Determining the effectiveness of landfill capping by reducing groundwater and surface water pollution

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Declaration

I Dean Mark Durant, hereby declare that this dissertation submitted by me for the completion of the Master of Science Degree at the North West University, Potchefstroom, is my own independent work and has not been submitted by me at another university. I furthermore cede copyright of the dissertation to the North West University.

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Abstract

Modern day activities have the potential to place significant strain on the environment. These processes make use of natural resources which, in turn, render useful products and consumables. Other outputs which are produced along with these include unwanted products, such as waste. Waste may occur in various forms and may have detrimental effects on various receptors if not disposed of appropriately. Some sensitive receptors include surface water and groundwater bodies. Industrial contaminants which are not managed appropriately may have the potential to contaminate the surrounding land and in turn may lead to the contamination of the surrounding surface water and groundwater environments.

Legislative requirements for the management of contaminated land have become more stringent. The onus lies on the owner of contaminated land to determine the significance thereof and take any and all necessary precautions in the management thereof. South Africa has established frameworks, which have been adopted from international standards, to follow when addressing contaminated land. The need to remediate contaminated land is determined by the outcome of a significance study. There are various remediation techniques which may be appropriate to specific contaminated land scenarios.

The aim of this dissertation is to determine the effectiveness of implementing capping as a remediation technique. Determining the effectiveness will be done by evaluating the effect capping will have on the migration of a contamination plume. The natural aquifer parameters and associated major contaminants were obtained from historical data.

A numerical model was developed to determine the extent of the contamination plume over time and to observe the effect that capping will have on mitigating the migration of the contamination plume. The results of the concentration and extent of the contamination plume for capping as a remediation technique is compared to the simulations of other remediation techniques.

It has been found that the effect of capping as a remediation technique hinders the extent to which a contamination migrates. Capping is a relatively inexpensive remediation technique and should be used in conjunction with another appropriate remediation technique for most effective results. The modelling exercise revealed that capping contaminated land hindered the migration of the contamination to plume to an extent where no sensitive receptors would be at risk.

Key Words

Receptors, Groundwater, Contamination, Remediation, Numerical Model, Contamination Plume

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List of Abbreviations

ANZECC – Australia and New Zealand Environment Conservation Council

CARACAS – Concerted Action on Risk Assessment for Contaminated Sites

CERCLA – Comprehensive Environmental Response, Compensation and Liability Act

CLARINET – Contaminated Land Rehabilitation Network for Environmental Technologies

CLEA – Contaminated Land Exposure Assessment

CMI – Corrective Measures Implementation

CMS – Corrective Measures Study

CSMWG – Contaminated Site Management Working Group

DEA – Department of Environmental Affairs

DEAT – Department of Environmental Affairs and Tourism

DEFRA – UK Department for Environment, Food and Rural Affairs

DEP – Department of Environmental Protection

DWAF – Department of Water Affairs and Forestry

HDPE – High Density Polyethylene

IAEA – International Atomic Energy Agency

LOD – Limit of Detection

mamsl – Meters Above Mean Sea Level

MAP – Mean Annual Precipitation

MEC – Member of the Executive Council

MODFLOW – Modular Three Dimensional Finite Difference Groundwater Flow Model

MT3DMS – Modular Three Dimensional Multispecies Transport Model Simulator

NEMA – National Environmental Management Act

NEMWA – National Environmental Management: Waste Act

NEPM – National Environment Protection Measure

NWA – National Water Act

PAH – Polycyclic aromatic hydrocarbon

PCB – Polychlorinated Biphenyl

QC/QA – Quality Control and Quality Assurance

R – Recharge

RCRA – Resource Conservation and Recovery Act

RFA – RCRA Facility Assessment

RFI – RCRA Facility Investigation

SANS – South African National Standards

SEPP – State Environment Protection Policy

SSVs – Soil Screening Values

US EPA – United States Environment Protection Agency

WMA – Water Management Area

WRC – Water Research Commission

List of Chemical Parameters

Ca – Calcium

$CaCO_3$ – Calcium Carbonate

Cl – Chloride

CO_2 – Corbon Dioxide

CS_2 – Carbon Disulfphide

EC – Electrical Conductivity

F - Fluoride

H - Hydrogen

H_2O – Water

K – Potassium

Mg – Magnesium

OH - Hydroxide

Na – Sodium

NO_3 – Nitrate

pH - Potential of hydrogen

SO_4 – Sulphate

TDS – Total Dissolved Solids

Chapter 1: Introduction

1.1 Background

Sometimes waste is disposed of in an improper manner which can lead to land contamination. There are many different factors which contribute to land contamination. "Too few adequate, compliant landfills and hazardous waste management facilities, which hinders the safe disposal of all waste streams" was a point in the National Waste Management Strategy problem statement (DEA, 2011). More than 2000 waste handling facilities are estimated to be in operation in South Africa, and it is said that a significant portion of these facilities are unpermitted (DEAT, 2007). The nature of industrial contaminants requires appropriate and consistent disposal thereof. Design requirements for modern landfill facilities are very stringent to ensure that contamination of the immediate environment, such as groundwater, does not occur. However, older landfills do not always meet these requirements which results in the potential for them to contaminate the environment. Such cases should prompt remediation on the contaminated and affected land (EPA, 1993).

When people fail to take the necessary precautions regarding hazardous waste disposal such as industrial contaminants, land contamination is more than likely to occur. In order to prevent further detrimental damage to the environment such as soil pollution, surface water and groundwater contamination, remediation techniques can be practiced which can improve the state of a contaminated land site (Hamby, 1996).

There are many provisions within South African legislation which dictate the manner in which contaminated land is addressed. These regulations have been adopted from international frameworks for the management of contaminated land and can be regarded as best practice. The potential risk that contaminated land may have on sensitive receptors will determine the need for remediation (DEA, 2009).

Remediation of contaminated land is a costly exercise and therefore depends greatly on the decision making process followed when determining the appropriate manner in which contaminated land should be addressed. There are best practice frameworks in place and the adoption thereof will provide a decision maker with the relevant information which will allow for an informed decision (CL:AIRE, 2010).

1.2 Problem statement, Objectives and Aims

The improper disposal of industrial contaminants may have detrimental effects on the environment. Capping is one of the remediation techniques used to manage contaminated land and reduce the negative impact it may have on the surrounding environment, such as soil, surface water and groundwater pollution (Bellandi, 1995).

The exercise of capping contaminated land cuts off the interface between the industrial contaminants (pollution plume) and the surrounding environment such as surface water and groundwater. Capping renders the plume immobile by reducing the potential for contaminants to migrate via surface or groundwater (Bellandi, 1995).

This study focuses on determining the effectiveness of capping industrial contaminants. Specific objectives of the study include gaining a better understanding of the significance of contaminated land, determining the need for remediation of contaminated land, establishing the various tools available which can aid in the decision making process when remediating contaminated land, evaluating various remediation techniques, and finally concluding whether capping was an effective remediation technique in this instance. Determining the effectiveness will be done by obtaining relevant site data which will be used to develop a numerical model in order to establish the effectiveness of capping as a remediation technique.

1.3 Layout

The layout of this dissertation is as follows:

- Chapter 1: Introduction of the study;
- Chapter 2: Literature review – Review of current requirements and decision making processes for the remediation of contaminated land;
- Chapter 3: Methodology – Formulation of feasible methodology based on the outcome of the literature review;
- Chapter 4: Background of the Study Area;
- Chapter 5: Results – Results from the remediation of contaminated land investigation are presented and discussed; and
- Chapter 6: Conclusions and Recommendations – Overview of the results from the remediation of contaminated land investigation.

Chapter 2: Literature Review

2.1 Land Contamination

2.1.1 Background

There has been a significant strain on the environment as a result of human activities since the dawn of industrialisation. This strain has resulted in widespread pollution and receptors of this pollution include air, water and land. Human activities release pollutants into to the environment and, depending on the industry, potential sources of the pollution could be organic pollutants, heavy metals or pesticides. Absorption of these pollutants in the human body could take place via contact of the skin, ingestion or inhalation of the pollutant which may result in significant harm in terms of human health (Hou & Al-Tabbaa, 2014).

The release of pollutants does not only have a detrimental effect on humans, but poses a great risk to ecological systems, too. Contaminated land has a higher probability of featuring in countries which are still developing. In countries such as China, up to 90% of the shallow groundwater has been polluted, with 37% polluted to such an extent that it is no longer possible to restore it to the point of potable water quality (Qiu, 2011).

For the sake of sustainable development, it is important that contaminated sites be remediated. Remediating contaminated sites decreases the risks which are posed to human health and the surrounding environment. Remediation of contaminated land has expanded from a small field of interest into a thriving industry which is currently worth billions of rands. Sustainable practices have become a greater focus in the remediation industry, which historically only focused on reducing the risk of harm which was posed by a contaminated site. Sustainable remediation allows one to consider the benefits and impacts of remediation in a holistic manner. Additional parameters in the decision making process for remediation may include risk management, public participation, carbon and water footprint, and renewable energy. As sustainable remediation is a growing practice, there are stumbling blocks associated with it. Various regulators consider it to be a cost-cutting exercise for liability owners. Social, economic and geographical location are also factors which influence the decision making processes and strategies to achieve sustainable remediation. Sustainable remediation should not be considered a practice which reduces the cost of remediation, rather a measure to identify potential secondary impacts which may be a result of remediation (Hou & Al-Tabbaa, 2014).

2.1.2 South African Legislative Requirements

It is imperative that the South African government places key focus on urban renewal and rural upliftment. One of the factors which may hinder progress in both the urban and rural context

is the presence of contaminated land which may be a result of either current or historical activities. The presence of contaminated land can potentially pose a health risk to humans or degradation of the environment due to the severe deterioration of surface and ground components of the surrounding water resources (DEA, 2009).
South African legislation makes provision for any owner of land, whether it is an individual or an organisation, to apply the "duty of care" principle in their activities. The primary legislation in terms of the "duty of care" requirements features in the National Water Act (NWA) and the National Environmental Management Act (NEMA).

Section 19 (1) of the NWA (South Africa, 1998) stipulates that "*anyone who owns or is in control of land on which activities have taken place that cause, have caused or are likely to cause pollution of a water resource must take all reasonable measures to prevent the pollution from occurring, continuing or recurring.*"

Section 28 (1) of the NEMA (South Africa, 1998) generalises the duty of care requirements more than that of the NWA. It stipulates that "*Every person who 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, or, in so far as such harm to the environment is authorised by law or cannot reasonably be avoided or stopped, to minimise and rectify such pollution or degradation of the environment.*"

Section 28 (1) can be regarded in a retrospective context, therefore if pollution has been caused prior to the commencement of the Act the obligations within the Act will still be applicable. The duty of care obligation can be regarded in a broad context which can be noticed in the manner in which reasonable measures are defined. Where there is potential, or if it is known, that pollution is present in a water resource of the environment; both the NWA [Section 19 (2)] and the NEMA [Section 28(3)] specify the actions which are to be taken:

- Investigate, assess and evaluate the impact on the environment;
- Inform and educate employees about the environmental risks associated with their work and how tasks need to be conducted to prevent environmental pollution or degradation;
- Cease, modify or control any act or process causing the pollution and/or environmental degradation;
- Contain or prevent the movement of pollutants;
- Eliminate any source of pollution; and
- Remediate the effects of the pollution and/or degradation.

Furthermore, both the Acts allocate a responsible party whereon the duty of care obligation will be placed. This is stipulated in Section 19(1) of the NWA (South Africa, 1998) and Section 28(2) of the NEMA (South Africa, 1998):

- "*Anyone who owns land or premises where pollution or environmental degradation could result from activities, processes or any other situation existing on that land or premises.*";
- "*A person who occupies or has a right to use the land or premises where pollution or environmental degradation could result from activities, processes or any other situation existing on that land or premises.*"; and
- "*Anyone who has control over land where activities, processes or any other situation exists that could cause pollution or environmental degradation.*"

When environmental pollution or degradation is present, authorities may call on any or all of the above mentioned parties to take remediation action if deemed necessary.

When purchasing or selling land in which environmental pollution or degradation is present, the onus is on the buyer and seller to specify who will be responsible for the remediation actions; this will allocate a responsible party who will fulfil the duty of care obligation.

Chapter 8 (Sections 35-41) of the National Environmental Management: Waste Act (NEMWA) governs the management of contaminated land. Before Chapter 8 of the NEMWA was promulgated, management of contaminated land was governed under Section 19 of NEMWA in which a waste management license had to be obtained to undertake any remedial activities (South Africa, 2008). Chapter 8 of the NEMWA makes provision for the declaration of contaminated land by either the Minister or MEC which is responsible for environmental affairs. Upon the declaration of contaminated land, an order for remediation would be issued in terms of Section 38 of the NEMWA. It is important to note that these provisions are to be read in conjunction with the duty of care obligations which emanate from the NWA and NEMA. Norms and standards for the Remediation of Contaminated Land and Soil (GNR 331 of 2 May 2014) provide a guide to determine whether remedial action will be deemed necessary, based on Soil Screening Values (SSVs). There are two categories of SSVs, namely SSV1 which relates to the protection of water resources, and SSV2 which relates the various land-use (informal residential, standard residential and commercial or industrial). SSV1s are the most stringent while the SSV2 for industrial or commercial land-use is the least stringent. One will have to consider the SSVs in terms of the environmental setting in which the contamination is present and if the applicable SSV is exceeded, remedial actions will need to be undertaken (DEA, 2014).

It is important to note that these SSVs should be used as a screening tool and should not be considered as the only trigger in terms of remediation. The Norms and Standards for Remediation of Contaminated Land encompass all the different types of contaminants but it does not consider water pollution. These SSVs allow for one to compare the degree of contamination of polluted land to the natural background concentration of the polluted land. There are other scientifically validated standards which should be used in conjunction with these Norms and Standards, especially when the contaminants of concern do not feature in the SSVs or where there is contamination of a different form, such as water.

When contamination of land has been deemed significant, Section 36(5) in Chapter 8 of the NEMWA obliges the landowner to lodge a notification to the authorities (South Africa, 2008).

Therefore according to (South Africa, 2008) "*An owner of land which is significantly contaminated, or a person who undertakes and activity that caused the land to be significantly contaminated, must notify the Minister and MEC of that contamination as soon as that person becomes aware of that contamination.*"

The degree of significance of contaminated land is therefore determined by the Norms and Standards and should be considered in conjunction with the National Framework for the Management of Contaminated Land. The National Framework can be regarded as a decision supporting framework for the assessment of contaminated land (Morris, 2016).

2.2 Framework for Management of Contaminated Land

2.2.1 International Practice

According to a report compiled by the DEA (2009), remediation policies have been in place in a range of countries, at least 32 in total, for over 30 years. These policies have guidelines which are applicable to the management of contaminated land and its associated impacts on surface or groundwater. Over the past 30 years these policies and guidelines have undergone major review and revision. The following components are common across international policies:

- The need to prevent or limit future pollution;
- The 'polluter pays' principle applies, but there are mechanisms in place to protect innocent land owners and to deal with orphan sites;

- The precautionary principle is applied;
- The approach to remediation is risk based and land/end-use specific;
- Assessment values are used as site screening tools and as an aid in prioritisation of high risk sites; and
- Where risk assessment indicates the need for remediation, site specific remediation criteria must be calculated based on the risk profile of the site;

Initially the approach to remediating contaminated land was pursuing maximum risk control in which pollution would be totally removed or completely contained. Over time, however, it was perceived that there were only a few significantly impacted sites which needed attention, rather than a vast problem with varying impacts associated with the specific land-use. This resulted in a change in policy regarding the decision making process, which went from following a stringent set of criteria to implementing a risk-based set of criteria (DEA, 2009).

As the modern approach to contaminated land remediation is risk based in nature. Prioritisation of significant risks is established using site screening tools which evaluates soil assessment values. If the need for remediation is determined by the risk assessment, site specific remediation criteria should be established based on the significance of the risk. A result based and phased approach to corrective actions is becoming a worldwide trend. The modern day approach also considers the end use potential of the land during the assessments (DEA, 2009).

Contaminated land is an issue throughout the world and it would be prudent for policies, procedures and best practice to represent a certain degree of uniformity. However, there are factors which may influence the policy and decision making differently for a given country. According to a report compiled by the DEA (2009), these influential factors are:

- "*The legislative structure of the host environmental administration has a significant political control on framework development, whether the political structure is strongly centralist or a highly devolved federalist system*";
- "*The significant scientific controls are related to the importance and sensitivity of water resource protection and particularly the relative importance of groundwater to the water-use needs of the country*"; and
- "*The role of local geology on the background concentrations of contaminants has a profound effect on the determination of screening levels to define the threshold of no impact and thus the criteria for a 'clean' site*".

This initial phase of framework development should not focus on numeric values of the different screening criteria established across various administrations, but rather on the fundamental scientific assumptions and policy based motivations which are used to derive the risk based approach in standards for international use.

2.2.1 Historical Development of Norms and Standards

Development of policies for contaminated land management came about as a result of increased incidents. The United States Environment Protection Agency (US EPA) established guidelines which were adopted and adapted by other countries which were also dealing with contaminated land challenges (DEA, 2009).

In response to increased pollution as a result of expanding industrialisation, the US Congress started promulgating various forms of legislation to deal with the pollution challenges. The Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) were established in 1980 to specifically address the pollution of soils and groundwater which resulted from uncontrolled hazardous waste landfill facilities. The CERCLA was established to remediate all contaminated sites in the US and was intended to be a five year program. The number and volume of contaminated sites were significantly underestimated which resulted in only 50 out of a total of 1700 sites undergoing remediation activities by the mid-1990s. Western Europe followed a similar environmental legislation evolution, particularly Germany, Netherlands, and Denmark who had established Environmental Agencies in the 1970s. In 1991, the United Kingdom followed suit by establishing their own Environmental Protection Agency (DEA, 2009).

In 1990, the Ministry of Housing, Spatial Planning and the Environment of the Netherlands established quality objectives for soil. These quality objectives gained global recognition and were used as reference values in many countries, including South Africa, for the reporting of contaminated land. In 1994 the German Ministry and their Environmental Agency coordinated the establishment of a Common Forum for Contaminated Land in the European Union. Concerted Action on Risk Assessment for Contaminated Sites (CARACAS) was a result of the European Union's initiative for assessing risks which may result from contaminated land (DEA, 2009).

CARACAS focused on the following topics (DEA, 2009):

- Human toxicology;
- Ecological risk assessment;
- Fate and transport contaminants;

- Site investigation and analysis;
- Models;
- Screening and guideline values; and
- Risk assessment methodologies.

The European Union continues its initiative in terms of developing recommendations for effective rehabilitation of contaminated land, which mainly focuses on socio economic conditions and technical issues. This initiative is known as CLARINET (Contaminated Land Rehabilitation Network for Environmental Technologies). Each member country within the European Union continues to establish legislation and frameworks for the management of contaminated land which caters for their specific needs (DEA, 2009).

There are not many developing countries which have promulgated legislation for the management of contaminated land, although there are a few which are implementing programs to achieve this. In the Far East, developed countries such as South Korea and Singapore have published standards for the management of contaminated land. The People's Republic of China established soil quality standards in 1995 and Hong Kong has recently updated its contaminated land management guidelines (DEA, 2009).

International approaches to the management of contaminated land are documented in Appendix A.

2.2.2 South African Framework for Management of Contaminated Land

South Africa published the National Framework for the Management of Contaminated Land (DEA, 2010), to standardise the manner in which remedial activities in terms of contaminated land may be conducted. The framework is a risk based approach and is adopted from international best practice standards. Many interested and affected parties were consulted in the establishment of this framework which included government, industry and local stakeholders.

The framework can be regarded as a decision support tool and comprises the following criteria:

- Protection of human health and the environment by constant methods in which contaminated land is assessed;
- Establishing a policy which considers the future land-use of a site once remedial activities have been concluded;

- A database in which one can make reference to the current land status and reference to the remediation of contaminated land activities; and
- A register which comprises of remediating activities and present status of contaminated land.

The following sections feature in the framework (DEA, 2010):

- Protocol for Site Risk Assessment;
- Reporting Norms and Standards for Contaminated Land;
- The Derivation and Use of Soil Screening Values;
- Application of Site Specific Risk Assessment; and
- Quality Control and Quality Assurance of Field Sampling and Laboratory Analysis.

Protocol for Site Risk Assessment

Assessment Protocol and Decision Support Tool

A source – pathway – receptor model has been adopted in order to follow a risk based methodology in determining contaminated land. Applying this conceptual model allows one to link a contaminant to a receptor (which could be humans, animals or plants). The three components of this conceptual model are described as:

- Source – contaminant or pollutant in question. The concentration of the contaminant is considered in order to determine the potential to cause harm to human health or surrounding ecology;
- Pathway – this comprises the route and the medium in which contaminants are released; and
- Receptor – can be humans, plants or animals. These are the aspects in which there is a potential for harm as a result of a pollutant.

The potential for risk occurs when the above components are linked one another, in other words when a contaminant can reach a receptor. These components can exist freely from one another, which will decrease the risk associated with contaminated land. Figure 1 is a decision tree which illustrates the process followed when conducting a conceptual model. Soil screening values are also used in the conceptual modelling process to assist in assessing the significance of contaminated land.

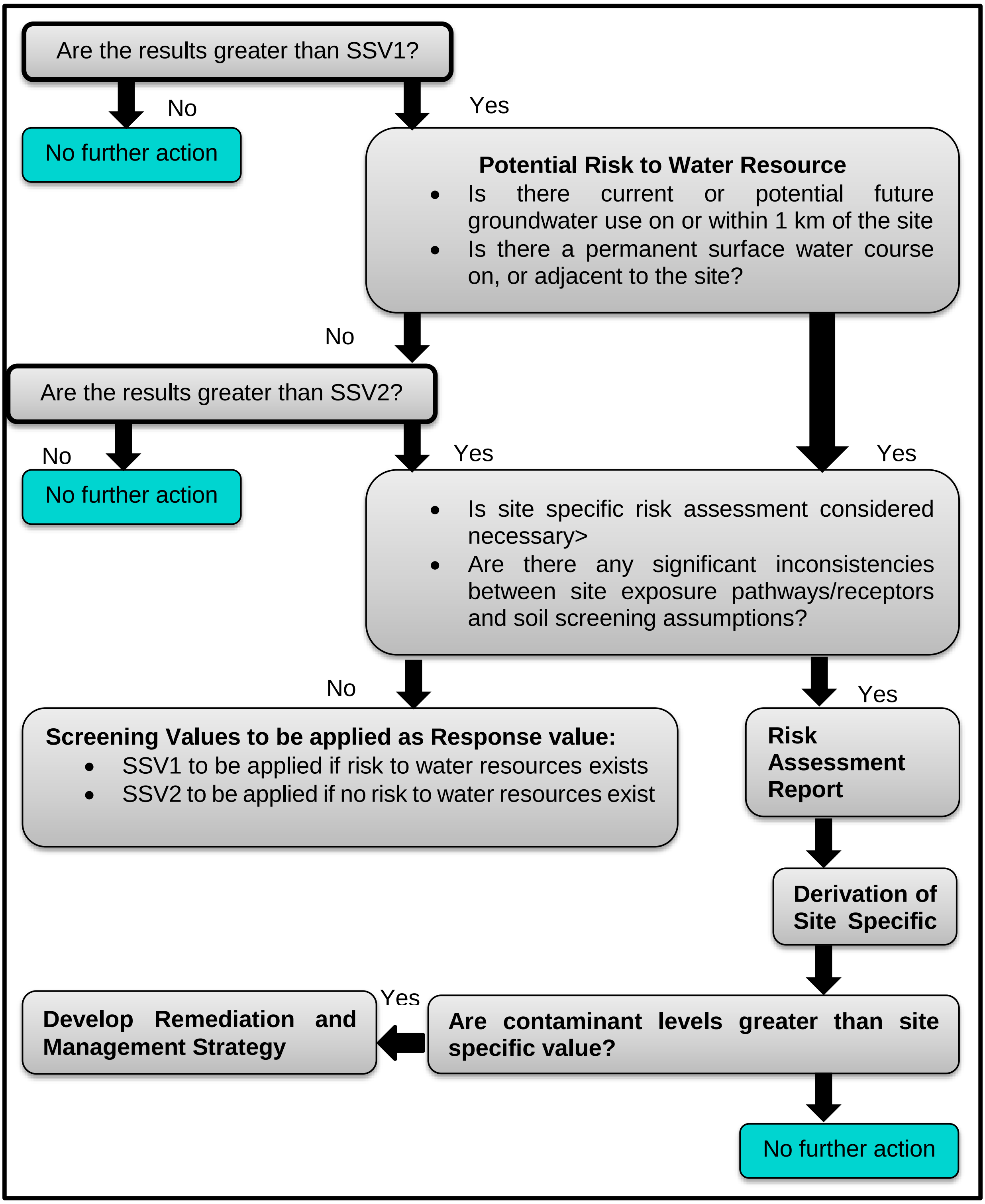

Figure 1: Decision Tree (DEA, 2010)

The first step in the screening process considers Soil Screening Value One (SSV1) concentrations. This considers the lowest concentration between the source, pathway and receptor components in the conceptual model.

According to the Framework for the Management of Contaminated Land (DEA, 2010), the following considerations should be addressed:

- Are groundwater resources at risk in terms of the pollutants?;
- Is there anyone who makes use of groundwater within 1km of the source of the pollutants?; and
- If off-site migration were to occur, will any surface water bodies be at risk as a result thereof?

If none of the above questions are triggered, then Soil Screening Value Two (SSV2) should be considered, which relates to the protection of human health. If any of the above mentioned questions are triggered, then the objective of the remediation actions should be to protect the water resource when compiling the site specific assessment. Target values in terms of remediation requirements and soil quality requirements will be obtained from the lowest of the assessment screening values.

SSV2 is divided into three categories which are related to specific land-use. These categories are informal residential, standard residential, and commercial and industrial land-use. The informal residential land-use is the most sensitive receptor of all the land-uses, as this considers exposure to children which may be exposed to any sources of pollution. A site can be deemed not contaminated, in terms of human health, when soil values are less than the most relevant land-use screening values.

When a site has been deemed contaminated, remediation plans can be based on Soil Screen Values 2 or site specific risk assessments can be undertaken to establish acceptable risk values. It is imperative that site conditions are consistent with either SSV1 or SSV2 values if it is decided that these values will be the basis of remediation objectives. Site specific risk assessments need to be adapted if ecological or aesthetical impacts are a potential risk due to remediation activities, it should be solely based on Soil Screening Values.

