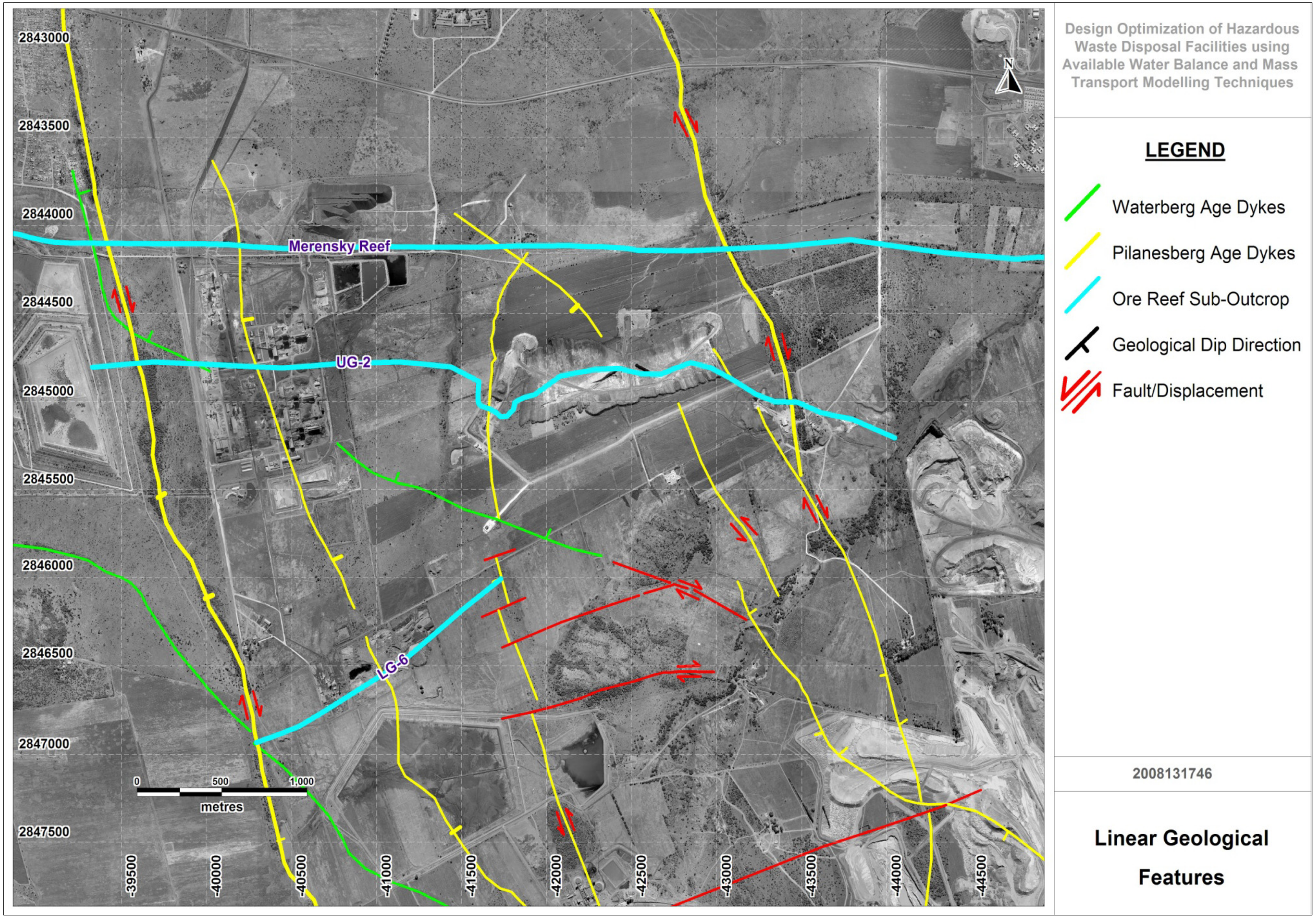


Figure 15: Linear Geological Features

There are two major dykes within the study area, one to the west and the other to the east of the study area. Both dykes are syenite dykes and are associated with the two major faults in the area. These two syenite dykes constitute the most noticeable topographic features, forming resistant linear ridges at the surface. Although the fault to the east of the study area is the larger of the two, the dyke associated with the fault to the west of the study area is the most visually prominent at the surface. This dyke dips to the east and forms a no-flow ground water boundary to the west of the study area. The syenite dykes form part of the Pilanesberg Age dyke swarm and are indicated in yellow on Figure 15.

Several fine grained dolerite dykes are also present within the study area. These dolerite dykes generally have north-west to south-east strikes and dip to the north-east. The dolerite dykes form part of the Waterberg Age dyke swarm and are indicated in green on Figure 15.

The western parts of the BIC have been extensively mined for chromium and platinum group elements within the critical zone, by both opencast and underground mining methods. The Lower Group (LG) chromitite layers of the Rustenburg Layered Suite form the base of the critical zone. Seven main layers are recognized, of which the so-called LG-6 is the most economically important. The UG-2 chromitite layer occurs within pyroxenite at the base of the overlying unit. The UG-2 is of considerable economic importance and potential, due to its PGE content.

Some of the more important and economically exploitable horizons within the BIC include the LG-6, UG-2, UG-1 and MG-1 chromititic layers as well as the Merensky Reef. The Merensky Reef, UG-2 chromitite layer and the LG-6 chromitite layer all sub-outcrop within the study area, the extents of which are indicated on Figure 15. The UG-2 and Merensky Reef have been predominantly mined for platinum and associated PGE's, whereas the LG-6 has been mined for chromite.

The Merensky Reef and UG-2 layers have east-west strikes and dip to the north, whereas the LG-6 layer has a north-east to south-west strike and dips to the north-west. All three layers are, however, laterally very extensive and homogenous with regards to average thickness across the study area.

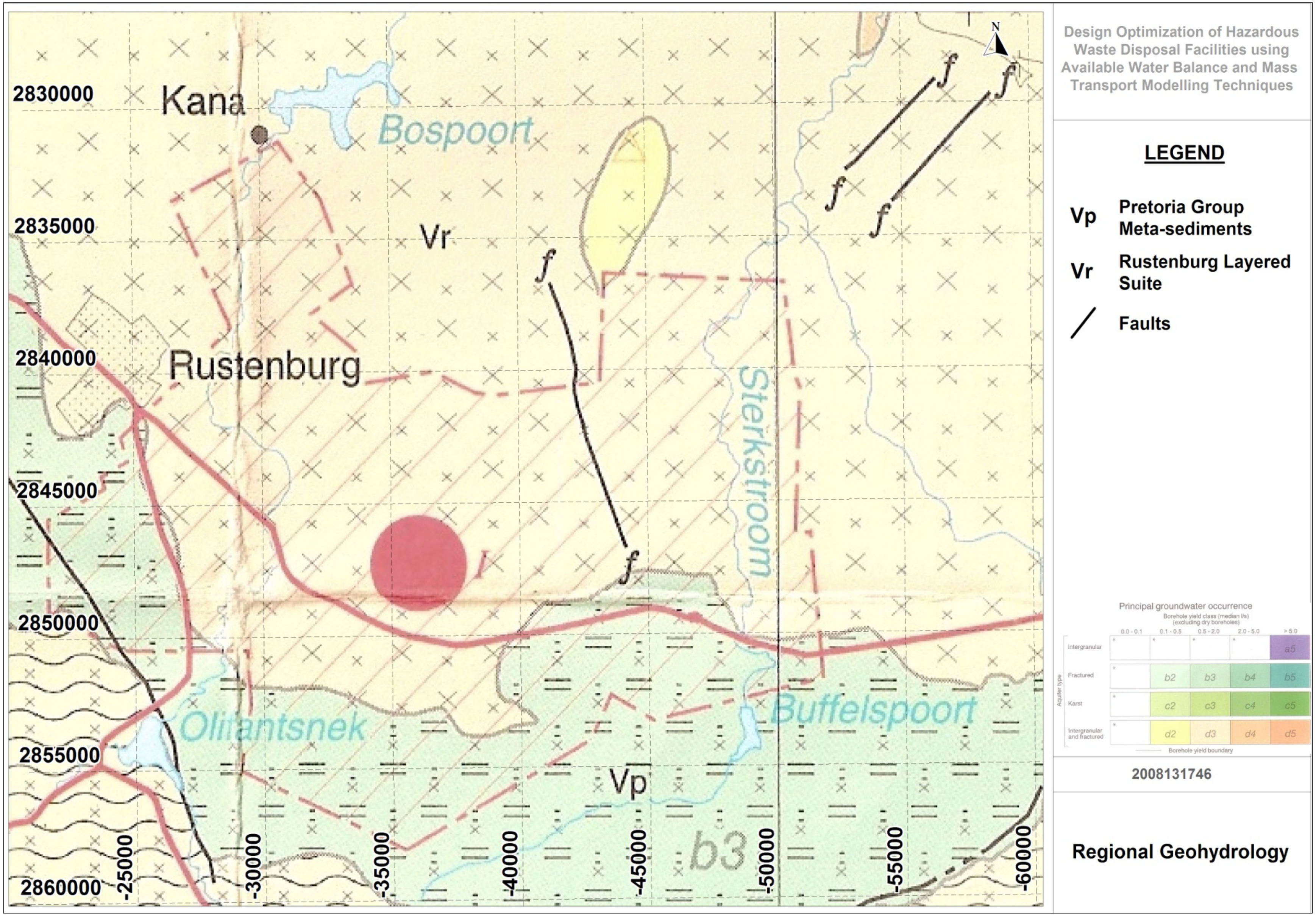


Figure 16: Regional Geohydrology

3.2.5 Regional Geohydrology

The regional geohydrology of the study area will be discussed with reference to the available information obtained from the map extract displayed as Figure 16. This map extract is a clipped region of the published 1:500 000 Hydrogeological Map Series of the Republic of South Africa - Sheet 2526 - Johannesburg, (Department of Water Affairs (1999)).

The regional geohydrological attributes of the study area are clearly a function of the geological formation distribution. Two distinctly separate stratigraphic zones occur within the study area, namely the Pretoria Group Meta-sediments (Vp) and the Rustenburg Layered Suite lithologies (Vr), each with their own geohydrological manifestations.

<u>Geohydrological Zone 1: Pretoria Group Meta-Sediments</u>

The southern fringe of the study area is predominantly underlain by meta-arenaceous rocks (quartzite) of the Pretoria Group - denoted by Vp on the map.

Within this zone the ground water occurs primarily within the joints and fractures of the competent arenaceous rocks, related to tensional or compressional stresses and offloading.

The borehole yielding potential within this geohydrological zone is classified as b3, which implies a median yield which varies between 0.5 l/s to 2.0 l/s. No large scale ground water abstraction is indicated to occur from these fractured aquifers within the bounds of the study area. The ground water potential for the southern area is given as less than 40%, which indicates the probability of drilling a successful borehole (yield > 1 l/s) whilst the probability of obtaining a yield in excess of 2 l/s is given as between 20% and 30% (Vegter, J.R (1995)).

The mean annual recharge (MAR) to the ground water system in the southern part of the study area is estimated to be between 37 mm and 50 mm per annum, which relates to between 5% and 10% of the mean annual precipitation. The ground water contribution to surface stream base flow is relatively low, estimated at between 10 mm to 25 mm per annum (Vegter, J.R (1995)).

The depths to ground water levels are estimated to be less than 9 m below the surface. The aquifer storativity (S) for the fractured aquifers in this part of the study area is estimated to be less than 0.001. The pristine ground water quality is good with a Total Dissolved Solids (TDS) range of between 300 mg/l to 500 mg/l and an Electrical Conductivity (EC) range of between 70 mS/m to 300 mS/m (Vegter, J.R (1995)).

There is a potential nitrate risk in this ground water zone, with nitrate concentrations exceeding 10 m/l as N across the area (Vegter, J.R (1995)). No correlation can be made for the relationship between the lithologies and these elevated nitrate levels. The exact cause of the elevated nitrate values is not yet identified, but is suggested to be as a result of agricultural practices at the surface or from native nitrogen-fixing vegetation. The ground water will be of the hydrochemical type B, with dominant cations Ca^{2+} and Mg^{2+} and dominant anion HCO_3^-.

Geohydrological Zone 2: Rustenburg Layered Suite

The majority of the study area (north of zone 1) is underlain by ultramafic/mafic intrusive rocks of the Rustenburg Layered Suite - denoted by Vr on the map.

Within this zone, the primary ground water occurrences are in the joints and fractures occurring in the contact zones related to the heating and cooling of the country rocks as well as in fractures in the transitional zones between the weathered and un-weathered rocks. The host rocks in this area are disturbed by a major N-S trending fault. The ground water and movement thereof will be influenced by the fault and associated shear zones.

The borehole yielding potential within this geohydrological zone is classified as d3, which implies an average yield which varies between 0.5 l/s to and 2.0 l/s which is similar as in Zone 1. Large volumes of ground water (>10 million m^3/annum) are extracted for irrigation from these intergranular and fractured rock aquifers to the south-west of the study area, indicated by the red circle on Figure 16 (Vegter, J.R (1995)).

As is the situation for the Pretoria Group Meta-Sediments, the ground water potential within the Rustenburg Layered Suite is given as less than 40%, which indicates the probability of drilling a successful borehole (yield > 1 l/s) whilst the probability of obtaining a yield in excess of 2 l/s is given as between 20% and 30% (Vegter, J.R (1995)).

The mean annual recharge to the ground water system for this the major part of the study area is estimated to be between 37 mm and 50 mm per annum, which also relates to between 5% and 10% of the mean annual precipitation. The ground water contribution to surface stream base flow is relatively low, between 10 mm to 25 mm per annum with the depths to ground water levels estimated to be 9 m below the surface. The aquifer storativity for these intergranular and fractured aquifers are estimated to be less than 0.001 (Vegter, J.R (1995)).

The regional pristine ground water quality is good with a Total Dissolved Solids (TDS) range of between 300 mg/l to 500 mg/l and an Electrical Conductivity (EC) range of between 70 mS/m to 300 mS/m. As in Zone 1, there is a potential nitrate risk in the area, with nitrate concentrations exceeding 10 mg/l across the area (Vegter, J.R (1995)). The ground water within this zone is expected to be of the hydrochemical type A, with dominant cations Ca^{2+} and Mg^{2+} and dominant anions Cl^{-} or SO_4^{2-}.

3.2.6 Regional Historical Mining

The study area occurs within the north-eastern parts of the North West Province, and is underlain by norites and anorthosites of the mafic to ultramafic Bushveld Igneous Complex. The land use within the eastern part of the North-West Province is as a result of the underlying geology, dominated by mining activities and the associated mineral beneficiation plants.

The study area has historically been extensively mined for both platinum and the associated platinum group elements as well as for chromium, by both opencast and underground mining methods. The extents of the historic opencast mining operations within the study area are indicated on Figure 17, whilst the extents of the underground mining operations are indicated on Figure 18.

Mining activities will inevitably have an influence on the ground water system as well as the geochemistry of the ground water. Standard board and pillar underground mining methods are used, which form new artificial conduits through which the ground water flows, altering the natural occurrence and movement thereof.

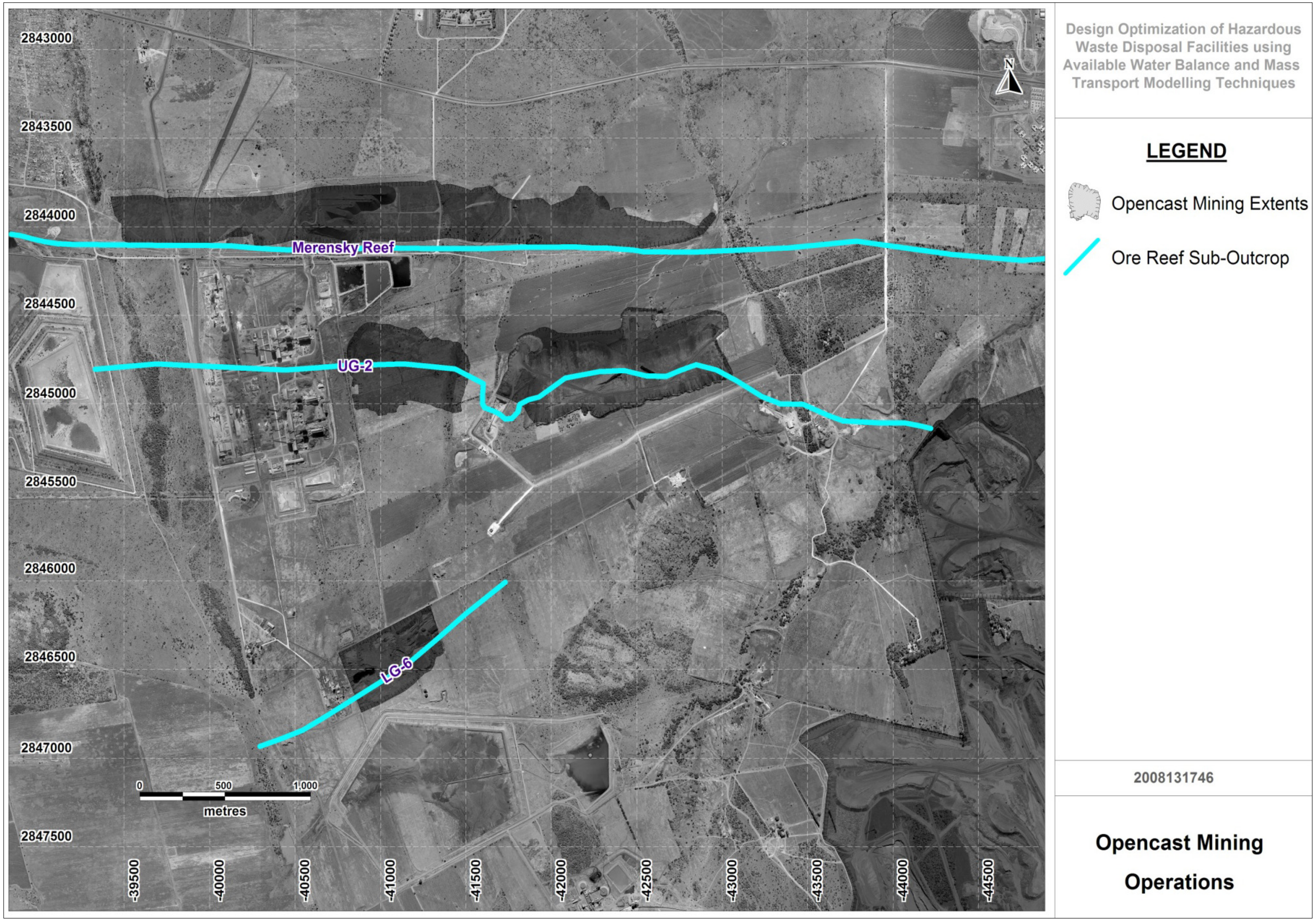


Figure 17: Extent of Opencast Mining Operations

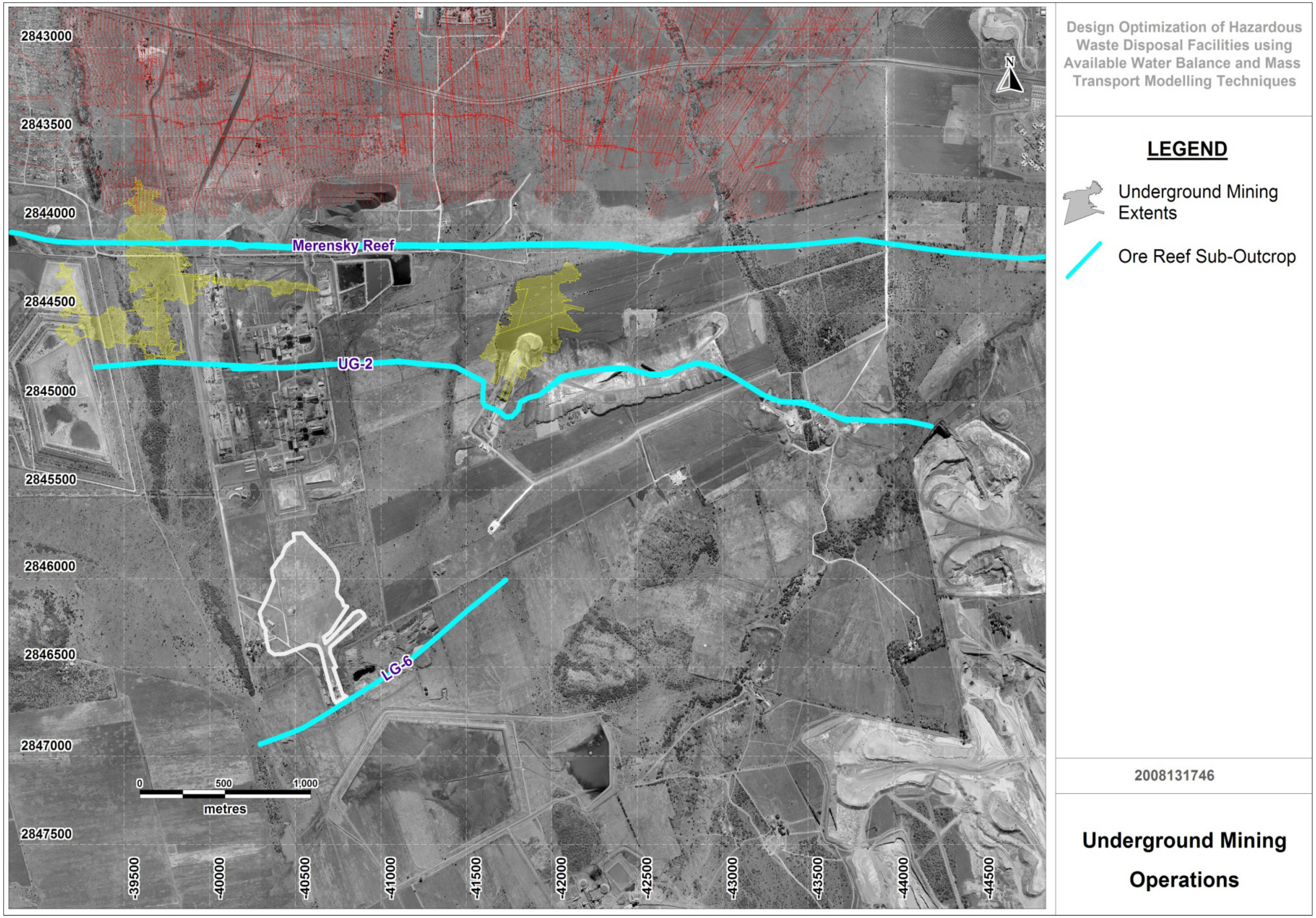


Figure 18: Extent of Underground Mining Operations

The impact that the mining operations will have on the water quality and availability of the natural ground water system will, however, not be addressed for the purpose of the comparative assessment investigated as part of this research project. The aquifer conditions used in the mass transport ground water model will represent natural ground water conditions, prior to the impact of the adjacent mining operations.

3.3 PHYSICAL AQUIFER DESCRIPTION

The physical description of the aquifers within the study area is based on the geological and geohydrological information generated during the various investigative field programmes conducted.

3.3.1 Aquifer Matrix (Soil and Geological Matrix)

During the drilling programme 15 geohydrological investigative boreholes were drilled within the study area and are located on Figure 19. The lithology penetrated, the associated weathering and fracturing status, as well as the water yielding capacity and depths were recorded during the drilling of each of the boreholes. Borehole Logs and Site Information reports were generated for each of the boreholes and are attached as APPENDIX I. The host rock matrix comprises predominantly of weathered, fractured and fresh norite, with an overburden and or topsoil cover at surface.

The topsoil consists predominantly of a dark, greyish black to brown clay-rich “turf” soil. The “turf” soil consists essentially of strongly structured fine grained vertic type soils. These vertic soils are poorly to moderately drained calcareous to non-calcareous soils and are predominantly derived from the noritic and anorthositic host rocks. The vertic soils sampled within the study area are separated into two forms, namely the Arcadia and Rensburg Forms, of which the Arcadia is the most dominant.

Due to their high clay content and the dominance of smectitic clay minerals, vertic soils possess the capacity to swell and shrink markedly in response to moisture changes. Once the soils are moist, the hydraulic conductivity becomes low to very low, and rainfall runs off laterally across the surface rather than infiltrating through the soils.

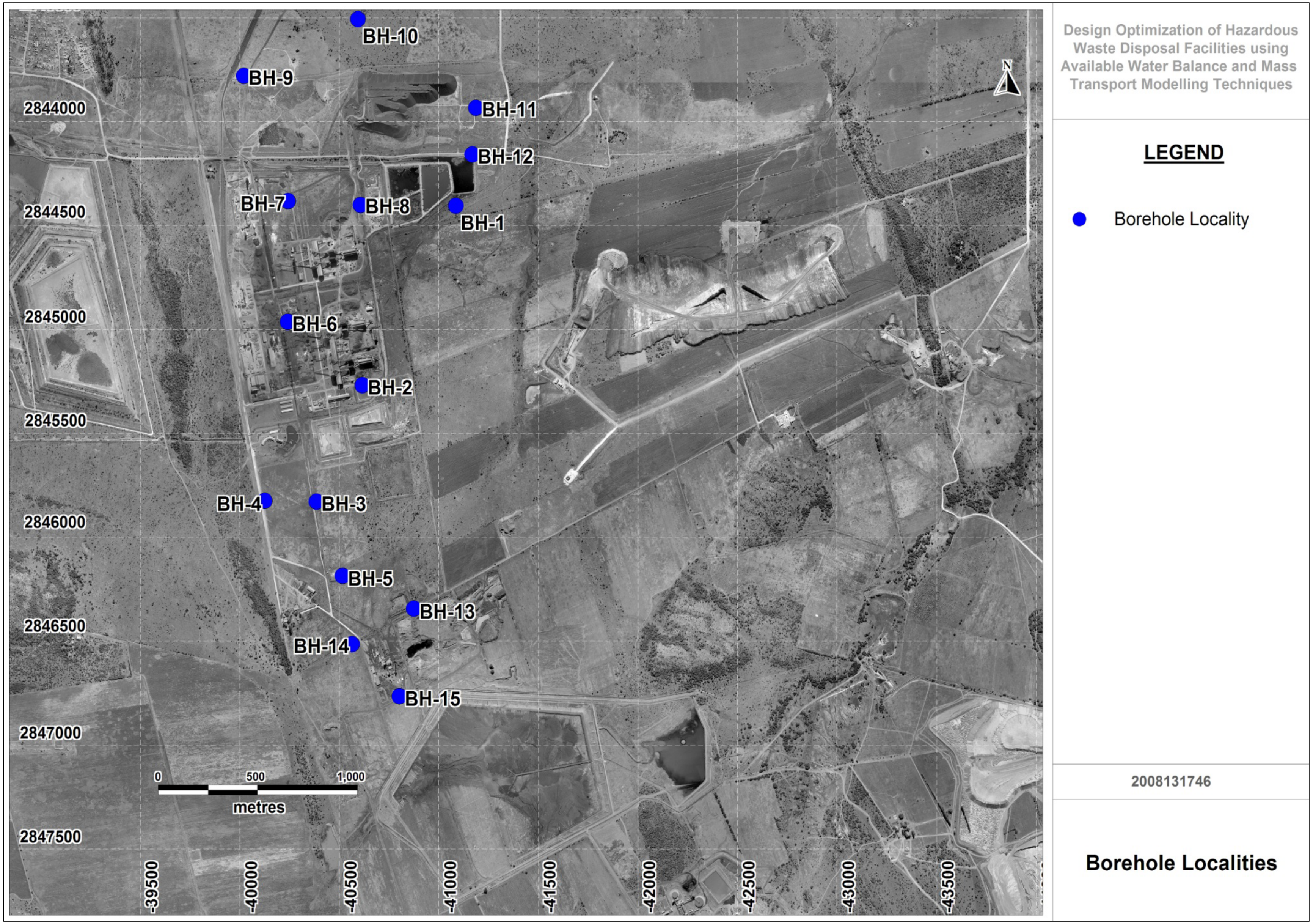


Figure 19: Geohydrological Investigative Borehole Localities

The soil varies in thickness between 0.2 m and 4.3 m with an average thickness of 2.11 m. Soils within the extents of the various plant operation areas have predominantly been removed and have been replaced with concrete or cement foundations or with gravel and building aggregate material.

The soils are underlain by medium to highly weathered norites and anorthosites. The depth of weathering and weathering related fracturing, is an important attribute from a geohydrological perspective. The weathering thickness addressed is a combination of the primary weathering profile, as well as the transitional fracturing zone, which occur directly above the fresh bedrock interface.

The depth of weathering within the study area is highly variable and varies between 9 mbgl and 25 mbgl, with an average weathering depth of 15 mbgl. This zone essentially represents the bulk of what is commonly referred to as the weathered zone aquifer. Within the study area, these weathered zone aquifers will constitute the major ground water zones, both from a recharge and storage perspective.

The occurrence and distribution of linear geological features are significant in the sense that they affect ground water occurrences (high yields due to fracturing associated with contact zones with host rock) and represent potential preferential ground water flow zones (along their contact zones). The linear geological features also define the lateral extent of the ground water zone that could potentially be influenced by surface activities within the study area in the sense that they potentially represent impermeable physical aquifer boundaries perpendicular to their strikes.

The occurrence and lateral extent of the major geological lineaments within the study area are indicated on Figure 15. The three major types of linear features identified within the study area, are namely Waterberg Age (dolerite) Dykes, Pilanesberg Age (syenite) Dykes and post BIC Faults/Displacements. In general it is safe to assume that these features will represent zones of high yielding boreholes with preferential ground water flow zones expected along their contacts and no-flow zones perpendicular to their strikes.

With reference to the linear features indicated on Figure 15, as well as the information obtained during the field investigations, it is verified that:

- Two parallel syenite dykes occur to the west and east of the study area respectively. The size and extent of these features as well as their relative location within the study area, qualify them to represent impervious physical aquifer boundaries for the study area.
- Smaller north-south trending syenite dykes bisect the central regions of the study area as well. The southern extension of this dyke beyond the study area boundary has been verified but it is uncertain how far north it extends. These syenite dykes are highly weathered are not expected to be impervious to ground water flow. They do therefore not represent lateral aquifer boundaries for the study area.

3.3.2 Aquifer Types (Primary, Weathered, Fractured, Karst)

In view of the geological setting of the study area and based on the geological and geohydrological information generated during the drilling of the geohydrological boreholes, it can be confirmed that two major aquifer types are present, namely weathered and fractured aquifer types.

The predominant aquifer type present is a shallow weathered zone aquifer which occurs in the weathered, and weathering related fractured zone, within the norite host rock matrix. This aquifer occurs across the entire surface area of the study area and has an average vertical thickness of 15 m.

This aquifer zone will store the bulk of ground water in the area and will also form the main recharge body for rainfall recharge. These aquifer types are laterally extensive and will display unconfined to semi-unconfined piezometric conditions and as a result will be highly susceptible to surface induced anthropogenic impacts such as pollutant infiltration from sources located on surface.

The fractured aquifers within the study area are restricted to the contact zones between the linear geological features and the host rock matrix. Although these aquifers have high yielding capacities and represent preferential ground water flow zones, they have limited storage capacities and restricted recharge characteristics. The bulk of the water supplied by these aquifers will be drained laterally from storage within the shallow weathered zone aquifers neighbouring onto them.

The fractured aquifers will display semi-confined to confined piezometric conditions and are important from a borehole yielding and preferential ground water flow conduit perspective. These aquifers could potentially transmit surface induced pollution over great distances, and as such should be viewed as aquifers of concern if their lateral continuation extends beyond recognized lateral aquifer boundaries.

In view of the abovementioned information and the scale of the study area it is assumed that the overall bulk of the ground water zone within the study will display porous ground water flow conditions. The fractured aquifer conditions encountered along the linear geological features will, due to their high frequency incidence and interconnectivity, also be accommodated as "porous" flow zones.

3.3.3 Unsaturated and Saturated Aquifer Zones

Due to its unconfined to semi-unconfined nature, the top of the unsaturated zone is terminated by the land surface whilst the bottom of the unsaturated zone is defined by the ground water table (level). The thickness of this zone is therefore defined by the depth to water table distribution as observed in the boreholes drilled into the weathered zone aquifer. The thickness of the unsaturated zone varies between 2.0 m and >30 m, with an average thickness of 12.2 m.

The shallow water levels recorded adjacent to several waste disposal and storage facilities are influenced by the infiltration of surface water from these facilities. The waste at these facilities is disposed of as a wet slurry material which increases the hydraulic head at the base of the disposal facility. The deeper water levels recorded to the north of the study area have been influenced by aquifer dewatering from the adjacent underground mining operations.

Based upon the physical makeup of the aquifers as well as the information recorded in the field, the natural depth to the water table is expected to vary between 8 m and 11 m below the surface. Shallower water levels indicate elevated ground water level conditions. These areas are influenced by surface induced infiltration around several of the waste disposal and storage facilities. Deeper water levels as observed to the north of the study area indicate a mining related dewatering impact.

The saturated zone is defined by the water table at the top and the interface between the weathered/fractured rock and the fresh bedrock at the bottom. Due to the highly variable weathering and weathering related fracturing depth of the norites as well as the varying ground water level depths, the saturated aquifer thickness is highly variable as well. The saturated aquifer thickness within the study area varies between 0.0 m (aquifer dewatering) and 18.4 m with an average thickness of 6.8 m.

3.3.4 Lateral Aquifer Boundaries (Physical, Hydraulic, Arbitrary)

The lateral aquifer boundaries within the study area delineated the ground water zone that could potentially be influenced by surface activities within the study area. In the natural environment lateral aquifer boundaries comprise of any one of, or combination of three possibilities, namely:

- Physical boundaries; such as linear geological intrusions (dykes), or geological contacts between rocks with different geohydrological attributes.
- Hydraulic boundaries; such as dams, rivers and streams, or alternatively, surface water and ground water divides.
- Arbitrary boundaries; selected in terms of ground water flow directions, usually chosen parallel to the ground water flow direction.

The lateral aquifer boundaries within the study area are delineated on Figure 20 and were selected according to the information obtained from the field investigations.

The western aquifer boundary is a physical boundary formed by the regional syenite dyke. Due to the minimal weathering of this dyke it is deemed impervious to ground water flow and as a result represents a no-flow ground water boundary.

The eastern boundary is also a physical boundary formed by a regional syenite dyke. Due to the thickness and limited weathering status and depth of this dyke it is also impervious to ground water flow and as result represents a no-flow ground water boundary.

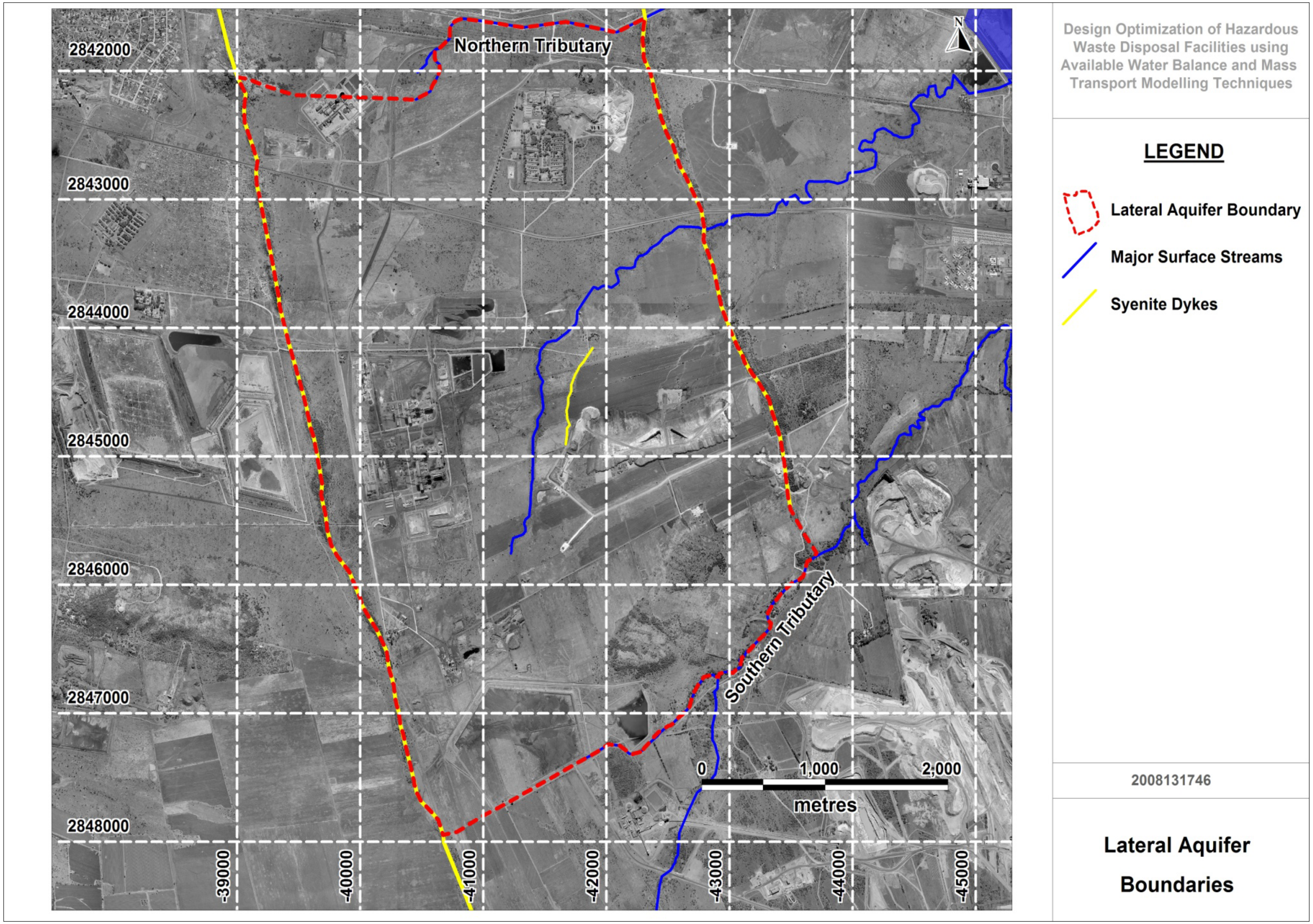


Figure 20: Lateral Aquifer Boundaries

The northern boundary is a hydraulic boundary and was selected partly along a surface water stream (Northern Tributary) and partly along the river diversion around a slimes dam. The boundary represents a ground water discharge boundary and will be accommodated into the numerical flow model as a constant head (Derichlet) boundary.

The southern boundary is a combined arbitrary and hydraulic boundary. The western section of the boundary was chosen parallel to the ground water flow direction (arbitrary no-flow boundary) whilst the eastern section was chosen along a surface water stream (Southern Tributary) representing a ground water discharge boundary which will be incorporated into the model as a constant head boundary as well.

3.4 HYDRAULIC AQUIFER DESCRIPTION

The hydraulic aquifer description relates to the attributes of the aquifers that govern the occurrence, storage and movement of ground water. The field studies conducted indicated that laterally extensive perched aquifer conditions do not occur within the study area and that the hydraulic aquifer description can thus comprehensively be discussed with regards to the unsaturated and saturated ground water zones. The hydraulic attributes for the unsaturated and saturated zones of the shallow weathered zone aquifer will essentially be the same, with the only difference being the degree of saturation.

3.4.1 Borehole Yields

During the drilling programme, borehole yields were recorded from 9 of the 15 boreholes drilled. The remaining six boreholes were dry and blow yields could thus not be recorded. Three of the boreholes at which blow yields did not occur were situated to the north of the study area and were dry due to the fact that the shallow weathered zone aquifer had been dewatered within these areas as a result of the adjacent underground mining operations.

The blow yields recorded varied between 0.02 l/s and 5.00 l/s, with an average blow yield of 1.36 l/s. The yields were all obtained in the weathered profile of the shallow weathered zone aquifer. The average blow yield of 1.36 l/s correlates well to the stated average yield for the regional geohydrological setting of the study area.

3.4.2 Aquifer Hydraulic Conductivity/Transmissivity

The Hydraulic Conductivity (**k** (m/day)) of an aquifer is a measure of the ease with which ground water can flow through it. The transmissivity (**T** (m^2/day)) is the product of the hydraulic conductivity and the saturated aquifer thickness (**D**) and represents the ground water flow potential through the entire saturated zone.

The hydraulic conductivity and transmissivity of the shallow weathered zone aquifers were calculated using the information obtained from the hydraulic conductivity (slug) tests. One borehole had an obstruction in and five of the 15 boreholes were dry/impacted by aquifer dewatering. Slug tests could thus not be carried out at these boreholes. The hydraulic conductivity of the aquifers adjacent to the boreholes is taken as the average of the permeability's calculated using the Hvorslev and Bouwer & Rice analysis methods.

The calculated permeability's and transmissivity values of the shallow weathered zone aquifers within the study area are listed in Table 6. The slug test summary and analyses sheets are attached as APPENDIX II.

Table 6: Calculated Aquifer Hydraulic Conductivity and Transmissivity Values

Borehole Number	Saturated Aquifer Thickness (m)	Slug Test Hydraulic Conductivity			Transmissivity
		Bouwer & Rice (m/day)	Hvorslev (m/day)	Average (m/day)	(m^2/day)
BH-1	18.43	3.92	3.77	3.85	70.86
BH-2	7.10	1.75	1.67	1.71	12.14
BH-3	13.00	0.87	0.94	0.90	11.75
BH-6	11.74	0.80	0.86	0.83	9.75
BH-8	14.27	0.34	0.38	0.36	5.08
BH-12	9.00	0.64	0.66	0.65	5.84
BH-13	4.93	0.42	0.48	0.45	2.21
BH-14	2.41	0.50	0.64	0.57	1.37
BH-15	11.26	1.78	2.01	1.90	21.34
Harmonic Mean		0.71	0.79	0.75	4.78
Geometric Mean		0.90	0.97	0.93	8.31
Arithmetic Mean		1.22	1.27	1.24	15.59

The calculated average permeability's vary between 0.36 m/day (131 m/year) and 3.85 m/day (1405 m/year) with an average hydraulic conductivity of 1.24 m/day (453 m/year). The calculated transmissivity (T = k * D) values vary between a minimum of

1.37 m^2/day (500 m/year) and a maximum of 70.86 m^2/day (25,864 m/year) with an average transmissivity of 15.59 m^2/day (5,690 m/year).

It is obvious from the hydraulic conductivity calculations that a large degree of heterogeneity is present throughout the weathered zone aquifer within the study area. Due to the heterogeneities inherent to weathered zone aquifers, it is reasonable to assume that the aquifer's hydraulic conductivity distribution will be log-normally distributed. Research has indicated that due to this phenomenon, the bulk hydraulic conductivity and transmissivity would best be represented by a value bounded by the harmonic mean and the geometric mean.

The hydraulic conductivity for the shallow weathered zone aquifer within the study area is therefore taken as 0.80 m/day (292 m/year) and a calculated transmissivity 6.50 m^2/day (2,373 m/year) is assigned to the aquifer within the study area.

3.4.3 Aquifer Storativity

The aquifer storativity is a measure of the volume of ground water that can effectively be drained under a unit gradient from a unit volume of aquifer host rock.

The aquifer storativity for the weathered zone aquifers within the study area is expected to vary between 0.001 and 0.005. This range has also been proven to be realistic for weathered zone aquifers within weathered granitic and noritic geological environments.

The storativity of the shallow weathered zone within the study area will be optimized during the numerical modelling exercise by making use of the inverse recharge assessment. During this assessment, the ground water level response to rainfall recharge within the study area is optimized subject to a calibrated aquifer storativity and hydraulic conductivity distribution assigned to the model.

3.4.4 Aquifer Porosity

The aquifer porosity relates to the total volume of pore space present in a unit volume of aquifer host rock. Not all water contained in the rock matrix can be drained under a unit gradient. The volume that can be drained is referred to as the drainable porosity and will in the case of the study area be similar to the storativity, which usually only represents a fraction of the total porosity.

Of more importance for this study is the effective porosity which is a measure of total volume of interconnected pores. The effective porosity is important as it plays a governing role in ground water flow velocity.

The clayey vertic topsoil has a large primary porosity, both total porosity (40%) and effective porosity (40%). This means that this layer will be able to store a relatively large volume of water per unit volume soil, whilst ground water flow through this layer will be slow. However, due to the very fine nature of clayey material the drainable porosity will be very small.

In the weathered bedrock formations, effective porosity will play the most significant role as it will determine the ground water seepage velocity, which also represents the velocity at which advective contaminant transport will take place. The effective porosity in the weathered zone aquifers within the study area vary between 0.01 and 0.07, with a bulk probable value of 0.03.

3.5 AQUIFER DYNAMICS

The aquifer dynamics of the shallow weathered zone aquifers within the study area relates to the transient attributes of the aquifers and represent those parameters that could potentially change with time.

3.5.1 Rainfall Recharge

Recharge to the shallow weathered zone aquifers within the study area occurs annually as a result of the infiltration of precipitation. The soil cover within the study area will readily allow rainfall infiltration into the subsurface and underlying shallow weathered zone aquifer systems. Rainfall recharge to the ground water system is expressed as a percentage of the mean annual precipitation, which is recorded as 621 mm/annum at the RWMS is assigned to the study area.

The mean annual recharge to the ground water system for the study area is estimated to be between 3% and 7% of the MAP. The mean annual recharge is therefore calculated to range between 19 mm/annum and 43 mm/annum. An average value of 31 mm (5% of MAP) will be used for general calculations. The recharge will however be optimized within the numerical ground water flow modelling analyses.

3.5.2 Ground Water Level Depths and Fluctuations

The depth to ground water level within the study area varies between 2.00 m and >30 m, with an average depth of 12.17 m recorded within the study area. Water level depths deeper than 9 m below surface indicate areas in which the ground water level has been affected by aquifer dewatering associated with the mining activities.

This is particularly evident to the north of the study area, in which case all three boreholes are "dry", indicating that the ground water level has been lowered to a depth that is deeper than that of the borehole. The boreholes to the south of the study area have also been also been affected, yet to a lesser degree than the boreholes to the north of the study area as a result of aquifer dewatering by the adjacent underground mining activities. The ground water levels recorded in the field are listed in Table 7.

Table 7: Recorded Collar Heights and Ground Water Levels

Borehole Number	Collar Height (m)	Water Level Depth (mbc)	Water Level Depth (mbgl)	Borehole Depth (mbgl)
BH-1	1.62	5.19	3.57	25.51
BH-2	0.55	3.95	3.40	26.56
BH-3	0.76	2.76	2.00	25.29
BH-4	0.61	4.45	3.84	22.21
BH-5	0.63	25.81	25.18	25.83
BH-6	0.70	4.96	4.26	23.94
BH-7	0.55	22.72	22.17	24.97
BH-8	0.67	3.30	2.63	24.86
BH-9	0.77	31.73	> 30.96	30.96
BH-10	0.66	30.63	> 29.97	29.97
BH-11	0.62	12.90	> 12.28	12.28
BH-12	0.55	4.55	4.00	30.28
BH-13	0.77	13.84	13.07	24.86
BH-14	0.49	17.08	16.59	24.48
BH-15	0.61	9.35	8.74	25.59

By excluding the water levels recorded in boreholes that have been affected by the underground mining operations, it is calculated that the average ground water level within the study area is 4.97 mbgl.

At a storage value of 0.003, the ground water level response to 1 mm of rainfall will be 0.33 m. This indicates that for every 3 mm of rainfall recharge the change in ground water storage would manifest as a rise in water level of 1 m.

The maximum possible fluctuation in ground water level would then of course be in the order of 10 m (5% of MAP of 621 mm = 31 mm). In view of the fact that not all the recharge will not take place at the same time but rather spread out over the summer months, ground water level fluctuations in excess of 3 m to 5 m is not expected.

3.5.3 Ground Water Elevations

The ground water elevations were calculated by subtracting the recorded depth to the water level (as recorded from the borehole collar) from the borehole collar elevation. The surface and borehole collar elevations of all the boreholes were accurately surveyed in order to facilitate the calculation of the ground water level elevation assessment and are indicated in Table 8.

The ground water elevations calculated at each of the boreholes are listed in Table 8. A map depicting the distribution of the ground water elevations is indicated as Figure 21.

Table 8: Surface and Ground Water Elevations

Borehole Number	X Coordinate (m)	Y Coordinate (m)	Surface Elevation (mamsl)	Ground Water Elevation (mamsl)
BH-1	41085.75	-2844403.88	1182.65	1179.08
BH-2	40615.32	-2845267.62	1194.83	1191.43
BH-3	40384.88	-2845828.07	1206.35	1204.35
BH-4	40124.67	-2845824.09	1210.00	1206.16
BH-5	40516.45	-2846184.85	1209.97	1184.79
BH-6	40239.92	-2844961.95	1196.53	1192.27
BH-7	40243.18	-2844380.96	1190.29	1168.12
BH-8	40606.06	-2844399.80	1187.33	1184.7
BH-9	40019.93	-2843778.87	1190.85	>1159.85
BH-10	40593.10	-2843505.53	1188.14	>1158.14
BH-11	41186.58	-2843932.07	1177.36	>1165.06
BH-12	41167.42	-2844156.51	1179.87	1175.87
BH-13	40874.87	-2846342.81	1210.14	1197.07
BH-14	40563.24	-2846512.78	1214.81	1198.22
BH-15	40802.21	-2846764.33	1213.56	1204.82

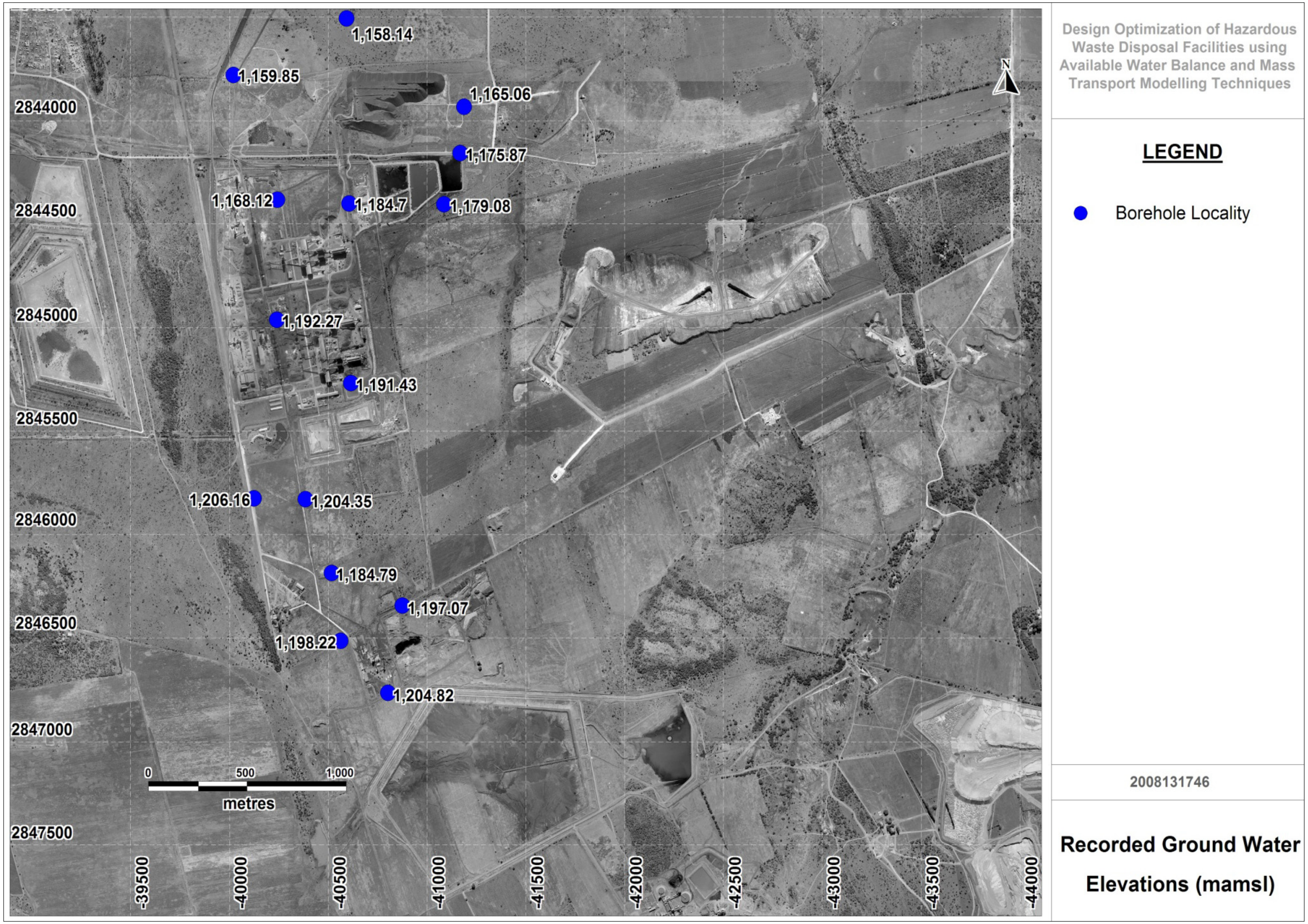


Figure 21: Ground Water Elevation Distribution

There was a 92.41% correlation between the un-impacted ground water elevations and the associated surface elevations. This verifies that the surface water elevations closely mimic that of the surface topography, as is commonly associated with unconfined shallow weathered zone aquifers. It is observed that the ground water elevations within the study area become lower towards the north-east.

In order to support the ground water flow model, an accurate steady state ground water level elevation contour map is required for the entire ground water influence zone, delineated by the lateral aquifer boundaries. The ground water elevations recorded at each of the boreholes was used to calibrate the steady state conditions of the mass transport ground water model. Boreholes at which the ground water levels have been influences by the adjacent underground mining activities were however ignored and not used to calibrate the steady state ground water elevations.

3.6 AQUIFER HYDROCHEMISTRY

Numerous sites and surface activities within the study area have been in operation for numerous years and as a result, the study area represents a “Brown-Fields” area. This classification of the area is made, due to the fact that the ground water within the study area may already have been impacted by the current surface activities. The hydrochemistry of the shallow weathered zone aquifer is therefore as a result discussed with regards to ground water samples collected from boreholes which are located away from any surface activities and are as a result deemed as un-impacted (UGBH-) ground water samples.

3.6.1 Ambient Ground Water Quality

The 5 UGBH- samples collected were analysed for the following ground water variables: pH, EC, TDS, Ca, Mg, Na, K, Si, T.Alk, F, Cl, SO_4, NO_3, NH_4, Al, Fe, Mn, Cr and Zn. The geochemical results obtained from the accredited laboratory where then used to assess realistic maximum ground water qualities expected for the selected series of water quality variables within the ambient ground water.

The ground water variables concentrations of the five UGBH- ground water samples are indicated in Table 9.

Table 9: Ambient Ground Water Quality

Variable		UGBH-1	UGBH-2	UGBH-3	UGBH-4	UGBH-5
pH		7.9	8.2	7.8	7.9	7.8
EC	mS/m	63	50	68	62	40
TDS	mg/l	397	353	417	385	236
Ca	mg/l	41	39	34	26	44
Mg	mg/l	39	14	36	26	17
Na	mg/l	44	77	86	91	20
K	mg/l	0.5	3.8	0.3	0.3	3.5
Si	mg/l	16	2	15	13	9
T Alk	mg/l	190	204	323	300	197
F	mg/l	0.5	0.2	0.55	0.53	0.22
Cl	mg/l	23	41	24	23	8
SO_4	mg/l	129	54	40	37	27
NO_3	mg/l	1.21	1.05	0.24	0.24	0.31
NH_4	mg/l	0.43	0.29	0.19	0.25	0.17
Al	mg/l	0.01	0.01	0.01	0.01	0.02
Fe	mg/l	0.63	0.13	0.18	0.34	0.02
Mn	mg/l	0.11	0.01	0.62	0.33	0.01
Cr	mg/l	0.01	0.01	0.01	0.01	0.01
Zn	mg/l	0.01	0.01	0.01	0.01	0.01

With the exception of the pH the maximum background value proposed was chosen as 1 standard deviation above the arithmetic mean of the analysed values. The average and maximum background value for each of the water quality variables as well as the standard deviation for each variable quality is listed in Table 10.

Table 10: Maximum Expected Ambient Ground Water Quality

Variable		Average	1 Standard Deviation	Maximum Background Value
pH		7.92	-	-
EC	mS/m	56.60	9.30	65.90
TDS	mg/l	357.60	58.65	416.25
Ca	mg/l	36.80	5.76	42.56
Mg	mg/l	26.40	9.07	35.47
Na	mg/l	63.60	24.89	88.49
K	mg/l	1.68	1.47	3.15
Si	mg/l	11.00	4.65	15.65
T Alk	mg/l	242.80	51.79	294.59
F	mg/l	0.40	0.14	0.54
Cl	mg/l	23.80	9.55	33.35
SO_4	mg/l	57.40	33.62	91.02
NO_3	mg/l	0.61	0.39	1.00
NH_4	mg/l	0.27	0.08	0.35
Al	mg/l	0.01	0.00	0.02
Fe	mg/l	0.26	0.19	0.45
Mn	mg/l	0.22	0.21	0.43
Cr	mg/l	0.01	0.00	0.01
Zn	mg/l	0.01	0.00	0.01

3.6.2 Ambient Ground Water Hydrochemical Image

The hydrochemical image of the ambient ground water was then assessed during which Piper and Durov diagrams were compiled using the WISH Version 3.02.181 software. The Piper and Durov Diagrams are compiled using the macro chemistry variables pH, EC, Ca, Mg, Na, K, Total Alkalinity, Cl, SO_4 and NO_3 of the ground water sample and are displayed in Figure 22 and Figure 23 respectively.

The Piper Diagram indicates that the ambient ground water within the study area has a distinct Type B to Type C hydrochemical image. The dominant cations are variable whilst the anions consist predominantly of HCO_3^-.

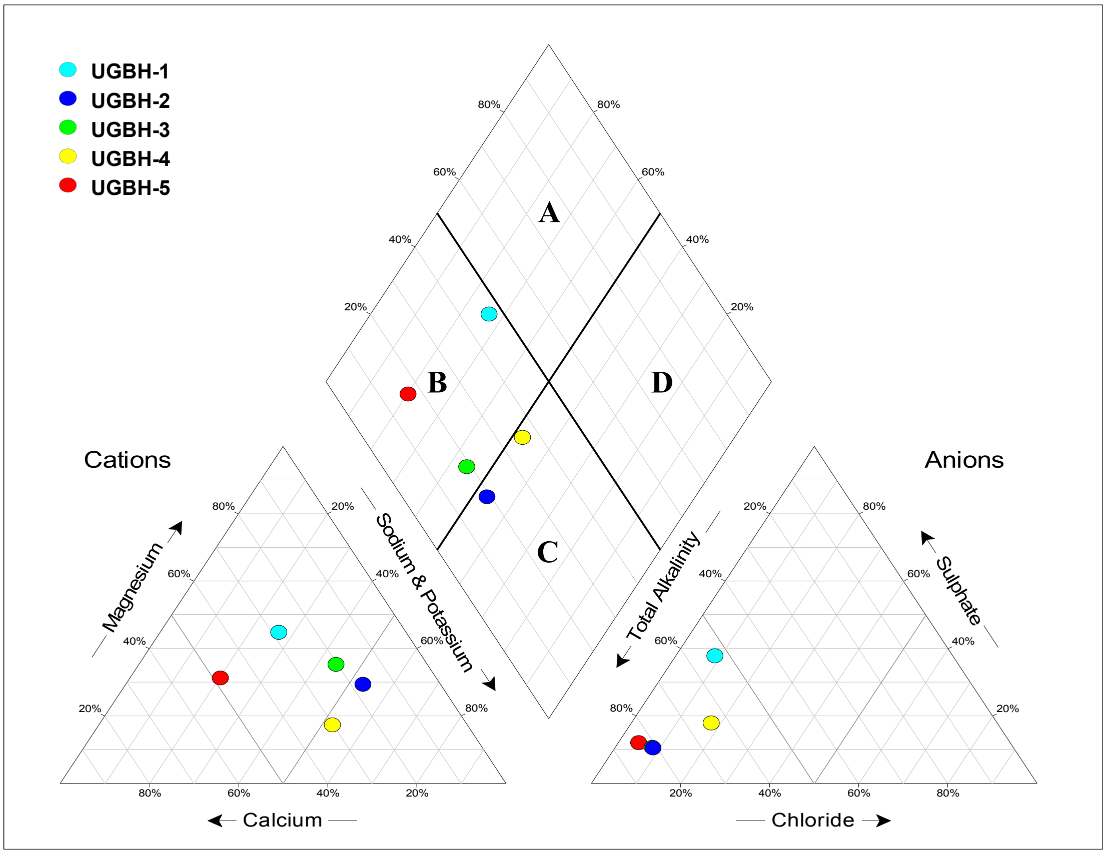


Figure 22: Piper Diagram – Ambient Ground Water Quality

The Durov Diagram further indicates that the pH of the ambient ground water varies slightly between 7.8 and 8.2 with an average pH of 7.9. The slightly alkaline pH is expected due to the dominant HCO_3^- equivalent concentrations.

The Electrical Conductivity (EC) which represents a measure of the total salinity of the ambient ground water ranges in concentration between 40 mS/m and 70 mS/m, with an average EC of 57 mS/m.

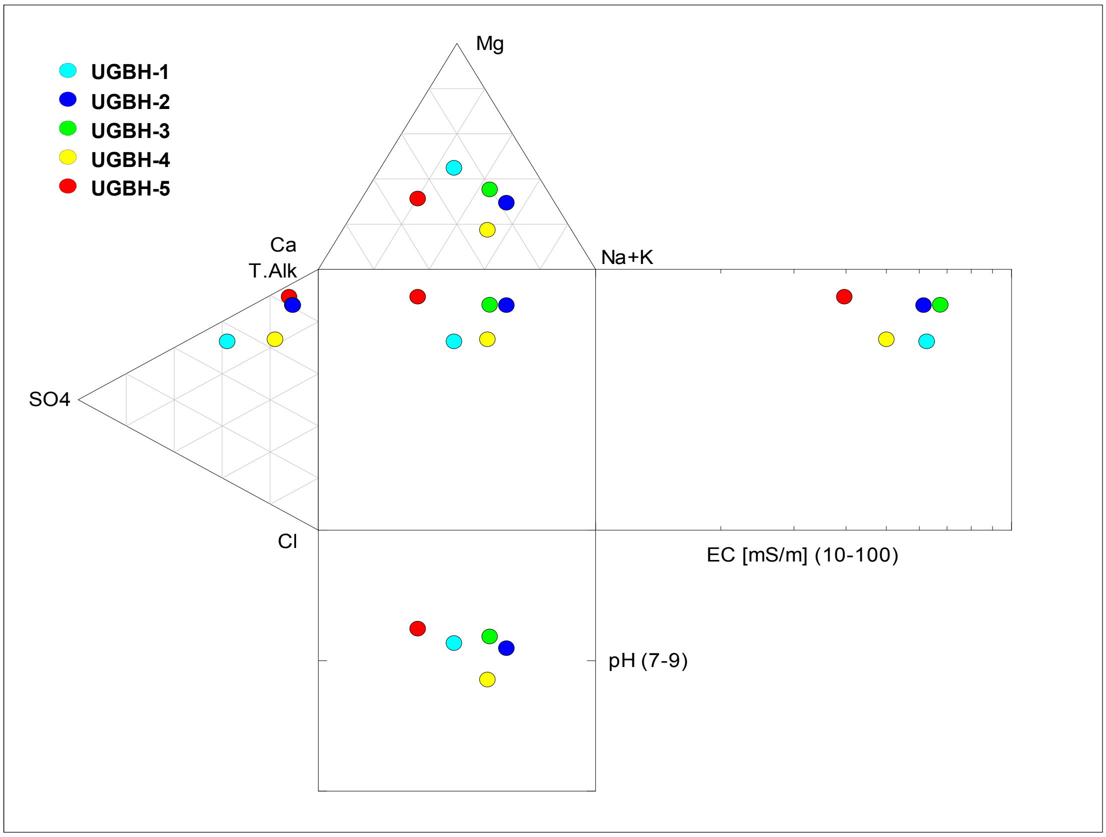


Figure 23: Durov Diagram – Ambient Ground Water Quality

The hydrochemical image of the ambient ground water quality is important from a ground water monitoring perspective in addition to ambient ground water quality. During future ground water monitoring, any impacts on the ground water quality are expected to affect the hydrochemical image thereof, which is dependent on the quality and composition of the impact source. It is thus vital that the hydrochemical of the ambient ground water be established and used as a reference during future ground water monitoring programmes adjacent to any landfill disposal facility.

4 GEOCHEMICAL COMPOSITION OF THE WASTE

The waste investigated (slag) is an inorganic metallurgical waste generated at a ferrochrome producing plant. During the process at a ferrochrome plant, slag and metal are concurrently tapped from furnaces into a separation point, utilizing a separator block and skimmer plate. The metal flows to the chill pans, whilst the less dense slag overflows and is accumulated. The slag is left to cool, harden and is then crushed before it is stockpiled and reworked at the metal recovery plants. After the slag has been reworked at the metal recovery plants it is typically disposed of at a slag disposal facility as a dry aggregate material with an average grain size of 20 mm in diameter.

Any leachate that infiltrates from the base of the slag dump originates primarily as a result of infiltrating precipitation that comes into contact with the slag. In order to optimally manage the waste disposal facility it is thus vital that the geochemistry of the slag be analysed and assessed. The geochemical assessment of the slag aims to determine the chemical make-up thereof as well as to identify and quantify any potentially hazardous substances that could be contained within the slag material. These chemicals of concern could be removed from the slag and ultimately end up in and contaminating the environment.

4.1 MINERALOGICAL AND ELEMENTAL COMPOSITION

The geochemical composition of the slag was determined using slag samples obtained during the field investigations within the study area. The mineralogy and elemental compositions of the different slag components, sampled at the ferrochrome plant, were analysed using X-Ray Diffraction (XRD) and X-Ray Fluorescence (XRF) techniques by XRD Analytical & Consulting cc.

X-Ray Diffraction is one of the primary techniques used to examine and determine the physio-chemical make-up of unknown solids and was used to analyse the slag. The XRD technique takes a sample of slag, powders it and places the powdered sample in a holder which is then bombarded and illuminated with X-rays of a fixed wave-length. The intensity of the reflected radiation is then recorded using a goniometer, which gives an indication of the shape of the molecule. The data is then analysed to determine the reflection angle and is used to calculate the interplanar spacing's.

During X-Ray Fluorescence the slag is exposed to relatively energetic X-Rays or gamma rays. The inner shell electrons are displaced by the high energy photons (X-rays or gamma rays) as a result of ionization of their component atoms. The removal of an electron causes the electronic structure of the atom to be unstable. As a result the electrons in the higher orbitals "fall" back to the lower orbital in order to stabilize the atom again. As they fall, energy is released in the form of a photon, the energy of which is equal to the energy difference of the two orbitals involved. The slag will thus emit radiation (light), which has energy characteristic of the atoms present. The XRF technique then measures characteristic "secondary" (or fluorescent) X-rays that are emitted using a spectrometer.

