

**Impact and risk assessment of groundwater
contaminated sites by chromium in both
saturated and unsaturated zones**

By

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DECLARATION

I, John Sibanyoni, declare that the thesis hereby submitted by me for the Master of Science degree at the University of the Free State. This is my own independent work and has not previously been submitted by me at another university/faculty. I further more cede copyright of the thesis in favour of the University of the Free State.

I also declare that all sources cited are indicated in references.

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EXECUTIVE SUMMARY

The challenges of chromium related activities such as ferrochromium industries is the disposal of waste containing chromium slag or dust with hexavalent chromium (Cr(VI)). Various investigations have shown that Cr(VI) is a serious concern to both environment and human health because of its mobility and carcinogenicity.

This study evaluated the impact of chromium related activities by human activities to groundwater for both unsaturated and saturated zones. South African ferrochromium industry based in Mpumalanga Province, (Middelburg) was selected as a case study assess waste dump of ferrochromium slag. The challenges regarding the dump of slag the oxidation of old slag (Cr(III) to Cr(VI) and also fine dust from open arc furnaces which contain hexavalent chromium. The Historic Dump Site (HDS) which is not lined was previous dumped (since 1964) with various waste materials including but not limited to:

- Ferrochromium slag
- Phenols
- Fine dust from open arc furnace (with Cr⁶⁺)
- Filter cake (with Cr⁶⁺)

Literature studies indicate that Cr(III) can be oxidized to Cr(VI) through presence of moisture, dissolved oxygen and manganese dioxide (MnO₄) (EPA, 1994). It is known from literature review that concentration of Cr(VI) of more than 1 mg/l imparts yellow colour (US EPA (1994) which was used as a visual (indicator) tool during field assessment at the HDS and presence of Cr(VI) was observed at toe of the dumps and low lying area with moisture content. The presence of Cr(VI) was also observed on monitoring records.

The mitigation that has taken place at site was the removal of hazardous waste such as Cr(VI) from fine dust and filter cake and dumped at hazardous waste site (Holfontein). Other on-going mitigation is the usage of ferrous sulphate at the capturing point called infiltration gallery to reduce Cr(VI). This study has indicated that although some remedial approaches have been performed, the contamination still exists at the site but with some improvement on some parts of the site.

The findings of the study assessment have indicated the following observations:

- Boreholes for Meltshop south (S) and north (N) (i.e. CSD 26 & 27) near the process plant indicated both contamination by Cr(III) while CSD 27 (Meltshop S) did not show impact of Cr(VI)
- Dam 4A and 4B indicated highest impact of Cr (VI) as well as other variables including sulphates.
- Eastern boreholes at the down-gradient of the HDS indicated pollution by Cr(VI), SO₄ and other parameters except boreholes on background such as CSD 16 and less pronounced SD1-2

- The western boreholes showed same trend of pollution by SO_4 except that it was not by Cr (III or VI). Again background boreholes (N3-880, WD9&10) did not show pollution which can be attributed that pollution source is both slimes and return water dams.
- Contamination to unsaturated zone is high but also fluctuate compared to contamination in saturated zones.
- Contamination by Cr(VI) is caused mainly by fluctuation of water table during water spraying to hot slag and rain season

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1. CHAPTER 1: INTRODUCTION

1.1. GENERAL

The Bushveld Igneous Complex (BIC) is one of the geologic formations in the world, which has valuable economic minerals. Chromium is one of the minerals which play a vital role in terms of the country's economic development. The Merensky Reef is located within the Rustenburg Layered Suite, and contains the most important economic minerals such as platinum group metals (PMGs), chromium and vanadium.

Chromium is mined and processed mostly by ferrochromium industries to produce various products including but not limited to alloys. South Africa alone contributed 44.8 % of the world chrome production in 2000 (Papp, 2002) when compared with the other countries. The two largest chromite ore producers, accounting for about two-thirds of world production are South Africa and Kazakstan. It will also be advantageous to envisage the future trends of production and waste minimization.

Furthermore, byproducts such as ferrochromium slag create many environmental and human health problems at waste dump hence this study focuses on its impact to groundwater systems (saturated & unsaturated zones).

1.1.1. Property of chromium

Chromium is a hard, brittle, semi-grey transition metal that exists naturally as the trivalent (III) form. Ores of chromite are dark and dull stones. Hexavalent(VI) and chromium (0) are generally produced by industrial processes. The name chrome is derived from the Greek *chroma* for colour, on account of the brilliant colours of its compounds. The most important chromium salts are sodium and potassium chromates and dichromates, and the potassium and ammonium chrome alums (Hodgman, et al., 1961).

Chromium is mostly found in three forms namely:

- Trivalent chromium [Cr(III)]:
 - This oxidation state occurs naturally in rocks, soil, plants, animals and volcanic dust. This form of chromium is stable and immobile; and has almost no negative impact to the environment.
- Chromium metal [Cr(0)]:
 - This chromium is not found naturally but is a man-made form of chromium in industrial processes.
- Hexavalent chromium [Cr(VI)]:
 - This form of chromium is very unstable, reactive and mobile. Hexavalent chromium usually emanate from the human activities such as ferrochromium process, electroplating operations, leather tanning industries, textile manufacturing etc.

The actual range of oxidation state for chromium is between -2 and +6. Other oxidation states except +3 and +6 are not easily encountered in the environment due to their very short half-life and because they are also very unstable. Only trivalent (Cr^{+3}) and hexavalent (Cr^{+6}) chromium are usual encountered in the environment. Therefore, most of this study focuses on these oxidation states (Cr^{3+} and Cr^{6+}) of chromium.

Among the two chromium oxidation states, chromium(III) is considered one of the essential elements for living organisms, whereas chromium(VI) is toxic to human, and was found to be carcinogenic (Xiashi et al., 2002). Hexavalent chromium is very strong oxidizing agent and that is the reason it is considered as carcinogen and toxic to human beings.

1.2. STUDY OBJECTIVES

The objective of this study is to investigate the impact of chromium in the subsurface. Although the investigation puts emphasis on hexavalent chromium as the main problem, it also includes trivalent chromium as it is where the regeneration of chrome six (Cr^{6+}) starts.

The current situation in South Africa, is that most of the slag and chromite ore handling and storage are carried outdoor and without lining the surface. Furthermore, in attempt to prevent air pollution dry chromite ore is being watered. This activity can result in leaching of chromium to the subsurface (unsaturated zone) and eventually reach the saturated zone if the floor is not well designed for that storage.

The notion is that chromium in slag is in trivalent form and no concern to the environment, if that chromium (in slag) is in trivalent form and thus no serious threat to the environment. Trivalent chromium can be oxidized to hexavalent form by oxygen in unsaturated zone before it reaches saturated zone.

The situation can cause serious concern to the environment, biodiversity and human health since hexavalent chromium is mobile, soluble, carcinogenic and toxic. It is with this basis, which has led the study to do much more work on groundwater contamination by chromium.

1.3. METHODOLOGY OF THE INVESTIGATION

The following approach has been inferred in terms of fulfilling of the study objectives:

- Integrating different outcomes from previous investigations (literature review) and derive the cohesive approach to the study.
- A feasible case study was conducted groundwater impact assessment. Results from study were successfully used to draw conclusions and recommendations. Field data were collected to perform processes that have to address the real world situation (i.e. chapter 3) rather than theory only.
- A Risk-Based Corrective Action (RBCA) popularly employed by the US EPA and DWAF “Minimum Requirements” were used to assess the risk in the subsurface.
- The source-pathway-receptor principle which works similar to RBCA was also used.

1.4. OUTLINE OF THE THESIS

Chapters of the thesis have been outlined as follows:

1.4.1. Chapter 2

This chapter has integrated different literatures as a review. The emphasis on the literature review was put on the following subheadings:

- Generic Risk Assessment methodology

- Ferrochromium processing leading to disposal of chrome slag and its associated impact to environment
- Chromium in the environment
- Impact and Risk Assessment of chromium in groundwater systems with respect to:
 - Chromium toxicity (the toxic chromium, Cr(VI), and non-toxic chromium, Cr(III)) to both environment and human health
 - Application of DWAF “Minimum Requirements” (1998) for hazardous waste disposal

1.4.2. Chapter 3

A case study has been selected and utilized as a practical example for the application of the above theory and hypothesis outlined in chapter 2. This chapter focuses on the redox reaction processes that lead to:

- Geochemical processes in the soil
- Characterization/identification of Cr-contamination in the field.
- Brief risk assessment
- Impact and Risk Assessment of chromium in groundwater systems with respect to:
- migration of the plume using source-pathway-receptor principle
- The field study and prediction of chromium in groundwater. The modeling program (GMS 7.1) was used to predict the extent of the plume.