Water Resource Sensitivity and Protection

Due to the character of certain geological areas in South Africa, associated groundwater is of such a low quality that it may be deemed not adequate to be considered a water resource. It is imperative that all water resources are protected, but in these cases the groundwater quality may not be the foundation in which the assessment of a contaminated site is based and setting of soil screening values. In the case that the groundwater quality is unknown, the precautionary approach should apply. That is, groundwater should be regarded to have significant exposure to pollutants and drinking water quality standards should be set as compliance objectives unless proven otherwise.

Boreholes allow one to establish an understanding of the relations between soil conditions and groundwater-surface water interactions. The following factors need to be considered for understanding this concept:

- Determine if the contaminated site has current use for groundwater or if there is potential for the use of groundwater;
- Determine if there are any surface water courses on or nearby the contaminated site;
- Assess any qualitative sensitivity in terms of pollution risk in the case that a water resource classification is applicable to the immediate area of the contaminated site.

When assessing the risk of contamination it is imperative to understand the broader concept, which is based on whether human or ecological receptors are affected by a potential exposure pathway resulting from pollutants.

Reporting Norms and Standards for Contaminated Land

Compliance with Section 37 of the Waste Act

Section 37 of the NEMWA specifies the manner in which a site assessment report should be conducted and specifies the consequences of identification and notification of contaminated investigation areas (DEA, 2009). The main purpose is to determine the significance of contaminated land and the potential it has to cause harm. According to Section 37 (2) of the NEMWA (South Africa, 2008):

"*(a) A site assessment report must comply with any directions that may have been published or given by the Minister or MEC in a notice contemplated in section 36(1) or (6) and must at least include information on whether the investigation area is contaminated .*

(b) Where the findings of the site assessment report are that the investigation area is contaminated, the site assessment report must at least contain information on whether:

(i) the contamination has already impacted on health or the environment;

(ii) the substances present in or on the land are toxic, persistent or bio-accumulative or are present in large quantities or high concentrations or occur in combinations;

(iii) there are exposure pathways available to the substances;

(iv) the use or proposed use of the land and adjoining land increases or is likely to increase the risk to health or the environment;

(v) the substances have migrated or are likely to migrate from the land;

(vi) the acceptable exposure for human and environmental receptors in that environment have been exceeded;

(vii) any applicable standards have been exceeded; and

(viii) the area should be remediated or any other measures should be taken to manage or neutralise the risk."

A three phase approach was adopted from international practice to establish a consistent manner in which reporting of contaminated land is conducted. Figure 2 illustrates the process which is followed:

- Phase 1 – consists of a desktop study, site visit and a limited amount of investigation and testing;
- Phase 2 – comprises comprehensive investigating and testing; and
- Phase 3 – comprises a report which describes the remediation plan and way forward.

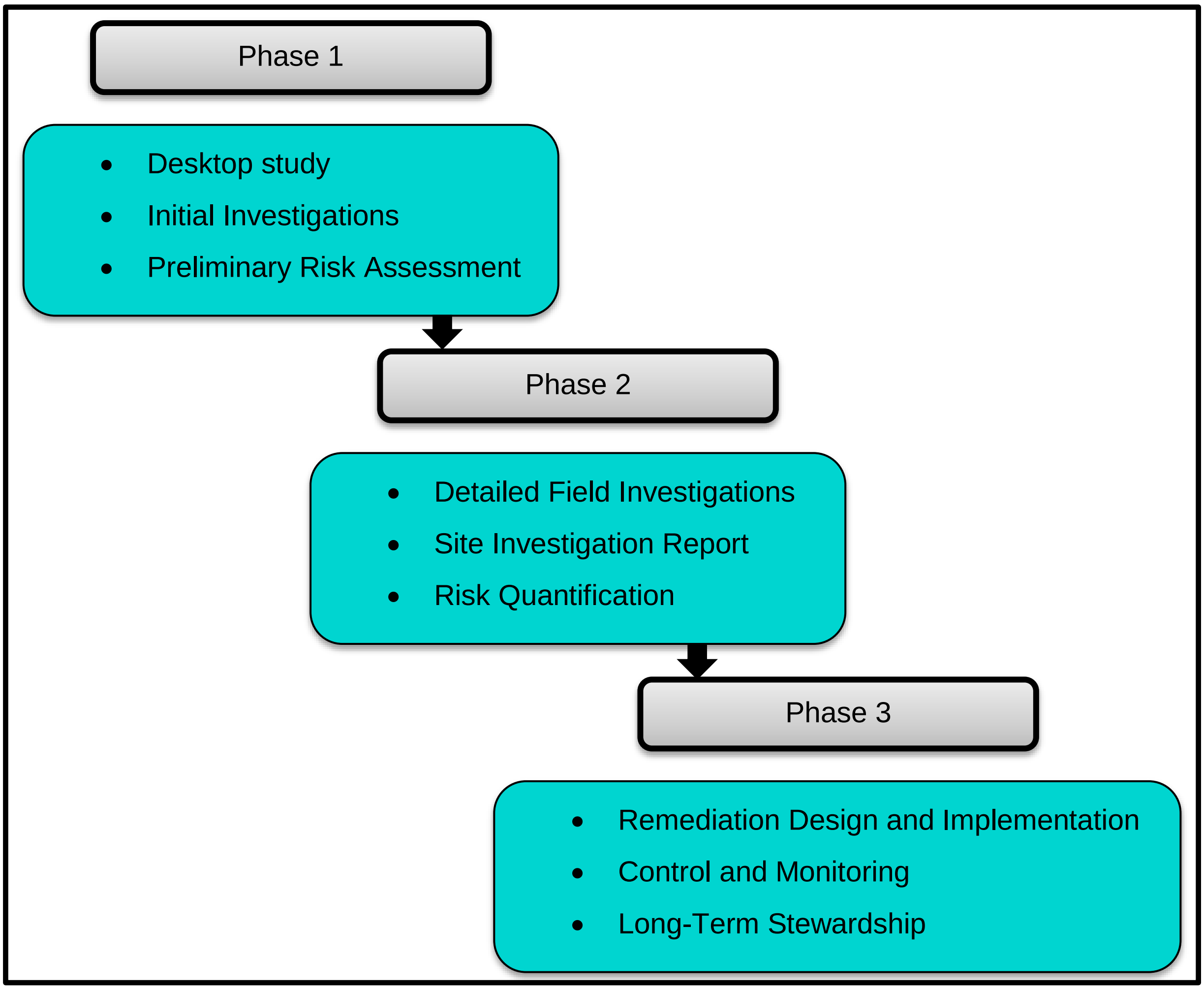

Figure 2: A phased approach for the assessment of contaminated land (DEA, 2010)

Phase 1: Preliminary Investigation Requirements

According to the Framework for the Management of Contaminated Land (DEA, 2010), the following components need to feature in an initial site evaluation:

- "*Site description – location and size;*
- *Nature and extent of the contamination, contaminants of concern or historical activities that may be sources of contamination. List all past and present activities at the site that involved the storage, production, use, treatment or disposal of hazardous materials that could contaminate the site;*
- *Describe the current condition of the site and the contents and results of any previous assessment reports;*
- *Local topography and geology, drainage, surface cover, vegetation;*
- *Status of groundwater, approximate depth to water table;*

- *Proximity to surface water;*
- *Proximity to drinking water supplies;*
- *Annual rainfall and flood potential;*
- *Land and water use for the site and nearby areas;*

Any other requirements as Regulated by the Minister under section 69 (u) and (v) of the Waste Act (2008)."

If there is an issue regarding the uncertainty or unavailability of data in terms of the above listed components, Phase 2 investigations may be prompted to gain clarity on the site characterisation. No further investigation may be necessary if the outcome of the Phase 1 report is of such a nature which illustrates that the site does not pose any potential risk in terms of contamination.

Phase 2: Site Investigation Requirements

Phase 2 investigations should be regarded as a follow up on Phase 1 investigations. This investigation focuses on site specific conditions and reporting thereof. According to the Framework for the Management of Contaminated Land (DEA, 2010), the following components need to be addressed during the Phase 2 investigation:

- A summary of the Phase 1 report;
- A comprehensive investigation of the site geology and hydrology which includes a detailed map and description of the site, description of the groundwater and surface water characteristics of the site, description of the nature and extent of monitoring wells on the site, description of any surface of groundwater bodies in the immediate vicinity, etc.;
- Elaboration on analysis plan and methodology of sampling which includes a description of the sampling objectives, a description regarding the planning of the sampling to be conducted, a detailed description of the manner in which sampling will be conducted, etc.;
- Quality assurance and control of on-site field sampling to ensure that scientifically accepted sampling protocol is followed;
- Quality assurance and control on the laboratory which performs analysis on field samples, this is to ensure that an accredited laboratory is used for analysis procedures, to obtain certificates of analysis, etc.;

- A summary of all results which draw comparisons between relevant guideline values, site plan indicating significance of pollution which specifies the guideline values, location and sample details of contaminated samples;
- Site characterisation, which includes all site assessments which pertain to the degree of contamination, extent of contamination, and potential exposure to receptors of this contamination; and
- Report recommendations to indicate the urgency of remedial activities and monitoring requirements of the site, if deemed necessary. The recommendations can however suggest that the site poses no harm to humans and the surrounding ecology, in which case, a motivation for no action can be compiled and forwarded to the relevant authorities.

It is imperative that any site assessment report addresses all requirements which are stipulated in the NEMWA and should stipulate if any of the clauses have been triggered in terms of Section 69 which touches basis on the degree of contamination of an investigation site (South Africa, 2008).

Phase 3: Remediation Plan Requirements

The remediation plan which is established for site clean-up should be based on the overall risk management strategies of the contaminated site.

According to the Framework for the Management of Contaminated Land (DEA, 2010), the following considerations need to be addressed during the preparation of a site remediation plan:

- Establish remediation objectives in accordance with the site's present or future anticipated land-use. These objectives need to ensure that there will be no significant risk which may harm either humans or the environment after remedial activities have been undertaken;
- Establish procedures which are to be undertaken to implement remedial activities and achieve remediation objectives;
- Establish a quality assurance plan to ensure that established procedures are followed; and
- Ensure that all legal requirements are identified and complied with for the remedial activities set to take place.

Determination of Preliminary Soil Screening Values for Assessment of Contaminated Land

Soil Screening Values of priority pollutants have been established to assist in the preliminary points of reference when developing remediation activities. These values can be utilised as conservative clean-up targets, benchmarks of reducing the potential for harmful risks, and triggers in terms of the compilation of a site specific risk assessment. Using Soil Screening values as a reference point creates a uniform approach in which one can determine the most suitable criteria and methodology when assessing contaminated land.

According to Framework for the Management of Contaminated Land (DEA, 2010):

"*Soil screening values are derived from complex processes and depend on the acceptability of certain scientific assumptions used in the development of standard equations used to model risk*."

Making use of Soil Screening Values and the notion of risk assessment has been accepted as an international practice. It should be noted that the application of these concepts is not an exact science, but is based on professional judgement.

Risk assessments are based on the specific land-use of a contaminated area and Soil Screening Values are therefore developed according to the different categories of land-use. These land-use categories are (DEA, 2010):

- Residential and urban parkland;
- Informal residential settlement; and
- Commercial or industrial.

In the event where multiple land-use categories are applicable to a single site, the most stringent Soil Screening Values will prevail while conducting the risk assessment.

Conceptual Approach for Derivation and Use of Soil Screening Values

The main assumptions which are considered when deriving Soil Screening Values in South Africa are related to the groundwater pathway, which include rainfall, infiltration, and recharge. A factor which has been re-evaluated recently is the human health exposure for people who live in informal settlements. Soil Screening Values should not be regarded as an independent standard which is to be used to establish clean-up targets.

According to Framework for the Management of Contaminated Land (DEA, 2010), Soil Screening Values are not:

- *"Default remediation standards;*
- *Applicable to every site under all circumstances;*
- *Absolute minimum values;*
- *Screening values applicable to occupational exposures;*
- *Applicable to risk property damage;*
- *Valid unless the assumptions inherent in the Soil Screening Values are broadly consistent with the actual site conditions; and*
- *A substitute for a thorough conceptual and qualitative understanding of a site's condition and the risks it might pose to human health and the environment."*

Technical Basis for Calculation of Soil Screening Values

Soil Screening Values which were established for the protection of human health considered the exposure routes, exposure parameters, and toxicological parameters.

Soil ingestion, volatile inhalation, dermal contact, and particulate inhalation are all exposure routes considered when calculating Soil Screening Values.

The model for most sensitive receptor in terms of the exposure parameters for residential land-use was based on a child. In order to make provision for a child, as a receptor, in an informal residential area, exposure values pertaining to dermal contact, dust inhalation and ingestion were increased. The model for commercial and industrial land-use exposures was based on an adult outdoor maintenance worker.

The data which was required for the toxicological calculation of Soil Screening Values were obtained from an international database which indicates the threshold health effects in terms of daily human population exposure. Soil Screening Values were concluded by selecting the lowest value for threshold and non-threshold effects for each land-use with regards to protection of human health.

Soil Screening Values for Protection of Water Resources

There are two tiers of Soil Screening Values which have been established for the protection of water resources namely Soil Screening Value One (SSV1) and Soil Screening Value Two (SSV2).

According to the DEA (2010), Soil Screening Value One (SSV1) values are the lowest which are calculated for human health and water resource protection parameters. Soil Screening Value Two (SSV2) values are land-use specific and can be applied as a screening level site assessment in cases where pathways in terms of water resources are not applicable.

Application of a Site Risk Assessment

Approach and Applicability

Site specific risk assessments are acknowledged as international best practice. The risk assessment allows one to understand the extent to which a site is contaminated and assists in determining if site remediation is necessary. In addition, the risk assessment aids in determining whether a tolerable amount of residual contamination can remain in place or assist in comparing the potential impacts associated with various remediation techniques.

According to the DEA (2010), international best practice for a quantitative risk assessment comprises these four components:

- *"Hazard Identification – identification of the key physical and chemical hazards associated with contaminants on the site;*
- *Toxicity Assessment – evaluation of the toxicological properties of the contaminants of concern on the site that pose a hazard including assessment of safe exposure levels;*
- *Exposure Assessment – identification and exposure assessment of human and ecological receptors on or near a site; and*
- *Risk Characterisation – numerical quantification of the risk."*

It is critical that all assumptions and data used as input in developing numerical risk models for the four components above are valid and appropriate. These four components are interlinked and the quality of input data may have an effect on the outcome of the numerical risk models. It is important to note that risk assessments are based on probabilities and not absolutes, which should be indicated in the decision-making process.

Quality Control and Quality Assurance (QC/QA) of Field Sampling and Laboratory Analysis

According to the DEA (2010), the data which is used in determining the risks associated with contaminated land must be relevant, sufficient, reliable and transparent. The quality of data obtained from soil sampling can be rated in accordance with the following factors:

- *"Choice of sampling points. Is it judgemental or random? How certain is it that contamination has been identified?;*
- *Sampling method. Does it follow good practice guidance? Does it maximise the integrity of the sample?;*
- *Sample handling and storage. Does it minimise contaminant losses or transformation?;*
- *Sample preparation. Is it in accordance with good practice and appropriate for the accurate determination of the contaminant?;*
- *Analytical detection limit relevant to the Soil Screening Value. The analytical limit of detection (LOD) should be sufficiently below the Soil Screening Value to satisfactorily address quantification uncertainty; and*
- *Analytical method quality assurance. Properly accredited laboratory analytical methods must be used when available."*

There are many factors which may influence the outcome of the analytical results of samples and therefore complete dependence of accurate results cannot be placed on the appointed laboratory. All relevant control measures which allow for accurate test results when assessing potentially contaminated land need to be identified by the appointed specialist undertaking the assessment (DEA, 2010).

Effective judgement of potential risk, identification of potential contaminants, and a strong conceptual understanding of probable exposure pathways, release mechanisms and the end result of transport path of the contaminants characterise a contaminated site. Undertaking effective QA/QC controls may be irrelevant if the above mentioned considerations are not conducted in an effective manner. It is therefore imperative that other elements of a site investigation are conducted in accordance with best practice standards so that QA/QC procedures can further substantiate the outcome of contaminated site assessment reports. In turn, this approach would result in information which is factual and scientifically defensible (DEA, 2010).

Pre-Sampling Activities

According to the DEA (2010):

"In order to implement a cost effective and technically feasible site investigation, it is necessary to have a properly formulated sampling strategy, based upon a strong conceptual understanding of the site conditions and history, as well as a clear understanding of the objectives of the site investigation itself. Without this preparation, it is unlikely that any investigation will be successful."

It is important to have an understanding of the following factors before sampling is to be undertaken (DEA, 2010):

- Objectives which have been outlined in the sampling plan;
- Sampling source;
- Location of sample points;
- Type of analysis to be conducted; and
- Identified and accredited laboratory service provider.

The sampling plan

Site history and site conditions, in terms of geological, hydrological and hydrogeological characteristics, should form the basis on which the sampling plan is designed. The objectives of the sampling plan usually comprise the determination of the existence or absence of contamination, the amount or degree of contamination, the potential contaminant migration pathways, and the potential risk receptors in terms of a particular land-use (DEA, 2010).

Sampling patterns

The person who is responsible for the site investigation should ensure that a site specific and suitable sampling plan is compiled. There are numerous sampling patterns which could be adopted which include site-history based, grid, and stratified sampling – these have been listed in order of preference (DEA, 2010).

- Site-history based sampling – site knowledge is used to determine where contaminated areas are located and sampling is localised to these specific areas;

- Grid sampling – this method can be adopted if there is insufficient information with regards to the site history and sampling would be covered across the entire site. Depending on the extent and topography of the site, a regular/offset grid or herringbone pattern can be used to plot proposed sampling points. The information obtained from this sampling can be used to determine potentially contaminated areas and additional sampling can be undertaking in these specific areas; and
- Stratified sampling – this may be a useful method to apply to large and complex sites. It entails dividing the site into numerous sections and applying specific sampling requirements to these sections.

Composite sampling

This comprises the mixing of two or more samples to form a single composite sample which may be analysed. Composite sampling may be appropriate to for the assessment of stockpiled or buried material which is characterised by the presence of non-volatile contaminants. This method of sampling cannot be applied to site specific health and ecological risk assessments due to the inherent uncertainties in the resulting data. Composite sampling is a suitable method of sampling, if a leaching test is to be undertaken for waste classification or on a site where it is preferable to leave a portion of the contaminated material in the ground (DEA, 2010).

QA/QC Procedures

The Framework for the Management of Contaminated Land (DEA, 2010), has established a policy for providing a minimum standard which should be considered when sampling is undertaken. This policy outlines standards and considerations which are made in terms of sample collection, sample analysis and field testing methods.

2.3 Modelling for Remediating Contaminated Land

Introduction

The general objective of the modelling process is to aid in making an informed decision as to what groundwater remediation actions would be most appropriate for a contaminated site and also to support other decision making processes. According to the International Atomic Energy Agency (IAEA), (1999), modelling can be used to develop and support the following:

- "*understanding the role and behaviour of the hydrologic system;*
- *understanding the groundwater pathway(s);*
- *assessment of contaminant transport and geochemical processes;*
- *evaluation of health risks, with and without corrective actions;*
- *evaluation of remediation techniques, including their effectiveness and cost benefits; and*
- *evaluation and prediction of post remediation or long term results*."

The modelling process can be utilised as a management tool in which one can organise and prioritise the collection of data, make predictions based on analysis results, and assist investigators in terms of their understanding of the factors influencing the groundwater regime (IAEA, 1999). Figure 3 illustrates the principles of the modelling application with regards to remedial analysis and design.

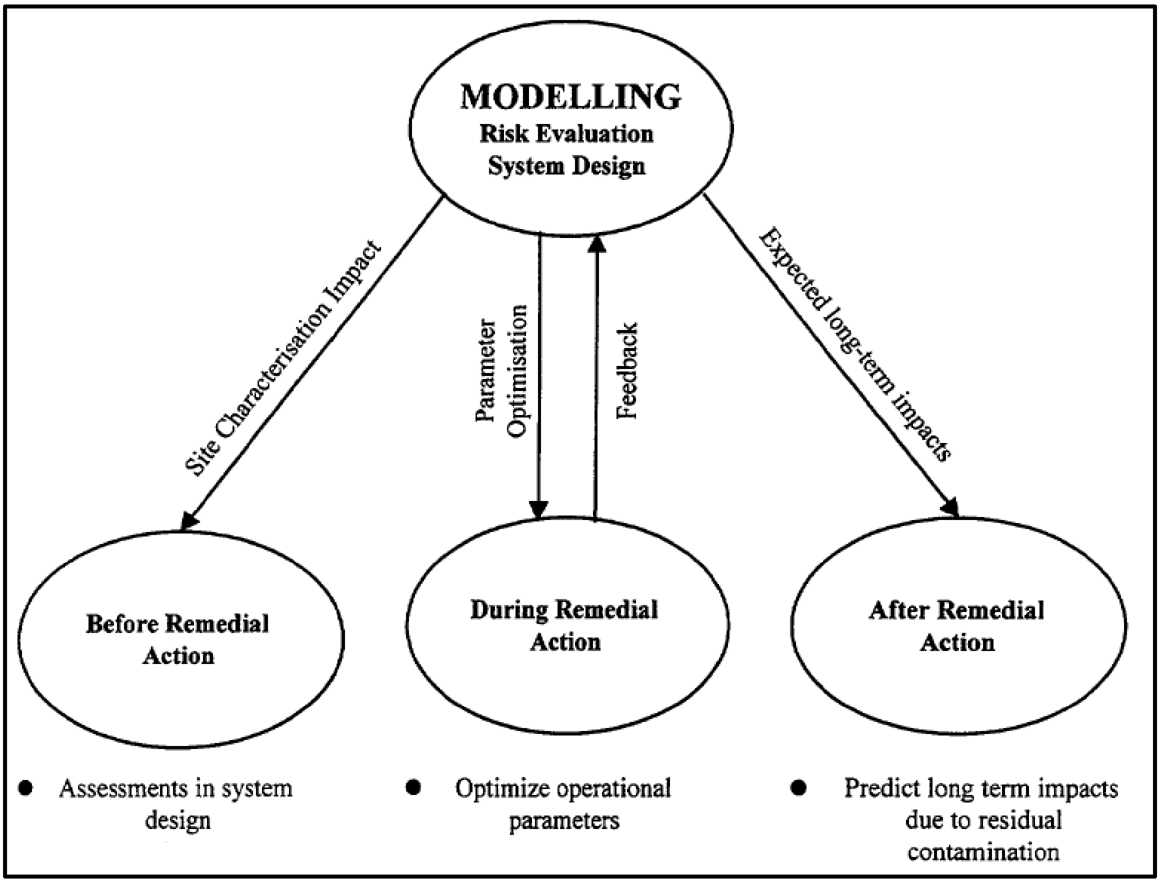

Figure 3: General principles of the modelling application (IAEA, 1999)

The main purpose of modelling is to measure long-term transport and fate of contaminants within a hydrological/hydrogeological environment, and to forecast concentrations of contaminants at exposure points in order determine the most appropriate remedial actions. One can then calculate the risk to potential receptors from exposure to contaminated water once the contaminant concentrations at the potential receptors are assessed. This may be achieved by utilising appropriate risk assessment methods, which range from simple concentration-dose conversion factors to more sophisticated approaches (IAEA, 1999).

Modelling Procedure

Modelling should be regarded as a progressive and repetitive process through which the development of the site is replicated, which allows for understanding of the site, and is flexible to process new data (IAEA, 1999). According to IAEA (1999) modelling of a groundwater pathway may typically include numerous key steps, as follows:

- "*clear definition of modelling objectives;*
- *development of conceptual model(s) of the hydrological/hydrogeological system;*
- *compiling/assembling of hydrological/hydrogeological and geochemical data (this, in itself, may involve a simplified level of modelling, e.g. the determination of hydraulic conductivity from aquifer pumping test would typically involve 'type curve' matching);*
- *formulation of mathematical model(s) of surface water/groundwater flow and contaminant transport processes;*
- *selection or development of an appropriate analytical/numerical model(s);*
- *calibrating model(s) using field observations and data;*
- *applying the model in a predictive manner; and*
- *comparing predictions against observations*."

Defining the objectives of the modelling process is crucial as this will reflect the intermediate as well as the ultimate goal of remediation.

Prior to developing a meaningful model, an adequate understanding of the site is necessary. Establishing a conceptual model can aid in this regard as it provides a proposition of how a system or process operates, and therefore aids in identifying the physical processes which control surface water/groundwater flow and transport. Mathematical models illustrate the relationship between relevant parameters and governing processes. When selecting a numerical model one should regard both the conceptual model as well as the matching mathematical description of the process (IAEA, 1999).

Site specific information, applicable published literature, historical information, and expert judgement constitute the parameters which are considered when compiling a numerical model. It is important to ensure that all input parameters are adequate as this will have an influence on the predictive capacity of the model. During the model calibration phase one will hone estimates of uncertain parameters in order to match observed data. Making use of laboratory and field studies will greatly aid in calibrating and honing the model which may result in a valuable tool for the purpose of remediation system design and performance optimization (IAEA, 1999).

Modelling Techniques and Approaches

The objectives and particular phase of the assessment and remediation process of a contamination problem should be reflected when selecting a modelling approach. There are two general approaches to groundwater modelling, namely (IAEA, 1999):

- pursue analytical solutions; or
- pursue numerical solutions.

If no significant amount of data is available during the preliminary assessment of the system, then the analytical solution approach is useful. Simplicity and computational efficiency are the primary advantages of analytical solutions. According to IAEA (1999):

"The general shortcoming of analytical models is their simplistic representation of the system (e.g. rather simple assumptions of homogeneity of subsurface environment, steady state flow, one-dimensional transport, etc. may be used)."

The analytical model is mostly appropriate to the scoping phase of remedial assessments.

The finite difference and finite element method are the two main types of numerical modelling methods. These are effective modelling techniques which are used to solve flow and contamination transport problems in intricate flow geometries. The finite difference method is conceptually straightforward and physically based while the finite element method has demonstrated to be more flexible in the handling of complex geometry (IAEA, 1999).

Substantial quantities of site specific data are required for modelling during the detailed assessment phase of remedial analysis. Particle tracking methods are used when interpreting flow paths and can provide valuable information regarding the travel time to receptors and the efficacy of a hydraulic containment system (IAEA, 1999).

According to IAEA (1999):

"*Off the shelf groundwater flow and contaminant transport software will usually incorporate the process of advection, diffusion, dispersion, equilibrium sorption, and radioactive decay. These may be steady state or transient. Pertinent modelling areas of active research include the flow* *in fractured media; multiphase flow; multi-species flow with chemical interactions; kinetically limited sorption/de-sorption processes; colloidal transport and the facilitated transport of complexes. Assessment of these processes may require development of research-level models and software, and generally requires a high level of scientific expertise of the modeller*."