Slag samples were taken from breaking floors at three furnace pairs to observe whether their compositions were the same or whether they varied from each other. The processes at each of the three furnaces are the same and it is expected that the composition of these slag samples thus be similar as well. Slag samples were also taken from two un-reworked and fine slag stockpiles as well as a grab sample from an existing slag dump.

By sampling the slag at various stockpiles and at different stages in the process from which it forms may indicate different leachate generation potentials and geochemical signatures thereof. The XRD results for the different slag components sampled and analysed are given in Table 11.

Table 11: XRD Results of the Different Slag Components

Weight %	S-1 (Un-reworked slag & fines)	S-2 (Un-reworked slag & fines)	S-3 (Slag - furnaces 1 & 2)	S-4 (Slag - furnaces 3 & 4)	S-5 (Slag - furnaces 5 & 6)	S-6 (Slag Stockpile)
Chromite	15.54	28.72	17.09	17.15	14.83	10.01
Chromium	1.30	2.16	3.69	4.39	3.13	3.31
Cristobalite	6.62	20.96	-	-	-	-
Enstatite	14.15	9.79	16.00	20.61	16.30	27.04
Hematite	1.05	-	-	0.20	-	-
Quartz	26.21	12.73	-	-	-	-
Spinel	35.13	25.64	63.23	57.66	65.73	59.65
Total	**100.00**	**100.00**	**100.01**	**100.01**	**99.99**	**100.01**

The XRD results given in Table 11 indicate that the major minerals present in all the slag components are predominantly spinel, enstatite and chromite. Spinel has the highest weight percentage for all the samples analysed (excluding S-2 which has a slightly higher chromite content) followed by enstatite and chromite.

Spinel is a magnesium aluminium oxide ($MgAl_2O_4$), enstatite is a magnesium bearing pyroxene ($MgSiO_3$) and chromite is a ferrous chromic oxide ($FeCr_2O_4$), all of which are commonly associated with basic igneous rocks as well.

The un-reworked slag and fines component (S-1 and S-2) has a slightly different signature to the slag sampled from adjacent to the furnaces (S-3, S-4 and S-5) and from the slag stockpile (S-6). The un-reworked slag and fines had large percentages of quartz (26.21% and 12.73%) and cristobalite (14.15% and 9.79%) present whilst the other samples had no quartz or cristobalite present. Quartz and cristobalite are both silicate minerals with the same elemental composition (SiO_2). Cristobalite is in fact simply the high-temperature form of quartz. Hematite is a metallic ferrous oxide (Fe_2O_3) mineral and was also only found in two slag samples analysed, namely S-1 and S-4.

In order to provide an indication of geochemical makeup of the slag in comparison to the geochemistry of host rock lithologies, the geochemistry of the slag was assessed with regards to the geochemistry of the average upper crust (AUC) lithologies, taken from Rudnick and Gao, 2003. The average upper crust values serve as a standard reference used to determine whether the analysed components within the slag are expected to be elevated or depleted in certain elements.

4.1.1 First Order Geochemistry Assessment of the Slag - AUC Concentrations

The average upper crust values were calculated by establishing the weighted averages of the compositions of rocks exposed at the surface of the earth, during large scale sampling programmes. The rocks taken were in-situ samples of the continental crust. The continental crust is divided into upper, middle and lower layers and shows wide lithological and geochemical variations (Rudnick and Gao (2003)).

The upper crust is readily accessible for direct sampling and extensive sampling and analysing programmes of the upper crust from Canada and China were carried out by Rudnick, Gao and many other geochemists. The average upper crust values given provide a baseline for assessing geochemical anomalies and all the major-element determinations of upper-crust composition, in fact, rely on this method.

The assessment of the major elemental compositions of the slag against the average upper crust values, gives an initial indication of whether the slag has the potential of producing a leachate with a quality that is poorer than the expected average upper crust lithologies and thus potentially contaminating the environment. Concentration elevations in terms of the average upper crust values provide a first order indication of the risk that the slag poses on contaminating the environment and not an indication of the leachability of the elevated elements from the material. The leachability of the elevated elements was assessed through the appropriate leaching tests.

The weight percentage (%) of the major elements present in the different slag components are listed in Table 12 and have been assessed against the AUC values (indicated in blue), taken from Rudnick and Gao (2003). The values given in red indicate weight percentages greater than those assigned to the AUC, whilst the values given in green indicate weight percentages below the stipulated AUC values.

Table 12: Major Element Composition of the Different Slag Components

Weight %	S-1	S-2	S-3	S-4	S-5	S-6	AUC*
	Un-reworked slag & fines	Un-reworked slag & fines	Slag - furnaces 1 & 2	Slag - furnaces 3 & 4	Slag - furnaces 5 & 6	Final Slag Stockpile	
SiO_2	33.26	34.98	33.81	35.93	35.28	34.86	66.60
Al_2O_3	25.31	17.37	29.11	28.66	32.13	30.45	15.40
Fe_2O_3 T	11.24	27.69	8.60	6.74	7.08	6.90	11.20
MnO	0.32	0.17	0.31	0.27	0.30	0.30	0.10
MgO	14.65	8.14	19.62	19.60	20.00	20.10	2.48
CaO	2.39	1.22	3.09	4.15	1.73	4.13	3.59
Na_2O	0.00	0.88	0.00	0.00	0.00	0.00	3.27
K_2O	0.09	0.04	0.00	0.00	0.00	0.00	2.80
TiO_2	1.00	0.67	0.98	0.82	1.17	0.97	0.64
P_2O_5	0.02	0.73	0.00	0.00	0.00	0.00	0.15

** Note: AUC (Average Upper Crust) values are taken from (Rudnick and Gao, 2003).*

The results listed in Table 12 provide a first order indication that all the slag components analysed have a potential of generating a leachate that poses a risk on contaminating the environment. The results indicate that the slag samples are predominantly elevated in Al_2O_3, MnO, MgO and TiO_2 with regards to the AUC values. The un-reworked slag and fines samples (S-1 and S-2) are elevated in the total Fe_2O_3 concentration as well.

It is further observed that the un-reworked slag and fines contain minor concentrations of Na_2O, K_2O and P_2O_5, whilst the slag samples taken adjacent to the furnaces (S-3, S-4 and S-5) and from the final slag stockpile (S-6) contain no concentrations of Na_2O, K_2O and P_2O_5. The Na_2O, K_2O and SiO_2 concentrations in all the slag samples taken are lower than the AUC concentrations determined by Rudnick and Gao (2003).

The concentrations of the trace elements present in the different slag components were analysed as well and are listed in Table 13. The trace element concentrations were determined using XRF techniques and have been assessed against the AUC concentrations, taken from Rudnick and Gao (2003) as well.

Table 13: Trace Element Composition of the different Slag Components

ppm	S-1	S-2	S-3	S-4	S-5	S-6	AUC*
S	404.50	644.30	612.83	709.03	588.60	682.42	621.00
Sc	30.52	20.47	37.89	30.68	38.79	36.27	14.00
V	886.21	1603.88	1072.50	911.39	917.55	970.10	97.00
Cr	25578.63	43021.89	31158.43	25340.63	28172.00	27545.85	92.00
Co	68.15	174.46	50.17	39.01	42.01	42.17	17.30
Ni	262.92	795.58	158.53	115.06	129.85	117.62	47.00
Cu	53.99	18.73	28.94	26.35	27.67	26.20	28.00
Zn	606.08	21288.71	184.03	159.10	140.26	167.75	67.00
Ga	26.59	115.93	15.91	13.36	15.27	14.51	17.50
Ge	1.08	0.00	0.00	0.00	0.00	0.00	1.40
As	5.20	9.66	5.15	6.99	8.32	7.95	4.80
Se	0.00	0.00	0.00	0.00	0.00	0.00	0.09
Br	0.65	2.03	0.00	0.20	0.77	0.00	1.60
Rb	17.00	10.35	7.82	7.90	8.96	8.72	84.00
Sr	71.06	64.28	82.17	93.49	83.26	99.21	320.00
Y	14.47	10.21	12.57	13.41	13.58	14.39	21.00
Zr	131.81	94.62	87.43	98.34	99.37	98.14	193.00
Nb	8.85	14.26	3.88	3.80	3.32	4.12	12.00
Mo	0.00	1.12	0.00	0.00	0.00	0.00	1.10
Ag	16.45	10.36	12.79	3.66	6.14	15.47	53.00
Cd	0.00	0.00	0.00	0.00	0.00	0.00	0.09
Sn	0.00	0.00	0.00	0.00	0.00	0.00	2.10
Sb	55.72	55.48	42.39	53.82	49.36	44.78	0.40
Te	0.00	0.00	0.00	0.00	0.00	0.00	-
I	0.00	0.00	0.00	0.00	0.00	0.00	1.40
Ba	208.15	159.49	168.18	183.26	179.97	195.45	628.00
Yb	0.00	0.00	0.00	0.00	0.00	0.00	2.00
Hf	1.67	0.00	1.69	4.92	3.00	2.25	5.30
Ta	14.66	205.25	9.55	7.75	5.90	10.16	0.90
W	2.98	0.00	7.42	10.71	7.53	11.53	1.90
Hg	0.00	0.00	0.00	0.00	0.00	0.00	0.05
Tl	2.22	3.36	0.00	0.75	5.13	0.00	0.90
Pb	11.63	197.92	0.00	0.28	0.43	0.04	17.00
Bi	5.45	8.61	3.97	4.12	4.32	4.70	0.16
Th	14.08	14.61	12.46	12.03	13.24	17.14	10.50
U	0.00	0.00	0.00	0.00	0.00	0.15	2.70

** Note: AUC (Average Upper Crust) values are taken from (Rudnick and Gao, 2003).*

The concentrations listed in Table 13 indicate that the trace elements Sc, V, Cr, Co, Ni, Zn, As, Sb, Ta, Bi and Th are all elevated with regards to the AUC concentrations in each of the slag components analysed. The element that is the most significantly elevated is Cr which has concentrations in the slag of up to more than 450 times than that stipulated for Cr in AUC concentrations. The trace elements V, Co and Ni all increase with an increase in the Cr concentration.

The trace elements Zn and Ta also show a strong positive relationship with an increase in the Cr concentration, although no direct association is present between these two elements and their correlation is more probably due to association with common elements/minerals than with each other (Fourie, P.J., 2009). The trace elements S, Cu, Ga, Br, Nb, Mo, W, Tl and Pb have elevated concentrations for a few of the slag components, but not all. The remainder of the trace elements occur at concentrations lower than the prescribed AUC concentration, with numerous of the trace elements not being detected at all.

From the assessment of the geochemistry of the slag with regards to those expected in the average upper crust (Rudnick and Gao 2003), it is identified that the certain elements in the slag are present at concentrations that potentially pose a risk on contaminating the environment, including the underlying ground water resources. The elements that are the most abundantly elevated and that appear to potentially pose the largest risk include, V, Cr, Co, Ni, Zn, Sb, Ta and Bi.

In order to validate this assessment of the slag, an additional assessment is made with regards to the elemental concentrations of the in-situ soils and weathered norite, which constitutes the majority of the host rock within the study area. The soil sample analysed is a vertic soil sample taken from adjacent to the existing slag dump and is representative of the majority of the soil within the study area.

A comparison of the average elemental concentrations of the most elevated elements identified in the slag, soil and weathered norite has been made and their elemental concentrations have been assessed according to the stipulated AUC concentrations taken from Rudnick and Gao (2003). The geochemistry assessment thereof is listed in Table 14.

Table 14: Average Concentrations of the Most Elevated Elements

Element		Slag	Soil	Weathered Norite
V	ppm	1060.27	313.3	98.1
Cr	ppm	30136.24	28904.0	2444.3
Co	ppm	69.33	54.0	53.6
Ni	ppm	263.26	244.3	319.3
Zn	ppm	3757.66	106.8	55.6
Sb	ppm	50.26	-	-
Ta	ppm	42.21	<2	<2
Bi	ppm	5.20	<3	<3

The average concentrations of the most elevated elements listed in Table 14 indicate that the slag has the highest elemental concentrations, followed by the soil and weathered norite respectively. The soil has higher concentrations for all the elements than the weathered norite, with the exception of Ni. Although the elemental concentrations in the soil and weathered norite are elevated with regards to the AUC concentrations, they are still significantly lower than the concentrations in the slag.

The elemental concentrations listed in Table 14 indicate that the elements V, Cr, Co and Ni are naturally elevated in the in-situ soils and weathered norite with respect to the average upper crust. The Cr content in the soils is of the same order of magnitude as in the slag and a lot higher than those recorded in the weathered norite. Elevated Cr concentrations in the slag therefore pose the same amount of risk on contaminating the underlying ground water system as the soil.

The geochemistry assessment of the slag with regards to the soils and weathered norite, indicate that although the in-situ soils and weathered norite are elevated in certain elements with regards to the AUC values, other elements are still significantly elevated in the slag. These elements therefore pose an apparent greater risk on contaminating the underlying ground water zones, than the soils and weathered norite.

4.1.2 Second Order Geochemistry Assessment of the Slag - SABS Code 0228 Tables

The geochemistry of the slag is thus further investigated and assessed with regards to the concentrations stipulated in the SABS Code 0228 Tables. The second order geochemistry assessment of the slag is done in accordance with the Hazardous Waste Classification Tables listed in the Minimum Requirement Documents and which have been derived from the SABS Code 0228.

This classification aids in the calculation of the Hazard Rating of the slag as well, based on the concentrations of potentially hazardous the slag with regards to the concentrations listed in the SABS 0228 Code, and are summarized in Table 15.

Table 15: Trace Element Compliance with regards to the SABS 0228 Code

ppm	S-1	S-2	S-3	S-4	S-5	S-6	HR	AER*	DA**
S	404.50	644.30	612.83	709.03	588.60	682.42	-	-	-
Sc	30.52	20.47	37.89	30.68	38.79	36.27	-	-	-
V	886.21	1603.88	1072.50	911.39	917.55	970.10	3	1.3	1970
Cr	25578.63	43021.89	31158.43	25340.63	28172.00	27545.85	2	0.02	30
Co	68.15	174.46	50.17	39.01	42.01	42.17	2	6.9	10454
Ni	262.92	795.58	158.53	115.06	129.85	117.62	2	1.14	1727
Cu	53.99	18.73	28.94	26.35	27.67	26.20	2	0.1	151
Zn	606.08	21288.71	184.03	159.10	140.26	167.75	2	0.7	1061
Ga	26.59	115.93	15.91	13.36	15.27	14.51	-	-	-
Ge	1.08	0.00	0.00	0.00	0.00	0.00	-	-	-
As	5.20	9.66	5.15	6.99	8.32	7.95	2	0.43	651
Se	0.00	0.00	0.00	0.00	0.00	0.00	2	0.26	394
Br	0.65	2.03	0.00	0.20	0.77	0.00	-	-	-
Rb	17.00	10.35	7.82	7.90	8.96	8.72	-	-	-
Sr	71.06	64.28	82.17	93.49	83.26	99.21	-	-	-
Y	14.47	10.21	12.57	13.41	13.58	14.39	-	-	-
Zr	131.81	94.62	87.43	98.34	99.37	98.14	3	2	3030
Nb	8.85	14.26	3.88	3.80	3.32	4.12	-	-	-
Mo	0.00	1.12	0.00	0.00	0.00	0.00	-	-	-
Ag	16.45	10.36	12.79	3.66	6.14	15.47	3	2	3030
Cd	0.00	0.00	0.00	0.00	0.00	0.00	1	0.03	47
Sn	0.00	0.00	0.00	0.00	0.00	0.00	-	-	-
Sb	55.72	55.48	42.39	53.82	49.36	44.78	2	0.07	106
Te	0.00	0.00	0.00	0.00	0.00	0.00	-	-	-
I	0.00	0.00	0.00	0.00	0.00	0.00	-	-	-
Ba	208.15	159.49	168.18	183.26	179.97	195.45	3	7.8	1181
Yb	0.00	0.00	0.00	0.00	0.00	0.00	-	-	-
Hf	1.67	0.00	1.69	4.92	3.00	2.25	-	-	-
Ta	14.66	205.25	9.55	7.75	5.90	10.16	-	-	-
W	2.98	0.00	7.42	10.71	7.53	11.53	-	-	-
Hg	0.00	0.00	0.00	0.00	0.00	0.00	1	0.02	24
Tl	2.22	3.36	0.00	0.75	5.13	0.00	-	-	-
Pb	11.63	197.92	0.00	0.28	0.43	0.04	2	0.1	151
Bi	5.45	8.61	3.97	4.12	4.32	4.70	-	-	-
Th	14.08	14.61	12.46	12.03	13.24	17.14	-	-	-
U	0.00	0.00	0.00	0.00	0.00	0.15	-	-	-

* AER = "Acceptable Environmental Risk" (*ppm)*
** DA = "Disposal Allowed (*g/ha/month)*

The hazard rating (HR) and amount of the element that is allowed to be disposed of for each of the elements are indicated in Table 15 as well. The HR and concentration that is allowed to be disposed of for each of the elements is determined according to the toxicity risk posed by the respective element.

The SABS 0228 Code includes a large list of elements and constituents, especially with regards to hydrocarbons and organic constituents. Despite the large number of constituents included in the SABS 0228 Code, it is evident from Table 15 that the Hazardous Waste Classification tables included in the Minimum Requirement Documents are in fact incomprehensive and that classifications could only be made for 15 of the 36 variables recorded in the slag.

Values given in red in Table 15 indicate concentrations that are higher than the Acceptable Environmental Risk (AER) values provided in the SABS 0228 Code. Values given in green in Table 15 indicate concentrations in the slag that are lower than the AER values listed in the SABS 0228 Code.

Table 15 indicates that 11 of the 15 parameters which could be classified had concentrations that were higher than stipulated AER concentrations. These parameters included V, Cr, Co, Cu, Zn, Ni, As, Zr, Ag, Ba and Pb. Two of the slag samples S-3 and S-6 did however have Pb concentrations below the AER concentrations. The elements Se, Cd, Sb and Hg had concentrations in each of the slag components that were lower than the AER concentrations given in the SABS 0228 Code.

Of the elevated elements, Cr is regarded as the variable in the slag that poses the highest potential risk on contaminating the environment, as it has the most elevated concentrations in the slag of the elements with a Hazard Rating of 2.

Based on the assessment of the slag with regards to the stipulated AUC and AER concentrations, the following is deemed important:

- A total of 5 trace elements (V, Cr, Co, Ni, and Zn) were abundantly elevated with regards to both the stipulated AUC and AER concentrations.

- A total of 11 trace elements (S, Sc, Ga, Br, Nb, Mo, Ta, W, Tl, Bi and Th) had elevated concentrations with regards to the AUC values, but did not have stipulated AER concentrations against which they could be classified.

- Sb was the only variable that had a concentration which was elevated with regards to the provided AUC concentration, but lower than the AER concentration.

- Zr, Ag and Ba on the other hand had concentrations that were lower than the stipulated AUC concentrations, but higher than the AER concentrations.

- In total 20 of the trace elements analysed for had at least one concentration in the slag that was higher than the stipulated AUC concentrations. 16 of the trace elements analysed for thus had concentrations that were lower for each slag sample analysed than the AUC concentrations.

- A total of 11 of the trace elements analysed for had at least one concentration in the slag material that was higher than the stipulated AER concentrations. Only 4 of the trace elements had concentrations that were lower than the AER concentrations and the remaining 21 trace elements, did not have stipulated AER concentrations against which they could be assessed.

Based on the classification according to the SABS 0228 Code, the slag is assigned an expected Hazard Rating of 2 and indicates that the most stringent requirements be adhered to during its disposal. Based on this classification of the slag, the Minimum Requirement Documents state that a H:H landfill is required for the disposal thereof.

The geochemical assessment of the slag provides an indication of the elements present as well as their respective concentrations in the slag. The assessment also provides an indication of the degree to which the slag is elevated in certain elements with regards to the average lithological units of the Upper Crust, soils and weathered norite material.

The geochemical assessment of the slag does however not provide an indication of the element concentrations that may potentially leach out from the slag and thus the quality of the expected leachate at the base of the slag disposal facility. The leachate generated at the base of the slag disposal facility has significant potential of entering the underlying ground water zones (environment) and is thus essentially viewed as the source of contamination associated with the slag dump. The expected geochemistry of the leachate generated at the base of the slag disposal facility is therefore assessed to provide a better indication of the potential risk that the slag poses on contaminating the adjacent environment.

4.2 LEACHING TESTS

Leaching tests were conducted on the slag in order to identify and quantify the elements that could potentially leach out of the slag aggregate material. The leaching tests are also used in order to determine whether it is suitable to delist the classification of the waste to a lower hazard rating and allow the waste to be disposed of at less stringent landfill options.

The slag is singularly disposed of at specified locations on the site and is disposed of as a dry aggregate material. The slag is therefore analysed using the Acid Rain Leaching Procedure. The Acid Rain Leaching Procedure is based on the fact that carbon dioxide dissolves in rainwater to form carbonic acid, which could potentially mobilize chemicals from the slag aggregate. Any leachate generated from the slag will primarily occur due to precipitation falling onto the slag dump, rather than the introduction of organic acids. The Toxicity Characteristic Leaching Procedure is used in environments where hazardous waste is co-disposed with organic waste and was therefore not used for this scenario.

The Acid Rain tests represent absolute worst case scenarios and aid in identifying the elements that will potentially leach out of waste. They do however not in fact reflect the site-specific concentration of these elements in the actual seepage as a different water to rock ratio, pH conditions and contact time will be present in the field.

The Acid Rain method entails the extraction of a sample of waste with a saturated solution of carbonic acid and represents the worst case scenario. A water:rock ratio 1:20 was used where 100 g of the slag sample was reacted with 2 litres of the carbonic acid (acid rain) solution for 20 hours. The resultant leachate was then analysed for the following variables: pH, EC, TDS, T.Alk, NH_4, NO_3, Cl, SO_4, F, Si, Na, K, Ca, Mg, Al, Fe, Mn, Cr(Total), Cr(III), Cr(VI) and Zn.

The geochemistry of the leachate generated during the Acid Rain test is listed in Table 16. The geochemistry of the leachate has been assessed with regards to the SANS 241:2006 Drinking Water Standard and provides an indication of the quality compliance of the leachate. It is also assumed that if a water/leachate quality is fit for human consumption, then it will be fit for livestock and agricultural purposes as well.

Table 16: Acid Rain Leaching Procedure Results

Constituents	S-1	S-2	S-3	S-4	S-5	S-6
pH	5.7	5.5	5.9	5.6	5.8	5.8
EC (mS/m)	35.2	6.5	9.7	7	10.5	17.1
TDS (mg/l)	208	44	65	47	70	115
T.Alk (mg/l)	168	24	44	24	44	44
NH_4 as N (mg/l)	0.2	0.2	<0.2	0.2	<0.2	0.4
NO_3 as N (mg/l)	0.2	0.2	0.2	<0.2	0.2	<0.2
Cl (mg/l)	<5	5	<5	<5	6	<5
SO_4 (mg/l)	8	<5	6	5	5	9
F (mg/l)	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Si (mg/l)	5.28	4	1.95	0.492	1.43	1.09
Na (mg/l)	9	5	2	<2	3	<2
K (mg/l)	4.3	<1.0	<1.0	<1.0	<1.0	<1.0
Ca (mg/l)	48	3	8	<2	8	2
Mg (mg/l)	14	5	4	<2	3	2
Al (mg/l)	<0.100	0.105	<0.100	<0.100	0.185	<0.100
Fe (mg/l)	0.04	0.74	5.11	7.10	6.57	7.82
Mn (mg/l)	0.381	0.238	5.60	0.331	0.724	2.49
Cr(T) (mg/l)	<0.025	<0.025	0.035	<0.025	0.173	<0.025
Cr(III) (mg/l)	<0.025	<0.025	0.035	<0.025	0.173	<0.025
Cr(VI) (mg/l)	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010
Zn (mg/l)	0.025	<0.025	<0.025	<0.025	0.166	<0.025
Balancing %	95.2	95.9	94.5	93.3	99.9	94.9

The SANS 241:2006 Drinking Water Standard specifies that it has been approved by the National Committee StanSA TC 5140.19, *Water* in accordance with procedures of Standards South Africa. It has been approved in compliance with annex 3 of the WTO/TBT agreement and was published in December 2006. The SANS 241:2006 Drinking Water Standard specifies two classes of drinking water quality, namely Class I and Class II, defined in terms of the microbiological, physical, organoleptic and chemical parameters.

The Class I variable concentrations indicate those which are considered to be "acceptable for lifetime consumption" and indicate the recommended compliance limit. The Class II variable concentrations are considered to represent an acceptable drinking water quality if "consumed for a limited period of time" and indicates the maximum allowable limit for a limited duration of time. This class specifies a water quality range that poses an increasing risk on consumers, dependent on the concentration of the variable within the specified range (SANS 241:2006 Drinking Water Standard). Variable concentrations that exceed the Class II concentrations are deemed as unfit for human consumption.

Variable concentrations in the leachate that fall within Class I of the SANS 241:2006 Drinking Water Standard are indicated in Green and are classified having concentrations that are "Fully Compliant" with regards to the SANS 241:2006 Drinking Water Standard.

Variable concentrations that fall within Class II are indicated in Orange and are classified as having concentrations that are "Marginally Compliant" with regards to the SANS 241:2006 Drinking Water Standard.

Variable concentrations that exceed the Class II concentrations are indicated in Red and are classified as having concentrations that are "Non-Compliant" with regards to the SANS 241:2006 Drinking Water Standard.

The values given in black indicate the variables that do not have stipulated concentrations within the SANS 241:2006 Drinking Water Standard against which they may be classified. Only 4 of the variables (T.Alk, Si, Cr(III) and Cr(VI)) did not have concentrations against which an assessment could be made.

The chemistry results of leachate listed in Table 16 indicate that the majority of the constituents in the leachate generated from the slag during the Acid Rain test have concentrations that are fully compliant with regards to the SANS 241:2006 Drinking Water Standard. The two elements that have consistently elevated concentrations in the leachate with regards to the SANS 241:2006 Drinking Water Standard are Fe and Mn.

The total Cr also has a slightly elevated concentration in sample S-5 (0.173 mg/l) with regards to the SANS 241:2006 Drinking Water Standard. The chemistry results of the leachate listed in Table 16 further indicate that Cr(T) is made up entirely of Cr(III) and that the Cr(VI) was not detected in the leachate generated from any of the slag samples during the Acid Rain tests.

It can be concluded from the leachate concentrations listed in Table 16 that slag will not generate a leachate with a high salt load and that the most elevated elements are Fe and Mn. The samples S-3 and S-5 were the only two slag samples which had Cr detected in the leachates. The Zn concentration from sample S-5 was also slightly elevated, but still at a concentration that was still fully compliant with regards to the SANS 241 Standard.

Based on the results from the Acid Rain tests, the following observations are made with regards to the elevated elemental concentrations (Cr, Fe, Mn and Zn) recorded in the leachate generated from the slag during the Acid Rain tests:

Chromium (Cr)

Cr(T) is assigned a hazard rating of 2, whilst Cr(VI) is assigned a Hazard Rating of 1, due to its carcinogenic properties. Table 16 depicts that Cr(VI) occurred at concentrations that were below the laboratories limit of detection (LOD) of 0.01 mg/l, although Cr(T) was detected in the leachate generated from two of the slag samples (S-3 and S-5). In both these samples the Cr(III) had the same concentration as the Cr(T), indicating that all the chromium detected in the leachate consists of Cr(III). By interpolation it is indicated that Cr(VI) is not present in the slag and that the Cr present in the slag is assigned a HR of 2.

Zinc (Zn)

According to the geochemistry analyses of the slag, zinc is the second most elevated element of concern in the slag relative to the AUC concentrations, after Cr. The leaching test results given in Table 16 however, indicate that not even an elevated element such as Zn was detected in the leachate generated from the slag.

Four out of the six samples had Zn concentrations in the leachate that were below the laboratory's limit of detection (0.025 mg/l). S-1 and S-5 had Zn concentrations of 0.025 mg/l and 0.016 mg/l respectively. Zinc is also assigned a HR of 2 indicating that it poses a potentially "high" risk on contaminating the environment.

Iron (Fe) and Manganese (Mn)

Iron and manganese are the two elements that were the most elevated in the leachate generated from the slag samples, with regards to the SANS 241:2006 Drinking Water Standard. Both Fe and Mn occurred at predominantly non-compliant or marginally compliant concentrations with regards to the SANS 241:2006 Drinking Water Standard.

The hazard rating assigned to iron (Fe) is 3 and indicates a "marginal" risk on contaminating the environment. The hazard rating assigned to manganese (Mn) is 2 and indicates a "high" risk on contaminating the environment. It is important to note that elevated concentrations in the metals Fe and Mn often only have cosmetic effects (such as skin or tooth discoloration) or aesthetic effects (such as taste, odour, or colour) in drinking water and may not have detrimental effects on the environment or human health (Fourie, P.J, 2009).

4.3 HAZARD RATING ASSIGNED TO THE SLAG

The mere presence of the variables of concern in the slag does not in fact singularly imply that they will leach out and have a detrimental effect on the environment. Unacceptable adverse effects on the environment imply any unreasonable risk to man or the environment. The risk assigned is merely a measure of the probability of and severity of adverse effects and is thus a function of the toxological hazard of the waste as well as the exposure.

The toxological hazard refers to characteristics of certain chemicals to cause an adverse effect on the environment. The exposure on the other hand refers to the amount of the chemical that can be exposed to man or the environment before it is adversely affected. When the level of an adverse effect as well as the amount of chemical available is known, the likelihood of an adverse effect can be determined.

Many pathways of exposure exist, the most common of which are air and water. The end point will however be some or other living creature such as humans or aquatic environment. The pathway of exposure which is used to quantify the risk of a certain chemical to man and the environment is stipulated by the regulating authorities as the aquatic environment. Due to the apparent sensitivity of the aquatic environment to pollution or contamination, it is deemed acceptable to prove that "*if the aquatic environment is not at risk to an elevated elemental concentration, then man and other mammals as well as plant life are not at a risk either*".

The risk posed to the aquatic environment is assessed as the likelihood that the aquatic environment will be affected by the introduction of certain elements within the leachate generated at slag disposal facility. According to the Minimum Requirement Documents the key to aquatic hazard analysis is to determine the environmental concentrations of contaminants and the effect that they would have on the environment.

The Minimum Requirement Documents stipulate that the EEC of the leachate generated at the base of the slag disposal facility be calculated and used during the hazard rating calculation of the slag. Seeing that the slag is disposed of by landfill, the most conservative way of calculating the EEC is by calculating the total contaminant concentration in the slag per unit area (ha), followed by the calculation of the resultant concentration in a body of water (dose), should the total amount of contaminant leach into the underlying ground water body over an indefinite period of time.

The quantity of the contaminant that may leach and migrate from the slag dump was thus determined according to the Minimum Requirements' fixed scenario approach. During the fixed scenario approach, it is assumed that the total mass of slag disposed of on one hectare of landfill will leach into one hectare of the underlying ground water body to a depth of 15 cm below the disposal site.

The tonnage of slag deposited on the slag dump was provided by the generic ferrochrome plant from which the slag samples were collected. It was indicated that an average of 30 000 tonnes of slag is deposited per month, across a surface footprint of 50 ha, for a 20 year lifetime.

The EEC was calculated for the elements Fe, Mn, Cr(T), and Zn, as specified in Appendix 8.3 of the Minimum Requirement for the Handling Classification and Disposal of Hazardous Waste (DWAF (1998)) and is summarized in Table 17.

Table 17: Calculation of the EEC for the Elevated Elements

Variables of Concern	Fe	Mn	Cr(T)	Zn
Concentrations in Leachate (mg/l)	7.82	5.60	0.10	0.10
Slag Disposal (ton/month)	30 000	30 000	30 000	30 000
Area of disposal site (ha)	50	50	50	50
Calculated Chemical in leachate (g/ha/month)	4692	3360	60	60
Dose (ppm)	3.13	2.24	0.04	0.04
EEC (ppm) = *(0.66 x Dose)*	2.06	1.48	0.03	0.03

The EEC calculated for each of the Fe, Mn, Cr(T) and Zn was then used to determine the Hazard Rating of the slag as indicated in Table 18. The AEC values stipulated in Table 18 were obtained from the Hazardous Waste Classification Tables included in Appendix 9.2, calculated for the elements Fe, Mn, Cr(T), and Zn, as specified in Appendix 8.3 of the Minimum Requirement for the Handling Classification and Disposal of Hazardous Waste (DWAF (1998)).

Table 18: Calculation of the Hazard Rating of the Slag Disposal Facility

Variables of Concern	Fe	Mn	Cr(T)	Zn
EEC (ppm)	2.06	1.48	0.03	0.03
AEC for chemical (ppm)	2	0.3	4.7	0.83
Hazard Rating of chemical	3	2	2	2

It is indicated in Table 18 that the EEC calculated for the Cr(T) and Zn in the leachate is lower than the stipulated AEC concentrations, indicating that the Cr(T) and Zn concentrations in the leachate are not expected to pose a risk on contaminating the aquatic environment.

The EEC values calculated for the elements Fe and Mn are however higher than the specified AEC for each of the two elements, indicating that they pose a potential risk on contaminating the environment. The EEC calculated for Fe is only slightly elevated with regards to the AEC, whist the EEC calculated for Mn is elevated by almost 5 times that of the AEC. Mn has a lower Hazard Rating than Fe and the slag is therefore assigned a Hazard Rating of 2.

Due to the Hazard Rating (2) assigned to the slag disposal facility the Minimum Requirement Documents specify that the slag is required to be disposed of at a landfill that is installed with an H:H liner system regardless of the water balance or site specific factors. The leachate intercepted and removed by the liner system at the foot of the slag disposal facility is required to be contained in a surface water dam / pond. The containment facility is required to be installed with an H:H Lagoon liner system, and is required to contain the captured leachate until it is treated to the appropriate quality. The efficiency of the H:H Lagoon liner is not investigated for the purpose of the research study which addresses solid waste disposal.

5 LINER DESIGN OPTIMISATION

Based on the geochemical analyses and classification of the slag in Section 6, the slag is assigned a Hazard Rating of 2, implying that the climatic water balance is ignored and the most stringent requirements are required regarding the disposal thereof. Based on the apparent risk posed by the elevated elements within the expected leachate generated from the slag dump on contaminating the environment the Minimum Requirement Documents stipulate that the slag is to be disposed of at a landfill that is installed with the most stringent (H:H) liner system.

The site specific data, that is required to be obtained, is also ignored and the landfill classification is made entirely according to the apparent risk posed by the leachate generated from the slag under acid rain conditions, assuming that all the entire leachate enters the underlying saturated ground water zone.

The potential benefits of using the required site specific data in optimizing the liner design for specific waste disposal facilities are therefore investigated in this research project, using available water balance and mass transport modelling techniques.

This section will firstly aim to investigate the potential benefits of using the site specific data during the calculation of the volume of leachate generated at the slag dump, as well as the influence and efficiency that the different liner components have on intercepting the leachate that is generated. This is achieved by means of comparative quantitative sensitivity analyses whereby the effectiveness of the various liner components is determined. The effect that any potential leachate generated at the base of the slag disposal facility might have on the ground water system, will be empirically analysed by running a set of models for the different liner option scenarios.

Use is made of available water balance and mass transport modelling techniques to investigate the sensitivity and influence that site specific parameters may have on the quality and quantity of leachate generated from the slag disposal facility. The sensitivity and influence that the different components within liner systems have on capturing and removing the generated leachate, will be investigated and assessed as well. The aim is thus essentially to assess the effectiveness of this method in determining the most suitable liner system for the waste disposal facility according to the Best Practicable Environmental Option norm at the most optimal cost.

5.1 OVERVIEW AND SOFTWARE USED

The modelling will be performed subject to the source-pathway-receptor hierarchy, and will investigate: the generation of soluble/mobile contaminants within the slag dump, the mobilization of these contaminants through the underlying liner systems, the mixing of these contaminants within the saturated zone, as well as the subsequent lateral migration of these contaminants away from the point of infiltration within the saturated zone assuming that all the contaminants are mobile and conservative, i.e. they won't break down or chemically react within the ground water system.

It is important to note here that a model is a simplification of a real world system and is only used as a simulation of the real world situation. The models will be used as indicative tools and are only as accurate as the data that is defined an inserted into the model. Care was thus taken during the quantification of the field work data, which is used as input data into the programs during the modelling exercises. Because a model is a simplified version of the real world phenomenon, various assumptions are made. The ground water models developed, will therefore be described in sufficient detail in order to indicate the appropriateness and accuracy of the input data as well as the model outcome for the scenario being simulated.

The volume of leachate generated at the base of the slag disposal facility, as well as the flux of leachate through the various liner options investigated is simulated using the Visual HELP 2.2 modelling software. HELP is a versatile modelling program developed by the United States of America Environmental Protection Agency (USEPA) for predicting landfill hydrological processes and testing the effectiveness of landfill and liner designs as well as recharge to the ground water system.

The use of HELP has in fact become a requirement for obtaining landfill operation permits in the United States of America. Visual HELP 2.2 was thus used to determine the volume of leachate that is expected to infiltrate through each of the proposed liner options investigated using the meteorological and site specific data obtained in the field.

Visual HELP 2.2 has a built in weather generator that provides weather conditions for a pre-selected area or simulates the weather conditions using specified local meteorological data. The HELP weather generator will be used to simulate the site specific weather conditions, using the data obtained from the Rustenburg Weather Monitoring Station (RWMS). The same meteorological data was used during the simulations for each of the scenarios investigated and thus provides constant meteorological conditions for each of the scenarios, from which a comparative assessment can be investigated.

The HELP 2.2 modelling software is therefore used as it incorporates the meteorological data, the specified liner parameters and properties, the waste properties as well as several site specific factors, to determine the daily evaporation, run-off, recharge/infiltration and moisture retention of the specified scenario investigated.

HELP is an analytical model and will be used to quantify and assess the leachate flux that can be mobilized from the slag, the flux captured by the layers in the liner, the flux through the different layers in the liner scenarios and into the underlying ground water system. The HELP models will also be used to optimize the determination of the EEC of contaminants within the leachate generated at the base of the slag disposal facility as a whole, with regards to the underlying ground water system.

Once the leachate volumes have been calculated and the effectiveness of the various liner options in containing these leachates has been quantified, a numerical model will subsequently be used to graphically illustrate the movement and attenuation of the leachates within the underlying saturated ground water zone.

Visual MODFLOW will be used and aims to simulate the ground water flow and mass transport of the leachate related to the different infiltration fluxes for each of the liner scenarios. The results obtained will be used to assess the extent of the ground water pollution plume formation and migration within the delineated ground water influence zone over time.

With reference to the conceptual model regarding the slag disposal facility including the various liner designs as well as the underlying aquifer hydraulics, the following issues will be addressed in detail:

- Optimisation of the slag dumps water balance calculations.
- Calculation of leachate flux through the various liner options.

- Sensitivity analyses of various liner components.
- Optimisation of the liner design by means of a comparative assessment.
- Calculation of mass transport of leachates within the saturated zone.
- Efficiency of using available water balance and mass transport modelling software in order to optimize the liner based on the meteorological and site specific data obtained in the field.

5.2 DATA INPUT AND ASSUMPTIONS

The volume of leachate generated at the base of the slag dump is calculated using the meteorological conditions obtained from the Rustenburg Weather Monitoring Station, the porosity and physical properties of the slag material at disposal, as well as the requirements stipulated for each of the layers within the different liner options.

In this regard, the HELP model is compiled to realistically reflect the physical attributes and effectiveness of the different liner designs, incorporating the site specific meteorological conditions as the main driving force behind the water balance. The final output will provide a simulated leachate flux rate through the various liners investigated and into the underlying saturated zone.

5.2.1 Physical Properties of the Slag Disposal Facility

The footprint of the slag disposal facility will cover an area of 50 ha (500 000m^2) with a maximum height of 20 m above the surface. The slag is deposited as a dry aggregate material with an initial moisture content of 0% and with an average grain size of 20 mm. The slag has a total porosity of 40% and is assigned a hydraulic conductivity of 0.01 cm/s (8.64 m/day).

The slag dump will not be vegetated and will be operated as a dry waste landfill disposal facility. Any leachate generated at the base of the slag dump is expected to be generated due to the infiltrating precipitation. The base of the slag disposal facility is identified and delineated as the potential contamination infiltration source.

5.2.2 Meteorological Data

The meteorological data obtained from the Rustenburg Weather Monitoring Station was used as input parameters for the weather generator within the HELP modelling software. The meteorological conditions represent the driving forces for the water balance of the slag disposal facility and as a result for the percolation and infiltration of the generated leachate through the disposal facility and underlying liner systems.

The average monthly temperatures, average monthly rainfall, evaporation, humidity, and wind speeds were all specified as input parameters for the weather generator. The evaporative depth for the site was selected as 25 cm and average wind speed of 1.48 m/s was used.

The weather generator was specified to simulate the conditions for a period of 100 years, using the specified meteorological conditions. Graphs depicting the simulated annual precipitation, annual temperature and annual solar radiation are displayed as Figure 24, Figure 25 and Figure 26 respectively.

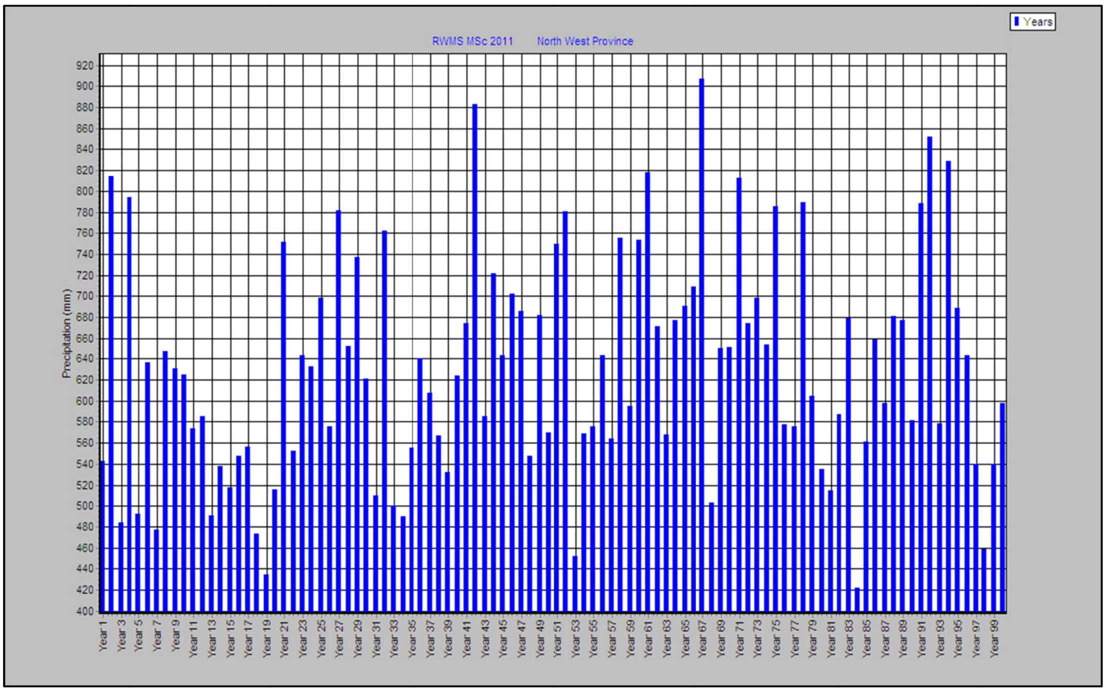


Figure 24: Simulated Annual Precipitation – 100 years

The average simulated annual rainfall for the 100 year period is 629.71 mm/annum, as opposed to the 621 annum, recorded at the Rustenburg Weather Monitoring Station between 1997 and 2007. An average annual rainfall of 629.71 mm/annum has been simulated and is used as the MAP for the model.

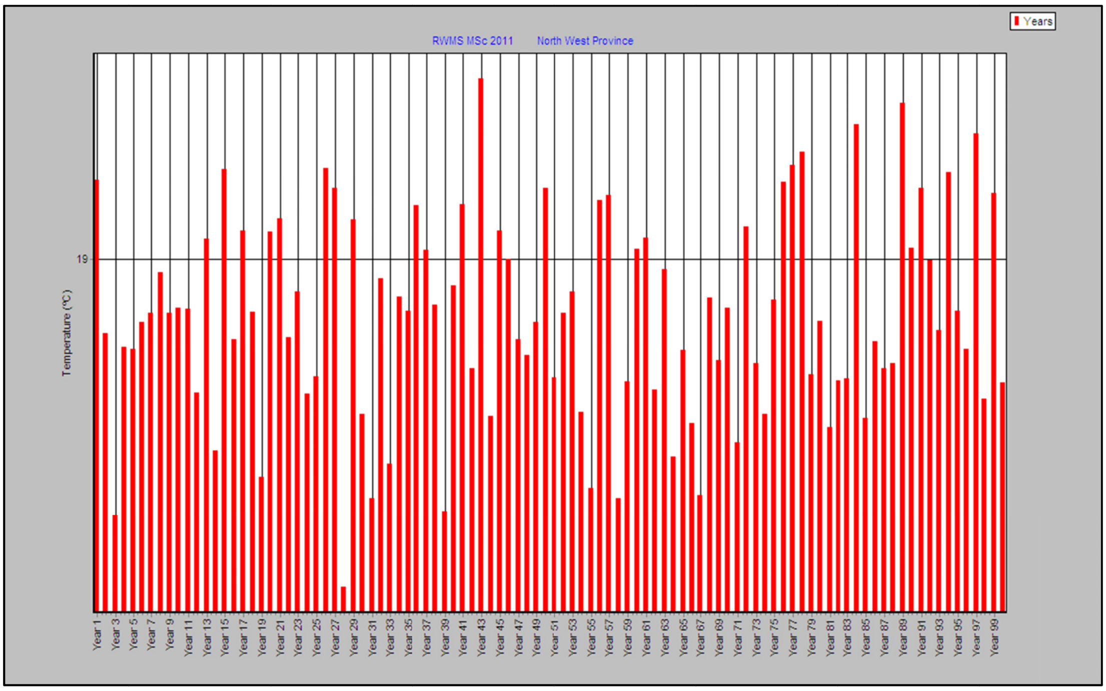


Figure 25: Simulated Annual Temperature – 100 years

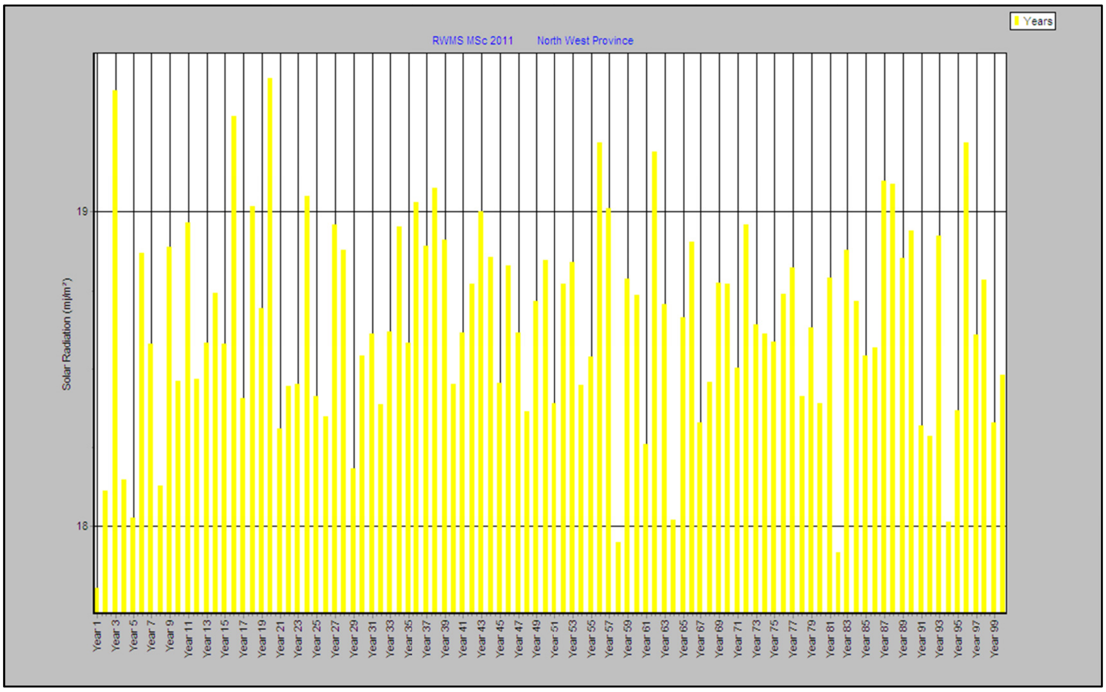


Figure 26: Simulated Annual Solar Radiation – 100 years

5.2.3 Infiltration Rates into the Saturated Zone

The infiltration rates/fluxes through the various liner options were investigated using the specified layer properties, provided within the Minimum Requirement Documents. The soil conditions observed within the study area will however be used to replace the specified base preparation layer. The slope of the natural surface below the footprint of the slag disposal facility is calculated as 0.013 and is used as the slope angle of the layer properties, unless stated otherwise.

In addition to the various liner options considered, the natural ground water recharge, and the volume of leachate that will enter the underlying saturated zone if no liner is implemented at the base of the slag disposal facility are investigated as well.

The infiltration rates calculated through the bottommost layer of the HELP model are further used as direct infiltration rates into the saturated zone mass transport (MODFLOW) model, which means that a steady state flux assumption has been made with regards to the unsaturated zone. The infiltration figures used as input into the saturated zone model therefore represent the worst case scenario.

5.2.4 Leachate Quality

The quality of the leachate generated from the slag during the acid rain leaching tests is used to represent the quality of any leachate generated at the base of the slag dump.

During the mass transport model, an infiltration concentration of 100 mg/l (100%) was assigned to the model across the extent of the slag dump footprint. The actual concentrations of the specific variables in the mass transport model are as a result normalized according the modelled concentrations within the saturated zone.

5.3 WATER BALANCE CALCULATIONS AND SENSITIVITY ANALYSES

5.3.1 Introduction

The slag disposal facility water balance calculations focus primarily on determining the leachate flux that could potentially infiltrate through the bottommost layer of the liner scenarios investigated. This simulated leachate flux is then used to determine the mass of variables that would potentially infiltrate through each of the liners and as a result indicate the respective EEC for each of the individual liner designs.

The volume of water captured and drained by each of the individual layers within the respective liner designs were assessed during the water balance calculation, in order to provide an indication of the effectiveness thereof. Each liner design is therefore individually assessed in order to determine the Best Practicable Environmental Option regarding the liner design for the slag disposal facility investigated.

During the water balance calculations, the following scenarios were investigated.

1) Natural Ground Water Recharge

   The natural ground water recharge to the underlying saturated zone was calculated through a 5 meter thick unsaturated zone as identified during the field investigations. This represents the natural recharge to the ground water system as a result of infiltrating precipitation at the surface of the unsaturated zone.

   The hydraulic conductivity of the modelled 5 m unsaturated zone (clay “turf” soil and highly weathered norite) below the slag disposal facility was taken as 3×10^{-5} cm/s and was assigned a total porosity of 0.47 with an initial moisture content of 5%.

2) Slag on Soil – (No Liner Installed)

   The second scenario investigated is that which exists if the slag is deposited directly on top of the in-situ soil without any base preparation at the base of the slag disposal facility. This scenario represents the absolute worst case scenario and is investigated to determine the volume of leachate that could potentially infiltrate into the saturated zone if no liner is installed below the slag disposal facility.

3) Liner Scenario’s

   According to the Minimum Requirement Documents, the slag is required to be disposed of at a facility that is installed with an H:H Liner. The effectiveness of an H:H liner with a clay permeability of 1×10^{-7} cm/s as well as the effectiveness of an H:H liner with a clay permeability of 1×10^{-6} cm/s were therefore investigated. In addition to the two H:H liner options, the effectiveness of several variations of the stipulated G:L:B$^+$/G:M:B$^+$ liner option was investigated as well.

A total of 15 liner designs/scenarios were investigated, and assessed in terms of their ability to intercept and remove any leachate generated at the base of the slag disposal facility and thus their ability to prevent the leachate from infiltrating into the underlying saturated ground water zone.

The 5 meter thick unsaturated zone observed on site was used in each of the 17 scenarios to replace the base preparation layer stipulated within the Minimum Requirement Documents. All the drainage collection layers were modelled with a saturated vertical conductivity value of 1 x 10^{-2} cm/s, except where specified differently. Drains installed at various distance apart have been assessed and are included in each of the liner scenarios investigated. The effect that the slopes of the layers have on capturing the leachate was assessed and is used as 0.013 unless stated otherwise.

A summary of the 15 liner scenarios investigated is indicated in Table 19.

Table 19: Summary of Liner Scenarios Investigated during Sensitivity Analysis

Variant	Liner Description
H:H Variants	
1	H:H liner with a clay permeability of 1 x 10^{-7} cm/s. Surface slope of 0.013.
2	H:H liner with a clay permeability of 1x 10^{-6} cm/s. Surface slope of 0.013.
G:L:B$^+$ / G:M:B$^+$ Variants	
1	4 x 150mm thick clay layers with a permeability of 1 x 10^{-8} cm/s. Surface slope of 0.013.
2	2 x 150mm thick clay layers with a permeability of 1 x 10^{-8} cm/s. Surface slope of 0.013.
3	1 x 150mm thick clay layers with a permeability of 1 x 10^{-8} cm/s. Surface slope of 0.013.
4	4 x 150mm thick clay layers with a permeability of 1 x 10^{-7} cm/s. Surface slope of 0.013.
5	2 x 150mm thick clay layers with a permeability of 1 x 10^{-7} cm/s. Surface slope of 0.013.
6	1 x 150mm thick clay layers with a permeability of 1 x 10^{-7} cm/s. Surface slope of 0.013.
7	4 x 150mm thick clay layers with a permeability of 1 x 10^{-7} cm/s. Surface slope of 0.02.
8	2 x 150mm thick clay layers with a permeability of 1 x 10^{-7} cm/s. Surface slope of 0.02.
9	1 x 150mm thick clay layers with a permeability of 1 x 10^{-7} cm/s. Surface slope of 0.02.
10	4 x 150mm thick clay layers with a permeability of 1 x 10^{-7} cm/s. Surface slope of 0.05.
11	2 x 150mm thick clay layers with a permeability of 1 x 10^{-7} cm/s. Surface slope of 0.05.
12	1 x 150mm thick clay layers with a permeability of 1 x 10^{-7} cm/s. Surface slope of 0.05.
Optimized Liner Design	
Optimized Liner Design, based on the information obtained from simulated HELP models	

*** Note: 1 x 10^{-7} cm/s = 8.64 x 10^{-5} m/day.**

The assessment of the associated containment facility to containing the captured is however not addressed during this research study. The specifications of each of the individual layers incorporated in the models are summarized in Table 20.

Table 20: Layer Specifications

	Slag	Soil	Clay	Geotextile	Drainage
Total Porosity	0.40	0.47	0.45	0.85	0.42
Field Capacity	0.032	0.310	0.419	0.010	0.045
Wilting Point	0.013	0.187	0.332	0.005	0.018
Saturated Hydraulic Conductivity (cm/s)	0.01	3 x10^{-5}	As Specified	10	0.01
Subsurface Inflow (mm/year)	0	0	0	0	0
Initial Moisture Content (%)	0	0	-	0	0

The High Density Polyethylene (HDPE) layer specified, has a saturated hydraulic conductivity of 2 x 10^{-10} cm/s (1.7 x 10^{-7} m/day) and is assigned a placement quality of 4, indicating a “poor” quality range of contact between the geomembrane and the underlying soil. The HDPE layer is further conservatively assigned a pinhole density of 2 as well as an installation defect of 2, which indicate the number of 1 mm holes per unit area resulting from manufacturing flaws as well as the number of holes (1 cm^2) per unit of liner installed as a result of liner installation errors respectively.

5.3.2 Natural Ground Water Recharge

The natural ground water recharge was simulated through the 5 m thick unsaturated zone with a vertical conductivity of 3 x 10^{-5} cm/s (0.026 m/day) and surface slope of 0.013. A summary of the water balance regarding the simulated natural ground water recharge within the study area is given in Table 21.

Table 21: Water Balance - Natural Ground Water Recharge

Natural Recharge	Units	% MAP
Precipitation (mm/annum)	629.71	100 %
Runoff (mm/annum)	31.88	5.06 %
Evapotranspiration (mm/annum)	546.26	86.75 %
Infiltration through the soil (mm/annum)	35.41	5.62 %

Table 21 indicates that of the simulated 629.71 mm of precipitation that falls over a period of 1 year, 31.88 mm/annum is lost due to surface run-off. A further 546.26 mm/annum is lost to evapotranspiration and only 35.41 mm/annum (5.6% MAP) infiltrates through the soil into the saturated ground water zone.

The simulated natural ground water recharge of 35.41 mm/annum falls within the expected ground water recharge (3% (19 mm/annum) to 7% (43 mm/annum) of the MAP) assigned to the geohydrological zone within the study area.

5.3.3 Slag on Soil – No Liner Implemented

The worst case scenario that could potentially exist is that which exists if the slag is deposited directly on top of the in-situ soil, without the installation of a liner system below the slag material. All the leachate generated from the slag dump would thus potentially infiltrate directly into and through the underlying in-situ soil zone and into the saturated ground water zone below the slag dump.

This scenario was investigated to determine the maximum volume of leachate that could potentially enter the saturated zone below the 20 m high slag disposal facility with a surface footprint of 50 ha and a natural surface slope of 0.013.

A summary of the water balance regarding the slag dump and underlying 5 m thick unsaturated soil zone is given in Table 22.

Table 22: Infiltration through Unsaturated Zone if No Liner is implemented

Slag on Soil	Units	% MAP
Precipitation (mm/annum)	629.71	100 %
Runoff (mm/annum)	1.04	0.17 %
Evapotranspiration (mm/annum)	438.82	69.69 %
Infiltration through the soil (mm/annum)	152.43	24.21 %

The simulated results indicate that if no liner is implemented below the slag dump 1.04 mm/annum of leachate is removed via surface runoff and 438.82 mm/annum is lost to evapotranspiration. A total of 189.85 mm/annum infiltrates from the slag material and accumulates to 94,925 m^3/annum across the 50 ha slag dump footprint. This indicates the maximum volume of leachate that could potentially percolate out from the base of the slag dump and infiltrate into the saturated ground water zone.

Of the 189.85 mm/annum of leachate that percolates out of the bottom of the slag material and into the underlying soils, 152.43 mm/annum (24.21% MAP) infiltrates through the soil and into the saturated ground water zone. The results indicate that by placing the slag on top of the in-situ soils without implementing a liner system increases the ground water recharge to the aquifer within the extent of the slag footprint as well. The infiltration below the slag dump increases to 152.43 mm/annum as opposed to the natural ground water recharge of 35.41 mm/annum.

The efficiency of the liner system below the slag disposal facility is essentially assessed with regards to its ability to intercept and remove the required volume of leachate, to a flux rate through the liner system that will not detriment the environment.

In order to determine the maximum leachate flux allowed to pass through the liner system, the EEC of the slag disposal facility is assessed, using the site specific data. The calculation of the EEC, based on the simulated leachate volume from the slag dump and is summarized in Table 23. The EEC is calculated for the four elements that were identified to be the most abundantly elevated in the slag.

Table 23: EEC Calculation of the leachate generated from the Slag Dump

Variables of Concern	Fe	Mn	Cr(T)	Zn
Concentration in Leachate (mg/l)	7.82	5.6	0.1	0.1
Total Leachate Volume (m^3/annum)	94925	94925	94925	94925
Total Leachate Volume (l/month)	7910417	7910417	7910417	7910417
Load per month (g/month)	61859	44298	791	791
Area of disposal site (ha)	50	50	50	50
Chemical in leachate (g/ha/month)	1237.19	885.97	15.82	15.82
Dose (g/ha/month)	2.47	1.77	0.03	0.03
EEC (ppm) = (0.66 x Dose)	1.63	1.17	0.02	0.02
AEC for chemical (ppm)	2	0.3	4.7	0.83
Hazard Rating of chemical	3	2	2	2

The simulated results listed in Table 23 indicate that calculated EEC for the elements Fe, Cr(T) and Zn are lower than the stipulated AEC concentrations and are therefore not expected to pose a risk on contaminating the environment, if the slag is disposed of directly on top of the soil surface.

The calculated EEC for the element Mn is however is higher than the stipulated AEC concentration and the slag is therefore still assigned a Hazard Rating of 2. This specifies that the slag poses a “high” risk on contaminating the underlying ground water system and is not permitted to be disposed of directly on top of the in-situ soil. The slag is therefore required to be disposed of at a landfill disposal facility that has a low permeability liner installed.

The simulated results indicate that the EEC calculated for Mn in the 189.85 mm/annum of leachate generated from the slag is 1.17 ppm and is significantly elevated with regards to the stipulated AEC concentration for Mn (0.3 ppm). To ensure that the leachate generated from the slag disposal facility poses no adverse risk on contaminating the environment, the optimal liner design is required to intercept the volume of leachate that would reduce the EEC to less than 10% of the AEC (0.03 ppm).

In order to ensure that the EEC of Mn in the leachate of the slag disposal facility as a whole is kept below 0.03 ppm it is calculated that only 4.75 mm/annum of leachate is permitted to pass through the liner system. This calculates to a total volume of 2,375 m^3/annum and represents the volume of leachate generated at the base of the disposal facility that is expected to have no adverse effect on the environment, if it passes through the liner system and into the underlying ground water zones. The most optimized liner design for the slag disposal facility investigated is thus required to intercept 185.10 mm of leachate per annum, at an optimal cost.

The efficiency of the individual layers stipulated within the H:H and various G:L:B^+ Variant Liner Options at capturing and removing the leachate generated at the base of the slag disposal facility are assessed, and will be used in designing the most optimal liner system for the slag disposal facility investigated.

5.3.4 Slag on H:H Liner with a Saturated Clay Permeability of 1 x 10^{-7} cm/s

Based on the classification of the slag, in accordance with the Minimum Requirement Documents, it is indicated that the slag is required to be disposed of at a landfill that is installed with an H:H Liner system. The effectiveness of the H:H Liner system with a saturated clay permeability 1 x 10^{-7} cm/s at intercepting and removing the leachate generated at the base of the slag disposal facility, with varying distances to the leachate removal drains, was therefore assessed and is summarized in Table 24.

Table 24: Infiltration through H:H Liner with a clay permeability of 1 x 10^{-7} cm/s

H:H Liner with a clay permeability of 1 x 10^{-7} cm/s							
Distance to Drains	1m	5m	10m	25m	50m	75m	100m
Infiltration through Liner (mm/annum)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

The simulated results obtained from the model indicate that if a H:H Liner is implemented with a clay permeability of 1 x 10^{-7} cm/s, no leachate is expected to infiltrate through the liner system and into the underlying saturated ground water zone.

A detailed water balance has been calculated for the each of the individual layers within the H:H Liner system with a clay permeability of 1 x 10^{-7} cm/s and is summarized in Table 25. It is observed that the same amount of water is lost to evapotranspiration (438.82 mm/a) and surface run-off (1.04 mm/a) irrespective of the distance to the drains implemented within the Leakage Detection and Collection Layer (Layer 6). These are the same volumes of water that are lost to surface run-off and evapotranspiration, if no liner is implemented below the slag dump. This indicates that the volume of water lost to surface runoff and evapotranspiration is independent of the liner implemented below the slag disposal facility.

170.21 mm/a of the 189.85 mm/a of leachate that effectively infiltrates from the base of the slag dump onto the top of the H:H Liner with a clay permeability of 1x10^{-7} cm/s is removed/drained by the 150 mm thick soil preparation layer. The 150 mm thick soil preparation layer has a permeability of 6 x 10^{-3} cm/s (5.2 m/day) and lies on top of a semi-impermeable HDPE layer. Due to the significantly higher lateral permeability of the soil layer than the vertical permeability of the HDPE layer below the soil layer, most of the leachate drains laterally and is removed from the system. Although 170.21 mm/a of the leachate is laterally drained, a head of 6.80 mm is generated on top of the HDPE layer within the soil. This head generated on top of the HDPE layer is sufficient to ensure that 0.44 mm/a of leachate infiltrates vertically through the semi-impermeable HDPE layer.

Of the 0.44 mm/a of leachate that infiltrates through the clay layers, 0.07 mm/a is removed by the second leakage detection and collection layer (Layer 6). The remaining 0.37 mm/a percolates through the clay layers and is adsorbed by the 5 m thick in-situ soil zone and indicates that 0.00 mm/a of leachate enters the saturated zone.

Table 25: Detailed Water Balance of an H:H Liner with a clay permeability of 1 x 10^{-7} cm/s

H:H Liner with a clay permeability of 1 x 10^{-7} cm/s	Distance to Drains (m)						
	1	5	10	25	50	75	100
Precipitation (mm/annum)	629.71	629.71	629.71	629.71	629.71	629.71	629.71
Runoff (mm/annum)	1.04	1.04	1.04	1.04	1.04	1.04	1.04
Evapotranspiration (mm/annum)	438.82	438.82	438.82	438.82	438.82	438.82	438.82
Lateral Drainage Collected from Layer 2 (mm/annum)	170.21	170.21	170.21	170.21	170.21	170.21	170.21
Percolation/Leakage through Layer 4 (mm/annum)	0.44	0.44	0.44	0.44	0.44	0.44	0.44
Average Head on top of Layer 3 (mm)	6.80	6.80	6.80	6.80	6.80	6.80	6.80
Lateral Drainage Collected from Layer 6 (mm/annum)	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Percolation/Leakage through Layer 7 (mm/annum)	0.37	0.37	0.37	0.37	0.37	0.37	0.37
Average Head on top of Layer 7 (mm)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Percolation/Leakage through Layer 8 (mm/annum)	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: - Layer Specifications - H:H Liner

Layer 1: Deposited Slag Aggregate

Layer 2: 150 mm thick Soil Protection Layer

Layer 3: 1 mm thick High Density Polyethylene (HDPE) Layer

Layer 4: 4 x 150 mm thick Clay Layers with a permeability of 1x10^{-7} cm/s

Layer 5: 5 mm thick Geotextile Layer

Layer 6: 150 mm thick Leakage Detection and Collection Layer

Layer 7: 2 x 150 mm thick Clay Layers with a permeability of 1x10^{-7} cm/s

Layer 8: 5 m thick In-Situ Soil representing the Unsaturated Zone with a slope of 0.013

It is observed that the volume of leachate removed by the H:H liner with a clay permeability of $1x10^{-7}$ cm/s, is independent on the lateral distance to the drains and removes 100% of the leachate that infiltrates from the base of the slag disposal facility.

It is further observed that 89.65% (170.21 mm/a) of the leachate that infiltrates from the base of the slag dump is removed by the uppermost soil layer of the H:H liner and only 0.23% (0.44 mm/a) passes through uppermost low permeability clay layers.