1.4.3. Chapter 4

Discussion on various remedial approaches with respect to chromium contamination within the subsurface. Conclusions about the studies forms part of chapter 4.

1.4.4. Chapter 5

All cited material (i.e. references) are found in this chapter

2. CHAPTER 2: LITERATURE REVIEW

2.1. GENERIC RISK ASSESSMENT METHODOLOGY

2.1.1. General

Risk Based Corrective Action (RBCA) is a risk assessment method developed by the American Society of Testing and Materials (ASTM) (E1739) (Wilson, 2005). ASTM standard E 1739 was original designed for "Guide for Risk-Based Corrective Action Applied at Petroleum Release Sites".

RBCA is a method that uses a tier approach and site classifications to screen and address sites based on their relative risk (US DOE, 1998). RBCA uses the following:

- Characterization of contaminant sources, migration pathways and receptors which is almost similar approach to the South African "Risk Averse Approach"
- Selective application of corrective measures as needed to control potential risks to both human health and the environment.

As mentioned earlier RBCA assess the environmental conditions through tier approach. These "Tiers" in the risk model are outlined as followed (US DOE, 1998):

- ***Tier I: Screening level***

This tier attempts to identify potential sources of contamination, preferential pathways (or simple pathways), receptors and point of exposures. After identification of the above sources of pollution Tier I suggest that risk-based screening levels (RBSL) be performed and also identifications of the relevant ecological screening criteria (RESC) and compared with site conditions.

- ***Tier II: Site specific***

In this tier it is suggested that more information/data be collected as necessary. This will be followed by reviewing and revising of site conceptual model. It further requires that tier 2 site-specific target levels (SSTL) are set and identifying site-specific ecological criteria (SSEC). It follows that assessment results be compared with site conditions.

- ***Tier III: Remedial criteria***

RBCA is also defined as part of management tool that takes a scientific approach to problem solving using risk assessment as the means to providing managed solutions (Wilson, 2005).

All three tier levels have almost the similar approach except that when one proceed to next tier more information is required and becomes more detailed. Two assessment questions are asked after each tier and they are as follows:

- Is there any interim remedial action approach
- If "yes", then have the condition on site changed or improved?

However, interim remedial will always lead to reclassification of the site and again apply tier I. Should there be no change on site conditions for all tiers after interim remedial action, it then leads to draw a full remedial action program which will then consider alternatives with combinations of remedial actions.

2.1.2. Application of RBCA to the study area

Background information obtained during the study indicates that initial assessments were performed at site. The following site investigations were performed:

- Geohydrological baseline study by JMA Consulting in 2007
- Licence Application for the disposal of solid waste at Middelburg Steel and Alloys, Middelburg by Watermeyer Legge Piesold and Uhlmann (WLP) in 1989:

Investigations by WLP (1989) indicated that slag dump site (now referred as HDS) is unsuitable for the co-disposal of inert wastes and effluents. Of importance, the infiltration gallery trench is inadequate and overloaded which causes contaminated water to spill to Vaalbank stream on occasions.

Furthermore, JMA (2007) studies also indicated that impacts to groundwater relates to elevated concentrations above the background water quality in boreholes sampled during hydro-census survey around the study area.

It was recommended by WLP that infiltration gallery trench and holding ponds should be sealed off by bentonite.

During this study it was observed that boreholes down-gradient of the HDS and the slimes dam was still polluted predominantly by SO_4 .

Using RBCA tier I- III, first and second site visits were made in 2006 and 2010 to obtain more information. Assessment of the data record from monitoring boreholes indicated that contamination to down-gradient boreholes still exists. This triggers that remedial action program for waste sites needs to be drawn according to tier III evaluation. It should be borne in mind that site-specific target a level (SSTL) in this study was set as to comply with South African Water Standards SANS 241 (2001 & 2005).

RBCA final stage, tier III, requires that monitoring results be compared with site and assess the interim remedial actions for effectiveness and improvement on results. The results indicated in section 3.8 (hydrochemical analysis) shows very little improvement. Tier III, then requires that remedial action program be drawn with considerations to have alternatives which can include combinations of remedial methods.

Further details on remedial action for study area have been made in chapter (section 4.1.1).

2.2. CHROMIUM IN THE ENVIRONMENT

2.2.1. Generic Occurrence of Chromite in the Bushveld Igneous Complex (BIC)

The discussion on the occurrence of chromite is more based on South African geology and more specific to the Bushveld Igneous Complex (BIC) structure. Most of chromite ores are found on the western and eastern limb of the Bushveld complex in Rustenburg Layered Suite as illustrated on **Figure 2.1** below (Viljoen and Reimold, 1999). Chromite is associated with ultramafic rocks owing to its physical characteristics similar to ultramafic rocks as indicated on **Table 2.1** below.

TABLE 2.1: Compositions of anorthosite, pyroxenite and chromite

Mineral	Feldspar composition (%)	Density (g/cm ³)	Group	Chemical composition	Increasing density
Anorthosite	90-100	2.72-2.75	Non-ferromagnesian silicate	[(Ca,Na)(Al,Si)(Si ₂ O ₈)]	↓
Pyroxenite	0-10	3.20-4.22	Ferromagnesian silicate	Ca(Mg, Fe,Al)(Al,Si ₂ O ₆)	
chromite	-	4.79	Ferromagnesian	FeCr ₂ O ₄	

- No data available

Ultramafic also called ultrabasic igneous rocks are feldspar-poor composed of combinations of the minerals olivine, orthorhombic pyroxene, monoclinic pyroxene and hornblende, or the secondary alteration products of these minerals. Iron oxide, chromite, spinel and biotite are common accessory minerals. The rocks falling within this definition are peridotites, pyroxenites and dunites.

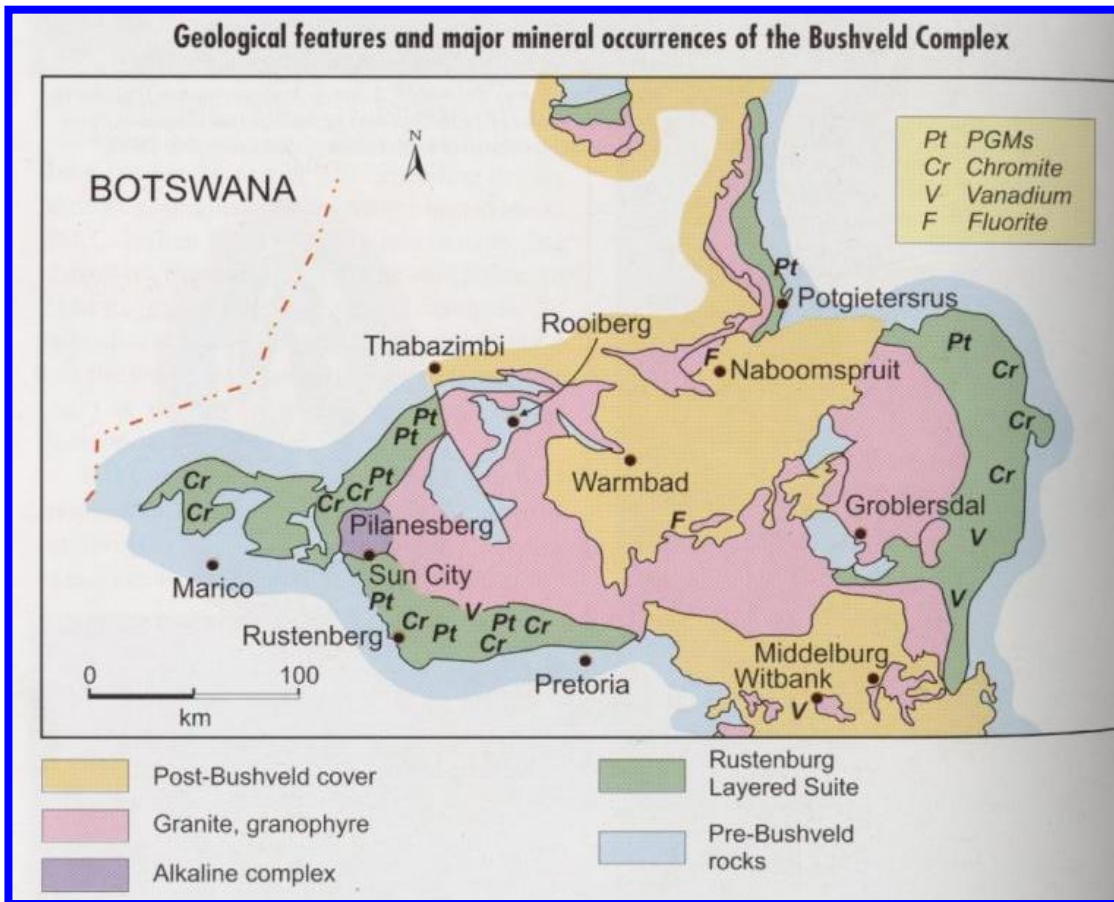


Figure 2-1: Localities of chromite ores in Bushveld Igneous Complex (Viljoen and Reimold, 1999)

Ultramafic rocks have a high concentration of chromium, typically about 1000 to 3000 ppm, compared with an average crustal abundance of about 100 ppm (Christie et al, 2003). The successions of the layers for both western and eastern rims of BIC are illustrated by **Figure 2.2** below.