According to Keupers and Willems (2017):

"*To assess the surface water status in a catchment and to investigate the impact of mediation actions, river water quality models are needed that can simulate the temporal evolution of the concentration of pollutants at different locations in the water body under different scenarios. To simulate fate and transport processes of pollutants released into river water bodies, mathematical equations are being used to describe the advection-dispersion of conservative pollutants and the biological and chemical transformation processes of non-conservative pollutants.*"

There are numerous models available for simulating river water quality and can cover variables such as nutrients, pathogens, some chemicals, plastics and river temperature (Keupers and Willems, 2017).

Limitations of Modelling

Complexities of the environment give rise to limitations in due the fact that there may be a lack of understanding of significant physical and chemical processes which may impact contaminant transport in the subsurface (IAEA, 1999).

According to IAEA (1999):

"*Significant groundwater modelling difficulties can arise due to the heterogeneity of physical and geochemical properties of natural rocks and soils (which may result in preferential flow and transport processes). It is often impossible to characterise geological heterogeneity on a field scale with a degree of detail needed for adequate modelling.*"

Future changes in influences on hydrogeological systems as a result of natural or anthropogenic factors (such as climate change or industrial activities) may have an effect on long term predictions of modelling. Reliable calibration of groundwater models also has difficulties when historical changes in the hydrogeological system are unknown (IAEA, 1999).

The predictive capacity of models during the early phase of remediation design evaluation is generally low due to its simple nature. Further development of a conceptual model and associated parameters will improve the confidence in modelling results. By improving the conceptual model and associated parameters, one would more likely address any initial uncertainties in the model. It is imperative to continuously check and hone model assumptions by using observed results. It is essential that model assumptions are always accompanied by some suggestion of reliability (IAEA, 1999).

For surface water modelling, most models these days attempt to incorporate as much details as possible. Challenges arise when attempting to link different models together, if different software programs are used it can become a technically difficult and time consuming exercise (Keupers and Willems, 2017).

2.4 Techniques for Remediating Contaminated Land

The remediation of contaminated land may prove to be a costly and technically challenging exercise. A remediation technique can be selected to address the potential contaminant and conditions of a contaminated site. Heavy engineering was recently the primary technique of remediation which offered relatively quick-fix solutions. In some cases heavy engineering is the most feasible option for remediation and it is usually associated with a high demand on resources and has significant environmental and social impact. In cases where heavy engineering is not required, techniques with a lesser impact can be used. These may include soil-treating in the form of bioremediation, or managing the risk without any treatment by deciding to fence off a site to prohibit any access to it (CL:AIRE, 2010).

There are various techniques which can be used for remediating contaminated land, this includes remediation of soils and remediation of groundwater and surface water. “Site remediation techniques supporting environmental restoration activities – a review” is an article written by Hamby (1996) which provides an overview of the different manners in which remediation can be implemented.

2.4.1 Remediation of soils

Biological treatments

Biodegradation is the breakdown of organic compounds by living organisms. Once these organic compounds have been broken down, the formation of carbon dioxide and water or methane occurs. Inorganic compounds do not possess the ability to be biodegraded, but they do possess the ability to be bio-transformed. Biotransformation results in compounds having mobility and toxicity levels more or less in relation to their initial form. The biodegradation process usually requires a specific microorganism to perform the desired task and specific environmental and dynamic conditions in which the microbe would best thrive (Hamby, 1996).

Chemical immobilisation

In situ immobilisation is a method by which a chemical treatment is introduced into the ground. The chemicals which are introduced into the ground specifically target problem materials and render then immobile. This introduction can be done by various means, such as spreading, suspension transport, filling, etc. The application of these chemicals will vary with site specific conditions. Soluble chemicals can be applied by saturating the soil, and the rate of saturation depends on the saturation needed; it can either be surface flooding or gentle spraying. Spreading, filling and forced injection are examples of the introduction of insoluble chemicals into the ground. Research has proved that chemical treatment can drastically decrease the mobility of heavy metals. Between 82 and 95% of the metals which were chemically treated were rendered immobile (Hamby, 1996).

Critical fluid extraction

Organic compounds, such as PCBs and PAHs, can be extracted from soils and sludges by means of a technique using liquefied gas (carbon dioxide, propane, butane, etc.). The gas is compressed to a fluid state by high pressure and moderate temperatures, mass transfer potential is optimum at the critical fluid state. The hazardous waste is added to a vessel which contains a critical fluid, any organics within the waste then accumulate at the top of the vessel which is then pumped to a second vessel. The organics from the second vessel are recovered and critical fluid is reused. Sediments which have been contaminated with PCBs have demonstrated extraction efficiencies of between 90 and 98%, while organics in liquid and semi-solid waste form have demonstrated extraction efficiencies of up to 99.9% in laboratory conditions (Hamby, 1996).

Capping

Capping can be implemented to cut off the interface between a contaminated portion of land (plume) and the surrounding surface and groundwater. This exercise renders the plume immobile by reducing the potential for contaminants to migrate via surface or groundwater. The capping cover typically comprises of a vegetation layer, a drainage layer, an impermeable layer, and a venting layer for any gas which might accumulate. It is imperative that the vegetation layer is well drained and has the ability to support vegetation, as this layer stabilises the surface layer. The integrity of the impermeable layer also needs to be a priority, therefore the roots of the vegetation should not damage it. Ballooning from gas accumulation can occur within the cap due to a number of reasons. These gases need to be vented in a controlled manner, as contaminated material could have the potential to produce a combustible gas (Hamby, 1996).

Incineration technologies

There are many types of incinerators, such as the rotary kiln, infrared furnaces, liquid injection, plasma arc, fluidised bed, and the multiple hearth. Combustion of hazardous waste occurs between temperatures of 800 to 1200ºC, as at these temperatures chemical bonds and other substances can be broken down. By effectively destroying chemical contaminants within hazardous waste, incineration does not just reduce the risk posed by the relevant waste, but also reduces the volumes of waste at waste sites. The composition of waste needs to be considered to make provision for any technical or financial complications. The rotary kiln has the ability to incinerate a wide range of wastes, including hazardous and non-hazardous wastes in liquid, slurry and solid form (Hamby, 1996).

In situ vitrification

According to Hamby (1996), in situ vitrification is the process of melting contaminated soil, buried wastes, or sludges in order to render the material non-hazardous. The vitrification process involves electrically heating the soil to temperatures which may range between 1600-2000ºC, and ultimately destroy organic contaminants by means of pyrolysis. In situ vitrification can be applied to a range of different contaminants such as soils, process sludge, mill tailings, sediments, process chemicals, and other inorganics. In situ vitrification has the capability to (Bellandi, 1995):

- Simultaneously contain organic, heavy metal, and radio-active waste;
- Effectively reduce the toxicity, mobility, and volume of waste material;
- Render the residual product relatively harmless; and
- Be applied to various forms of waste, such as water, debris and soil.

Although vitrification is a very effective method for treating contaminated land, it is a very expensive exercise and is therefore not always feasible (Hamby, 1996).

2.4.2 Remediation of surface and groundwater

Electron-beam irradiation

When water is irradiated with electron beams, free electrons and radicals are produced. The radicals are in the form of H+ and OH- and when they react with trichloroethylene or carbon tetrachloride they become harmless. Once the reaction has occurred, CO_2, H_2O, salts and other compounds are formed. Low dose rates are more effective than higher dose rates because of radical recombination. Pulsed linear induction accelerators have been developed to provide a lower dose rate than the usual electrostatic electron and single pulsed accelerators. These new accelerators are more practical than conventional accelerators, but it cannot be verified which of the two is the more effective (Rosocha *et al*, 1994).

Air sparging/air stripping

Water which is contaminated can either be remediated above the ground or below the ground. Air sparging is the method used for remediating water below the ground. There are two different techniques involving air sparging, namely, in-well aeration and air injection. The pump and treat method is used to remediate water above the ground. The pump and treat method involves pumping water out of the ground, treating it by air stripping and/or treating it by granular activated absorption. In-well aeration involves creating a circulation cell of water flow within a well, water will then absorb oxygen which will volatise any contaminants. The oxygen also induces biodegradation as bacteria growth is promoted. Directly injecting air into an aquifer is known as air injection. Volatile substances can be removed as the air rises up into the extraction well (Hinchee, 1994).

Incineration techniques

The viability of incinerating waste depends on the composition of the waste and the general chemistry of the waste. The combustibility of the waste depends on its organic composition and the ash and chloride content will determine the volume and the character of the solid residues as well as the air emissions which would be emitted. Products of incomplete combustion result when waste is not completely incinerated. These products are organics with different structures and properties, and are most likely to be more toxic. Wastes containing hydrocarbons, metals, and sulphur can be problematic with regards to emissions. The generation of unwanted products of incineration can be minimised by adjusting the temperature, the residence time of the incinerator, and the oxygen injection in the incineration process. Factors which are to be considered with waste incineration are combustibility, water content, and viscosity. Wastes in soil and groundwater have less combustibility than petroleum waste, and therefore require a larger energy input (Hamby, 1996).

Permeable reactive barrier

Permeable reactive barriers are a relatively new and innovative technique used for in situ remediation of soil and groundwater. The permeable reactive barrier technique comprises of the placement of a reactive barrier perpendicular to the flow of the contaminated groundwater. The contaminated groundwater flows through this barrier under the influence of the natural hydraulic gradient. The barrier reacts with the contaminants in the groundwater to render a less hazardous substance or it could render the contaminants immobile (Obiri-Nyarko *et al.*, 2014).

According to Obiri-Nyarko *et al.* (2014), contaminant removal in permeable reactive barriers generally occurs in close proximity of the reactive media and, depending on the type of barrier used, contaminants can be removed downstream from the barrier. Contaminants can be removed by barriers through physical contact, and others remove contaminants by altering the biochemical process in the treatment zone. This biochemical alteration stimulates contaminant immobilisation and biodegradation.

Phyto-remediation

Phytoremediation can be seen as a plant-mediated process of decontaminating or detoxifying contaminated areas. Phytoremediation removes pollutants from air, land or water which renders pollutants harmless with no effect on the biological activity, structure and fertility of soils. Phytoremediation is a modern, efficient, cost effective and environmentally friendly method for the rehabilitation of contaminated land. One of the processes which results from phytoremediation is 'phytoextraction', which involves the use of plants which possess the ability to extract or remove metals from soil, also known as hyperaccumulators. The metals will concentrate in a harvestable part of the plant which makes the contaminants then available for removal and disposal. These plants are allotted a certain amount of time to grow and, in turn, extract or remove contaminants. They are then harvested and disposed of in the appropriate landfill site or incinerator. A similar manner in which heavy metals can be hindered from leaching is known as 'phytostabilisation'. This entails the use of metal-tolerant plants which possess a dense mat of adventitious root systems and rhizosphere microbes which are able to hinder the leaching of heavy metals. Plants which are used for phytoremediation are usually able to remediate a specific source of pollution. Even though these plants are able to remove specific the pollutants from the soil, the pollutants generally hinder the effectiveness in which the plants grow. Plants which are used for phytoremediation purposes can serve as a source of biomass, biofuel production or carbon sequestration (Rajkumar *et al*., 2012).

2.5 Case studies pertaining to capping as remediation technique

Geosyntec Consultants (2010) conducted an independent study on landfills that evaluates liner and capping success and the associated protection of groundwater. They state that "*landfills are engineered to provide overlapping measures for environmental, health, and safety protection. These measures include monitors and back-up systems that help protect the integrity of landfills in the event of emergencies or natural disasters"*. Liners and capping must function together with natural geologic conditions to increase the environmental performance of a landfill site. They conclude that their findings indicate that no single remediation option should be implemented, instead two of more should be implemented to contain possible pollution movement from the landfill site. They also highlighted the importance of monitoring groundwater systems.

Henken-Mellies and Gartung (2004) conducted large-scale field tests to determine the effectiveness of landfill capping systems. Large-scale lysimeters were installed on a landfill site. Water flowing out of the capped system is measured. A thick loamy sand was placed in a lysimeter. The second lysimeter was filled with 1 m of top soil, a drainage geocomposite and a geosynthetic clay liner. A water balance over a four year period was calculated based on the field observations for both lysimeters. The results indicate that the lysimeter filled a thick loamy clay is not as effective as the second lysimeter which was filled with a combination of materials as mentioned above. In the second study less than 1% of precipitation seeped through the capping.

Stief (2001) studied the post-closure care of landfill sites. The study concluded that if the waste deposited at a landfill site is not pre-treated and if landfill did not operate correctly leaching of pollutants could take place. One of the reasons for insufficient post-closure care is the lack of funds leading to inability of employing experts to supervise post-closure care. It is suggested if economic benefit can be obtained from capped landfill sites, the monitoring and maintenance of these sites would improve.

Meggyes *et. al,* (1998) conducted a review of the engineering technicalities of landfill capping in Germany. They concluded that capping systems are site specific and therefore location and available materials must be taken into account. The Germans tend to use temporary cappings, until the landfill site has settled and stabilized, thereafter a final capping will be implemented. Landraising and the implications on future landfill sites is noted as an aspect that will highlight the importance of utilizing the correct capping methodologies.

Chapter 3: Methods of Investigation

3.1 Introduction

The investigation made use of historical data which was provided by the owner of the contaminated land. All of the historical data which was available was then screened in order to obtain all data which is relevant to and may aid in the investigation. A methodology was then established to assess the degree to which the contaminated land impacts the surrounding groundwater and surface water.

A detailed literature review was established which contained information pertaining to both national and international norms and standards. From the literature which was obtained, it was evident that the following points needed to be addressed to ensure the effective management of contaminated land (DEA, 2009):

- The degree to which the site is contaminated;
- The urgency regarding the need for remediation; and
- The objectives in terms of mitigation.

Due to the fact that all data which is to be used in this study is readily available in the form of historical information gathered by the land owner, this dissertation can be considered a desktop study and therefore the sampling and associated procedures will not be included. However it is suggested that DWAF (2006) and WRC (2007) be consulted for sampling procedures.

The data collected includes (but it not limited) to the following data sets:

- Site infrastructure maps;
- Borehole information (locations, water levels, geological logs (if available) and water quality);
- Surface water bodies (locations, flow data and water quality);
- Rainfall data;
- Geological maps; and
- Aquifer parameters (hydraulic conductivity/transmissivity, storativity and porosity). Aquifer testing might be necessary to determine some of these parameters. The WRC (2002) report documents the relevant tests in detail.

3.2 Data Analysis

Groundwater level measurements and groundwater chemical analysis have been undertaken as part of routine monitoring by the owner of the contaminated land. Historical data has therefore been made available for the purpose of this study.

3.2.1 Groundwater Level Measurements

A number of reliable monitoring points were selected to determine the groundwater gradient. According to Krantz and Wilke (2000), groundwater gradients in the Karoo aquifers generally tend to mimic the topography.

An interpolation technique, using the available data, was used to simulate water levels over the entire model area. The interpolation technique used is referred to as Bayesian interpolation where water levels are correlated with the ground elevation. All available groundwater levels, which were obtained from a sampling exercise undertaken in November 1999, were plotted against ground elevation for the weathered and fractured rock aquifers as shown in Figure 4 and Figure 5. The results indicate a correlation of approximately 80% in the shallow aquifer and 85% in the deeper aquifer. Bayesian interpolation is valid and used to calculate water levels for both aquifers.

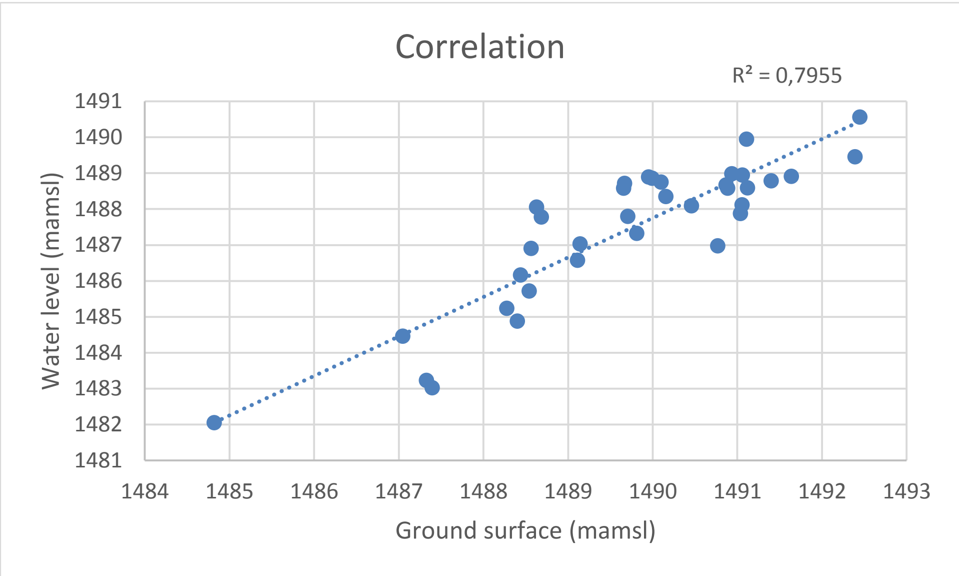

Figure 4: Correlation between ground surface and groundwater levels for the shallow aquifer

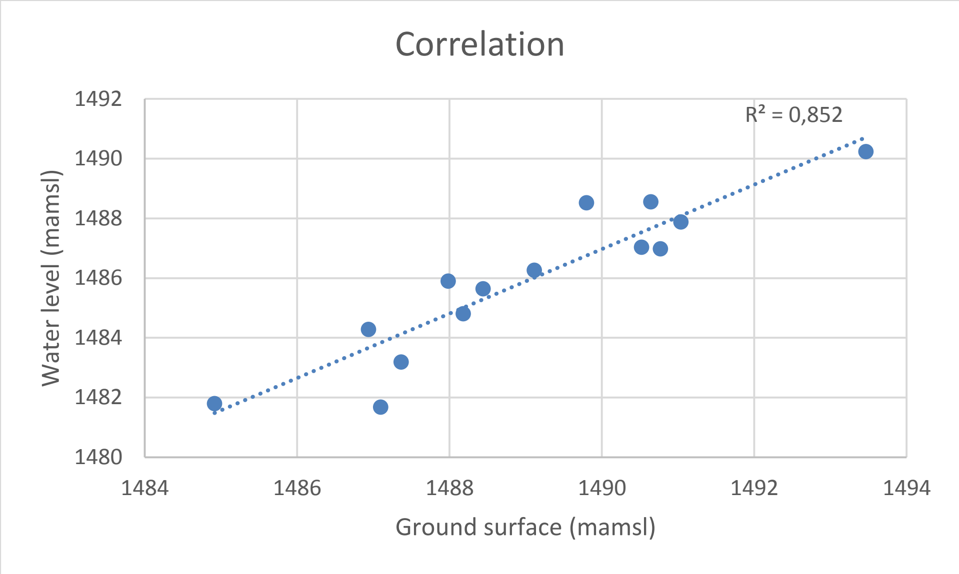

Figure 5: Correlation between ground surface and groundwater levels for the deep aquifer

3.2.2 Recharge

Recharge is defined as the process by which water is added from outside to the zone of saturation of an aquifer, either directly into a formation, or indirectly by way of another formation. According to Krantz and Wilke (2000), it can be estimated that the mean annual recharge within the Sasolburg area is in the order of 2% of the Mean Annual Precipitation. Any variation in the recharge would depend on the permeability of strata, the degree of development in the study area and the potential for artificial recharge from leaking servitudes. It can therefore be estimated that a recharge figure of 1.5% to 2% of the Mean Annual Precipitation will be appropriate to the study area. The groundwater recharge (*R*) for the area is also calculated using the chloride method (Bredenkamp *et al.*, 1995) and is expressed as a percentage of the Mean Annual Precipitation (MAP).

The method is based on the following equation:

$$R = \frac{Chloride\ concentration\ in\ rainfall}{Harmonic\ mean\ of\ chloride\ concetration\ in\ groundwater} x\ 100$$

3.2.3 Groundwater Chemical Analysis

Historical data for numerous monitoring boreholes were utilised in determining the groundwater quality. The most complete and comprehensive set of data for the chemical analysis of the groundwater quality for the study area was undertaken in November 1999.

There are a total of 27 monitoring boreholes for the shallow weathered aquifer and a total of 14 monitoring boreholes for the deeper fractured aquifer.

The chemical analysis on the groundwater samples undertaken for the above mentioned monitoring wells can be seen below. These values will be compared to the SANS 241 standards for recommended concentrations for domestic use (SANS, 2011). These recommendations can be grouped into two classes (SANS, 2011):

- Class 1 – recommended limit, which is the acceptable domestic water quality for lifetime consumption.
- Class 2 – maximum allowable limit for specified consumption duration.

Piper diagrams are plotted to determine the character of the water.

For the purposes of this study, SO_4 was considered a priority pollutant which needs to be addressed and was therefore used to define the initial concentration (3860 mg/l) for the contaminant migration simulation from the specific pollution source.

3.3 Risk Assessment

A risk assessment methodology consists of three interactive phases: problem formulation, analysis and risk characterisation. The whole process leads into a decision making phase known as risk management. The three phases are briefly discussed below:

- Problem formulation: Establishes whether there are potential hazards and considers the consequences of the hazard. The goals of the risk assessment are established;
- Analysis: Calculates the magnitude and probability of consequences; and
- Risk characterisation: Evaluates the risk or determines the significance of the risk to those concerned or affected.

In this study risk was quantified by comparing water quality tog

3.4 Conceptual Model

Groundwater conceptual modelling comprises of taking geohydrological and hydrostratigraphic characteristics obtained in field observations and translating them into a numerical format. In the case where data and time-dependent observations are limited, previous experience and knowledge of the host lithologies may be incorporated in the model (Krantz and Wilke, 2000).

According to the US EPA (1992), the initial assumptions which establish a conceptual model should relate to the following:

- *"The geometry of the boundaries of the investigated aquifer domain;*
- *The kind of solid matrix comprising the aquifer;*
- *The mode of flow in the aquifer;*
- *The flow regime;*
- *The properties of the water;*
- *The presence of sharp fluid-fluid boundaries, such as a phreatic surface;*
- *The relevant state variables and the area, or volume, over which the averages of such variables are taken;*
- *Sources and sinks of water and of relevant contaminants, within the domain and on its boundaries;*
- *Initial conditions within the considered domain; and*
- *The conditions on the boundaries of the considered domain that express the interactions and its surrounding environment."*

Based on the above mentioned requirements, the historical data which are readily available were screened to obtain all relevant information which constitutes a comprehensive conceptual model.

3.5 Modelling

3.5.1 Surface water modelling

Due to there being no surface water bodies in the direct vicinity of the site only a basic particle tracking of the potential surface flow paths was simulated using Global Mapper Version 18.1 developed by Blue Marble Geographics.

3.5.2 Groundwater flow and mass transport modelling

It is evident from the groundwater conceptual model that the groundwater modelling exercise should consider the rainfall recharge and hydrogeological characteristics of the site - which include a shallow weathered aquifer and a deeper fractured rock aquifer - and if necessary the interaction between the surface water systems and the groundwater regime. This modelling exercise utilises the features that are included in the internationally recognised MODFLOW software, which was developed by the United States Geological Survey.

A MODFLOW groundwater model was set up by using the catchments and the rivers in the vicinity of the study area as fixed head boundaries. The groundwater levels were first calibrated in a regional groundwater model before a refined groundwater model was set up specifically for the site. A number of scenarios were then run to test various mitigation options.

MT3DMS was used for the contamination transport modelling because this software is designed to be used in conjunction with MODFLOW.

3.5.3 Modelling Assumptions

In order to simplify the complex nature of natural groundwater systems it is necessary to establish assumptions to simulate groundwater in the most accurate way possible. The establishing of assumptions aids in focusing the modelling process and supporting accurate calibration of the numerical model. The assumptions established are as follows:

- The flow of groundwater is described using Darcy's law (water with a higher potential moves to a location with lower potential);
- Rainfall recharge is spatially uniform;
- During the model setup boundary conditions are assumed – rivers are regarded fixed head boundaries;
- The contaminant source in the shallow weathered aquifer is the primary source of contamination entering the groundwater. There are various contaminants within the investigation site, however SO_4 was considered a priority pollutant which needs to be addressed and was therefore used to define the initial concentration (3860 mg/l) for the contaminant migration simulation from the specific pollution source; and
- Permeabilities for remedial material were assumed based on relevant literature, which were otherwise unknown.

3.5.4 Numerical Modelling

Definition of the Model Domain

During the modelling exercise the model domain should ideally be selected so as to coincide with the physical hydrogeological boundaries, such as watersheds.

The lateral discretisation of the model domain is important to ensure that there is a good resolution of the simulation results. The refined groundwater model domain covers an area of 11200 m by 11200 m with a grid node spacing of 25 m (Figure 17). Topographic map 2627DD and Quaternary Catchment C22K were used to establish the extent of the study area and used to establish the boundaries of the study area, respectively.