5.3.5 Slag on H:H Liner with a Saturated Clay Permeability of 1 x 10^{-6} cm/s

It is indicated that an H:H liner with a clay permeability of 1 x 10^{-7} cm/s intercepts and removes all the leachate that is generated at the base of the slag disposal facility. No leachate is therefore expected to enter the saturated ground water zone if an H:H liner with a clay permeability of 1 x 10^{-7} cm/s is implemented. To reduce the costs of the H:H liner, it is recommended that the clays be compacted to a permeability of 1 x 10^{-6} cm/s and represents the first of the sensitivity analysis scenarios.

The effectiveness of the H:H Liner with a clay permeability of 1 x 10^{-6} cm/s with varying distances to the leachate removal drains, is summarized in Table 26.

Table 26: Infiltration through H:H Liner with a clay permeability of 1 x 10^{-6} cm/s

H:H Liner with a clay permeability of 1 x 10^{-6} cm/s							
Distance to Drains	1m	5m	10m	25m	50m	75m	100m
Infiltration through Liner (mm/annum)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

The simulated results obtained from the model indicate that if an H:H Liner with a clay permeability of 1 x 10^{-6} cm/s is installed at the base of the slag disposal facility, no leachate is expected to infiltrate through the liner and into the underlying saturated ground water zone. This yields the same result as an H:H liner with a clay permeability of 1 x 10^{-7} cm/s, and is yet more cost effective to install.

A detailed water balance has been calculated for each of the individual layers within the H:H Liner with a clay permeability of 1 x 10^{-6} cm/s and is summarized in Table 27.

Table 27: Detailed Water Balance of an H:H Liner with a clay permeability of 1 x 10^{-6} cm/s

H:H Liner with a clay permeability of 1 x 10^{-6} cm/s	Distance to Drains (m)						
	1	5	10	25	50	75	100
Precipitation (mm/annum)	629.71	629.71	629.71	629.71	629.71	629.71	629.71
Runoff (mm/annum)	1.04	1.04	1.04	1.04	1.04	1.04	1.04
Evapotranspiration (mm/annum)	438.82	438.82	438.82	438.82	438.82	438.82	438.82
Lateral Drainage Collected from Layer 2 (mm/annum)	170.16	170.16	170.16	170.16	170.16	170.16	170.16
Percolation/Leakage through Layer 4 (mm/annum)	0.49	0.49	0.49	0.49	0.49	0.49	0.49
Average Head on top of Layer 3 (mm)	6.80	6.80	6.80	6.80	6.80	6.80	6.80
Lateral Drainage Collected from Layer 6 (mm/annum)	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Percolation/Leakage through Layer 7 (mm/annum)	0.42	0.42	0.42	0.42	0.42	0.42	0.42
Average Head on top of Layer 7 (mm)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Percolation/Leakage through Layer 8 (mm/annum)	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: - Layer Specifications – H:H Liner

- Layer 1: Deposited Slag Aggregate
- Layer 2: 150 mm thick Soil Protection Layer
- Layer 3: 1 mm thick High Density Polyethylene (HDPE) Layer
- Layer 4: 4 x 150 mm thick Clay Layers with a permeability of 1x10^{-6} cm/s
- Layer 5: 5 mm thick Geotextile Layer
- Layer 6: 150 mm thick Leakage Detection and Collection Layer
- Layer 7: 2 x 150 mm thick Clay Layers with a permeability of 1x10^{-6} cm/s
- Layer 8: 5 m thick In-Situ Soil representing the Unsaturated Zone with a slope of 0.013

The simulated results indicates that of the 629.71 mm of rainfall that falls per annum, 1.04 mm/a is lost to surface run-off and 438.82 mm/a is lost to evapotranspiration, irrespective of the distance to the drains within the leakage detection and collection layer. This verifies that 1.04 mm and 438.82 mm of the 629.71 mm of rainfall that falls per annum is lost to surface run-off and evapotranspiration respectively, irrespective of the liner implemented below the slag dump.

170.16 mm/a (89.63%) of the 189.85 mm/a of leachate that effectively percolates out from the slag dump is removed/drained by the 150 mm thick soil preparation layer. The 150 mm thick soil preparation has a permeability of 6 x 10^{-3} cm/s and lies on top of a semi-impermeable HDPE layer. Due to the significantly higher lateral permeability of the slag and soil layer than the vertical permeability of the HDPE layer below the soil layer, most of the leachate drains laterally and is removed from the system. Although 170.16 mm/a of the leachate is laterally drained, a head of 6.80 mm is generated on top of the HDPE layer. This head generated on top of the HDPE layer is sufficient to ensure that 0.49 mm/a of leachate infiltrates vertically through the semi-impermeable HDPE layer.

Of the 0.49 mm/a of leachate that infiltrates through the HDPE layer, 0.07 mm/a is removed by the second leakage detection and collection layer (Layer 6). The remaining 0.42 mm/a percolates through and is adsorbed by the 5 m thick in-situ soil zone and indicates that 0.00 mm/a of leachate enters the saturated zone.

It is observed that the volume of leachate removed by the H:H liner with a clay permeability of $1x10^{-6}$, is independent on the lateral distance to the drains and removes 100% of the leachate that infiltrates from the base of the slag disposal facility.

The results obtained from the two H:H Liner scenarios yield similar results and indicate that both H:H liner options intercept and remove 100% of the leachate generated at the base of the slag dump. It is more cost effective to install an H:H liner with a clay permeability of 1 x 10^{-6} cm/s than that one with a clay permeability of 1 x 10^{-7} cm/s and is therefore the BPEO of the two H:H liner options for the slag disposal facility investigated. In addition to the H:H liner options, the effectiveness of several $G:L:B^{+}$ variant liner options are investigated, with special attention paid to the effectiveness of the individual layers within the liner designs.

5.3.6 Slag on a G:L:B$^+$ Liner with a Saturated Clay Permeability of 1 x 10^{-8} cm/s

The first set of G:L:B$^+$ variant liner designs that were investigated consist of three options all of which have a clay permeability of 1 x 10^{-8} cm/s. The variance between the liner options comes in the number of clay layers implemented within each of the liner designs. The three variants are sequentially numbered as follows:

- **G:L:B$^+$ Variant 1**: G:L:B$^+$ with 4 x 150mm thick clay layers with a permeability of 1 x 10^{-8} cm/s and a slope of 0.013
- **G:L:B$^+$ Variant 2**: G:L:B$^+$ with 2 x 150mm thick clay layers with a permeability of 1 x 10^{-8} cm/s and a slope of 0.013
- **G:L:B$^+$ Variant 3**: G:L:B$^+$ with 1 x 150mm thick clay layer with a permeability of 1 x 10^{-8} cm/s and a slope of 0.013

A summary of the simulated infiltration rates through the G:L:B$^+$ liners with a clay permeability of 1 x 10^{-8} cm/s and a slope of 0.013 is given in Table 28.

Table 28: Infiltration through G:L:B$^+$ Liners with a clay permeability of 1 x 10^{-8} cm/s

G:L:B$^+$ Liners with a clay permeability of 1 x 10^{-8} cm/s and a slope of 0.013							
Distance to Drains	1m	5m	10m	25m	50m	75m	100m
G:L:B$^+$ Variant 1 (mm/annum)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
G:L:B$^+$ Variant 2 (mm/annum)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
G:L:B$^+$ Variant 3 (mm/annum)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

The simulated results obtained from the HELP model indicate for each of the three G:L:B$^+$ Variant liner options with a clay permeability of 1 x 10^{-8} cm/s, no leachate is expected to infiltrate through the liner and into the underlying saturated ground water zone. This yields the same result as both H:H liner options.

A detailed water balance has been calculated for each of the individual layers within the three G:L:B$^+$ Variant liner options with a clay permeability of 1 x 10^{-8} cm/s and is summarized in Table 29.

Table 29: Detailed Water Balance for the G:L:B$^+$ Variant Liner options with a clay permeability of 1 x 10^{-8} cm/s

G:L:B$^+$ Liner with a clay permeability of 1 x 10^{-8} cm/s		Distance to Drains (m)						
		1	5	10	25	50	75	100
Precipitation (mm/annum)		629.71	629.71	629.71	629.71	629.71	629.71	629.71
Runoff (mm/annum)		1.04	1.04	1.04	1.04	1.04	1.04	1.04
Evapotranspiration (mm/annum)		438.82	438.82	438.82	438.82	438.82	438.82	438.82
4 x 150mm clay layers (Variant 1)	Lateral Drainage collected from Layer 1 (mm/annum)	167.99	167.99	167.99	167.99	167.99	167.99	167.99
	Percolation/Leakage through Layer 2 (mm/annum)	2.96	2.96	2.96	2.96	2.96	2.96	2.96
	Average Head on top of Layer 2 (mm)	5.21	5.21	5.21	5.21	5.21	5.21	5.21
	Lateral Drainage collected from Layer 4 (mm/annum)	0.07	0.07	0.07	0.07	0.07	0.07	0.07
	Percolation/Leakage through Layer 5 (mm/annum)	2.89	2.89	2.89	2.89	2.89	2.89	2.89
	Average Head on top of Layer 5 (mm)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Percolation/Leakage through Layer 6 (mm/annum)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2 x 150mm clay layers (Variant 2)	Lateral Drainage collected from Layer 1 (mm/annum)	167.96	167.96	167.96	167.96	167.96	167.96	167.96
	Percolation/Leakage through Layer 2 (mm/annum)	2.99	2.99	2.99	2.99	2.99	2.99	2.99
	Average Head on top of Layer 2 (mm)	5.21	5.21	5.21	5.21	5.21	5.21	5.21
	Lateral Drainage collected from Layer 4 (mm/annum)	0.08	0.08	0.08	0.08	0.08	0.08	0.08
	Percolation/Leakage through Layer 5 (mm/annum)	2.91	2.92	2.92	2.92	2.92	2.92	2.92
	Average Head on top of Layer 5 (mm)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Percolation/Leakage through Layer 6 (mm/annum)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1 x 150mm clay layers (Variant 3)	Lateral Drainage collected from Layer 1 (mm/annum)	167.91	167.91	167.91	167.91	167.91	167.91	167.91
	Percolation/Leakage through Layer 2 (mm/annum)	3.04	3.04	3.04	3.04	3.04	3.04	3.04
	Average Head on top of Layer 2 (mm)	5.21	5.21	5.21	5.21	5.21	5.21	5.21
	Lateral Drainage collected from Layer 4 (mm/annum)	0.07	0.07	0.07	0.07	0.07	0.07	0.07
	Percolation/Leakage through Layer 5 (mm/annum)	2.97	2.97	2.97	2.97	2.97	2.97	2.97
	Average Head on top of Layer 5 (mm)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Percolation/Leakage through Layer 6 (mm/annum)	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: - Layer Specifications – G:L:B$^+$ Liner with a clay permeability of 1 x 10^{-8} cm/s

Layer 1: Deposited Slag Aggregate

Layer 2: (4/2/1) x 150 mm thick Clay Layers with a permeability of 1x10^{-8} cm/s

Layer 3: 5 mm thick Geotextile Layer

Layer 4: 150 mm thick Leakage Detection and Collection Layer

Layer 5: 150 mm thick Clay Layers with a permeability of 1x10^{-8} cm/s

Layer 6: 5 m thick In-Situ Soil representing the Unsaturated Zone with a slope of 0.013

The results obtained from the HELP model indicate that of the 629.71 mm/annum of rainfall that falls per annum, 1.04 mm/a is lost to surface run-off from the slag dump and 438.82 mm/a is lost to evapotranspiration, irrespective of the distance to the drains within the leakage detection and collection layer.

The results indicate, that although each of the three liner options intercept and remove 100% of the leachate that infiltrates from the base of the slag dump, minor differences are observed with regards to the water balances within the individual layers.

The G:L:B$^+$ liner options do not have an upper soil protection layer and the simulated results obtained from the model indicate that the slag itself is the most effective leachate removal (drainage) layer. The results indicate that 167.99 mm/a (88.49%), 167.96 mm/a (88.47%) and 167.91 mm/a (88.44%) of leachate is removed from the base of the slag dump, for the G:L:B$^+$ Variant 1, Variant 2 and Variant 3 liner options respectively.

<u>G:L:B$^+$ Variant 1</u>

An average head of 5.21 mm builds up on top of the 4 x 150 mm thick clay layers (Layer 2), whilst 2.96 mm/a of leachate infiltrates through Layer 2. Of the 2.96 mm/a of leachate that infiltrates through the clay layers, 0.07 mm/a is removed by the 150 mm thick leakage detection and collection layer (Layer 4), irrespective of the distance to the drains. The model indicates that the remaining 2.89 mm/a percolates through the bottom 150 mm thick clay layer, and is adsorbed by the 5 m thick in-situ soil zone and indicates that 0.00 mm of leachate enters the saturated zone per annum.

G:L:B$^+$ Variant 2

An average head of 5.21 mm builds up on top of the 2 x 150 mm thick clay layers (Layer 2), whilst 2.99 mm/a of leachate infiltrates through Layer 2. Of the 2.99 mm/a of leachate that infiltrates through the clay layers, 0.08 mm/a is removed by the 150 mm thick leakage detection and collection layer (Layer 4) irrespective of the distance to the drains. The model indicates that the remaining 2.91 mm/a percolates through the bottom 150 mm thick clay layer, and is adsorbed by the 5 m thick in-situ soil zone and indicates that 0.00 mm of leachate enters the saturated zone per annum.

G:L:B$^+$ Variant 3

An average head of 5.21 mm builds up on top of the 150 mm thick clay layer (Layer 2), whilst 3.04 mm/a of leachate infiltrates through Layer 2. Of the 2.99 mm/a of leachate that infiltrates through the clay layers, 0.07 mm/a is removed by the 150 mm thick leakage detection and collection layer (Layer 4), irrespective of the distance to the drains. The model indicates that the remaining 2.97 mm/a percolates through the bottom 150 mm thick clay layer, and is adsorbed by the 5 m thick in-situ soil zone and indicates that 0.00 mm of leachate enters the saturated zone per annum.

It is known that it is extremely difficult to compact clays to permeability of 1 x 10^{-8} cm/s and although G:L:B$^+$ liners with a clay permeability of 1 x 10^{-8} cm/s effectively remove 100% of the leachate generated from the base of the slag disposal facility, the construction and installation thereof may be extremely difficult and costly to achieve.

5.3.7 Slag on a G:L:B$^+$ Liner with a Saturated Clay Permeability of 1 x 10^{-7} cm/s

It has been indicated that to compact a clay to a permeability of 1 x 10^{-7} cm/s is more readily and uniformly achievable, and the effectiveness of G:L:B$^+$ liner options with a clay permeability of 1 x 10^{-7} cm/s is therefore investigated.

The second set of G:L:B$^+$ variant liner designs investigated consist of a further three G:L:B$^+$ Variant liner options (Variants 4, 5 and 6) all of which have a clay permeability of 1 x 10^{-7} cm/s. The variance between the individual liner designs comes in the number of clay layer implemented within each of the designs.

The three variants are sequentially numbered as follows:

- **G:L:B$^+$ Variant 4**: G:L:B$^+$ with 4 x 150mm thick clay layers with a permeability of 1 x 10^{-7} cm/s and a slope of 0.013
- **G:L:B$^+$ Variant 5**: G:L:B$^+$ with 2 x 150mm thick clay layers with a permeability of 1 x 10^{-7} cm/s and a slope of 0.013
- **G:L:B$^+$ Variant 6**: G:L:B$^+$ with 1 x 150mm thick clay layer with a permeability of 1 x 10^{-7} cm/s and a slope of 0.013

A summary of the simulated infiltration rates through the various G:L:B$^+$ liners with a clay permeability of 1 x 10^{-7} cm/s and a slope of 0.013 is given in Table 30.

Table 30: Infiltration through G:L:B$^+$ Liner with a clay permeability of 1 x 10^{-7} cm/s

G:L:B$^+$ Liners with a clay permeability of 1 x 10^{-7} cm/s and a slope of 0.013							
Distance to Drains	1m	5m	10m	25m	50m	75m	100m
G:L:B$^+$ Variant 4 (mm/annum)	11.74	11.78	11.81	11.86	11.90	11.92	11.93
	1.86%	1.87%	1.88%	1.88%	1.89%	1.89%	1.89%
G:L:B$^+$ Variant 5 (mm/annum)	11.75	11.83	11.89	11.98	12.06	12.09	12.11
	1.87%	1.88%	1.89%	1.90%	1.91%	1.92%	1.92%
G:L:B$^+$ Variant 6 (mm/annum)	11.77	11.91	12.02	12.21	12.36	12.43	12.48
	1.87%	1.89%	1.91%	1.94%	1.96%	1.97%	1.98%

The simulated results obtained from the HELP model indicate that for each of the G:L:B$^+$ variant options with a clay permeability of 1 x 10^{-7} cm/s, varying amounts of leachate will infiltrate into the saturated ground water zone. The results also indicate that distances to the drains play a role in the volume of leachate that is intercepted from the individual liner options. The smaller the distance to the drains, the more effective the liner is at removing the leachate intercepted.

A graph depicting the leachate flux that infiltrates through the three G:L:B$^+$ liner options with a clay permeability of 1 x 10^{-7} cm/s is depicted as Figure 27. The simulated infiltration rates obtained from the model (Table 30 and Figure 27) indicate the importance of the distance to drains within the individual liners, as well as the effectiveness of the thicker clay layers at intercepting and removing the leachate within the liner.

The infiltrations rates depicted on Figure 27 clearly indicate that the thickness of the clay layers is more efficient at preventing the leachate from infiltrating through the liner system than the number of drains implemented in the liner are at removing the leachate generated for the slag disposal facility simulated.

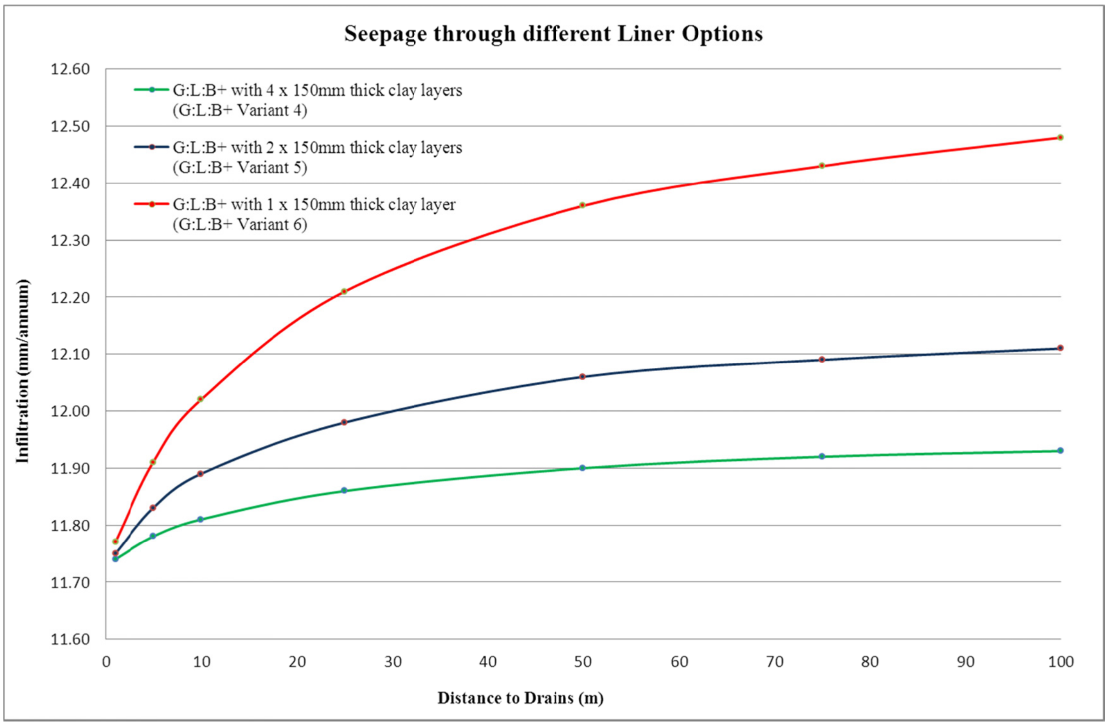


Figure 27: Infiltration through G:L:B^+ Liner with a clay permeability of 1 x 10^{-7} cm/s

A detailed water balance has been calculated for each of the individual layers within the three G:L:B^+ Variant options with a clay permeability of 1 x 10^{-7} cm/s and a surface slope of 0.013 and is summarized in Table 31.

The simulated results obtained from the models indicate that of the 629.71 mm/a of precipitation that falls per annum, 1.04 mm/a is lost to surface run-off from the slag dump and 438.82 mm/a is lost to evapotranspiration, irrespective of the distance to the drains within the leakage detection and collection layer.

The G:L:B^+ liner options do not have an upper soil protection layer and the simulated results indicate that the slag itself is the most effective leachate removal (drainage) layer. The models indicate that 142.19 mm/a (74.90%), 141.95 mm/a (74.77%) and 141.46 mm/a (74.51%) of leachate is removed from the base of the slag dump, for the G:L:B^+ Variant 4, Variant 5 and Variant 6 liner options respectively.

Table 31: Detailed Water Balance for the G:L:B$^+$ Variant Liner options with a clay permeability of 1 x 10^{-7} cm/s

G:L:B$^+$ Liner with a clay permeability of 1 x 10^{-7} cm/s		Distance to Drains (m) 1	5	10	25	50	75	100
Precipitation (mm/annum)		629.71	629.71	629.71	629.71	629.71	629.71	629.71
Runoff (mm/annum)		1.04	1.04	1.04	1.04	1.04	1.04	1.04
Evapotranspiration (mm/annum)		438.82	438.82	438.82	438.82	438.82	438.82	438.82
4 x 150mm clay layers (Variant 4)	Lateral Drainage collected from Layer 1 (mm/annum)	142.19	142.19	142.19	142.19	142.19	142.19	142.19
	Percolation/Leakage through Layer 2 (mm/annum)	28.76	28.76	28.76	28.76	28.76	28.76	28.76
	Average Head on top of Layer 2 (mm)	4.65	4.65	4.65	4.65	4.65	4.65	4.65
	Lateral Drainage collected from Layer 4 (mm/annum)	0.24	0.20	0.16	0.11	0.07	0.05	0.04
	Percolation/Leakage through Layer 5 (mm/annum)	28.45	28.49	28.52	28.58	28.61	28.63	28.64
	Average Head on top of Layer 5 (mm)	0.04	0.16	0.26	0.44	0.58	0.65	0.69
	Percolation/Leakage through Layer 6 (mm/annum)	11.74	11.78	11.81	11.86	11.90	11.92	11.93
2 x 150mm clay layers (Variant 5)	Lateral Drainage collected from Layer 1 (mm/annum)	141.95	141.95	141.95	141.95	141.95	141.95	141.95
	Percolation/Leakage through Layer 2 (mm/annum)	29.00	29.00	29.00	29.00	29.00	29.00	29.00
	Average Head on top of Layer 2 (mm)	4.64	4.64	4.64	4.64	4.64	4.64	4.64
	Lateral Drainage collected from Layer 4 (mm/annum)	0.47	0.39	0.33	0.23	0.15	0.12	0.09
	Percolation/Leakage through Layer 5 (mm/annum)	28.46	28.54	28.60	28.70	28.78	28.81	28.84
	Average Head on top of Layer 5 (mm)	0.08	0.31	0.52	0.91	1.21	1.37	1.47
	Percolation/Leakage through Layer 6 (mm/annum)	11.75	11.83	11.89	11.98	12.06	12.09	12.11
1 x 150mm clay layers (Variant 6)	Lateral Drainage collected from Layer 1 (mm/annum)	141.46	141.46	141.46	141.46	141.46	141.46	141.46
	Percolation/Leakage through Layer 2 (mm/annum)	29.49	29.49	29.49	29.49	29.49	29.49	29.49
	Average Head on top of Layer 2 (mm)	4.64	4.64	4.64	4.64	4.64	4.64	4.64
	Lateral Drainage collected from Layer 4 (mm/annum)	0.94	0.79	0.67	0.48	0.33	0.25	0.20
	Percolation/Leakage through Layer 5 (mm/annum)	28.48	28.63	28.74	28.93	29.09	29.16	29.21
	Average Head on top of Layer 5 (mm)	0.15	0.62	1.07	1.89	2.58	2.94	3.16
	Percolation/Leakage through Layer 6 (mm/annum)	11.77	11.91	12.02	12.21	12.35	12.43	12.48

Note: - Layer Specifications – G:L:B$^+$ Liner

Layer 1: Deposited Slag Aggregate

Layer 2: (4/2/1) x 150 mm thick Clay Layers with a permeability of $1x10^{-7}$ cm/s

Layer 3: 5 mm thick Geotextile Layer

Layer 4: 150 mm thick Leakage Detection and Collection Layer

Layer 5: 150 mm thick Clay Layers with a permeability of $1x10^{-7}$ cm/s

Layer 6: 5 m thick In-Situ Soil representing the Unsaturated Zone with a slope of 0.013

G:L:B$^+$ Variant 4

An average head of 4.65 mm builds up on top of the 4 x 150 mm thick clay layers (Layer 2), whilst 28.76 mm/a of leachate infiltrates through Layer 2. Of the 28.76 mm/a of leachate that infiltrates through the clay layers, varying volumes of leachate is removed by the 150 mm thick leakage detection and collection layer (Layer 4). The volume of leachate removed by layer 4 is dependent on the distance to the drains within the layer.

The model indicates that the further the distance is between the drains in layer 4, the larger the potential is for a significant head to build up on top of the low permeability clay layer (layer 5). This build-up of the hydraulic head is inevitably responsible for the greater volume of leachate that infiltrates through the underlying low permeability clay layers. It is therefore of vital importance that the leachate collected on top of layer 5 be removed before it builds up a sufficient hydraulic potential to infiltrate vertically through the layer.

G:L:B$^+$ Variant 5

An average head of 4.64 mm builds up on top of the 2 x 150 mm thick clay layers (Layer 2), whilst 29.00 mm/a of leachate infiltrates through Layer 2. Of the 29.00 mm/a of leachate that infiltrates through the clay layers, varying volumes of leachate is removed by the 150 mm thick leakage detection and collection layer (Layer 4). The volume of leachate removed by layer 4 is dependent on the distance to the drains within the layer, as stated above.

The volume of leachate that infiltrates through the simulated 5 m thick in-situ soil zone (Layer 6) assigned to the G:L:B$^+$ Variant Number 5 varies between 1.00 and 1.02 times greater than the volume of leachate that infiltrates through the simulated 5 m thick in-situ soil zone below the G:L:B^+ Variant Number 4.

G:L:B^+ Variant 6

An average head of 4.64 mm builds up on top of the 150 mm thick clay layer (Layer 2), the same as the average build-up in the head on top of the 2 x 150 mm thick clay layers (G:L:B^+ Variant 4). 29.49 mm/a of leachate however infiltrates through Layer 2, as opposed to the 29.00 mm/a which infiltrates through the 2 x 150 mm thick clay layers.

Of the 29.49 mm of leachate that infiltrates through the clay layers, varying volumes of leachate is removed by the 150 mm thick leakage detection and collection layer (Layer 4). The volume of leachate removed by layer 4 is dependent on the distance to the drains within the layer, as stated previously.

The volume of leachate that infiltrates through the simulated 5 m thick in-situ soil zone (Layer 6) assigned to the G:L:B^+ Variant Number 6 varies between 1.00 and 1.05 times more than the volume of leachate that infiltrates through the simulated 5 m thick in-situ soil zone assigned to the G:L:B^+ Variant Number 4, and between 1.00 and 1.03 times more than the volume of leachate that infiltrates through the simulated 5 m thick in-situ soil zone assigned to the G:L:B^+ Variant Number 5.

The results obtained from the simulated G:L:B^+ Liners with a clay permeability of 1×10^{-7} cm/s indicate that the volume of leachate that infiltrates through the liner is dependent on the number of 150 mm thick clay layers implemented as well as the distance to the leakage removal drains within layer 4. It is observed from the simulated infiltration rates that the number of clay layers installed is more efficient at preventing the leachate from infiltrating through the liner system than the number of drains implemented in the liner is at removing the leachate generated for the slag disposal facility simulated.

Of significant importance to note is that the volume of leachate removed by the G:L:B^+ Variant 4 liner option, with drains located 100 m apart is more effective at removing the leachate than the G:L:B^+ Variant 6 liner option, with drains located 5 meters apart.

5.3.8 Slag on a G:L:B$^+$ Liner with a Saturated Clay Permeability of 1 x 10^{-7} cm/s with a slope of 0.02

It was observed from the simulated results provided in Section 7.3.7 that a G:L:B$^+$ Variant Liner option with a clay permeability of 1 x 10^{-7} cm/s constructed with a natural surface slope of 0.013 can effectively remove the majority of the leachate generated from the base of the slag dump, but not all of it.

It was also observed that both the number of clay layers present within the liner as well as the distance to the drains within the leakage detection and collection layer influence the volume of leachate intercepted by the liner to varying degrees. The sensitivity of, or the effect that the slopes of the individual layers within the liner have on removing the leachate is further investigated.

The third set of G:L:B$^+$ variant liner options investigated consist of three liner designs all of which have a clay permeability of 1 x 10^{-7} cm/s, and a slope of 0.02. The Minimum Requirement Documents specify that the slope of G:L:B$^+$ liners are required to be at least 0.02 and these are therefore the most representative of the G:L:B$^+$ liner options. The variance between the three liner options is again the number of clay layers implemented within each of the individual liner options.

The three individual liner options are sequentially numbered as follows:

- **G:L:B$^+$ Variant 7**: G:L:B$^+$ with 4 x 150mm thick clay layers with a permeability of 1 x 10^{-7} cm/s and a slope of 0.02
- **G:L:B$^+$ Variant 8**: G:L:B$^+$ with 2 x 150mm thick clay layers with a permeability of 1 x 10^{-7} cm/s and a slope of 0.02
- **G:L:B$^+$ Variant 9**: G:L:B$^+$ with 1 x 150mm thick clay layer with a permeability of 1 x 10^{-7} cm/s and a slope of 0.02

A summary of the simulated infiltration rates through the G:L:B$^+$ liners with a clay permeability of 1 x 10^{-7} cm/s and a slope of 0.02 is given in Table 32.

Table 32: Infiltration through G:L:B+ Liner with a clay permeability of 1 x 10^{-7} cm/s and a slope of 0.02

Liner Option	Distance to Drains						
	1m	5m	10m	25m	50m	75m	100m
G:L:B+ Variant 7 (mm/annum)	11.74	11.78	11.81	11.86	11.89	11.91	11.92
	1.86 %	1.87 %	1.88 %	1.88 %	1.89 %	1.89 %	1.89 %
G:L:B+ Variant 8 (mm/annum)	11.74	11.81	11.86	11.96	12.03	12.07	12.09
	1.86 %	1.88 %	1.88 %	1.90 %	1.91 %	1.92 %	1.92 %
G:L:B+ Variant 9 (mm/annum)	11.76	11.88	11.98	12.16	12.31	12.39	12.44
	1.87 %	1.89 %	1.90 %	1.93 %	1.95 %	1.97 %	1.98 %

A graph depicting the leachate flux through the three G:L:B+ liner options with a clay permeability of 1 x 10^{-7} cm/s and a slope of 0.02 is depicted as Figure 28.

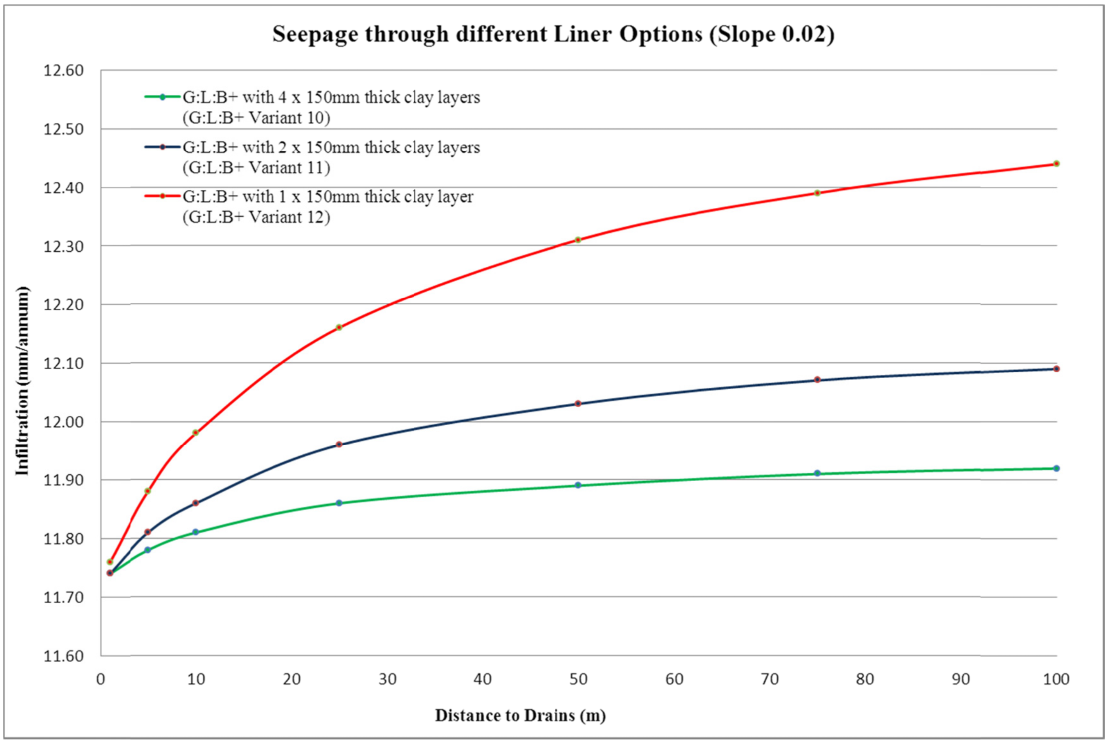


Figure 28: Infiltration through G:L:B+ Liner with a clay permeability of 1 x 10^{-7} cm/s and a slope of 0.02

A detailed water balance has been calculated for each of the individual layers within the three G:L:B+ Variant options with a clay permeability of 1 x 10^{-7} cm/s and surface slope of 0.02, and is summarized in Table 33.

Table 33: Detailed Water Balance for the G:L:B+ Variant Liner options with a clay permeability of 1 x 10^{-7} cm/s with a slope of 0.02

G:L:B+ Liner with a clay permeability of 1 x 10^{-7} cm/s and slope of 0.02		Distance to Drains (m)						
		1	5	10	25	50	75	100
Precipitation (mm/annum)		629.71	629.71	629.71	629.71	629.71	629.71	629.71
Runoff (mm/annum)		1.04	1.04	1.04	1.04	1.04	1.04	1.04
Evapotranspiration (mm/annum)		438.82	438.82	438.82	438.82	438.82	438.82	438.82
4 x 150mm clay layers (Variant 7)	Lateral Drainage collected from Layer 1 (mm/annum)	142.15	142.15	142.15	142.15	142.15	142.15	142.15
	Percolation/Leakage through Layer 2 (mm/annum)	28.76	28.76	28.76	28.76	28.76	28.76	28.76
	Average Head on top of Layer 2 (mm)	4.63	4.63	4.63	4.63	4.63	4.63	4.63
	Lateral Drainage collected from Layer 4 (mm/annum)	0.24	0.20	0.17	0.12	0.08	0.06	0.05
	Percolation/Leakage through Layer 5 (mm/annum)	28.45	28.49	28.52	28.57	28.61	28.63	28.64
	Average Head on top of Layer 5 (mm)	0.03	0.13	0.23	0.40	0.54	0.61	0.65
	Percolation/Leakage through Layer 6 (mm/annum)	11.74	11.78	11.81	11.86	11.89	11.91	11.92
2 x 150mm clay layers (Variant 8)	Lateral Drainage collected from Layer 1 (mm/annum)	141.96	141.96	141.96	141.96	141.96	141.96	141.96
	Percolation/Leakage through Layer 2 (mm/annum)	29.00	29.00	29.00	29.00	29.00	29.00	29.00
	Average Head on top of Layer 2 (mm)	4.62	4.62	4.62	4.62	4.62	4.62	4.62
	Lateral Drainage collected from Layer 4 (mm/annum)	0.48	0.40	0.35	0.25	0.17	0.13	0.11
	Percolation/Leakage through Layer 5 (mm/annum)	28.45	28.52	28.58	28.67	28.75	28.79	28.81
	Average Head on top of Layer 5 (mm)	0.06	0.27	0.46	0.82	1.12	1.29	1.39
	Percolation/Leakage through Layer 6 (mm/annum)	11.74	11.81	11.86	11.96	12.03	12.07	12.09
1 x 150mm clay layers (Variant 9)	Lateral Drainage collected from Layer 1 (mm/annum)	141.47	141.47	141.47	141.47	141.47	141.47	141.47
	Percolation/Leakage through Layer 2 (mm/annum)	29.48	29.48	29.48	29.48	29.48	29.48	29.48
	Average Head on top of Layer 2 (mm)	4.61	4.61	4.61	4.61	4.61	4.61	4.61
	Lateral Drainage collected from Layer 4 (mm/annum)	0.94	0.81	0.70	0.51	0.36	0.28	0.23
	Percolation/Leakage through Layer 5 (mm/annum)	28.47	28.60	28.70	28.89	29.04	29.12	29.17
	Average Head on top of Layer 5 (mm)	0.12	0.53	0.93	1.69	2.38	2.75	2.99
	Percolation/Leakage through Layer 6 (mm/annum)	11.76	11.88	11.98	12.16	12.31	12.39	12.44

Note: - Layer Specifications – G:L:B+ Liner

Layer 1: Deposited Slag Aggregate
Layer 2: (4/2/1) x 150 mm thick Clay Layers with a permeability of $1x10^{-7}$ cm/s
Layer 3: 5 mm thick Geotextile Layer
Layer 4: 150 mm thick Leakage Detection and Collection Layer
Layer 5: 150 mm thick Clay Layers with a permeability of $1x10^{-7}$ cm/s
Layer 6: 5 m thick In-Situ Soil representing the Unsaturated Zone with a slope of 0.02

The simulated results indicate that similar volumes of leachate infiltrate through the G:L:B+ Liner options with a clay permeability of 1×10^{-7} cm/s and a slope of 0.02, as the volumes that infiltrate through the G:L:B+ Liner options with a clay permeability of 1×10^{-7} cm/s and a slope of 0.013.

The largest variation in the infiltrating leachate flux rate through the liner options, is that between the G:L:B+ Variant 9 and G:L:B+ Variant 6 liner options, with a distance of 100 m between the drains in Layer 4. 12.44 mm/annum of leachate infiltrates through the G:L:B+ Variant 12, as opposed to the 12.48 mm/annum for G:L:B+ Variant 6. This is some mere 0.04 mm/annum difference between the two liner options.

<u>G:L:B+ Variant 7</u>

An average head of 4.63 mm builds up on top of the 4 x 150 mm thick clay layers (Layer 2), as opposed the 4.65 mm of head that builds up for the equivalent liner option with a slope of 0.013 (G:L:B+ Variant 4). The same leachate flux (28.76 mm/annum) however infiltrates through Layer 2 for both the G:L:B+ Variant 4 and G:L:B+ Variant 7 liner options.

Of the 28.76 mm/a of leachate that infiltrates through the clay layers, varying volumes of leachate is removed by the 150 mm thick leakage detection and collection layer (Layer 4). The results obtained from the model further indicate that the volume of leachate collected from the leakage collection layer is similar for the G:L:B+ Variant 4 and G:L:B+ Variant 7 liner options. The results obtained from the model do however again indicate that the volume of leachate removed by layer 4 is dependent on the distance to the drains within the layer.

The volume of leachate that infiltrates through the simulated 5 m thick in-situ soil zone (Layer 6) assigned to the G:L:B$^+$ Variant 7 liner option remain similar to the volumes of leachate that infiltrates through layer 6 in the G:L:B$^+$ Variant 4 liner option.

G:L:B$^+$ Variant 8

An average head of 4.62 mm builds up on top of the 4 x 150 mm thick clay layers (Layer 2), as opposed the 4.64 mm of head that builds up for the equivalent liner option with a slope of 0.013 (G:L:B$^+$ Variant 5). The same leachate flux (29.00 mm/annum) however infiltrates through Layer 2 for both the G:L:B$^+$ Variant 5 and G:L:B$^+$ Variant 8 liner options. Of the 29.00 mm/annum of leachate that infiltrates through the clay layers, varying volumes of leachate is removed by the 150 mm thick leakage detection and collection layer (Layer 4).

The results obtained from the model further indicate that the volume of leachate collected from the leakage collection layer is similar for the G:L:B$^+$ Variant 5 and G:L:B$^+$ Variant 8 liner options. The results obtained from the model do however indicate that the volume of leachate removed by layer 4 is again dependent on the distance to the drains within the layer.

The volume of leachate that infiltrates through the simulated 5 m thick in-situ soil zone (Layer 6) assigned to the G:L:B$^+$ Variant 8 liner option remain similar to the volumes of leachate that infiltrates through layer 6 in the G:L:B$^+$ Variant 5 liner option.

G:L:B$^+$ Variant 9

An average head of 4.61 mm builds up on top of the 4 x 150 mm thick clay layers (Layer 2), as opposed to the 4.64 mm of head that builds up for the equivalent liner option with a slope of 0.013 (G:L:B$^+$ Variant 6). The head on top of layer 2 within the G:L:B$^+$ Variant 9 liner option, is however smaller than the head on top of layer 2 in the G:L:B$^+$ Variant 8 liner option, which is subsequently smaller than the head on top of layer 2 in the G:L:B$^+$ Variant 7 liner option. The total clay layer in the G:L:B$^+$ Variant 9 liner option is thinner than the total clay layer within the G:L:B$^+$ Variant 8 and G:L:B$^+$ Variant 7 liner options respectively. As a result of a thinner clay layer, the leachate has a larger potential to infiltrate through the clay layer, and reduces the potential of the leachate build up a head on top of the clay layer.

29.48 mm of leachate infiltrates through Layer 2 for the G:L:B$^+$ Variant 9 per annum as opposed to the 29.49 mm of leachate infiltrates through Layer 2 for both the G:L:B$^+$ Variant 6 liner option per annum. Of the 29.48 mm/a of leachate that infiltrates through the clay layers, varying volumes of leachate is removed by the 150 mm thick leakage detection and collection layer (Layer 4). The results obtained from the model further indicate that the volume of leachate collected from the leakage collection layer is similar for the G:L:B$^+$ Variant 6 and G:L:B$^+$ Variant 9 liner options. The results obtained from the model do however again indicate that the volume of leachate removed by layer 4 is again dependent on the distance to the drains within the layer.

The volumes of leachate that infiltrate through the G:L:B$^+$ Variants (7-9) are similar to the volumes of leachate that infiltrate through the G:L:B$^+$ Variants (4-6), and indicate that by increasing the slope of the individual liner options to 0.02 does not make a significant difference to the volume of leachate intercepted and removed by the liner.

5.3.9 Slag on a G:L:B$^+$ Liner with a Saturated Clay Permeability of 1 x 10^{-7} cm/s with a slope of 0.05

The effect that the slope of the individual layers within the liners have on capturing the leachate generated is further assessed, and a slope of 0.05 was assigned to the individual layers within the liner.

The fourth set of G:L:B$^+$ variant liner options investigated therefore consist of three options all of which have a clay permeability of 1 x 10^{-7} cm/s, and a slope of 0.05. The variance between the three liner options is again the number of 150 mm thick clay layers implemented within each of the individual liner options.

The three individual liner options are sequentially numbered as follows:

- **G:L:B$^+$ Variant 10**: G:L:B$^+$ with 4 x 150mm thick clay layers with a permeability of 1 x 10^{-7} cm/s and a slope of 0.05
- **G:L:B$^+$ Variant 11**: G:L:B$^+$ with 2 x 150mm thick clay layers with a permeability of 1 x 10^{-7} cm/s and a slope of 0.05
- **G:L:B$^+$ Variant 12**: G:L:B$^+$ with 1 x 150mm thick clay layer with permeability of 1 x 10^{-7} cm/s and a slope of 0.05

The effectiveness that each of the fourth set of G:L:B+ Variants have on intercepting and removing the leachate generated at the base of the slag disposal facility were individually assessed using the HELP modelling software.

A summary of the infiltration rates through the G:L:B+ liners with a clay permeability of 1×10^{-7} cm/s and a slope of 0.05 is given in Table 34.

Table 34: Infiltration through G:L:B+ Liner with a clay permeability of 1×10^{-7} cm/s with a slope of 0.05

Liner Option	Distance to Drains						
	1m	5m	10m	25m	50m	75m	100m
G:L:B+ Variant 10 (mm/annum)	11.69	11.73	11.76	11.8	11.84	11.86	11.87
	1.86 %	1.86 %	1.87 %	1.87 %	1.88 %	1.88 %	1.88 %
G:L:B+ Variant 11 (mm/annum)	11.71	11.77	11.82	11.91	11.98	12.02	12.05
	1.86 %	1.87 %	1.88 %	1.89 %	1.90 %	1.91 %	1.91 %
G:L:B+ Variant 12 (mm/annum)	11.72	11.83	11.93	12.09	12.24	12.32	12.37
	1.86 %	1.88 %	1.89 %	1.92 %	1.94 %	1.96 %	1.96 %

A graph depicting the leachate flux through the three G:L:B+ liner options with a clay permeability of 1×10^{-7} cm/s and a slope of 0.05 is depicted as Figure 29.

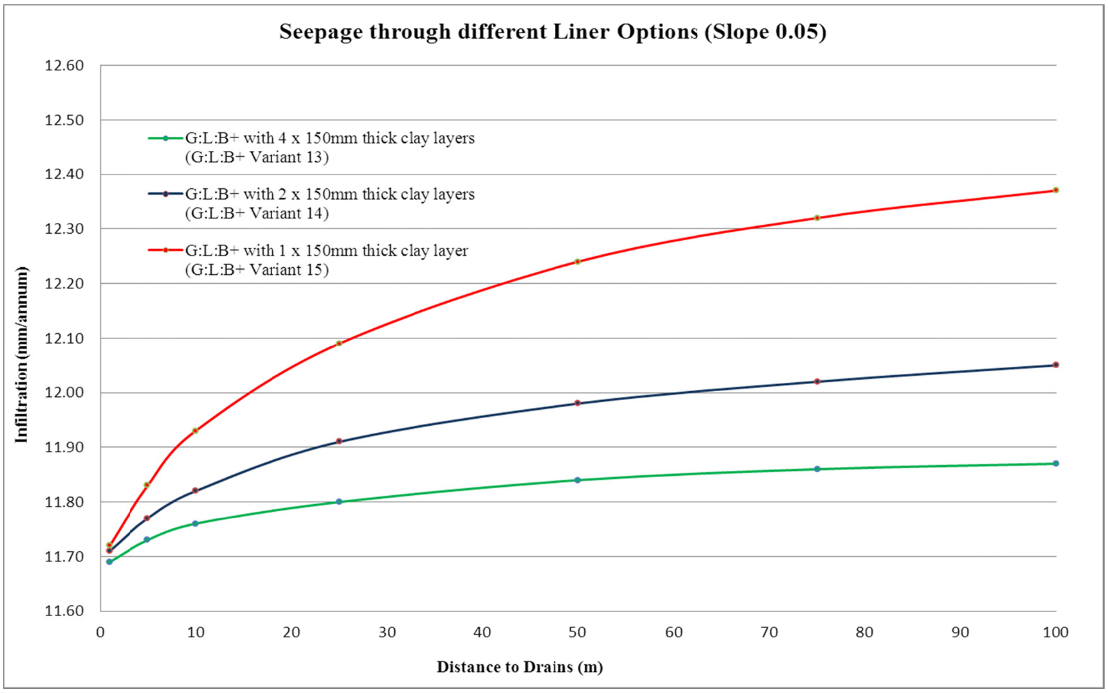


Figure 29: Infiltration through G:L:B+ Liner with a clay permeability of 1×10^{-7} cm/s with a slope of 0.05

The simulated results obtained from the model indicate that similar volumes of leachate infiltrate through the G:L:B$^+$ Liner options with a clay permeability of 1 x 10^{-7} cm/s and a slope of 0.05, as the volumes that infiltrate through the G:L:B$^+$ Liner options with a clay permeability of 1 x 10^{-7} cm/s and a slope of 0.02 and 0.013 respectively.

The maximum variation in the leachate flux through the various liner options, is that between the G:L:B$^+$ Variant 12 and G:L:B$^+$ Variant 6 liner options, with a distance of 100 m between the drains in Layer 4. 12.37 mm/annum of leachate infiltrates through the G:L:B$^+$ Variant 12, as opposed to the 12.48 mm/annum for G:L:B$^+$ Variant 6. This is a mere 0.11 mm/annum difference between the two liner options and indicates that although the volume of leachate intercepted by the liner varies according to the slope of layers within the liner, the alteration is negligible.

A detailed water balance has been calculated for each of the individual layers within the three G:L:B$^+$ Variant options with a clay permeability of 1 x 10^{-7} cm/s and a slope of 0.05, and is summarized in Table 35.

G:L:B$^+$ Variant 10

It is simulated that 142.22 mm/annum of leachate is laterally drained from the base of the slag dump and an average head of 4.53 mm builds up on top of the 4 x 150 mm thick clay layers (Layer 2) in the G:L:B$^+$ Variant 10 Liner option. This is slightly less than the 4.63 mm and 4.65 mm of head that builds up for the equivalent liner options with a slope of 0.02 (G:L:B$^+$ Variant 7) and 0.013 (G:L:B$^+$ Variant 4) respectively. Slightly less leachate (28.71 mm/annum) infiltrates through the underlying clay layers as well. Of the 28.71 mm/annum of leachate that infiltrates through the clay layers, varying volumes of leachate is removed by the 150 mm thick leakage detection and collection layer.

The simulated leachate flux through the 5 m thick in-situ soil zone (Layer 6) below the G:L:B$^+$ Variant 10 liner option remains similar to the volumes of leachate that infiltrates through layer 6 in the G:L:B$^+$ Variant 7 and Variant 4 liner options, indicating that the slope does not play a major role in reducing the volume of leachate that infiltrates through the liner.

Table 35: Detailed Water Balance for the G:L:B+ Variant Liner options with a clay permeability of 1 x 10^{-7} cm/s with a slope of 0.05

G:L:B+ Liner with a clay permeability of 1 x 10^{-7} cm/s and slope of 0.05		Distance to Drains (m) 1	5	10	25	50	75	100
Precipitation (mm/annum)		629.71	629.71	629.71	629.71	629.71	629.71	629.71
Runoff (mm/annum)		1.04	1.04	1.04	1.04	1.04	1.04	1.04
Evapotranspiration (mm/annum)		438.82	438.82	438.82	438.82	438.82	438.82	438.82
4 x 150mm clay layers (Variant 10)	Lateral Drainage collected from Layer 1 (mm/annum)	142.22	142.22	142.22	142.22	142.22	142.22	142.22
	Percolation/Leakage through Layer 2 (mm/annum)	28.71	28.71	28.71	28.71	28.71	28.71	28.71
	Average Head on top of Layer 2 (mm)	4.53	4.53	4.53	4.53	4.53	4.53	4.53
	Lateral Drainage collected from Layer 4 (mm/annum)	0.24	0.21	0.18	0.13	0.09	0.07	0.06
	Percolation/Leakage through Layer 5 (mm/annum)	28.40	28.44	28.46	28.51	28.55	28.57	28.58
	Average Head on top of Layer 5 (mm)	0.03	0.11	0.19	0.34	0.47	0.54	0.58
	Percolation/Leakage through Layer 6 (mm/annum)	11.69	11.73	11.76	11.80	11.84	11.86	11.87
2 x 150mm clay layers (Variant 11)	Lateral Drainage collected from Layer 1 (mm/annum)	141.99	141.99	141.99	141.99	141.99	141.99	141.99
	Percolation/Leakage through Layer 2 (mm/annum)	28.96	28.96	28.96	28.96	28.96	28.96	28.96
	Average Head on top of Layer 2 (mm)	4.53	4.53	4.53	4.53	4.53	4.53	4.53
	Lateral Drainage collected from Layer 4 (mm/annum)	0.47	0.41	0.35	0.26	0.18	0.14	0.12
	Percolation/Leakage through Layer 5 (mm/annum)	28.41	28.48	28.53	28.62	28.70	28.74	28.77
	Average Head on top of Layer 5 (mm)	0.05	0.21	0.37	0.69	0.97	1.13	1.24
	Percolation/Leakage through Layer 6 (mm/annum)	11.71	11.77	11.82	11.91	11.98	12.02	12.05
1 x 150mm clay layers (Variant 12)	Lateral Drainage collected from Layer 1 (mm/annum)	141.52	141.52	141.52	141.52	141.52	141.52	141.52
	Percolation/Leakage through Layer 2 (mm/annum)	29.43	29.43	29.43	29.43	29.43	29.43	29.43
	Average Head on top of Layer 2 (mm)	4.52	4.52	4.52	4.52	4.52	4.52	4.52
	Lateral Drainage collected from Layer 4 (mm/annum)	0.93	0.81	0.71	0.54	0.39	0.31	0.25
	Percolation/Leakage through Layer 5 (mm/annum)	28.43	28.55	28.64	28.81	28.96	29.04	29.10
	Average Head on top of Layer 5 (mm)	0.10	0.43	0.75	1.42	2.06	2.43	2.68
	Percolation/Leakage through Layer 6 (mm/annum)	11.72	11.83	11.93	12.09	12.24	12.32	12.37

Note: - Layer Specifications – G:L:B$^+$ Liner

Layer 1: Deposited Slag Aggregate
Layer 2: (4/2/1) x 150 mm thick Clay Layers with a permeability of $1x10^{-7}$ cm/s
Layer 3: 5 mm thick Geotextile Layer
Layer 4: 150 mm thick Leakage Detection and Collection Layer
Layer 5: 150 mm thick Clay Layers with a permeability of $1x10^{-7}$ cm/s
Layer 6: 5 m thick In-Situ Soil representing the Unsaturated Zone with a slope of 0.05

The simulated results obtained from the model further indicate that the volume of leachate collected from the leakage collection layer is similar for the G:L:B$^+$ Variant 4 and G:L:B$^+$ Variant 7 liner options. The results obtained from the model do however indicate that the volume of leachate removed by layer 4 is dependent on the distance to the drains within the layer.

G:L:B$^+$ Variant 11

The simulated results indicate that 141.99 mm/annum of leachate is laterally drained from the base of the slag dump and an average head of 4.53 mm builds up on top of the 2 x 150 mm thick clay layers (Layer 2). Although the build-up of head up on top of layer 2 is the same for the G:L:B$^+$ Variant 11 liner option as for the G:L:B$^+$ Variant 10 liner option, more leachate infiltrates through layer 2 in the G:L:B$^+$ Variant 11 option. The volume of leachate that infiltrates through layer 2 (28.96 mm/annum) is slightly less than the 29.00 mm/annum of leachate that infiltrates through layer 2 for both the G:L:B$^+$ Variant 8 and Variant 5 liner options.

The same leachate flux (29.00 mm/annum) however infiltrates through Layer 2 for both the G:L:B$^+$ Variant 5 and G:L:B$^+$ Variant 8 liner options. Of the 29.00 mm/annum of leachate that infiltrates through the clay layers, varying volumes of leachate is removed by the 150 mm thick leakage detection and collection layer (Layer 4). The results obtained from the model indicate that the volume of leachate collected from the leakage collection layer is similar for the G:L:B$^+$ Variant 5 and G:L:B$^+$ Variant 8 liner options.

The simulated leachate flux through the 5 m thick in-situ soil zone (Layer 6) assigned to the G:L:B$^+$ Variant 11 liner option remains similar to the leachate flux that infiltrates through layer 6 in the G:L:B$^+$ Variant 8 and Variant 5 liner options, further indicating that the slope does not play a major role in reducing the volume of leachate that infiltrates through the liner.

G:L:B$^+$ Variant 12

The simulated results indicate that 141.52 mm/annum of leachate is laterally drained from the base of the slag dump and an average head of 4.52 mm builds up on top of the 150 mm thick clay layer (Layer 2). The build-up of head up on top of layer 2 is marginally less than the head of 4.53 mm on top of layer 2 for both the G:L:B$^+$ Variant 11 and Variant 10 liner options respectively. Slightly more leachate however infiltrates through layer 2 in the G:L:B$^+$ Variant 12 option (29.43 mm/annum), than through the same layer for the G:L:B$^+$ Variant 11 option (28.96 mm/annum) and the G:L:B$^+$ Variant 10 liner option (28.71 mm/annum).

Of the 29.43 mm/annum of leachate that infiltrates through the clay layers, varying volumes of leachate is removed by the 150 mm thick leakage detection and collection layer (Layer 4). The results obtained from the model further indicate that the volume of leachate collected from the leakage collection layer is similar for the G:L:B$^+$ Variant 6 and G:L:B$^+$ Variant 9 liner options. The results obtained from the model again indicate that the volume of leachate removed by layer 4 is again dependent on the distance to the drain within the layer.

The simulated leachate flux that that infiltrates through the 5 m thick in-situ soil zone (Layer 6) assigned to the G:L:B$^+$ Variant 12 liner option remains similar to flux that infiltrates through layer 6 in the G:L:B$^+$ Variant 9 and Variant 6 liner options. This further verifies that the slope does not play a major in reducing the volume of leachate that infiltrates through the liner.

The simulated leachate flux that infiltrates through the G:L:B$^+$ Variants (10-12) are similar to the leachate flux that infiltrates through the G:L:B$^+$ Variants (4-6) and Variants (7-9). This indicates that by increasing the slope of the individual liner options to 0.02 and further to 0.05 does not make a significant difference to the volume of leachate intercepted and removed by the liner system. The results do however indicate that the majority of the leachate (>70%) generated at the base of the slag material, drains laterally on top of the liner system through the slag material itself.

The simulated results indicate that although the number of clay layers as well the distance to the drains influence the volume of leachate intercepted and removed by the liner system, the slope of the layers is less effective in doing so.

5.3.10 Optimized Liner Design

Based on the sensitivity analysis results obtained with regards to each of the simulated liner options and the associated water balance calculations, an optimized liner design has been proposed that takes amongst others the cost of installation, potential installation flaws, slope, clay permeability, clay thickness and distance to leakage collection drains into consideration.

Several liner design variations were simulated until the optimized liner design was determined, according to the factors listed above. The optimized liner design for the slag dump scenario investigated has a total thickness of 900 mm, excluding the 5 m thick in-situ soil zone and is depicted in Figure 30.

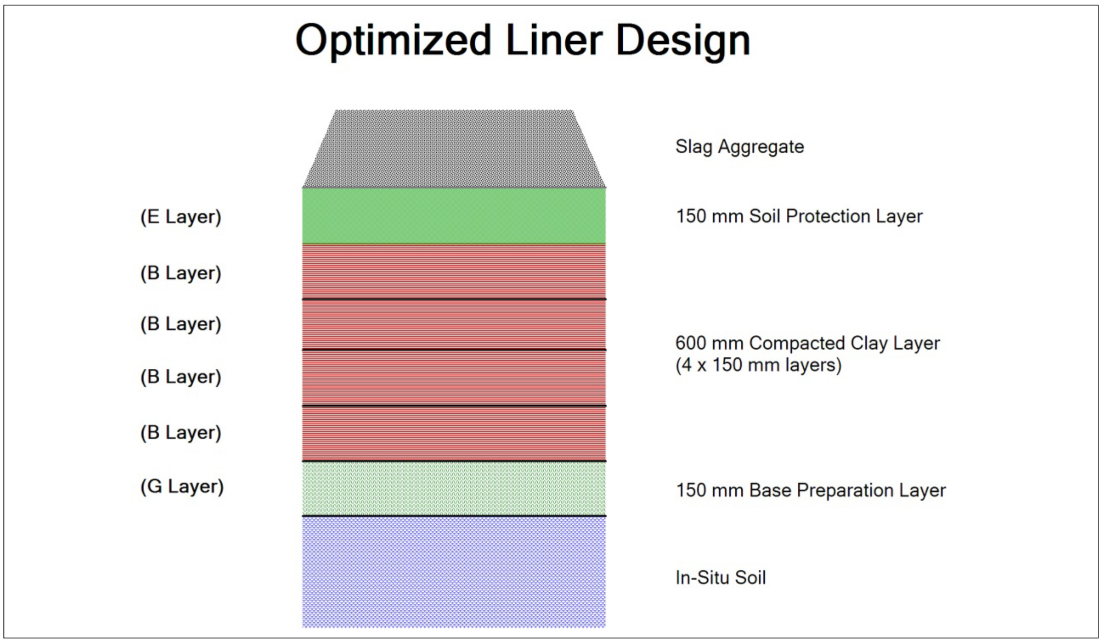


Figure 30: Optimized Liner Design

This optimized liner represents the Best Practicable Environmental Option for the slag dump scenario investigated and is capable of capturing the required 185.10 mm/annum of leachate at the base of the simulated slag dump.

The bottommost layer used within the model represents the 5 m thick in-situ soil zone with a slope of 0.013. The layer placed on top of the 5 m thick in-situ soil zone is essentially the bottom layer within the liner and entails a 150 mm thick base preparation layer consisting of reworked "turf" soil that is obtained from within the study area. The primary purpose of this layer is to ensure that the gradient of liner can be manipulated to create a constant slope of 0.02.

A slope of 0.02 has been used in the model to ensure that no ponding of leachate occurs below the slag dump. The soil is also used to create a flat and uniform base layer on which the overlying low permeability clay layers can be installed. By increasing the slope to 0.02 as opposed to 0.013 is expected to increase the degree of care taken during the installation of liner design. If a natural slope of 0.013 was assigned, less care would be carried out as the slope has already been naturally generated and is not consistent across the footprint of the slag disposal facility.

The soil is assigned a total porosity of 0.417, field capacity of 0.045, wilting point of 0.018 and a saturated hydraulic conductivity of 0.01 cm/s (8.64 m/day) all of which are representative of the soil within the study area. Drains will be inserted in the base preparation layer to intercept the leachate that could potentially infiltrate through the low permeability clay layers installed on top of the base preparation.

The clay layers consist of four 150 mm thick compacted clay layers installed on top of one another. Not only do the clay layers form a comprehensively thick low permeability layer, but also minimize the effects of the clay potentially pinching out during construction and installation thereof. The clay is assigned a total porosity of 0.451, field capacity of 0.419, wilting point of 0.332 and an average saturated hydraulic conductivity of 1×10^{-7} cm/s (8.64×10^{-5} m/day). Once the low permeability clay layers have been installed they are covered with a soil protection layer.

The 150 mm thick soil protection layer forms the uppermost layer of the model and serves to protect the underlying clay layers from being damaged during the disposal of the slag aggregate material. The soil used in the model is assigned a total porosity of 0.437, field capacity of 0.062, wilting point of 0.024 and a saturated hydraulic conductivity of 0.07 cm/s (60.5 m/day). A summary of the water balance obtained from the simulated model for the optimized liner design is given on Table 36.

Table 36: Detailed Water Balance for the Optimized Liner Design

Optimized Liner Design with a slope of 0.02		Distance to Drains (m)						
		1	5	10	25	50	75	100
Precipitation (mm/annum)		629.71	629.71	629.71	629.71	629.71	629.71	629.71
Runoff (mm/annum)		1.04	1.04	1.04	1.04	1.04	1.04	1.04
Evapotranspiration (mm/annum)		438.82	438.82	438.82	438.82	438.82	438.82	438.82
Optimized Liner	Lateral Drainage Collected from Layer 2 (mm/annum)	150.51	150.51	150.51	150.51	150.51	150.51	150.51
	Percolation / Leakage through Layer 3 (mm/annum)	20.15	20.15	20.15	20.15	20.15	20.15	20.15
	Average Head on top of Layer 3 (mm)	6.17	6.17	6.17	6.17	6.17	6.17	6.17
	Percolation / Leakage through Layer 5 (mm/annum)	3.63	3.63	3.63	3.63	3.63	3.63	3.63

Note: - Layer Specifications – Optimized Liner

Layer 1: Deposited Slag Aggregate

Layer 2: 150 mm thick Soil Preparation Layer

Layer 3: 4 x 150 mm thick Clay Layers with a permeability of $1x10^{-7}$ cm/s and a surface slope of 0.02

Layer 4: 150 mm thick Base Preparation Layer

Layer 5: 5 m thick In-Situ Soil representing the Unsaturated Zone

The soil protection layer, as well as the slag itself also effectively represent drainage layers due to their high permeability's. The liner is therefore installed with drains all along the perimeter of the slag dump footprint, to ensure that any leachate that is drained/removed on top of the low permeability clay layers is intercepted and conveyed to the leachate collection pond/dam.

The simulated results for the optimized liner design indicate that the distance to the drains in the liner does not affect the quantity of leachate captured by the drains. The reason that there is not a change in the quantity of leachate captured by the drains is due to the relatively limited build-up of head on top of layer 3 (6,17 mm). It is therefore proposed that the drains be installed at distances 100 m apart. It is not recommended that the drains be installed a greater distance than 100 m in the case of severe rainfall events, during which a larger build-up of hydraulic head on top of layer 3 may potentially occur.

The simulated results further indicate that the distance to the drains does not affect the volume of leachate that infiltrates through the liner and into the underlying saturated ground water zone. The simulated results indicate that 3.63 mm of leachate infiltrates into the underlying saturated ground water zone per annum, irrespective of the distance to the drains within the drainage layer. Across a surface footprint of 50 ha, this culminates to a total volume of 1,815 m^3 of leachate that infiltrates into the saturated ground water zone per annum.

This calculates to a volume that is smaller than the volume permissible through the liner to ensure that the EEC of the slag disposal facility is lower than the AEC for the underlying ground water system. This indicates that the volume of leachate that infiltrates through the optimized liner system within the study area is small enough to ensure that the aquatic ecosystems are not expected to be influenced by the quality of the infiltrating leachate below the slag disposal facility.

The simulated results indicate that the optimized liner design will intercept and remove 98.09% of the leachate generated at the base of the slag disposal facility, which is sufficient in ensuring that the underlying ground water system is not impacted as a result of the infiltrating leachate. The cost of installing the optimized liner design is expected to be R1,100,000/ha, using the site specific material and current engineering and installation costs, as opposed to R4,500,000/ha calculated for the H:H liner system.

5.4 MASS TRANSPORT OF CONTAMINANTS WITHIN THE SATURATED ZONE

The Visual MODFLOW modelling software is used to graphically illustrate the extent and normalized concentration of the potential contaminant migration within the shallow weathered zone aquifer. MODFLOW is an acronym for the USGS Modular Three-Dimensional Groundwater Flow Model and Visual Modflow Premium 4.3 (VMOD), a graphical user interface for MODFLOW, is used during the ground water mass transport modelling of the saturated zone. Ground water flow within the aquifer is simulated using a block-centred finite-difference approach. Layers are simulated as displaying unconfined and semi un-confined conditions.

The simulated volume of leachate that infiltrates into the saturated zone for three liner options are graphically illustrated. These are namely the:

- No Liner Option, which represents the worst case scenario,
- H:H Liner Option, which represents the most stringent liner option, and
- Optimized Liner Option.

The simulated volume of leachate flux that infiltrates through the bottommost layer in each of the three abovementioned liner options will be used as input leachate flux into the transient state mass transport models.