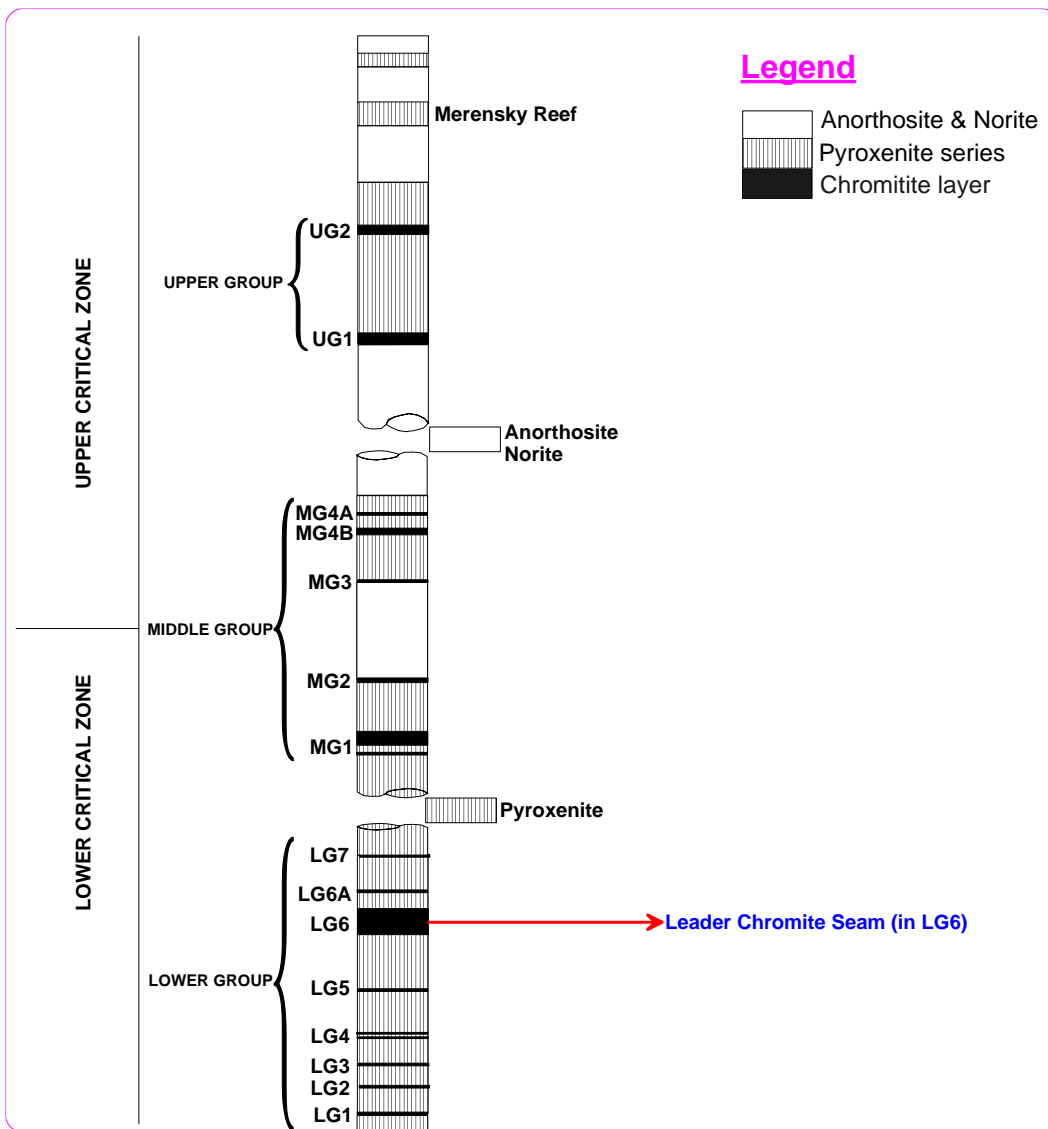


Figure 2-2: Stratigraphic section of the chromitite layers of the Bushveld Complex (not drawn to scale), (Cawthorn, 1999)

The rock successions in the eastern and western lobes of the Bushveld Complex are very similar (Viljoen and Reimold, 1999). It is likely that chromite is associated with platinum presumably because of their similar physical and chemical properties, such as high resistance to corrosion through water. Evidence from Cawthorn (1999) indicated that... the Middle Group (MG) Chromitites could be exploited for their platinum and chromium and ... has a major impact on smelter capacity as has Cr₂O₃ control in the concentrator (Watson and Harvey, 1992). However, it is worth to note that in general chromite will be naturally present in small quantities in any favorable environment.

2.3. MINING AND PROCESSING OF THE CHROMITE

2.3.1. General

The only commercially important ore of Cr is chromite (FeCr_2O_4). This is the chromium analogue of magnetite, Fe_3O_4 , which is better written as $\text{Fe}^{\text{II}}\text{Fe}_2^{\text{III}}\text{O}_4$ (Lee, 1996). As illustrated earlier, most of chromite ore deposits are located in the western and eastern limb of the Bushveld Complex, thus most of the mines are also located in these areas. Very few mines are found in the Northern limb of the Bushveld because of very few chromite and its uneconomical deposits.

The in depth detail of mining process is beyond the scope of the thesis and thus only the storage, handling and processing of chromite will be focused.

The mined chromite ores are dispatched to the ferrochrome industries.

2.3.2. Mining techniques

Mining of chromite ore will depend upon the depth of chromite layer within the subsurface. Chromite ore found in shallow depths is mined through an open-cast mining.

Open-cast mining is a surface mining operation in which blocks of earth are dug from the surface to extract the ore contained in them. The upper part of the surface is excavated creating deeper pit until mining operation terminates.

Underground mine is mostly applicable to ores located at deeper strata. Generally, chromite ore is extracted in a mineral seam with a mechanized method called bord (room) and pillar. Pillars of equal dimensions are left behind in order to support the roof and/or prevention of surface subsidence. The following table represents five major South African chromite ore mining companies and their respective mining techniques.

Table 2.2: Major Chromite ore mining companies in South Africa (I.C.D.A., 2004)

Company name	Mining technique	Location	Dipping angle (degrees)
Assmang	Opencast	Dwarsrivier (Steelpoort)EBIC	NA
Bayer	Board and pillar	Rustenburg WBIC	NA
Hernic	Opencast in MG and also inclined shaft underground	Rustenburg (Brits) WBIC	NA
Samancor (consists of seven mines)	Board and pillar Underground mining	Both western and eastern limb of BIC	9-13
Xstrata	Board and pillar And Updip	MG & LG in western Rim of BIC (Rustenburg)	11-13
Legend EBIC = Eastern limb of Bushveld Igneous Complex WBIC = Western limb of Bushveld Igneous Complex BIC = Bushveld Igneous Complex MG = Middle Group LG = Lower Group NA = No data available			

Open cast mining technique is mainly employed when economically ore is shallow, for example, visible outcrop of the chromite ore. However, as mining progresses, the ore seam gradual gets deeper and thus open cast technique becomes unfeasible. Therefore, underground mining is feasible for ore seams located at greater depths. Approximately 80% of mined chromite ore in the Bushveld Igneous Complex is by underground mining technique and others is by opencast method (I.C.D.A., 2004).

Typically, ore dressing and beneficiation methods are employed by heavy separation, hydroclassification and gravity separation for the removal of silica.