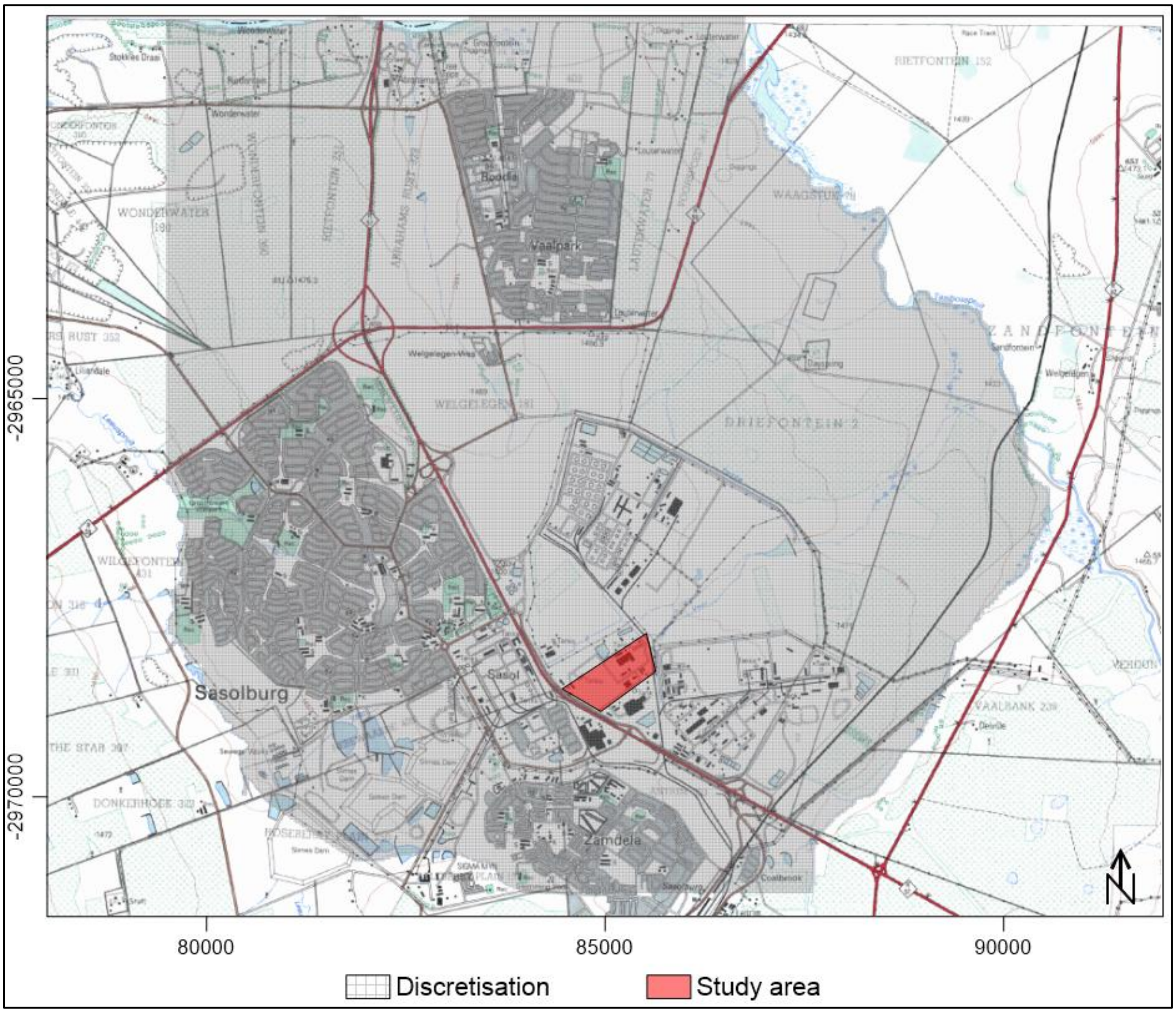

Figure 6: Model discretisation

Two types of aquifers, a shallow weathered and a deeper fractured aquifer, have been identified within the region of the site. The shallow aquifer extends from the surface down to the base of the weathered aquifer which is usually in the order of 5 m below surface. The deeper fractured rock aquifer has been delineated from the base of the weathering profile to a depth of approximately 25 m below the surface, making this layer 20 m thick. These two layers are each represented in the MODFLOW model so that the aquifer parameters of the respective units may be considered in the groundwater model simulations.

Initial Aquifer Parameters

A number of boreholes were pump tested to determine the parameters for the aquifers underlying the investigation site in previous studies. The results of pump testing were collated to provide the initial aquifer parameters for the purpose of groundwater modelling. According to Krantz and Wilke (2000) certain aquifer parameters are difficult to measure in the field and are therefore estimated on the basis of past experience.

The initial aquifer parameters for the groundwater modelling exercise, established by Krantz and Wilke (2000) are presented in Table 1.

Table 1: Initial aquifer input parameters (Krantz & Wilke, 2000)

Parameter	Value	Aquifer	Source
Transmissivity	0.007 m/day – 0.624 m/day x 5 m	Shallow Weathered	Historical field tests
Transmissivity	0.00218 m/day – 0.0519 m/day x 20 m	Deeper Fractured	Historical field tests
Vertical Hydraulic Conductivity	0.0007 m/day – 0.0624 m/day	Shallow Weathered	Estimated
Vertical Hydraulic Conductivity	0.000218 m/day – 0.00519 m/day	Deeper Fractured	Estimated
Storage Coefficient	0.003	Shallow Weathered	Estimated
Rainfall Recharge	1.5% - 2.5% of MAP	Shallow Weathered	Estimated

Initial Groundwater Levels

It has been previously documented that the groundwater water levels generally mimic the topography. This relationship is therefore used to interpolate the groundwater levels from the observed water levels using the baysian interpolation method. The digitized topographic points are used as known values from which the groundwater levels may be determined by utilizing the observed groundwater elevations from the monitoring boreholes.

Initial Chemical Concentrations

Prior to remediation of the significantly polluted portion of land within the investigation site, waste was disposed of in an inappropriate manner. The source of the waste is miscellaneous in nature and consisted of, but not limited to, old rubber, CS_2, sulphur, chemical accelerators and tars. The contamination source for this specific portion of land is heterogeneous with contaminant concentrations ranging from 1550 mg/l to 3167 mg/l SO_4, 289 mg/l to 3063 mg/l Cl, and 384 mg/l to 2909 mg/l of Na (Krantz and Wilke, 2000).

For the purpose of this groundwater model, the initial chemical concentration of 3167 mg/l of SO_4 will be used when simulating contaminant transport.

Model Calibration Results

Contaminant transport simulations utilise the groundwater flow velocities and direction as key model inputs. These values are combined with the contaminant transport parameters to produce the resultant rate of contamination migration (Krantz and Wilke, 2000).

It is important for the model calibration to have a reasonable correlation between the simulated and observed groundwater elevations.

A total of 34 boreholes from the shallow weathered aquifer and 14 boreholes from the deeper fractured aquifer were used to compare the simulated versus observed groundwater elevations. It can be seen from Tables 2 and 3 that there is a reasonable agreement between the simulated and observed levels for both aquifers.

Initial input parameters were adjusted during the calibration of the model, such as rainfall recharge and transmissivity, in order to obtain a reasonable correlation of the groundwater simulated and observed groundwater levels for both the shallow and weathered aquifers.

Table 2: Comparison between the observed and simulated groundwater elevations

Deeper Fractured Aquifer			
Borehole	**Observed Groundwater level (masl)**	**Simulated Groundwater level (masl)**	**Observed-Simulated Difference (m)**
B1D	1490.42	1488.09	2.33
B7D	1487.03	1488.595	-1.565
B8D	1486.98	1488.482	-1.502
B14D	1484.81	1485.95	-1.14
B15D	1486.26	1486.5	-0.24
B18D	1484.19	1485.38	-1.19
B20D	1483.68	1485.114	-1.434
B21D	1485.64	1486.123	-0.483
B22D	1485.9	1486.082	-0.182
B23D	1484.28	1485.292	-1.012
B26D	1488.52	1487.456	1.064
B33D	1488.55	1488.018	0.532
B36D	1490.23	1488.145	2.085
B37D	1481.8	1484.277	-2.477

Table 3: Comparison between the observed and simulated groundwater elevations

Shallow Weathered Aquifer			
Borehole	**Observed Groundwater level (masl)**	**Simulated Groundwater level (masl)**	**Observed-Simulated Difference (m)**
P2	1487.876	1488.56	-0.684
P4	1489.953	1488.592	1.361
P6	1488.671	1488.599	0.072
P7	1488.124	1488.597	-0.473
B2S	1490.561	1488.471	2.09
B3S	1488.917	1488.563	0.354
B4S	1488.946	1488.617	0.329
B5S	1488.99	1488.567	0.423
B6S	1488.79	1488.492	0.298
B10S	1487.322	1488.119	-0.797
B11S	1488.06	1487.412	0.648
B12S	1487.03	1486.975	0.055
B13S	1486.91	1486.699	0.211
B14S	1484.88	1485.984	-1.104
B15S	1486.58	1486.496	0.084
B16S	1487.78	1487.352	0.428
B18S	1484.23	1485.391	-1.161
B19S	1486.17	1486.098	0.072
B20S	1484.03	1485.075	-1.045
B21S	1485.72	1486.137	-0.417
B22S	1485.24	1486.09	-0.85
B23S	1484.46	1485.266	-0.806
B24S	1487.8	1486.985	0.815
B25S	1488.722	1487.492	1.23
B27S	1488.58	1487.474	1.106
B28S	1488.35	1487.413	0.937
B29S	1488.86	1487.662	1.198
B30S	1488.9	1487.76	1.14
B31S	1488.75	1487.767	0.983
B32S	1488.09	1488.13	-0.04
B33S	1488.58	1488.041	0.539
B34S	1488.59	1487.943	0.647
B35S	1489.46	1488.248	1.212
B37S	1482.05	1484.3	-2.25

The degree of the model calibration may be verified by means of correlation percentage between the observed versus simulated groundwater levels. The result of the correlation verification is presented in Figures 7 and 8. The correlation graph confirms that the degree of groundwater model calibration is reasonable with a correlation percentage of 83.8%.

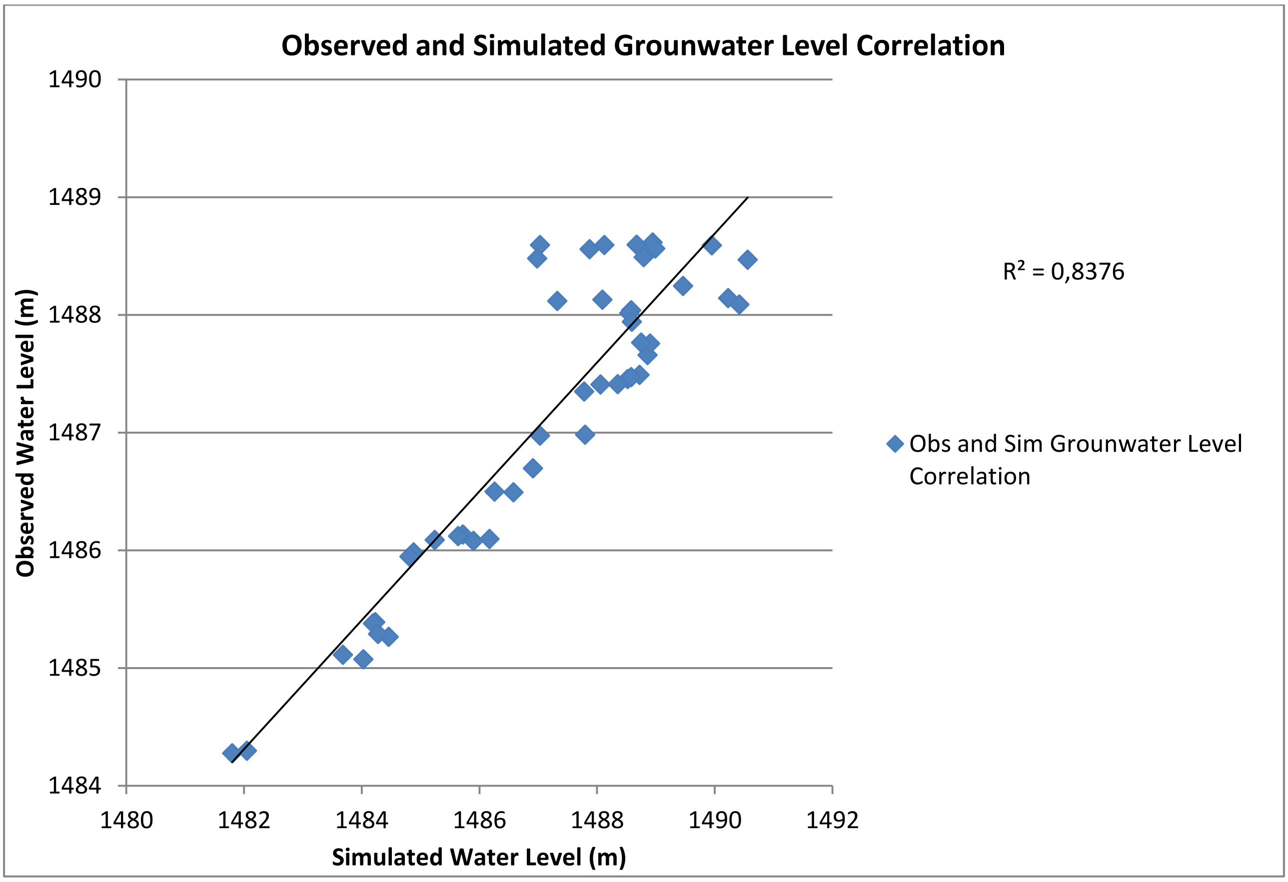

Figure 7: Correlation between observed vs simulated groundwater levels

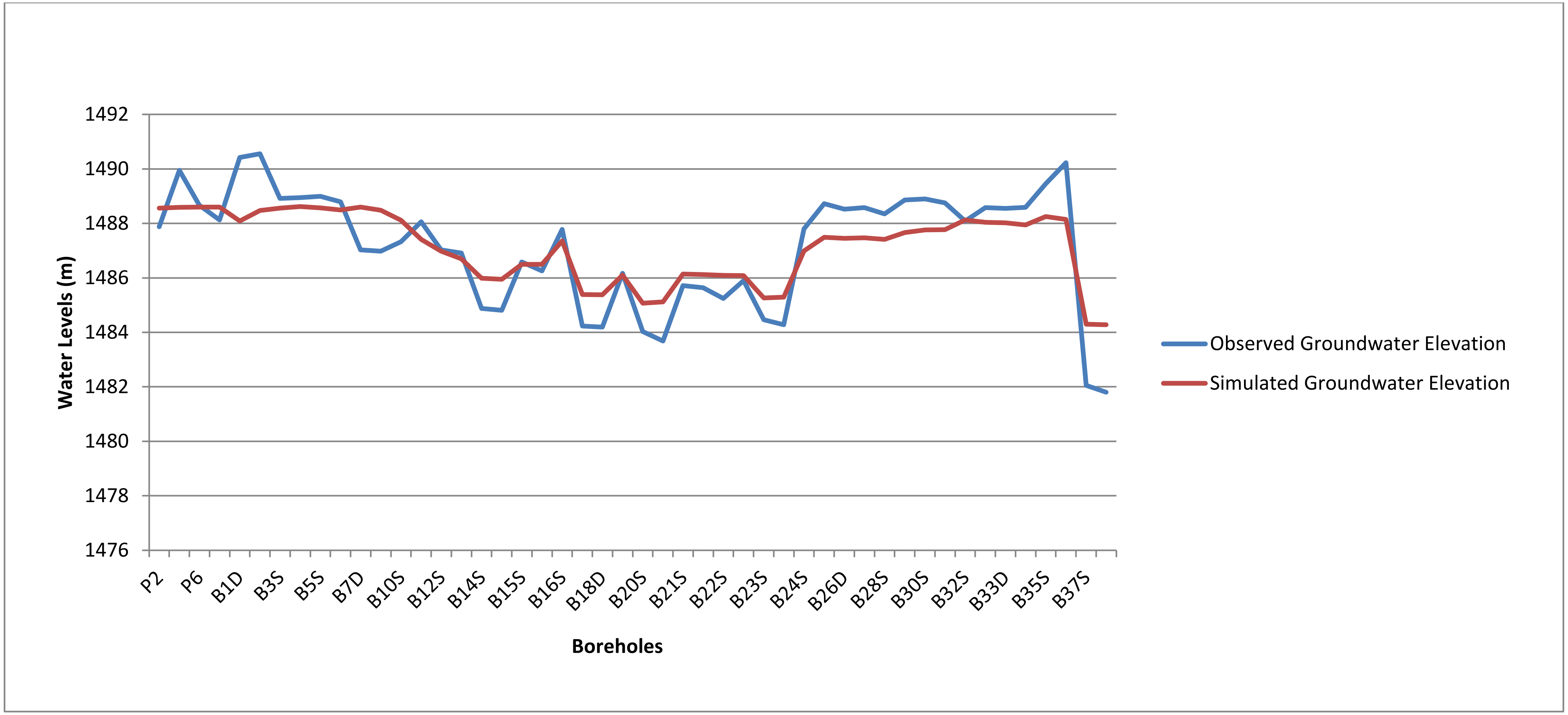

Figure 8: Observed vs simulated groundwater elevations

3.6 Costing Analysis

A costing analysis was established to aid in the decision-making process to determine the most appropriate remediation technique in this instance. This analysis included the suggested remedial activity to be undertaken, complexity, cost, and pros and cons of each option. Contaminated land remediation is a costly exercise and requires meticulous thought and planning prior to any decision-making. In this particular contaminated land case, Jones and Wagener (2006) compiled a remedial options analysis prior to the capping of the investigated contaminated land. This analysis described the complexity, pros, cons and cost of each presented option in Table 4.

Table 4: Remedial options analysis (Jones and Wagener, 2006)

Option	Description	Pros	Cons
1	Leave as is, i.e. 'do nothing'.	There is little cost involved and contaminants will dissipate over time.	This may result in increased salinities in the deeper aquifer with contaminants migrating off-site. Dissipation will take a long time.
2	Leave as is and establish a programme of thorough groundwater monitoring in order to monitor the 'natural attenuation'.	No large layout cost incurred as current monitoring system and be used.	May require the authorisation of relevant authorities and require long term monitoring – 10 to 20 years.
3	Implement capping and grade the surface of the contamination source to promote runoff.	Relatively cheap and easy to achieve in a short time span. In addition it will limit infiltration and through-flow.	Will not be entirely effective in controlling lateral flow particularly in the shallow aquifer.
4	Cap contamination source and plant high water use trees to promote the uptake of saline waters.	Relatively cheap exercise and promotes the use of natural processes.	Will require the identification of suitable trees and will be a slow and long term process. Trees may also be a fire hazard.
5	Excavate and remove the contaminated material.	Removes the bulk of the high salinity material.	Very costly exercise and there is limited landfill capacity in most towns.
6	Install effective cut-off barriers and establish a groundwater monitoring programme.	This is proven technology which will contain the high salinity groundwater on site. Relatively inexpensive to implement.	Will require some excavation activities. The intercepted groundwater will need to be managed.
7	Solidification / stabilization of the contaminated soil material.	This exercise is achievable. This exercise will transport and off-site disposal costs.	Requires a large amount of excavation and re-engineering. Contaminated material will need to blended with

			lime and ash and compaction of material will be required.
8	Subsurface (in-situ) flushing of the contaminated material.	Little disturbance.	Costly and slow process. This may be ineffective in clay materials. Unlikely to achieve success due to the developed preferential flow paths.
9	Combination of options 2, 3, 4 and 5 above with phases and modifications as follows: Phase 1: Establish a comprehensive groundwater monitoring programme and cap the contamination source. Phase 2: Install a cut-off barrier and interception trench around contamination source. Plant deep rooted trees with high evapo-transpiration rates and use the water intercepted at the cut-off trench to irrigate the trees.	This is a practical solution which allows phasing of actions. These actions minimise the potential of off-site migration of the contaminants. Reasonable cost incurred for benefits to be achieved.	Long term solution. Limits the future land-use potential of the area and does not remedy the unstable geotechnical conditions in the area.

Chapter 4: Background of the Study Area

4.1 Background

4.1.1 Locality of study area

The study area falls within the Leeuspruit and Taaibosspruit catchment, which is a sub-catchment of the Vaal Dam to Vaal Barrage catchment in the Upper Vaal Water Management Area (WMA) located in the eastern interior of South Africa (Golder Associates, 2012).

The investigation site is located within the industrial area of Sasolburg and is surrounded by industrial activities. The investigation site is likely to remain an industrial site for the foreseeable future. The vegetation surrounding the Sasolburg area consists of grasslands and farmlands. The Vaal river runs from east to west about 20km north of the study area, which itself is located on relatively high ground with drainage towards the north east, east and south east (Rademeyer, 2013). Figure 9 illustrates the locality of the investigation site.

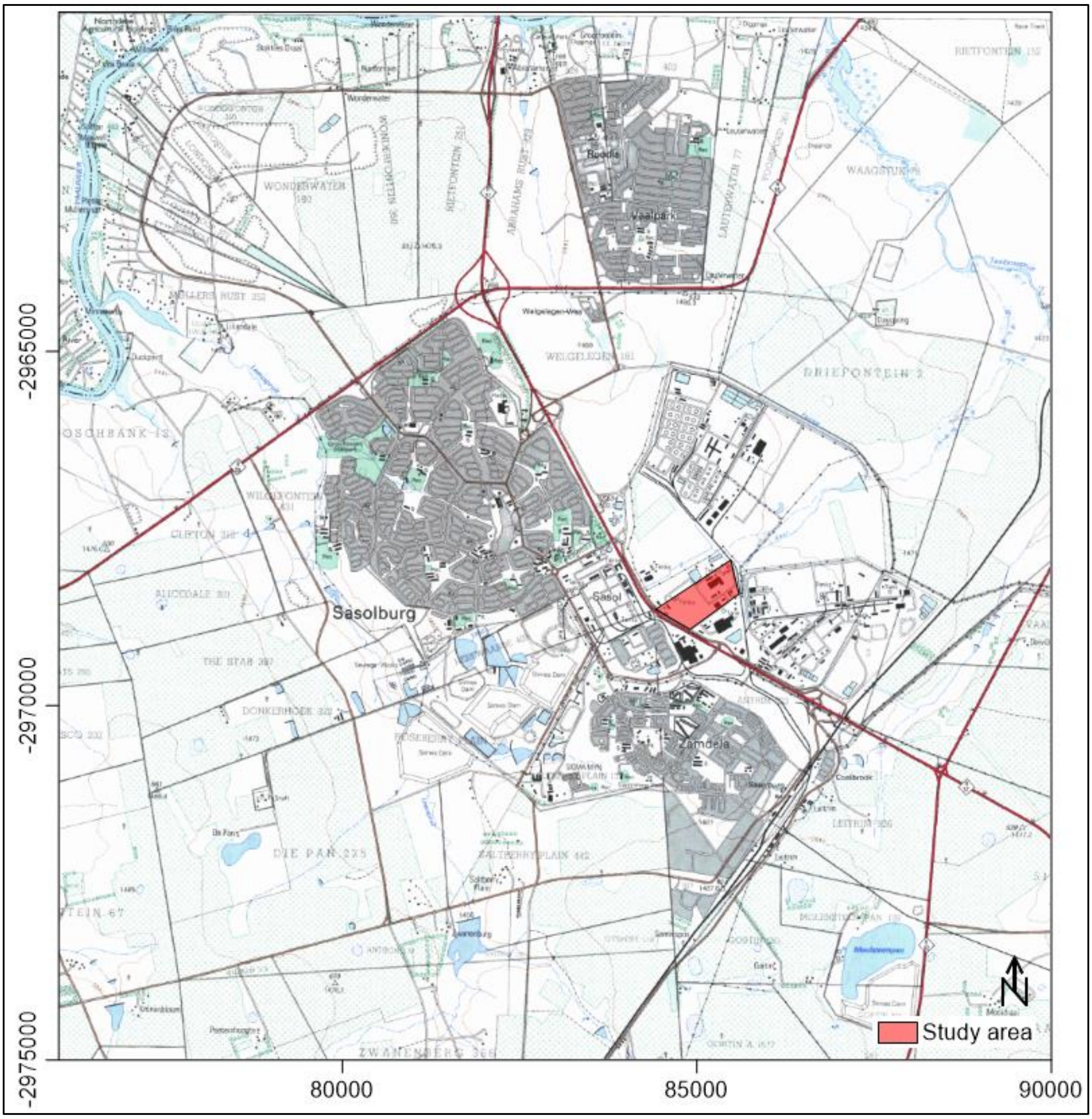

Figure 9: Locality of investigation site

4.1.2 History of the study area

Historically up to 40 years ago drummed wastes were disposed into what was known as the waste site under investigation. Consequently, the subsurface of the site has historically been impacted by salts associated with these wastes. In 2012 the owners of the waste site capped the site and included a subsurface cut-off curtain around the contamination source. This work was completed during 2012 and included the following Morris (2016):

- Re-profiling of the waste site's footprint area was also done to enable more gentle slopes and a protective soil cover over the area;
- Compaction of the soil cover;
- Installation of an impermeable subsurface barrier in the form of an HDPE curtain around the broader area to a depth of 3 m below grade. Included in this is a sub-drain at the base of the impermeable barrier so that the area can be dewatered if groundwater accumulates. Dewatering boreholes in the form of large diameter (110 mm) piezometer and slot for sampling and water level monitoring purposes;
- Installing a HDPE protective liner over the whole of the demarcated waste site and adjacent area, i.e. to cover the area surrounded the cut-off barrier;
- Placing a protective vegetated soil cap over the cover liner; and
- Installing passive vents for any gases that may accumulate below the cover liner to prevent upwelling and displacement of the liner. They also facilitate aeration and natural degradation of any contaminants below the liner – commonly referred to as enhanced natural degradation.

4.1.3 Drainage, vegetation, land-use, and climate

Due to high level of urbanisation and economic activity in the Upper Vaal WMA the water resources are highly developed and regulated. The Upper Vaal WMA functions as a central point in which water is transferred to other WMAs (Golder Associates, 2012).

The Leeuspruit-Taaibosspruit catchment includes 1.6% of the 2098 km^2 area covering the Upper Vaal WMA. The groundwater in the area is primarily utilised for rural domestic needs and livestock watering, with a significant quantity also being abstracted from the dolomitic aquifers for urban, agricultural and mining use. The Leeuspruit and Taaibosspruit rivers flow in a north-westerly direction towards the Vaal River and joins in above the Vaal Barrage (Golder Associates, 2012). The rivers/streams within the study area are shown in Figure 10.