The ground water flow and mass transport models are used to predict the lateral movement of the contaminants within the saturated zone away from their infiltration source below the slag disposal facility. The concentrations at which the contaminants reach the saturated zone represent worst case scenario concentrations and are taken as the concentrations determined from the leaching tests.

The simulated concentrations within the mass transport models represent normalized concentrations, indicating that the concentration of leachate/contaminant that enters saturated ground water zone is 100% and is incorporated in the model as 100 mg/l. The concentrations of each of the contaminant variables can thus as a result be calculated from the normalized concentrations as required.

5.4.1 Input Parameters for the Ground Water Flow and Mass Transport Models

5.4.1.1 Assigned Model Area

The study area used for the ground water flow and mass transport model is delineated by the following lateral aquifer boundaries:

- The western aquifer boundary is a physical boundary formed by a regional syenite dyke. Due to the minimal weathering of this dyke it is deemed impervious to ground water flow and as a result represents a no-flow ground water boundary.
- The eastern boundary is also a physical boundary formed by a regional syenite dyke. Due to the thickness and limited weathering status and depth of this dyke it is also impervious to ground water flow and as result al represents a no-flow ground water boundary.
- The northern boundary is a hydraulic boundary and was selected partly along a surface stream (Northern Tributary) and partly along the river diversion around a slimes dam. The boundary represents a ground water discharge boundary and will be accommodated into the numerical flow model as a constant head (Derichlet) boundary.
- The southern boundary is a combined arbitrary and hydraulic boundary. The western section of the boundary was chosen parallel to the ground water flow direction (arbitrary no flow boundary) whilst the eastern section was chosen along a surface stream (Southern Tributary) representing a ground water discharge boundary which will be incorporated into the model as a constant head (Derichlet) boundary.

In order to incorporate each of the lateral aquifer boundaries within the model area, the model grid was defined by the four corner coordinates listed in Table 37. The coordinates listed in Table 37 are geo-referenced according the WGS84 system, using the LO27 longitude.

Table 37: Model Grid Corner Coordinates

Grid Corner	Y- Coordinate (m)	X- Coordinate (m)
North West	- 2 841 400	38 500
North East	- 2 841 400	44 400
South West	- 2 848 000	38 500
South East	- 2 848 000	44 400

The allocated model grid was discretized up into 20m x 20m cells giving rise to 330 rows and 295 columns. The model grid area (active and inactive zones) is delineated on Figure 31.

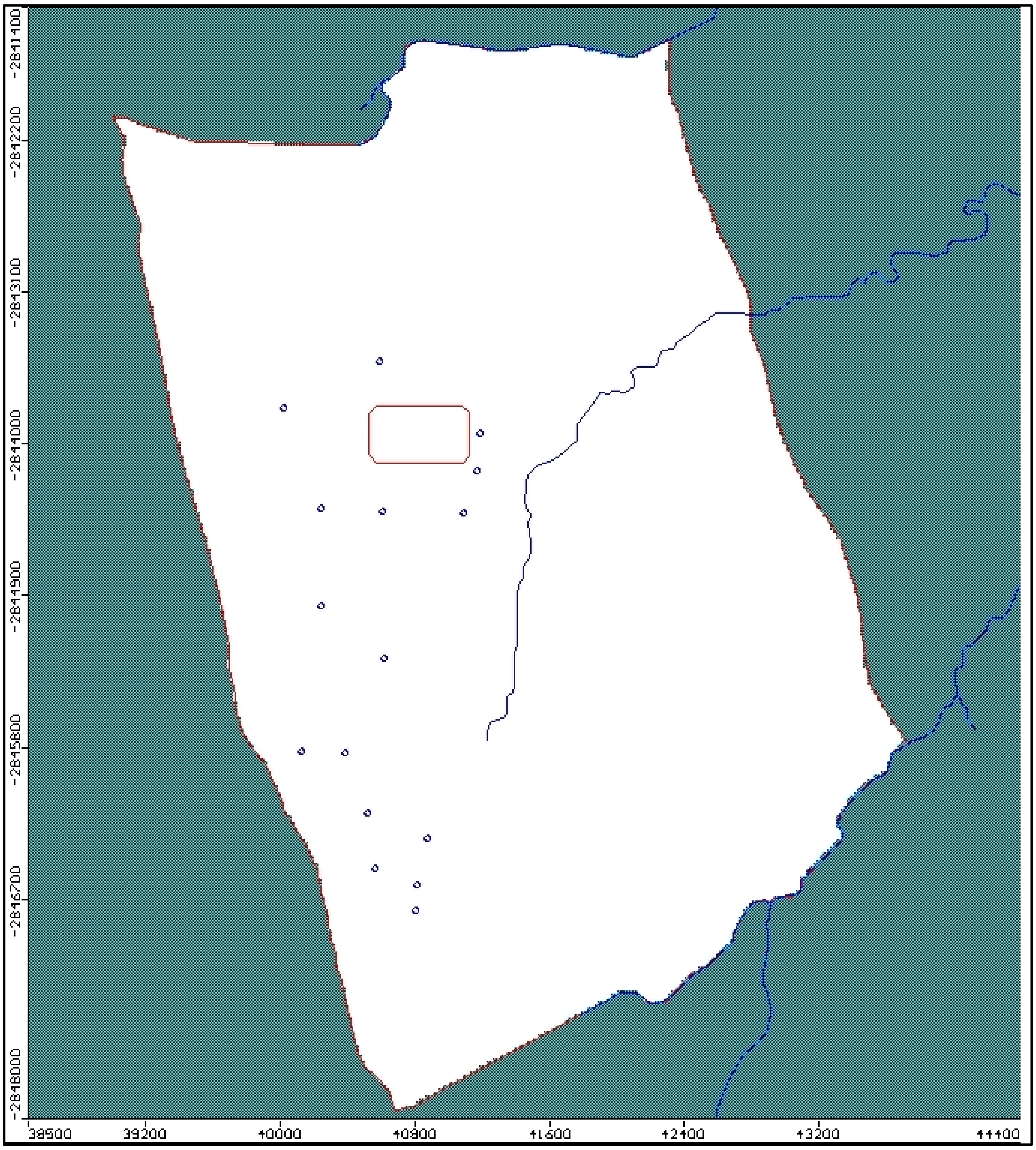


Figure 31: Model Grid Area and Slag Disposal Facility Footprint

The area indicated in white represents the active cells (study area) as defined by the lateral aquifer boundaries, whilst the area indicated in green represents the inactive cells within the model grid area. The extent of the slag dump footprint is indicated in red, the surface water streams are delineated in blue and the boreholes are indicated by the blue circles on Figure 31.

5.4.1.2 Surface Topography

The surface topography is discussed with reference to the information obtained from the digital terrain model (DTM) data for the study area. The surface elevations obtained from the DTM were incorporated into the model and the surface topography of the model area is depicted in Figure 32. The topography of the study area ranges in elevation between 1250 mamsl and 1165 mamsl and generally slopes towards the north-east, and gives rise to three major drainage areas.

The two lineaments of syenite ridges are clearly evident on Figure 32 and form the western and eastern lateral aquifer boundaries for the study area. The three streams and lower lying surface areas are evidently delineated on Figure 32 as well.

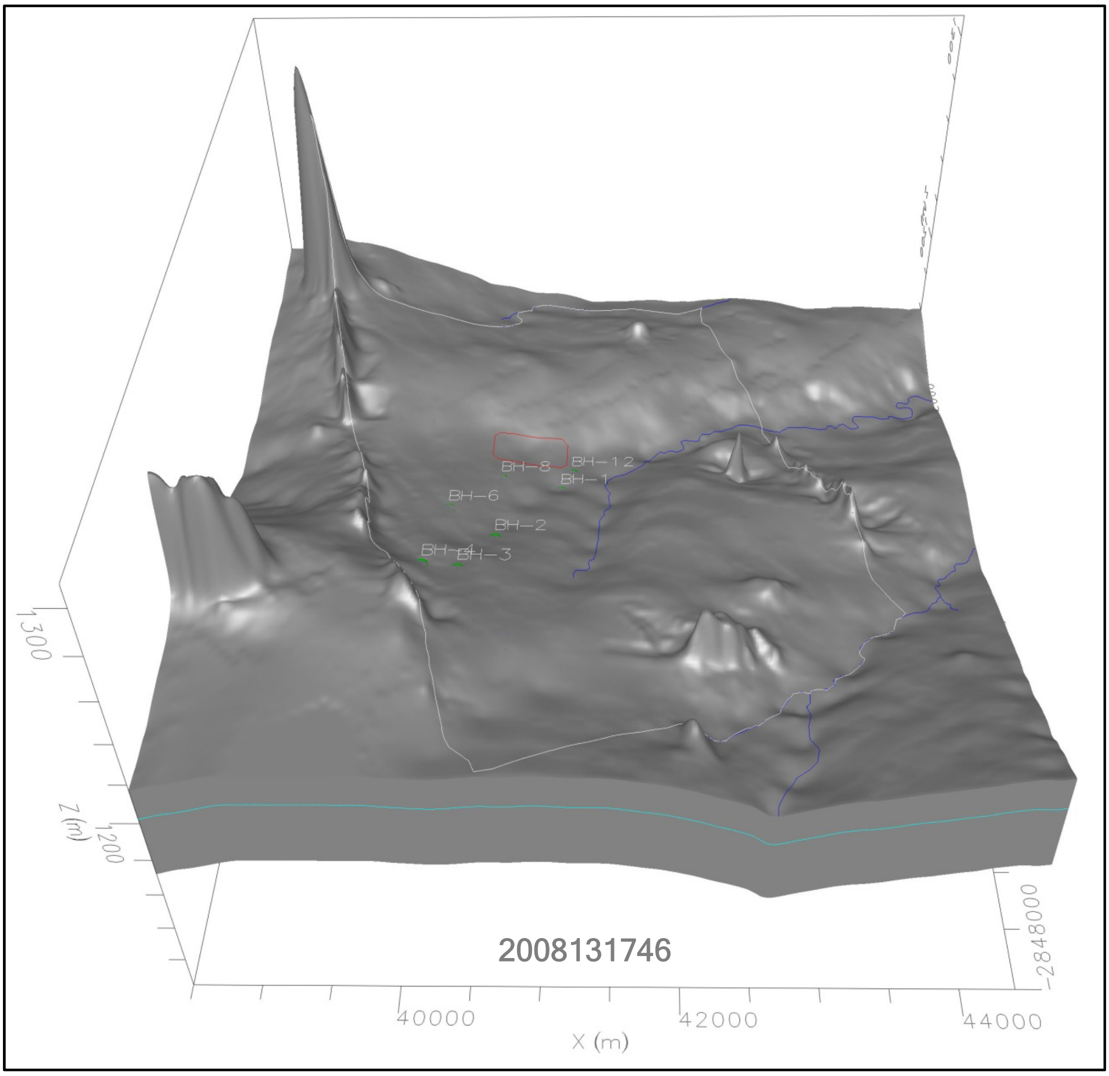


Figure 32: Surface Topography of the Model Area

5.4.1.3 Model Layer Properties

The weathering and weathering related fracturing depth recorded in the field varied between 9.0 and 25.0 mbgl with an average depth of 15 mbgl, below which the norite became fresh and hard. Two layers were therefore assigned to the model, namely the weathered/fractured norite and the fresh norite host rock. The properties of the two individual layers assigned to the model are summarized in Table 38.

Table 38: Model Layer Properties

Layer	Layer Type	Depth (mbgl)	Porosity (fraction)	Effective Porosity (fraction)	Hydraulic Conductivity (m/day)
Weathered/Fractured Norite	Unconfined	0 - 15	0.05	0.03	0.80
Fresh Norite	Semi-Confined	15 - 45	0.03	0.001	0.01

5.4.1.4 Initial Hydraulic Heads

The initial hydraulic heads assigned to the steady state ground water model were calibrated using the ground water levels recorded in the ground water observation boreholes. The calibrated steady state ground water levels were further used as the initial heads for the transient state models.

Water level depths deeper than 9 m below ground level indicate areas in which the ground water level has been affected by aquifer dewatering associated with the underground mining activities and will thus be excluded. The ground water levels recorded from these boreholes were excluded during the calibration of the hydraulic head in the steady model.

By excluding the water levels recorded in boreholes that have been affected by the underground mining operations, the average ground water level within the study area is calculated as 4.97 mbgl.

5.4.1.5 Aquifer Recharge

The recharge assigned to ground water system within the model was taken as 5% of the mean annual rainfall, which accumulates to 31 mm/annum. The aquifer recharge was further calibrated in the steady state model, along with the ground water levels and aquifer's hydraulic conductivity.

The recharge assigned to model within the extent of the slag disposal facility footprint area, varied according to the simulated flux of leachate that infiltrates through each of the three liners options, namely: the No Liner Option, the H:H Liner Option and the Optimized Liner Option.

5.4.1.6 Seepage from Liner Options

The simulated leachate fluxes through each of the liner options were obtained from the HELP models and are listed in Table 39.

Table 39: Seepage Rates through each of the Liner Options

Liner Option	Area (ha)	Flux (mm/annum)	Seepage (m^3/annum)
No Liner	50	152.43	76,215
H:H Liner	50	0.00	0.00
Optimized Liner	50	3.63	1,815

A leachate infiltration concentration of 100mg/l (100%) was assigned to the model within the area delineated by the slag disposal facility footprint, and is used as a normalized concentration. The concentration of the individual contaminants/variables can thus as a result be directly calculated from the normalized concentrations simulated in the model.

5.4.1.7 Model Time

The ground water flow and mass transport models were set-up to simulate the conditions for a total period of 100 years in order to investigate the long term behaviour and development of any potential contaminants and contaminant plume if the contaminants enter the shallow weathered zone aquifer.

5.4.2 Model Scenarios

A total of four model scenarios (1 steady state model and 3 transient state models) were set-up during the ground water flow and mass transport assessment. The first model developed (Model I) was a steady state model, used to calibrate the hydraulic head and predict the steady state ground water elevations, flow directions and gradients of the model area. The three transient state models (Model II to Model IV) were used to investigate and predict the ground water flow and contaminant transport conditions of the leachate that infiltrates through the liner designs and into the saturated zone of the shallow weathered zone aquifers. The contaminant concentration and migration conditions simulated within the shallow weathered zone for each of the three transient state models were calculated using the implicit Generalized Conjugate Gradient (GCG) solver.

5.4.2.1 Model I – Steady State Model

The steady state model was run in order to calibrate the modelled ground water heads, by altering the aquifer's hydraulic conductivity, storativity as well as the natural aquifer recharge for the study area. The simulated steady state hydraulic heads obtained from the model were used for each of the three transient state models (Model II to Model IV).

5.4.2.2 Model II –No Liner

Model II simulates the scenario that is expected to arise if the slag is deposited directly onto the soil surface, without the implementation of a liner system. A leachate flux of 152.43 mm/annum was calculated to infiltrate into the saturated zone if no liner in installed below the slag dump and is therefore assigned to the 50 ha surface footprint of the slag disposal facility investigated in the model.

5.4.2.3 Model III – H:H Liner

Model III simulates the scenario that is expected to occur if the slag is deposited on top of an H:H Liner system. The H:H liner represents the most stringent liner option, and a leachate flux of 0.00 mm/annum was calculated to pass through the H:H Liner system. No infiltration is therefore assigned to the 50 ha footprint area of the slag disposal facility investigated in the model.

5.4.2.4 Model IV – Optimized Liner

Model IV simulates the scenario that is expected to occur if the slag is deposited on top of the Optimized Liner system. A leachate flux of 3.63 mm/annum was calculated to pass through the optimized liner system and is thus assigned to the 50 ha surface footprint of the slag disposal facility investigated in the model.

5.4.3 Model I – Steady State Model

In the steady state model the ground water elevations (hydraulic heads) were calibrated using the ground water levels recorded in the field, the ground water recharge, aquifer storativity as well as the hydraulic conductivity of the weathered zone (layer 1) within the study area. The model calibration relates to the changing of certain input parameter values, such as the aquifer's hydraulic conductivity and recharge, in order to match the observed ground water level field conditions within some acceptable spectrum.

Topographically higher areas were assigned slightly higher recharge values, whilst the lower lying areas were assigned lower recharge values. The areas adjacent to the surface streams were also assigned higher hydraulic conductivity values to incorporate the higher hydraulic conductivity sands and sediments associated with the meandering streams in the study area.

The bulk of the aquifer was assigned a horizontal hydraulic conductivity of 0.8 m/day and a recharge of 31 mm/annum. The vertical hydraulic conductivity was 0.08 m/day, with the specific storage of 0.003, effective porosity of 0.03, storativity of 0.03 and a longitudinal dispersivity of 10 m.

The ground water levels recorded from 7 of the 15 boreholes within the study area were used during the calibration of the ground water elevations. The localities of the 7 boreholes are indicated on Figure 33. The ground water levels recorded in the remaining 8 boreholes have been affected by the adjacent underground mining operations, and have therefore not been used as they do not represent the natural ground water levels.

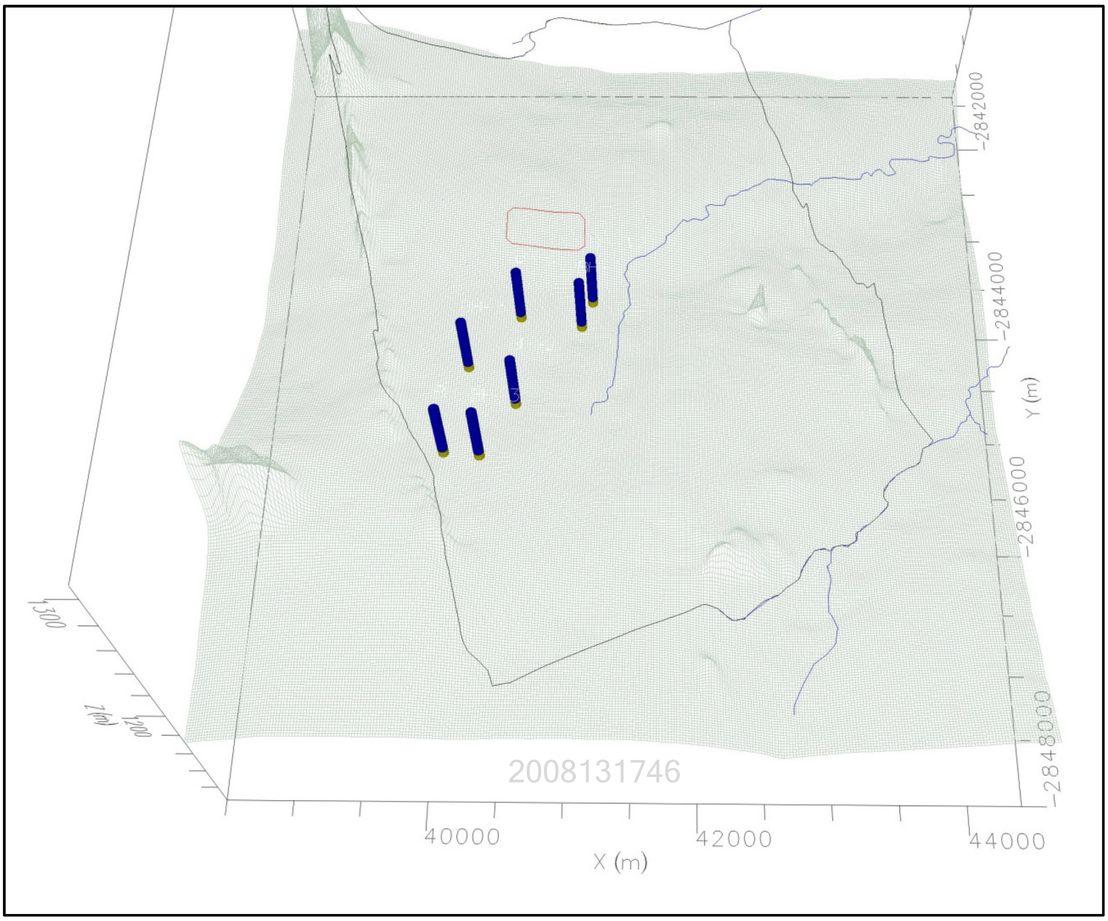


Figure 33: Observation Boreholes used to the calibrate the Hydraulic Heads

During the calibration of the steady state ground water elevations, a root mean squared value of 0.97 m was calculated between the observed (field) ground water elevations and the calibrated ground water elevations at the 7 boreholes. A graph depicting the observed vs. calibrated steady state heads is displayed as Figure 34. The simulated steady state ground water elevations and flow directions are displayed on Figure 35.

The largest difference between the observed and the calibrated ground water elevations is indicated as 1.357 m (BH-6), whilst the smallest difference is indicated as 0.34 m (BH-8), with an average deviation of 0.532 m between the observed and the calibrated ground water elevations of the model. The calculated normalized Root Mean Square (RMS) between the observed and the calibrated ground water elevations in the model is 3.143%. The correlation coefficient is calculated as 0.998 and the standard error of the estimate, calculated by the model is 0.333 m.

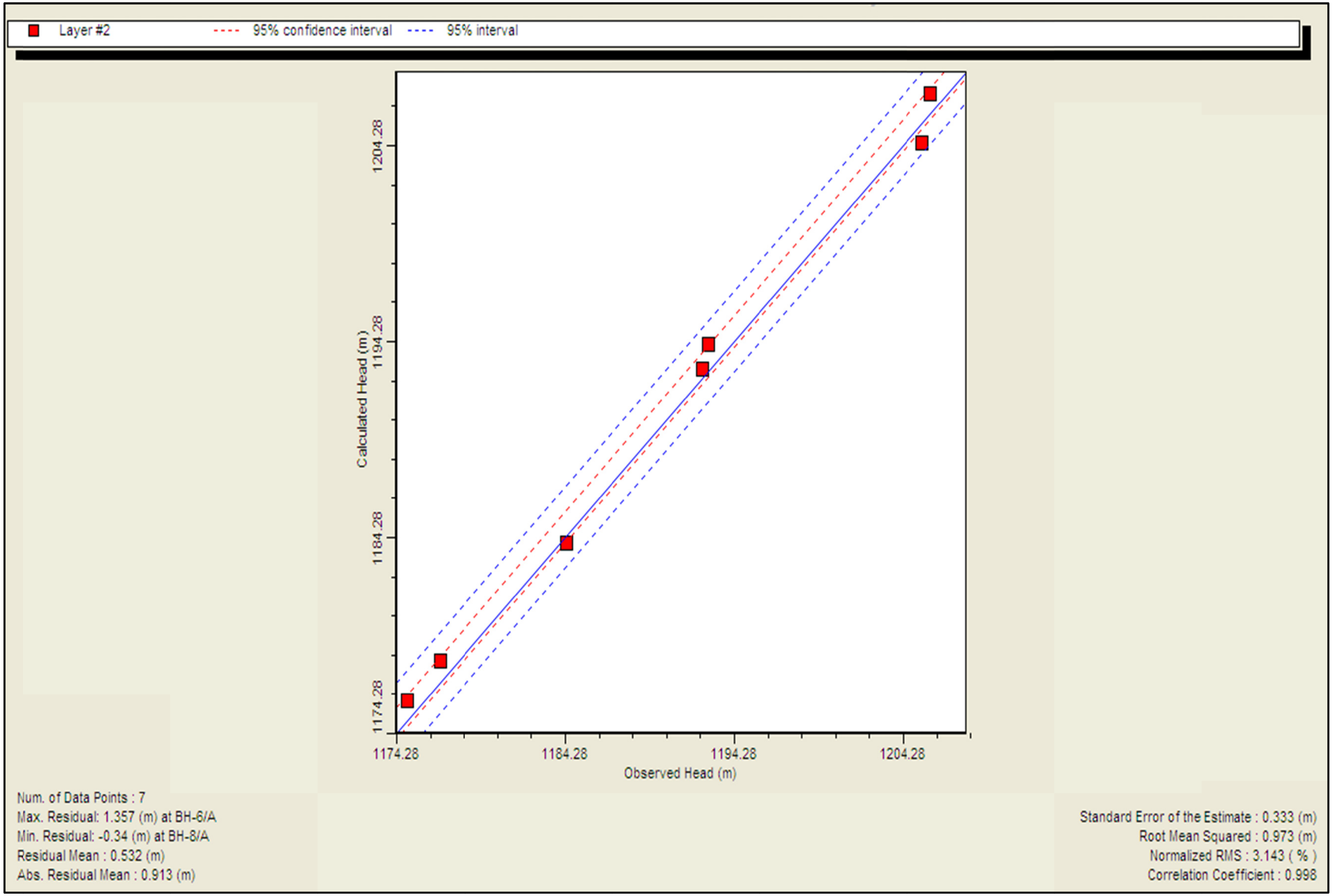


Figure 34: Calibrated vs. Observed Steady State Heads

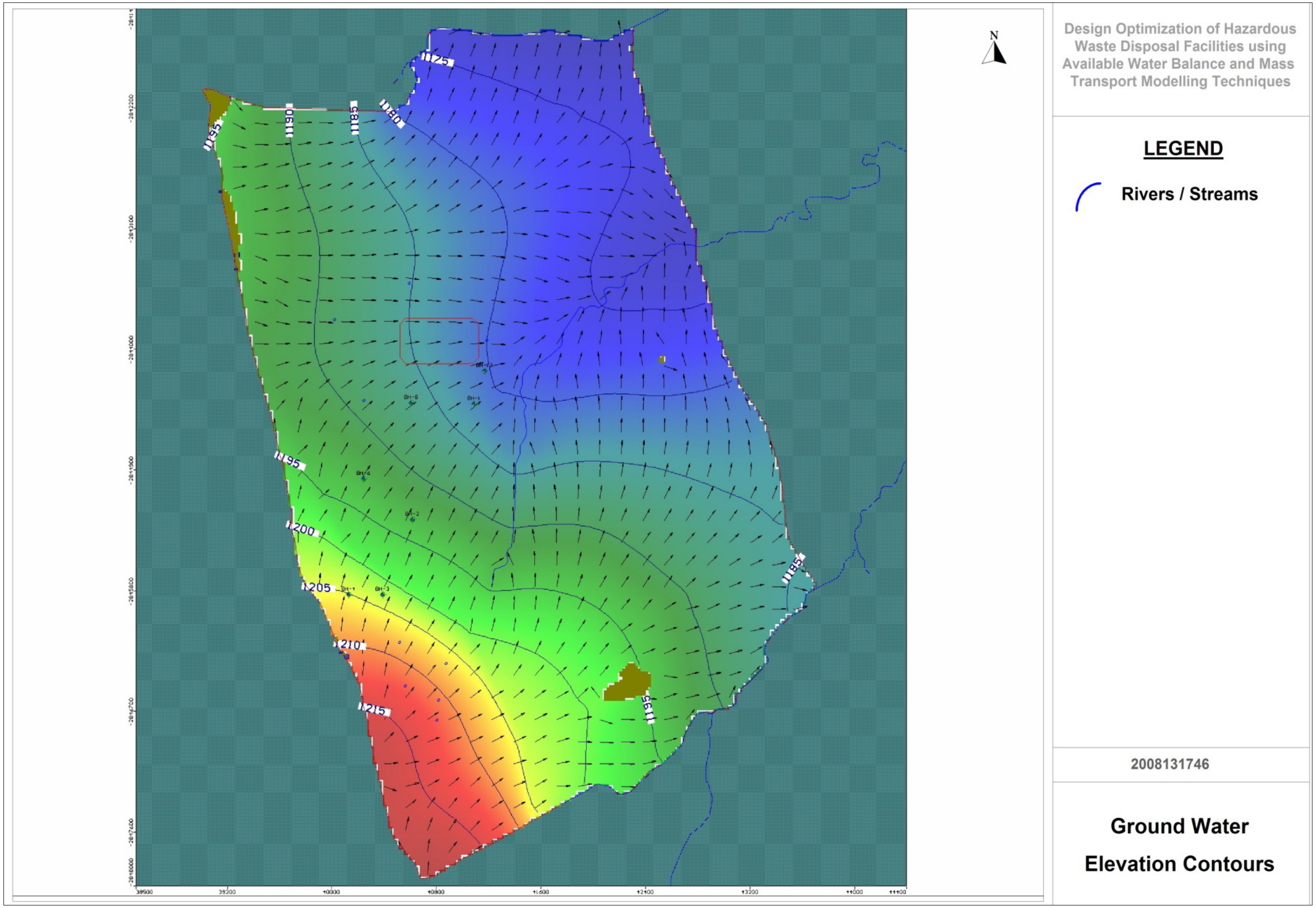


Figure 35: Steady State Ground Water Elevation Contours and Flow Directions

The simulated ground water elevations are indicated by the dark blue lines on Figure 35, whilst the ground water flow directions are indicated by the black arrows on Figure 35.

The ground water below the slag dump is simulated to flow to in an easterly direction towards the Central Tributary drainage system within the study area. The hydraulic gradient below the slag dump is calculated as 0.009 towards the east.

The simulated steady state ground water elevations mimic that of the surface topography and generally flows towards the north east across the extent of the study area. The hydraulic gradient ranges between 0.007 and 0.025 across the study area, with a bulk gradient of 0.011 towards the north-east.

Based on the information obtained from the steady state model it is important to establish a realistic quantum for the ground water flow velocity within the study area. The ground water seepage velocity (Vs) represents the most realistic expression of the actual velocity at which dissolved contaminants will migrate as a result of advection through the shallow weathered zone aquifer and is calculated as follows:

$$Vs = (k * i) / \theta$$

where

Vs	=	Ground Water Seepage Velocity (m/day)
k	=	Aquifer Hydraulic Conductivity (m/day)
i	=	Ground Water Gradient
θ	=	Effective Porosity

Vs_{min} = (0.80 * 0.007)/0.05 = 0.112 m/day = 41 m/year

Vs_{max} = (0.80 * 0.025)/0.05 = 0.400 m/day = 146 m/year

Vs_{bulk} = (0.80 * 0.011)/0.05 = 0.176 m/day = 64 m/year

The seepage velocity calculated above represents the bulk seepage velocity across the entire study area and will of course vary across the study area as a function of the variability in hydraulic conductivity, gradient and porosity. The natural seepage velocity within the study area is expected to vary between 41 m/year and 146 m/year, with a bulk seepage velocity of 64 m/year.

The ground water below the slag dump footprint is calculated as having a gradient of 0.009 towards the east. This indicates that the natural seepage velocity below the slag disposal facility is calculated to be 53 m/year towards the east. The Central Tributary drainage system (receptor), drains across the central regions of the study area is some 690 m to the east of the slag dump footprint. This indicates that any contaminants which enter the saturated zone below the slag disposal facility will take some 13 years to reach the tributary under the natural hydraulic aquifer conditions.

5.4.4 Model II – No Liner Option

Model II is the first transient state model generated and simulates the conditions that are expected to occur if the slag is deposited directly on top of the in-situ soils at the surface. Any leachate generated within the slag dump is thus assumed to infiltrate directly into the saturated ground water zone. It was simulated in the HELP model that 152.43 mm/annum of leachate generated at the base of the slag disposal facility will infiltrate into the saturated zone if no liner is installed. Once in the saturated zone the contaminants contained within the leachate will migrate laterally, predominantly as a result of the advective flow of the ground water.

The migration of the contaminants within the shallow weathered zone aquifer was simulated for a period of up to 100 years after the disposal of the slag. Simulated outputs indicating the concentrations, extent and migration of the potential contamination plume, which originates from the base of the slag dump are displayed for the simulated years 5, 10, 50 and 100.

The full volume of slag was simulated to be deposited immediately which represents the most conservative conditions. The model assumes that the contaminants are conservative and will not breakdown once in the saturated ground water zone. This indicates that all the contaminants that enter the saturated zone will remain in solution and be transported towards the ground water receptors.

The simulated outputs adjacent to the slag disposal facility for Model II are indicated as Figures 8.4(a) to 8.4(d) for the simulated conditions after 5 years, 10 years, 50 years and 100 years respectively. The simulated conditions for the entire study area are indicated in APPENDIX III.

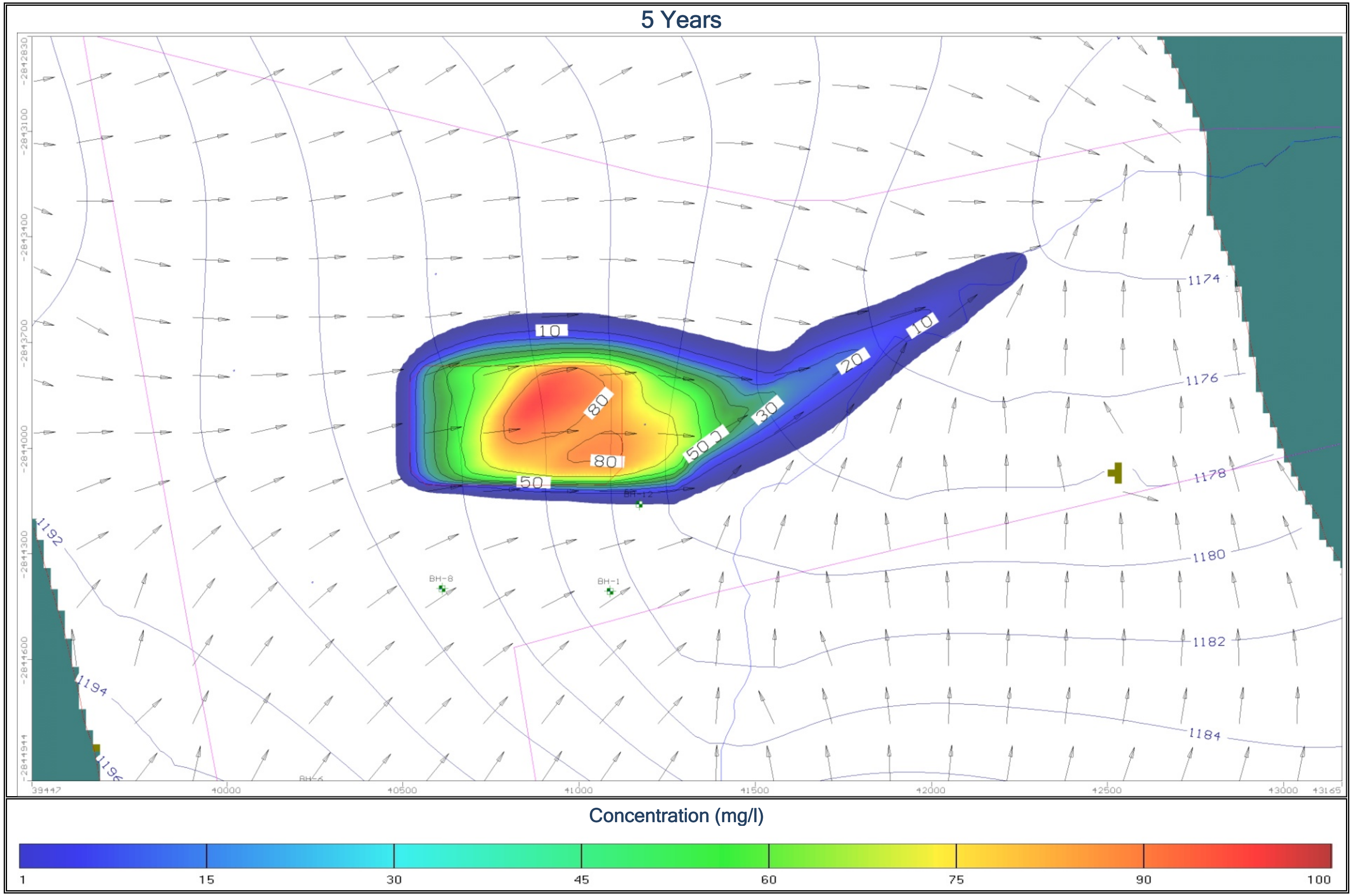


Figure 36: Simulated Ground Water Contamination Plume for Model II after 5 years

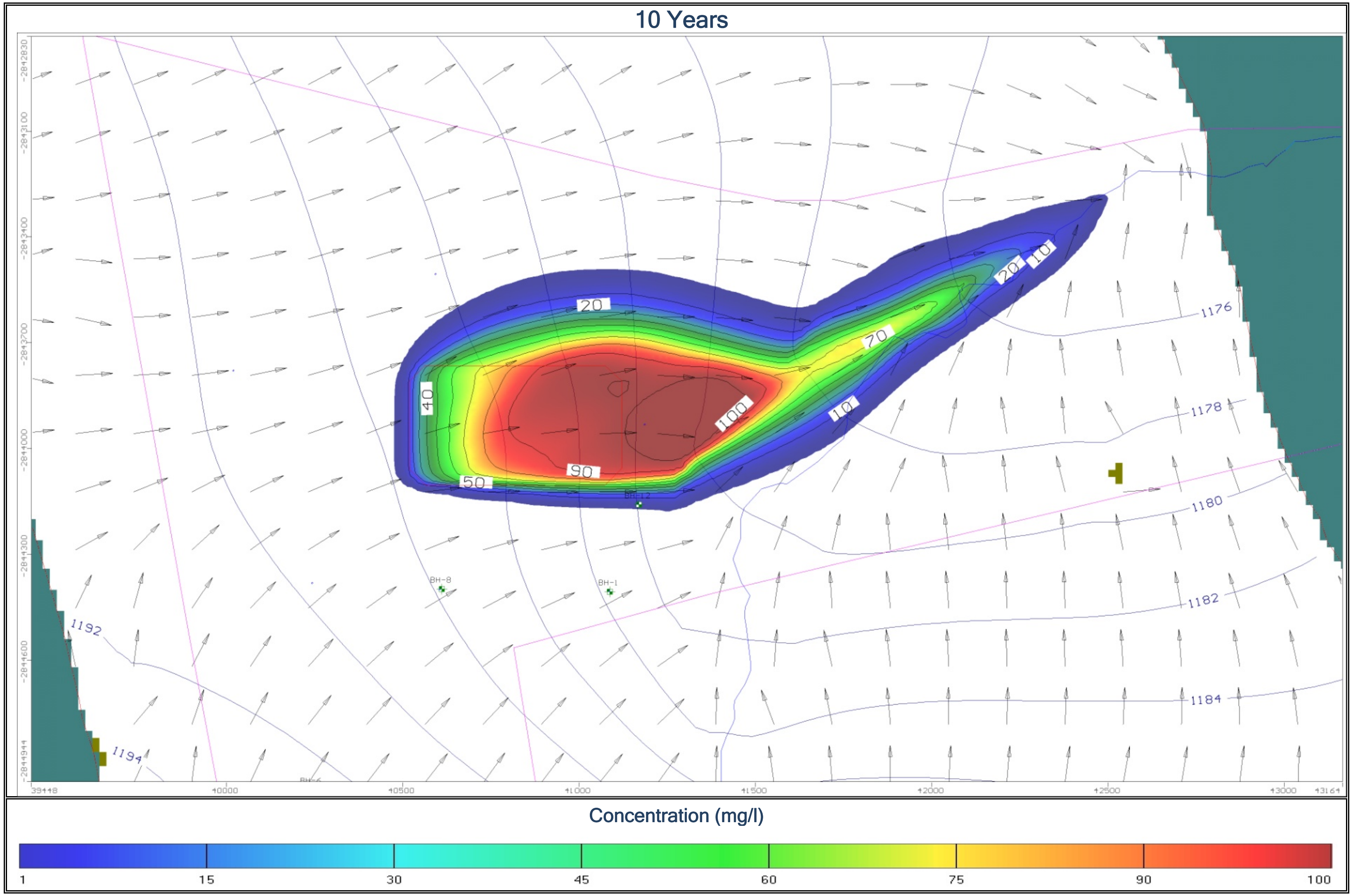


Figure 37: Simulated Ground Water Contamination Plume for Model II after 10 years

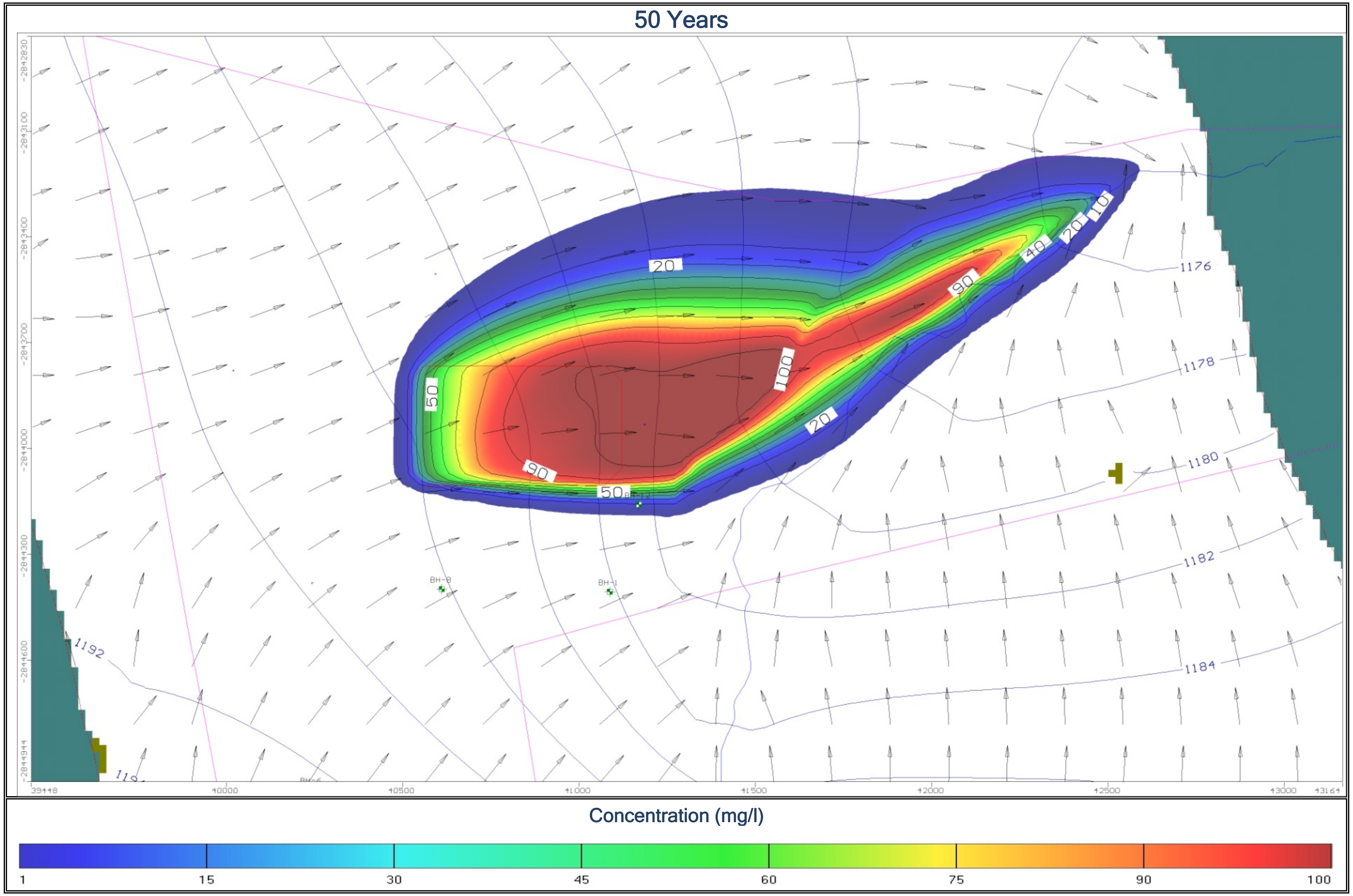


Figure 38: Simulated Ground Water Contamination Plume for Model II after 50 years

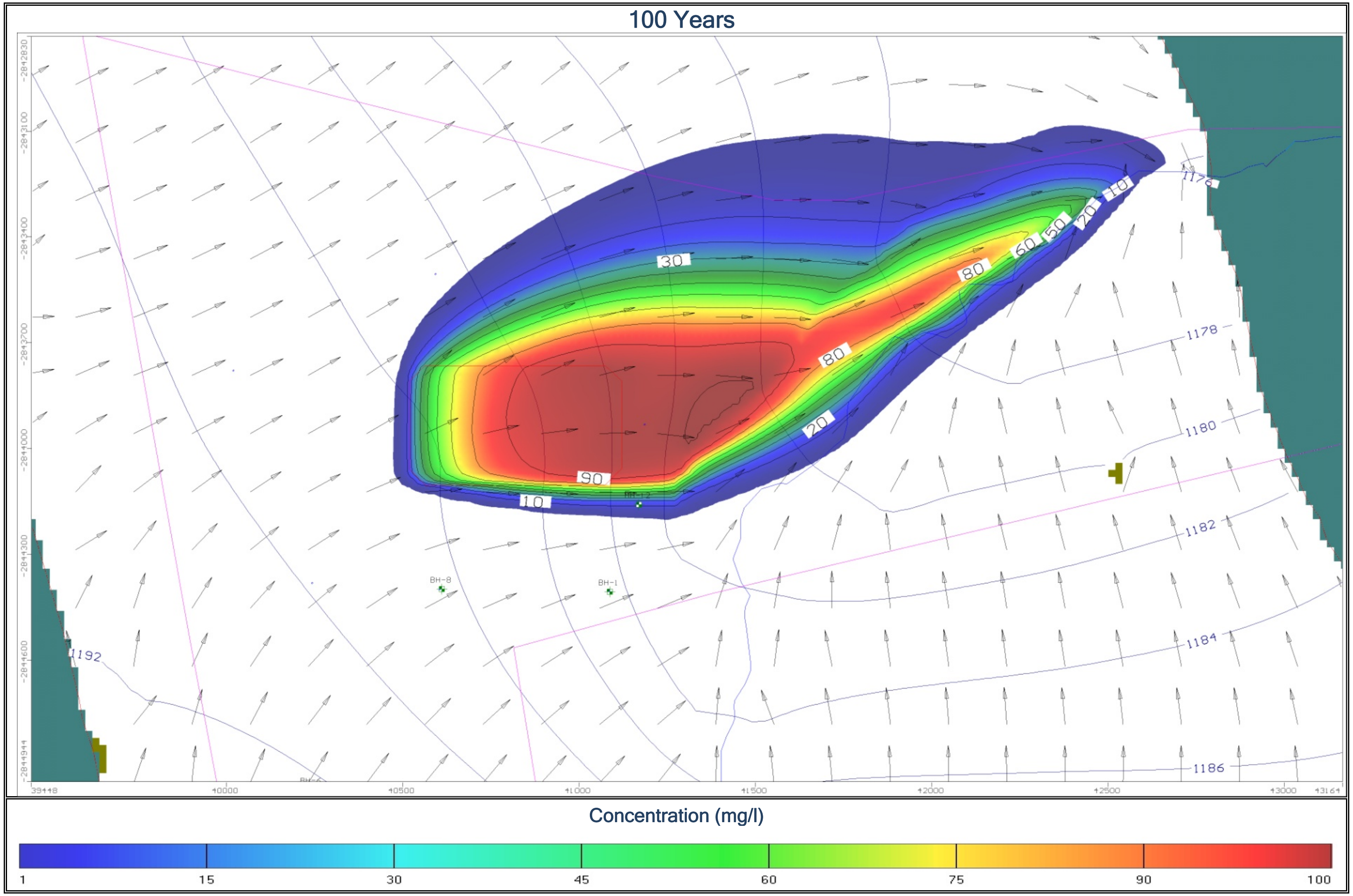


Figure 39: Simulated Ground Water Contamination Plume for Model II after 100 years

The concentrations represented in Figures 8.4(a) to 8.4(d) are normalized concentrations, indicating a leachate infiltration concentration of 100 mg/l. The bottom cut-off limit of the simulated contamination plume is taken as 1 mg/l. The ground water elevation contour lines are indicated by the black lines on Figures 8.4(a) to 8.4(d) and have been indicated at 2 m intervals.

The simulated results obtained from the model indicate that any contaminants which enter the saturated ground water zone below the slag disposal facility will initially be transported to the east until they enter the flow regime of the Central Tributaries drainage system, after which they are transported in a north-easterly direction away from the slag disposal facility.

The simulated results for model II indicate that any contaminants within the leachate will arrive at the Central Tributary's drainage system (Receptor) within 5 years after disposal of the slag, although at very low concentrations. The results indicate that the Mn concentration at the Central Tributary drainage system is expected to be 0.67 ppm after 5 years, 2.80 ppm after 10 years, 3.86 ppm after 50 years and 4.59 ppm after 100 years.

This indicates that if no liner system is implemented, Mn will enter the central tributary's drainage system at a concentration that exceeds the stipulated AEC concentration within 5 years of disposing the slag within the delineated disposal area.

The increase in the infiltration to the ground water system within the extent of the slag disposal facility affects the ground water elevations below the slag disposal facility as well. After 5 years the ground water elevation along the eastern perimeter of the slag disposal facility is 1181.74 mamsl, which increases to 1182.48 mamsl after 10 years, 1183.20 mamsl after 50 years and 1183.77 mamsl after 100 years. This indicates that the natural ground water elevations (hydraulic head) will increase by 2.03 m over the simulated 100 year period, forming a hydraulic head mound below the slag disposal facility.

5.4.5 Model III – H:H Liner Option

Model III is the second transient state model generated and simulates the conditions that are expected to occur if the slag is deposited on top of an H:H Liner system. The H:H liner is the most stringent liner design that may accommodate solid waste disposal by landfill and is as a result the most expensive to install as well.

According to the classification of the slag as stipulated in the Minimum Requirements, the slag is required to be deposited at a landfill that has an H:H liner installed. It was simulated in the HELP model that the H:H liner effectively captures 100% (189.85 mm/annum) of the leachate generated at the base of the slag dump. This indicates that no leachate or contaminants are expected to enter the saturated ground water zone below the slag disposal facility if an H:H liner is implemented.

The area delineated by the slag disposal facility footprint is consequently assigned an infiltration flux of 0 mm/annum, indicating that no infiltration is assigned to the aquifer within this area. The model was run for a period of 100 years after the disposal of the slag. The full volume of slag was simulated to be deposited immediately and represents the most conservative conditions.

Simulated outputs indicating the concentrations, extent and migration of the potential contamination plume, which originates from the base of the slag dump are displayed for the simulated years 5, 10, 50 and 100. The simulated outputs indicate that no contaminants will enter the saturated ground water zone and will therefore not have an impact on the saturated ground water zone.

The simulated outputs adjacent to the slag disposal facility for Model III are indicated as Figures 8.5(a) to 8.5(d) for the simulated conditions after 5 years, 10 years, 50 years and 100 years of disposal respectively. The simulated conditions for the entire study area are indicated in APPENDIX III.

The H:H liner system is the most conservative of the liner systems and indicates that the ground water quality will not be affected due to the absence of infiltrating leachate through the H:H liner system.

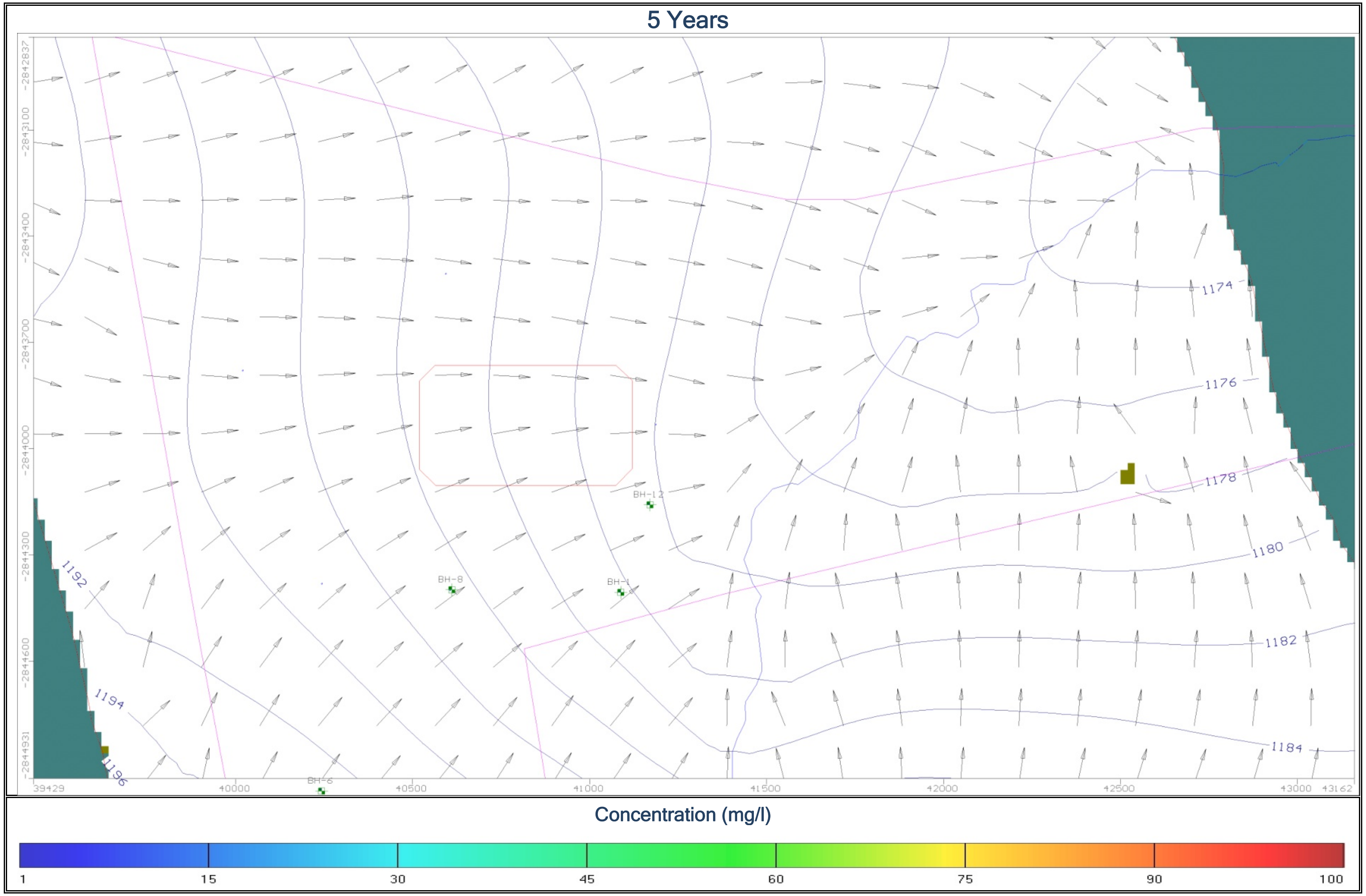


Figure 40: Simulated Ground Water Contamination Plume for Model III after 5 years

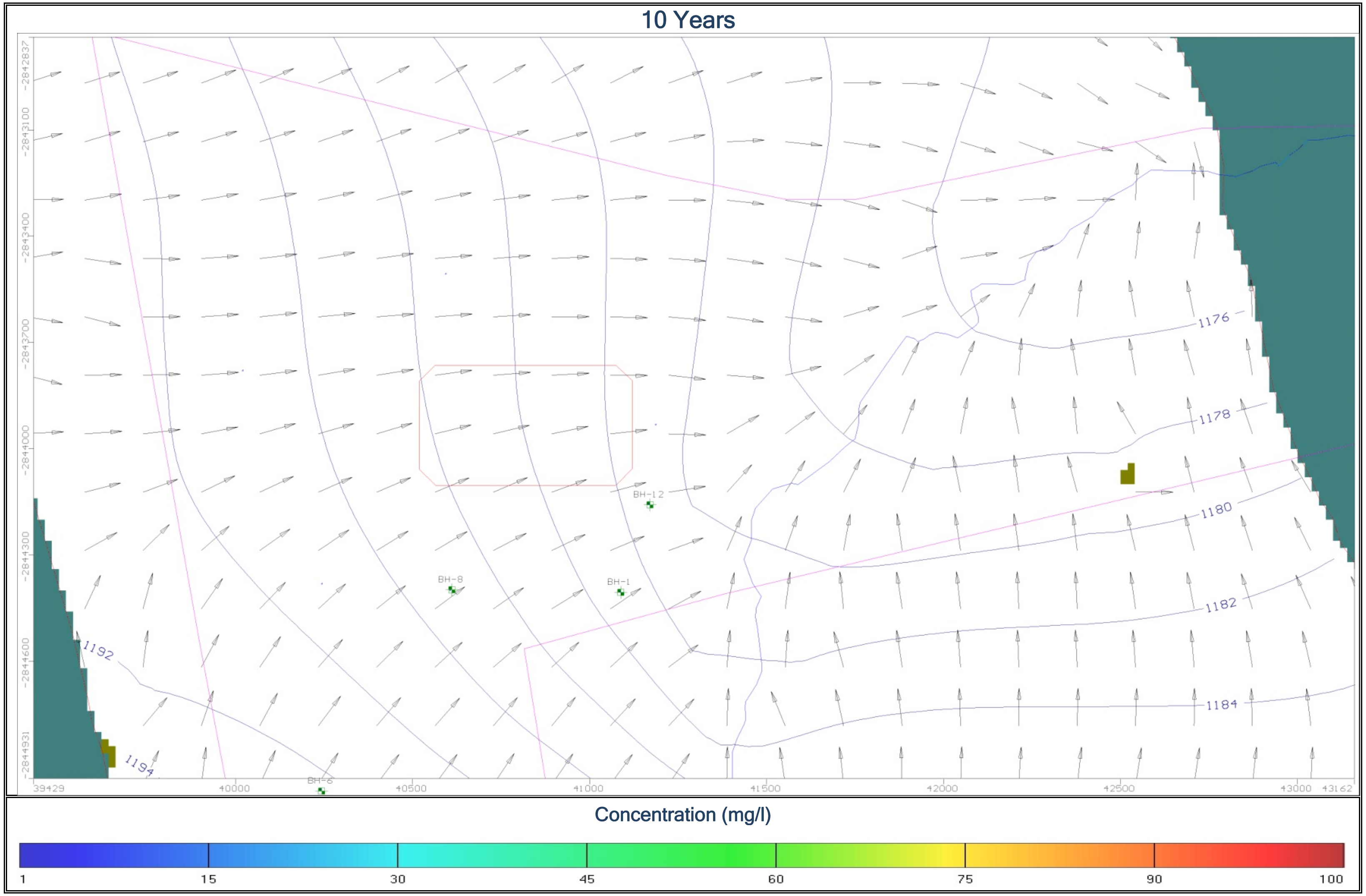


Figure 41: Simulated Ground Water Contamination Plume for Model III after 10 years

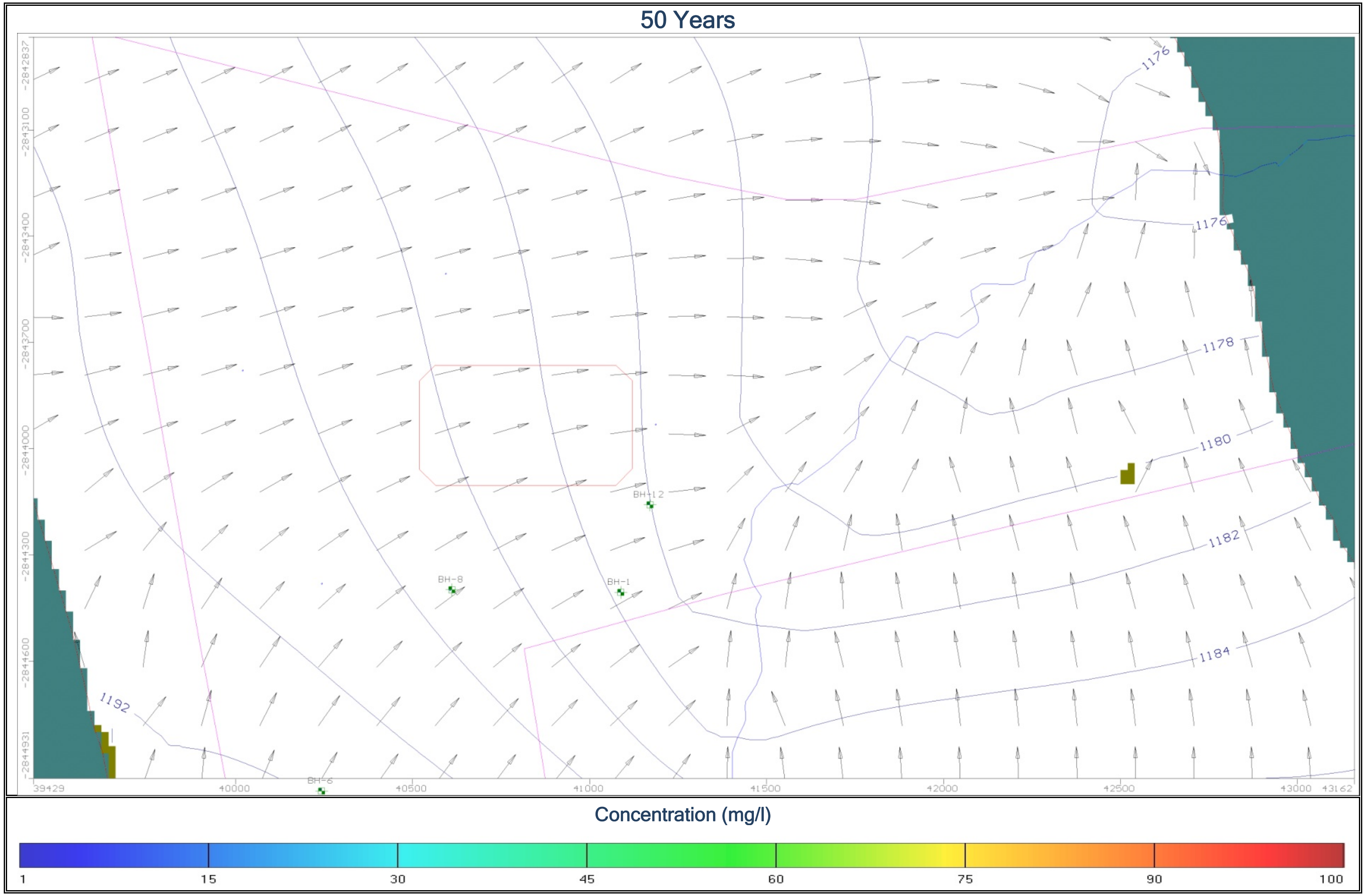


Figure 42: Simulated Ground Water Contamination Plume for Model III after 50 years

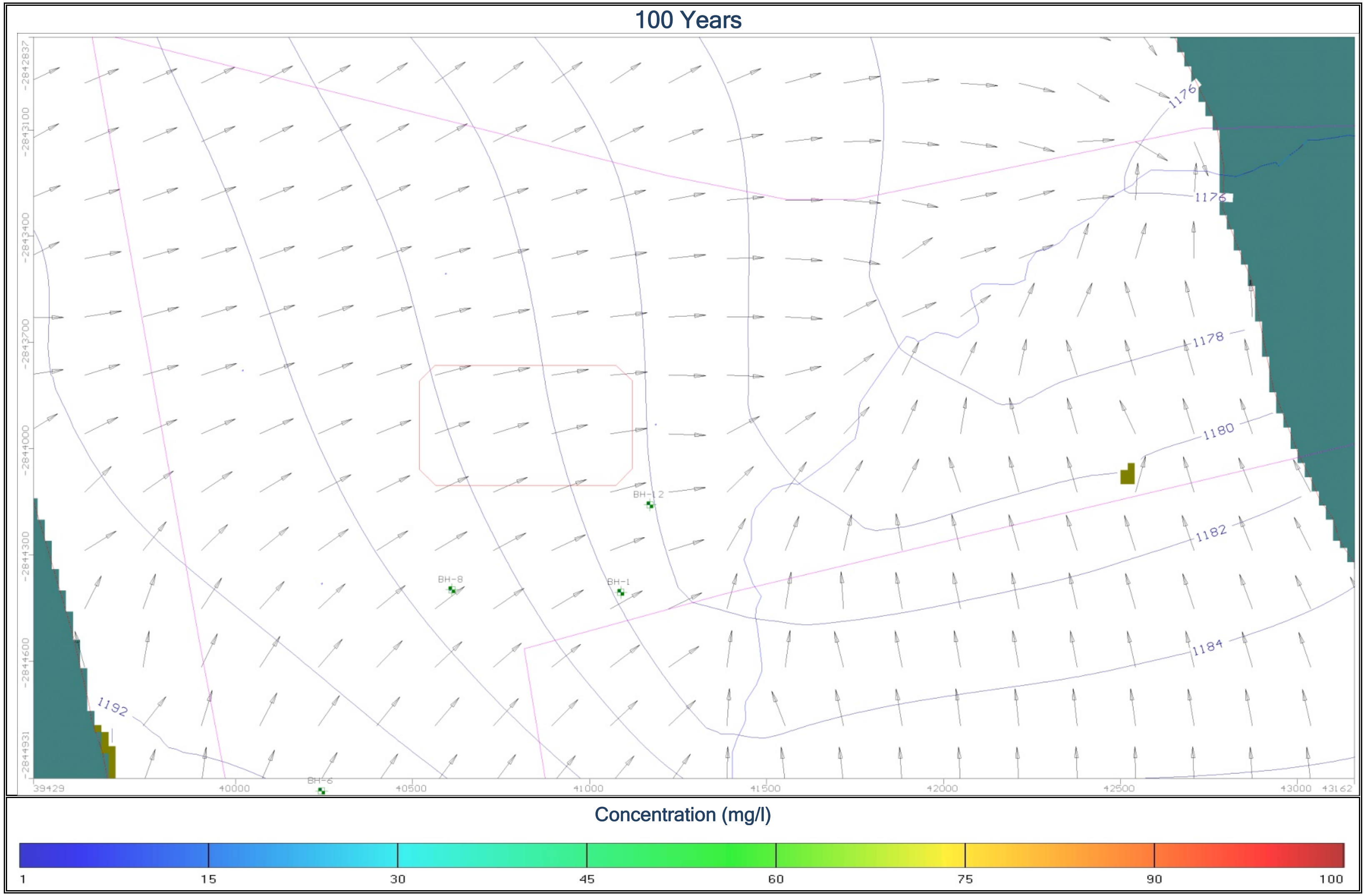


Figure 43: Simulated Ground Water Contamination Plume for Model III after 100 years

5.4.6 Model IV – Optimized Liner Option

Model IV is the third of the transient state models generated for the investigative study and simulates the conditions that are expected to occur if the slag is deposited on top of the optimized liner. Any leachate generated within the slag dump and that infiltrates through the liner is assumed to infiltrate directly into the saturated ground water zone and will be incorporated as such in the model.

It was simulated in the HELP model that 3.63 mm/annum of the leachate generated at the base of the slag disposal facility will infiltrate into the saturated zone if the optimized liner is installed. Once in the saturated zone the contaminants contained within the leachate will migrate laterally, predominantly as a result of the advective flow of the ground water. The model assumes that the contaminants are conservative and will not breakdown once in the saturated ground water zone indicating that all the contaminants will remain in solution and be transported towards the ground water receptors.

The migration of the contaminants within the shallow weathered zone aquifer was simulated for a period of up to 100 years after the disposal of the slag. Simulated outputs indicating the concentrations, extent and migration of the potential contamination plume, which originates from the base of the slag disposal facility, are displayed for the simulated years 5, 10, 50 and 100.