Furthermore, chromite ore is processed in the ferrochrome industries where the main product is ferrochromium. The lumpy form of chromite ore is fed directly into the smelting arc-furnace. Fine or friable ore can only be fed into the smelting process after it has been sintered (fused) and briquetted. In briquetting process all the fine raw material (fine chrome ore) including the binders such as dolomite, bentonite are bonded together for the sufficient strength before the smelting process.

Bord and pillar mining method

Bord and pillar (also called room and pillar) is a mining method system in which the mined material is extracted across a horizontal plane while leaving "pillars" of untouched material to support the roof overburden leaving open areas or "rooms" underground. It is usually used for relatively flat-lying deposits, such as those that follow a particular stratum¹.

The room and pillar system is used in mining coal, iron and base metals ores particularly when found as manto or blanket deposits, stone and aggregates, talc, soda ash and potash.

¹http://en.wikipedia.org/wiki/Room_and_pillar

2.3.3. GENERAL FERROCHROMIUM PROCESS

INTRODUCTION

Two ferrochromium processes from different countries were selected to be discussed in this chapter generic and chapter 3 (study case in South Africa). The first ferrochromium process is based on Europe (Finland) and the second is based in South Africa. Ferrochrome plants having been used to highlight potential issues to groundwater impact. These are dealt with in detail in subsequent chapters. Ferrochromium industries supply over 80% of the world's ferrochrome to stainless steel industries for electroplating.

The discussion in this chapter begins with the ferrochromium process as the major contributor to groundwater contamination by chromium.

Within this section the following topics have relevance to theoretical background of hexavalent chrome:

- Handling and storage of raw material.
- Ferrochromium processes.
- Release of product and waste dump of ferrochrome slag.

Raw material handling systems are the means of receiving, storing and handling various raw materials that are going to be processed thereafter (McKirdy and Madonsela, 2003). Chrome ores used in ferrochromium production contain the following additives:

- Reduced iron (FeO).
- Chrome oxides (Cr₂O₃).
- Slag forming-oxides which also contain the following:
 - Aluminium oxides (Al₂O₃).
 - Quartzite (SiO₂).
 - Magnesium oxides (MgO).
 - Calcium oxides (CaO).

The following ferrochromium process is based on *Outokumpu Chrome Oy Technology* in Europe (Finland). The Outokumpu process is regarded as the most modern and environmentally friendly ferrochrome production process available world-wide. Indeed, the technology was developed in Finland where strict environmental standards are applied (McKirdy and Madonsela, 2003).

The ferrochromium process consists of the following stages:

- Pelletizing plant.
- Sintering.
- Preheating.
- Smelting furnaces.

The following table is a list of most general additives used in ferrochrome process.

Table 2.3: Materials used in ferrochromium process

Material	Chemical formula	Function
Chrome ore fines	FeCr ₂ O ₄ (solid form)	
Chrome concentrate	FeCr ₂ O ₄ (moistened ore fines)	
Coke	Carbon (C)	Reductant
Lumpy ore	FeCr ₂ O ₄ (solid form but in bigger granules)	
Coke dust		
Surface coke	Carbon (C)	
Char	Carbon solid residue (C)	Reductant
Quartzite	SiO ₂	Flux in smelting plant
Bentonite	Al ₂ O ₃ 4SiO ₂ H ₂ O	Binding agent
Dolomite	(Ca,Mg) ₂ (CO ₃) ₂	Flux in pelletizing plant

Thirty percent of natural chrome resource is *lumpy ore*, 70 % *fine* or *friable ore*. The fine ore cannot be fed directly to a submerged furnace without causing dangerous blow-outs and must therefore be agglomerated before charging in smelting furnaces (Vanhanen, 1999).

2.3.4. FERROCHROMIUM PROCESS STAGES

Figure 2.3 illustrates general stages for chromite ore mining, ferrochromium process and implication to the environment.

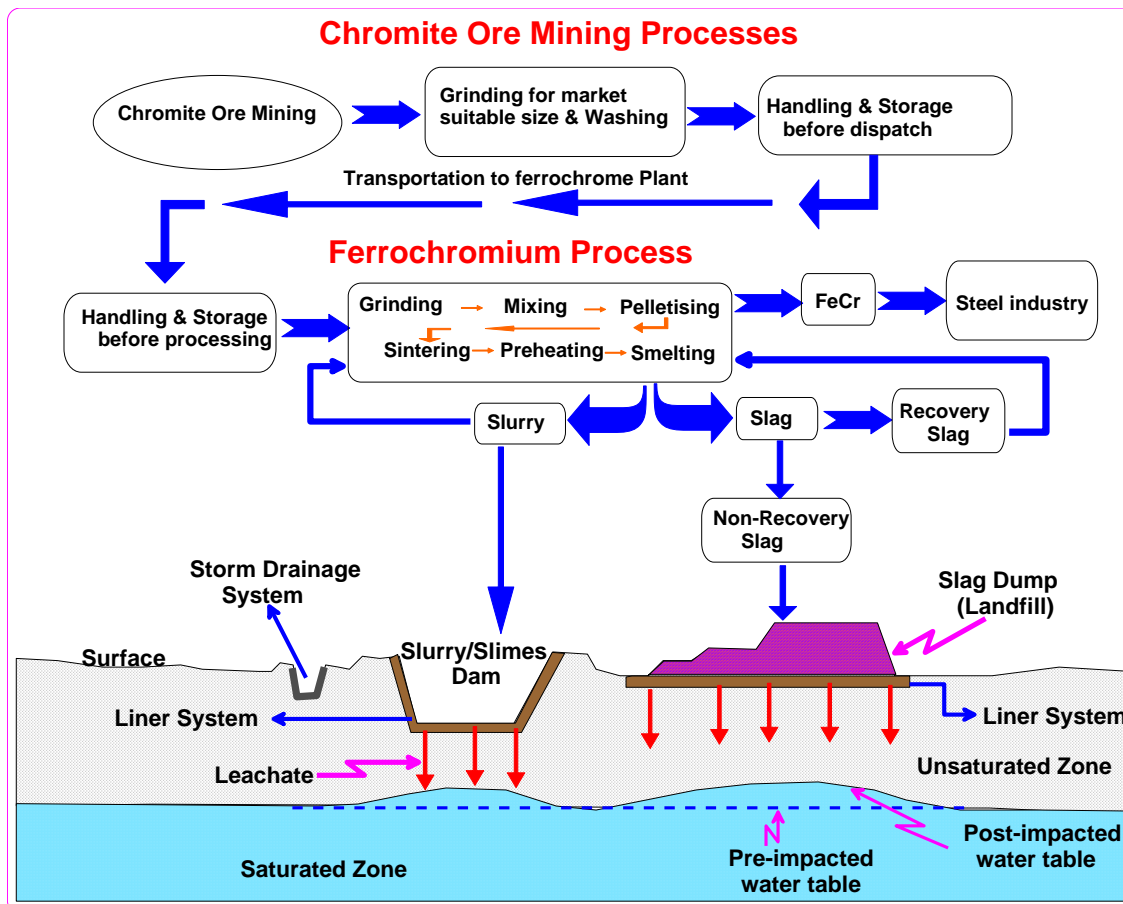


Figure 2-3: General schematic representation of ferrochromium processes

The stages involved in chromium process are as follows:

- Grinding process
- Mixing process
- Pelletising

The above mentioned processes require input material as listed below:

- Chromite ore fines.
- Chromite concentrates.
- Coke fine.
- Char.

It further requires flux and binding agents such as: bentonite, quartzite, coke dust and dolomite are added in the mixture.

Dolomite.

The main aim of grinding is to obtain the suitable grain size and grain size distribution for both pelletizing and sintering process (Vanhanen, 1999).

Small quantities (about 0.7-1% of chromite) of bentonite are added in a very fine form to mix homogeneously with hematite (Fe_2O_3). Hematite increases the iron content in ferrochrome. Generally, the composition of ferrochrome obtained is as follows: Cr 52%, Si 4.0%, C 7.0% and

Fe 36% (Mukherjee, 1998). Therefore, it can be observed that hematite is the second in terms of abundance in ferrochrome product.

Water is fed into the slurry tank in relation to material. Chromite slurry is pumped into the capillary disc filters from mixing slurry tank.

Moisture content of the slurry is estimated between 8 and 8.5% resembling that of pelletizing material. Materials are well mixed and pelletized in the rotary kiln to form small ball shapes (see **Figure. 2.4**) of 12-13 mm in diameter called green pellets.