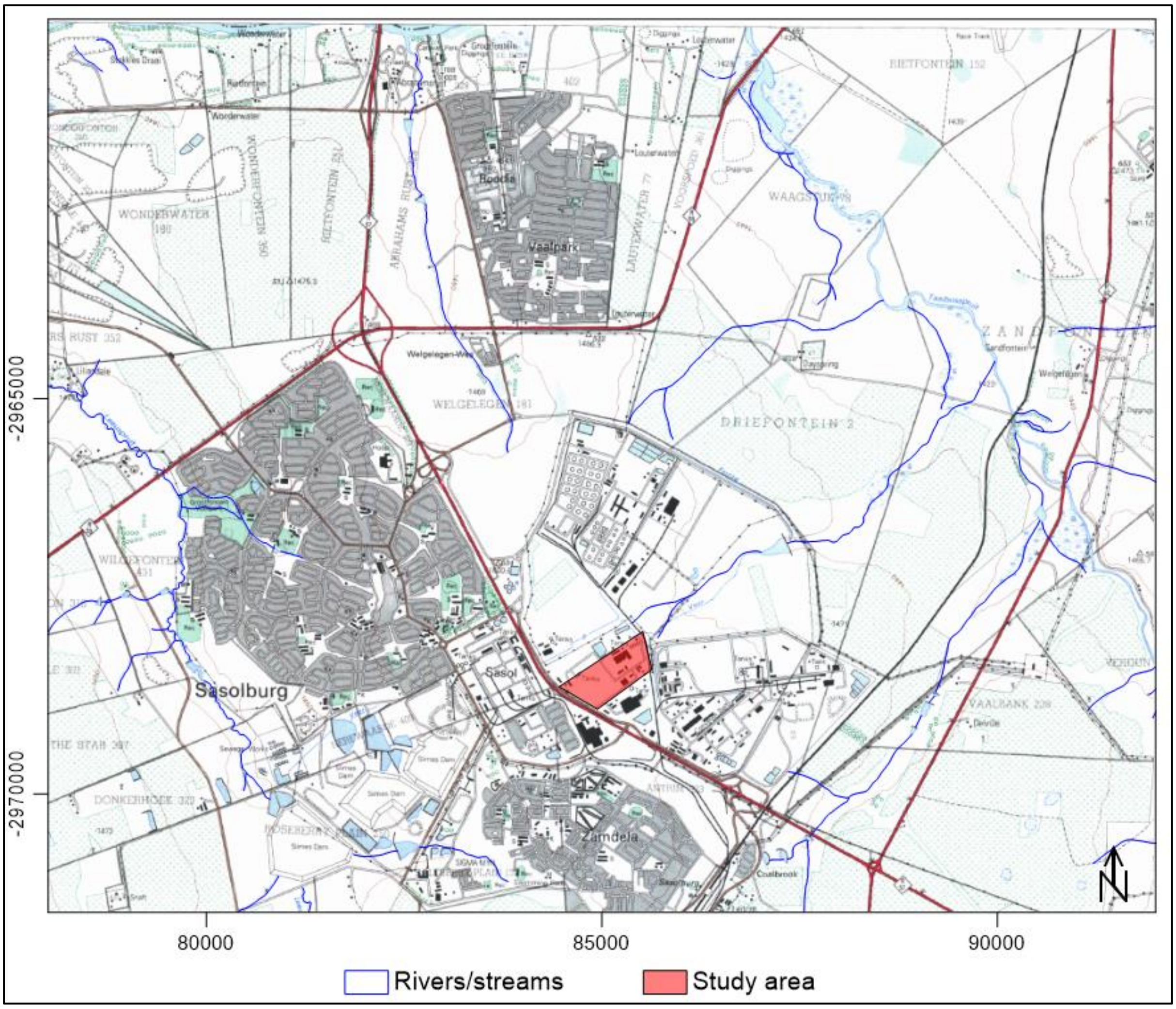

Figure 10: Rivers and streams

Mining and industrial discharge of associated salinity loads form the major impact on water quality within the catchment. Another source of impact is the sewage return flows which further contribute to the salinity and nutrient loads of the Vaal River. There is no indication of potential future growth of the WMA for the Leeuspruit-Taaibosspruit catchment, particularly in the urban and industrial areas of Vereeniging and Vanderbijlpark, or for additional development in coal mining (Golder Associates, 2012).

The catchment experiences warm summers with temperatures ranging between 19°C and 22°C, and relatively cold winters with daily average temperatures ranging between 10°C and 17°C. Summer months are conducive to Highveld thundershowers while winters are generally cold with daily average temperatures ranging between 10°C and 17°C (Golder Associates, 2012).

Rainfall data was obtained from rainfall station C2E001, which is the Vaalplaats and Vaal River Barrage station. The average rainfall between the years 1970 and 2015 is 718 mm, ranging from 400mm to 1100mm per annum. Figure 11 is a graphical illustration of the annual rainfall data collected at rainfall station C2E001 from 1970 to 2015. Rainfall occurs as convective thunderstorms and may be accompanied by hail at times (Golder Associates, 2012).

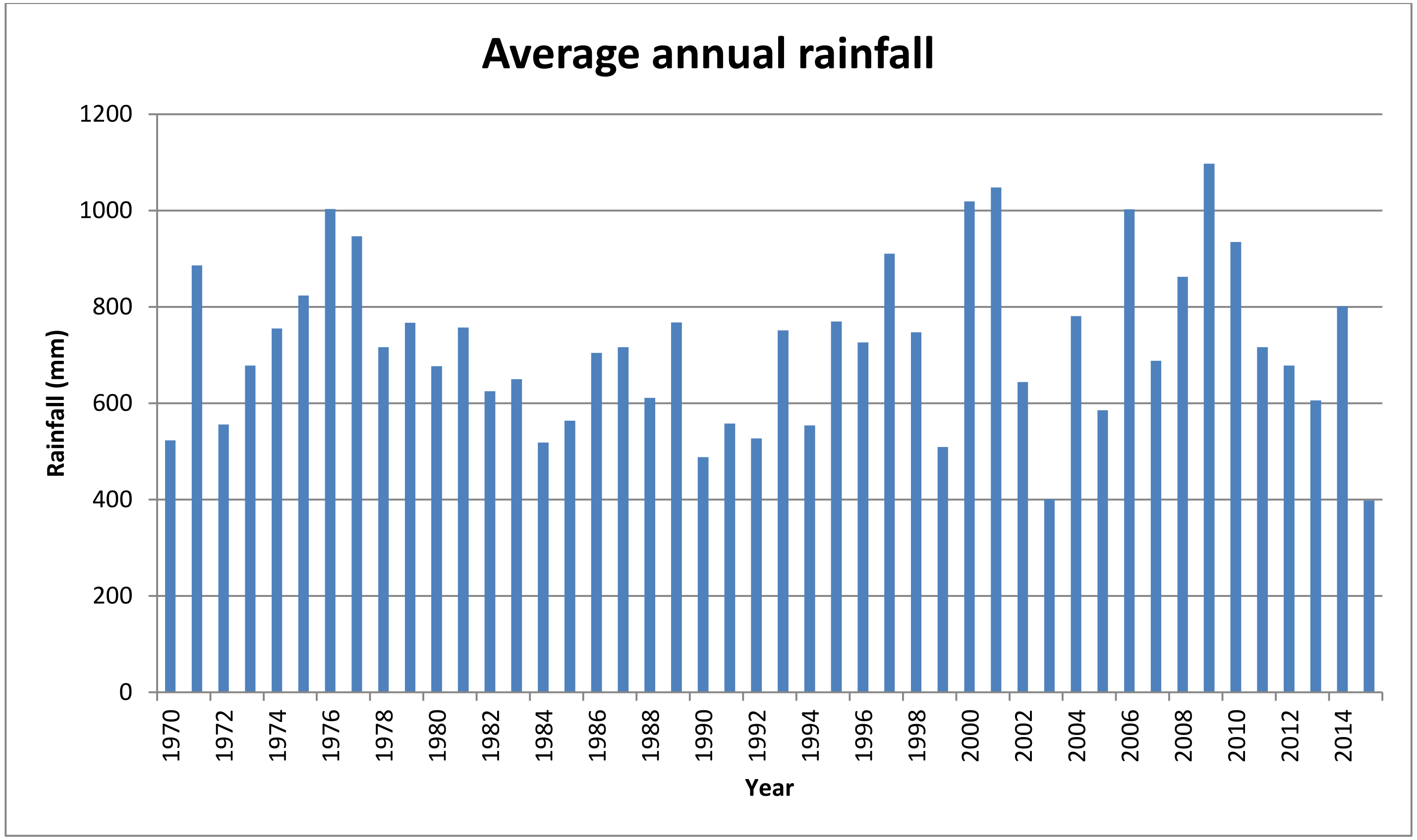

Figure 11: Annual rainfalls (mm) for rainfall station C2E001 from 1970 to 2015

4.1.4 Regional Geology

The study area is located at the north-east margin of the Sigma basin within the Vereeniging-Sasolburg Coalfield. The Vereeniging-Sasolburg Coalfield is part of the northern coal province of the Lower Permian to Lower Jurassic age fluviodeltaic complex of the Karoo Basin of South Africa (Steyn et al, 1986).

The Sigma basin is underlain by rocks of the Ventersdorp Supergroup and Transvaal Sequences. The overlaying Karoo Sequences, in which the coal deposits are found, form part of the Vryheid Formation of the Ecca Group consisting of sandstones, siltstones and shales with basal Dwyka formations (Krantz and Wilke, 2000).

There are two major doleritic sill intrusions of post-Karoo age within the basin. Both sills are present in the southern portion of the Basin but only the younger sill is present in the Sasolburg area. The dolerite sill which has intruded the Karoo sequence is generally present below a depth of about 5m. Post-Karoo minor faults and joints are common throughout the basin (Krantz and Wilke, 2000). Figure 12 and 13 illustrates the geology underlying and surrounding the investigation site.

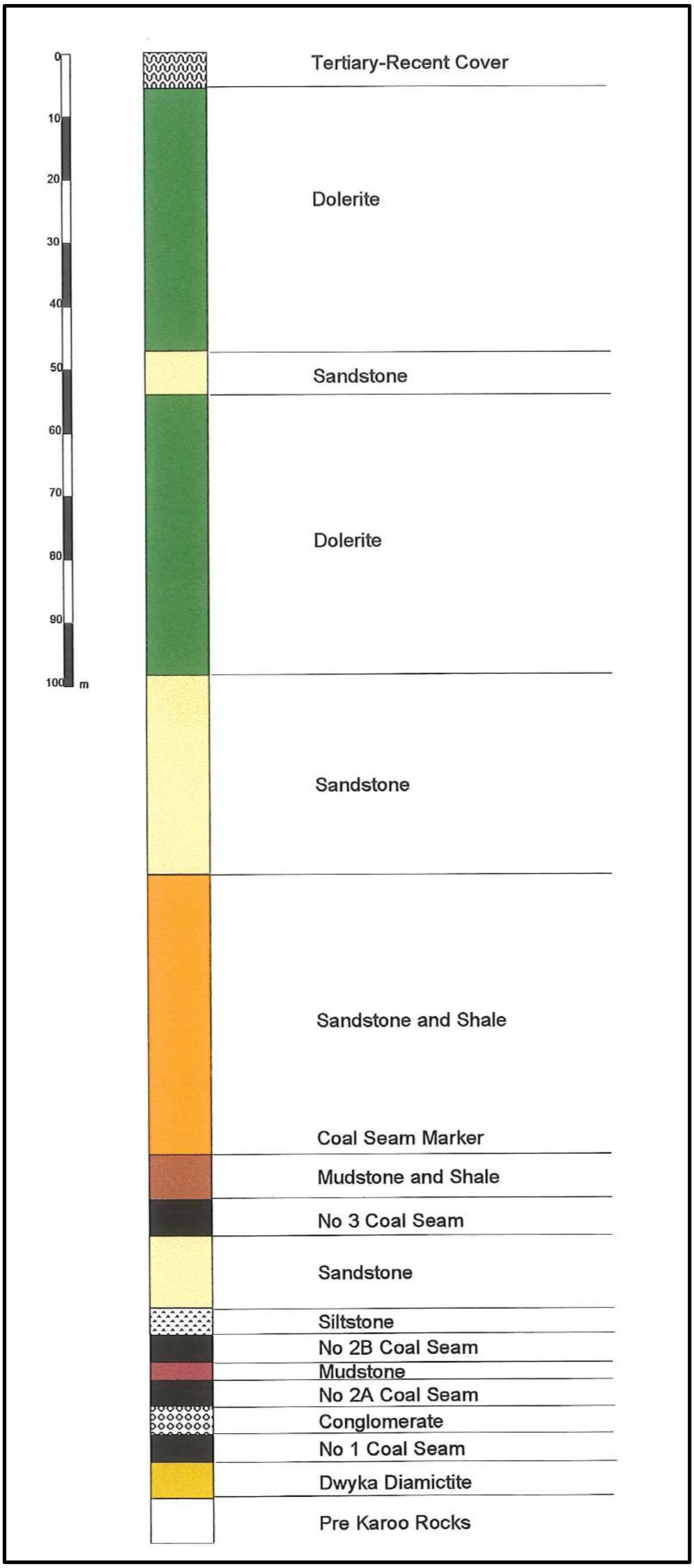

Figure 12: Geological sequence of study area (Krantz and Wilke, 2000)

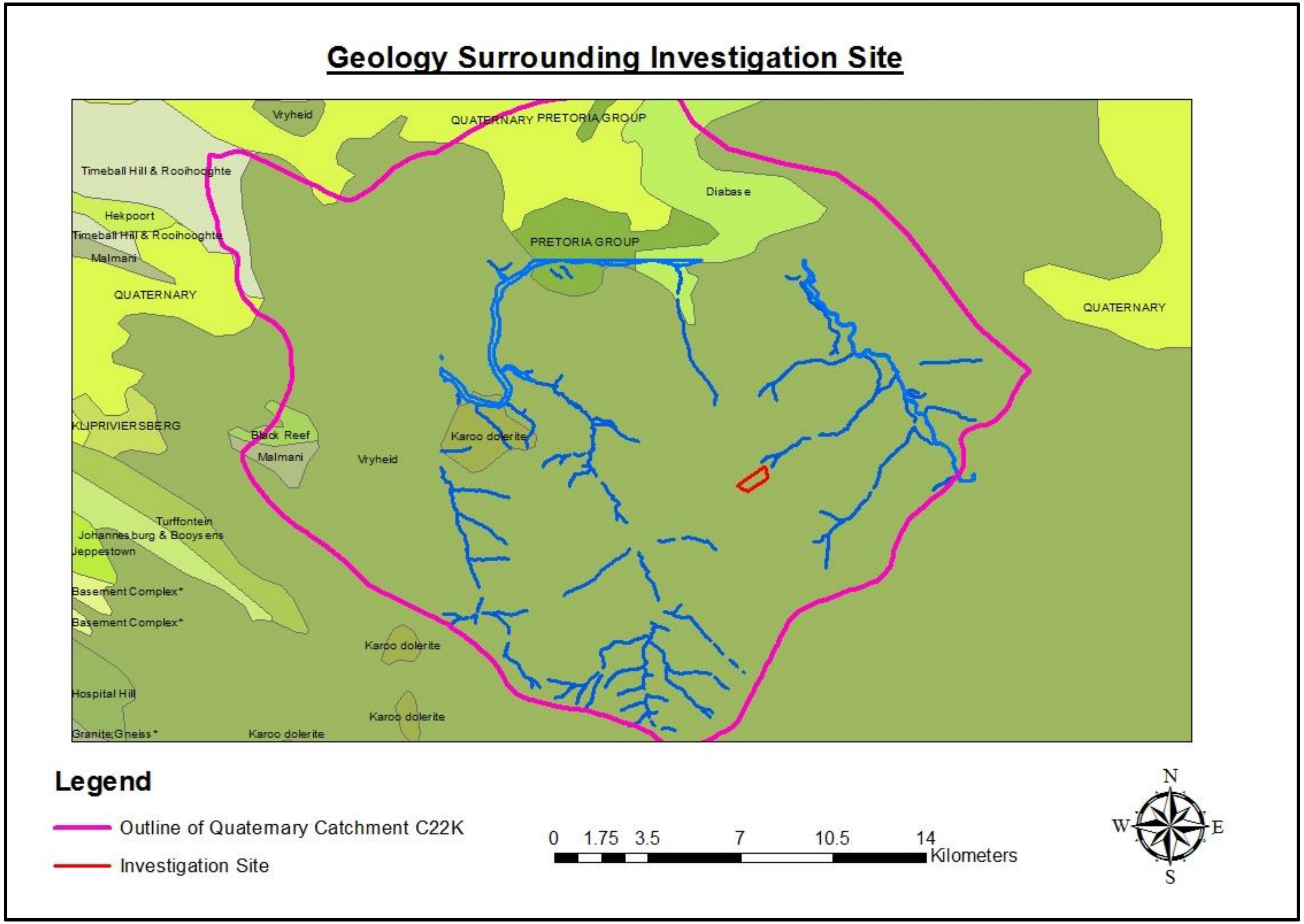

Figure 13: Geology surrounding investigation site

4.1.5 Site Geology

The detailed near-surface geology of the study area consists of post-Karoo doleritic sill overlain by a cover of Tertiary to recent deposits. Borehole data from the study area shows the sill transgressing Karoo strata. In the central and western parts of the study area the sill thickness exceeds 30 meters but narrows towards the east and south-east, where it is deeply weathered. The sill has a well-developed weathered zone below the cover units throughout. The recent deposits cover developed to a maximum thickness of 10 meters includes a brownish clayey soil, sand, hill wash, residual dolerite, siltstone and sandstone (Jones and Wagener, 2006).

Soil Profile

The natural soil profile within the industrial site area as encountered in the numerous holes excavated within the study area is summarised in Table 5 (Jones and Wagener, 2006).

Table 5: General lithological succession for the contaminated site

Depth from surface (m)	Lithology
0 – 5m	Clayey Sand
5 – 12m	Weathered Dolerite
12 – 30m	Fresh Dolerite or Carbonaceous Shale

Seepage

Seepage was generally either within the fill at a depth of approximately 1.2 m to 1.3 m or close to the fill/transported soil/residual soil interface.

Within the gullywash area, seepage was generally recorded at a depth below 4.0 m, often at or close to the interface of the calcretised alluvium and residual profile; alternately at a depth of roughly 2.5 m at the fill/in-situ profile interface. Within the northern areas, seepage was typically recorded at the contact of the Karoo and residual dolerite (Jones and Wagener, 2006).

4.1.6 Hydrogeological Setting

Unsaturated Zone

The depth to groundwater varies from 0.73 m to 5.025 m below surface. Any attenuation capacity of the unsaturated zone is unlikely to be significant in the developed areas of the site given the depth of the foundations for the infrastructure and depth of the storage trenches that are located in the South Western portion of study site in Sasolburg. Previous investigations have indicated that the hydraulic conductivity of the weathered material may be as low as 0.0070 m/day. Some attenuation of any vertical contaminant migration is therefore likely where the silty, clayey sand is relatively undisturbed and where the source of contamination, such as spillage, is on the surface (Johnstone *et al.,* 2006).

Weathered aquifer

The shallow aquifer consists of brown clayey soil and sand which has been interpreted as residual dolerite, yellow brown silty sandy clay (residual sandstone) and brown filled material. Although the weathered strata are very different in origin, they have similar hydrogeological characteristics in their weathered state and are therefore taken to represent a composite hydrostratigraphic unit. The depth of the weathering varies from 3 m to 15 m below surface (Johnstone *et al.,* 2006).

Given the slight groundwater elevation difference between the shallow and the underlying fractured rock aquifer (0.2 to 1.0 m), it is anticipated that the vertical and horizontal hydraulic conductivity of the underlying strata are similar. The hydraulic conductivity of the shallow weathered aquifer is variable ranging from 0.0070m/day to 0.62m/day with an average hydraulic conductivity of 0.35m/day. This variable hydraulic conductivity is to be expected where the weathered strata consists primarily of residual bedrock (Jones & Wagener, 2006).

Given the variable thickness and yield of this aquifer, the utilisation would be limited to domestic, garden or stock watering applications (Johnstone *et al.,* 2006).

Fractured aquifer

The primary porosity of the Vryheid formation is negligible. Secondary porosity, which provides the strata with its water bearing capacity, is primarily associated with joints, bedding planes and faults. However, where igneous intrusions are present, such as the thick (more than 30 m) dolerite sill that underlies the study area, the water bearing capacity of the strata is associated with cooling joints and fractures. The vertical hydraulic conductivity generally mimics the horizontal hydraulic conductivity under these circumstances especially where the dolerite dominates such as within the study area (Jones & Wagener, 2006).

The fractured rock hydraulic conductivity ranges from 0.0022 m/day to 0.052 m/day with an average of 0.015 m/day (Jones & Wagener, 2006).

4.1.7 Groundwater levels

As discussed in Section 3.2.1, the water levels for the two aquifers are generated using Bayesian interpolation and are shown in Figure 14 and Figure 15.

As groundwater levels follow topography it can be assumed that groundwater flow takes place under unconfined to semi-confined conditions.

The difference between groundwater levels and ground elevation are shown in Figure 16 and Figure 17 for water levels measured in November 1999.

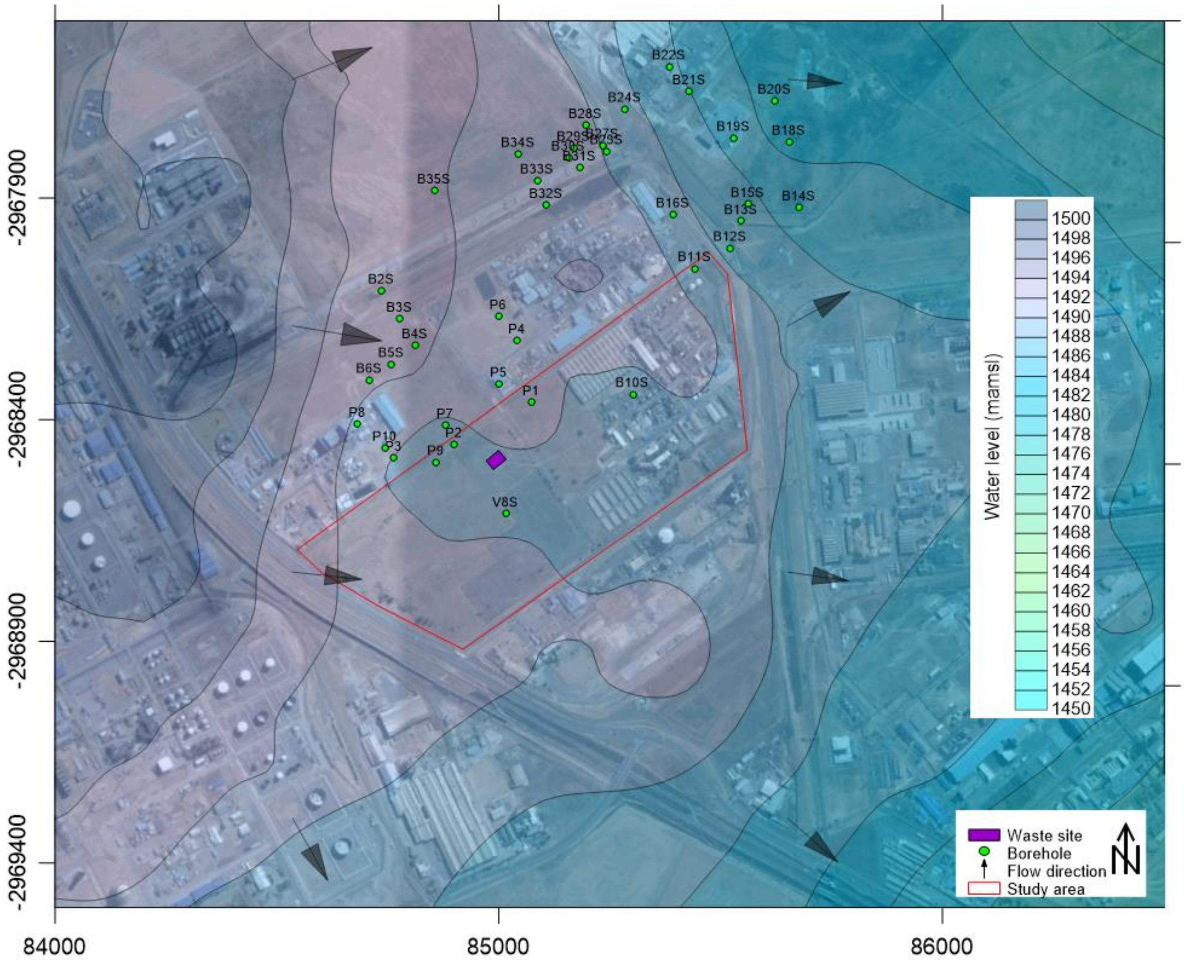

Figure 14: Groundwater levels for the shallow aquifer

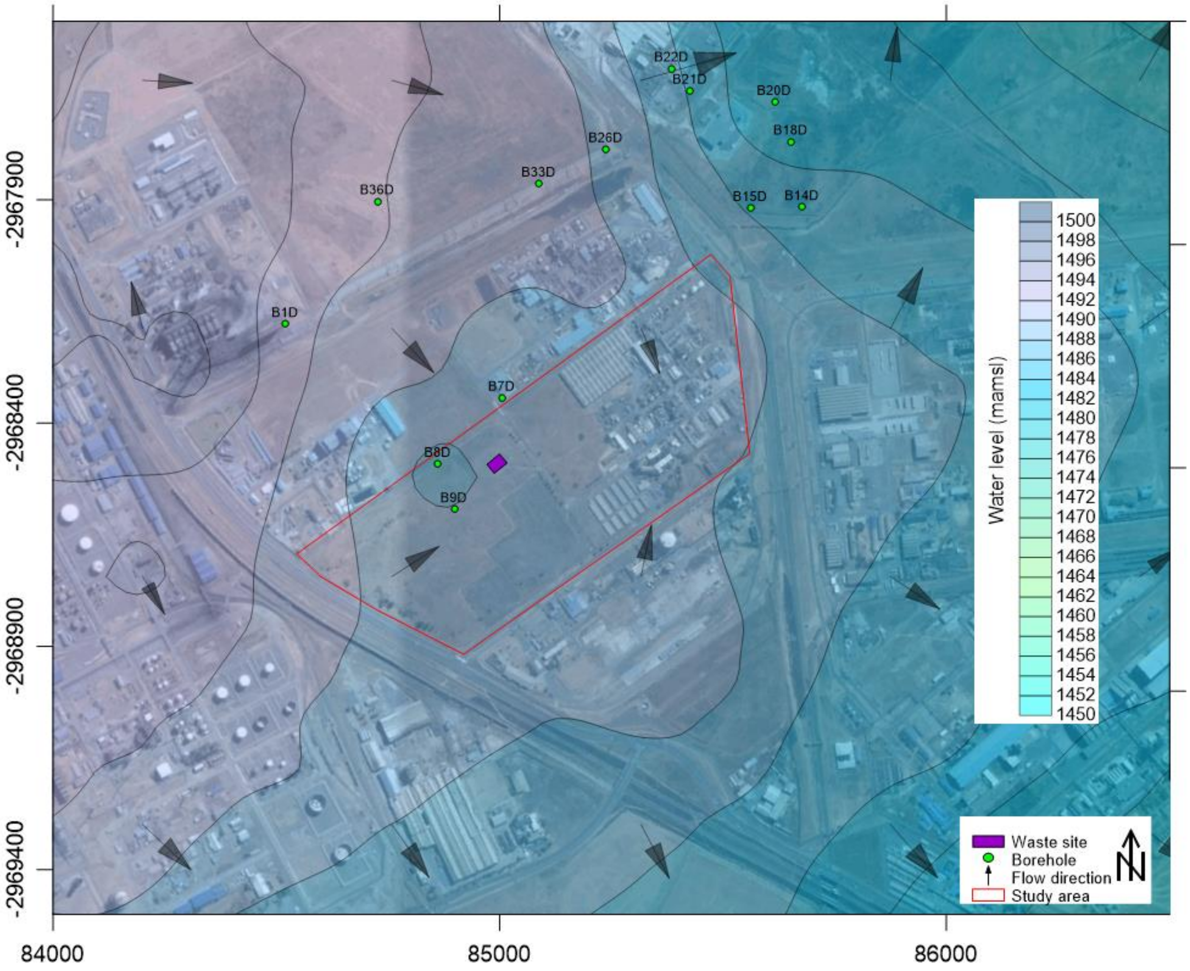

Figure 15: Groundwater levels for the deep aquifer

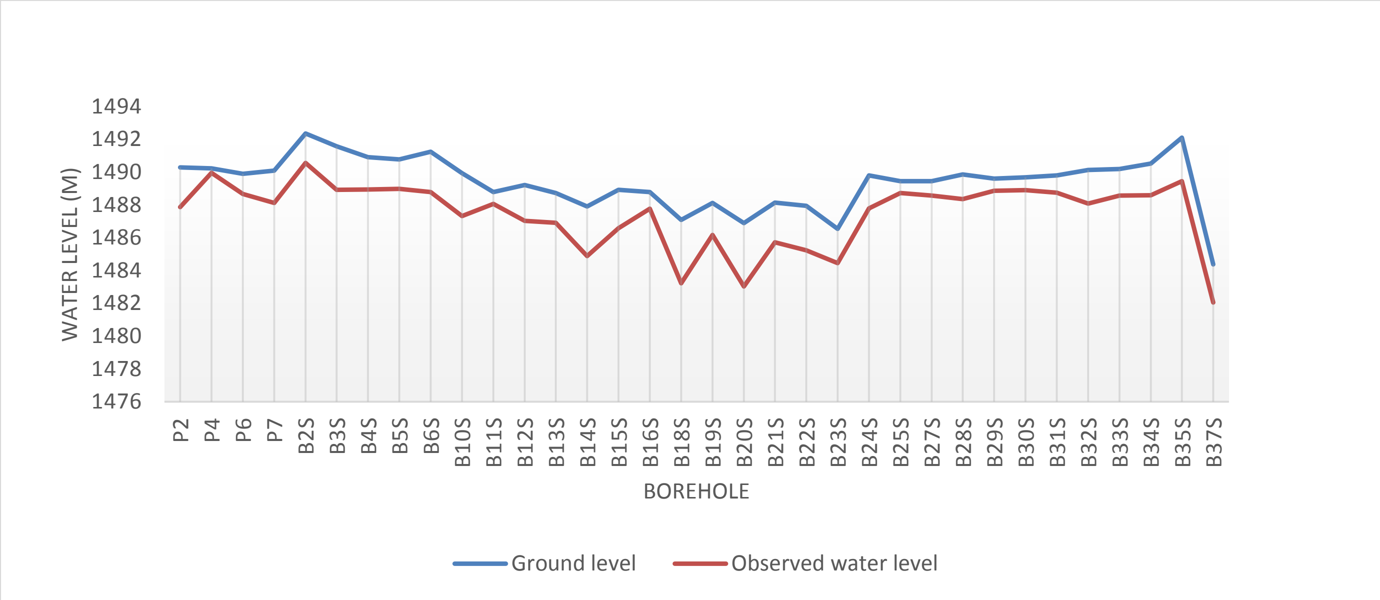

Figure 16: Ground level elevations vs observed water levels (November 1999) for the shallow aquifer