The full volume of slag was simulated to be deposited immediately and therefore represents the most conservative conditions. The simulated outputs adjacent to the slag disposal facility for Model IV are indicated as Figures 8.6(a) to 8.6(d) for the simulated conditions after 5 years, 10 years, 50 years and 100 years of disposal respectively. The simulated conditions for the entire study area are indicated in APPENDIX III.

The concentrations represented in Figures 8.6(a) to 8.6(d) are normalized concentrations, indicating a leachate infiltration concentration of 100 mg/l. The bottom cut-off limit of the simulated contamination plume is taken as 1 mg/l. The ground water elevations contour lines are indicated by the black lines on Figures 8.6(a) to 8.6(d) and are displayed at 2 m intervals.

The simulated results obtained from the model indicate that any contaminants which enter the saturated ground water zone below the slag disposal facility will initially be transported to the east until they enter the flow regime of the Central Tributary, assuming that the contaminants are conservative and that they will remain in solution. Once the contaminants enter the Central Tributary's drainage system, they are transported in a north-easterly direction away from the slag disposal facility.

The simulated results for optimized liner scenario (Model IV) indicate that any contaminants within the leachate will only reach the Central Tributary's drainage system (Receptor) after 10 years of disposing the slag. Although it is indicated that contaminants may potentially enter the central tributary's drainage system after 10 years, it is evident that it will be at very low concentrations.

The simulated results indicate that the Mn concentration at the Central Tributary's drainage system is expected to be 0.00 mg/l after 5 years, 0.06 mg/l after 10 years and 0.08 mg/l after 50 years and 100 years respectively.

The simulated results indicate that if the optimized liner is implemented below the slag disposal facility, the Mn concentrations expected to enter the Central Tributary's drainage system will be present at concentrations that are more than three times lower (0.08 mg/l) than the stipulated AEC for Mn. This indicates that the leachate that infiltrates through the optimized liner system enters the saturated ground water zone below the slag disposal facility at a concentration that will not have an impact on the adjacent ground water system and aquatic environment.

This liner design is thus sufficient in capturing the required volume of leachate generated at the base of the slag dump and has been optimally designed according to: 1) the site specific information regarding the geochemistry of the slag, 2) the physical properties of the slag, 3) the disposal specifications of the slag, 4) the site specific meteorological data and 5) the hydrogeological data of the study area investigated.

The liner system has thus sequentially been optimally designed using site specific information as well as available water balance and mass transport modelling techniques, according to the Best Practicable Environmental Option norm at the most optimal cost.

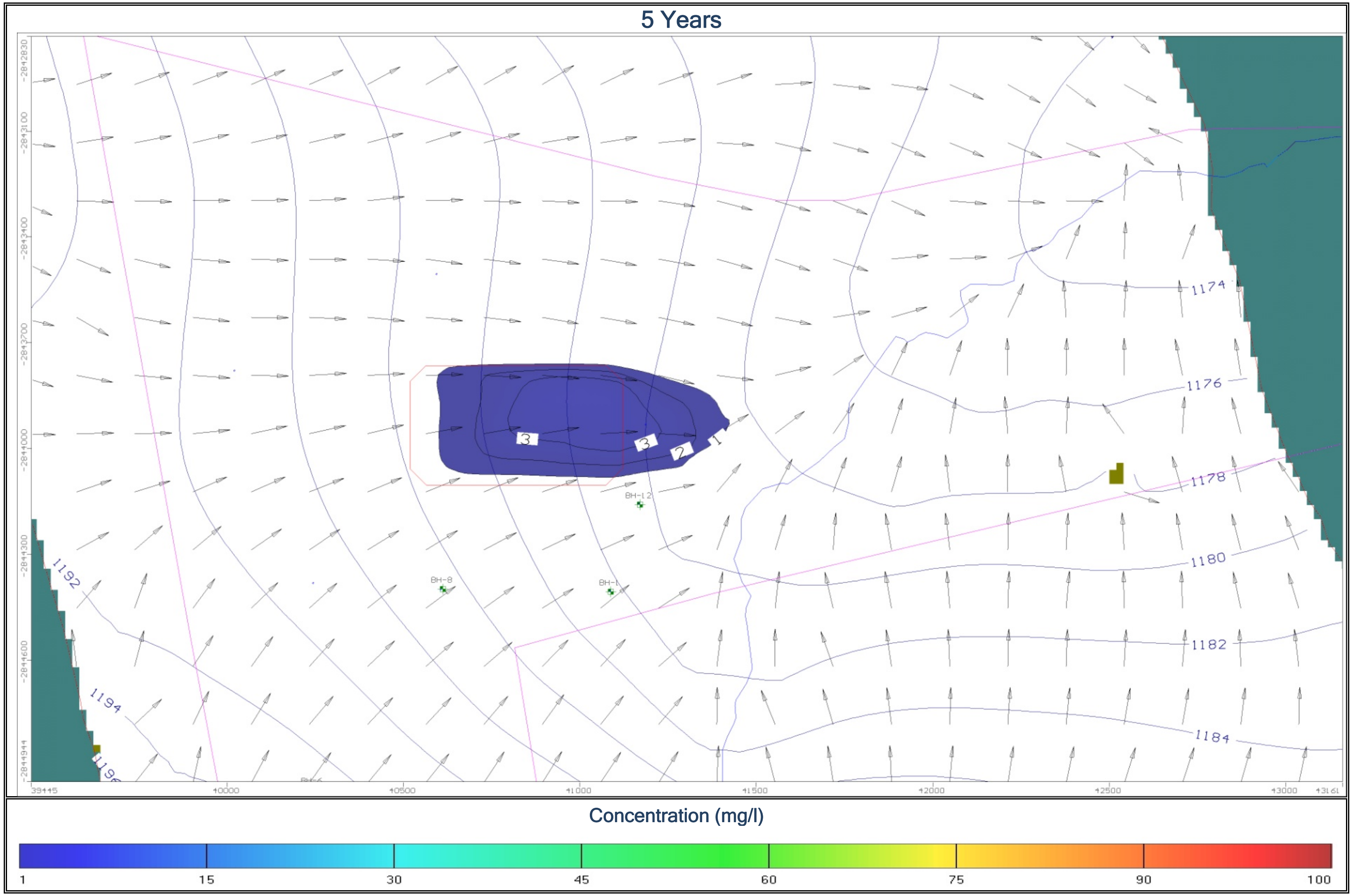


Figure 44: Simulated Ground Water Contamination Plume for Model IV after 5 years

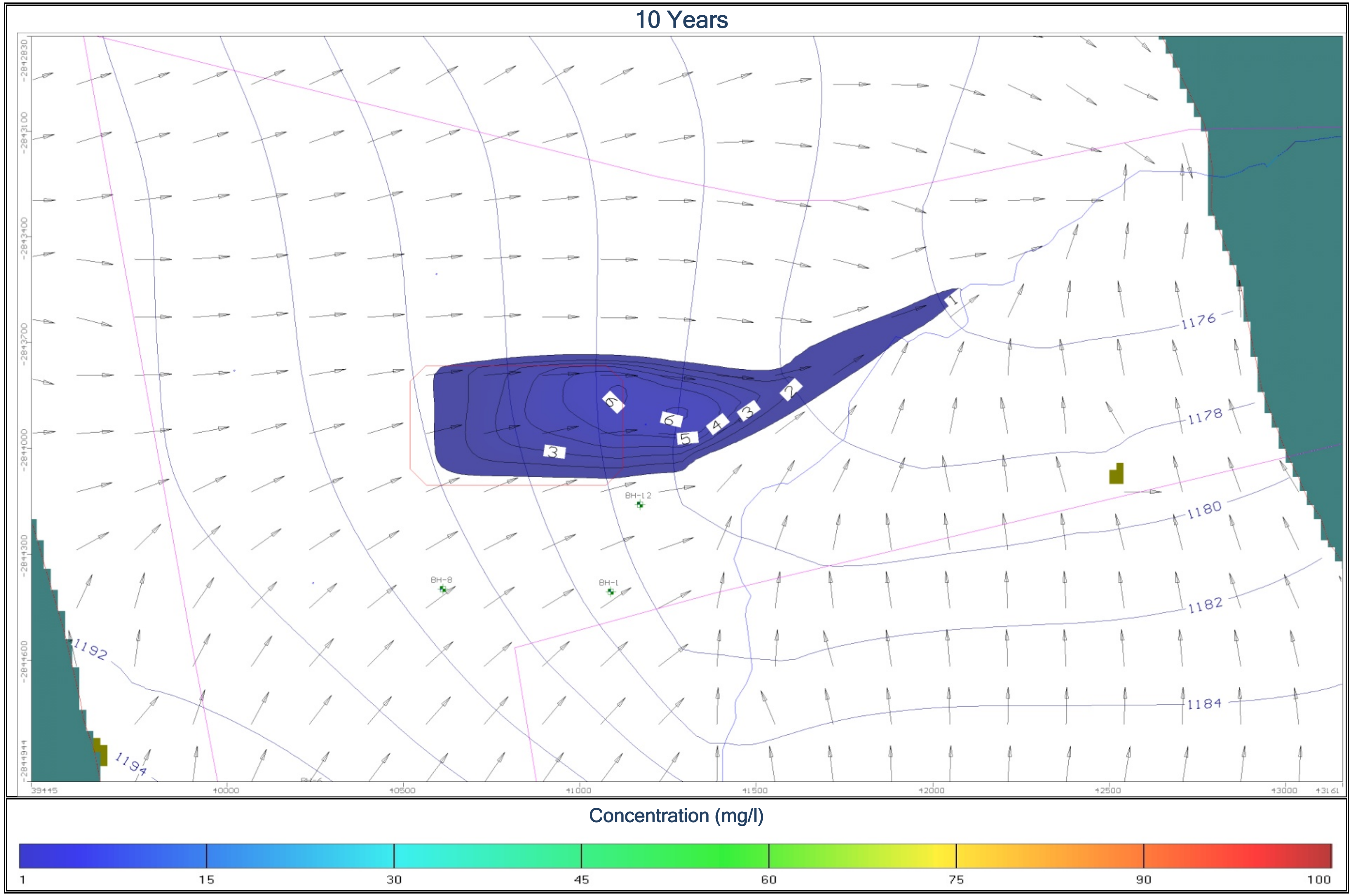


Figure 45: Simulated Ground Water Contamination Plume for Model IV after 10 years

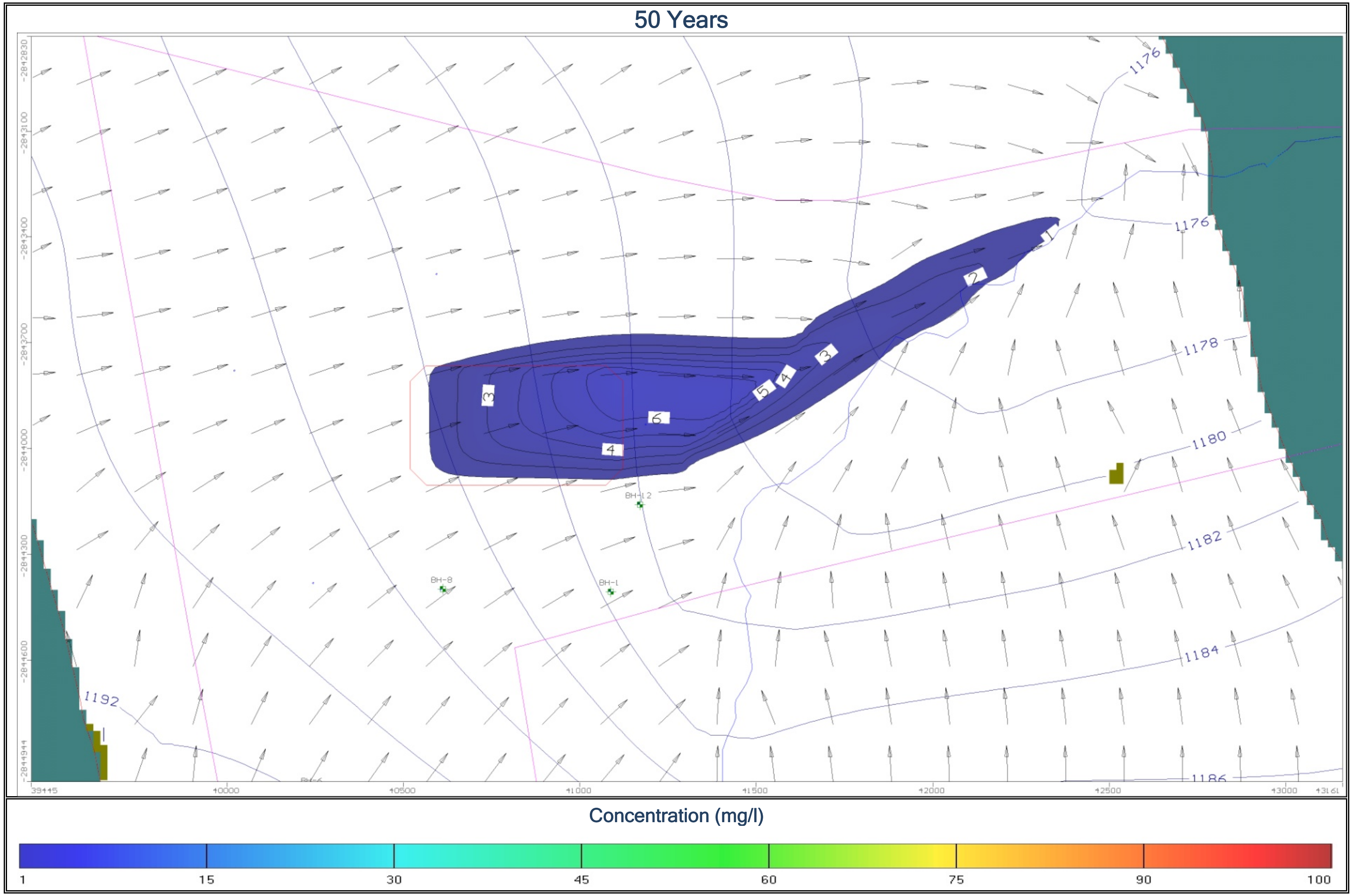


Figure 46: Simulated Ground Water Contamination Plume for Model IV after 50 years

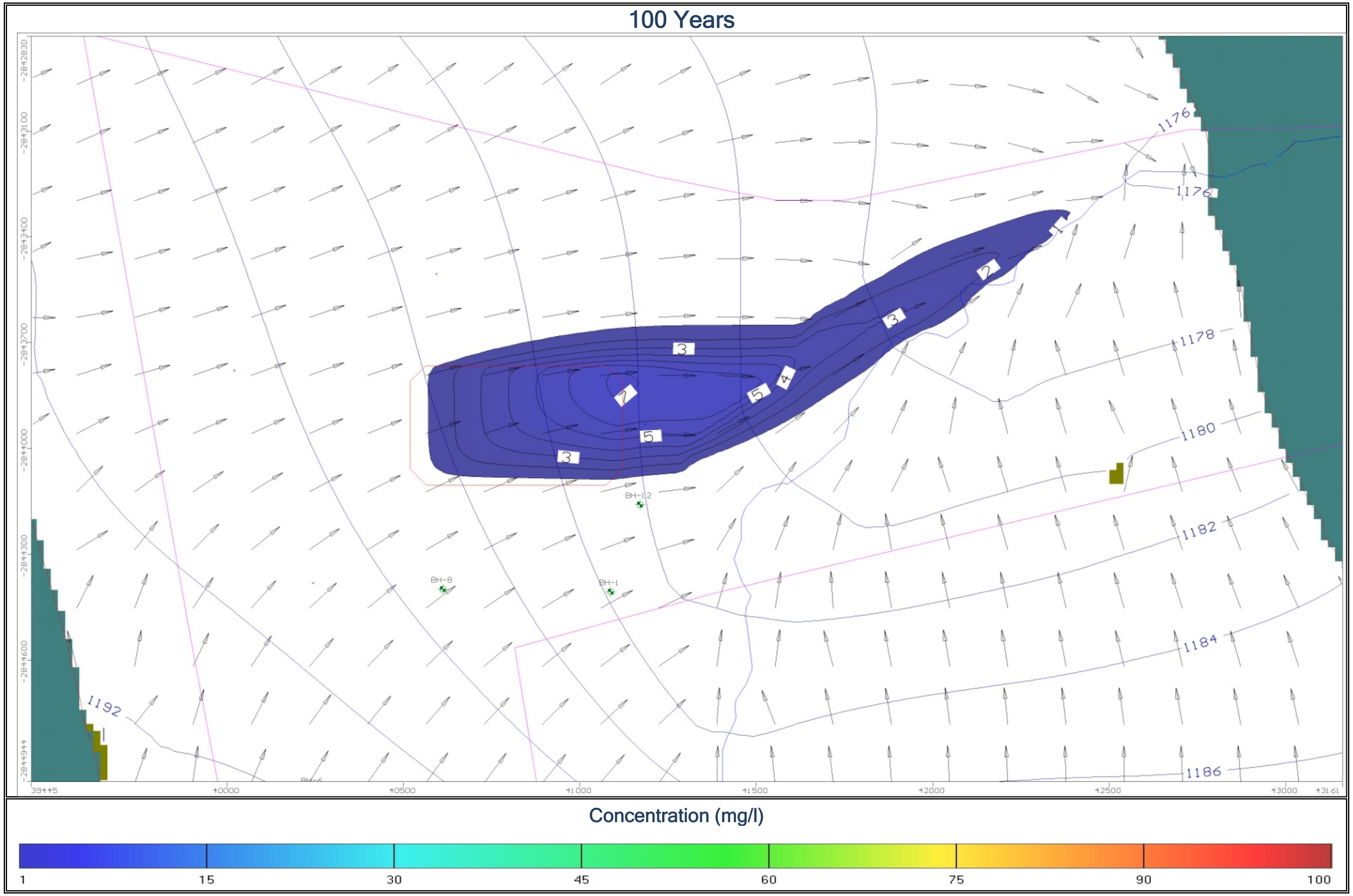


Figure 47: Simulated Ground Water Contamination Plume for Model IV after 100 years

6 CONCLUSIONS

Slag is an inorganic metallurgical waste that is generated at ferrochrome producing plants in South Africa and is disposed of by means of landfill as a dry aggregate material with an average grain size of 20 mm. Any leachate that infiltrates through the base of the slag dump originates primarily as a result of infiltrating precipitation that comes into contact with the slag. The quality of the leachate generated is variable and is dependent on, amongst others, the geochemistry of the slag, the residence time of infiltrating precipitation as well as the geochemistry of the infiltrating precipitation which occurs predominantly in the form of short-lived thunderstorms during the summer months.

In order to optimally design and manage the waste disposal facility to ensure that the waste does not have an adverse effect on the environment, it is vital that the geochemistry thereof be assessed. The assessment of the slags geochemistry is in fact legally required and should aim to identify and quantify any potentially hazardous substances contained within the slag that could potentially end up in the leachate and adjacent environment. The geochemistry of the slag was assessed at six stockpile areas along its process of being stockpiled, re-worked and disposed. Three samples were taken adjacent to breaking floors at each of three furnace pairs, two samples at un-reworked and fine slag stockpiles adjacent to a metal recovery plant and one sample was collected from a slag dump.

The major compounds present in the slag components analysed are spinel, enstatite and chromite. Spinel has the highest weight percentage in all the samples analysed, excluding one of the un-reworked and fine slag samples collected, which has a slightly higher chromite content, followed by enstatite and chromite. Spinel is a magnesium aluminium oxide ($MgAl_2O_4$), enstatite is a magnesium baring pyroxene ($MgSiO_3$) and chromite is a ferrous chromic oxide ($FeCr_2O_4$), all of which are commonly associated with basic igneous rocks as well.

The un-reworked and fine slag component of the slag has a slightly different signature to the slag sampled from adjacent to the furnaces and from the slag stockpile. The un-reworked slag and fines had large percentages of quartz (26.21% and 12.73%) and cristobalite (14.15% and 9.79%) present whilst the other samples had no quartz or cristobalite present.

The geochemistry of the slag samples was further assessed with regards to the Average Upper Crust (AUC) concentrations obtained from Rudnick and Gao (2003). The average upper crust values provide a baseline for assessing geochemical anomalies. The assessment of the slags geochemistry with regards to that of the AUC concentrations is therefore used to determine whether specific elements within the slag are elevated or depleted with regards to the average upper crust lithologies. This assessment provides a first order indication of whether the slag has the potential of producing a leachate that could potentially contaminate the underlying ground water system.

It was identified during the geochemical analyses of the slag that all the slag components have a potential of generating a leachate that poses a risk on contaminating the environment. The results indicate that the slag samples are predominantly elevated in Al_2O_3, MnO, MgO and TiO_2 with regards to the AUC values. The trace elements Sc, V, Cr, Co, Ni, Zn, As, Sb, Ta, Bi and Th are all elevated with regards to the AUC concentrations in each of the slag components analysed as well. The element that is the most significantly elevated is Cr which has concentrations in the slag of up to more than 450 times than that stipulated for Cr in AUC concentrations.

In order to validate this assessment of the slag, an additional assessment is made with regards to the elemental concentrations of the in-situ soils and weathered norite, which constitutes the majority of the host rock within the study area. The soil sample analysed is a vertic soil sample taken from adjacent to the existing slag dump and is representative of the majority of the soil within the study area.

The geochemistry assessment of the slag with regards to the vertic soil and weathered norite, indicate that although the vertic soils and weathered norite are elevated in certain elements with regards to the AUC values, certain elements are still significantly elevated in the slag. These elements therefore pose an apparent greater risk on contaminating the underlying ground water zones than the soils and weathered norite.

This indicates that a barrier is required to be installed that separates the slag from the underlying soils. The barrier associated with landfill disposal facilities consists of a low permeability “liner system”, the nature of which is dependent on the apparent risk that the slag poses on contaminating the environment as well as the potential of the slag material to generate a significant leachate.

The geochemistry of the slag is thus further investigated and assessed with regards to the concentrations stipulated in the SABS Code 0228 in order to determine the apparent risk associated with the slag. This second order geochemistry assessment of the slag is therefore done in accordance with the Hazardous Waste Classification Tables (derived from the SABS Code 0228) listed in the DWAF's Minimum Requirements for the Handling Classification and Disposal of Hazardous Waste.

During this classification the slag is assigned a Hazard Rating based on the concentrations of potentially hazardous substances in the slag with regards to the SABS Code 0228. The slag is assigned a Hazard Rating of 2 during this classification, which indicates that the most stringent requirements are required be adhered to during its disposal. Based on this classification of the slag, the Minimum Requirement Documents state that the slag is required to be disposed of at a landfill that is installed with an H:H liner system.

The assessment of the slag indicates the risk that the slag poses on contaminating the environment if consumed in its entirety and does however not provide an indication on the expected quality of the leachate generated from the slag. The quality of the leachate is determined during leaching tests conducted on the slag material. The leaching tests are also used in order to determine whether it is suitable to delist the classification of the waste to a lower hazard rating and allow the waste to be disposed of at less stringent landfill options.

The slag is singularly disposed of as a dry aggregate material and is therefore analysed using the Acid Rain Leaching Procedure. The Acid Rain Leaching Procedure represents the worst case scenario and indicates the expected leachate quality that generated under acidic conditions. The results obtained from the Acid Rain Leaching Procedure tests indicate that the several elements in the leachate occur at concentrations that are expected to have an adverse effect on the environment.

The elements that were the most abundantly elevated in the leachate are namely Fe, Mn, Cr(T) and Zn. The total chrome (Cr(T)) measured in the leachate consists entirely of Cr(III) and no Cr(IV) was detected in the leachate generated from any of the slag samples. Cr(III) is less deleterious than Cr(IV) and does not pose as significant a risk as Cr(IV) does on contaminating the environment.

The Estimated Environmental Concentration (EEC) of each of the elements Fe, Mn, Cr(T) and Zn were then determined according to the stipulated fixed scenario approach and are used to determine the Hazard Rating of the waste. The EEC calculated for Mn and Fe are elevated with regards to the AEC for each of the two elements respectively and the slag is assigned a Hazard Rating of 2.

This specifies that the slag remains in the same Hazard Rating and poses a “high risk” on contaminating the underlying ground water system. The slag is thus not permitted to be disposed of directly on top of the in-situ soil and is required to be disposed of at a landfill disposal facility that has a low permeability liner installed. The Minimum Requirement Documents stipulate that the slag (HR2) is required to be disposed of at a landfill is installed with an H:H Liner system, regardless of the water balance of the site.

The volume of leachate generated at the base of the slag disposal was assessed using the HELP modelling software and indicates that an H:H liner system is capable of capturing 100% of the leachate. If no liner is implemented below the slag dump, 1.04 mm/annum of leachate is removed via surface runoff and 438.82 mm/annum is lost to evapotranspiration. The remaining 189.85 mm/annum percolates out the bottom of the slag material and has the potential of entering the underlying ground water system, which accumulates to 94,925 m^3/annum across the 50 ha slag dump footprint.

Of the 189.85 mm/annum of leachate that infiltrates out of the bottom of the slag material and into the underlying soils, 152.43 mm/annum (24.21% MAP) infiltrates through the soil and into the saturated ground water zone. This is a significant increase in the flux below the slag dump as opposed to the natural ground water recharge of 35.41 mm/annum. This indicates that the slag material retains the precipitation falling onto it and builds up a slight head on the surface, which is responsible for the increased infiltration flux into the underlying saturated ground water zone

In order to determine the optimal liner design, the EEC of the entire slag disposal facility is re-assessed to determine the volume of leachate that is required to be captured and removed in order to keep the EEC below 10% of the AEC. 10% of the AEC is the concentration at which the variable of concern is expected to have no adverse impact if it enters the underlying ground water system.

The simulated results indicate that the EEC calculated for Mn (the most elevated variable) in the 189.85 mm/annum of leachate generated from the slag is 1.17 ppm and is significantly elevated with regards to the stipulated AEC concentration for Mn (0.3 ppm). In order to ensure that the EEC of Mn in the leachate of the slag disposal facility as a whole is kept below 0.03 ppm it is calculated that only 4.75 mm/annum of leachate is permitted to pass through the liner system. This calculates to a total volume of 2,375 m^3/annum and indicates the volume of leachate is expected to have no adverse effect on the environment if it passes through the liner system.

The most optimized liner design for the slag disposal facility investigated is thus required to capture 185.10 mm of leachate per annum, at an optimal cost. Because the slag is classified as a hazardous waste all the liner systems investigated have been designed with leachate removal drains from an environmental protection perspective.

The volume of leachate intercepted and drained by each of the individual layers within the respective liner designs were assessed during water balance calculations in order to determine the effectiveness thereof. The simulated results indicate that the thickness and permeability of the clay layers are the most important parameters, followed by the distance to the drains and slope of the liner system. Although the distances to the drains play a significant role in removing the leachate, this is only evident if a significant build-up of head occurs. Due to the limited build of head within the liner below the slag dump the distance to the drains will not affect the volume of leachate removed by the liner system. The drains were however implemented at a distance of 100 m apart, which makes provision for extreme rainfall events.

The optimized liner design for the slag disposal facility investigated has a total thickness of 900 mm, excluding the unsaturated zone. This optimized liner represents the Best Practicable Environmental Option for the slag disposal facility investigated and is capable of capturing the required 185.10 mm/annum of leachate at the base of the simulated slag dump.

A schematic diagram of the layers incorporated in the optimized liner design for the slag disposal facility investigated during this research study is depicted in Figure 48.

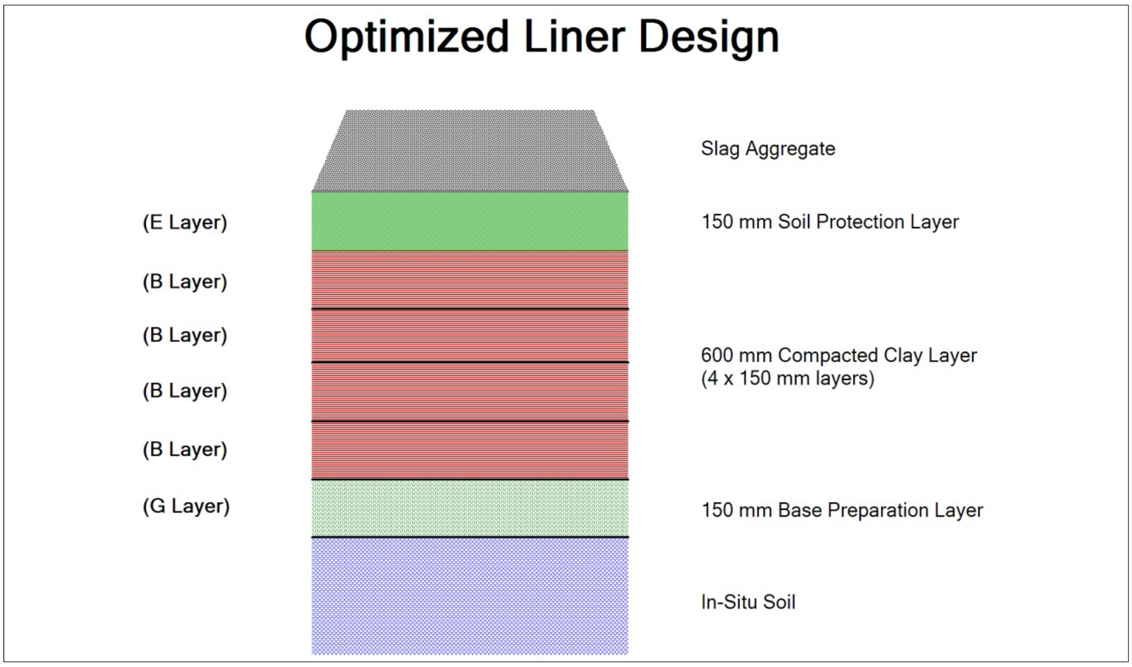


Figure 48: Optimized Liner Design

The optimized liner system has been designed on top of the 5 m thick in-situ soil zone and consists initially of a 150 mm thick base preparation layer that consists of reworked vertic soil that is obtained from within the study area. The primary purpose of this layer is to ensure that the gradient of liner can be manipulated to create a constant slope of 0.02. A slope of 0.02 has been used in the model to ensure that no ponding of leachate occurs below the slag dump. The soil is also used to create a flat and uniform base layer on which the overlying low permeability clay layers can be installed.

The soil is also used to create a flat and uniform base layer on which the overlying low permeability clay layers can be installed. By increasing the slope to 0.02 as opposed to 0.013 is expected to increase the degree of care taken during the installation of liner design.

The soil is assigned a total porosity of 0.417, field capacity of 0.045, wilting point of 0.018 and a saturated hydraulic conductivity of 0.01 cm/s all of which are representative of the soil within the study area. Drains will be inserted in the base preparation layer to capture the leachate that could potentially infiltrate through the low permeability clay layers installed on top of the base preparation.

The clay layers consist of four 150 mm thick compacted clay layers installed on top of one another. Not only do the clay layers form a comprehensively thick low permeability layer, but also minimize the effects of the clay potentially pinching out during construction and installation thereof. The clay is assigned a total porosity of 0.451, field capacity of 0.419, wilting point of 0.332 and an average saturated hydraulic conductivity of 1 x 10^{-7} cm/s. Once the low permeability clay layers have been installed they are covered with a soil protection layer.

The 150 mm thick soil protection layer forms the uppermost layer of the model and serves to protect the underlying clay layers from being damaged during the disposal of the slag aggregate material. The soil used in the model is assigned a total porosity of 0.437, field capacity of 0.062, wilting point of 0.024 and a saturated hydraulic conductivity of 0.07 cm/s.

Once in the saturated zone the contaminants contained within the leachate will migrate laterally, predominantly as a result of the advective flow of the ground water. The migration of the contaminants within the shallow weathered zone aquifer was simulated for a period of up to 100 years after the disposal of the slag. Once in the saturated zone, the leachate and associated contaminants are initially transported towards the east until they enter the Central Tributary's drainage system, after which they are transported in a north-easterly direction away from the slag disposal facility.

If no liner is implemented below the slag dump, the contaminants within the leachate will arrive at the Central Tributary's drainage system (Receptor) within 5 years after disposal of the slag. The results indicate that the Mn concentration at the Central Tributary's drainage system is expected to be 0.67 ppm after 5 years, 2.80 ppm after 10 years, 3.86 ppm after 50 years and 4.59 ppm after 100 years. This indicates that if no liner is installed, Mn will enter the central tributary's drainage system at a concentration that exceeds the AEC concentration within 5 years of disposing the slag within the delineated disposal area.

If the optimized liner system is installed below the slag dump, the Mn concentrations will enter the ground water system at a concentration (0.08 ppm) which is more than three times lower than the stipulated AEC for Mn. This indicates that the leachate that infiltrates through the optimized liner system, enters the saturated ground water zone below the slag disposal facility at a concentration that is not expected to have an impact on the adjacent ground water system and environment.

The optimized liner design is thus sufficient in capturing the required volumes of leachate generated at the base of the slag disposal facility in order to protect the environment from any adverse effects culminating from the slag.

This liner design is thus sufficient in capturing the required volume of leachate generated at the base of the slag dump and has been optimally designed according to: 1) the site specific information regarding the geochemistry of the slag, 2) the physical properties of the slag, 3) the disposal specifications of the slag, 4) the site specific meteorological data and 5) the hydrogeological data of the study area investigated.

The liner system has thus sequentially been optimally designed using site specific information as well as available water balance and mass transport modelling techniques, according to the Best Practicable Environmental Option norm at the most optimal cost of R1,100,000/ha.

The results obtained from the research study indicate that it may well be beneficial to use the required site specific data as well as the physical and chemical properties of the waste being disposed in order to determine the optimized liner design using available water balance and ground water modelling techniques. This software is readily available to South Africans and may effectively be used to optimize the liner designs associated with the disposal of waste by landfill in South Africa. This technique has the additional benefit in that it may be used to optimize the future monitoring programmes and post closure requirements associated with the landfill disposal facility.

REFERENCES

1. **Bear, J., Beljin, M. S., and Ross, R. R. (1992).** *Fundamentals of Ground-Water Modelling*. United States Environmental Protection Agency, Groundwater Issue EPA/540/5-92/005, Washington DC, USA.

2. **Chief Directorate: Surveys and Mapping, (1996).** Published 1:50 000 Topographical Map of South Africa. Sheet 2527CB – (Rustenburg East), Fourth Edition, 1996.

3. **Chief Directorate: Surveys and Mapping, (2004).** Published 1:10 000 Orthophoto Image. Sheet 2527 CB – Photo 18, 2004.

4. **Chief Directorate: Surveys and Mapping, (2004).** Published 1:10 000 Orthophoto Image. Sheet 2527 CB – Photo 19, 2004.

5. **Chief Directorate: Surveys and Mapping, (2004).** Published 1:10 000 Orthophoto Image. Sheet 2527 CB – Photo 23, 2004.

6. **Chief Directorate: Surveys and Mapping, (2004).** Published 1:10 000 Orthophoto Images. Sheet 2527 CB – Photo 24, 2004.

7. **Department of Environmental Affairs, (1998).** National Environmental Management Act 107 of 1998.

8. **Department of Environmental Affairs, (2008).** National Environmental Management Waste Act 59 of 2008.

9. **Department of Environmental Affairs, (2010).** Draft Standard for Assessment of Waste for Landfill Disposal.

10. **Department of Environmental Affairs and Tourism, (1992).** The Integrated Environmental Management Procedure, Pretoria, 1992.

11. **Department of Environmental Affairs and Tourism; University of Pretoria and GIS Business Solutions, (2000).** Environmental Potential Atlas for the North West Province – 3D Image Map.

12. **Department of Minerals and Energy Affairs, (1981).** Published 1:250 000 Geological Map Series of South Africa. Sheet 2526 – Rustenburg, 1981.

13. **Department of Water Affairs, (1998).** National Water Act 36 of 1998.

14. **Department of Water Affairs & Forestry, Second Edition, (1998)**. *Waste Management Series. Minimum Requirements for the Handling, Classification and Disposal of Hazardous Waste*. (Document 1).

15. **Department of Water Affairs & Forestry, Second Edition, (1998)**. *Waste Management Series. Minimum Requirements for Waste Disposal by Landfill.* (Document 2).

16. **Department of Water Affairs & Forestry, Second Edition, (1998)**. *Waste Management Series. Minimum Requirements for Monitoring at Waste Management Facilities.* (Document 3).

17. **Department of Water Affairs and Forestry, (1999)**. Published 1:500 000 Hydrogeological Map Series of the Republic of South Africa. Sheet 2526 – Johannesburg, 1999.

18. **Fourie. P.J. (2009).** Quantification of Seepage from and Classification of Waste Material. Report No. V0010709.

19. **Glazewski, J. (2000).** *Environmental Law in South Africa*. Butterworths. Durban. ISBN 0 409 02936 X.

20. **Rudnick. R.L., and Gao. S. (2003)**. The Composition of the Continental Crust. In: *The Crust*, edited by R.L. Rudnick, Treatise on Geochemistry (eds. H.D. Holland and K.K. Turekian). Elsevier-Pergamon, Oxford. 3, 1-64.

21. **South African National Standard 241, (2006)**. Edition 6.1. Drinking Water

22. **Statutes of the Republic of South Africa – Constitutional Law (1996)**. Constitution of the Republic of South Africa No. 108 of 1996.

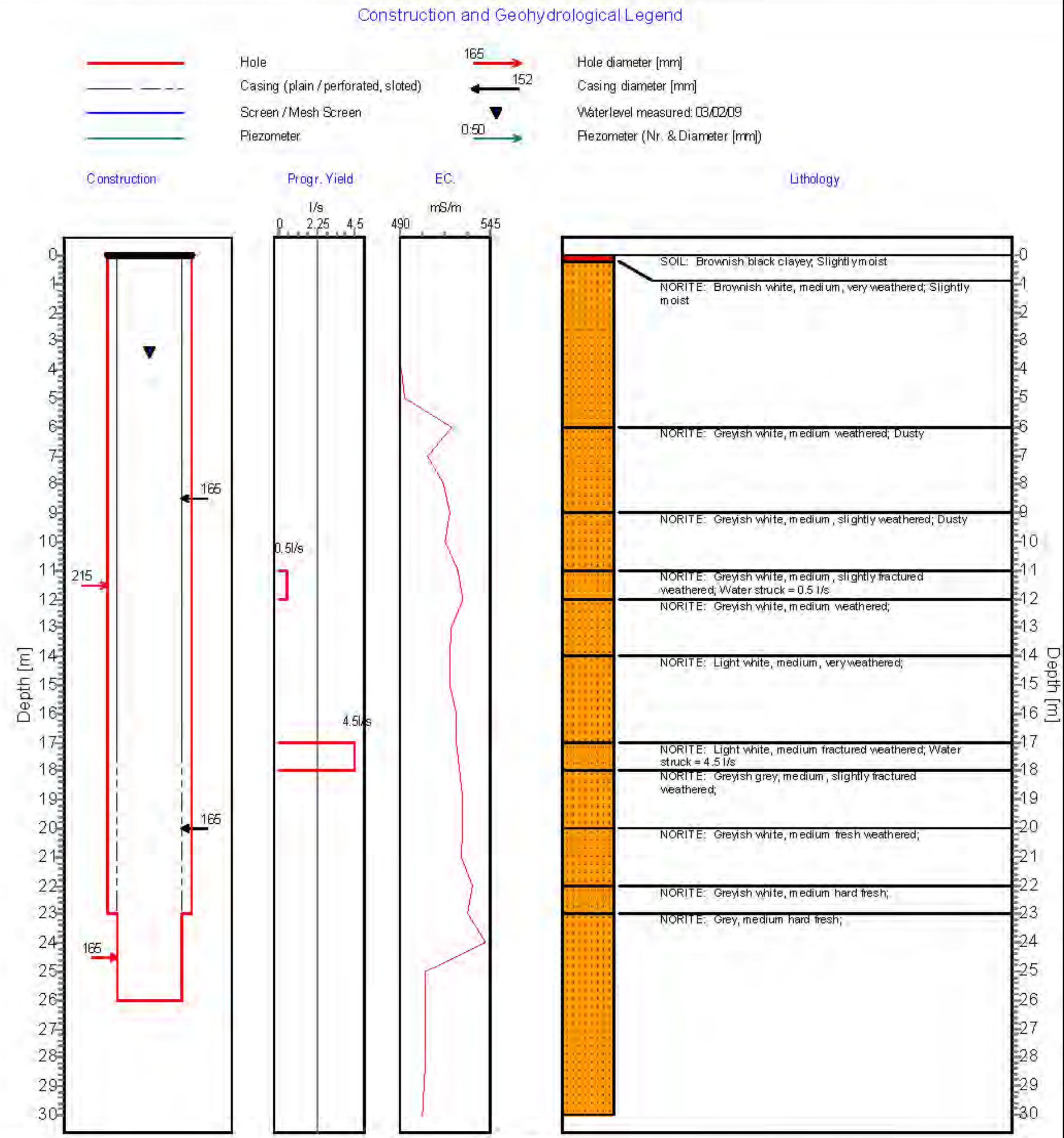
23. **Vegter. J.R. (1995).** An Explanation of a Set of National Groundwater Maps. Water Research Commission. Department of Water Affairs and Forestry. TT 74/95.

APPENDIX I

BOREHOLE LOGS AND SITE INFORMATION REPORTS

Y Coord. [m]: -41085.75	**BH-1**	**Topo-set.:** Flat surface, plain	**Depth [m]:** 26.00
X Coord. [m]: 2844403.88		**Site status:** In use	**Col. ht. [m]:** 0
Altitude [m]: 1182.65		**Site purp.:** Observation	**Diam. [mm]:** 165
Coord. acc.: Accurate to within 1 unit		**Use applic.:** Industrial - mining	**Drain. reg.:**
Coord. meth.: Levelled or surveyed		**Equipment:** No equipment	**Rep. inst.:**

Coordinate System: South African LO Transverse Mercator, Hartebeesthoek94 (WGS 84)



Y Coord. [m]: -41087.00	**BH-1**	***Topo-set.:*** Flat surface, plain		***Depth [m]:*** 26.00	
X Coord. [m]: 2844409.00		***Site status:*** In use		***Col. ht. [m]:*** 0	
Altitude [m]: 1183.00		***Site purp.:*** Observation		***Diam. [mm]:*** 165	
Coord. acc.: Accurate to within 10 units		***Use applic.:*** Industrial - mining		***Drain. reg.:***	
Coord. meth.: Global Positioning System		***Equipment:*** No equipment		***Rep. inst.:***	

Coordinate System: South African LO Transverse Mercator, Hartebeesthoek94 (WGS 84)

CONSTRUCTION:

Date const.	*Contractor*	*Constr. meth.*	*Type finish*	*Development Method*	*Durat.*	*Special treatment*	*Constr. cost*
20081028		Air percussion	Open bottom	Compressed air			

HOLE DIAMETER:

Rep. Inst.	*Depth to Top [m]*	*Depth to Bottom [m]*	*Diameter [mm]*	*Date const.*	*Comment*
	0.00	23.00	215	20081028	
	23.00	26.00	165	20081028	

CASING DETAILS:

Date inst.	*Dep. to top [m]*	*Bot. [m]*	*Diam. [mm]*	*Material*	*Thickn. [mm]*	*Opening Type*	*Length*	*Width*	*Hori. dist.*	*Vert. dist.*
20081028	0.00	17.00	165	Steel	3					
20081028	17.00	23.00	165	Steel	3	Perforated or slotted	300	3	100	50

AQUIFER:

Rep. Inst.	*Depth to Top [m]*	*Bot. [m]*	*Yield [l/s]*	*Method meas.*	*Aquifer type*	*Info source*	*Comment*
	11.00	12.00	0.50	Estimated			
	17.00	18.00	4.50	Estimated			

GEOLOGY:

Dep. Top [m]	*Bot. [m]*	*Lithology code*	*Colour Primary*	*Secondary*	*Texture*	*Feature Primary*	*Secondary*
0.00	0.20	SOIL	Black	Brownish		Clayey	
0.20	6.00	NORITE	White	Brownish	Medium	Weathered	
6.00	9.00	NORITE	White	Greyish	Medium	Weathered	
9.00	11.00	NORITE	White	Greyish	Medium	Weathered	
11.00	12.00	NORITE	White	Greyish	Medium	Weathered	Fractured
12.00	14.00	NORITE	White	Greyish	Medium	Weathered	
14.00	17.00	NORITE	White	Light	Medium	Weathered	
17.00	18.00	NORITE	White	Light	Medium	Weathered	Fractured
18.00	20.00	NORITE	Grey	Greyish	Medium	Weathered	Fractured
20.00	22.00	NORITE	White	Greyish	Medium	Weathered	Fresh
22.00	23.00	NORITE	White	Greyish	Medium	Fresh	Hard
23.00	30.00	NORITE	Grey		Medium	Fresh	Hard

WATER LEVEL:

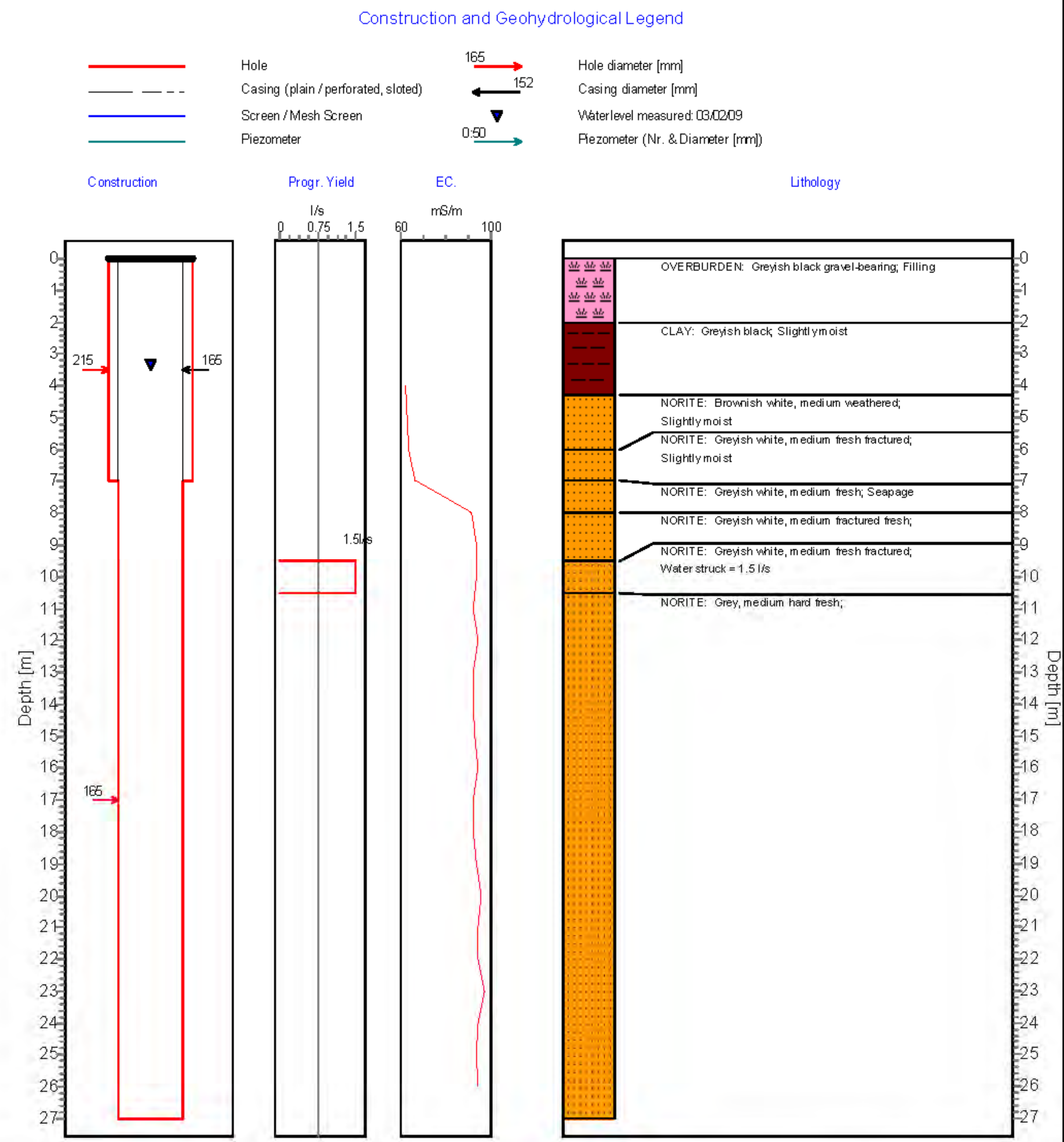
Meth. meas.	*Level status*	*Piez.*	*Info source*	*Date meas.*	*Time meas.*	*Sec.*	*Water lev. [m]*	*Comment*
Electrical contact	Static	0	Field checked	20090203	1200	0.00	3.39	
Electrical contact	Static	0	Field checked	20090209	1309	0.00	3.60	

TESTING DETAILS:

Description	*Date started*	*Durat. [s]*	*Depth to intk. [m]*	*Disch. rate[l/s]*	*Drawd. [m]*	*Recovery: [m]*	*%*	*[min]*	*Trans. [m²/d]*	*Perm. [m/d]*	*Storat.*	*Comment*

Y Coord. [m]:	-40615.32	**BH-2**	***Topo-set.:***	Flat surface, plain	***Depth [m]:***	27.00
X Coord. [m]:	2845267.62		***Site status:***	In use	***Col. ht. [m]:***	0
Altitude [m]:	1194.83		***Site purp.:***	Observation	***Diam. [mm]:***	165
Coord. acc.:	Accurate to within 1 unit		***Use applic.:***	Industrial - mining	***Drain. reg.:***	
Coord. meth.:	Levelled or surveyed		***Equipment:***	No equipment	***Rep. inst.:***	

Coordinate System: South African LO Transverse Mercator, Hartebeesthoek94 (WGS 84)



Y Coord. [m]:	-40607.00	**BH-2**	*Topo-set.:*	Flat surface, plain	*Depth [m]:*	27.00
X Coord. [m]:	2845268.00		*Site status:*	In use	*Col. ht. [m]:*	0
Altitude [m]:	1192.00		*Site purp.:*	Observation	*Diam. [mm]:*	165
Coord. acc.:	Accurate to within 10 units		*Use applic.:*	Industrial - mining	*Drain. reg.:*	
Coord. meth.:	Global Positioning System		*Equipment:*	No equipment	*Rep. inst.:*	

Coordinate System: South African LO Transverse Mercator, Hartebeesthoek94 (WGS 84)

CONSTRUCTION:

Date const.	Contractor	Constr. meth.	Type finish	Development Method	Durat.	Special treatment	Constr. cost
20081028		Air percussion	Open bottom	Compressed air			

HOLE DIAMETER:

Rep. Inst.	Depth to Top [m]	Depth to Bottom [m]	Diameter [mm]	Date const.	Comment
	0.00	7.00	215	20081028	
	7.00	27.00	165	20081028	

CASING DETAILS:

Date inst.	Dep. to top [m]	Bot. [m]	Diam. [mm]	Material	Thickn. [mm]	Opening Type	Length	Width	Hori. dist.	Vert. dist.
20081028	0.00	7.00	165	Steel	3					

AQUIFER:

Rep. Inst.	Depth to Top [m]	Bot. [m]	Yield [l/s]	Method meas.	Aquifer type	Info source	Comment
	9.50	10.50	1.50	Estimated			

GEOLOGY:

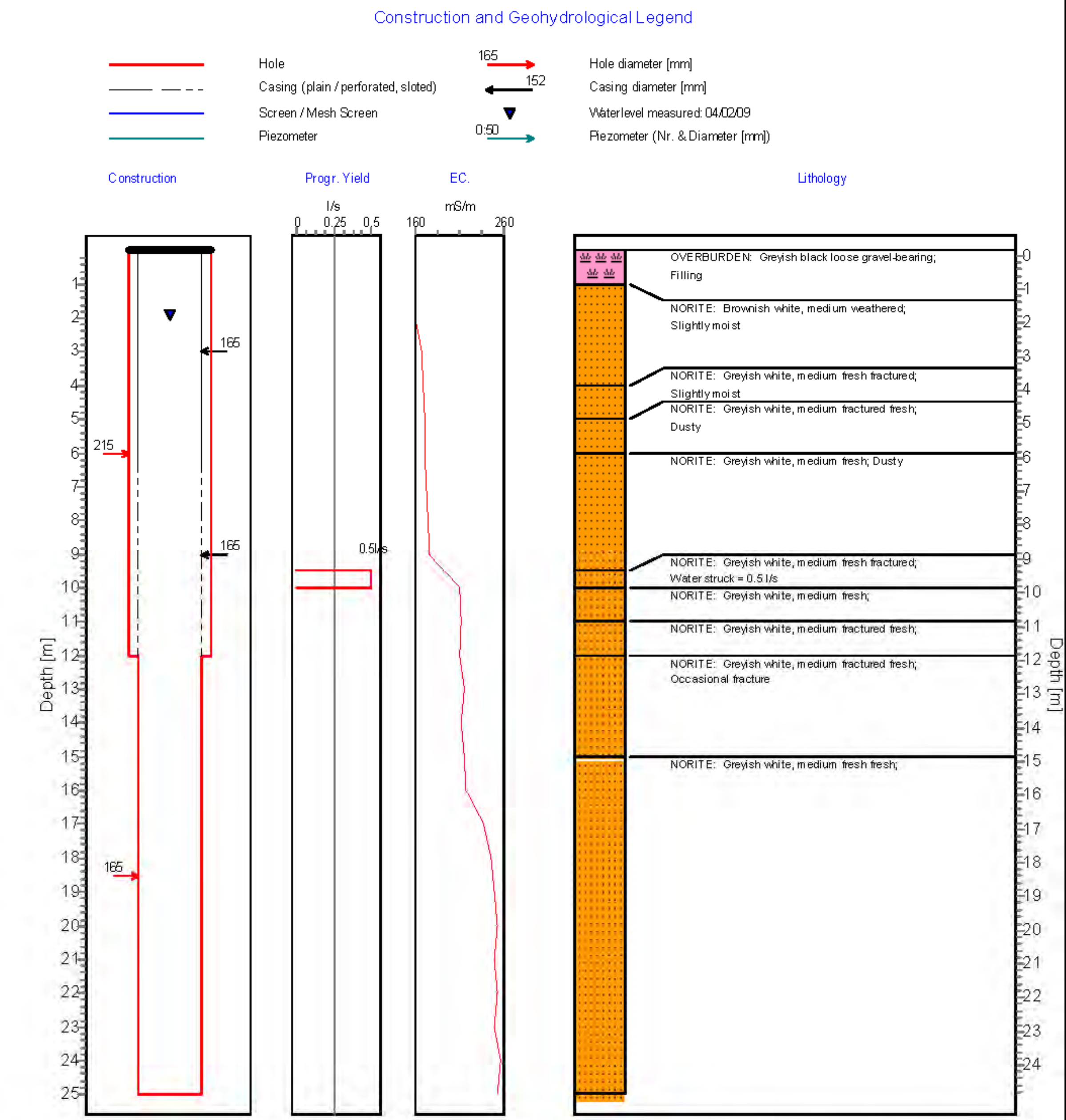
Dep. Top [m]	Bot. [m]	Lithology code	Colour Primary	Secondary	Texture	Feature Primary	Secondary
0.00	2.00	OVERBURDEN	Black	Greyish		Gravel-bearing	
2.00	4.30	CLAY	Black	Greyish			
4.30	6.00	NORITE	White	Brownish	Medium	Weathered	
6.00	7.00	NORITE	White	Greyish	Medium	Fractured	Fresh
7.00	8.00	NORITE	White	Greyish	Medium	Fresh	
8.00	9.50	NORITE	White	Greyish	Medium	Fresh	Fractured
9.50	10.50	NORITE	White	Greyish	Medium	Fractured	Fresh
10.50	27.00	NORITE	Grey		Medium	Fresh	Hard

WATER LEVEL:

Meth. meas.	Level status	Piez.	Info source	Date meas.	Time meas.	Sec.	Water lev. [m]	Comment
Electrical contact	Static	0	Field checked	20090203	1245	0.00	3.33	
Electrical contact	Static	0	Field checked	20090209	1420	0.00	3.40	

Y Coord. [m]:	-40384.88	**BH-3**		*Topo-set.:*	Flat surface, plain	*Depth [m]:*	25.00
X Coord. [m]:	2845828.07			*Site status:*	In use	*Col. ht. [m]:*	0
Altitude [m]:	1206.35			*Site purp.:*	Observation	*Diam. [mm]:*	165
Coord. acc.:	Accurate to within 1 unit			*Use applic.:*	Industrial - mining	*Drain. reg.:*	
Coord. meth.:	Levelled or surveyed			*Equipment:*	No equipment	*Rep. inst.:*	

Coordinate System: South African LO Transverse Mercator, Hartebeesthoek94 (WGS 84)



Design Optimization of Hazardous Waste Disposal Facilities through the Application of Water Balance and Mass Transport Modelling

Y Coord. [m]:	-40378.00	**BH-3**	***Topo-set.:***	Flat surface, plain	***Depth [m]:***	25.00
X Coord. [m]:	2845834.00		***Site status:***	In use	***Col. ht. [m]:***	0
Altitude [m]:	1210.00		***Site purp.:***	Observation	***Diam. [mm]:***	165
Coord. acc.:	Accurate to within 10 units		***Use applic.:***	Industrial - mining	***Drain. reg.:***	
Coord. meth.:	Global Positioning System		***Equipment:***	No equipment	***Rep. inst.:***	

Coordinate System: South African LO Transverse Mercator, Hartebeesthoek94 (WGS 84)

CONSTRUCTION:

Date const.	Contractor	Constr. meth.	Type finish	Development Method	Durat.	Special treatment	Constr. cost
20081105		Air percussion	Open bottom	Compressed air			

HOLE DIAMETER:

Rep. Inst.	Depth to Top [m]	Depth to Bottom [m]	Diameter [mm]	Date const.	Comment
	0.00	12.00	215	20081105	
	12.00	25.00	165	20081105	

CASING DETAILS:

Date inst.	Dep. to top [m]	Bot. [m]	Diam. [mm]	Material	Thickn. [mm]	Opening Type	Length	Width	Hori. dist.	Vert. dist.
20081105	0.00	6.00	165	Steel	3					
20081105	6.00	12.00	165	Steel	3	Perforated or slotted	300	3	50	100

AQUIFER:

Rep. Inst.	Depth to Top [m]	Bot. [m]	Yield [l/s]	Method meas.	Aquifer type	Info source	Comment
	9.50	10.00	0.50	Estimated			

GEOLOGY:

Dep. Top [m]	Bot. [m]	Lithology code	Colour Primary	Secondary	Texture	Feature Primary	Secondary
0.00	1.00	OVERBURDEN	Black	Greyish		Gravel-bearing	Loose
1.00	4.00	NORITE	White	Brownish	Medium	Weathered	
4.00	5.00	NORITE	White	Greyish	Medium	Fractured	Fresh
5.00	6.00	NORITE	White	Greyish	Medium	Fresh	Fractured
6.00	9.50	NORITE	White	Greyish	Medium	Fresh	
9.50	10.00	NORITE	White	Greyish	Medium	Fractured	Fresh
10.00	11.00	NORITE	White	Greyish	Medium	Fresh	
11.00	12.00	NORITE	White	Greyish	Medium	Fresh	Fractured
12.00	15.00	NORITE	White	Greyish	Medium	Fresh	Fractured
15.00	25.00	NORITE	White	Greyish	Medium	Fresh	Fresh

WATER LEVEL:

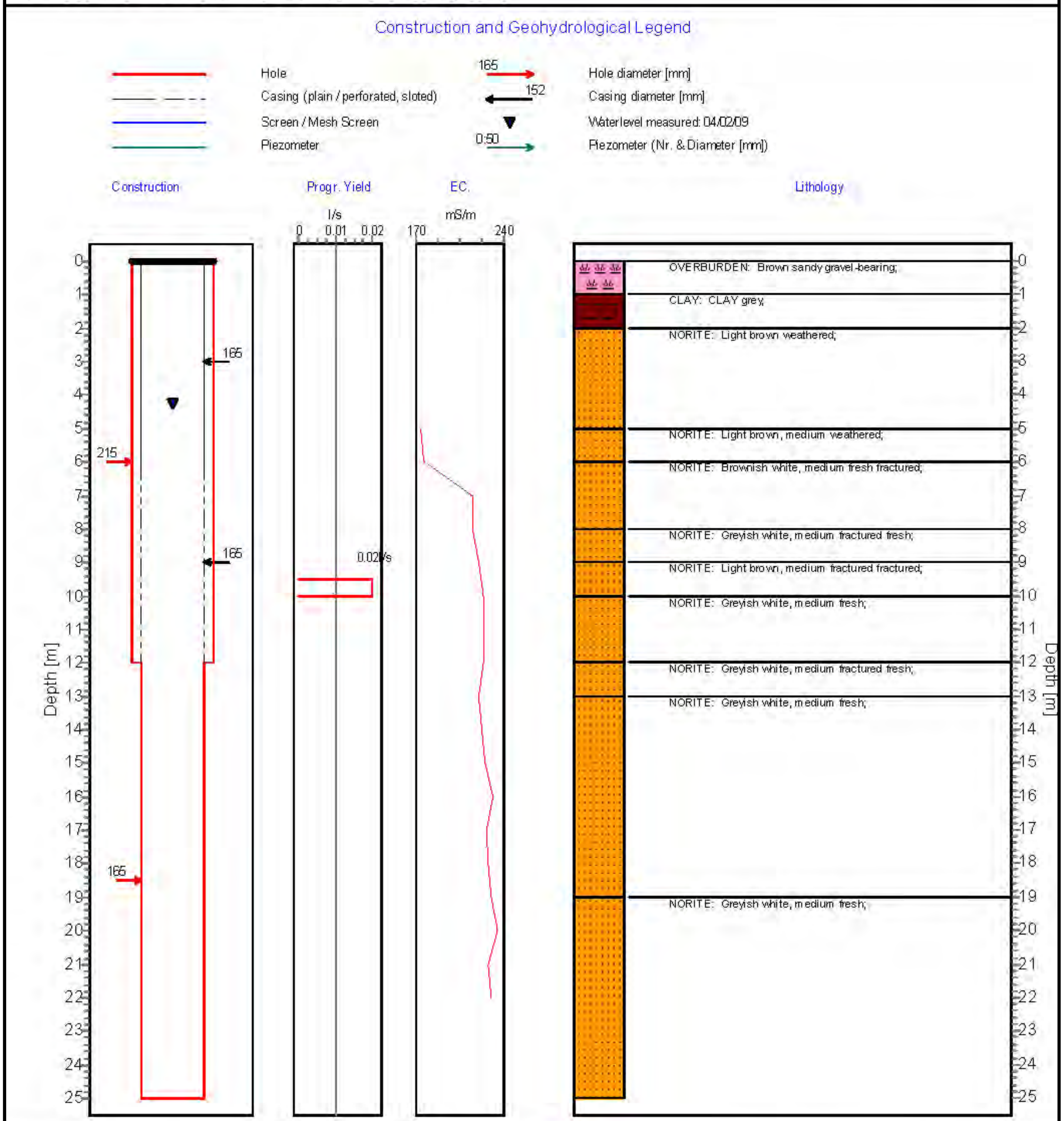
Meth. meas.	Level status	Piez.	Info source	Date meas.	Time meas.	Sec.	Water lev. [m]	Comment
Electrical contact	Static	0	Field checked	20090204	0745	0.00	1.92	
Electrical contact	Static	0	Field checked	20090210	1035	0.00	1.00	

TESTING DETAILS:

Description	Date started	Durat. [s]	Depth to intk. [m]	Disch. rate[l/s]	Drawd. [m]	Recovery: [m]	%	[min]	Trans. [m²/d]	Perm. [m/d]	Storat.	Comment

Y Coord. [m]:	-40124.67	**BH-4**	***Topo-set.:***	Flat surface, plain	***Depth [m]:***	25.00
X Coord. [m]:	2845824.09		***Site status:***	In use	***Col. ht. [m]:***	0
Altitude [m]:	1210.00		***Site purp.:***	Observation	***Diam. [mm]:***	165
Coord. acc.:	Accurate to within 1 unit		***Use applic.:***	Industrial - mining	***Drain. reg.:***	
Coord. meth.:	Levelled or surveyed		***Equipment:***	No equipment	***Rep. inst.:***	

Coordinate System: South African LO Transverse Mercator, Hartebeesthoek94 (WGS 84)



Y Coord. [m]: -40126.00	**BH-4**	*Topo-set.:* Flat surface, plain	*Depth [m]:* 25.00
X Coord. [m]: 2845823.00		*Site status:* In use	*Col. ht. [m]:* 0
Altitude [m]: 1208.00		*Site purp.:* Observation	*Diam. [mm]:* 165
Coord. acc.: Accurate to within 10 units		*Use applic.:* Industrial - mining	*Drain. reg.:*
Coord. meth.: Global Positioning System		*Equipment:* No equipment	*Rep. inst.:*

Coordinate System: South African LO Transverse Mercator, Hartebeesthoek94 (WGS 84)

CONSTRUCTION:

Date const.	Contractor	Constr. meth.	Type finish	Development Method	Durat.	Special treatment	Constr. cost
20081104		Air percussion	Open bottom	Compressed air			

HOLE DIAMETER:

Rep. Inst.	Depth to Top [m]	Depth to Bottom [m]	Diameter [mm]	Date const.	Comment
	0.00	12.00	215	20081104	
	12.00	25.00	165	20081104	

CASING DETAILS:

Date inst.	Dep. to top [m]	Bot. [m]	Diam. [mm]	Material	Thickn. [mm]	Opening Type	Length	Width	Hori. dist.	Vert. dist.
20081104	0.00	6.00	165	Steel	3					
20081104	6.00	12.00	165	Steel	3	Perforated or slotted	300	3	50	100

AQUIFER:

Rep. Inst.	Depth to Top [m]	Bot. [m]	Yield [l/s]	Method meas.	Aquifer type	Info source	Comment
	9.50	10.00	0.02	Estimated			

GEOLOGY:

Dep. Top [m]	Bot. [m]	Lithology code	Colour Primary	Secondary	Texture	Feature Primary	Secondary
0.00	1.00	OVERBURDEN	Brown			Gravel-bearing	Sandy
1.00	2.00	CLAY	Grey	Grey			
2.00	5.00	NORITE	Brown	Light		Weathered	
5.00	6.00	NORITE	Brown	Light	Medium	Weathered	
6.00	8.00	NORITE	White	Brownish	Medium	Fractured	Fresh
8.00	9.00	NORITE	White	Greyish	Medium	Fresh	Fractured
9.00	10.00	NORITE	Brown	Light	Medium	Fractured	Fractured
10.00	12.00	NORITE	White	Greyish	Medium	Fresh	
12.00	13.00	NORITE	White	Greyish	Medium	Fresh	Fractured
13.00	19.00	NORITE	White	Greyish	Medium	Fresh	
19.00	25.00	NORITE	White	Greyish	Medium	Fresh	

WATER LEVEL:

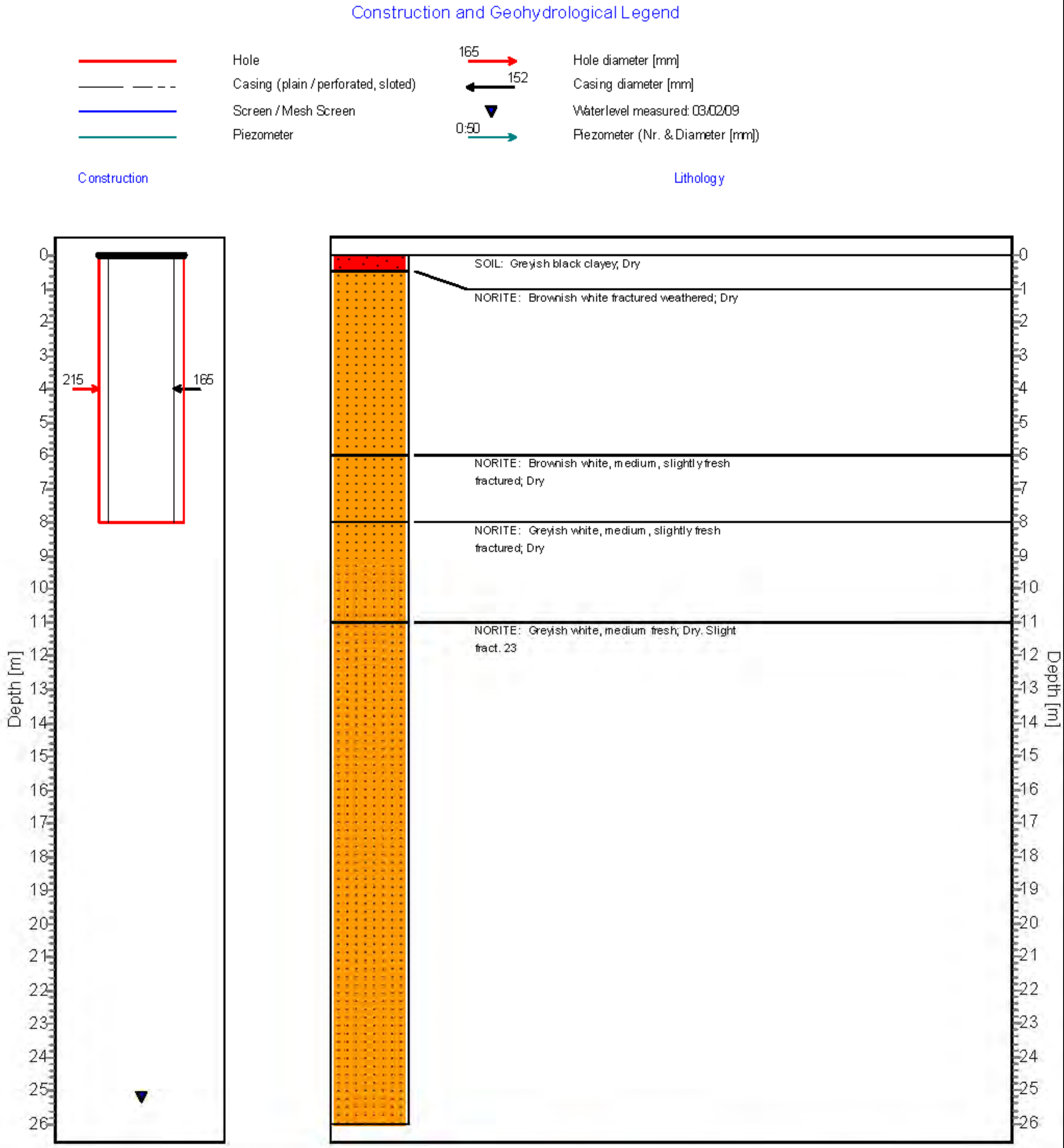
Meth. meas.	Level status	Piez.	Info source	Date meas.	Time meas.	Sec.	Water lev. [m]	Comment
Electrical contact	Static	0	Field checked	20090204	0805	0.00	4.25	
Electrical contact	Static	0	Field checked	20090210	1002	0.00	4.24	

TESTING DETAILS:

Description	Date started	Durat. [s]	Depth to intk. [m]	Disch. rate[l/s]	Drawd. [m]	Recovery: [m]	%	[min]	Trans. [m²/d]	Perm. [m/d]	Storat.	Comment

Y Coord. [m]:	-40516.45	**BH-5**	***Topo-set.:*** Flat surface, plain	***Depth [m]:***	26.00
X Coord. [m]:	2846184.85		***Site status:*** In use	***Col. ht. [m]:***	0
Altitude [m]:	1209.97		***Site purp.:*** Observation	***Diam. [mm]:***	165
Coord. acc.:	Accurate to within 1 unit		***Use applic.:*** Industrial - mining	***Drain. reg.:***	
Coord. meth.:	Levelled or surveyed		***Equipment:*** No equipment	***Rep. inst.:***	

Coordinate System: South African LO Transverse Mercator, Hartebeesthoek94 (WGS 84)



Y Coord. [m]:	-40516.00	**BH-5**	
X Coord. [m]:	2846185.00		
Altitude [m]:	1215.00		
Coord. acc.:	Accurate to within 10 units		
Coord. meth.:	Global Positioning System		

Topo-set.:	Flat surface, plain
Site status:	In use
Site purp.:	Observation
Use applic.:	Industrial - mining
Equipment:	No equipment

Depth [m]:	26.00
Col. ht. [m]:	0
Diam. [mm]:	165
Drain. reg.:	
Rep. inst.:	

Coordinate System: South African LO Transverse Mercator, Hartebeesthoek94 (WGS 84)

CONSTRUCTION:

Date const.	Contractor	Constr. meth.	Type finish	Development Method	Durat.	Special treatment	Constr. cost
20081030		Air percussion	Open bottom	Compressed air			

HOLE DIAMETER:

Rep. Inst.	Depth to Top [m]	Depth to Bottom [m]	Diameter [mm]	Date const.	Comment
	0.00	8.00	215	20081030	

CASING DETAILS:

Date inst.	Dep. to top [m]	Bot. [m]	Diam. [mm]	Material	Thickn. [mm]	Opening Type	Length	Width	Hori. dist.	Vert. dist.
20081030	0.00	8.00	165	Steel	3					

GEOLOGY:

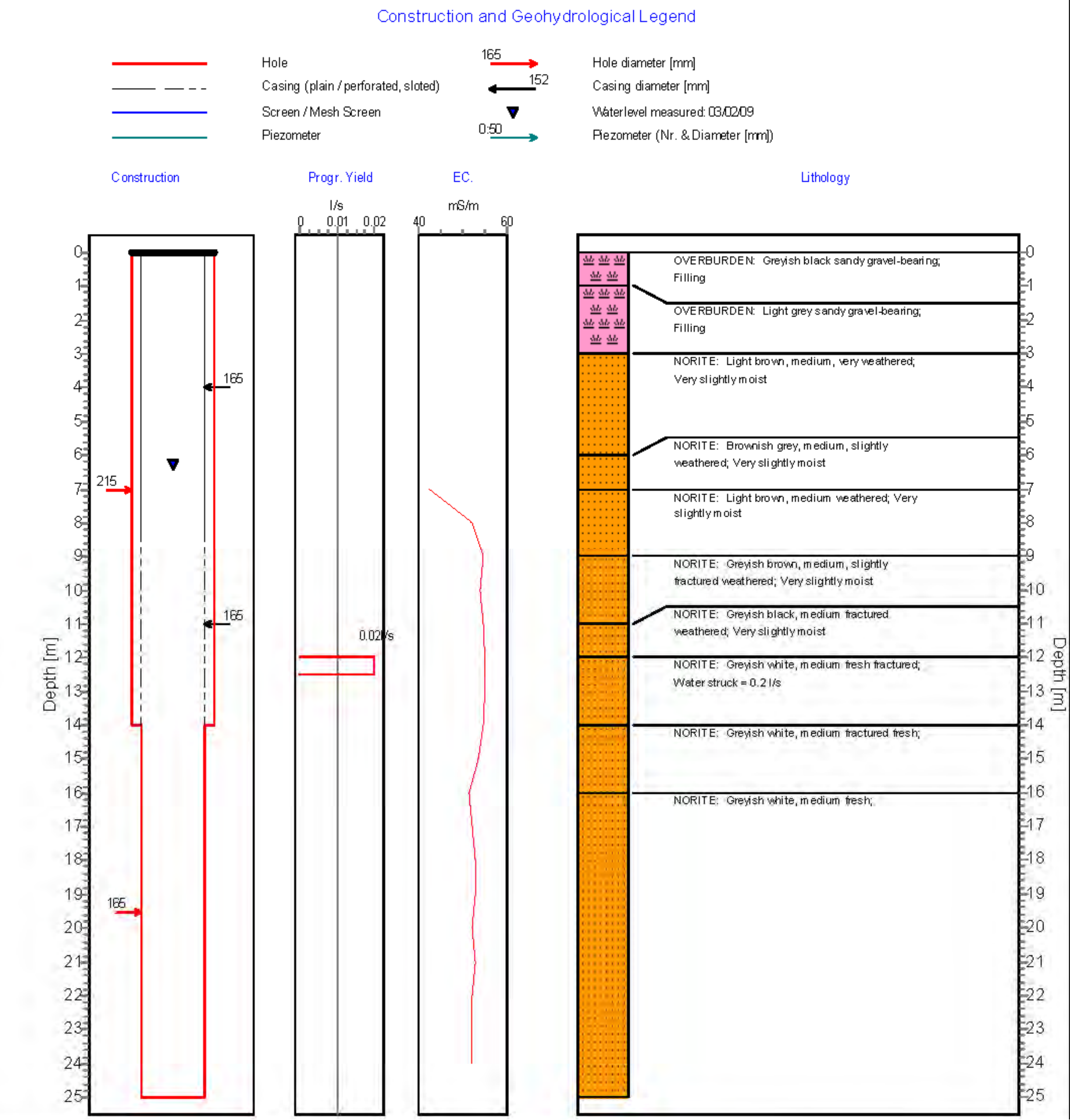
Dep. Top [m]	Bot. [m]	Lithology code	Colour Primary	Secondary	Texture	Feature Primary	Secondary
0.00	0.50	SOIL	Black	Greyish		Clayey	
0.50	6.00	NORITE	White	Brownish		Weathered	Fractured
6.00	8.00	NORITE	White	Brownish	Medium	Fractured	Fresh
8.00	11.00	NORITE	White	Greyish	Medium	Fractured	Fresh
11.00	26.00	NORITE	White	Greyish	Medium	Fresh	

WATER LEVEL:

Meth. meas.	Level status	Piez.	Info source	Date meas.	Time meas.	Sec.	Water lev. [m]	Comment
Electrical contact	Static	0	Field checked	20090203	0000	0.00	25.18	

Y Coord. [m]: -40239.92	**BH-6**	***Topo-set.:*** Flat surface, plain	***Depth [m]:*** 25.00
X Coord. [m]: 2844961.95		***Site status:*** In use	***Col. ht. [m]:*** 0.70
Altitude [m]: 1196.53		***Site purp.:*** Observation	***Diam. [mm]:*** 165
Coord. acc.: Accurate to within 1 unit		***Use applic.:*** Industrial - mining	***Drain. reg.:***
Coord. meth.: Levelled or surveyed		***Equipment:*** No equipment	***Rep. inst.:***

Coordinate System: South African LO Transverse Mercator, Hartebeesthoek94 (WGS 84)



Design Optimization of Hazardous Waste Disposal Facilities through the Application of Water Balance and Mass Transport Modelling

Y Coord. [m]: -40241.00	**BH-6**	*Topo-set.:* Flat surface, plain	*Depth [m]:* 25.00
X Coord. [m]: 2844959.00		*Site status:* In use	*Col. ht. [m]:* 0.70
Altitude [m]: 1196.00		*Site purp.:* Observation	*Diam. [mm]:* 165
Coord. acc.: Accurate to within 10 units		*Use applic.:* Industrial - mining	*Drain. reg.:*
Coord. meth.: Global Positioning System		*Equipment:* No equipment	*Rep. inst.:*

Coordinate System: South African LO Transverse Mercator, Hartebeesthoek94 (WGS 84)

CONSTRUCTION:

Date const.	Contractor	Constr. meth.	Type finish	Development Method	Durat.	Special treatment	Constr. cost
20081105		Air percussion	Open bottom	Compressed air			

HOLE DIAMETER:

Rep. Inst.	Depth to Top [m]	Depth to Bottom [m]	Diameter [mm]	Date const.	Comment
	0.00	14.00	215	20081105	
	14.00	25.00	165	20081105	

CASING DETAILS:

Date inst.	Dep. to top [m]	Bot. [m]	Diam. [mm]	Material	Thickn. [mm]	Opening Type	Length	Width	Hori. dist.	Vert. dist.
20081105	0.00	8.00	165	Steel	3					
20081105	8.00	14.00	165	Steel	3	Perforated or slotted	300	3	50	100

AQUIFER:

Rep. Inst.	Depth to Top [m]	Bot. [m]	Yield [l/s]	Method meas.	Aquifer type	Info source	Comment
	12.00	12.50	0.02	Estimated			

GEOLOGY:

Dep. Top [m]	Bot. [m]	Lithology code	Colour Primary	Secondary	Texture	Feature Primary	Secondary
0.00	1.00	OVERBURDEN	Black	Greyish		Gravel-bearing	Sandy
1.00	3.00	OVERBURDEN	Grey	Light		Gravel-bearing	Sandy
3.00	6.00	NORITE	Brown	Light	Medium	Weathered	
6.00	7.00	NORITE	Grey	Brownish	Medium	Weathered	
7.00	9.00	NORITE	Brown	Light	Medium	Weathered	
9.00	11.00	NORITE	Brown	Greyish	Medium	Weathered	Fractured
11.00	12.00	NORITE	Black	Greyish	Medium	Weathered	Fractured
12.00	14.00	NORITE	White	Greyish	Medium	Fractured	Fresh
14.00	16.00	NORITE	White	Greyish	Medium	Fresh	Fractured
16.00	25.00	NORITE	White	Greyish	Medium	Fresh	

WATER LEVEL:

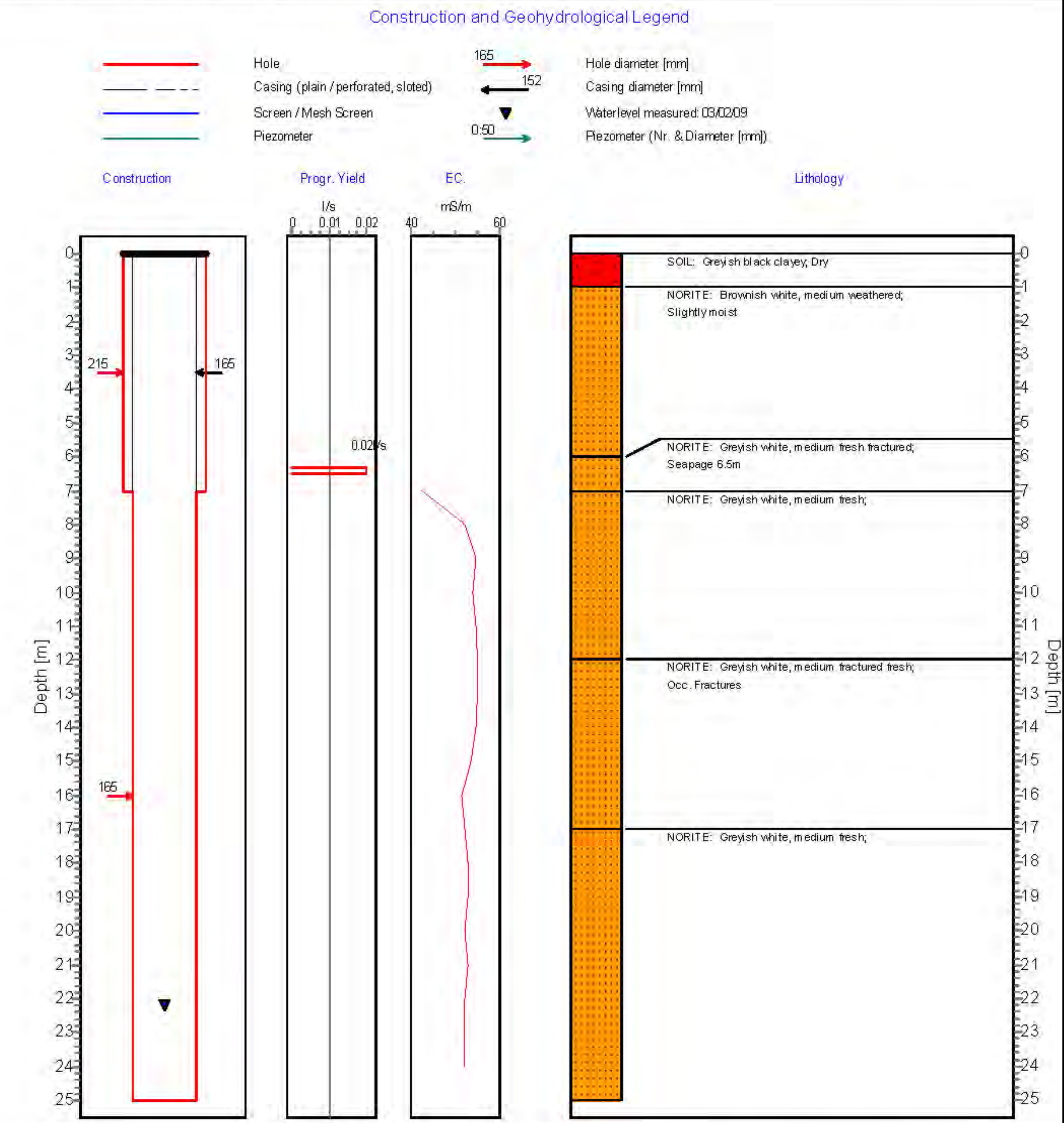
Meth. meas.	Level status	Piez.	Info source	Date meas.	Time meas.	Sec.	Water lev. [m]	Comment
Electrical contact	Static	0	Field checked	20090203	1355	0.00	6.27	
Electrical contact	Static	0	Field checked	20090209	1525	0.00	6.26	

TESTING DETAILS:

Description	Date started	Durat. [s]	Depth to intk. [m]	Disch. rate[l/s]	Drawd. [m]	Recovery: [m]	%	[min]	Trans. [m³/d]	Perm. [m/d]	Storat.	Comment

Y Coord. [m]:	-40243.18	**BH-7**	***Topo-set.:***	Flat surface, plain	***Depth [m]:***	25.00
X Coord. [m]:	2844380.96		***Site status:***	In use	***Col. ht. [m]:***	0
Altitude [m]:	1190.29		***Site purp.:***	Observation	***Diam. [mm]:***	165
Coord. acc.:	Accurate to within 1 unit		***Use applic.:***	Industrial - mining	***Drain. reg.:***	
Coord. meth.:	Levelled or surveyed		***Equipment:***	No equipment	***Rep. inst.:***	

Coordinate System: South African LO Transverse Mercator, Hartebeesthoek94 (WGS 84)



Design Optimization of Hazardous Waste Disposal Facilities through the Application of Water Balance and Mass Transport Modelling

Y Coord. [m]:	-40244.00	*Topo-set.:*	Flat surface, plain
X Coord. [m]:	2844386.00	*Site status:*	In use
Altitude [m]:	1193.00	*Site purp.:*	Observation
Coord. acc.:	Accurate to within 10 units	*Use applic.:*	Industrial - mining
Coord. meth.:	Global Positioning System	*Equipment:*	No equipment

BH-7

Depth [m]:	25.00
Col. ht. [m]:	0
Diam. [mm]:	165
Drain. reg.:	
Rep. inst.:	

Coordinate System: South African LO Transverse Mercator, Hartebeesthoek94 (WGS 84)

CONSTRUCTION:

Date const.	Contractor	Constr. meth.	Type finish	Development Method	Durat.	Special treatment	Constr. cost
20081029		Air percussion	Open bottom	Compressed air			

HOLE DIAMETER:

Rep. Inst.	Depth to Top [m]	Depth to Bottom [m]	Diameter [mm]	Date const.	Comment
	0.00	7.00	215	20081029	
	7.00	25.00	165	20081029	

CASING DETAILS:

Date inst.	Dep. to top [m]	Bot. [m]	Diam. [mm]	Material	Thickn. [mm]	Opening Type	Length	Width	Hori. dist.	Vert. dist.
20081029	0.00	7.00	165	Steel	3					

AQUIFER:

Rep. Inst.	Depth to Top [m]	Bot. [m]	Yield [l/s]	Method meas.	Aquifer type	Info source	Comment
	6.30	6.50	0.02	Estimated			

GEOLOGY:

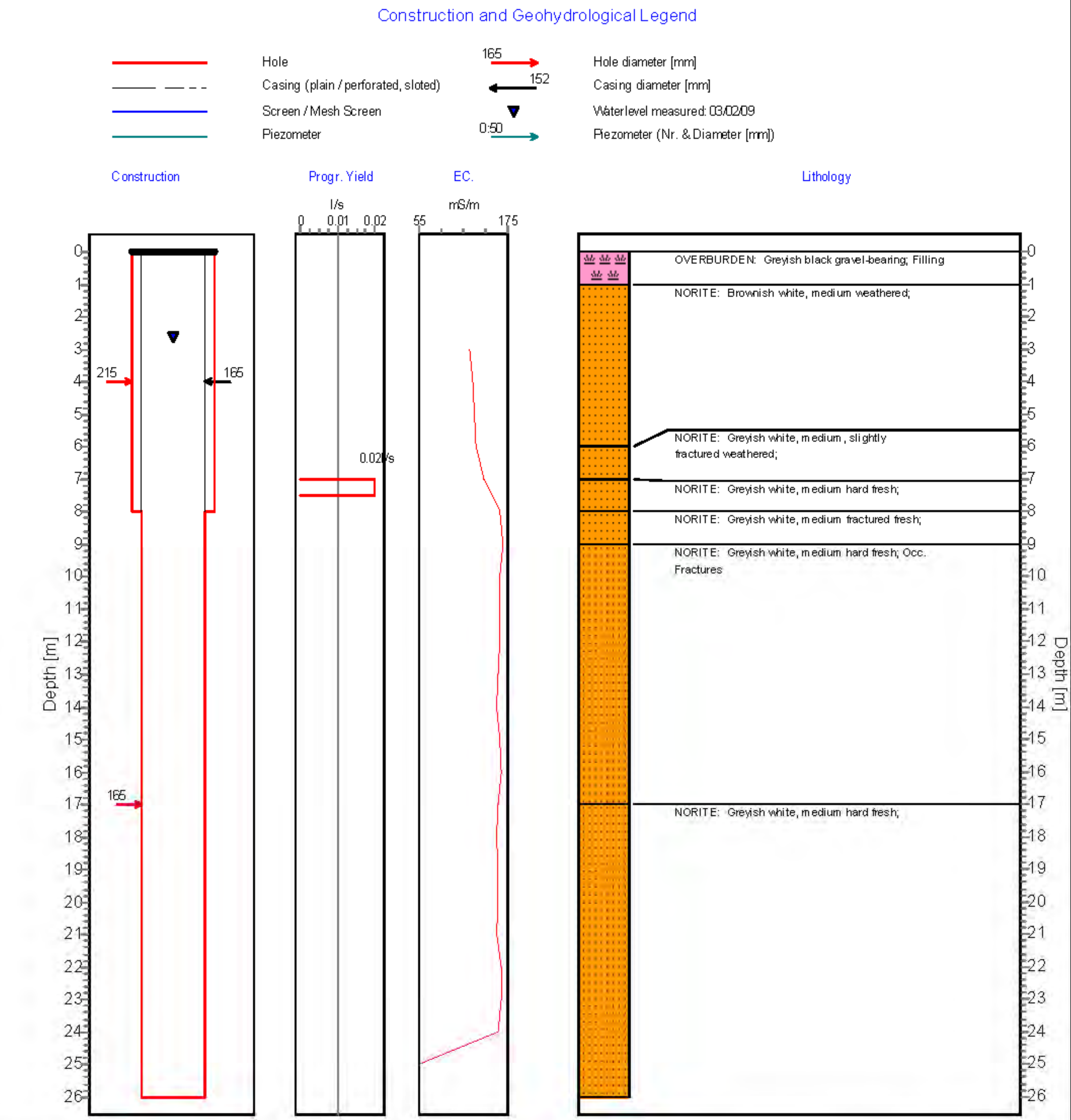
Dep. Top [m]	Bot. [m]	Lithology code	Colour Primary	Secondary	Texture	Feature Primary	Secondary
0.00	1.00	SOIL	Black	Greyish		Clayey	
1.00	6.00	NORITE	White	Brownish	Medium	Weathered	
6.00	7.00	NORITE	White	Greyish	Medium	Fractured	Fresh
7.00	12.00	NORITE	White	Greyish	Medium	Fresh	
12.00	17.00	NORITE	White	Greyish	Medium	Fresh	Fractured
17.00	25.00	NORITE	White	Greyish	Medium	Fresh	

WATER LEVEL:

Meth. meas.	Level status	Piez.	Info source	Date meas.	Time meas.	Sec.	Water lev. [m]	Comment
Electrical contact	Static	0	Field checked	20090203	1335	0.00	22.17	

Y Coord. [m]:	-40606.06	**BH-8**	***Topo-set.:***	Flat surface, plain	***Depth [m]:***	26.00
X Coord. [m]:	2844399.80		***Site status:***	In use	***Col. ht. [m]:***	0
Altitude [m]:	1187.33		***Site purp.:***	Observation	***Diam. [mm]:***	165
Coord. acc.:	Accurate to within 1 unit		***Use applic.:***	Industrial - mining	***Drain. reg.:***	
Coord. meth.:	Levelled or surveyed		***Equipment:***	No equipment	***Rep. inst.:***	

Coordinate System: South African LO Transverse Mercator, Hartebeesthoek94 (WGS 84)



Design Optimization of Hazardous Waste Disposal Facilities through the Application of Water Balance and Mass Transport Modelling

Y Coord. [m]: -40602.00	**BH-8**	*Topo-set.:* Flat surface, plain		*Depth [m]:* 26.00	
X Coord. [m]: 2844402.00		*Site status:* In use		*Col. ht. [m]:* 0	
Altitude [m]: 1189.00		*Site purp.:* Observation		*Diam. [mm]:* 165	
Coord. acc.: Accurate to within 10 units		*Use applic.:* Industrial - mining		*Drain. reg.:*	
Coord. meth.: Global Positioning System		*Equipment:* No equipment		*Rep. inst.:*	

Coordinate System: South African LO Transverse Mercator, Hartebeesthoek94 (WGS 84)

CONSTRUCTION:

Date const.	Contractor	Constr. meth.	Type finish	Development Method	Durat.	Special treatment	Constr. cost
20081028		Air percussion	Open bottom	Compressed air			

HOLE DIAMETER:

Rep. Inst.	Depth to Top [m]	Depth to Bottom [m]	Diameter [mm]	Date const.	Comment
	0.00	8.00	215	20081028	
	8.00	26.00	165	20081028	

CASING DETAILS:

Date inst.	Dep. to top [m]	Bot. [m]	Diam. [mm]	Material	Thickn. [mm]	Opening Type	Length	Width	Hori. dist.	Vert. dist.
20081028	0.00	8.00	165	Steel	3					

AQUIFER:

Rep. Inst.	Depth to Top [m]	Bot. [m]	Yield [l/s]	Method meas.	Aquifer type	Info source	Comment
	7.00	7.50	0.02	Estimated			

GEOLOGY:

Dep. Top [m]	Bot. [m]	Lithology code	Colour Primary	Secondary	Texture	Feature Primary	Secondary
0.00	1.00	OVERBURDEN	Black	Greyish		Gravel-bearing	
1.00	6.00	NORITE	White	Brownish	Medium	Weathered	
6.00	7.00	NORITE	White	Greyish	Medium	Weathered	Fractured
7.00	8.00	NORITE	White	Greyish	Medium	Fresh	Hard
8.00	9.00	NORITE	White	Greyish	Medium	Fresh	Fractured
9.00	17.00	NORITE	White	Greyish	Medium	Fresh	Hard
17.00	26.00	NORITE	White	Greyish	Medium	Fresh	Hard

WATER LEVEL:

Meth. meas.	Level status	Piez.	Info source	Date meas.	Time meas.	Sec.	Water lev. [m]	Comment
Electrical contact	Static	0	Field checked	20090203	1315	0.00	2.63	
Electrical contact	Static	0	Field checked	20090209	1453	0.00	2.63	

Y Coord. [m]: -40019.93	**BH-9**	***Topo-set.:***	Flat surface, plain	***Depth [m]:***	31.00
X Coord. [m]: 2843778.87		***Site status:***	In use	***Col. ht. [m]:***	0
Altitude [m]: 1190.85		***Site purp.:***	Observation	***Diam. [mm]:***	165
Coord. acc.: Accurate to within 1 unit		***Use applic.:***	Industrial - mining	***Drain. reg.:***	
Coord. meth.: Levelled or surveyed		***Equipment:***	No equipment	***Rep. inst.:***	

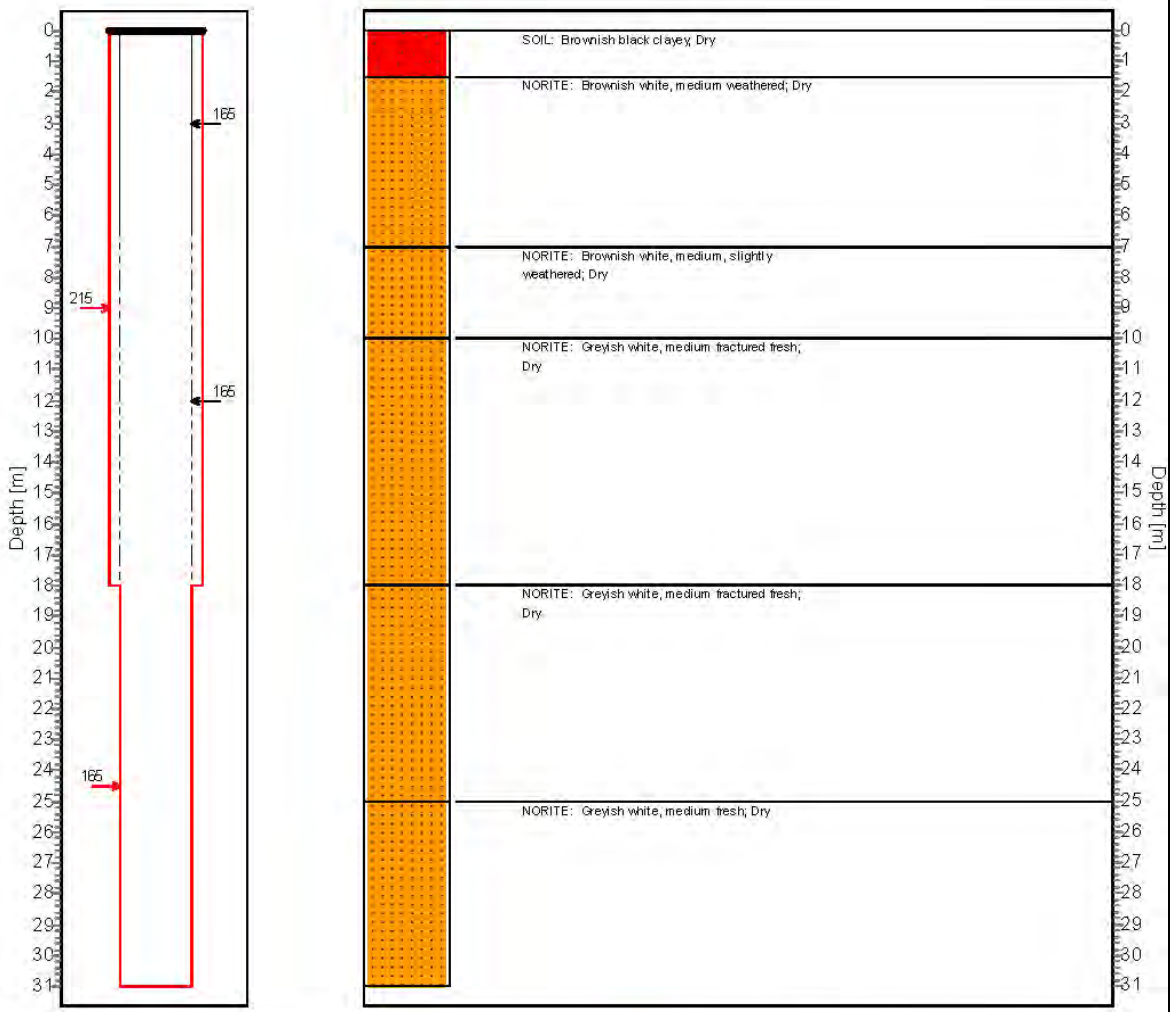
Coordinate System: South African LO Transverse Mercator, Hartebeesthoek94 (WGS 84)

Construction and Geohydrological Legend

Hole	165 →	Hole diameter [mm]
Casing (plain / perforated, sloted)	← 152	Casing diameter [mm]
Screen / Mesh Screen	▼	Waterlevel with date meas.
Piezometer	0:50 →	Piezometer (Nr. & Diameter [mm])

Construction

Lithology



Y Coord. [m]:	-40020.00	**BH-9**	**Topo-set.:** Flat surface, plain	**Depth [m]:**	31.00
X Coord. [m]:	2843779.00		**Site status:** In use	**Col. ht. [m]:**	0
Altitude [m]:	1196.00		**Site purp.:** Observation	**Diam. [mm]:**	165
Coord. acc.:	Accurate to within 10 units		**Use applic.:** Industrial - mining	**Drain. reg.:**	
Coord. meth.:	Global Positioning System		**Equipment:** No equipment	**Rep. inst.:**	

Coordinate System: South African LO Transverse Mercator, Hartebeesthoek94 (WGS 84)

CONSTRUCTION:

Date const.	Contractor	Constr. meth.	Type finish	Development Method	Durat.	Special treatment	Constr. cost
20081024		Air percussion	Open bottom	Compressed air			

HOLE DIAMETER:

Rep. Inst.	Depth to Top [m]	Depth to Bottom [m]	Diameter [mm]	Date const.	Comment
	0.00	18.00	215	20081024	
	18.00	31.00	165	20081024	

CASING DETAILS:

Date inst.	Dep. to top [m]	Bot. [m]	Diam. [mm]	Material	Thickn. [mm]	Opening Type	Length	Width	Hori. dist.	Vert. dist.
20081024	0.00	6.00	165	Steel	3					
20081024	6.00	18.00	165	Steel	3	Perforated or slotted	300	3	50	100

GEOLOGY:

Dep. Top [m]	Bot. [m]	Lithology code	Colour Primary	Secondary	Texture	Feature Primary	Secondary
0.00	1.50	SOIL	Black	Brownish		Clayey	
1.50	7.00	NORITE	White	Brownish	Medium	Weathered	
7.00	10.00	NORITE	White	Brownish	Medium	Weathered	
10.00	18.00	NORITE	White	Greyish	Medium	Fresh	Fractured
18.00	25.00	NORITE	White	Greyish	Medium	Fresh	Fractured
25.00	31.00	NORITE	White	Greyish	Medium	Fresh	

Y Coord. [m]: -40593.10	**BH-10**	***Topo-set.:***	Flat surface, plain	***Depth [m]:***	30.00
X Coord. [m]: 2843505.53		***Site status:***	In use	***Col. ht. [m]:***	0
Altitude [m]: 1188.14		***Site purp.:***	Observation	***Diam. [mm]:***	165
Coord. acc.: Accurate to within 1 unit		***Use applic.:***	Industrial - mining	***Drain. reg.:***	
Coord. meth.: Levelled or surveyed		***Equipment:***	No equipment	***Rep. inst.:***	

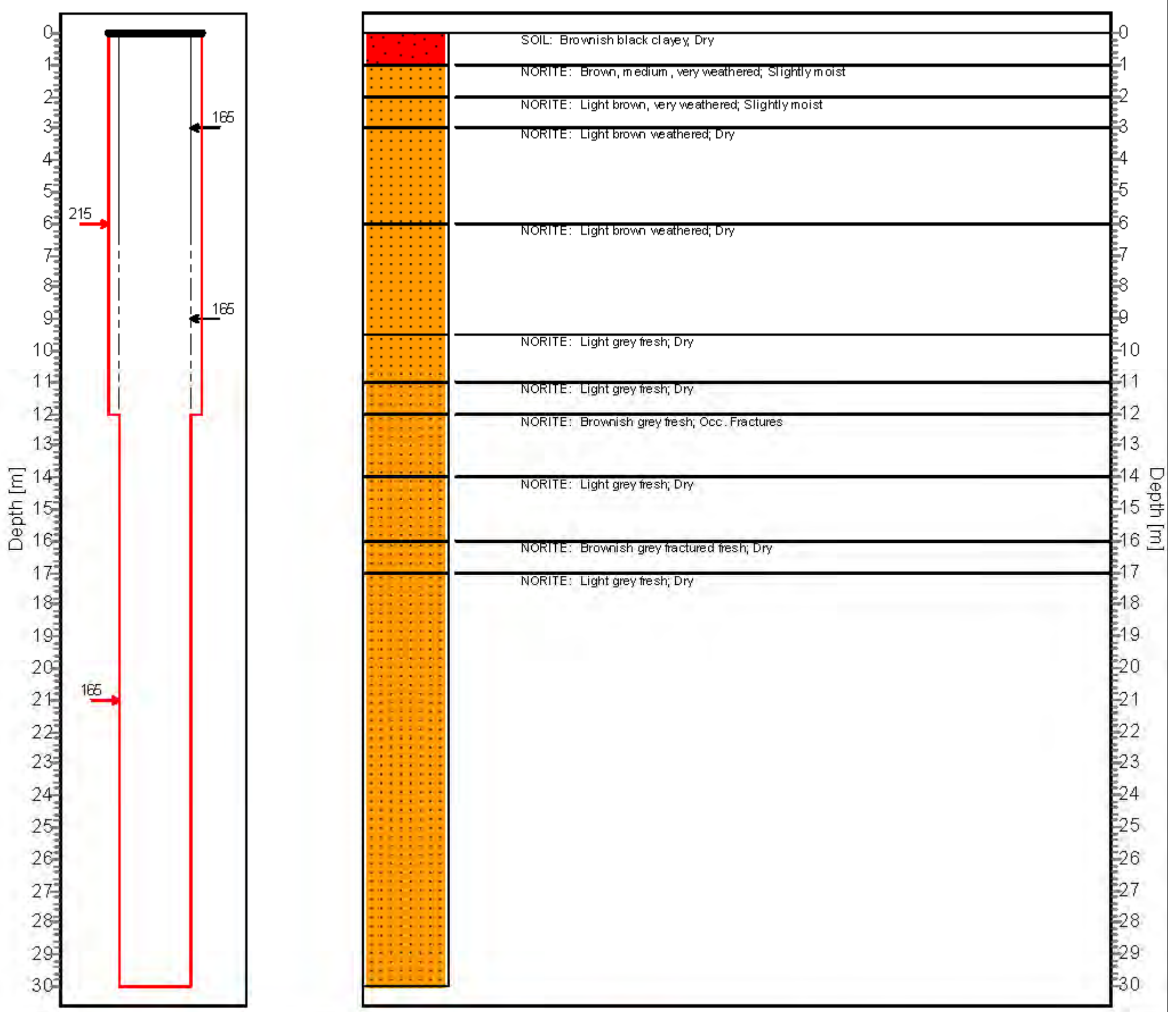
Coordinate System: South African LO Transverse Mercator, Hartebeesthoek94 (WGS 84)

Construction and Geohydrological Legend

(red line)	Hole	165 (red arrow)	Hole diameter [mm]
(solid / dashed line)	Casing (plain / perforated, sloted)	152 (black arrow)	Casing diameter [mm]
(blue line)	Screen / Mesh Screen	▼	Waterlevel with date meas.
(teal line)	Piezometer	0:50 (teal arrow)	Piezometer (Nr. & Diameter [mm])

Construction

Lithology



Y Coord. [m]: -40593.00	**BH-10**	*Topo-set.:* Flat surface, plain	*Depth [m]:* 30.00
X Coord. [m]: 2843508.00		*Site status:* In use	*Col. ht. [m]:* 0
Altitude [m]: 1198.00		*Site purp.:* Observation	*Diam. [mm]:* 165
Coord. acc.: Accurate to within 10 units		*Use applic.:* Industrial - mining	*Drain. reg.:*
Coord. meth.: Global Positioning System		*Equipment:* No equipment	*Rep. inst.:*

Coordinate System: South African LO Transverse Mercator, Hartebeesthoek94 (WGS 84)

CONSTRUCTION:

Date const.	Contractor	Constr. meth.	Type finish	Development Method	Durat.	Special treatment	Constr. cost
20081024		Air percussion	Open bottom	Compressed air			

HOLE DIAMETER:

Rep. Inst.	Depth to Top [m]	Depth to Bottom [m]	Diameter [mm]	Date const.	Comment
	0.00	12.00	215	20081024	
	12.00	30.00	165	20081024	

CASING DETAILS:

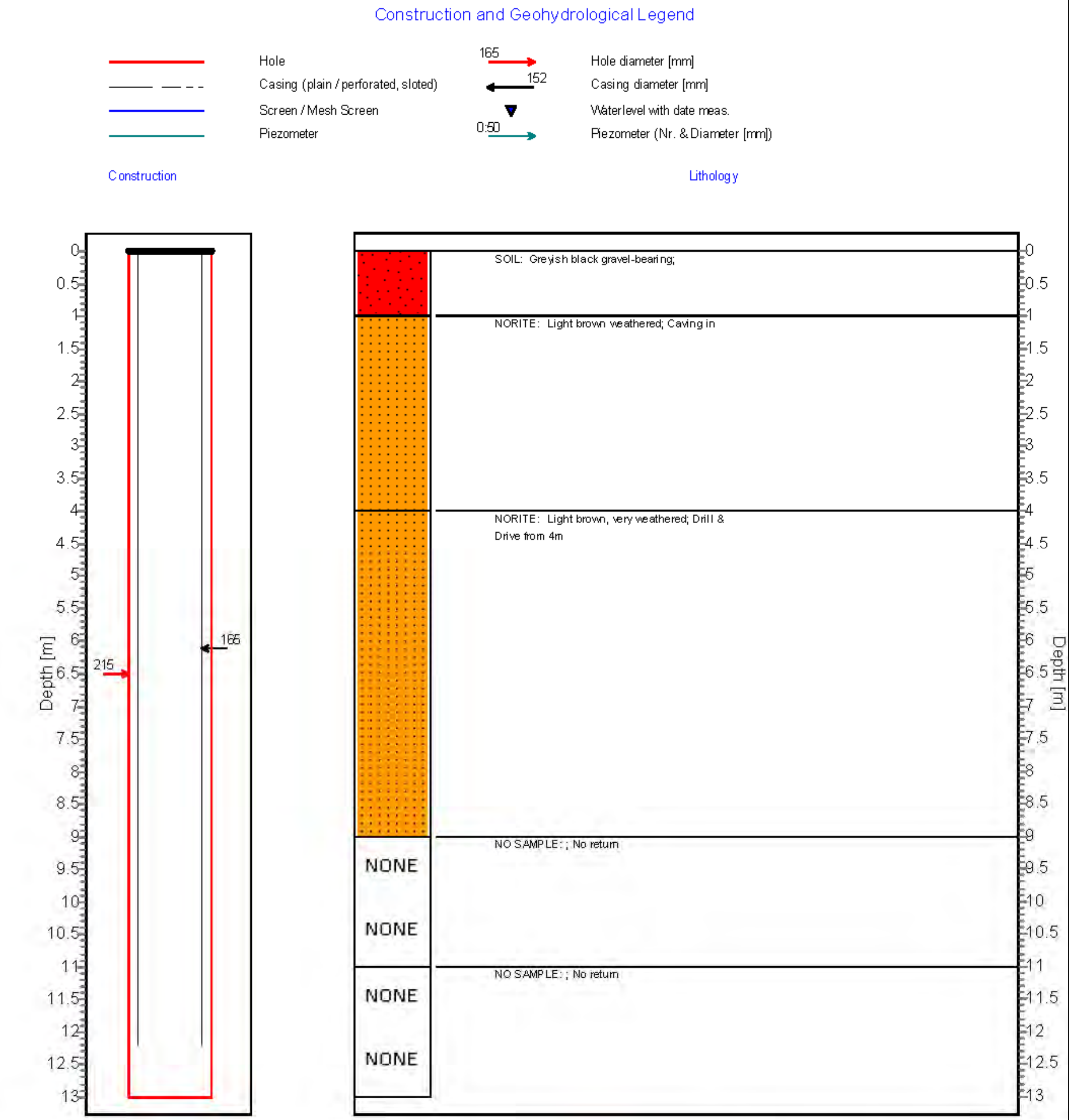
Date inst.	Dep. to top [m]	Bot. [m]	Diam. [mm]	Material	Thickn. [mm]	Opening Type	Length	Width	Hori. dist.	Vert. dist.
20081024	0.00	6.00	165	Steel	3					
20081024	6.00	12.00	165	Steel	3	Perforated or slotted	300	3	100	50

GEOLOGY:

Dep. Top [m]	Bot. [m]	Lithology code	Colour Primary	Secondary	Texture	Feature Primary	Secondary
0.00	1.00	SOIL	Black	Brownish		Clayey	
1.00	2.00	NORITE	Brown		Medium	Weathered	
2.00	3.00	NORITE	Brown	Light		Weathered	
3.00	6.00	NORITE	Brown	Light		Weathered	
6.00	9.50	NORITE	Brown	Light		Weathered	
9.50	11.00	NORITE	Grey	Light		Fresh	
11.00	12.00	NORITE	Grey	Light		Fresh	
12.00	14.00	NORITE	Grey	Brownish		Fresh	
14.00	16.00	NORITE	Grey	Light		Fresh	
16.00	17.00	NORITE	Grey	Brownish		Fresh	Fractured
17.00	30.00	NORITE	Grey	Light		Fresh	

Y Coord. [m]: -41186.58	**BH-11**	***Topo-set.:*** Flat surface, plain	***Depth [m]:*** 12.30
X Coord. [m]: 2843932.07		***Site status:*** In use	***Col. ht. [m]:*** 0
Altitude [m]: 1177.36		***Site purp.:*** Observation	***Diam. [mm]:*** 165
Coord. acc.: Accurate to within 1 unit		***Use applic.:*** Industrial - mining	***Drain. reg.:***
Coord. meth.: Levelled or surveyed		***Equipment:*** No equipment	***Rep. inst.:***

Coordinate System: South African LO Transverse Mercator, Hartebeesthoek94 (WGS 84)



Design Optimization of Hazardous Waste Disposal Facilities through the Application of Water Balance and Mass Transport Modelling

Y Coord. [m]:	-41186.00	**BH-11**	
X Coord. [m]:	2843933.00		
Altitude [m]:	1198.00		
Coord. acc.:	Accurate to within 10 units		
Coord. meth.:	Global Positioning System		

Topo-set.:	Flat surface, plain
Site status:	In use
Site purp.:	Observation
Use applic.:	Industrial - mining
Equipment:	No equipment

Depth [m]:	12.30
Col. ht. [m]:	0
Diam. [mm]:	165
Drain. reg.:	
Rep. inst.:	

Coordinate System: South African LO Transverse Mercator, Hartebeesthoek94 (WGS 84)

CONSTRUCTION:

Date const.	Contractor	Constr. meth.	Type finish	Development Method	Durat.	Special treatment	Constr. cost
20081024		Air percussion	Open bottom	Compressed air			

HOLE DIAMETER:

Rep. Inst.	Depth to Top [m]	Depth to Bottom [m]	Diameter [mm]	Date const.	Comment
	0.00	13.00	215	20081024	

CASING DETAILS:

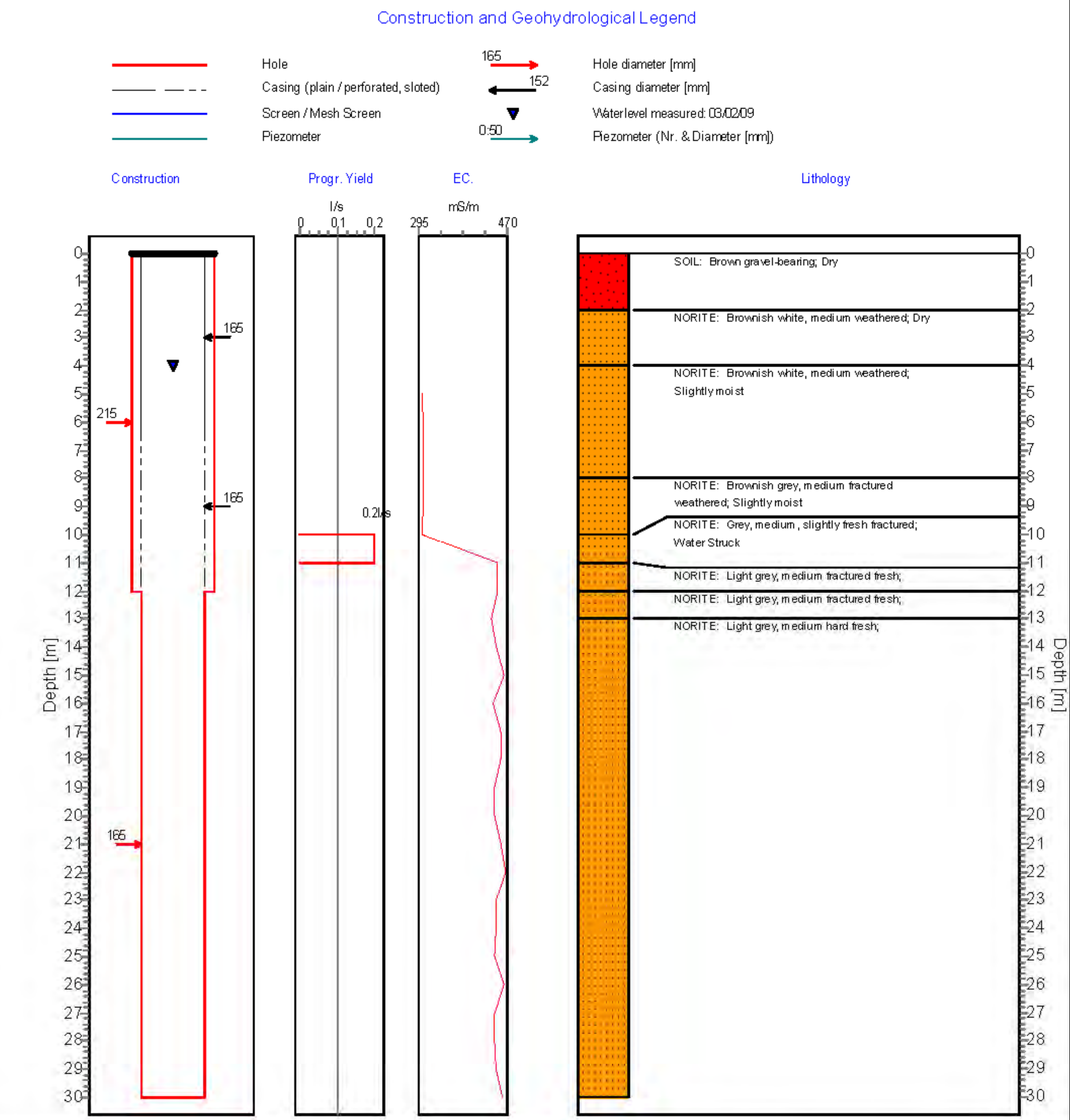
Date inst.	Dep. to top [m]	Bot. [m]	Diam. [mm]	Material	Thickn. [mm]	Opening Type	Length	Width	Hori. dist.	Vert. dist.
20081024	0.00	12.20	165	Steel	3					

GEOLOGY:

Dep. Top [m]	Bot. [m]	Lithology code	Colour Primary	Secondary	Texture	Feature Primary	Secondary
0.00	1.00	SOIL	Black	Greyish		Gravel-bearing	
1.00	4.00	NORITE	Brown	Light		Weathered	
4.00	9.00	NORITE	Brown	Light		Weathered	
9.00	11.00	NO SAMPLE					
11.00	13.00	NO SAMPLE					

Y Coord. [m]:	-41167.42	**BH-12**	***Topo-set.:***	Along dam, lake or swamp	***Depth [m]:***	30.00
X Coord. [m]:	2844156.51		***Site status:***	In use	***Col. ht. [m]:***	0
Altitude [m]:	1179.87		***Site purp.:***	Observation	***Diam. [mm]:***	165
Coord. acc.:	Accurate to within 1 unit		***Use applic.:***	Industrial - mining	***Drain. reg.:***	
Coord. meth.:	Levelled or surveyed		***Equipment:***	No equipment	***Rep. inst.:***	

Coordinate System: South African LO Transverse Mercator, Hartebeesthoek94 (WGS 84)



Y Coord. [m]:	-41130.00	**BH-12**	*Topo-set.:*	Along dam, lake or swamp	*Depth [m]:*	30.00
X Coord. [m]:	2844385.00		*Site status:*	In use	*Col. ht. [m]:*	0
Altitude [m]:	1184.00		*Site purp.:*	Observation	*Diam. [mm]:*	165
Coord. acc.:	Accurate to within 10 units		*Use applic.:*	Industrial - mining	*Drain. reg.:*	
Coord. meth.:	Global Positioning System		*Equipment:*	No equipment	*Rep. inst.:*	

Coordinate System: South African LO Transverse Mercator, Hartebeesthoek94 (WGS 84)

CONSTRUCTION:

Date const.	Contractor	Constr. meth.	Type finish	Development Method	Durat.	Special treatment	Constr. cost
20081028		Air percussion	Open bottom	Compressed air			

HOLE DIAMETER:

Rep. Inst.	Depth to Top [m]	Depth to Bottom [m]	Diameter [mm]	Date const.	Comment
	0.00	12.00	215	20081028	
	12.00	30.00	165	20081028	

CASING DETAILS:

Date inst.	Dep. to top [m]	Bot. [m]	Diam. [mm]	Material	Thickn. [mm]	Opening Type	Length	Width	Hori. dist.	Vert. dist.
20081028	0.00	6.00	165	Steel	3					
20081028	6.00	12.00	165	Steel	3	Perforated or slotted	300	3	100	50

AQUIFER:

Rep. Inst.	Depth to Top [m]	Bot. [m]	Yield [l/s]	Method meas.	Aquifer type	Info source	Comment
	10.00	11.00	0.20	Estimated			

GEOLOGY:

Dep. Top [m]	Bot. [m]	Lithology code	Colour Primary	Secondary	Texture	Feature Primary	Secondary
0.00	2.00	SOIL	Brown			Gravel-bearing	
2.00	4.00	NORITE	White	Brownish	Medium	Weathered	
4.00	8.00	NORITE	White	Brownish	Medium	Weathered	
8.00	10.00	NORITE	Grey	Brownish	Medium	Weathered	Fractured
10.00	11.00	NORITE	Grey		Medium	Fractured	Fresh
11.00	12.00	NORITE	Grey	Light	Medium	Fresh	Fractured
12.00	13.00	NORITE	Grey	Light	Medium	Fresh	Fractured
13.00	30.00	NORITE	Grey	Light	Medium	Fresh	Hard

WATER LEVEL:

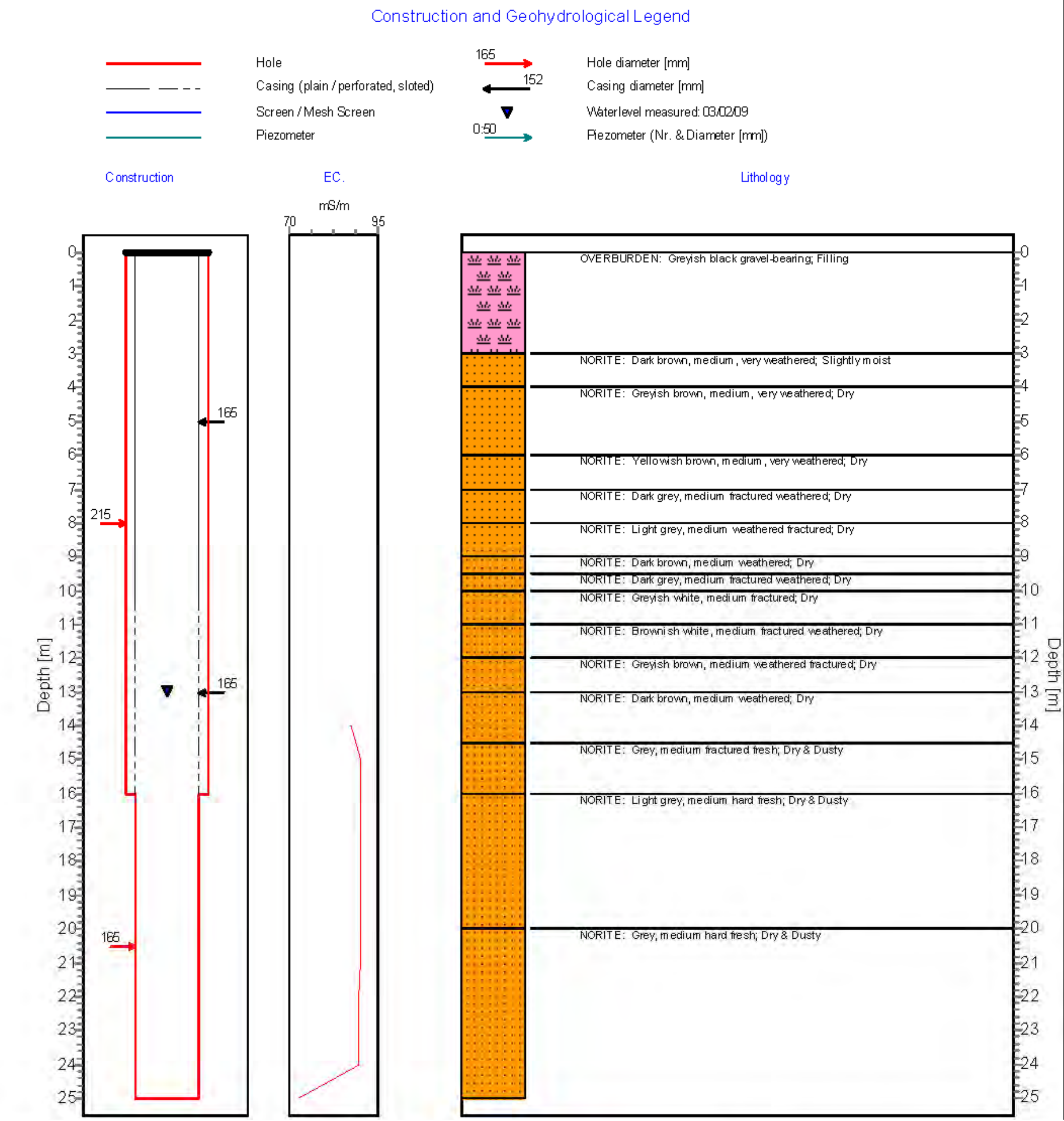
Meth. meas.	Level status	Piez.	Info source	Date meas.	Time meas.	Sec.	Water lev. [m]	Comment
Electrical contact	Static	0	Field checked	20090203	1135	0.00	3.99	
Electrical contact	Static	0	Field checked	20090209	1242	0.00	4.00	

TESTING DETAILS:

Description	Date started	Durat. [s]	Depth to intk. [m]	Disch. rate[l/s]	Drawd. [m]	Recovery: [m]	%	[min]	Trans. [m²/d]	Perm. [m/d]	Storat.	Comment

Y Coord. [m]:	-40874.87	**BH-13**	***Topo-set.:***	Flat surface, plain	***Depth [m]:***	25.00
X Coord. [m]:	2846342.81		***Site status:***	In use	***Col. ht. [m]:***	0
Altitude [m]:	1210.14		***Site purp.:***	Observation	***Diam. [mm]:***	165
Coord. acc.:	Accurate to within 1 unit		***Use applic.:***	Industrial - mining	***Drain. reg.:***	
Coord. meth.:	Levelled or surveyed		***Equipment:***	No equipment	***Rep. inst.:***	

Coordinate System: South African LO Transverse Mercator, Hartebeesthoek94 (WGS 84)



Y Coord. [m]:	-40875.00	**BH-13**	
X Coord. [m]:	2846344.00		
Altitude [m]:	1215.00		
Coord. acc.:	Accurate to within 10 units		
Coord. meth.:	Global Positioning System		

Topo-set.:	Flat surface, plain
Site status:	In use
Site purp.:	Observation
Use applic.:	Industrial - mining
Equipment:	No equipment

Depth [m]:	25.00
Col. ht. [m]:	0
Diam. [mm]:	165
Drain. reg.:	
Rep. inst.:	

Coordinate System: South African LO Transverse Mercator, Hartebeesthoek94 (WGS 84)

CONSTRUCTION:

Date const.	Contractor	Constr. meth.	Type finish	Development Method	Durat.	Special treatment	Constr. cost
20081030		Air percussion	Open bottom	Compressed air			

HOLE DIAMETER:

Rep. Inst.	Depth to Top [m]	Depth to Bottom [m]	Diameter [mm]	Date const.	Comment
	0.00	16.00	215	20081030	
	16.00	25.00	165	20081030	

CASING DETAILS:

Date inst.	Dep. to top [m]	Bot. [m]	Diam. [mm]	Material	Thickn. [mm]	Opening Type	Length	Width	Hori. dist.	Vert. dist.
20081030	0.00	10.00	165	Steel	3					
20081030	10.00	16.00	165	Steel	3	Perforated or slotted	300	3	100	50

GEOLOGY:

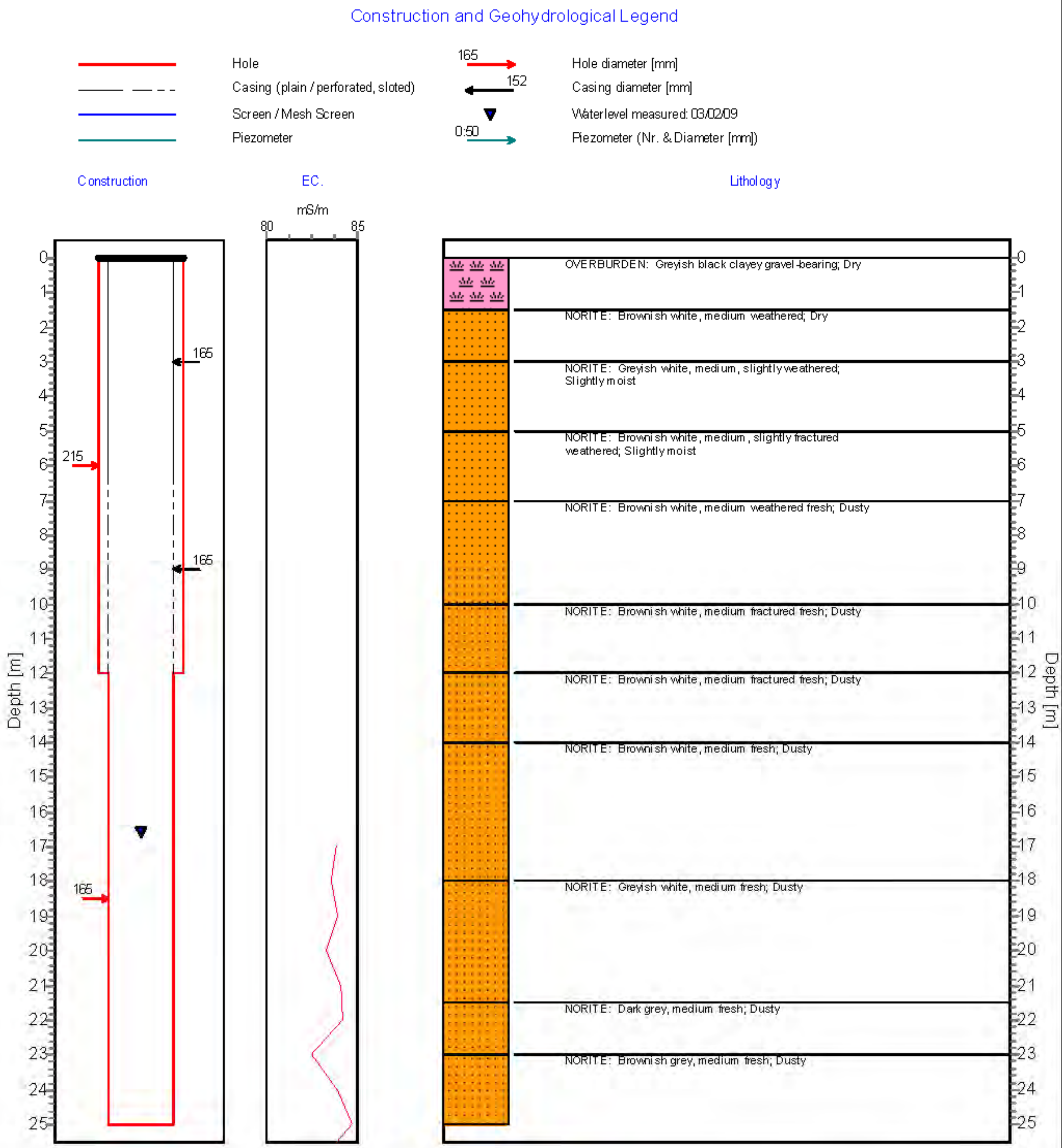
Dep. Top [m]	Bot. [m]	Lithology code	Colour Primary	Secondary	Texture	Feature Primary	Secondary
0.00	3.00	OVERBURDEN	Black	Greyish		Gravel-bearing	
3.00	4.00	NORITE	Brown	Dark	Medium	Weathered	
4.00	6.00	NORITE	Brown	Greyish	Medium	Weathered	
6.00	7.00	NORITE	Brown	Yellowish	Medium	Weathered	
7.00	8.00	NORITE	Grey	Dark	Medium	Weathered	Fractured
8.00	9.00	NORITE	Grey	Light	Medium	Fractured	Weathered
9.00	9.50	NORITE	Brown	Dark	Medium	Weathered	
9.50	10.00	NORITE	Grey	Dark	Medium	Weathered	Fractured
10.00	11.00	NORITE	White	Greyish	Medium	Fractured	
11.00	12.00	NORITE	White	Brownish	Medium	Weathered	Fractured
12.00	13.00	NORITE	Brown	Greyish	Medium	Fractured	Weathered
13.00	14.50	NORITE	Brown	Dark	Medium	Weathered	
14.50	16.00	NORITE	Grey		Medium	Fresh	Fractured
16.00	20.00	NORITE	Grey	Light	Medium	Fresh	Hard
20.00	25.00	NORITE	Grey		Medium	Fresh	Hard

WATER LEVEL:

Meth. meas.	Level status	Piez.	Info source	Date meas.	Time meas.	Sec.	Water lev. [m]	Comment
Electrical contact	Static	0	Field checked	20090203	1600	0.00	12.99	
Electrical contact	Static	0	Field checked	20090210	0921	0.00	13.07	

Y Coord. [m]: -40563.24	**BH-14**	***Topo-set.:***	Flat surface, plain	***Depth [m]:***	25.00
X Coord. [m]: 2846512.78		***Site status:***	In use	***Col. ht. [m]:***	0
Altitude [m]: 1214.81		***Site purp.:***	Observation	***Diam. [mm]:***	165
Coord. acc.: Accurate to within 1 unit		***Use applic.:***	Industrial - mining	***Drain. reg.:***	
Coord. meth.: Levelled or surveyed		***Equipment:***	No equipment	***Rep. inst.:***	