Figure 2-4: Green (wet) pellets on ferrochrome plant conveyor belt (Vehviläinen, 2005)

The product (filter cake) is conveyed to the cake bins by conveyor belt as indicated on **Figure 2.4** above. The main filtrate is pumped into the plant water tank. From environmentally pollution perspective, poor storage of this filtrate can cause a very serious concern to groundwater components.

SINTERING

Green pellets (small ball shapes from pelletizing process) are fed into sintering furnace. Sintering means heating of chromite pellets where silicates (quartz) and hematite melt to the high temperature (up to 3000 °C, see **Figure. 2.5**) in which the chromite grains in pellets are fused together. The sintering reactions take place in oxidizing conditions, and the iron in chromite oxidizes in significant amounts from Fe^{2+} to Fe^{3+} . This reaction releases energy, which benefits the whole sintering process. This process is done to obtain strong structures which can withstand thermal and mechanical treatment on the next stage (smelting). Before sintering can take place, pellets are subject to be dried at 300 °C by circulating gases. Carbon is burnt inside the bed to supply more energy (temperature increases). Sintered pellets are cooled in other compartment.

Smelting processes

Smelting furnaces can be closed, semi-closed or open.

Closed furnace

The following factors are relevant to the closed furnace:

- Closed smelting furnace, with closable hoods are substantially more favourable when compared to semi-closed and/or open smelting furnaces. The former releases carbon monoxide gas (CO-gas) in reduction reaction hence carbon monoxide serves as energy provider.
- The other major environmental advantage is that CO-gas has high quality fuel with very low sulphur and this implies that, there's a very low emission sulphur dioxide (SO₂) gas.
- Provided that there is a good furnace sealing, CO-gas emission can be in very small volume.
- CO-gas is also used in coke drying, sintering, preheating and heating of ladles and can also be used in stainless steel industry (Vanhanen, 1999). In this process insignificant Cr(VI) is released when compared to semi-closed and open smelting furnaces.
- High pressure venturi scrubbers (see Figure. 2.3) are used to wash CO-gas and dust formed in closed furnace. Not only CO-gas washed off but also other impurities such as emissions of sulphur dioxide, oxides of nitrogen (NO_x), carbon dioxide as well as remains of chromium in both trivalent and hexavalent state.

The generation of residual dust from bag-filters, which encompasses various impurities as mentioned above, is the major concern to the environmental point of view. This residual dust (or settled sludge) from scrubbers is unsuitable for recycling and has to be discarded. As a result, environment may be impacted by the disposal of such impurities without considerations of environmental impact.

Figure 3.11 (section 3.6) provides further explanations on how these impurities are generated and released to the environment.

Semi-closed and open furnaces

In these two processes, dust and carbon dioxide (CO₂) are experienced due to burning of carbon monoxide (CO). Open furnaces are the most common type, and also have the highest potential for chromium- containing particulate emissions (U.S. EPA, 1984).

Smelting procedures

As stated earlier, fine ore has to be pre-treated (agglomerated) to have certain size and strength to withstand smelting process. Lumpy ore is more expensive compared to fine ore. The reasons for expensive lumpy ore are:

- Can be directly charged into this process (smelting process) without pelletising and sintering.
- Most of the world chromite ore is in the fine form.
- Lumpy ore is very scarce.

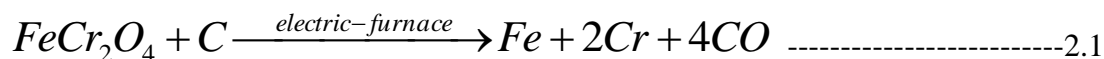
Depending on the raw material that is used, the production of ferro-alloys can be carried out as a primary or secondary process. The principal chemistry of both processes can be shown as follows:

Primary processes

Simple chemical reaction process is as follows:

- Metal oxide + Reductant + (energy) \longrightarrow (ferro) metal + Reductant oxide

The following equation account for this process:



The net result of chemical reaction is that carbon combines with oxygen from the ore to form carbon monoxide (CO) and carbon dioxide, CO₂, gases that evolve from the melted mixture leaving an iron-chromium rich melt (ferrochromium) covered by a slag (see **Figure 2.5**) containing other residual materials (Hattingh and Friend, 2003).

Under this aerobic reaction conditions, it can be seen that CO-gas is released and is used as energy provider in the process. Other possible slag additives that can be expected in this process are:

- Bauxite (Al₂O₃•2H₂O) (impure hydrated aluminium oxide).
- Olivine ((Mg, Fe)₂SiO₄).
- Limestone (CaCO₃).
- Calcite. Calcite is the primary mineral component of limestone and has the same chemical formula as limestone.

Above-mentioned additives are fluxes used in arc-furnace which react with the undesirable gangue material/impurities and also remove ash slag.

Secondary processes

Simple chemical reaction applies:

- Metal scrap + iron scrap \longrightarrow ferro-metal alloy.

Ore fines of chromite can only be charged into smelting arc furnace without prior agglomeration, if direct current (D.C.) arc technology is applied.

The arc furnace (D.C.) uses two graphite electrodes acting as the cathodes and the base as anode (see **Figure. 2.5** below).

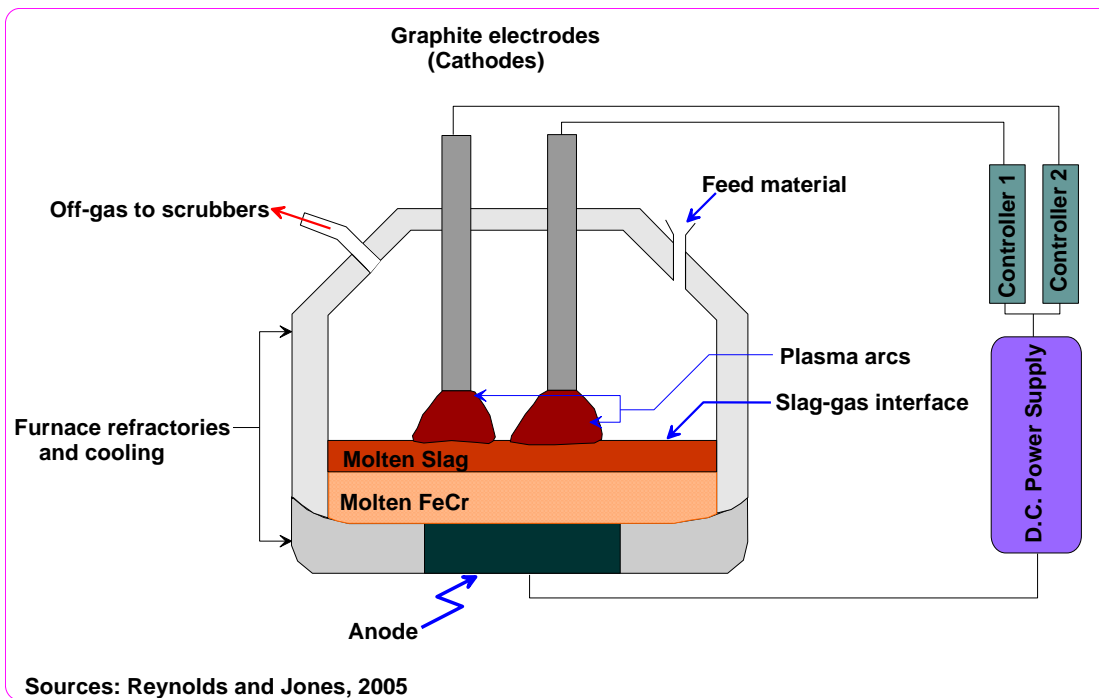


Figure 2-5: D.C. arc furnace (twin-electrode furnace)

Investigations on twin-electrode furnace by Reynolds and Jones (2005) indicated that the two electrodes produce a single arc at the centre of the furnace, reducing wear of sidewall refractory linings and ensuring that scrap falls into the hot spot and melts rapidly. However, there are also D.C. arc furnaces that use a single central hollow graphite electrode.

During the submerged electrode arc-smelting process, the chromite ore is blended with carbon-rich material (reductants) and fluxes (dolomite, quartz etc) to produce the feedstock (Hattingh and Friend, 2003).

The most important process in smelting is the carbothermic reduction process. The major role of carbothermic reduction process is the extraction of impurities (gangue) found in chromite ore.

Smelting of chromite ores and concentrates is dominated by the electric submerged arc furnace and it has become entrenched as the recognized production unit for ferrochromium alloys (Vanhanen, 1999). Smelted products (ferrochrome) settle at the bottom of the furnace and the slag floats on top of ferrochrome (see **Figure 2.5** below). Generally, ferrochrome contains 50-55% chrome, 7% of carbon and 3-5% of silicon. The solid products obtained from smelting ferrochromium are metal, slag and dust. The dust is scrubbed in a venturi system and is produced as slurry or filter cake.