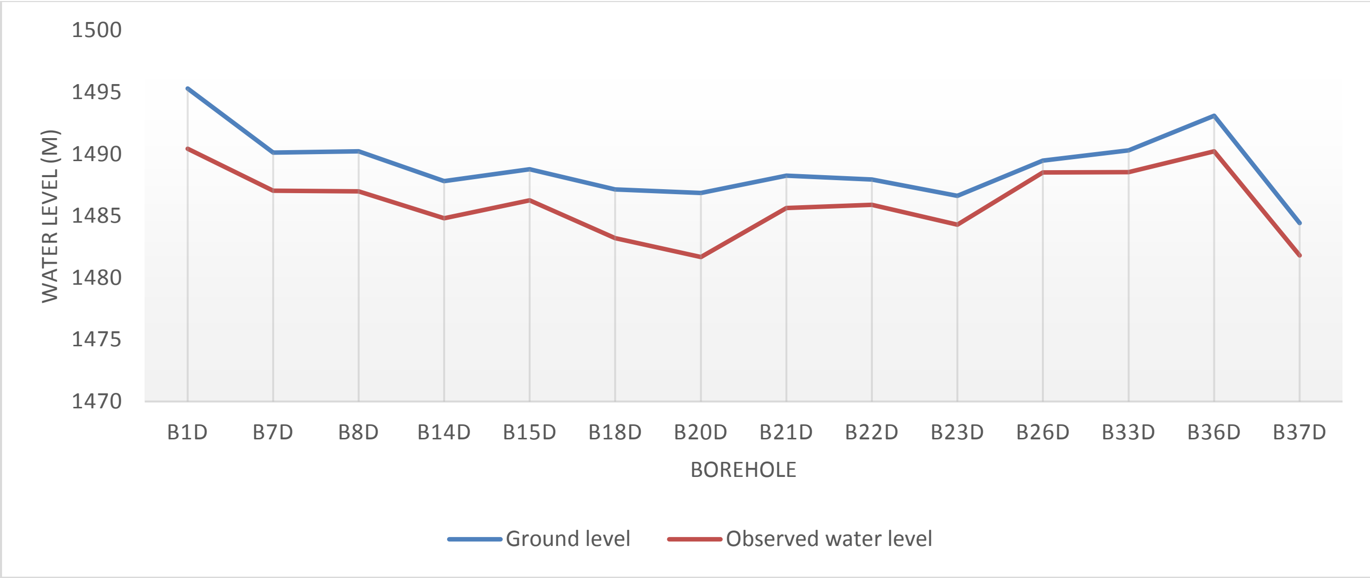

Figure 17: Ground level elevations vs observed water levels (November 1999) for the deep aquifer

4.1.8 Groundwater Recharge

As already mentioned, the groundwater recharge (*R*) for the area was also calculated using the chloride method (Bredenkamp *et al.*, 1995) with the average chloride in rainfall for areas inland being approximately 1mg/l, therefore according to the equation in Section 3.2.2:

$$R = \frac{1}{72}\, x\, 100 = 1.3\%$$

Where 72 mg/l is the harmonic mean of chloride concentration values in deeper groundwater samples obtained from the study area.

4.2 Water Quality of Investigation Area

Table 6 to Table 10 below, which illustrate the groundwater quality of the study area, are divided into two data sets: the deep borehole and shallow borehole data set. The deep borehole data represent the monitoring points which are in place for the deeper fractured aquifer of the investigation site, while the shallow borehole data represent the monitoring points of the shallow weathered aquifer of the investigation site.

Table 6: Water quality of the Deep Boreholes of the investigation site

Borehole (Deep)	B14D	B15D	B18D	B20D	B21D	B22D	B23D	Class 1	Class 2
pH	7.6	7.6	7.8	7.7	7.4	7.4	7.4	**5.0-9.5**	**4.0-10.0**
EC (mS/m)	87	249	219	141	1592	2065	135	**150**	**370**
TDS	570	2212	2018	1092	12936	14676	940	**1000**	**2400**
Alk ($CaCO_3$)	110	133	80	120	233	143	135	**-**	**-**
Ca	156	373	228	176	2200	2844	124	**150**	**300**
Mg	55	140	103	53	750	1227	50	**70**	**100**
Na	30	35	59	32	452	181	51	**200**	**400**
K	4.8	9.4	7.2	2.3	11.9	12.9	5.2	**50**	**100**
Mn	0.519	0.061	0.39	<0.025	0.281	1.15	0.181	**0.1**	**1**
Fe	0.299	0.152	0.101	0.063	0.393	0.283	0.263	**0.2**	**2**
F	0.4	1.6	1.2	0.7	3.5	1.7	2.6	**1**	**1.5**
NO_3	36	56	70	51	22	30	7.3	**44**	**88**
PO_4	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	2.2	**-**	**-**
Cl	282	163	424	259	5322	8592	260	**200**	**600**
SO_4	22	928	155	85	1517	582	77	**400**	**600**

Green – Class 1
Yellow – Class 2
Red – Exceeds maximum allowable drinking water standard
No colour fill – not analysed/no prescribed limit

Table 7: Water quality of the deep boreholes of the investigation site

Borehole (Deep)	B26D	B33D	B36D	B37D	B1D	B7D	B8D	Class 1	Class 2
pH	7.6	8	7.8	7.6	7.7	7.2	8.1	**5.0-9.5**	**4.0-10.0**
EC (mS/m)	244	139	67	500	40	655	101	**150**	**370**
TDS	1760	982	574	3766	338	4736	756	**1000**	**2400**
Alk ($CaCO_3$)	265	135	104	163	168	113	165	**-**	**-**
Ca	245	149	70	433	53	560	88	**150**	**300**
Mg	126	48	25	152	13	271	20	**70**	**100**
Na	90	45	25	449	11	494	78	**200**	**400**
K	5.4	3.9	6.8	8.9	5.5	15.1	6.2	**50**	**100**
Mn	6.2	0.079	0.025	0.881	0.025	0.25	0.18	**0.1**	**1**
Fe	0.587	0.118	0.144	0.386	0.2	0.22	0.125	**0.2**	**2**
F	1.3	0.6	0.5	1.4	0.2	1.2	0.9	**1**	**1.5**
NO_3	0.2	4.5	26	2.5	4.1	26	24	**44**	**88**
PO_4	<0.2	<0.2	<0.2	<0.2	0.2	0.2	0.2	**-**	**-**
Cl	391	294	69	1450	9	2020	38	**200**	**600**
SO_4	414	76	37	403	5	289	138	**400**	**600**

Green – Class 1
Yellow – Class 2
Red – Exceeds maximum allowable drinking water standard
NA – not analysed

Table 8: Water quality of the shallow boreholes of the investigation site

Borehole (Shallow)	B10S	B11S	B12S	B13S	B14S	B15S	B16S	B18S	B19S	Class 1	Class 2
pH	7.3	7.5	7.9	7.6	7.6	7.4	6.8	7.2	7.5	**5.0-9.5**	**4.0-10.0**
EC (mS/m)	1857	84	5980	420	87	330	149	139	83	**150**	**370**
TDS	17850	568	77720	2885	570	2714	966	964	494	**1000**	**2400**
Alk ($CaCO_3$)	55	295	855	145	115	115	30	55	70	**-**	**-**
Ca	441	84	561	112	76	421	68	118	38	**150**	**300**
Mg	352	47	194	60	50	194	35	77	16	**70**	**100**
Na	4130	35	21900	709	17	95	112	26	93	**200**	**400**
K	658	3.2	1323	15	3	48	53	2.8	11	**50**	**100**
Mn	40	0.8	214	0.886	0.519	0.265	1.11	0.363	1.05	**0.1**	**1**
Fe	4.16	0.775	0.973	0.23	0.3	0.445	0.797	0.818	0.738	**0.2**	**2**
F	0.2	0.6	0.2	1.6	0.3	1.4	1.2	0.8	0.7	**1**	**1.5**
NO_3	44	0.2	281	106	36	52	72	61	16	**44**	**88**
PO_4	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	**-**	**-**
Cl	1380	42	6110	460	90	197	39	168	64	**200**	**600**
SO_4	3860	142	38960	857	39	1328	260	134	172	**400**	**600**

Green – Class 1
Yellow – Class 2
Red – Exceeds maximum allowable drinking water standard
NA – not analysed

Table 9: Water quality of the shallow boreholes of the investigation site

Borehole (Shallow)	B20S	B21S	B22S	B23S	B24S	B25S	B27S	B28S	B29S	Class 1	Class 2
pH	7.3	7.1	7	7	6.6	7.4	8.2	7.4	7.6	**5.0-9.5**	**4.0-10.0**
EC (mS/m)	203	881	2546	459	562	351	240	342	176	**150**	**370**
TDS	1426	5290	24500	3658	6900	2990	1786	2520	1164	**1000**	**2400**
Alk ($CaCO_3$)	160	215	353	213	90	170	135	280	270	**-**	**-**
Ca	130	822	3086	536	301	802	220	301	210	**150**	**300**
Mg	139	425	1526	288	474	219	109	170	47	**70**	**100**
Na	50	377	1128	125	173	324	287	278	106	**200**	**400**
K	1.1	12	16.9	1	97	23	21	4.6	1.6	**50**	**100**
Mn	0.041	4.04	0.44	2.48	1.5	24	4.21	4.45	1.08	**0.1**	**1**
Fe	0.163	0.651	0.57	0.111	0.07	2.38	0.735	0.539	0.226	**0.2**	**2**
F	0.7	1.5	2.1	1.8	4.2	1.9	2.1	1.4	1.2	**1**	**1.5**
NO_3	43	1.2	8.1	7.5	0.6	11	5.8	5.7	15	**44**	**88**
PO_4	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	0.3	**-**	**-**
Cl	416	2583	10066	1000	30	99	99	320	172	**200**	**600**
SO_4	53	610	1100	1059	3573	1671	993	1139	307	**400**	**600**

Green – Class 1
Yellow – Class 2
Red – Exceeds maximum allowable drinking water standard
NA – not analysed

Table 10: Water quality of the shallow boreholes of the investigation site

Borehole (Shallow)	B30S	B31S	B32S	B33S	B34S	B35S	B37S	P6	P7	Class 1	Class 2
pH	7.5	3.2	7.5	7.4	7.3	7.1	7.6	7.1	7.1	**5.0-9.5**	**4.0-10.0**
EC (mS/m)	92	1681	279	279	426	446	640	488	156	**150**	**370**
TDS	534	21412	1496	1736	2358	3796	3502	3776	1100	**1000**	**2400**
Alk ($CaCO_3$)	355	5	135	180	155	105	145	130	380	**-**	**-**
Ca	116	701	265	291	301	421	461	80	92	**150**	**300**
Mg	23	911	117	113	207	263	243	80	49	**70**	**100**
Na	61	2615	73	110	242	333	463	686	164	**200**	**400**
K	1.5	13	2.2	1.8	3.4	6.3	6	106	1.6	**50**	**100**
Mn	3.45	202	1.63	0.467	2.01	1.76	0.53	19	0.2	**0.1**	**1**
Fe	2.14	254	0.224	0.156	0.327	0.456	<0.025	468	0.1	**0.2**	**2**
F	1	17	0.2	1.7	0.9	1.7	0.7	9.3	1.2	**1**	**1.5**
NO_3	<0.2	0.8	1.5	35	0.4	38	20	0.3	43	**44**	**88**
PO_4	0.4	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	0.2	0.2	**-**	**-**
Cl	39	1675	739	429	986	99	1675	294	89	**200**	**600**
SO_4	63	12116	61	420	324	1786	295	2000	173	**400**	**600**

Green – Class 1
Yellow – Class 2
Red – Exceeds maximum allowable drinking water standard
NA – not analysed

The dominant contaminants for the site include Sodium, Calcium, Magnesium, Sulphate and Chloride with occasional Nitrates and Fluoride. Manganese is another contaminant which features throughout the site as a result of historical industrial processes.

The Piper diagram (Figure 18) for the shallow weathered aquifer does not plot in any group of the anion section due to the variations in the proportion of sulphate and chloride. The samples on the cation section also plot across the Piper diagram.

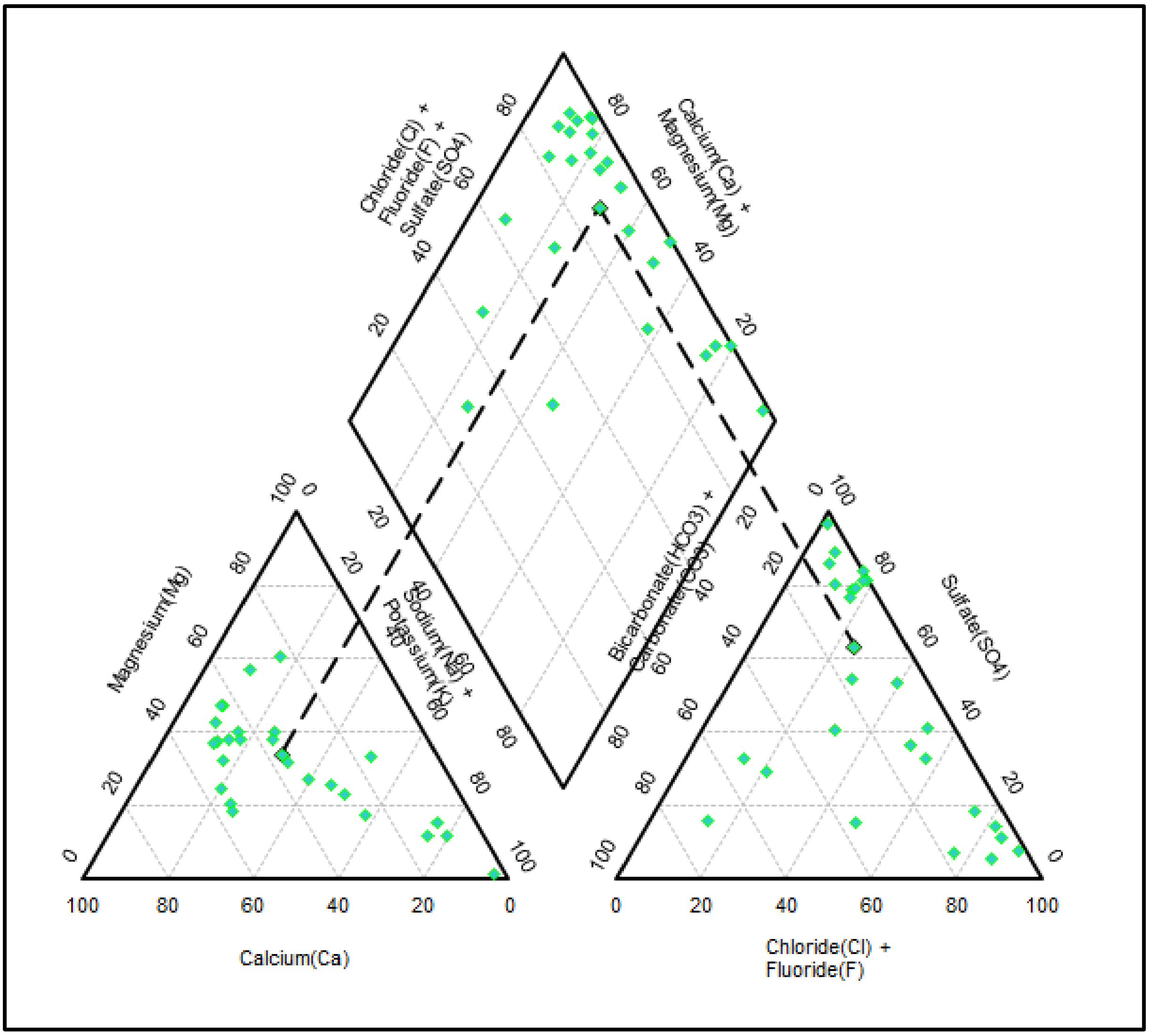

Figure 18: Piper diagram for shallow weathered aquifer of the investigation site

The Piper diagram (Figure 19) for the deeper fractured aquifer recognisably plots in favour of chlorides in the anion section and calcium in the cation section.

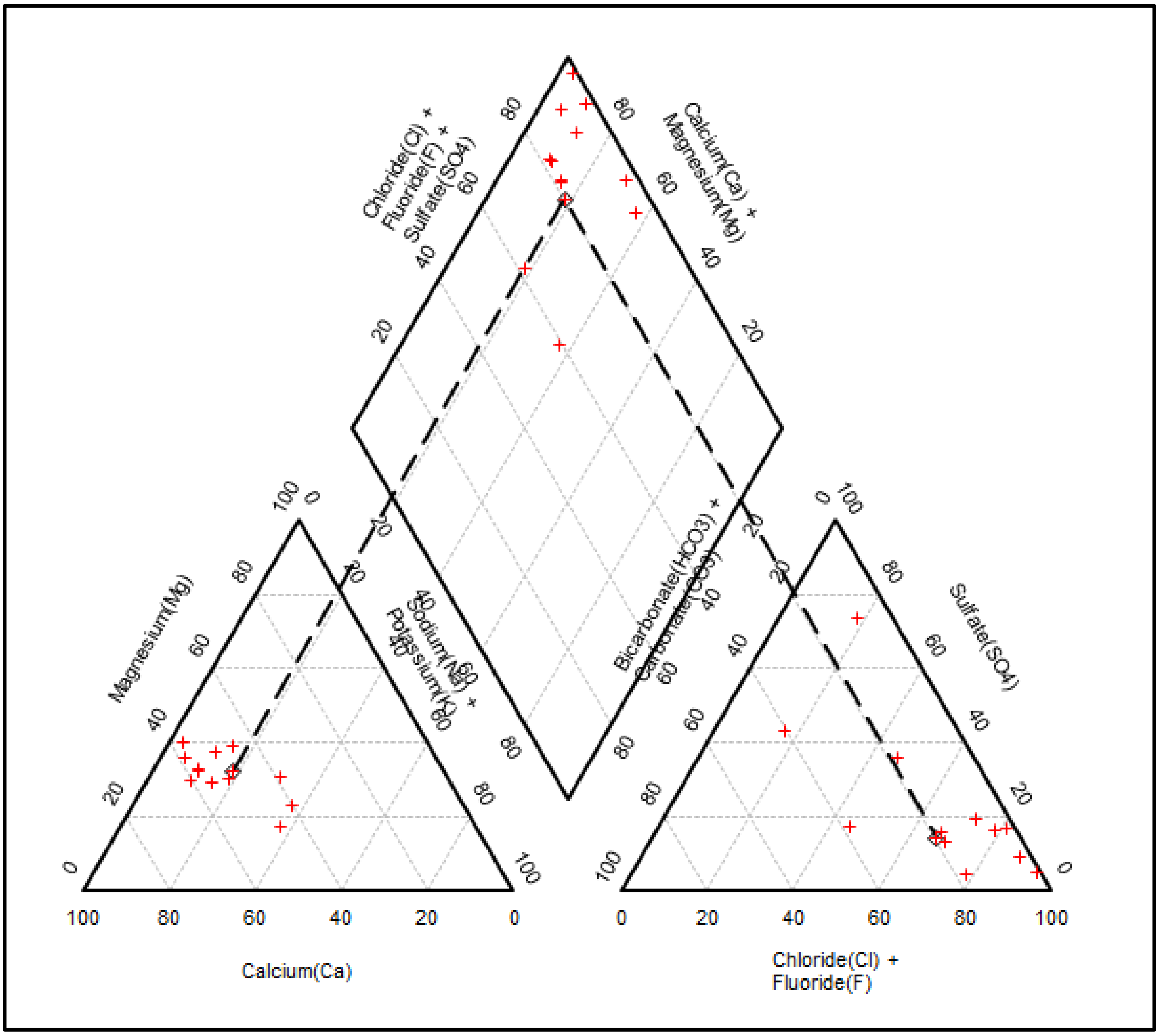

Figure 19: Piper diagram for deeper fractured aquifer of the investigation site

Elevated concentrations in pollutants of concern could be as a result of the hydrogeological conditions associated with Vryheid Formation rocks. The Ekurhuleni Metropolitan Municipality State of the Environment report provides typical groundwater conditions for the Vryheid Formation, which can be seen in Table 6 - 10.

According to Ekurhuleni (2003), "*due to the association with coal bearing horizons, there is a high variation in sodium, chloride and sulphate*."

From Table 11 it can be noted that pH, EC, Na, Cl, SO_4^{2-} and nitrates (NO_3^-) can range considerably under natural conditions. This would be influenced by the proximity of the groundwater to coal seams and whether the aquifer is sandstone or shale in nature. It is important to note that the values listed in Table 11 are under natural conditions and are not associated with industrial contamination. Some of the parameters listed in Table 11 have maximum concentrations which are higher than that of the SANS 241 – 2011 water standards for domestic use.

Table 11: Typical groundwater quality of the Vryheid Formation (Ekurhuleni Metropolitan Municipality, 2003)

Element/Parameter	Minimum	Maximum
pH	4.8	8.5
EC (mS/m)	3.7	344.0
TDS (mg/l)	33.0	1835.0
Ca (mg/l)	1.0	184.0
Mg (mg/l)	1.0	174.0
Na (mg/l)	1.0	492.0
K(mg/l)	0.3	38.0
Cl (mg/l)	1.0	919.0
SO_4 (mg/l)	1.0	919.0
Total Alkalinity (mg/l) $CaCO_3$	12.0	539.0
NO_3 (mg/l)	0.1	80.0
F (mg/l)	0.1	2.6

4.3 Conceptual Model

The development of the conceptual model included considerations for conceptual model development established by the US EPA (1992) which was stipulated in Section 3.4 above. These considerations were evaluated against the site data which was available in order to establish the conceptual model.

Recharge from rainfall or from leaking services percolates into the shallow weathered aquifer through the relatively thin unsaturated zone. It may be possible for contaminant migration to occur directly into the fractured rock aquifer where the weathered material has been excavated. This scenario is most likely to occur in the vicinity of foundations or informal disposal trenches. The relatively small difference between the piezometric pressure in the shallow aquifer and the deeper fractured aquifer indicates that the horizontal and vertical hydraulic conductivity is in a similar order of magnitude for both hydrostratigraphic units (Krantz and Wilke, 2000).

A thick dolerite sill underlies the residual dolerite, sandstones, siltstones and shales that comprise the weathered profile. There is little, if any, attenuation capacity within the fresh dolerite given the crystalline silicate matrix of this rock type. The rate and direction of groundwater contamination will depend on the hydraulic conductivity of the underlying strata and the direction of the groundwater gradients (Krantz and Wilke, 2000).

Conservative contaminant migration will generally mimic the topography within unconfined/semi-confined Karoo aquifers. This can be observed in Figures 12 and 13 where the comparison of the altitude and the observed water levels of the selected monitoring points are illustrated. However, geological structures such as faults and dolerite dykes may alter these groundwater flow patterns. A dolerite dyke that is located to the North East of the factory appears to influence the direction of contaminant migration in the immediate vicinity of the surface water course (Krantz and Wilke, 2000).

The lateral groundwater flow migration will converge in the immediate vicinity of the surface streams where the contamination enters the rivers as base flow. These contaminants subsequently contribute to the salt loading of the catchment in which the study area is located (Krantz and Wilke, 2000).

Chapter 5: Results

5.1 Surface water results

A digital elevation model was developed for the quaternary catchment (C22K) in which the waste site is located. The Global Mapper software generated possible drainage lines based on the digital elevation model. The results of are illustrated in Figure 20. It can be seen that there are no drainage lines in the vicinity of the waste site.