Coordinate System: South African LO Transverse Mercator, Hartebeesthoek94 (WGS 84)



Design Optimization of Hazardous Waste Disposal Facilities through the Application of Water Balance and Mass Transport Modelling

Y Coord. [m]: -40561.00	**BH-14**	*Topo-set.:* Flat surface, plain	*Depth [m]:* 25.00
X Coord. [m]: 2846516.00		*Site status:* In use	*Col. ht. [m]:* 0
Altitude [m]: 1217.00		*Site purp.:* Observation	*Diam. [mm]:* 165
Coord. acc.: Accurate to within 10 units		*Use applic.:* Industrial - mining	*Drain. reg.:*
Coord. meth.: Global Positioning System		*Equipment:* No equipment	*Rep. inst.:*

Coordinate System: South African LO Transverse Mercator, Hartebeesthoek94 (WGS 84)

CONSTRUCTION:

Date const.	Contractor	Constr. meth.	Type finish	Development Method	Durat.	Special treatment	Constr. cost
20081029		Air percussion	Open bottom	Compressed air			

HOLE DIAMETER:

Rep. Inst.	Depth to Top [m]	Depth to Bottom [m]	Diameter [mm]	Date const.	Comment
	0.00	12.00	215	20081029	
	12.00	25.00	165	20081029	

CASING DETAILS:

Date inst.	Dep. to top [m]	Bot. [m]	Diam. [mm]	Material	Thickn. [mm]	Opening Type	Length	Width	Hori. dist.	Vert. dist.
20081029	0.00	6.00	165	Steel	3					
20081029	6.00	12.00	165	Steel	3	Perforated or slotted	300	3	100	50

GEOLOGY:

Dep. Top [m]	Bot. [m]	Lithology code	Colour Primary	Secondary	Texture	Feature Primary	Secondary
0.00	1.50	OVERBURDEN	Black	Greyish		Gravel-bearing	Clayey
1.50	3.00	NORITE	White	Brownish	Medium	Weathered	
3.00	5.00	NORITE	White	Greyish	Medium	Weathered	
5.00	7.00	NORITE	White	Brownish	Medium	Weathered	Fractured
7.00	10.00	NORITE	White	Brownish	Medium	Fresh	Weathered
10.00	12.00	NORITE	White	Brownish	Medium	Fresh	Fractured
12.00	14.00	NORITE	White	Brownish	Medium	Fresh	Fractured
14.00	18.00	NORITE	White	Brownish	Medium	Fresh	
18.00	21.50	NORITE	White	Greyish	Medium	Fresh	
21.50	23.00	NORITE	Grey	Dark	Medium	Fresh	
23.00	25.00	NORITE	Grey	Brownish	Medium	Fresh	

WATER LEVEL:

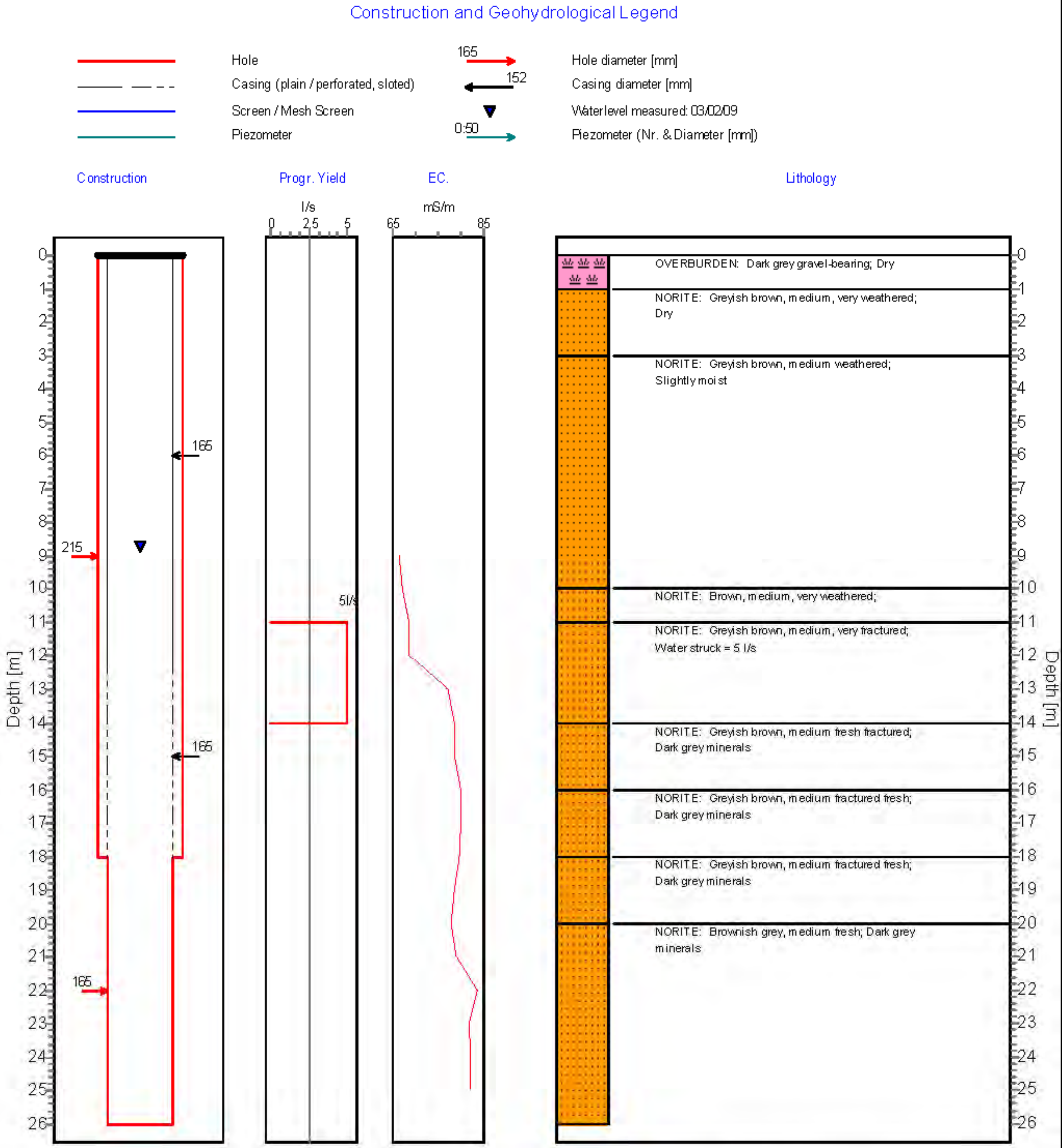
Meth. meas.	Level status	Piez.	Info source	Date meas.	Time meas.	Sec.	Water lev. [m]	Comment
Electrical contact	Static	0	Field checked	20090203	1535	0.00	16.55	
Electrical contact	Static	0	Field checked	20090210	0811	0.00	16.59	

TESTING DETAILS:

Description	Date started	Durat. [s]	Depth to intk. [m]	Disch. rate[l/s]	Drawd. [m]	Recovery: [m]	%	[min]	Trans. [m²/d]	Perm. [m/d]	Storat.	Comment

Y Coord. [m]: -40802.21	**BH-15**	**Topo-set.:**	Flat surface, plain	**Depth [m]:**	26.00
X Coord. [m]: 2846764.33		**Site status:**	In use	**Col. ht. [m]:**	0
Altitude [m]: 1213.56		**Site purp.:**	Observation	**Diam. [mm]:**	165
Coord. acc.: Accurate to within 1 unit		**Use applic.:**	Industrial - mining	**Drain. reg.:**	
Coord. meth.: Levelled or surveyed		**Equipment:**	No equipment	**Rep. inst.:**	

Coordinate System: South African LO Transverse Mercator, Hartebeesthoek94 (WGS 84)



Y Coord. [m]:	-40802.00	**BH-15**	
X Coord. [m]:	2846764.00		
Altitude [m]:	1220.00		
Coord. acc.:	Accurate to within 10 units		
Coord. meth.:	Global Positioning System		

Topo-set.:	Flat surface, plain	*Depth [m]:*	26.00
Site status:	In use	*Col. ht. [m]:*	0
Site purp.:	Observation	*Diam. [mm]:*	165
Use applic.:	Industrial - mining	*Drain. reg.:*	
Equipment:	No equipment	*Rep. inst.:*	

Coordinate System: South African LO Transverse Mercator, Hartebeesthoek94 (WGS 84)

CONSTRUCTION:

Date const.	Contractor	Constr. meth.	Type finish	Development Method	Durat.	Special treatment	Constr. cost
20081029		Air percussion	Open bottom	Compressed air			

HOLE DIAMETER:

Rep. Inst.	Depth to Top [m]	Depth to Bottom [m]	Diameter [mm]	Date const.	Comment
	0.00	18.00	215	20081029	
	18.00	26.00	165	20081029	

CASING DETAILS:

Date inst.	Dep. to top [m]	Bot. [m]	Diam. [mm]	Material	Thickn. [mm]	Opening Type	Length	Width	Hori. dist.	Vert. dist.
20081029	0.00	12.00	165	Steel	3					
20081029	12.00	18.00	165	Steel	3	Perforated or slotted	300	3	50	100

AQUIFER:

Rep. Inst.	Depth to Top [m]	Bot. [m]	Yield [l/s]	Method meas.	Aquifer type	Info source	Comment
	11.00	14.00	5.00	Estimated			

GEOLOGY:

Dep. Top [m]	Bot. [m]	Lithology code	Colour Primary	Secondary	Texture	Feature Primary	Secondary
0.00	1.00	OVERBURDEN	Grey	Dark		Gravel-bearing	
1.00	3.00	NORITE	Brown	Greyish	Medium	Weathered	
3.00	10.00	NORITE	Brown	Greyish	Medium	Weathered	
10.00	11.00	NORITE	Brown		Medium	Weathered	
11.00	14.00	NORITE	Brown	Greyish	Medium	Fractured	
14.00	16.00	NORITE	Brown	Greyish	Medium	Fractured	Fresh
16.00	18.00	NORITE	Brown	Greyish	Medium	Fresh	Fractured
18.00	20.00	NORITE	Brown	Greyish	Medium	Fresh	Fractured
20.00	26.00	NORITE	Grey	Brownish	Medium	Fresh	

WATER LEVEL:

Meth. meas.	Level status	Piez.	Info source	Date meas.	Time meas.	Sec.	Water lev. [m]	Comment
Electrical contact	Static	0	Field checked	20090203	1505	0.00	8.72	
Electrical contact	Static	0	Field checked	20090210	0740	0.00	8.74	

APPENDIX II

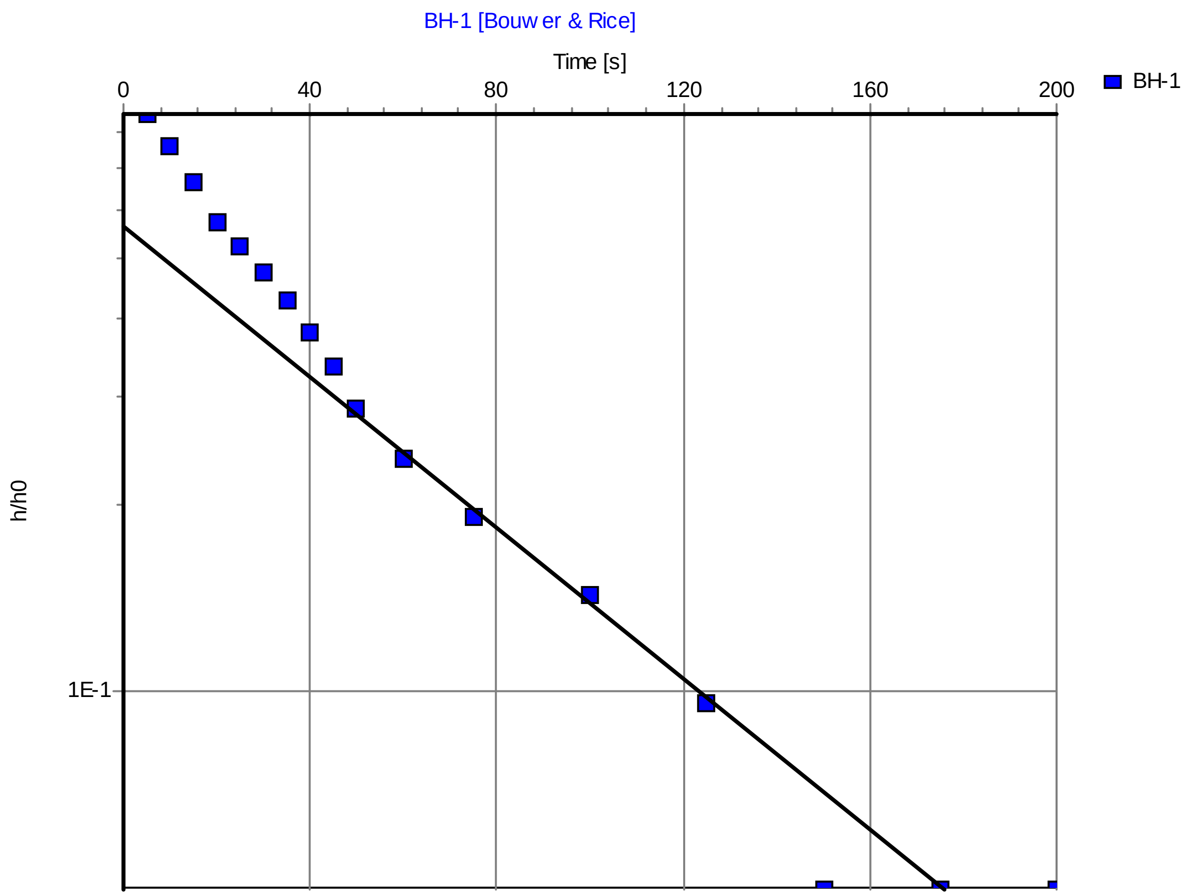
SLUG TEST SUMMARY AND ANALYSES SHEETS

2008131746 Case Study	Slug Test Data Report Project: Case Study Number: 2008131746 Client:	Page 1

Test Well:	**BH-1**	**Slug Test:**	**BH-1**
		Test Well:	BH-1
Depth to Static WL:	3.57 [m]	Casing radius:	0.0825 [m]
Location:		Boring radius:	0.1075 [m]
Recorded by:	2008131746	Screen length:	4 [m]
Date:	2009/02/09	Aquifer Thickness:	18.43 [m]

	Time [s]	Depth to WL [m]	Drawdown [m]
1	0	3.36	-0.21
2	5	3.39	-0.18
3	10	3.41	-0.16
4	15	3.43	-0.14
5	20	3.45	-0.12
6	25	3.46	-0.11
7	30	3.47	-0.10
8	35	3.48	-0.09
9	40	3.49	-0.08
10	45	3.50	-0.07
11	50	3.51	-0.06
12	60	3.52	-0.05
13	75	3.53	-0.04
14	100	3.54	-0.03
15	125	3.55	-0.02
16	150	3.56	-0.01
17	175	3.56	-0.01
18	200	3.56	-0.01
19	225	3.57	0.00

2008131746	**Slug Test Analysis Report**
	Project: Case Study
Case Study	Number: 2008131746
	Client:



Slug Test: **BH-1**

Analysis Method: **Bouwer & Rice**

Analysis Results: Conductivity: 3.92E+0 [m/d]

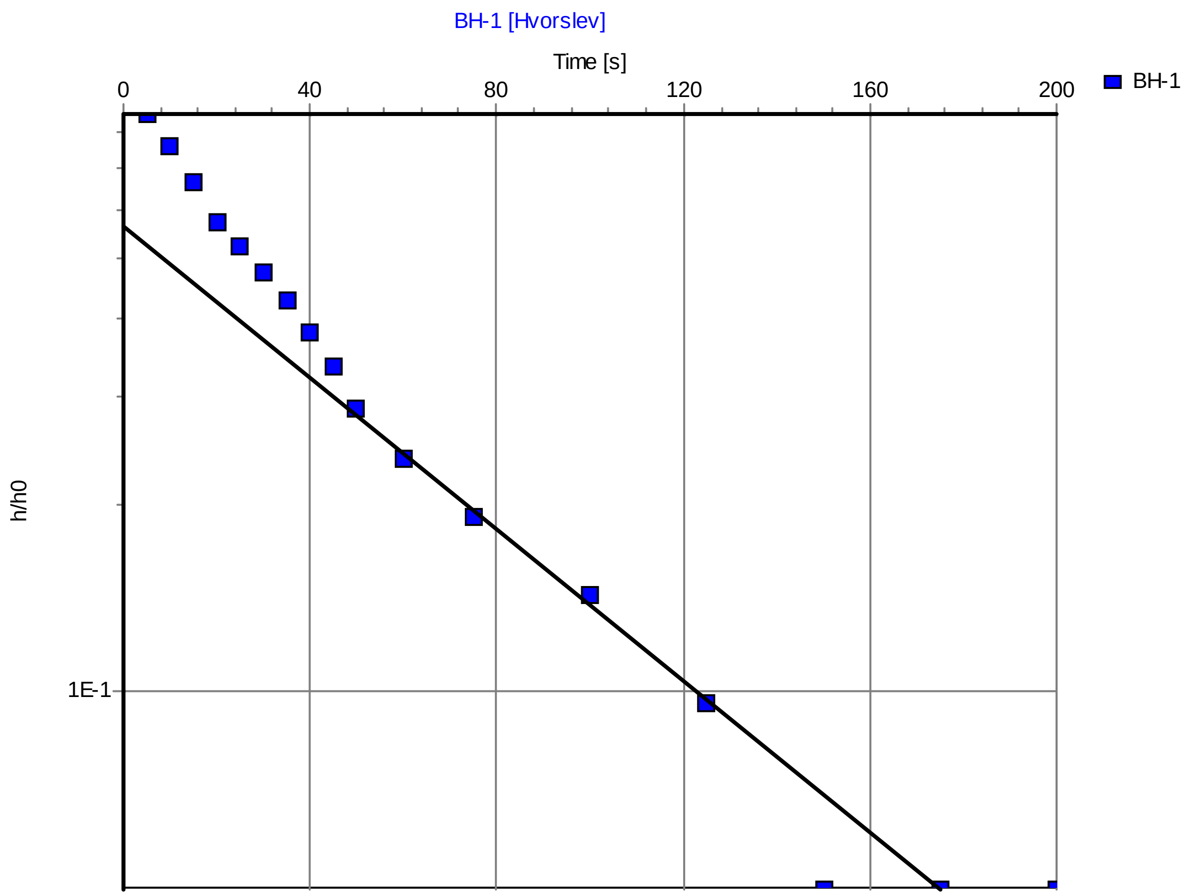
Test parameters:				
	Test Well:	BH-1	Aquifer Thickness:	18.43 [m]
	Casing radius:	0.0825 [m]	Gravel Pack Porosity (%)	25
	Screen length:	4 [m]		
	Boring radius:	0.1075 [m]		
	r(eff):	0.089 [m]		

Comments: Design Optimization for Hazardous Waste Disposal Facilities through the Application of Water Balance and Mass Transport Modelling

Evaluated by: 2008131746

Evaluation Date: 2009/05/01

2008131746	**Slug Test Analysis Report**
	Project: Case Study
Case Study	Number: 2008131746
	Client:



Slug Test: **BH-1**

Analysis Method: **Hvorslev**

Analysis Results: Conductivity: 3.77E+0 [m/d]

Test parameters:

Test Well:	BH-1	Aquifer Thickness:	18.43 [m]
Casing radius:	0.0825 [m]		
Screen length:	4 [m]		
Boring radius:	0.1075 [m]		

Comments: Design Optimization for Hazardous Waste Disposal Facilities through the Application of Water Balance and Mass Transport Modelling

Evaluated by: 2008131746

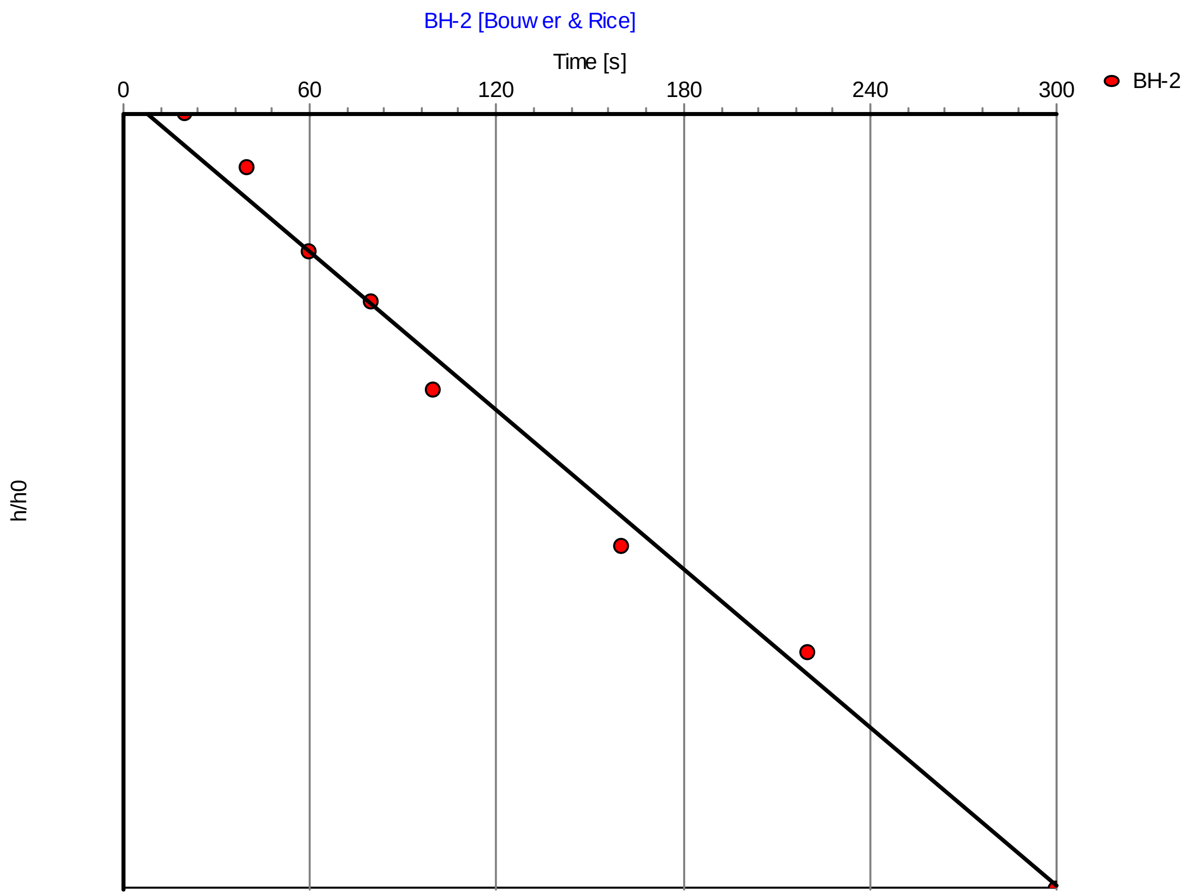
Evaluation Date: 2009/05/01

2008131746	**Slug Test Data Report**	
Case Study	Project: Case Study	
	Number: 2008131746	
	Client:	Page 1

Test Well:	**BH-2**	**Slug Test:**	**BH-2**
		Test Well:	BH-2
Depth to Static WL:	3.4 [m]	Casing radius:	0.0825 [m]
Location:		Boring radius:	0.1075 [m]
Recorded by:	2008131746	Screen length:	4 [m]
Date:	2009/02/09	Aquifer Thickness:	7.1 [m]

	Time [s]	Depth to WL [m]	Drawdown [m]
1	0	3.11	-0.29
2	20	3.15	-0.25
3	40	3.18	-0.22
4	60	3.22	-0.18
5	80	3.24	-0.16
6	100	3.27	-0.13
7	160	3.31	-0.09
8	220	3.33	-0.07
9	300	3.36	-0.04
10	400	3.38	-0.02
11	500	3.39	-0.01
12	600	3.40	0.00

2008131746	**Slug Test Analysis Report**
	Project: Case Study
Case Study	Number: 2008131746
	Client:



Slug Test: **BH-2**

Analysis Method: **Bouwer & Rice**

Analysis Results: Conductivity: 1.75E+0 [m/d]

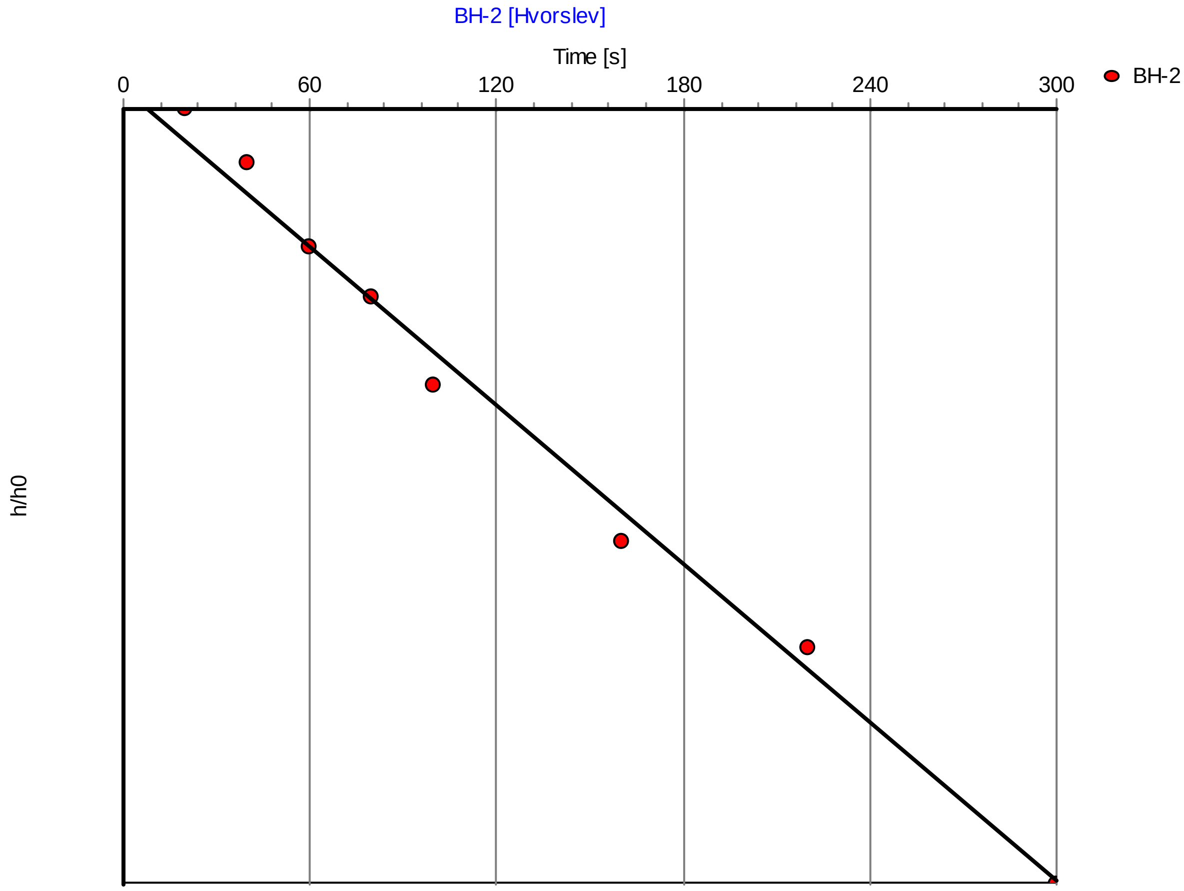
Test parameters:				
	Test Well:	BH-2	Aquifer Thickness:	7.1 [m]
	Casing radius:	0.0825 [m]	Gravel Pack Porosity (%)	25
	Screen length:	4 [m]		
	Boring radius:	0.1075 [m]		
	r(eff):	0.089 [m]		

Comments: Design Optimization for Hazardous Waste Disposal Facilities through the Application of Water Balance and Mass Transport Modelling

Evaluated by: 2008131746

Evaluation Date: 2009/05/01

2008131746	**Slug Test Analysis Report**
Case Study	Project: Case Study
	Number: 2008131746
	Client:



Slug Test: **BH-2**

Analysis Method: **Hvorslev**

Analysis Results: Conductivity: 1.67E+0 [m/d]

Test parameters:				
	Test Well:	BH-2	Aquifer Thickness:	7.1 [m]
	Casing radius:	0.0825 [m]		
	Screen length:	4 [m]		
	Boring radius:	0.1075 [m]		

Comments: Design Optimization for Hazardous Waste Disposal Facilities through the Application of Water Balance and Mass Transport Modelling

Evaluated by: 2008131746

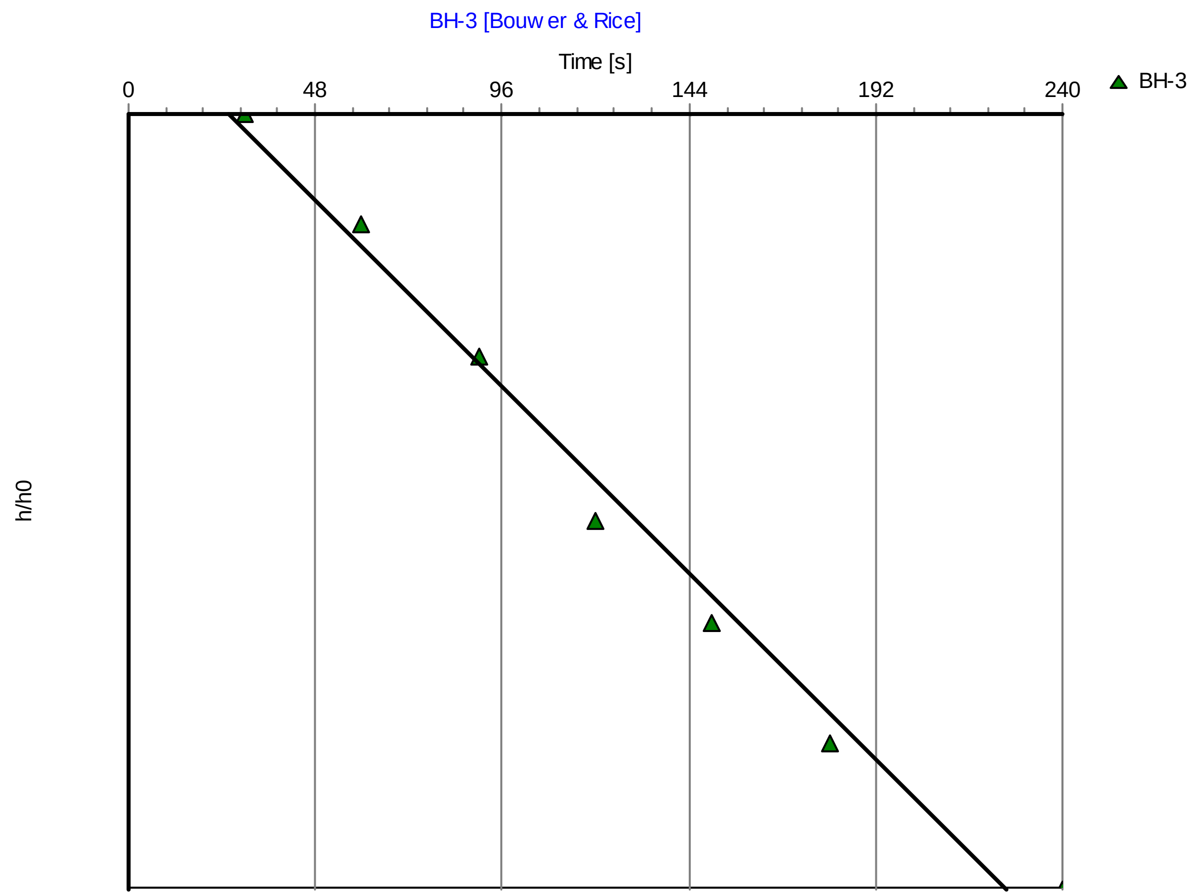
Evaluation Date: 2009/05/01

2008131746 Case Study	**Slug Test Data Report** Project: Case Study Number: 2008131746 Client:	Page 1

Test Well:	**BH-3**	**Slug Test:**	**BH-3**
		Test Well:	BH-3
Depth to Static WL:	2 [m]	Casing radius:	0.0825 [m]
Location:		Boring radius:	0.1075 [m]
Recorded by:	2008131746	Screen length:	8 [m]
Date:	2009/02/09	Aquifer Thickness:	13 [m]

	Time [s]	Depth to WL [m]	Drawdown [m]
1	0	1.84	-0.16
2	30	1.87	-0.13
3	60	1.89	-0.11
4	90	1.91	-0.09
5	120	1.93	-0.07
6	150	1.94	-0.06
7	180	1.95	-0.05
8	240	1.96	-0.04
9	270	1.96	-0.04
10	300	1.97	-0.03
11	350	1.98	-0.02
12	400	1.99	-0.01
13	450	2.00	0.00

2008131746	**Slug Test Analysis Report**
	Project: Case Study
Case Study	Number: 2008131746
	Client:



Slug Test: **BH-3**

Analysis Method: **Bouwer & Rice**

Analysis Results: Conductivity: 8.68E-1 [m/d]

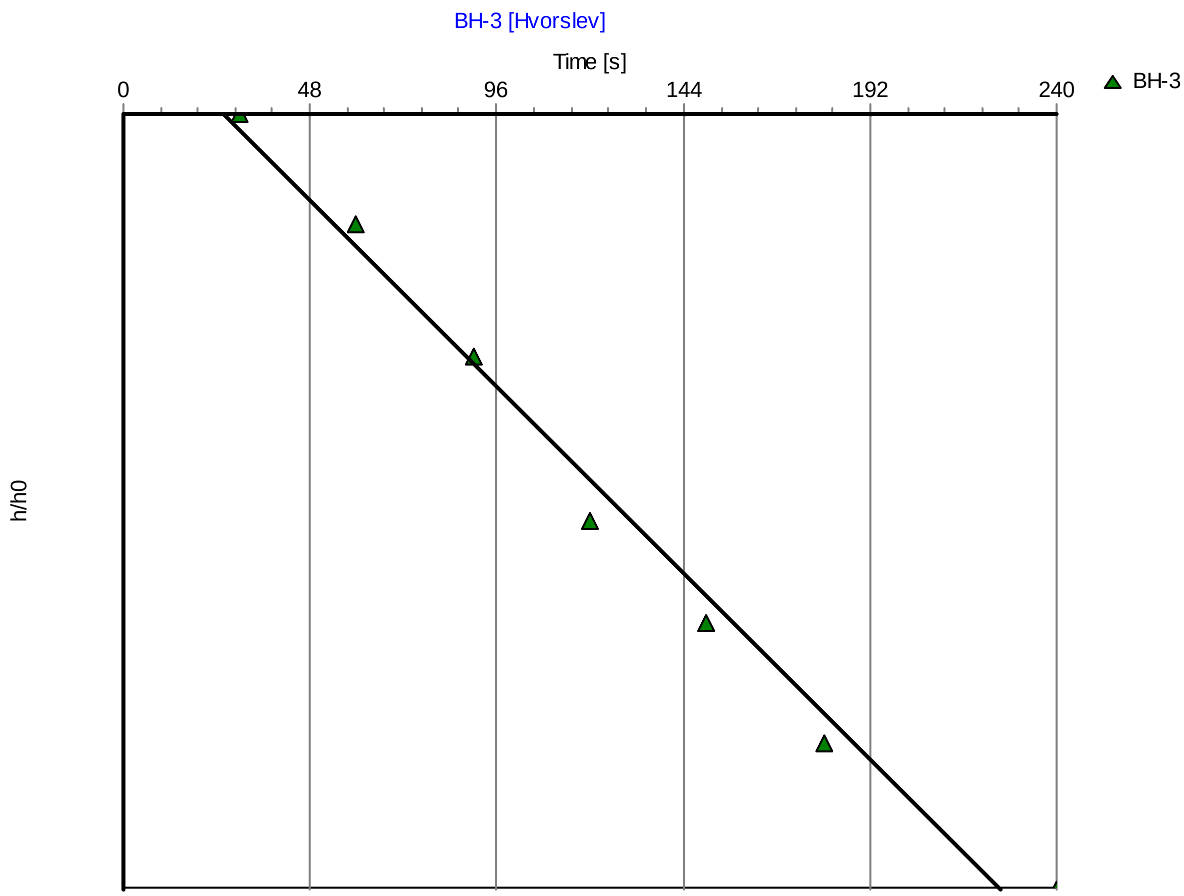
Test parameters:				
	Test Well:	BH-3	Aquifer Thickness:	13 [m]
	Casing radius:	0.0825 [m]	Gravel Pack Porosity (%)	25
	Screen length:	8 [m]		
	Boring radius:	0.1075 [m]		
	r(eff):	0.089 [m]		

Comments: Design Optimization for Hazardous Waste Disposal Facilities through the Application of Water Balance and Mass Transport Modelling

Evaluated by: 2008131746

Evaluation Date: 2009/05/01

2008131746 Case Study	**Slug Test Analysis Report**
	Project: Case Study
	Number: 2008131746
	Client:



Slug Test: **BH-3**

Analysis Method: **Hvorslev**

Analysis Results: Conductivity: 9.39E-1 [m/d]

Test parameters:				
	Test Well:	BH-3	Aquifer Thickness:	13 [m]
	Casing radius:	0.0825 [m]		
	Screen length:	8 [m]		
	Boring radius:	0.1075 [m]		

Comments: Design Optimization for Hazardous Waste Disposal Facilities through the Application of Water Balance and Mass Transport Modelling

Evaluated by: 2008131746

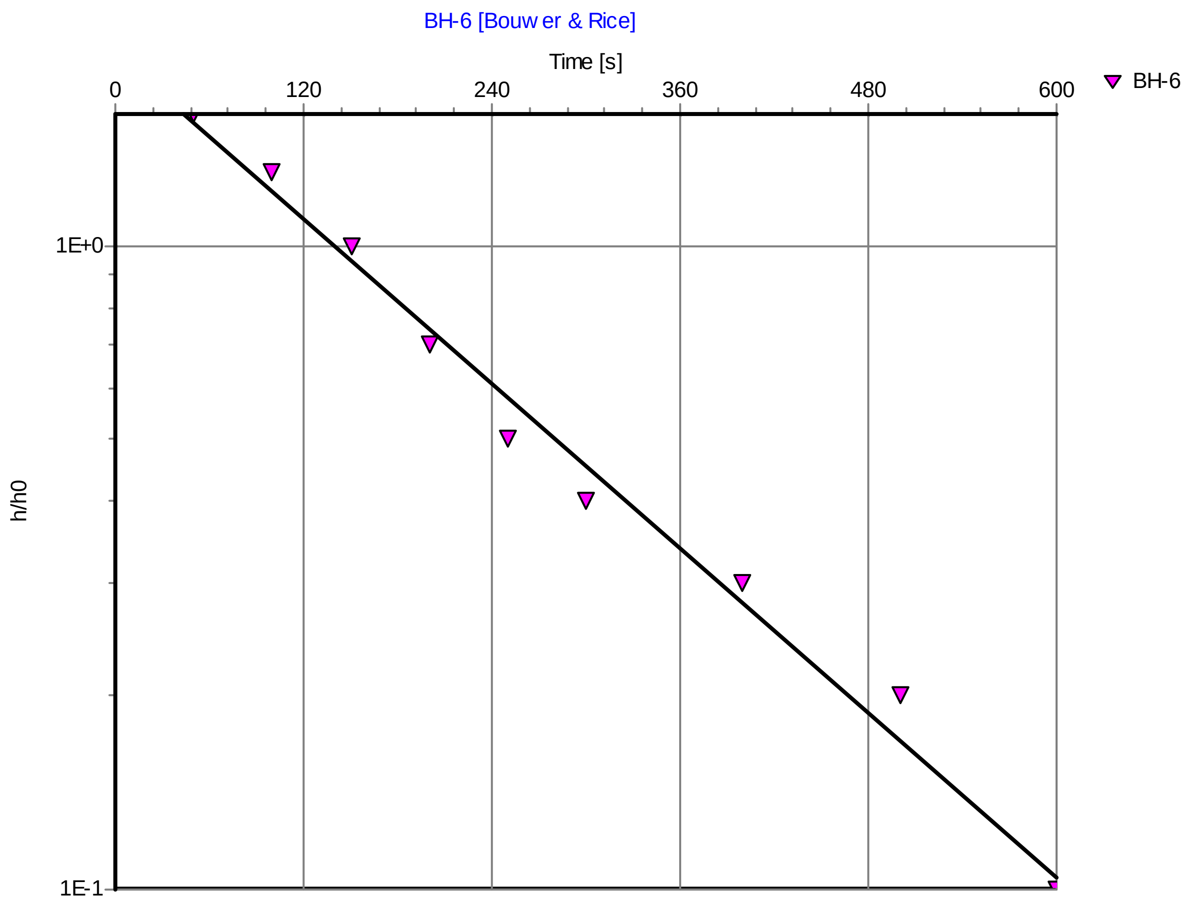
Evaluation Date: 2009/05/01

2008131746	**Slug Test Data Report**	
Case Study	Project: Case Study	
	Number: 2008131746	
	Client:	Page 1

Test Well:	**BH-6**	**Slug Test:**	**BH-6**
		Test Well:	BH-6
Depth to Static WL:	4.26 [m]	Casing radius:	0.0825 [m]
Location:		Boring radius:	0.1075 [m]
Recorded by:	2008131746	Screen length:	7 [m]
Date:	2009/02/09	Aquifer Thickness:	11.74 [m]

	Time [s]	Depth to WL [m]	Drawdown [m]
1	0	4.06	-0.20
2	50	4.10	-0.16
3	100	4.13	-0.13
4	150	4.16	-0.10
5	200	4.19	-0.07
6	250	4.21	-0.05
7	300	4.22	-0.04
8	400	4.23	-0.03
9	500	4.24	-0.02
10	600	4.25	-0.01
11	750	4.26	0.00

2008131746	**Slug Test Analysis Report**
	Project: Case Study
Case Study	Number: 2008131746
	Client:



Slug Test: **BH-6**

Analysis Method: **Bouwer & Rice**

Analysis Results: Conductivity: 7.97E-1 [m/d]

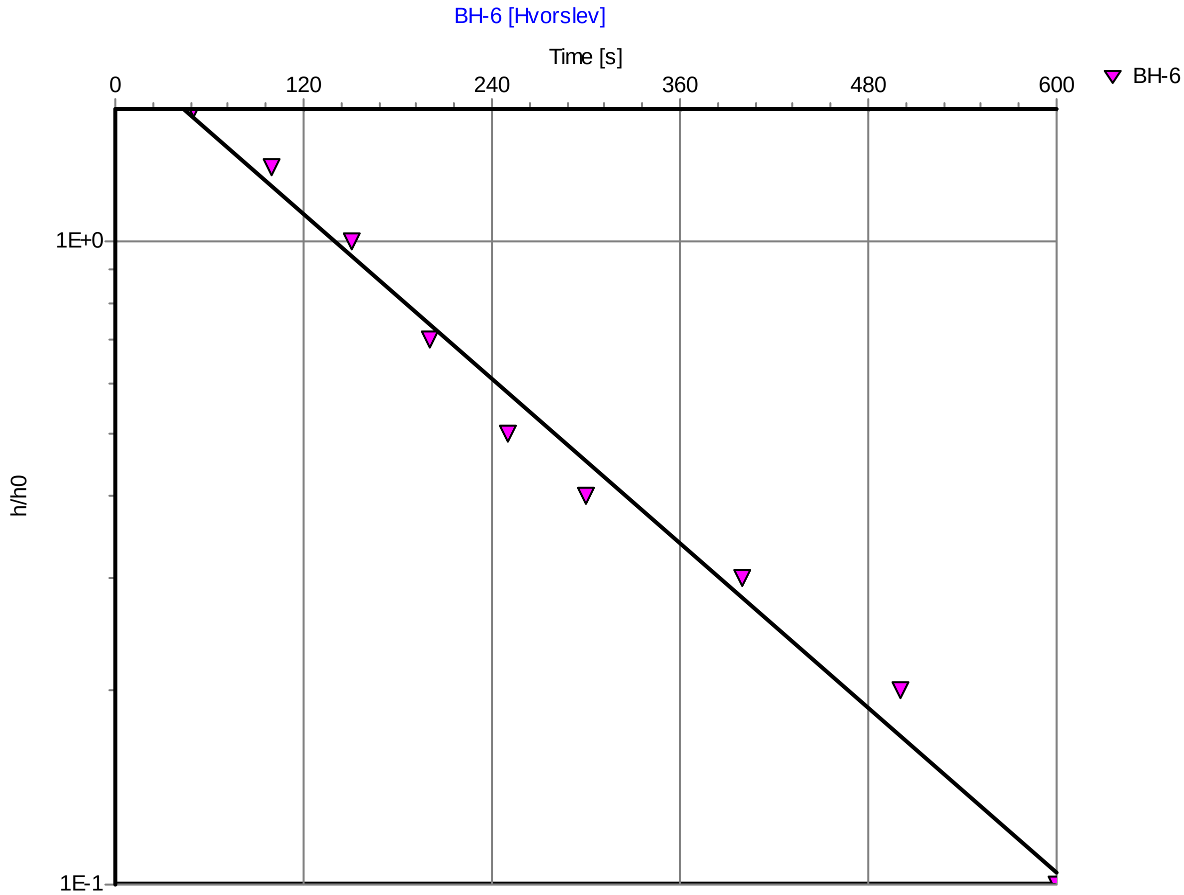
Test parameters:				
	Test Well:	BH-6	Aquifer Thickness:	11.74 [m]
	Casing radius:	0.0825 [m]	Gravel Pack Porosity (%)	25
	Screen length:	7 [m]		
	Boring radius:	0.1075 [m]		
	r(eff):	0.089 [m]		

Comments: Design Optimization for Hazardous Waste Disposal Facilities through the Application of Water Balance and Mass Transport Modelling

Evaluated by: 2008131746

Evaluation Date: 2009/05/01

2008131746	**Slug Test Analysis Report**
	Project: Case Study
Case Study	Number: 2008131746
	Client:



Slug Test: **BH-6**

Analysis Method: **Hvorslev**

Analysis Results: Conductivity: 8.64E-1 [m/d]

Test parameters:				
	Test Well:	BH-6	Aquifer Thickness:	11.74 [m]
	Casing radius:	0.0825 [m]		
	Screen length:	7 [m]		
	Boring radius:	0.1075 [m]		

Comments: Design Optimization for Hazardous Waste Disposal Facilities through the Application of Water Balance and Mass Transport Modelling

Evaluated by: 2008131746

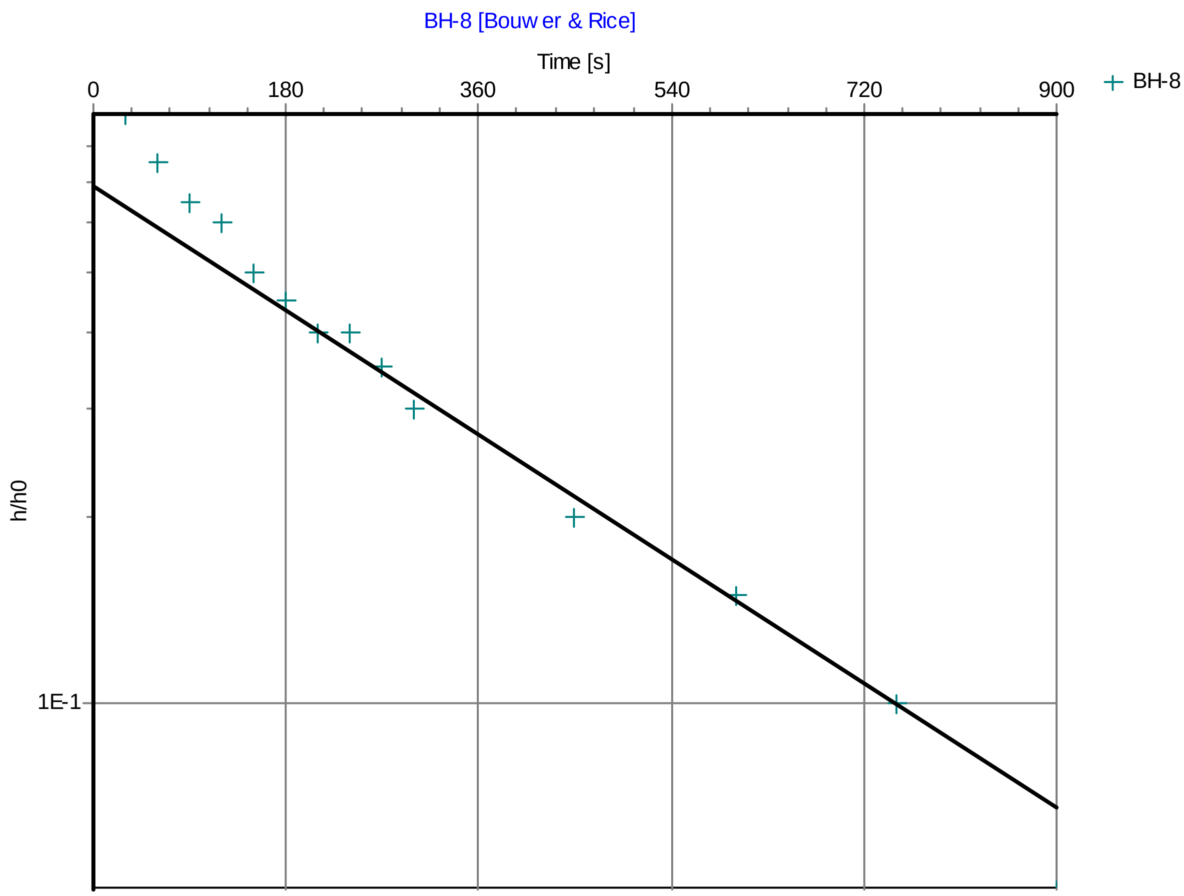
Evaluation Date: 2009/05/01

2008131746	**Slug Test Data Report**
	Project: Case Study
Case Study	Number: 2008131746
	Client: Page 1

Test Well:	**BH-8**	**Slug Test:**	**BH-8**
		Test Well:	BH-8
Depth to Static WL:	2.63 [m]	Casing radius:	0.0825 [m]
Location:		Boring radius:	0.1075 [m]
Recorded by:	2008131746	Screen length:	9 [m]
Date:	2009/02/09	Aquifer Thickness:	14.27 [m]

	Time [s]	Depth to WL [m]	Drawdown [m]
1	0	2.43	-0.20
2	30	2.45	-0.18
3	60	2.48	-0.15
4	90	2.50	-0.13
5	120	2.51	-0.12
6	150	2.53	-0.10
7	180	2.54	-0.09
8	210	2.55	-0.08
9	240	2.55	-0.08
10	270	2.56	-0.07
11	300	2.57	-0.06
12	450	2.59	-0.04
13	600	2.60	-0.03
14	750	2.61	-0.02
15	900	2.62	-0.01

2008131746	**Slug Test Analysis Report**
	Project: Case Study
Case Study	Number: 2008131746
	Client:



Slug Test: **BH-8**

Analysis Method: **Bouwer & Rice**

Analysis Results: Conductivity: 3.37E-1 [m/d]

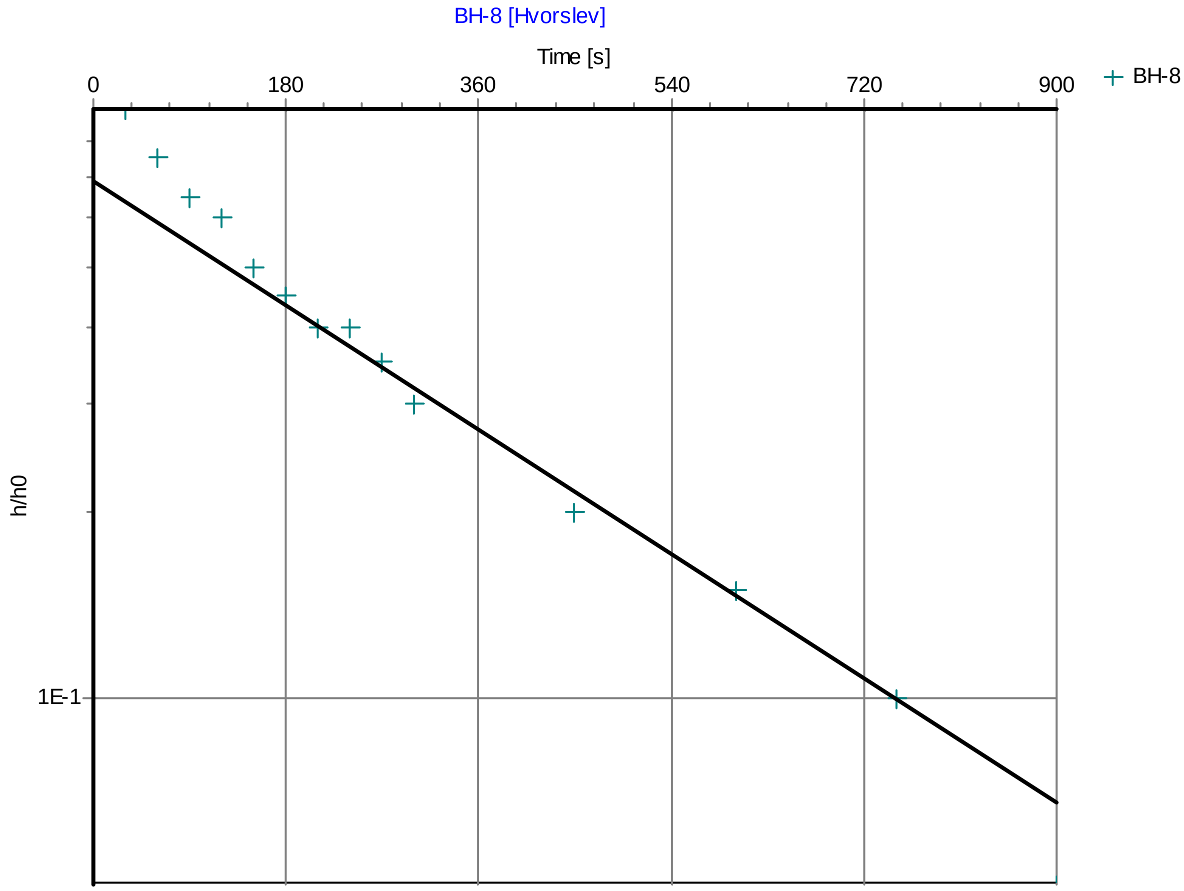
Test parameters:				
	Test Well:	BH-8	Aquifer Thickness:	14.27 [m]
	Casing radius:	0.0825 [m]	Gravel Pack Porosity (%)	25
	Screen length:	9 [m]		
	Boring radius:	0.1075 [m]		
	r(eff):	0.089 [m]		

Comments: Design Optimization for Hazardous Waste Disposal Facilities through the Application of Water Balance and Mass Transport Modelling

Evaluated by: 2008131746

Evaluation Date: 2009/05/01

2008131746 Case Study	**Slug Test Analysis Report** Project: Case Study Number: 2008131746 Client:



Slug Test: **BH-8**

Analysis Method: **Hvorslev**

Analysis Results: Conductivity: 3.75E-1 [m/d]

Test parameters:				
	Test Well:	BH-8	Aquifer Thickness:	14.27 [m]
	Casing radius:	0.0825 [m]		
	Screen length:	9 [m]		
	Boring radius:	0.1075 [m]		

Comments: Design Optimization for Hazardous Waste Disposal Facilities through the Application of Water Balance and Mass Transport Modelling

Evaluated by: 2008131746

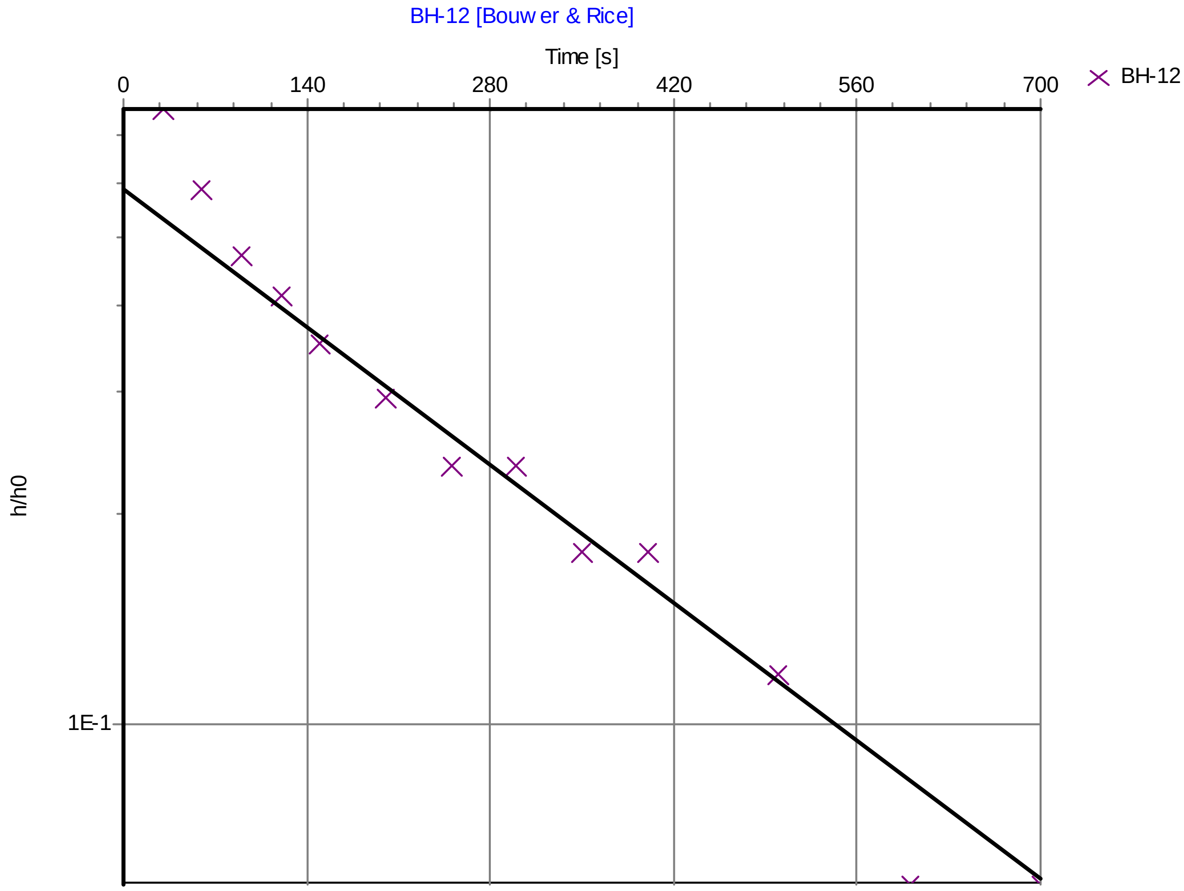
Evaluation Date: 2009/05/01

2008131746	Slug Test Data Report	
	Project: Case Study	
Case Study	Number: 2008131746	
	Client:	Page 1

Test Well:	**BH-12**	**Slug Test:**	**BH-12**
		Test Well:	BH-12
Depth to Static WL:	4 [m]	Casing radius:	0.0825 [m]
Location:		Boring radius:	0.1075 [m]
Recorded by:	2008131746	Screen length:	6 [m]
Date:	2009/02/09	Aquifer Thickness:	9 [m]

	Time [s]	Depth to WL [m]	Drawdown [m]
1	0	3.83	-0.17
2	30	3.87	-0.13
3	60	3.90	-0.10
4	90	3.92	-0.08
5	120	3.93	-0.07
6	150	3.94	-0.06
7	200	3.95	-0.05
8	250	3.96	-0.04
9	300	3.96	-0.04
10	350	3.97	-0.03
11	400	3.97	-0.03
12	500	3.98	-0.02
13	600	3.99	-0.01
14	700	3.99	-0.01
15	800	4.00	0.00
16	800	4.00	0.00

2008131746	**Slug Test Analysis Report**
	Project: Case Study
Case Study	Number: 2008131746
	Client:



Slug Test: **BH-12**

Analysis Method: **Bouwer & Rice**

Analysis Results: Conductivity: 6.40E-1 [m/d]

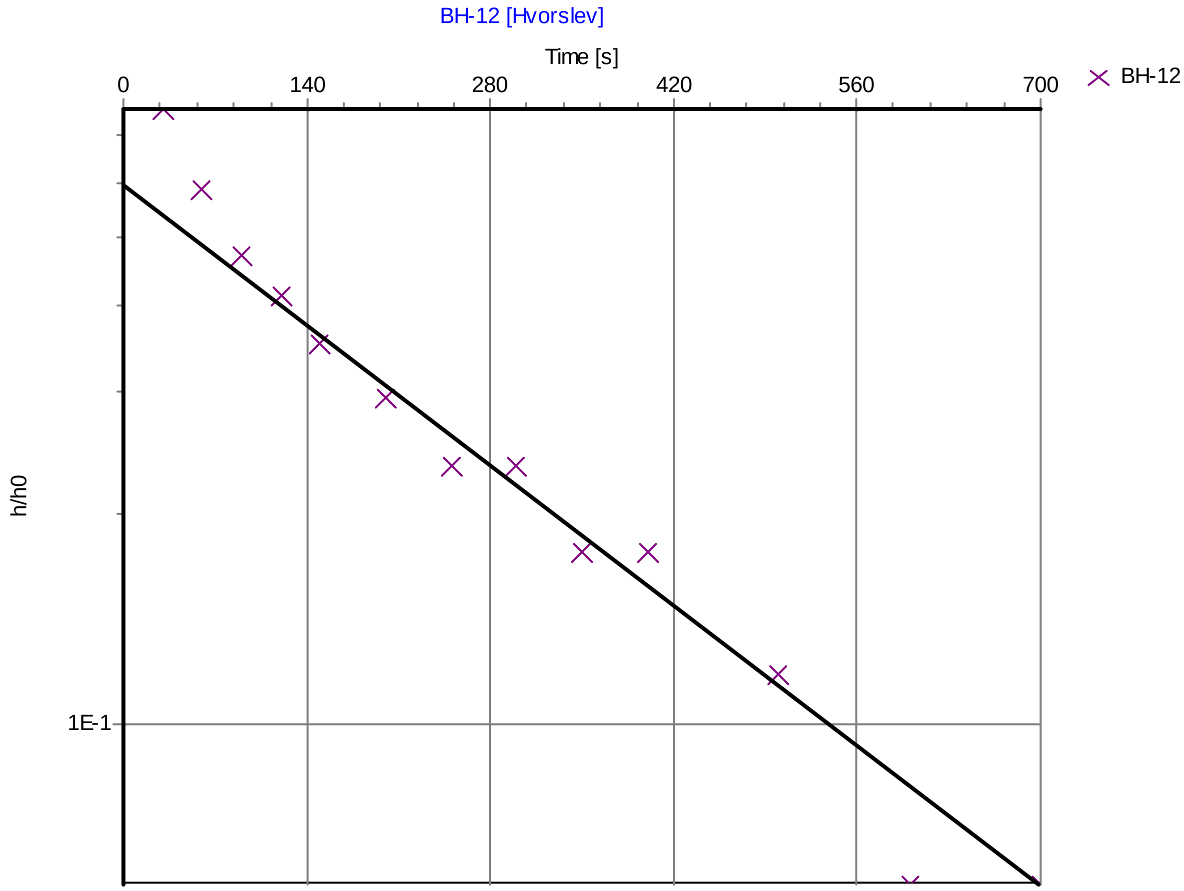
Test parameters:				
	Test Well:	BH-12	Aquifer Thickness:	9 [m]
	Casing radius:	0.0825 [m]	Gravel Pack Porosity (%)	25
	Screen length:	6 [m]		
	Boring radius:	0.1075 [m]		
	r(eff):	0.089 [m]		

Comments: Design Optimization for Hazardous Waste Disposal Facilities through the Application of Water Balance and Mass Transport Modelling

Evaluated by: 2008131746

Evaluation Date: 2009/05/01

2008131746 Case Study	**Slug Test Analysis Report**
	Project: Case Study
	Number: 2008131746
	Client:



Slug Test: **BH-12**

Analysis Method: **Hvorslev**

Analysis Results: Conductivity: 6.57E-1 [m/d]

Test parameters:			
Test Well:	BH-12	Aquifer Thickness:	9 [m]
Casing radius:	0.0825 [m]		
Screen length:	6 [m]		
Boring radius:	0.1075 [m]		

Comments: Design Optimization for Hazardous Waste Disposal Facilities through the Application of Water Balance and Mass Transport Modelling

Evaluated by: 2008131746

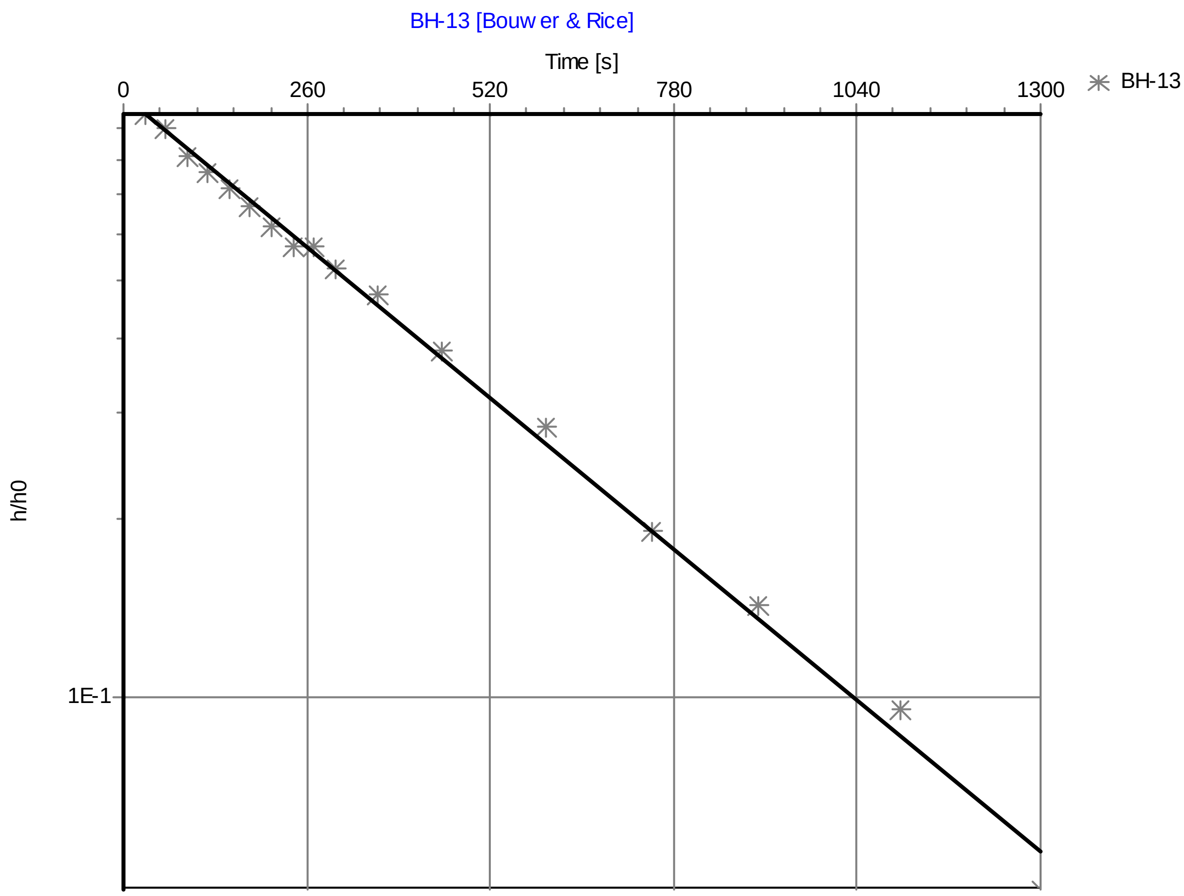
Evaluation Date: 2009/05/01

2008131746 Case Study	**Slug Test Data Report**	
	Project: Case Study	
	Number: 2008131746	
	Client:	Page 1

Test Well:	**BH-13**	**Slug Test:**	**BH-13**
		Test Well:	BH-13
Depth to Static WL:	13.07 [m]	Casing radius:	0.0825 [m]
Location:		Boring radius:	0.1075 [m]
Recorded by:	2008131746	Screen length:	5.5 [m]
Date:	2009/02/10	Aquifer Thickness:	4.93 [m]