An effective monitoring for the charge composition, sizing and slag composition are very important for effective operation of submerged arc furnace. In this process chromite is reduced both in solid and liquid form.

2.3.5. South African ferrochrome processing

Although different ferrochromium production methods are applied; in South Africa, the submerged electrode arc smelting process is mainly used (Hattingh and Friend, 2003).

About 85% of the ore in South Africa, goes to ferrochrome smelters, and the remainder is exported (Coakley, 2001). One of the uses of chromium is metal finishing for its versatile corrosion prevention.

A detailed South African ferrochromium process from study case has been outlined in chapter, sub-section 3.5.3.

2.3.6. Reductants used in ferrochrome process

As mentioned earlier, the dominating reductants in the ferroalloy processes are various types of coke, coal, charcoal and wood chips. Metallurgical coke, of the same type used in blast furnaces, is the most common reductant in the ferrochrome process.

During the submerged electrode arc-smelting process, the chromite ore is blended with carbon-rich material (reductants) and fluxes (quartz, dolomite, etc) to produce the feedstock. The feedstock is fed into an electric-arc furnace where it is melted (Papp, 2000).

The smelting process uses electrical energy to melt the feedstock, raising the melt to a temperature at which the mixture will chemically react. The net result of the chemical reaction is that carbon (C) combines with oxygen (O) from the ore to form carbon monoxide (CO) and carbon dioxide (CO₂) gases that evolve from the melted mixture leaving a Fe-Cr rich melt (ferrochromium), as well as a slag (waste material) containing other residual materials (Hattingh and Friend, 2003). Since ferrochrome is heavier than slag, it will settle at the bottom and slag will float on top (see **Figure 2.6** below).

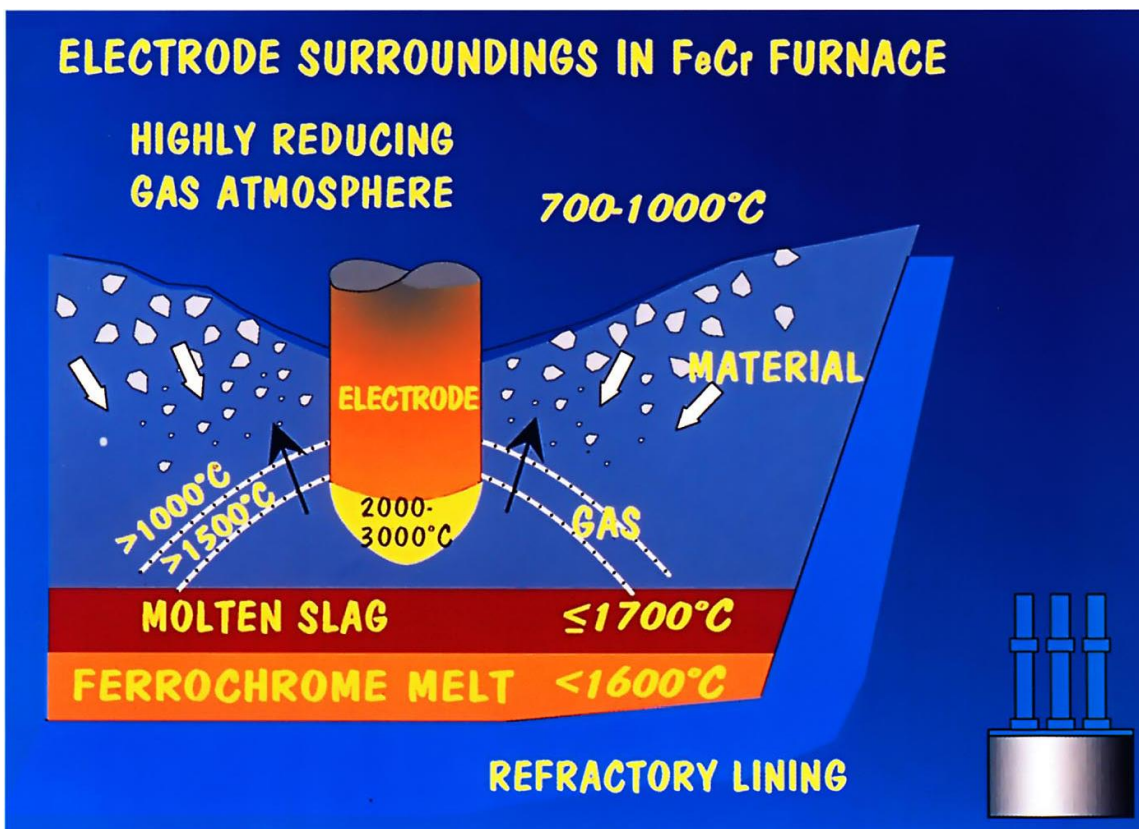


Figure 2-6: Inside submerged arc furnace (Vanhanen, 1999)

The smelting process produces ferrochromium, slag and CO-gas, depending on the type of furnace. The next chapter provides more detailed information on the ferrochrome process, type of furnaces, all gas emissions and slag composition and their impact to the environment.

2.3.7. FINAL PRODUCTS OF FERROCHROMIUM PROCESS

The smelting process produces ferro-metal, slag and CO-rich off-gas. As mentioned earlier, CO-rich gas is utilized in the closed arc furnace as the energy supply and mitigates the consumption of electricity. However, other gases such NO_x, SO₂ and CO₂ are scrubbed off by wet gas scrubbers and released into the scrubber ponds.

The main final products of ferrochromium process are as follows:

- Ferrochrome
- Slag
- Slurry/filter cake/fine dust in open arc furnace

Groundwater implications and concerns lie over chromite slurry and slag. The disposal of the two products (non-recovery slag and slurry) needs a very careful environmental assessment.

Hydrogen and sodium cyanides can be produced during the heating stages in a furnace. Sodium cyanide can be converted at high temperatures in the presence of carbon oxides into sodium carbonate (IPPC, 2003).

2.3.8. Effect of ferrochromium ratio on slag production

The ratio between chrome and iron in the ore controls the chrome content in the metal. In normal ores, the ratio can vary between 1.5 and 3.5. The low ratio ores are used for producing charge chrome with a chrome content of 50–60 %. For producing high carbon ferrochrome, with 4–6 %C and 65–70 % Cr, ores with higher ratios are used. Investigation done by Vanhanen (1999) further states that, ratio of greater than 3 ores can be used for producing low carbon ferrochrome. A table (**Table 2.4**) with ferrochromium ratio has been established in order to classify South Africa's slag production quantity.

Generally, South Africa produces high carbon ferrochrome as it can be seen by its low ratio (ratio = 1.55) in table 2.3. The special name for this type of ferrochrome (high carbon ferrochrome) is called “ferrochrome carburé”

Table 2.4: The composition of ores from different origins (Vanhanen, 1999)

Origin country	Cr ₂ O ₃	FeO	SiO ₂	MgO	Al ₂ O ₃	CaO	P	Cr:Fe Ratio
Kazakhstan	50	12.1	6.6	19.2	6.8	0.2	0.002	3.62
South Africa	39.5	22.4	8	11.2	14.4	1	0.004	1.55
Zimbabwe	48.5	11.6	6.1	14.8	12.3	1.8	0.002	3.68
Turkey	47	12.9	7.8	19.4	10.2	0.8	0.001	3.2
India	49.5	14.5	6.5	15.5	11	0.2	0.007	3
Albania	43	11.6	10.5	22	7.3	0.2	0.002	3.25
Finland	27.2	12.2	17.7	18.4	10.1	1.9	0.004	1.51
Philippines	32.1	12.8	4.6	17.5	30	0.6	—	2.2

The amount of slag production produced in smelting process is determined by the ratio between chromium/iron oxides and other oxides such as silicon dioxide (SiO₂), magnesium oxide (MgO) and aluminium oxide (Al₂O₃). The lower the ratio, the higher the slag production. High slag production is not only a problem to groundwater system but also in smelting process because more energy is required.

From **Table 2.4** above, South Africa, categorically, falls on second lowest in chromium and iron (Cr: Fe) ratio. This implies that the country (South Africa) has a high production of slag due to lower ratio observed from above table.