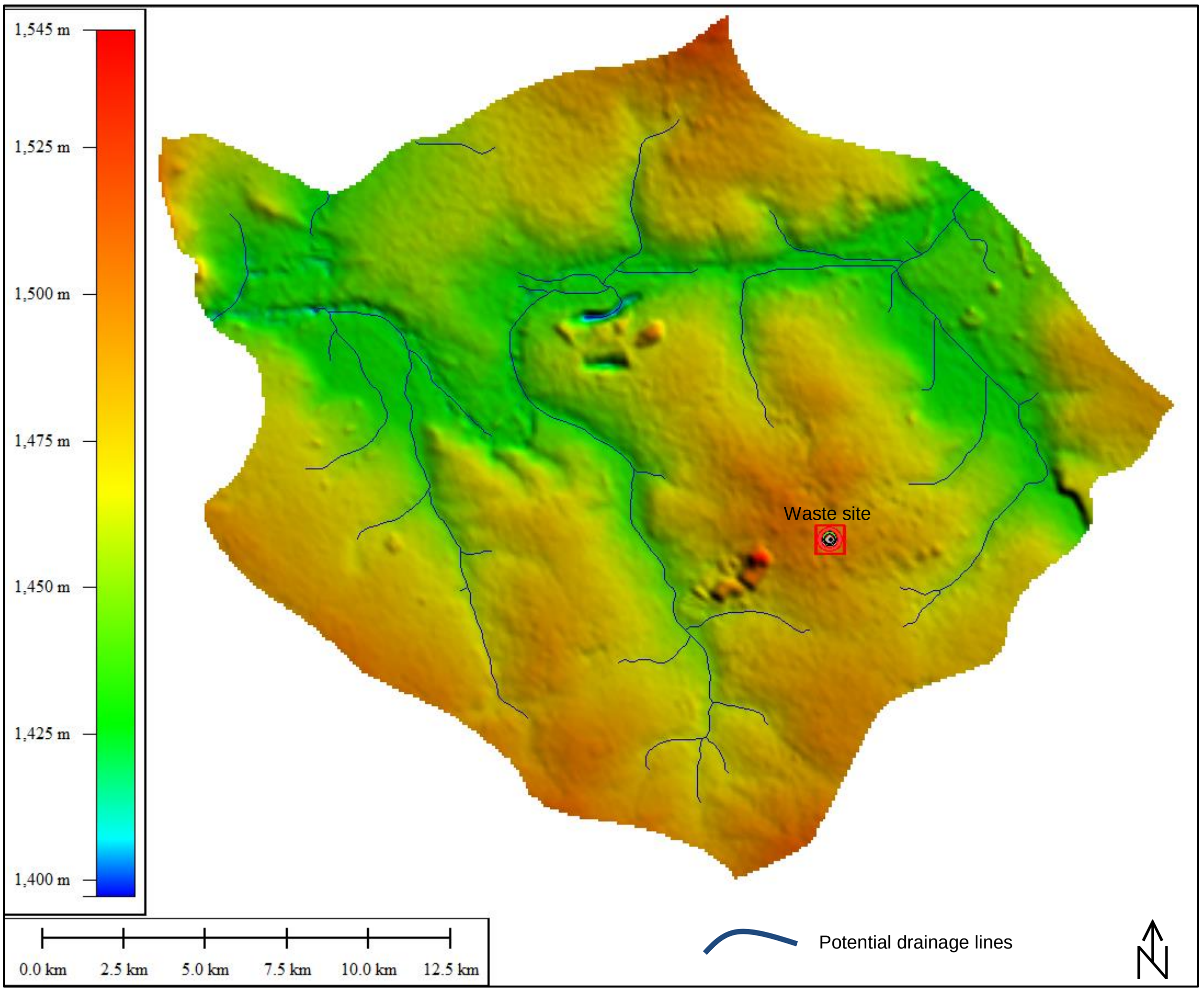

Figure 20: Digital elevation model and simulated drainage lines

Particles were then added at the waste site to determine the pathway contaminants would take if there was a discharge from the waste site. The results are shown in Figure 21. The particles flow to the east before joining a northward flowing stream.

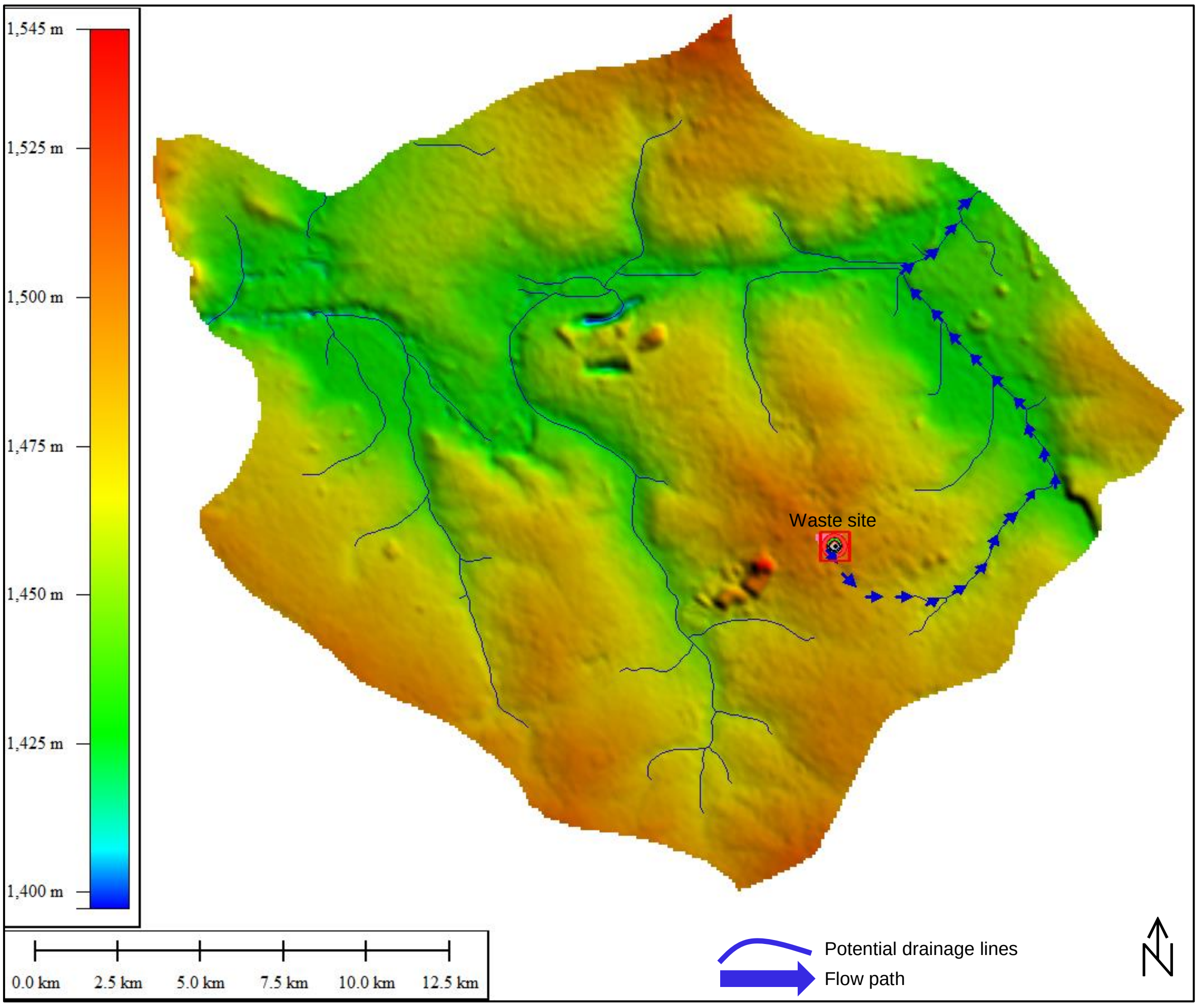

Figure 21: Digital elevation model and simulated drainage lines

5.2 Groundwater modelling

The ability of the groundwater model to simulate the concentrations and elevations across the site allowed for the extent of current pollution sources to be simulated. Different scenarios were simulated to determine the extent of the migration of SO_4 as a pollutant, with its initial concentration of 3860 mg/l.

The different simulation scenarios include:

- No remediation simulated for 40 years;
- No remediation simulated for 60 years;
- No remediation simulated for 80 years;
- Capping (with two different material values) as a remediation simulated technique for 40 years;

- Pumping as a remediation simulated technique for 40 years;
- Cut-off walls as a remediation simulated technique for 40 years;
- Lining of the pollution source simulated for 40 years; and
- A combination of capping (with two different material values) and pumping as a remediation technique for 40 years.

All simulations indicated that the most significant area of contamination occurs within the first layer of the groundwater model, which is the shallow weathered aquifer. The source of the contamination is present in this aquifer which justifies the increased extent and concentration of the contamination plume for the shallow weathered aquifer in comparison to the deeper fractured aquifer.

No remediation simulated for 40 years

The purpose of the initial simulation was to predict the extent of the contamination plume after 40 years. In order to understand the nature of the contamination migration under no controls and after 40 years, no remediation techniques were incorporated into this simulation.

Figure 22 illustrates the extent and the concentrations of the contamination plume when simulated with no remediation, after a period of 40 years. The contamination plume migrates for an approximate distance of 70 m from the source of contamination. The concentration of the contaminants decreases with the increase in extent of the plume.

The extent of the plume does not migrate outside the boundaries of the investigation site and is not in the vicinity of any natural surface-water bodies.

Figure 22: 40-year simulation of contamination plume with no remediation

5.2 No remediation simulated for 60 years

This simulation was run in order to predict the extent of the contamination plume after 60 years. No remediation techniques were incorporated into this simulation so that an understanding of the nature of the contamination migration could be obtained for no controls and after 60 years.

Figure 23 illustrates the extent and the concentrations of the contamination plume when simulated with no remediation, after a period of 60 years. The contamination plume migrates for an approximate distance of 110 m towards the east. The concentration of the contaminants decreases with the increase in extent of the plume.

The extent of the plume does not migrate outside the boundaries of the investigation site and is not in the vicinity of any natural surface-water bodies.

Figure 23: 60-year simulation of contamination plume with no remediation

5.3 No remediation simulated for 80 years

This simulation was run in order to predict the extent of the contamination plume after 80 years. No remediation techniques were incorporated into this simulation so that an understanding of the nature of the contamination migration could obtained for no controls after 80 years.

Figure 24 illustrates the extent and the concentrations of the contamination plume when simulated with no remediation, after a period of 80 years. The contamination plume migrates for an approximate distance of 150 m towards the east of the contamination plume. The concentration of the contaminants decreases with the increase in extent of the plume. The extent of the plume after 80 years is present in the operational facilities.

The extent of the plume is slowly migrating past the northern boundary of the investigation site but is not in the vicinity of any natural surface-water bodies.

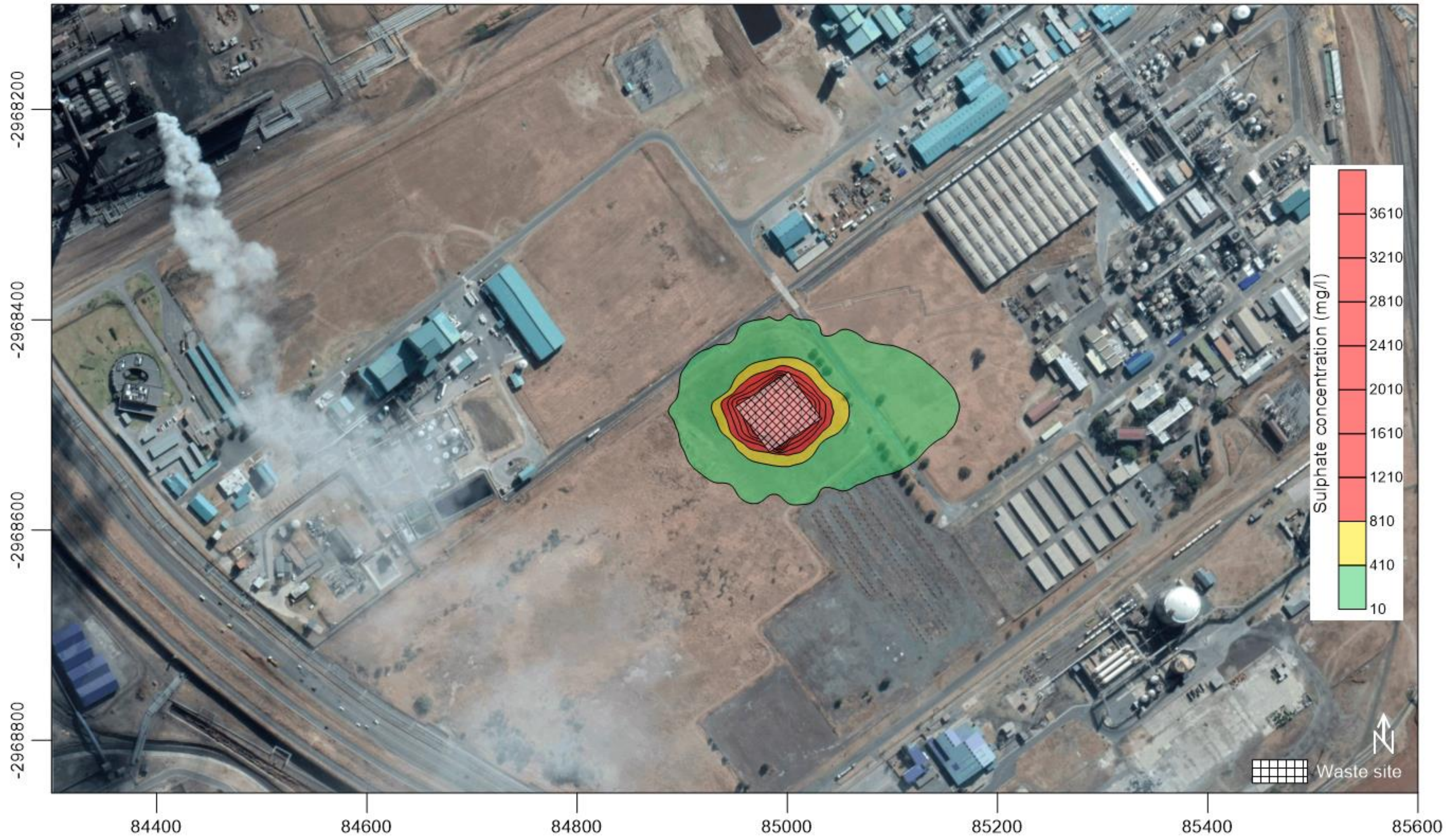

Figure 24: 80-year simulation of contamination plume with no remediation

5.4 Capping as remediation technique simulated for 40 years

This simulation was run in order to predict the extent of the contamination plume after 40 years, in the scenario where capping is implemented. Cut-off walls were added around the contamination source to serve as the vertical barriers for the capping simulation. A third layer was added to serve as the capping layer, and together with the vertical barriers represents a true reflection of the manner in which the contamination source was capped. A hydraulic conductivity of $1x10^{-6}$ m/day was used for the vertical and horizontal barriers in this simulation. This value for capping material, such as high density plastic, was obtained from a best practice guideline published by the Department of Water Affairs and Forestry (DWAF) in 2007. Hydraulic conductivity values for capping material in Figure 25 and Figure 26 was obtained from Weber and Zornberg (2005) and indicates that geomembrane materials have hydraulic conductivity values in the order of $8.64x10^{-11}$ m/day, while clay materials have hydraulic conductivity values in the order of $8.64x10^{-5}$ m/day.

Figures 25 and 26 illustrate the extent and the concentrations of the contamination plume when simulated with capping as a remediation technique, after a period of 40 years. The contamination plume for the clay capping is reduced by approximately 20 m. The contamination plume with the geomembrane is reduced by 35 m when comparing it to Figure 22. There are no sensitive receptors within the proximity of the contamination.

The extent of the plume does not migrate outside the boundaries of the investigation site and is not in the vicinity of any natural surface-water bodies.

Figure 25: 40-year simulation of contamination plume with geomembrane capping as a remediation technique

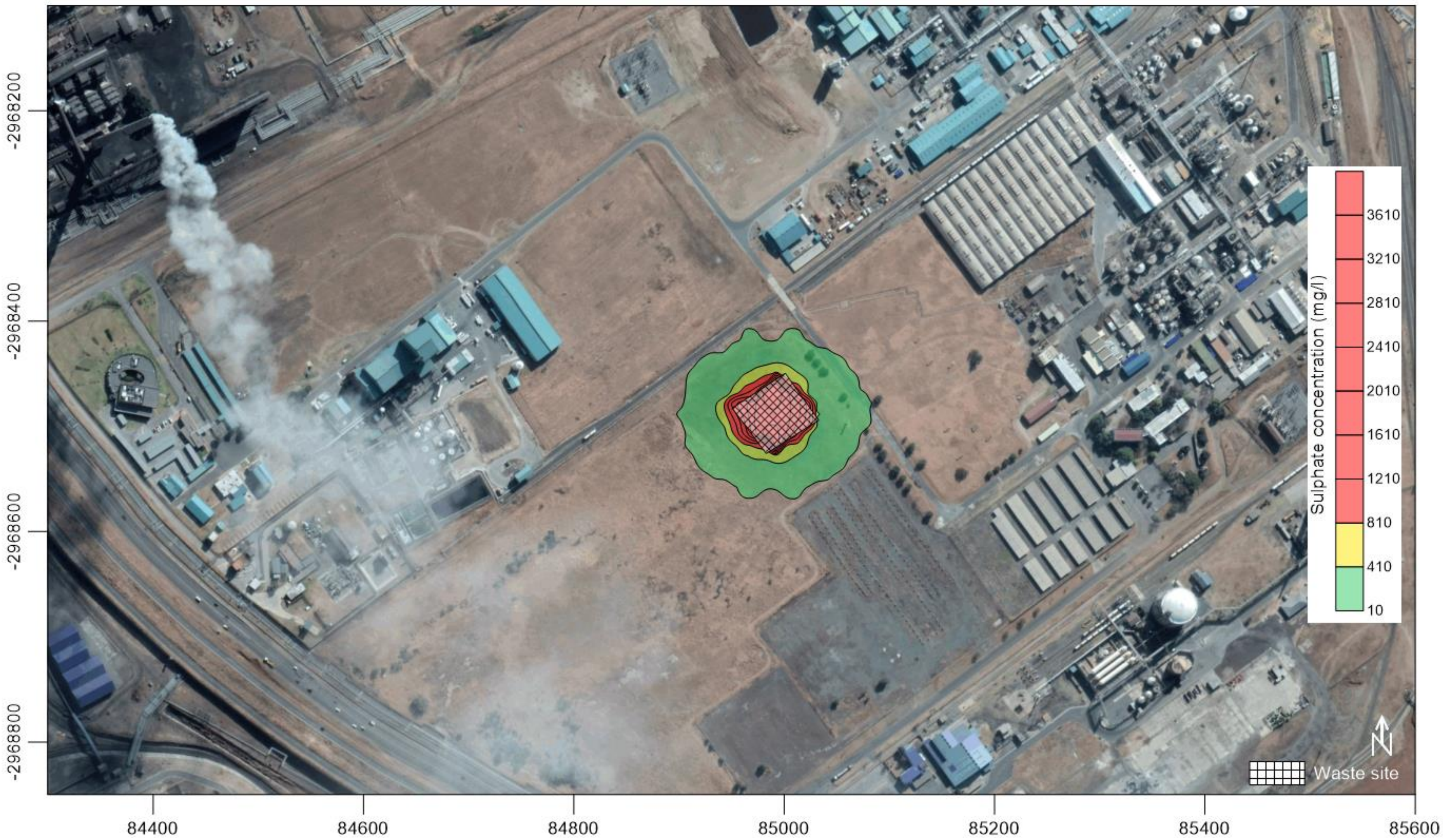

Figure 26: 40-year simulation of contamination plume with clay capping as a remediation technique

5.5 Pumping as remediation technique simulated for 40 years

This simulation was run in order to predict the extent of the contamination plume after 40 years, in the scenario that pumping is implemented. Pumping boreholes were placed on the eastern side of the contamination source. In order to avoid abstraction surpassing the rate of recharge, each pumping well was allocated an abstraction rate of 216 l/day.

Figure 24 illustrates the extent and the concentrations of the contamination plume when simulated with pumping as a remediation technique, after a period of 40 years. When comparing the results to the simulation with the clay capping, the clay capping is more effective in reducing the plume in the east. The pumping has managed to reduce the plume slightly more in the other directions when comparing with the clay capping. The results of the geomembrane capping scenario indicates that this capping technique is more effective than pumping.

Figure 27: 40-year simulation of contamination plume with pumping as a remediation technique

5.6 Cut-off walls as remediation technique simulated for 40 years

This simulation was run in order to predict the extent of the contamination plume after 40 years, in the scenario where cut-off walls are implemented. Cut-off walls were added around the contamination source to serve as the vertical barriers for the capping simulation. A hydraulic conductivity of $1x10^{-9}$ m/day was used for the vertical and horizontal barriers in this simulation. This value for cut-off wall material was obtained from a best practice guideline published by the Department of Water Affairs and Forestry (DWAF, 2007).

Figure 28 illustrates the extent and the concentrations of the contamination plume when simulated with cut-off walls as a remediation technique, after a period of 40 years. When comparing this scenario to those discussed thus far, it is the least effective one with a maximum decrease of 8 m in the size of the plume in the easterly direction.

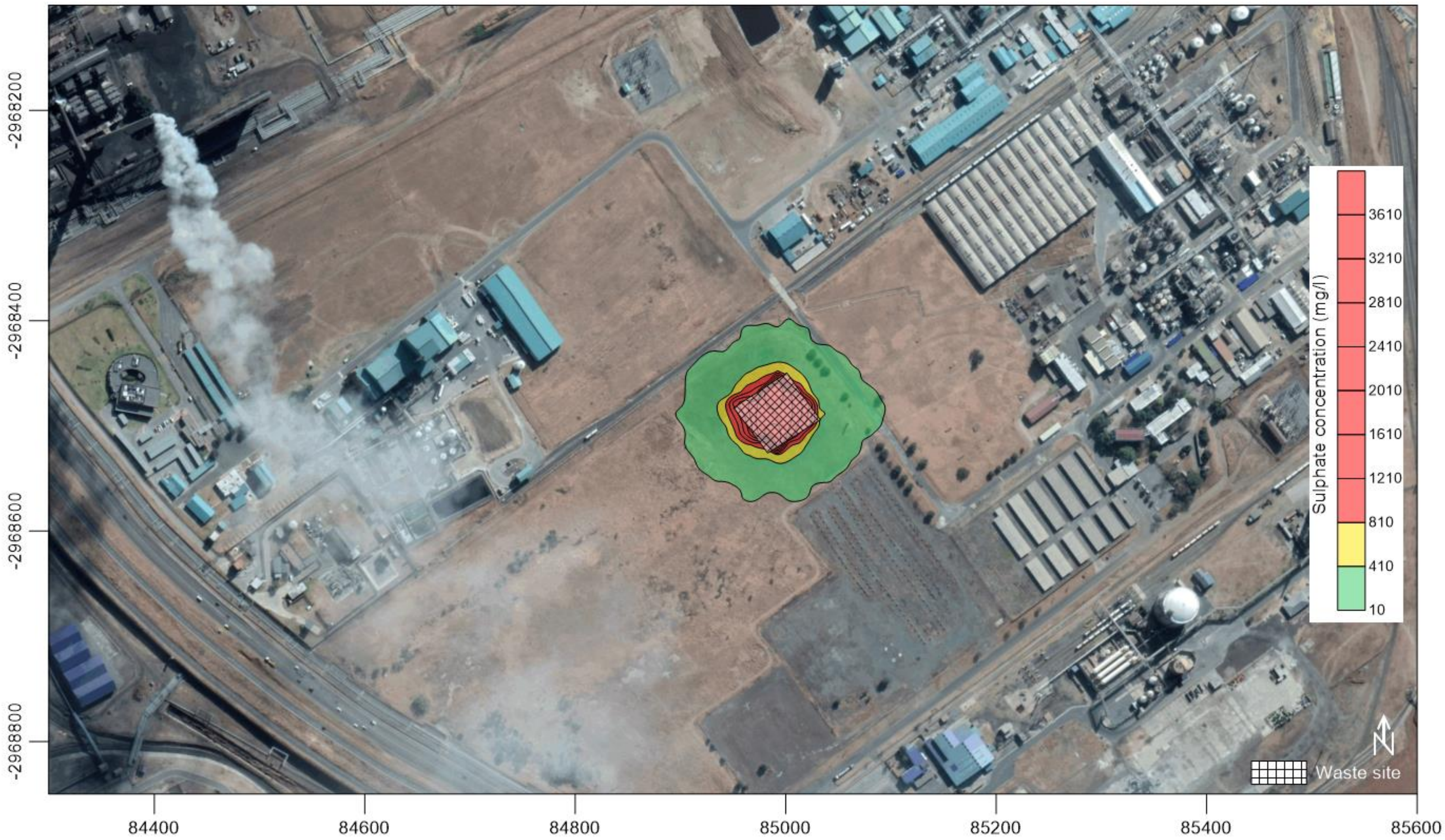

Figure 28: 40-year simulation of contamination plume with cut-off walls as a remediation technique

5.7 Lining of the contamination source prior to disposal simulated for 40 years

This simulation was run in order to predict the extent of the contamination plume after a period of 40 years, for the scenario where a formal lining of the disposal site would be installed prior to waste disposal. A transmissivity value of 8.64×10^{-6} m^2/day was allocated across the contamination source in this simulation. The value for the lining material was obtained from a best practice guideline published by the Department of Water Affairs and Forestry (DWAF, 2007).

Figure 29 illustrates the extent and the concentrations of the contamination plume when simulated with lining of the contamination source prior to disposal, after a period of 40 years. The results of this study are almost identical to the previous scenario in which the cut-off walls were discussed.