	Time [s]	Depth to WL [m]	Drawdown [m]
1	0	12.86	-0.21
2	30	12.87	-0.20
3	60	12.88	-0.19
4	90	12.90	-0.17
5	120	12.91	-0.16
6	150	12.92	-0.15
7	180	12.93	-0.14
8	210	12.94	-0.13
9	240	12.95	-0.12
10	270	12.95	-0.12
11	300	12.96	-0.11
12	360	12.97	-0.10
13	450	12.99	-0.08
14	600	13.01	-0.06
15	750	13.03	-0.04
16	900	13.04	-0.03
17	1100	13.05	-0.02
18	1300	13.06	-0.01

2008131746 Case Study	**Slug Test Analysis Report**
	Project: Case Study
	Number: 2008131746
	Client:



Slug Test: **BH-13**

Analysis Method: **Bouwer & Rice**

Analysis Results: Conductivity: 4.21E-1 [m/d]

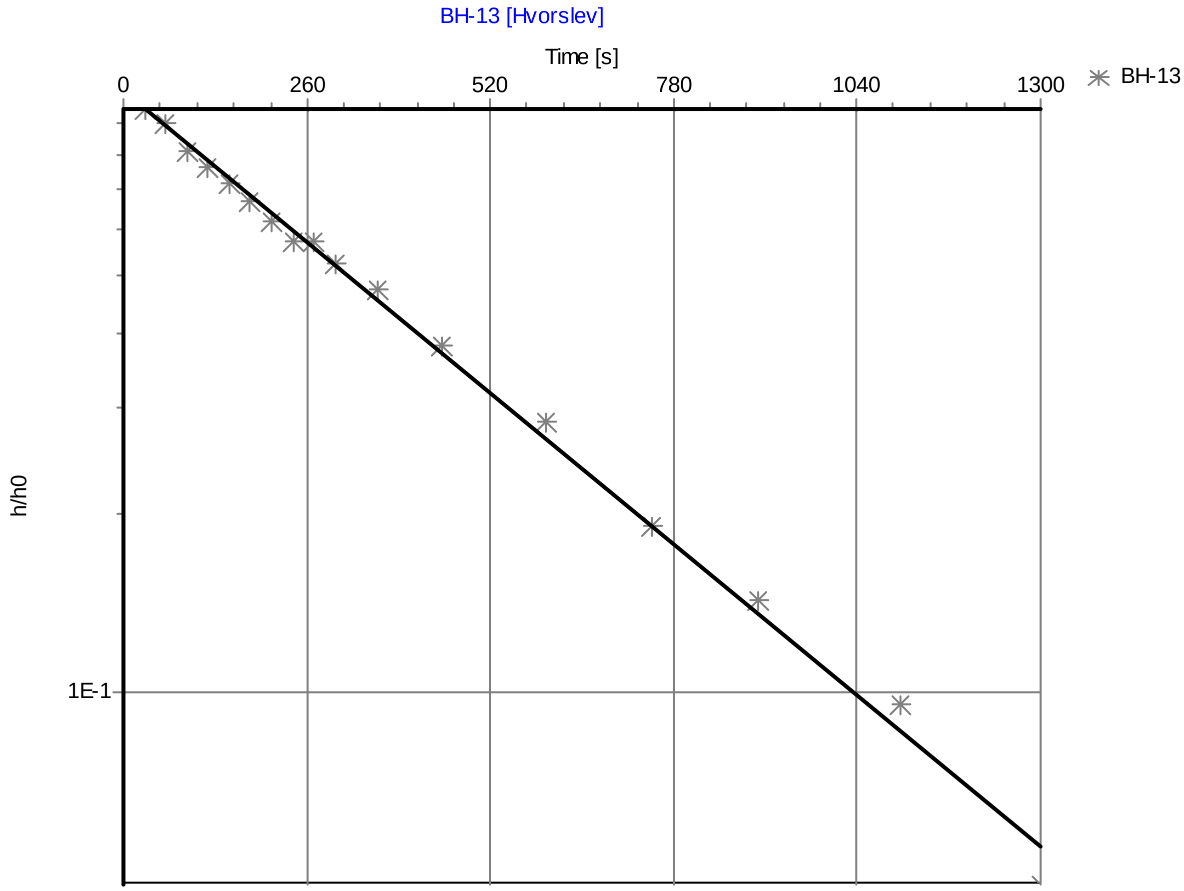
Test parameters:				
	Test Well:	BH-13	Aquifer Thickness:	4.93 [m]
	Casing radius:	0.0825 [m]	Gravel Pack Porosity (%)	25
	Screen length:	5.5 [m]		
	Boring radius:	0.1075 [m]		
	r(eff):	0.089 [m]		

Comments: Design Optimization for Hazardous Waste Disposal Facilities through the Application of Water Balance and Mass Transport Modelling

Evaluated by: 2008131746

Evaluation Date: 2009/05/01

2008131746	**Slug Test Analysis Report**
	Project: Case Study
Case Study	Number: 2008131746
	Client:



Slug Test: **BH-13**

Analysis Method: **Hvorslev**

Analysis Results: Conductivity: 4.75E-1 [m/d]

Test parameters:				
	Test Well:	BH-13	Aquifer Thickness:	4.93 [m]
	Casing radius:	0.0825 [m]		
	Screen length:	5.5 [m]		
	Boring radius:	0.1075 [m]		

Comments: Design Optimization for Hazardous Waste Disposal Facilities through the Application of Water Balance and Mass Transport Modelling

Evaluated by: 2008131746

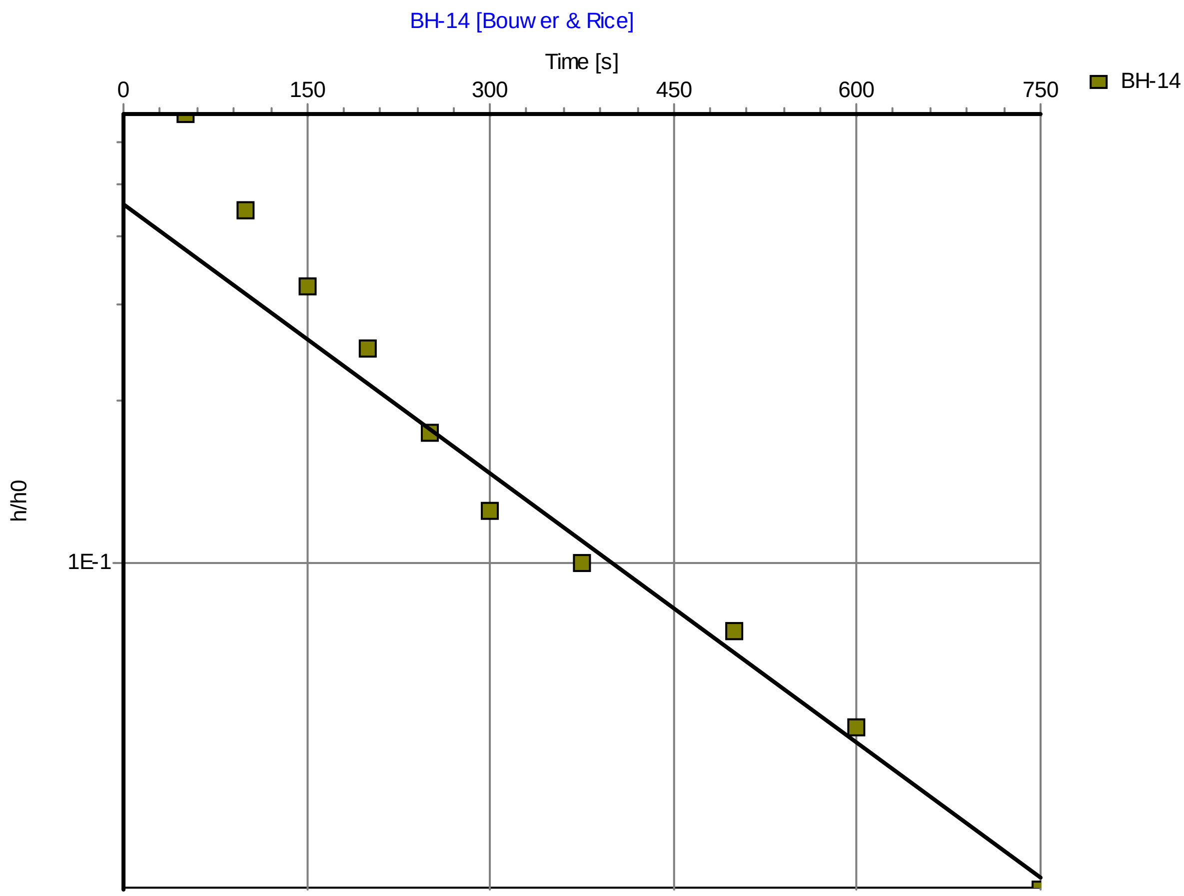
Evaluation Date: 2009/05/01

2008131746 Case Study	**Slug Test Data Report** Project: Case Study Number: 2008131746 Client:	Page 1

Test Well:	**BH-14**	**Slug Test:**	**BH-14**
		Test Well:	BH-14
Depth to Static WL:	16.59 [m]	Casing radius:	0.0825 [m]
Location:		Boring radius:	0.1075 [m]
Recorded by:	2008131746	Screen length:	7.5 [m]
Date:	2009/02/10	Aquifer Thickness:	2.41 [m]

	Time [s]	Depth to WL [m]	Drawdown [m]
1	0	16.19	-0.40
2	50	16.32	-0.27
3	100	16.41	-0.18
4	150	16.46	-0.13
5	200	16.49	-0.10
6	250	16.52	-0.07
7	300	16.54	-0.05
8	375	16.55	-0.04
9	500	16.56	-0.03
10	600	16.57	-0.02
11	750	16.58	-0.01
12	1000	16.59	0.00

2008131746 Case Study	**Slug Test Analysis Report** Project: Case Study Number: 2008131746 Client:



Slug Test: **BH-14**

Analysis Method: **Bouwer & Rice**

Analysis Results: Conductivity: 4.95E-1 [m/d]

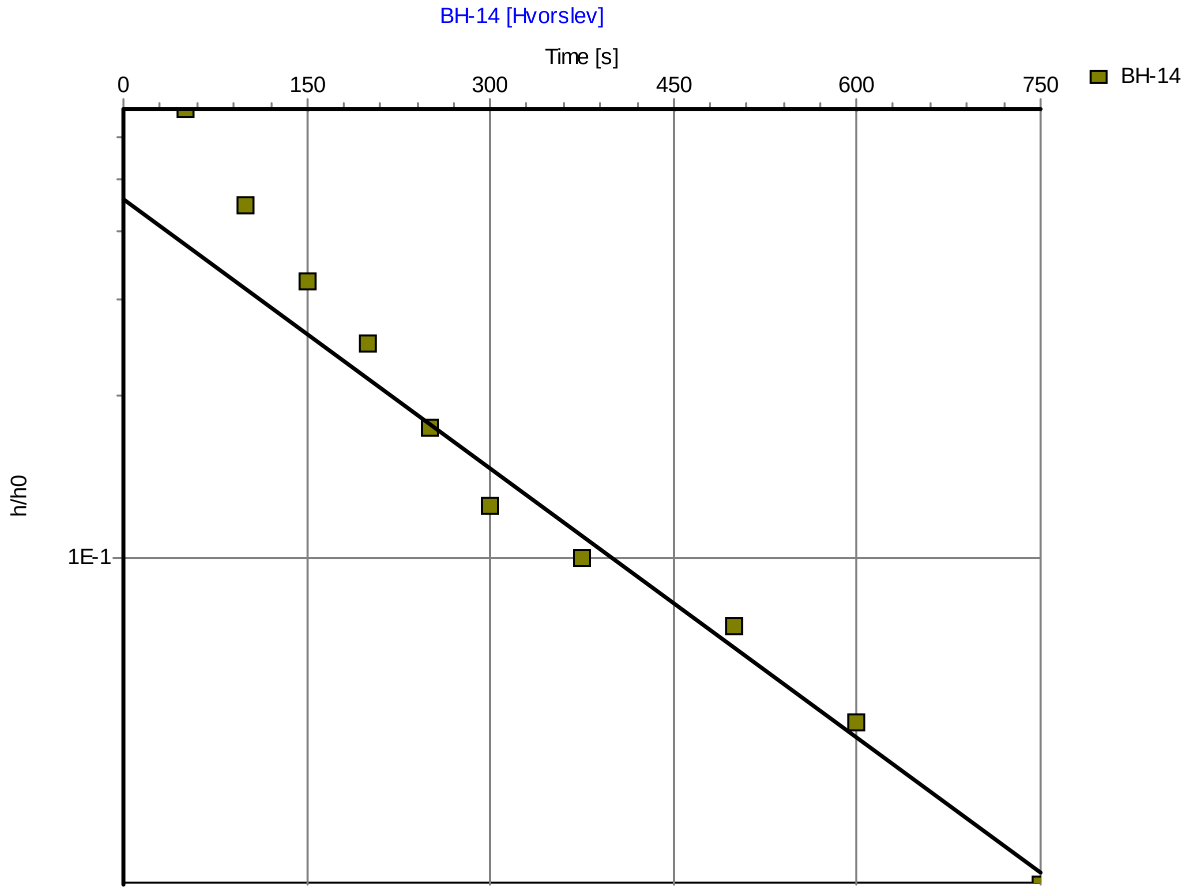
Test parameters:				
	Test Well:	BH-14	Aquifer Thickness:	2.41 [m]
	Casing radius:	0.0825 [m]	Gravel Pack Porosity (%)	25
	Screen length:	7.5 [m]		
	Boring radius:	0.1075 [m]		
	r(eff):	0.089 [m]		

Comments: Design Optimization for Hazardous Waste Disposal Facilities through the Application of Water Balance and Mass Transport Modelling

Evaluated by: 2008131746

Evaluation Date: 2009/05/01

2008131746 Case Study	**Slug Test Analysis Report**
	Project: Case Study
	Number: 2008131746
	Client:



Slug Test: **BH-14**

Analysis Method: **Hvorslev**

Analysis Results:			Conductivity:	6.38E-1 [m/d]
Test parameters:	Test Well:	BH-14	Aquifer Thickness:	2.41 [m]
	Casing radius:	0.0825 [m]		
	Screen length:	7.5 [m]		
	Boring radius:	0.1075 [m]		

Comments: Design Optimization for Hazardous Waste Disposal Facilities through the Application of Water Balance and Mass Transport Modelling

Evaluated by: 2008131746

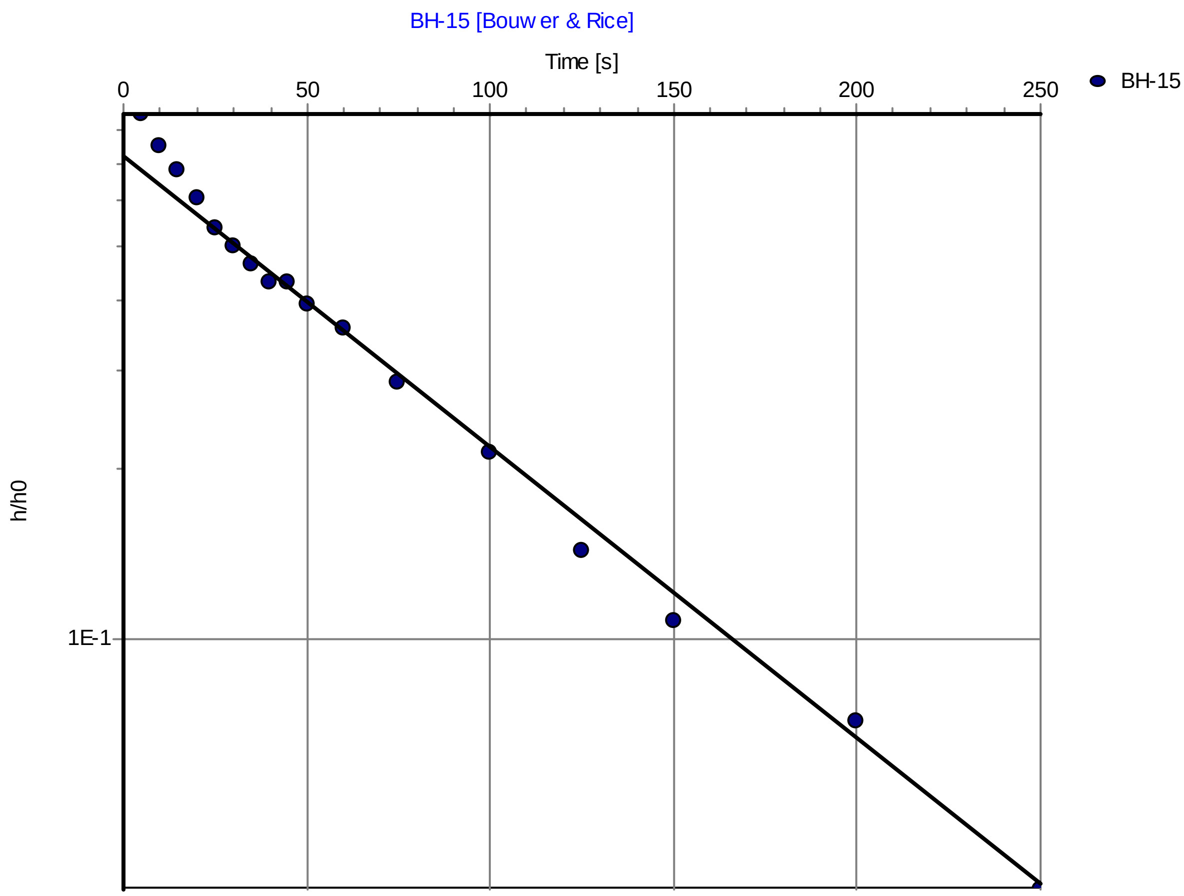
Evaluation Date: 2009/05/01

2008131746 Case Study	**Slug Test Data Report**	
	Project: Case Study	
	Number: 2008131746	
	Client:	Page 1

Test Well:	**BH-15**	**Slug Test:**	**BH-15**
		Test Well:	BH-15
Depth to Static WL:	8.74 [m]	Casing radius:	0.0825 [m]
Location:		Boring radius:	0.1075 [m]
Recorded by:	2008131746	Screen length:	7.5 [m]
Date:	2009/02/10	Aquifer Thickness:	11.26 [m]

	Time [s]	Depth to WL [m]	Drawdown [m]
1	0	8.46	-0.28
2	5	8.50	-0.24
3	10	8.53	-0.21
4	15	8.55	-0.19
5	20	8.57	-0.17
6	25	8.59	-0.15
7	30	8.60	-0.14
8	35	8.61	-0.13
9	40	8.62	-0.12
10	45	8.62	-0.12
11	50	8.63	-0.11
12	60	8.64	-0.10
13	75	8.66	-0.08
14	100	8.68	-0.06
15	125	8.70	-0.04
16	150	8.71	-0.03
17	200	8.72	-0.02
18	250	8.73	-0.01
19	300	8.74	0.00

2008131746	**Slug Test Analysis Report**
Case Study	Project: Case Study
	Number: 2008131746
	Client:



Slug Test: **BH-15**

Analysis Method: **Bouwer & Rice**

Analysis Results: Conductivity: 1.78E+0 [m/d]

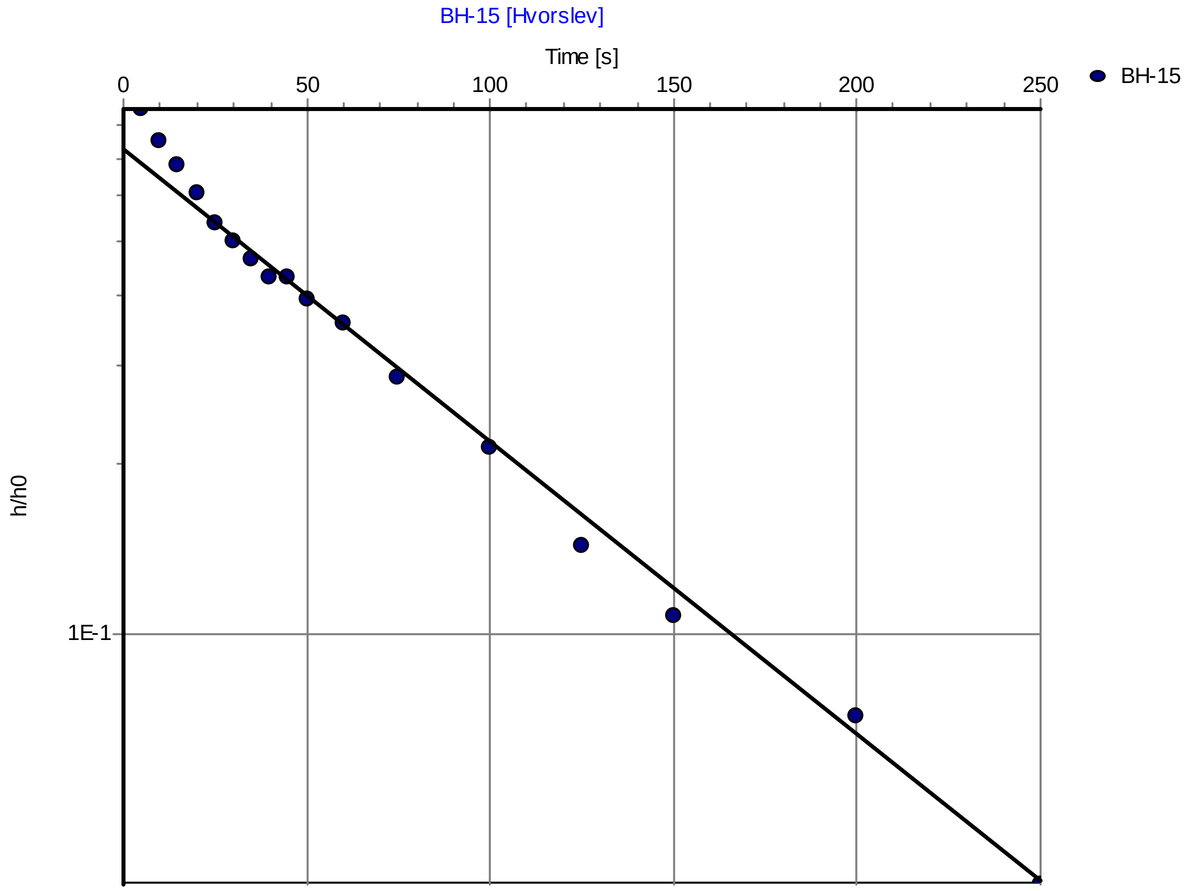
Test parameters:				
	Test Well:	BH-15	Aquifer Thickness:	11.26 [m]
	Casing radius:	0.0825 [m]	Gravel Pack Porosity (%)	25
	Screen length:	7.5 [m]		
	Boring radius:	0.1075 [m]		
	r(eff):	0.089 [m]		

Comments: Design Optimization for Hazardous Waste Disposal Facilities through the Application of Water Balance and Mass Transport Modelling

Evaluated by: 2008131746

Evaluation Date: 2009/05/01

2008131746 Case Study	**Slug Test Analysis Report** Project: Case Study Number: 2008131746 Client:



Slug Test: **BH-15**

Analysis Method: **Hvorslev**

Analysis Results: Conductivity: 2.01E+0 [m/d]

Test parameters:

Test Well:	BH-15	Aquifer Thickness:	11.26 [m]
Casing radius:	0.0825 [m]		
Screen length:	7.5 [m]		
Boring radius:	0.1075 [m]		

Comments: Design Optimization for Hazardous Waste Disposal Facilities through the Application of Water Balance and Mass Transport Modelling

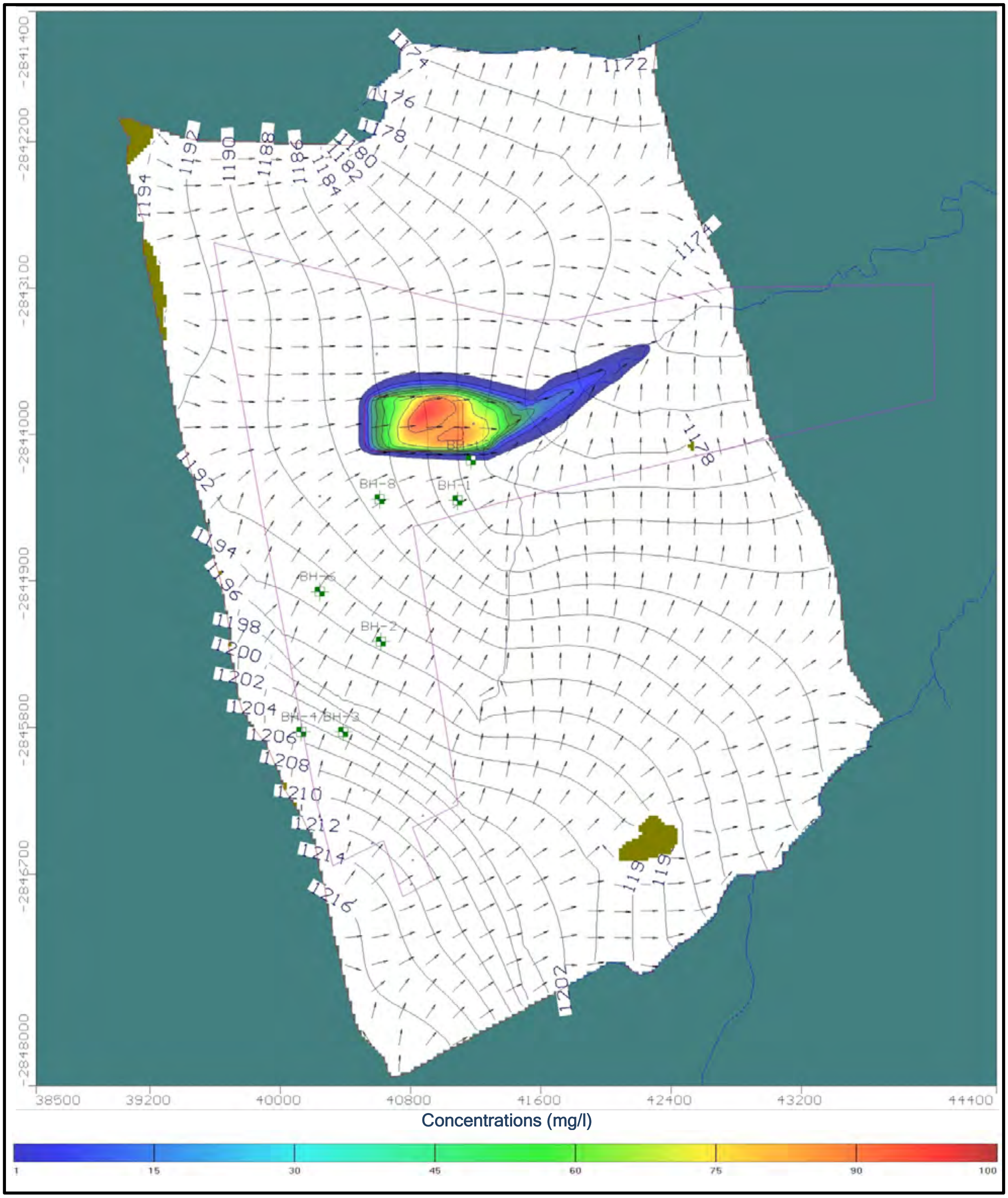
Evaluated by: 2008131746

Evaluation Date: 2009/05/01

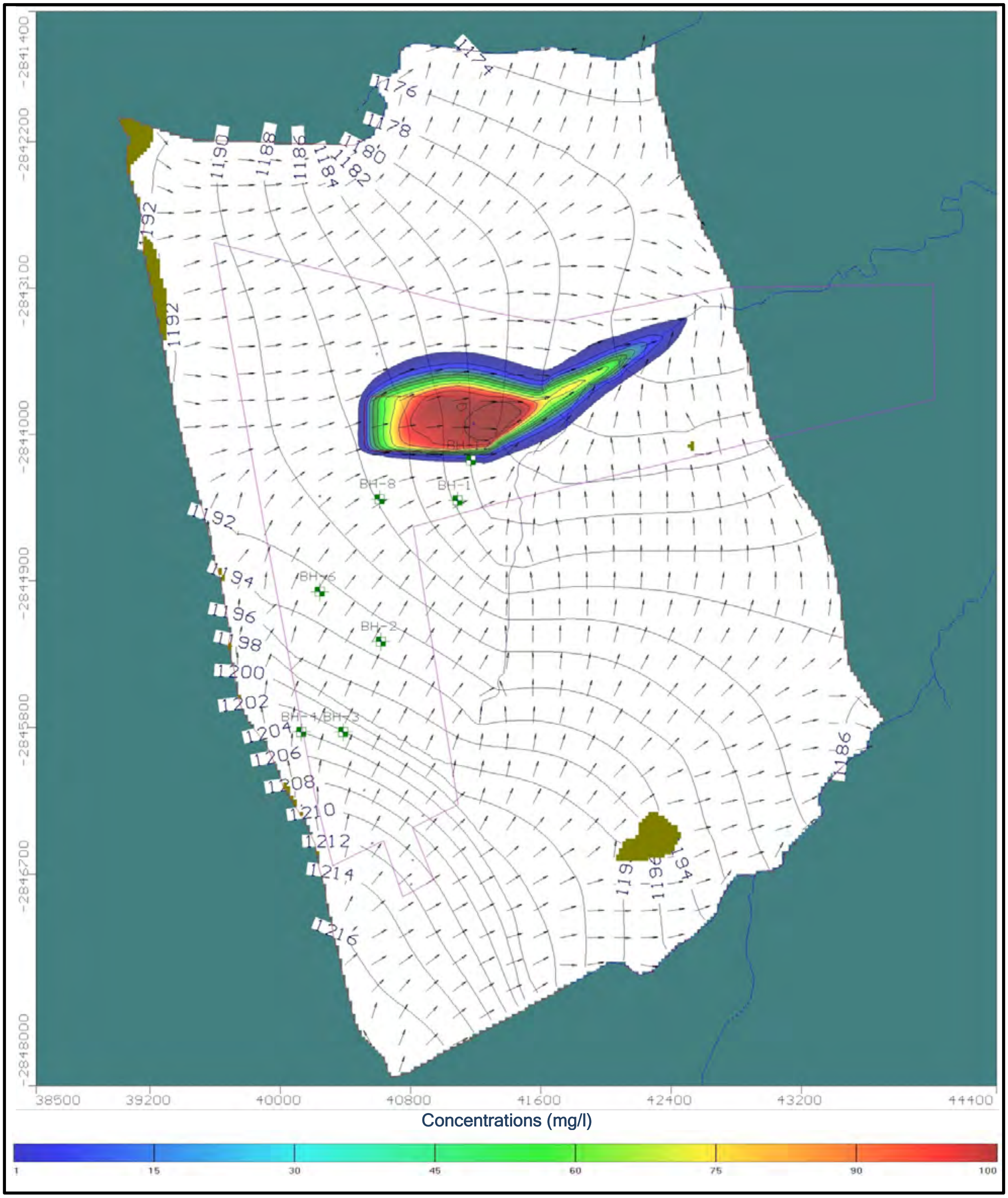
APPENDIX III

SIMULATED GROUND WATER CONTAMINATION PLUMES

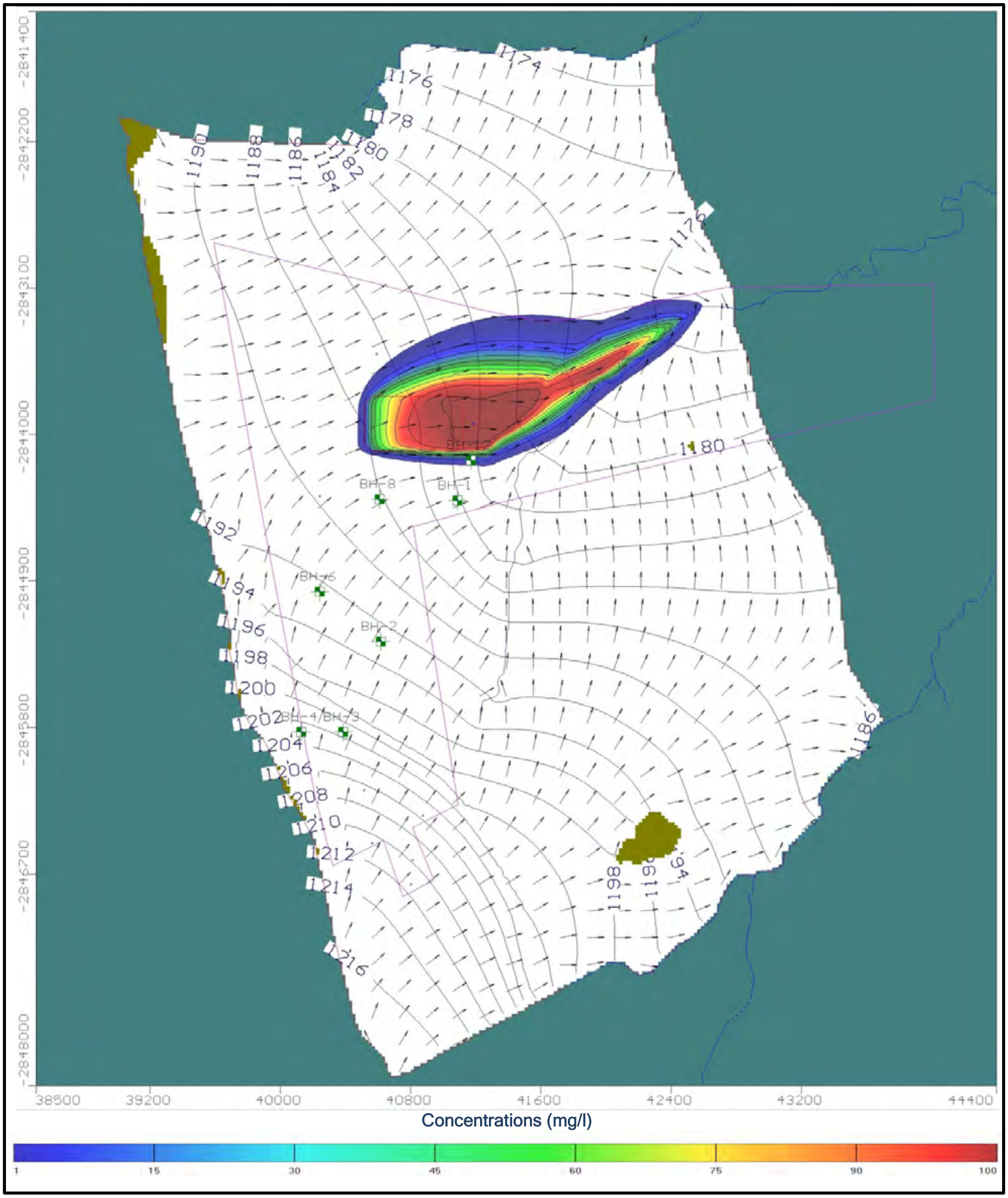
Simulated Ground Water Contamination Plume for Model II after 5 years



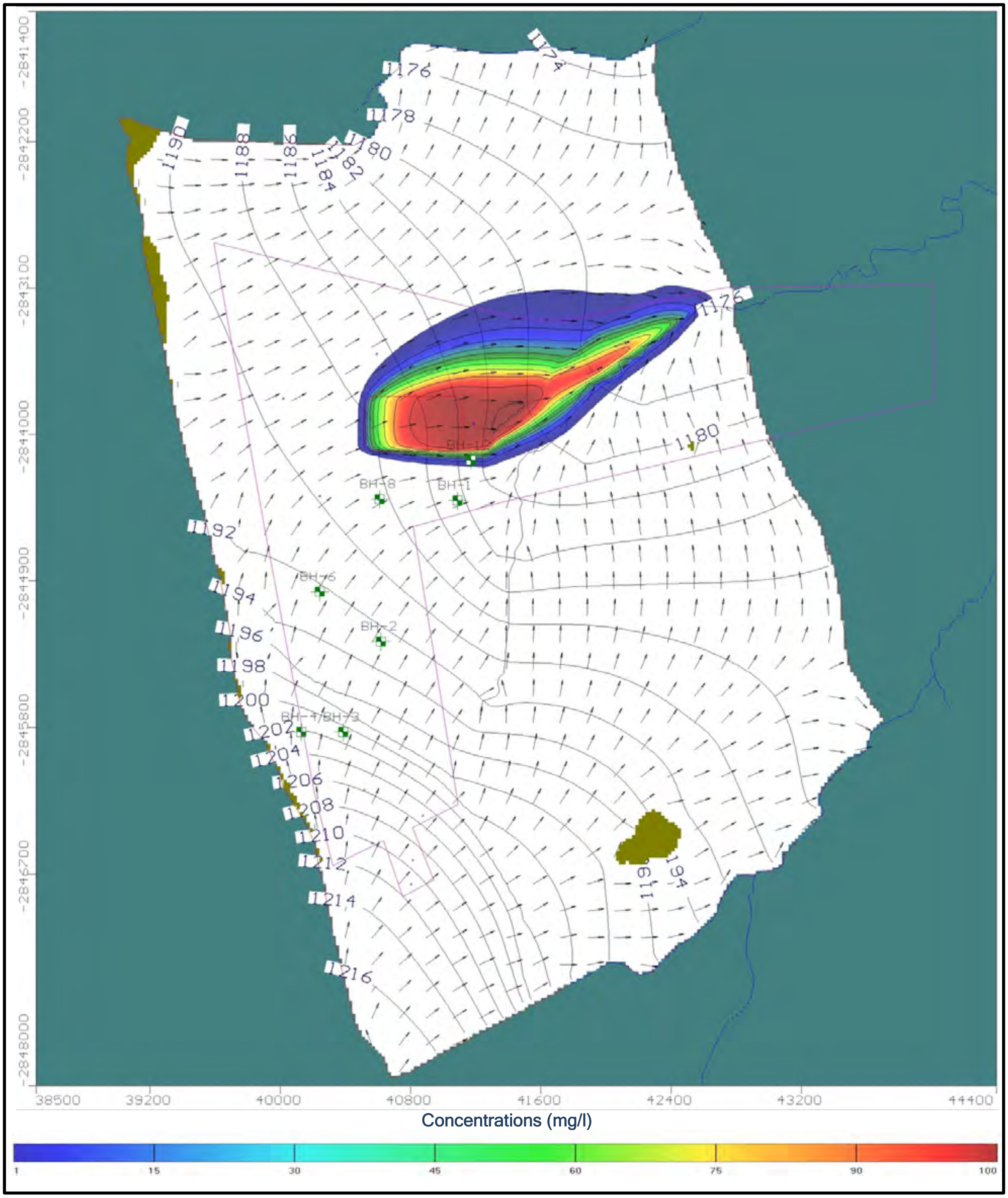
Simulated Ground Water Contamination Plume for Model II after 10 years



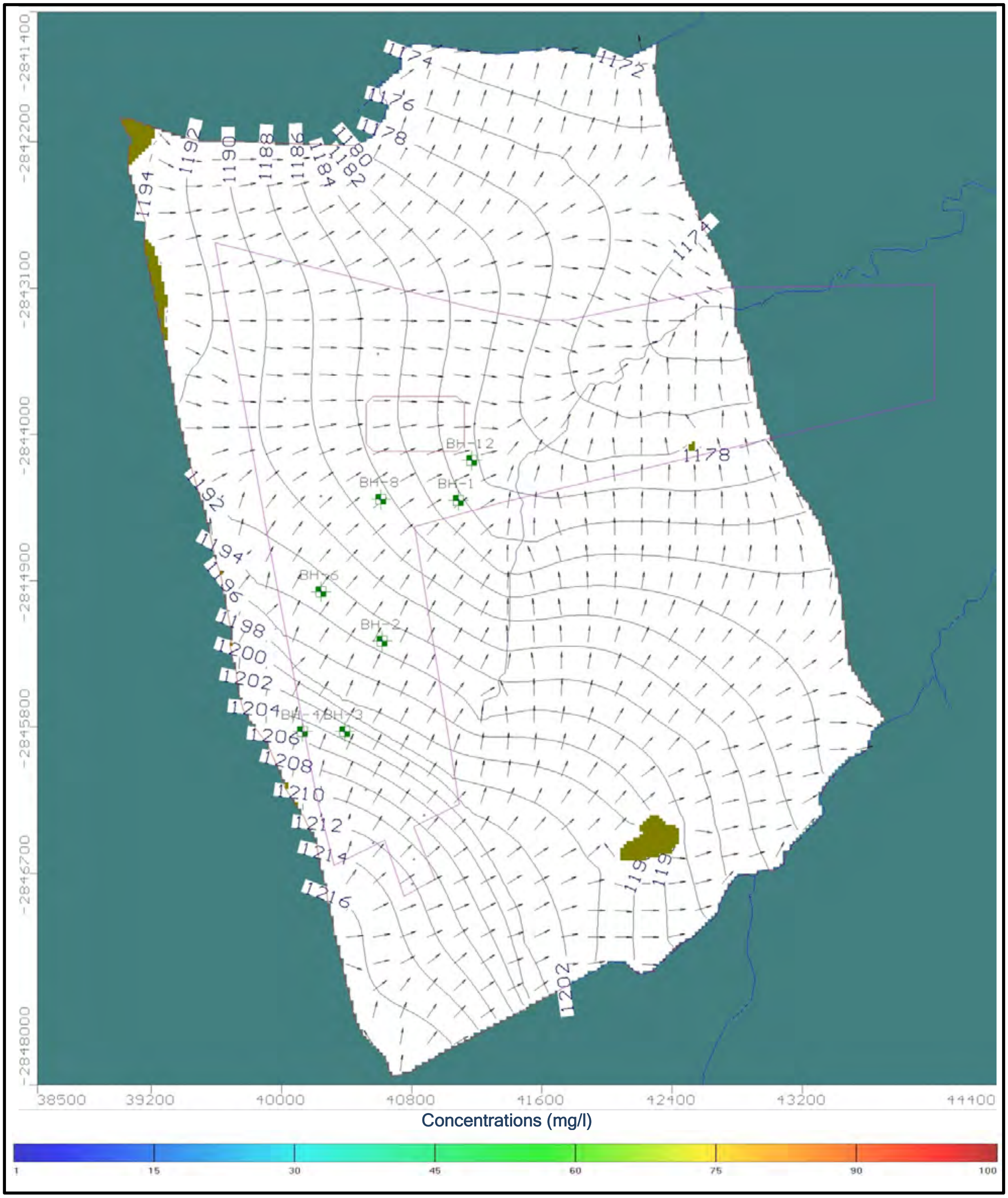
Simulated Ground Water Contamination Plume for Model II after 50 years



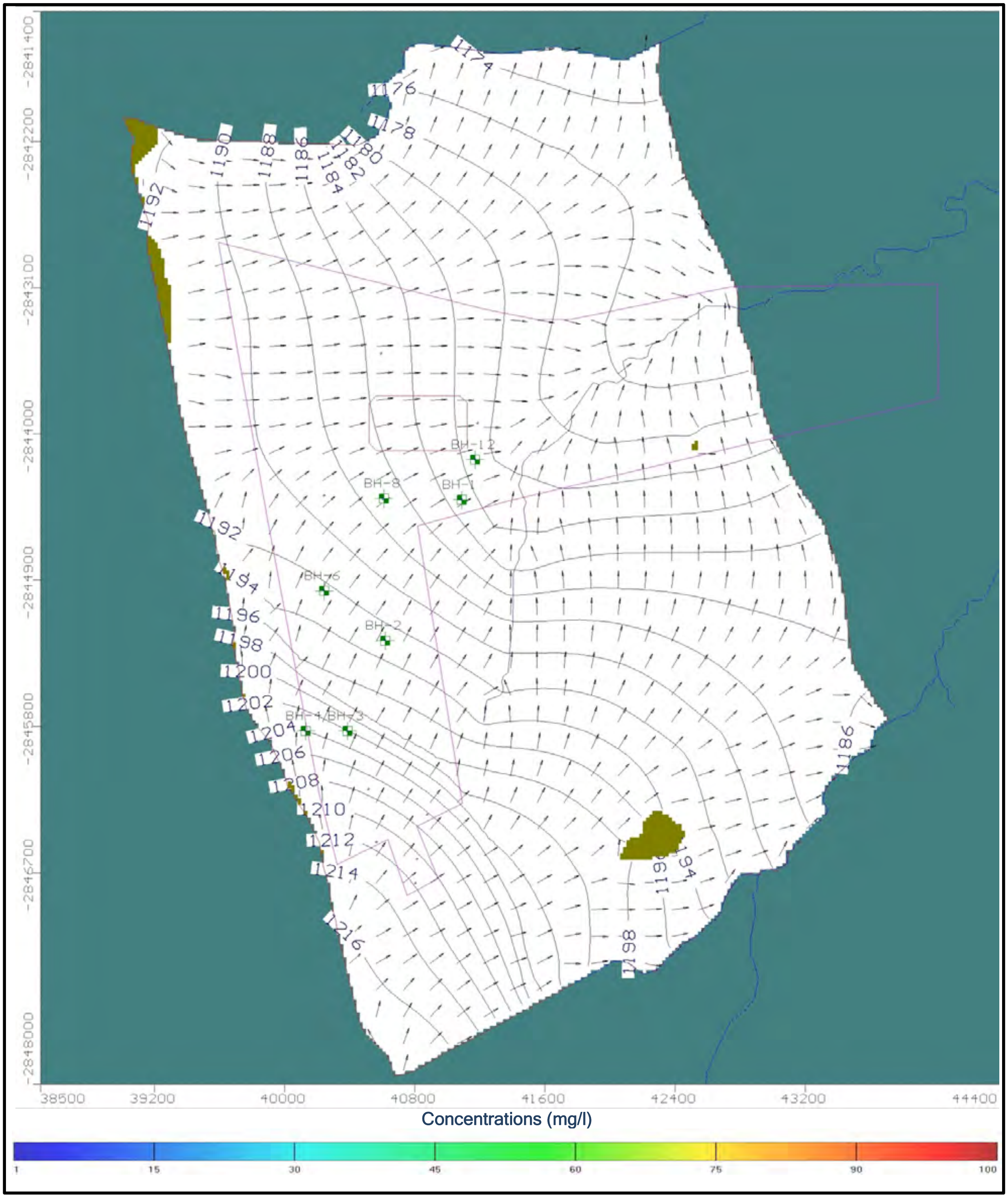
Simulated Ground Water Contamination Plume for Model II after 100 years



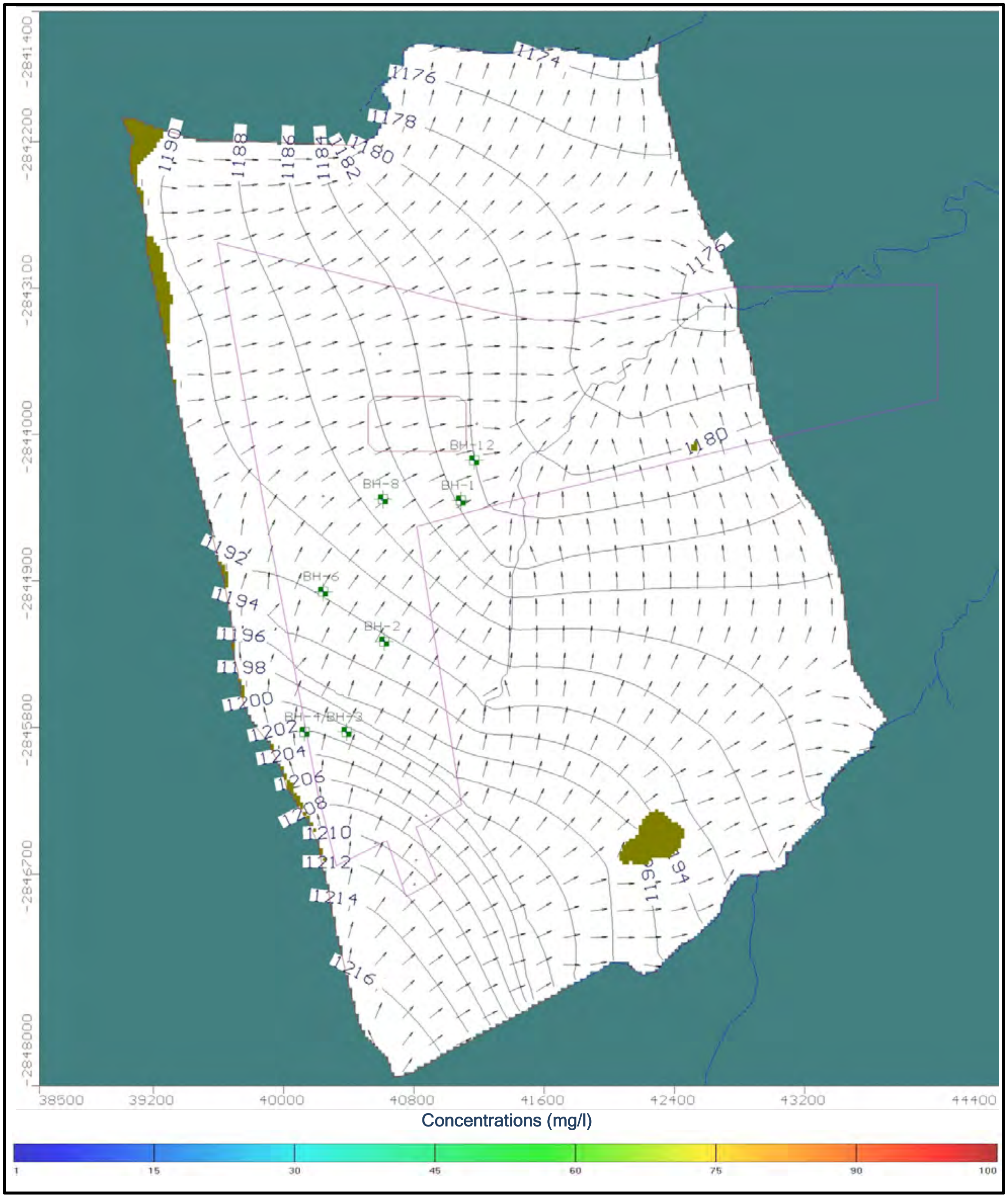
Simulated Ground Water Contamination Plume for Model III after 5 years



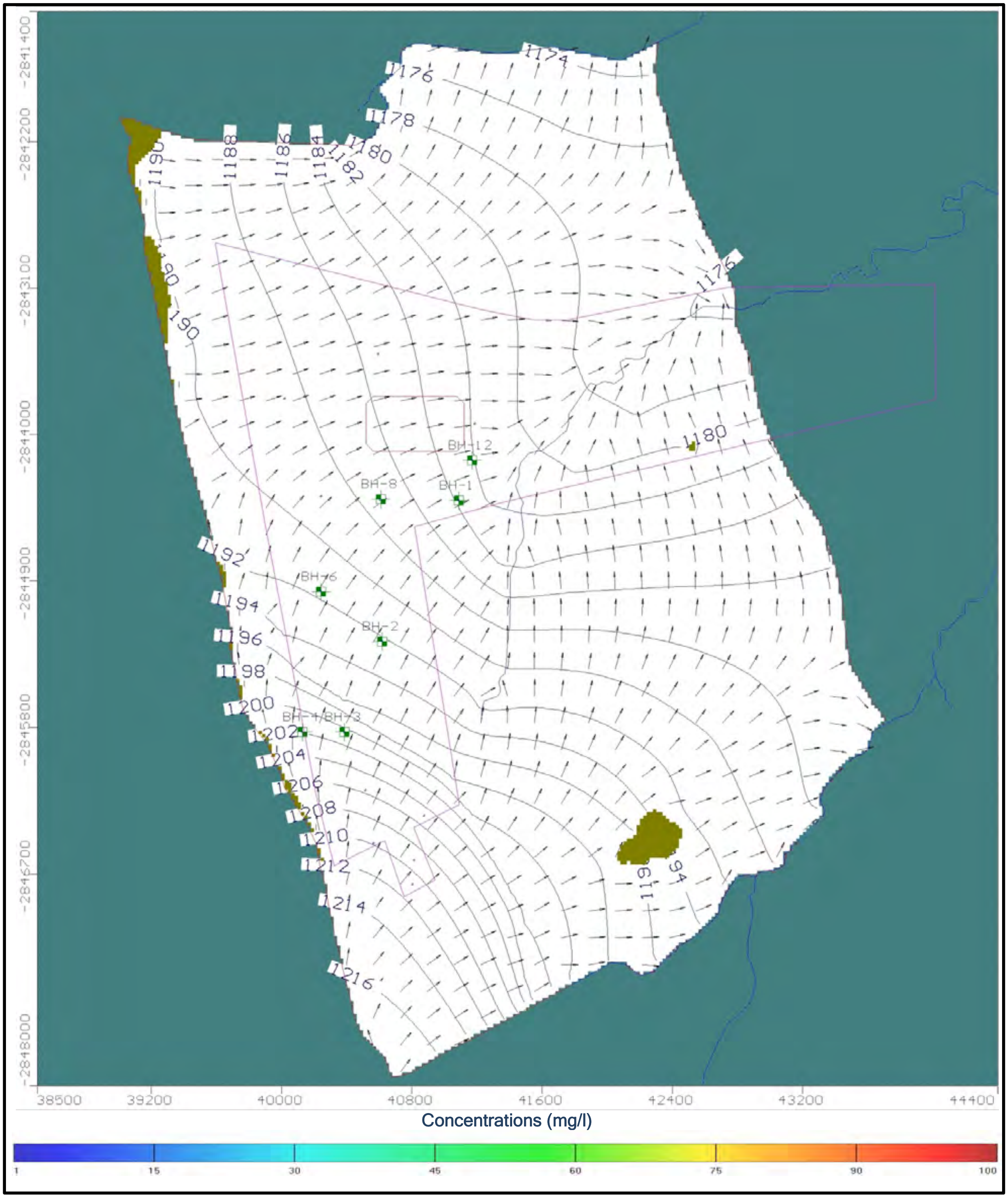
Simulated Ground Water Contamination Plume for Model III after 10 years



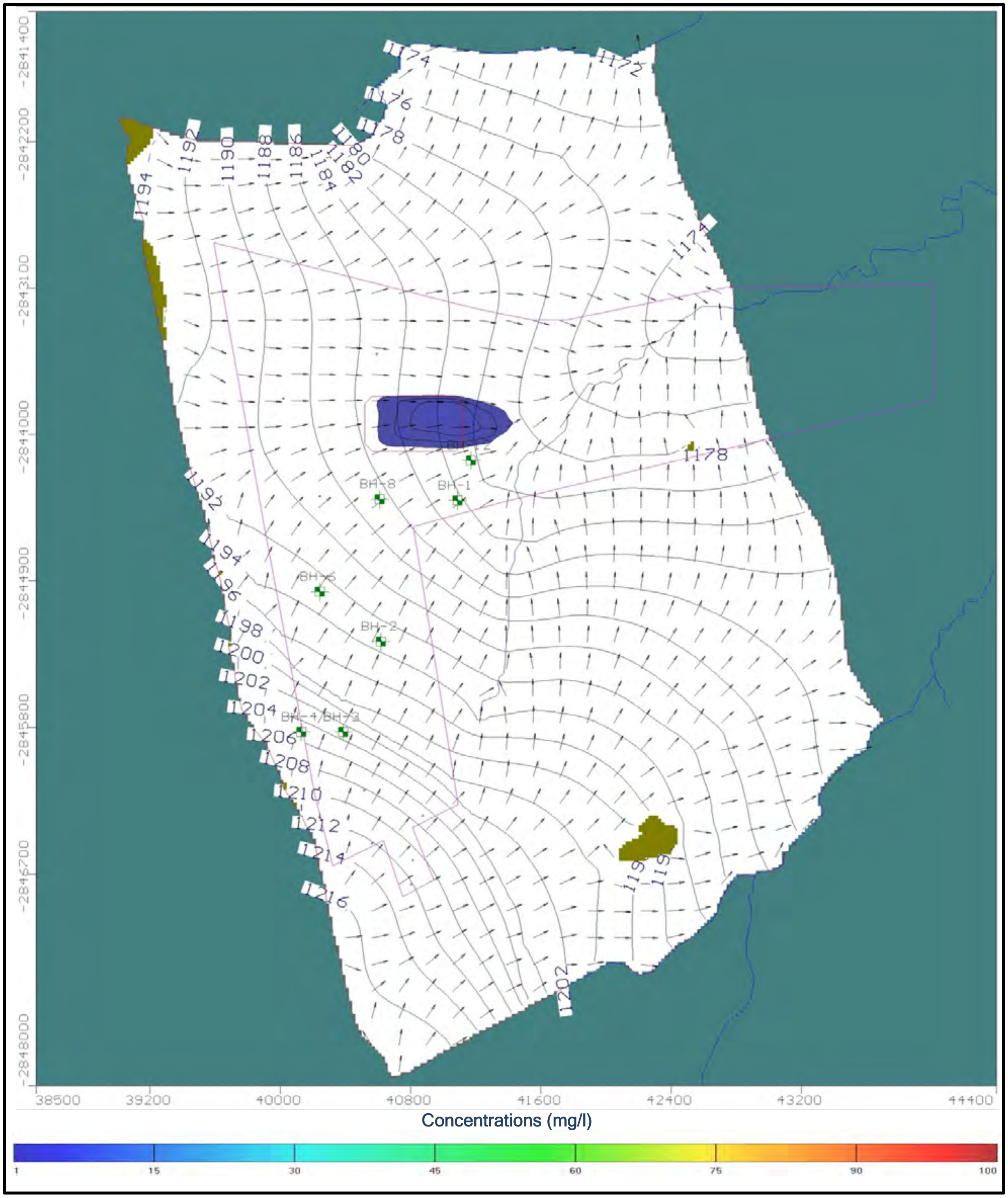
Simulated Ground Water Contamination Plume for Model III after 50 years



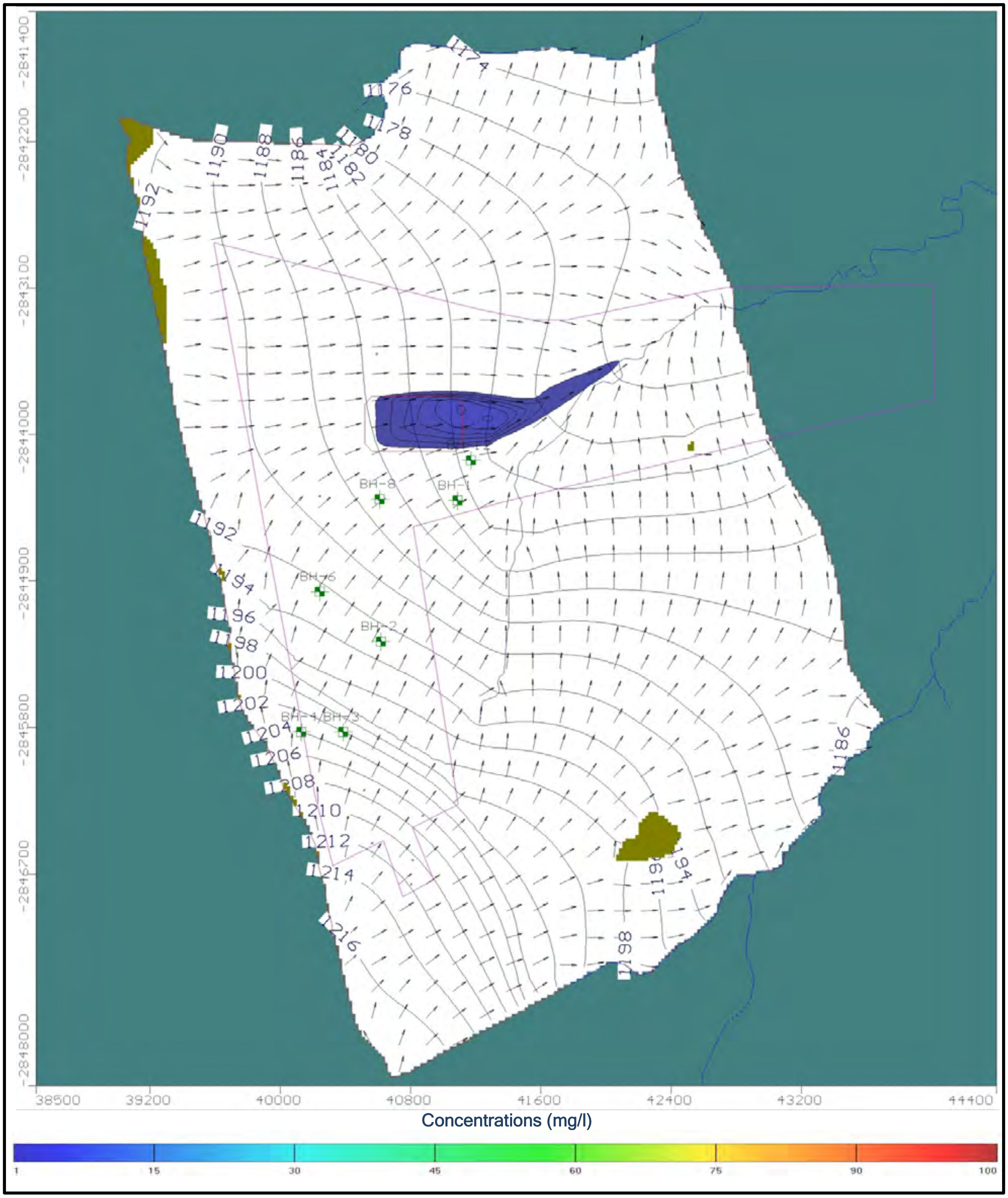
Simulated Ground Water Contamination Plume for Model III after 100 years



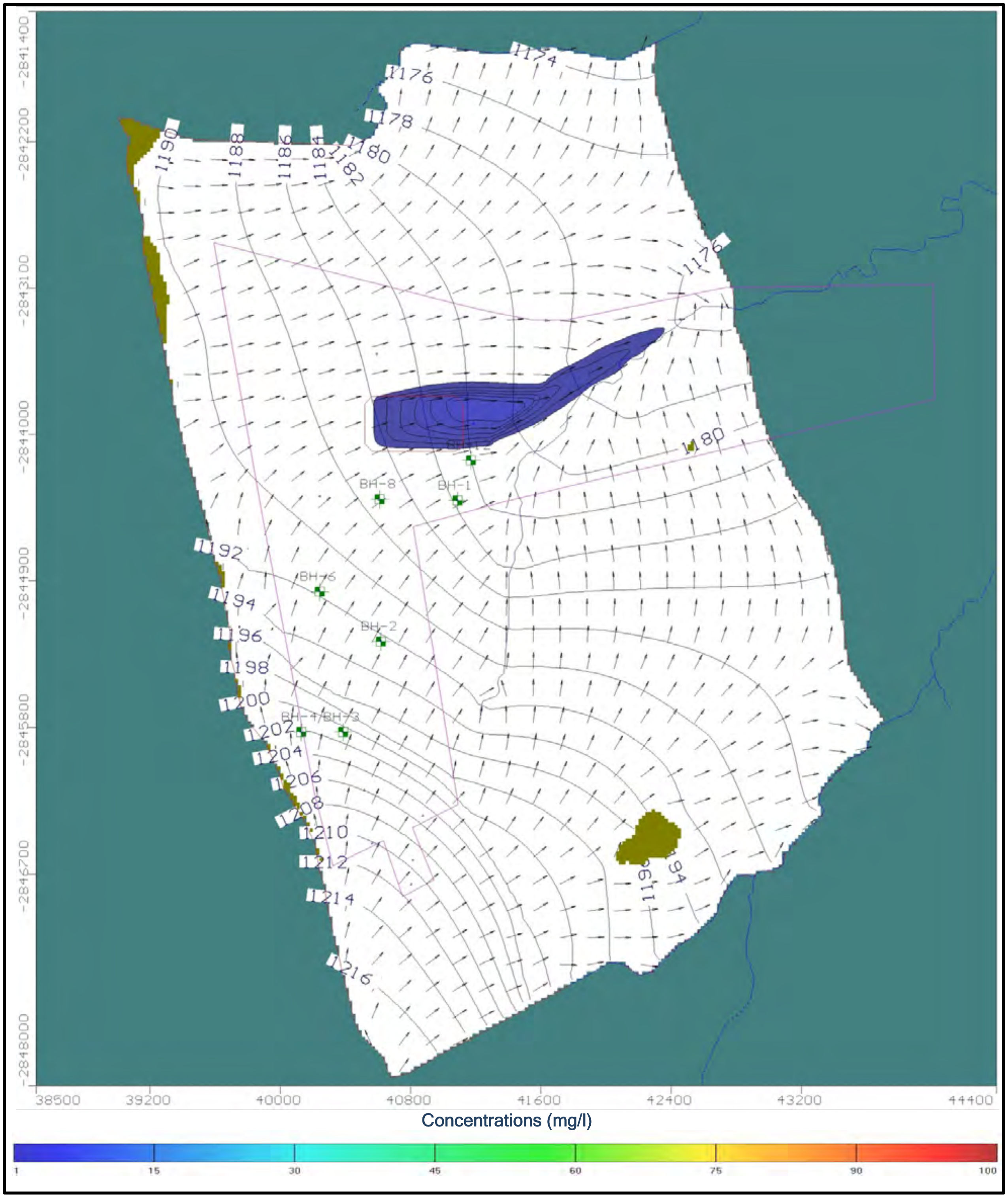
Simulated Ground Water Contamination Plume for Model IV after 5 years



Simulated Ground Water Contamination Plume for Model IV after 10 years



Simulated Ground Water Contamination Plume for Model IV after 50 years



Simulated Ground Water Contamination Plume for Model IV after 100 years