2.3.9. THE WORLD PRODUCTION STATUS OF CHROMIUM

The aim of this section is to compare South Africa with the other countries in terms of chromium production. It will also be advantageous to envisage the future trends of production and waste minimization. South Africa alone contributed 44.8 % of the world chrome production in 2000 (Papp, 2002). **Table 2.5** has been compiled to compare South Africa with other countries.

Table 2.5: Chrome production and reserves in kilotonnes (USGS, 2000)

Countries	Mine production			Reserves	Reserve base
	1995	1996	2000	(shipping grade)	
United States	-	-		-	10,000
Albania	250	250	-	6,100	6,100
Brazil	360	350	589	14,000	23,000
Finland	610	600	628	38,000	46,000
India	1230	1,100	1947	27,000	67,000
Iran	129	100	153	2,400	2,400
Russia	151	150	92	4,000	460,000
South Africa	5,100	5,000	6,662	3,100,000	5,500,000
Kazakhstan	2,400	2,400	2620	320,000	320,000
Turkey	800	800	562	8,000	20,000
Zimbabwe	631	600	652	140,000	930,000
Other countries	368	350	842	29,000	37,000
World total (may be rounded)	12,000	12,000	14866	3,700,000	7,500,000

The two largest chromite ore producers, accounting for about two-thirds of world production are South Africa and Kazakstan.

South Africa has been the major supplier of chromite ore to Western industrialized countries (USGS, 1997). According to **Table 2.5** above, South Africa, contributes approximately 73% of the world chromium reserve.

This implies that, increase in mining of chromite ore and production of ferrochrome is expected in future. It is therefore, expected to have environmental concerns related to groundwater pollution, if no reasonable measures or adequate environmental protection measures for slag disposal.

Environmental awareness and protections measures including effective remedial approaches need to be increased as to mitigate environmental pollution from abovementioned industries' activities. Furthermore, alleviation of groundwater pollution by heavy metal such as chromium requires a geochemical knowledge of chromium within the groundwater systems.

2.3.10. Behaviour of chromium in the environment

observations, Hansel et al., (2003) has concluded that the process can be considered as biotic-abiotic reaction pathways (see **Figure 2.7** below).

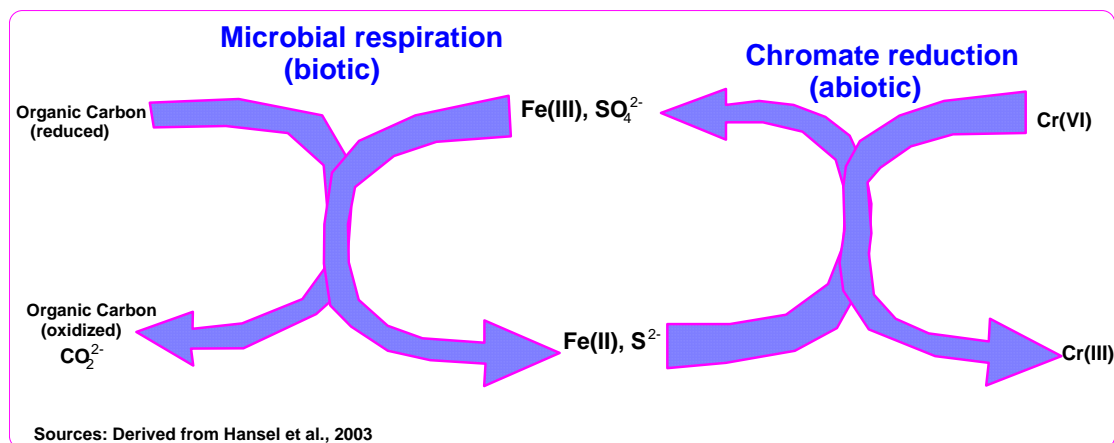


Figure 2-8: Redox cycling of iron (Fe) and sulphur (S) in natural attenuation (Hansel et al., 2003)

In this process, Fe(II)(aq) or H₂S is produced during microbial respiration, which catalyzes the reduction of hexavalent chromium. Microbial activity has an indirect but crucial bearing on hexavalent chromium cycling because the generation of Fe(II) and sulphide hinges upon microbial respiration of Fe(III) and sulphate. Redox cycling of Fe and sulphur can be driven by microbial respiration, which can lead to chromate reduction (Hansel et al., 2003).

The overall ideas of **Figure 2.8** above, is the representation of chromium reduction via cycling of iron (Fe) and sulphur (S) enhanced by microbial respiration which can be considered as natural attenuation.

Therefore, identification of specific reductants within the aquifer is warranted. Other reactive minerals having capability to reduce Cr(VI) and also containing ferrous iron are:

- **Biotite** → K(Mg,Fe)₃(Al,Fe)Si₃O₁₀(OH)₂. ferromagnesian silicate group
- **Ilmenite** (*Iron Titanium Oxide*) → FeTiO₃.
- **Smectite** → (½Ca,Na)(Al,Mg,Fe)₄(Si,Al)₈O₂₀(OH)₄nH₂O.
- **Magnetite** (iron oxide) → Fe₃O₄.

The above chemical formula (Fe₃O₄) is simplified in empirical formula Fe²⁺Fe³⁺₂O₄. Meaning that we have both ferric (Fe³⁺)(2 moles) and ferrous iron (Fe²⁺) in magnetite(Fe₃O₄).

- **Hematite** → Fe₂O₃
- **Chlorite** → (Fe, Mg, Al)₆(Si, Al)₄O₁₀(OH)₈.

The abovementioned minerals, contain iron in their chemical formulae and possibly may release or generate ferrous iron responsible to reduce chromates via hydrolysis (mixing with water, HO⁻) process (Zachara et al., 2003). However, if that ferrous iron is initially incorporated into unreactive solid phase, then, there may be no effect on reduction of chromate (CrO₄²⁻).

The implication to groundwater is that coated ferrous iron will not react or reduce chromated to Cr(III). The result of unreacted ferrous iron is that Cr(VI) will still be mobile in groundwater and the plume will extent further.

2.4. RISK ASSESSMENT

Risk assessment refers to the technical, scientific assessment of the nature and magnitude of risk and uses a factual base to define the health effects of exposure of individuals or populations to hazardous contaminants and situations (CCME, 1996a).

Since impact and risk of chromium to biodiversity depends on inter-conversion between trivalent and hexavalent form, it is essential to focus on their oxidation states through ground water systems.

Receptors of chromium pollution have been identified and discussed in chapter 3 (section 3.11). Risk assessment can be classified into following components (NRC, 1994):

- Hazard identification.
- Exposure assessment.
- Risk characterization.
- Toxicity assessment.
- Dose-response assessment.

The emphasis on the above components depends on goals required to achieve. Most of the goals are concerned over legitimate risk levels, required by the authorities as guideline levels. It was therefore decided that the risk performed in this study should be more based on South African Drinking Water Standards 241 SANS (2001 & 2005).

2.4.1. Hazard identification

"Hazardous Waste" is waste that has the potential, even in low concentrations, to have a significant adverse effect on public health and the environment because of its inherent toxicological, chemical and physical characteristics (DWAF, 2005). Data collection and evaluation are very important for hazard identification.

Hazard identification of a given substance is an informed judgment based on verifiable toxicity data from animal models or human studies. However, a guideline for hazardous waste disposal (from DWAF, 1998 & 2005) has been utilized in this study to identify the hazardousness of chromium to both human health and the environment.

With the aid of literature and guidelines for hazardous waste disposal, chromium has been classified as a hazardous waste substance.

Hazardous properties include (EPA, 1992):

- Ignitability.
- Corrosivity.
- Reactivity.
- Toxicity (determined by the extraction procedure).
- Radioactivity.
- Infectiousness.
- Phytotoxicity.
- Teratogenicity.
- Mutagenicity.

However, there exist some similarities with regard to the properties listed by EPA (1992) with those listed by DWAF (1998).

2.4.2. Exposure assessment

An exposure assessment is the determination or estimation (qualitative or quantitative) of the magnitude, frequency, duration, and route of exposure for each potential or actual receptor population to be evaluated in the risk assessment (RAIS, 1999). During the exposure assessment, the risk assessor:

- characterizes the exposure setting to identify the potentially exposed receptors, their activity patterns, and any other characteristics that might increase/decrease their likelihood of exposure;
- identifies exposure routes (develops a conceptual site model) and scenarios;
- exposure frequency;
- duration of exposure;
- intensity of the contaminant;
- estimates the exposure concentration; and
- calculates a chemical-specific intake or dose.