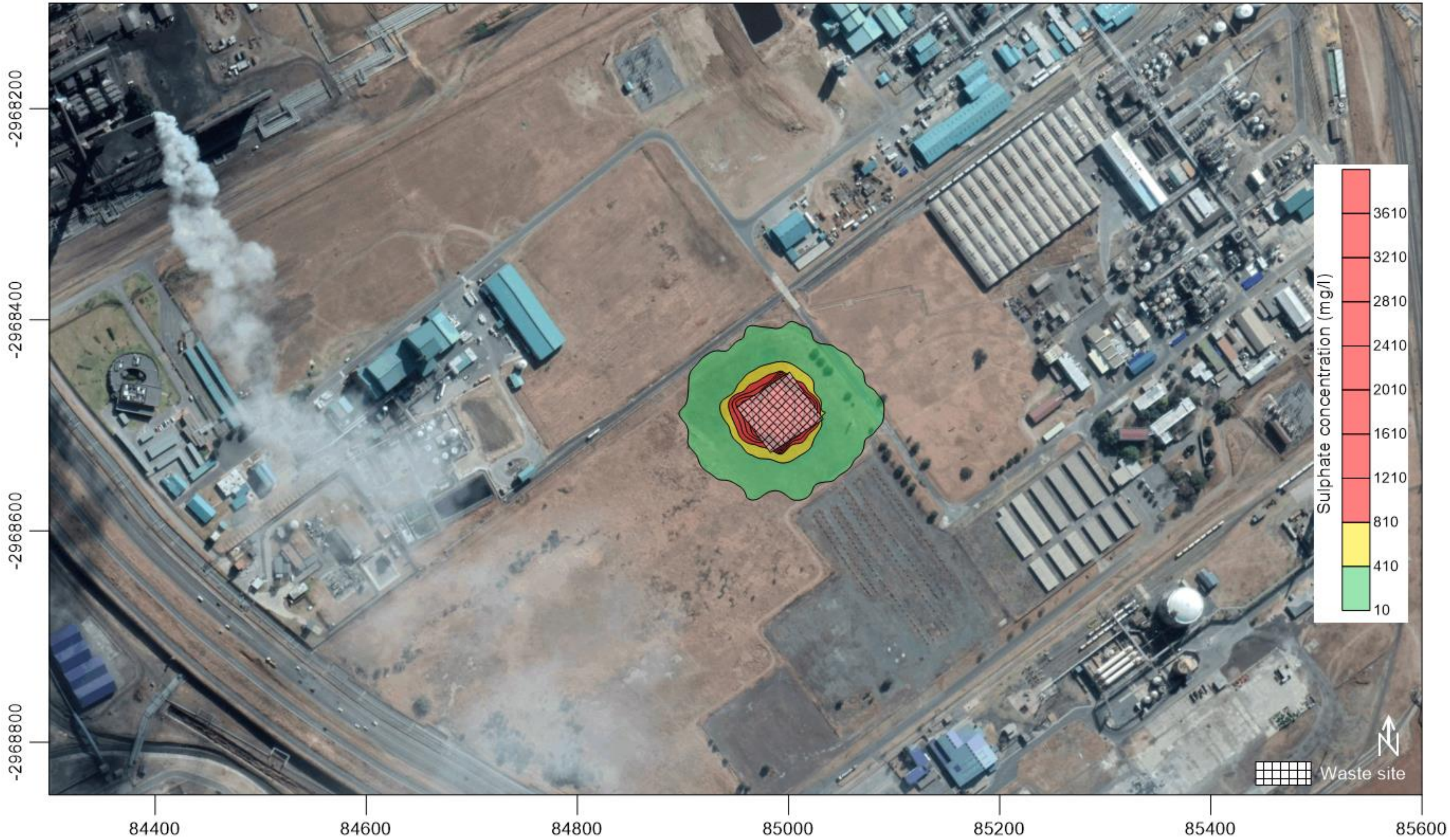

Figure 29: 40 year's simulation of contamination plume with lining prior to disposal

5.8 Capping and pumping as remediation technique simulated for 40 years

This simulation was run in order to predict the extent of the contamination plume after 40 years, for the scenario where capping and pumping is implemented. This simulation was done by combining the methodologies of the capping and pumping simulations described above.

Figures 30 and 31 illustrate the extent and the concentrations of the contamination plume after a period of 40 years, when simulated with capping (with hydraulic conductivity values as described above) and pumping as a remediation technique. The results indicate that it is more effective to cap the waste site with a geomembrane capping than to have a combination of a geomembrane and abstraction boreholes. The same applies for the clay capping as this is more effective than the combination of clay capping and pumping boreholes.

Although the extent of the contamination plume is present outside the boundaries of the investigation site, it is not present in the vicinity of any natural surface-water bodies.

5.9 Limitations of the modelling exercise

The level of accuracy of the modelling was accomplished in accordance with the amount of data which was available. Contaminants which were simulated, SO_4, were assumed to be conservative unreacted tracers. There were many considerations undertaken to produce an accurate model, however it should be noted that assumptions were made for data which were not available. Complexities of the hydrogeological environment contribute to the controlling of subsurface physical and chemical processes and, as a result, the exact concentration of contaminants cannot be determined. It was also assumed that there are no other sources of pollution and that there are no abstraction boreholes in the vicinity of the study area.

Figure 30: 40-year simulation of contamination plume with geomembrane capping and pumping as a remediation techniques

Figure 31: 40-year simulation of contamination plume with clay capping and pumping as a remediation techniques

5.10 Considerations for capping as a remediation technique

The professional official who facilitated the implementation of the capping exercise outlined numerous considerations during the construction and operational phase of the remediation activity. These considerations would promote a robust capping remedial exercise which would be effective in the years to come. Morris (2013) outlined the following actions for the construction and operational phase of the capping exercise.

Construction phase:

- Re-profiling the contamination source area to enable more gentle slopes and a protective soil cover over the area;
- Compaction of the soil cover area;
- Placing a protective vegetation soil cap over the installed capping material; and
- Installing passive vents for any gases that may accumulate below the cover liner to prevent upwelling and displacement of the capping material.

Operational phase:

- Regular annual groundwater sampling is important to obtain a better understanding of the seasonal effects over the groundwater. Regular groundwater monitoring downgradient of the contamination source will allow one to detect any spikes in contaminant concentrations. Detecting spikes in contaminant concentrations would trigger one to question the integrity of the capping material and prompt a thorough inspection thereof;
- Installing protection for the monitoring wells utilised for the groundwater monitoring of the contamination source. It is imperative that all reliable monitoring wells be preserved in order to record a comprehensive database of groundwater quality in the vicinity of the contamination source; and
- Monitor the condition of the surface of the capping material to timely detect any damage to the capping material. Damage can be a result of unwanted vegetation growth on the protective vegetation cover or from animals burrowing on the capping facility.

Ensuring the implementation of the above mentioned actions will extend the effectiveness of the remedial activity which was undertaken.

Chapter 6: Conclusions and Recommendations

6.1 Conclusions

The following conclusions can be made from what was discussed in the preceding sections:

- Understanding of the significance of contaminated land – South African legislation makes provision for any owner of land, whether it is an individual or an organisation, to apply the "duty of care" principle in their activities. Where there is potential or if it is known that pollution is present on a given land, it is the responsibility of the land owner to investigate, assess and evaluate the potential impact of the contamination on the surrounding environment. Norms and standards for the Remediation of Contaminated Land and Soil (DEA, 2014) provide a guide to determine whether remedial action will be deemed necessary based on Soil Screening Values. These Soil Screening Values can be regarded as a decision supporting framework for determining the significance of the contamination of land;
- Determining the need for remediation of contaminated land – International practice for the remediation of contaminated land indicates that policies have been in place for approximately the past 30 years. The common components which feature in these policies include the need to prevent or limit future pollution, the 'polluter pays' principle applies, the precautionary principle applies, approach to remediation is risk based and land/end-use specific, assessment values are used as screening tools, and remediation criteria must be calculated based on the risk profile of the site (DEA, 2009). South Africa has adopted these international policies in order to establish a framework for the management of contaminated land, namely, *The National Framework for Management of Contaminated Land* (DEA, 2010);
- Tools to aid in the decision-making process for remediating contaminated land – The and groundwater modelling process is a tool which can aid in making an informed decision as to what groundwater remediation actions would be most appropriate for a contaminated site and is used to support other decision making processes. The modelling process can be utilised as a management tool in which one can organise and prioritise the collection of data, make predictions based on analysis results, and assist investigators in terms of their understanding of the factors influencing the groundwater regime (IAEA, 1999); and
- Remediation techniques – The remediation of contaminated land may prove to be a costly and technically challenging exercise. A remediation technique can be selected to address the potential contaminant and conditions of a contaminated site. There are

various techniques which can be used for remediating contaminated land, this includes remediation of soils and remediation of ground and surface water which range from capping, biological treatments and phyto-remediation (Hamby, 1996). The technique which will be most appropriate for remediation will be determined by the outcome of the decision making tools utilised.

A digital elevation model was developed for the quaternary catchment (C22K) in which the waste site is located. Particles were then added at the waste site to determine the pathway contaminants would take if there was a discharge from the waste site. The particles flow to the east before joining a northward flowing stream.

The ability of the groundwater model to simulate the concentrations and elevations across the site allowed for the extent of current pollution sources to be simulated. Different scenarios were simulated to determine the extent of the migration of SO_4 as a pollutant, with its initial concentration of 3860 mg/l.

All simulations indicated that the most significant area of contamination occurs within the first layer of the groundwater model, which is the shallow weathered aquifer. The first scenario served to predict the extent of the contamination plume after 40 years. The contamination plume migrates for an approximate distance of 70 m from the source of contamination. The concentration of the contaminants decreases with the increase in extent of the plume. This scenario was repeated for a period of 60 and 80 years. The contamination plume migrates for an approximate distance of 110 m towards the east over a 60 year period and 150 m over 80 years.

In the second scenario a combination of capping materials and cut-off walls are simulated. The contamination plume for the clay capping (and cut-off wall) is reduced by approximately 20 m. The contamination plume with the geomembrane (and cut-off wall) is reduced by 35 m.

In the third scenario pumping boreholes were placed on the eastern side of the waste site. In order to avoid abstraction surpassing the rate of recharge, each pumping well was allocated an abstraction rate of 216 l/day. The scenario was run for a period of 40 years. When comparing the results to the simulation with the clay capping, the clay capping is more effective in reducing the plume in the east. The pumping has managed to reduce the plume slightly more in the other directions when comparing with the clay capping. The results of the geomembrane capping scenario indicates that this capping technique is more effective than pumping.

Cut-off walls were simulated in the fourth scenario. When comparing this scenario to those discussed thus far, it is the least effective one with a maximum decrease of 8 m in the size of the plume in the easterly direction.

In the fifth scenario lining of the contamination source prior to disposal was simulated for a 40 year period. The results of this study are almost identical to the previous scenario in which the cut-off walls were discussed.

The last scenario a combination of capping the waste site and abstraction boreholes was considered. The results indicate that it is more effective to cap the waste site with a geomembrane capping than to have a combination of a geomembrane capping and abstraction boreholes. The same applies for the combination of clay capping and abstraction boreholes

Capping of contaminated land is a relatively inexpensive remedial technique. It has the ability to hinder the migration of groundwater contaminants which may potentially impact sensitive receptors. Practical limitations are that it is seldom possible to wholly contain or isolate the contaminant source and the future land-use may be limited. For the best remedial results, capping should be undertaken in combination with other techniques such as phytoremediation or chemical reactive barriers.

6.2 Recommendations

The numerical model was based on old monitoring data, dating back to 1999. Obtaining new data would allow for simulating the current state of contamination of the investigation site. The data collected in 1999 were comprehensive in nature and covered a large portion of the investigation site. Numerous monitoring boreholes included in that data set does not exist currently and it would be a costly exercise to replicate the monitoring at this present time. However obtaining this data would assist in validating the results of this study.

MODLOW flow packages have a limited ability to incorporate remedial techniques when simulating mitigation measures for contaminant migration. Numerous remedial techniques were not included in the contaminant migration due to this limitation. In order to make provision for alternative remedial techniques a different software program or method would need to be utilised for simulating models which include remediation techniques such as phytoremediation, chemical reactive barriers, etc.

The permeability of the capping material was not available and its value was therefore assumed. Obtaining the actual permeability of the material used when capping of the contaminated land was undertaken would provide a more accurate contaminant transport simulation. This will in turn provide a more accurate result in terms of the extent and concentration of the contaminant plume.

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Chapter 8: Appendix A

International Approaches to the Management of Contaminated Land

United States

The original implementation of the CERCLA policy provided the US with over 20 years of experience which served as the basis of their current policy. Contaminated land investigation and remediation in the original US EPA requirements were based on stringent requirements. This was a multi-phased approach which comprised the following steps (DEA, 2009):

Step 1 - The Resource Conservation and Recovery Act (RCRA) Facility Assessment (RFA). The RFA comprised the reviewing of existing information, a site visit and sampling (if deemed necessary) of the facility in question. The potential of a contaminated site to affect human health and ecological concerns would determine whether remediation would be necessary or not. If it is not necessary, the EPA would issue a 'Determination of No Further Action'.

Step 2 - The RCRA Facility Investigation (RFI). The RFI comprised a detailed investigation that allowed one to obtain enough information to develop a strategy in which the contaminated land could be addressed.

Step 3 - The Corrective Measures Study (CMS). Results of the RFI would determine the need for implementing further actions. The CMS therefore provides an examination of the available options in terms of further actions. Development of the CMS focused on identifying measures in which release impacts could be mitigated in an effective manner. This included considerations such as cost, time, public participation, etc.

Step 4 - The Corrective Measures Implementation (CMI). The CMI comprised all aspects such as design, construction, operation and maintenance in terms of implementing the selected corrective measures.

In the 1990s various parties, such as identified stakeholders, state regulators and the community, noticed that RCRA corrective actions were not very effective. The US EPA then streamlined the clean-up process by focusing on a results-based approach. This approach emphasised environmental indicators as a measure of progress in terms of reducing risk, conducting innovative approaches, increasing public participation, and taking advantage of any redevelopment potential (DEA, 2009).

The objective of remediation emphasises the protection of human health and the environment; expects remediation actions to be effective enough to render land and water resources to a usable quality; and highlights the importance of source control while allowing for flexibility in terms of remediation of soil and water (DEA, 2009).

In order to determine if a facility is achieving particular goals, performance monitoring is conducted. The details in terms of performance monitoring are facility specific and include factors such as type, location and frequency. These factors are flexible and performance monitoring can change in terms of scope and frequency if deemed necessary (DEA, 2009).

There are many manuals and guides which have been published by the US EPA with regards to remediation of contaminated land which has set a benchmark for framework development around the world (DEA, 2009).

Canada

The Contaminated Site Management Working Group (CSMWG) was established in 1995 to address the historical manner in which the identification, assessment and management of contaminated land was undertaken. This was the function of the federal government department, which resulted in many inconsistencies and rendered Canada with distorted picture of the risks, costs and liabilities which resulted from contaminated land (DEA, 2009).

Promoting and developing a consistent approach for the management of contaminated land is the core purpose of the CSMWG. This is done by integrating sustainable development and pollution prevention principles while adhering to relevant environmental regulations, ensuring the protection of public health, and setting a forum where existing technologies, policies and guidelines can be discussed (DEA, 2009).

The Canadian Soil Quality Guidelines have been established for benchmarking purposes. These guidelines are used in determining the need for further investigation, significance identification and classification, and assessing the necessity of remediating actions for contaminated land. These guidelines regard human health and ecological receptors of which the more vulnerable of the two would be prioritised. In these guidelines, four land-uses are considered which include agricultural, residential, commercial and industrial (DEA, 2009).

According to a report compiled by DEA (2009) the soil quality guidelines make provision for a broad literature review and a detailed assessment of a pollutant which includes:

- Production and use in Canada;
- Existing criteria and guidelines;
- Levels in the Canadian environment;
- Environmental fate and transport behaviour; and
- Human and terrestrial plant and animal toxicology.

Notable revisions regarding contaminated land assessment were published in 2006, which illustrated the move to a more risk based approach. Matters addressed in the revision included (DEA, 2009):

- Separate guidelines for coarse soil (sands) and fine soils (silt/clay), particularly for organic compounds;
- Provision for non-toxic based end-points i.e. aesthetics and hydrocarbon free-product as a check mechanism;
- Protection of freshwater life in nearby water bodies, livestock watering and irrigation water sources are considered in addition to the protection of potable groundwater;
- Soil and food ingestion by livestock and wildlife, with secondary and tertiary consumers considered for substances that biomagnify;
- Off-site migration is evaluated for both environmental and human health; and
- Soil quality guidelines for commercial and industrial land-use.

The Netherlands

In terms of developing a detailed framework for the management of contaminated land, the Netherlands was one the first countries in Europe to do so. The Soil Protection Act was established in 1987, and this formed the basis for the prevention of soil pollution. According to the Soil Protection Act, the significance of contamination, urgency and the objective of remediating actions should be considered prior to any remediating activities (DEA, 2009).

Accountability in terms of the cost for remediation of contaminated land has been allocated in current Dutch legislation. The ‘polluter pays’ principle applies, and if this is not possible the onus is shifted on to the land owner. In the case of innocent land owners, public money will be made use of for the remediation costs. The current process gives the owners of contaminated land more capacity in terms of decision making when it comes to remediation, which holds them increasingly responsible for costs incurred (DEA, 2009).

The Dutch soil policy follows a risk based approach with regards to soil quality objectives for the remediation of contaminated land. There were about 100 substances which were allocated target and intervention values for soil and water quality. These values can also be varied based on the different natures of soils. Target values for contaminant concentration were set as low as possible to achieve a target of 'As Low as Reasonably Achievable'.

According to a report compiled by WSP (2009) the following considerations were used in establishing target values for soil:

- Protection of the ecological function so as the risk to the ecosystem should be negligible;
- Protection of the functional properties of the environment so as the functions of the environment should be guaranteed completely; and
- Target values in a compartment (medium) should not result in pollution of other compartments above the target value.

Intervention values were established to trigger a state of emergency if concentrations prove greater than that of the intervention values. The following scenarios can result from a site investigation (DEA, 2009):

- Concentration values are less than target values, which means that there are no restrictions;
- Concentration values are greater than target values but smaller than intervention values, which means that the soil is marginally contaminated and minor restrictions can be enforced; and
- Concentration values are greater than target values and intervention values, which triggers a state of emergency.

The Dutch approach had undergone a significant review in the late 1990s. They had two approaches in terms of remediation: a total clean-up and an isolate, control and monitor (ICM) approach in cases where total clean-up was not possible. These two approaches were too rigid in nature and too costly. A phased approach to remediation was introduced on the condition that any immediate threat from the contaminated land had to be addressed as soon as possible. This allowed for the investigation of other potential solutions (DEA, 2009).

Belgium

The Flemish Decree was approved in 1995 and is known as an influential legislative framework in terms of contaminated land. A number of new concepts regarding the management of contaminated land were introduced to the Flemish Decree which included a phased approach for the investigating and reporting of contaminated land, the establishment of a register of all polluted sites, and an obligation for soil investigation for the transfer of properties or the termination of certain installations. The establishment of the polluted site register is multipurpose, it can be utilised as a database for policy decisions and can also be used as a source of information for potential buyers of polluted land (DEA, 2009).

In Belgium stringent procedures are in place for soil investigation and remediation. The first step is a preliminary soil investigation, or if necessary a comprehensive investigation of the site, which may result in remedial plans and actions (DEA, 2009).

Preliminary investigations include a brief investigation into the history of the site and may include limited sampling. The presence of pollutants is indicated as a result of the preliminary investigation, and further assessment is conducted by comparing concentrations to soil clean-up values. The primary objective of the investigation is to obtain a detailed understanding of the character of the pollutant. Such details should include the following – nature, degree, concentration, source, spatial variability, and migration potential of the pollutant as well as the risk from contact to humans, the environment, surface water and groundwater (DEA, 2009).

Where contaminated land has the potential to harm human health and the environment, soil clean-up levels are triggered. These soil clean-up levels also consider the nature and purpose of the soil. Based on the Dutch model, the exposure assessment considers six different land-uses which are divided into four classes, namely industrial, agricultural, residential and recreational. Scales for each contaminant were established which indicate tolerable pollutant values and high risk pollutant values. Potable water standards are used for the protection of groundwater sources (DEA, 2009).

The protocol which is used as a guideline for comprehensive soil investigations is flexible in nature which allows consultants to make use of their expertise (DEA, 2009).

Sweden

The Environmental Code for Sweden, which was established in 1999, makes the following provisions for contaminated land (DEA, 2009):

- If any contaminated land or water is identified there is an obligation to have it reported;
- The potential to enforce restrictions in terms of land-use when one registers a property; and
- 'Polluter pays' principle applies, where the polluter will be responsible for conducting the investigation and remediation of contaminated land. If this is not possible, the owner of the land would then be liable for conducting the investigation and remediation.

Guidance values to determine the severity of contaminated land have been allocated to three different land uses: residential areas which are sensitive in nature, commercial and industrial areas which have groundwater abstraction, and areas which are not sensitive in nature and have no groundwater abstraction. These guidance values are similar to that of international benchmarking, but have been adapted to accommodate Swedish specific conditions, such as geology, land-use sensitivity, exposure and policy (DEA, 2009).

United Kingdom

The main objective of the legislation which relates to the management of contamination in the United Kingdom is to identify contaminated land, eliminate any risk which could harm human health or the environment, and obtain a useful purpose for 'brownfield' sites (DEA, 2009).

A series of contaminated land reports were published in order to supply scientific information and technical support for the management of contaminated land.

Identification of contaminated land is a risk based process. In order for land to be classified as contaminated, there has to be a link between the pollutant and a receptor. The potential for significant harm must exist before a site can be classified as contaminated. Factors which are used in the risk based identification include the character of the pollutant, the receptors which may be harmed, and the pathway in which the receptor may be reached (DEA, 2009).

Similar to other countries, the 'polluter pays' principle applies in terms of remediating contaminated land, and when this is not possible, the owner or occupant of the land would then be held liable (DEA, 2009).

Local authorities have been allocated the responsibility of implementing the regulatory framework in terms of contaminated land but, in the case of special sites, this mandate could be escalated to a national level. Special sites are contaminated sites which cause significant water pollution, pose a high level of difficulty with regard to remediation, are presently governed by the Environmental Agency, and are occupied by other government bodies (DEA, 2009).

The UK Department for Environment, Food and Rural Affairs (DEFRA) and the Environmental Agency produced a series of documents which pertained to the management of contaminated land to provide relevant stakeholders with scientifically based guidance on determining risks which may result from contaminated land (DEA, 2009).

When assessing risks in terms of contaminated land, links between the source, pathway and receptor followed by the UK. For common soil contaminants, precautionary threshold trigger values have been established and in cases where trigger values are not available, or appropriate and site conditions are particularly complex, a detailed site specific risk assessment is conducted. Site specific risk assessments have been used to establish guidelines for soil values and can be used for sites which fit these parameters (DEA, 2009).

A computer based model, known as Contaminated Land Exposure Assessment (CLEA), combines relevant information to simulate conditions which may result from contaminated land. Intervention values are generated from these simulations which assist in determining any potential risk to harm human health (DEA, 2009).

One of the shortcomings in the Contaminated Land Reports is that it only considers the risk of contaminated land in terms of human health over a lifetime, and does not consider any potential impacts as a result of the construction phase of remedial activities. The guideline values are based on three standard land-uses, namely residential, plots, and commercial industrial land-uses. If a contaminated site is to have more than one land-use, a more detailed and site specific assessment is undertaken to effectively determine the potential risks which may arise as a result of the contamination (DEA, 2009).

Australia

There are two guidelines which are used for the management of contaminated land in Australia, namely the “National Environment Protection Measure (NEPM) – Assessment for Site Contamination” and the “Guidelines for the Assessment of Contaminated Sites” which is also applied in New Zealand. The governance of environmental legislation is enforced at a state government level (DEA, 2009).

In Western Australia, the Department of Environmental Protection (DEP) has established assessment levels for soils which are to be used as guidelines for assessment purposes. There are many sources on which these assessment levels were based, such as the Dutch Standards, National Environmental Protection Measures (NEPM), US EPA, etc. It is mandatory to develop site-specific response levels for cases where no guidelines are available (DEA, 2009).

Investigation levels on contaminated soil have been established by the DEP which consider two factors, the threat to human health and the environment. In exceeding these levels, an investigation will be triggered which is separated into two sections, Health Investigation Levels and Ecological Investigation Levels. One should note that these levels do not necessarily require clean-up actions and should be regarded as triggers (DEA, 2009).

In Victoria, the State Environment Protection Policy (SEPP) published a document in 2002 which was named “Prevention and Management of Contaminated Land”. This was seen to be a more organised approach towards the management of contaminated land. The goal of the policy was to manage the land in a sustainable manner, therefore emphasis was placed on preventing pollution. Principles such as socio-economic factors and the precautionary approach are incorporated into the legislation (DEA, 2009).

SEPP divides land-use into six different types which includes industrial, commercial, recreational, residential, agricultural, and parks and reserves. When the contamination levels of land hinder the beneficial use of that specific land, it can be regarded as polluted. Different land-uses have five associated beneficial uses for which indicators have been established to determine the degree of contamination, this is compared to the investigation and trigger levels (DEA, 2009).

Site investigations need to be conducted when a request is submitted to change a land-use (e.g. industrial to residential) which will illustrate that the new site will comply with relevant land-use requirements (DEA, 2009).

Sediment and soil contamination levels are managed separately in Western Australia and Victoria. The Australia and New Zealand Environment Conservation Council (ANZECC) published water quality guidelines which address the sediment contamination levels and regarded more of a water management strategy than a contaminated land management strategy (DEA, 2009).

New Zealand

National environmental standards as well as best practice guidelines were incorporated in the latest review of the policy framework for the management of contaminated land in New Zealand (DEA, 2009).

New Zealand established guidelines from 2008 onwards which make reference to risk screening, guideline values, the management of contaminated land classification and the information relating thereto, and guidelines regarding investigation and analysis of contaminated land. Risk screening is used as a decision support tool when the reporting of a contaminated site is deemed necessary. National procedures have been established which create a uniform approach towards classifying, managing and releasing information in terms of contaminated land (DEA, 2009).

This framework was adopted from the United Kingdom DEFRA. The source, pathway, receptor principle is utilised in determining contaminated land which eventually forms part of a national register (DEA, 2009).

South Korea

There are two standards which govern the management of contaminated land in terms of the Soil Conservation Act. One standard relates to the potential harm contaminated land may inflict on human health and the environment, while the other specifies the remedial actions which may be required if soil pollution exceeds threshold values (DEA, 2009).

Soil quality guidelines are based on the specific land-use of a site, which is divided into two categories. Farms and forests are considered as sensitive areas and are named ‘Ga’ sites, while industrial areas are considered less sensitive and are named ‘Na’ sites. ‘Ga’ sites require more protection in terms of their exposure to risks than that for ‘Na’ sites (DEA, 2009).

The Minister of Environment co-ordinates all of the surveying which is conducted to determine soil pollution, and responsibilities are filtered down to provincial and local authorities. Major industries collaborated with the government to establish targets for contaminated soil to assist in determining contaminated land (DEA, 2009).

Thailand

Thailand also makes use of soil quality standards for benchmarking and assisting in the determination of contaminated land. Furthermore, standards were published for land-use which did not have a conventional purpose (DEA, 2009).

People's Republic of China

Environmental quality guidelines for soils were developed in 1995 to deal with the extreme rate of industrialisation which resulted in extensive pollution across China. There are three parameters which are considered when assessing contaminated land which include background levels, soil pollution threshold values and soil environmental quality standards (DEA, 2009).

When soil pollution exceeds that of background levels, immediate actions need to be identified to address any potential risks. Immediate action is also required when soil pollution values exceed the threshold, which may have a negative impact on human health. Soil screening limits are also used in the assessment process, when pollution levels are less than the established limits the soil is then deemed uncontaminated and no further action may be required (DEA, 2009).