People working in the wood preservative may also be exposed to chromium by chemical preservative such as chromium copper arsenate (CCA) compound. Chromated copper arsenate (CCA) is an inorganic chemical used to preserve wood. It is believed that this type of chemical can be dislodged from wood. Therefore workers dealing with this type of wood (wood preserved under CCA) can be directly exposed to chromium.

It is well established that both inorganic arsenic compounds (such as arsenic

pentoxide) and sodium dichromate can produce serious adverse health effects, in particular cancer, and both are regarded as human carcinogens (DEFRA, 2003). Risk exposure to human mainly occurs when the operation of the process is uncontrolled. Nonetheless, human health is mainly exposed to chromium by drinking Cr-contaminated water from borehole, dam or streams.

2.4.3. Risk characterization

Generally, a baseline risk assessment is conducted to characterize the current and future potential threats to human health and the environment that may be posed by hazardous substances, pollutants, and contaminants at a site (EPA, 2002).

This implies that information from site characterization and exposure assessment is integrated as to determine the probability of human health being endangered by the contaminant.

Chromium is believed to be relatively soluble, mobile and toxic to living organisms in the forms of chromate (CrO_4^{2-}), hydrochromate (HCrO_4^-) and dichromates ($\text{Cr}_2\text{O}_4^{2-}$). Pedersen (1997) emphasizes that risk characterization finalizes phases of the health risk assessment process. These phases are as follows:

- Hazard Identification.
- Dose-Response Assessment.
- Exposure Assessment.

After integration of all information obtained about contaminant and demographic/epidemiological studies (including human population, average body weight and intake) a permissible concentration can be calculated. Permissible concentrations for chemicals in the environment are calculated based on body weight, intake, frequency and duration of exposure, and the Reference Dose (RfD). Permissible concentration is given by the following equation (Pedersen, 1997):

And this equation can be expressed mathematically as:

$$P_c = \frac{RfD \times B_w}{I_t \times D_t \times F_q} \text{-----2.1}$$

Where:

P_c = Permissible Concentration

RfD = Reference Dose

B_w = Body weight

I_t = Intake (food or drinking water)

D_t = Duration

F_q = Frequency

If sufficient data has been collected, permissible concentration can be calculated using the above equation 2.1.

2.4.4. Route of chromium exposure to human

The routes for hexavalent chromium that enters the human body are: air (breathe), food intake and drinking water contaminated by chromium. Chromium, particularly Cr(VI), being classified as hazardous substance (according to SABS Code 0228 hazard classes) may need to be re-analysed for its residue after a pre-treatment (DWAF, 1998) and ultimately the following must be determined:

- Toxicity,
- Ecotoxicity,
- Mutagenicity,
- Teratogenicity,
- Persistence,
- Environmental fate and
- Estimated Environmental Concentration (EEC) of waste to be disposed.

Estimated Environmental Concentration (EEC) is the amount of the substance that is available to man and the environment and also represents exposure in a body of water (aquifer) because it is believed that the pathway for the escape of contaminant in waste is water (DWAF, 1998). In groundwater, possible escape of a substance in waste is usually water and EEC will then be assessed with regard to a body of water. DWAF (1998) further provides that EEC is used to:

- Determine the amount of a substance in the waste that can be disposed of at a landfill per hectare per month
- Determine the total amount of a substance that can be of at a landfill before the site must be closed for total load
- Assess whether, after treatment or test, a waste can be reclassified to fall into a lower Hazard Rating or disposed of at a general waste site approved by the Competent Authority

After calculation of EEC, the results are compared with Acceptable Exposure to indicate whether either the aquatic environment or human health will be at risk. Nevertheless, this research focuses mainly on groundwater.

Estimated Environmental Concentration (EEC) and toxicological hazard of the substance are determined as the major components in Hazard Rating. Toxicological hazard relates to the chronic toxicity which represents specific effect or response (DWAF, 1998). The following terms have relevance to the toxicological hazard of a substance:

- Lethal concentration (LC_{50}) and
- Lethal Dose (LD_{50})

Lethal concentration (LC_{50} , in mg/kg) is the abbreviation used for the exposure concentration of a toxic substance lethal to half (50%) of the aquatic tested animals, also known as acute ecotoxicity of substances in waste, expressed as LC_{50} (mg/kg).

LD_{50} Lethal Dose (LD_{50}) is the abbreviation used for the dose which kills 50% of the test population, also called acute mammalian toxicity of substances in waste, expressed as LD_{50} mg/kg. These two parameters are used to quantify the results of different tests so that they may be compared. However, the preceding terms (EEC, Hazard Rating and LC_{50}) are more relevant when performing risk assessment.

Based on health effects studies done by World Health Organization (WHO) (1988), chromium route of exposure occurs in the following ways:

- Inhalation exposure
- Oral exposure
- Dermal exposure

Although the abovementioned exposure will form part of detailed risk assessment, are not covered in this study as it mainly focuses on groundwater pathway and exposures

2.4.5. Human health risk assessment

Human health risk assessment can be referred to as the evaluation of probability (the likelihood and severity) of adverse health consequences, and accompanying uncertainties factors, to humans caused by the presence of chemical (either at solid, aqueous or gaseous state) at a given site . Since Cr(VI) is a very strong oxidizing agent in body cells, it is therefore expected to be toxic to human being. As mentioned earlier, the entry routes of chromium into the human body are inhalation, ingestion, and dermal absorption.

Occupational exposure generally occurs through inhalation and dermal contact, whereas the general population is exposed to chromium most often by ingestion through chromium content in soil, food, and water (ATSDR, 2000). The following figure (**Figure 2.9**) represents a conceptual model of risk assessment exposure to human health and its effects.

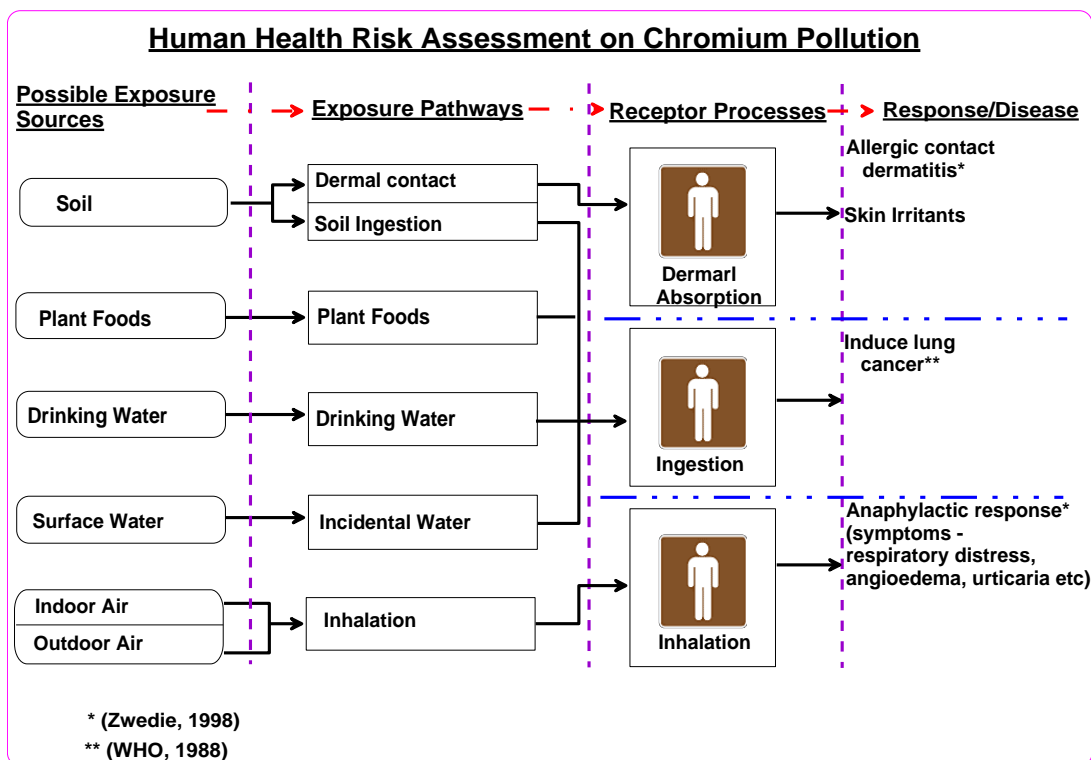


Figure 2-9: Schematic representation of human health exposure assessment

From the above figure, the following information is relevant:

- Human health is exposed to chromium through:
 - Soil
 - Drinking water
 - Surface water (when comes to contact with skin (e.g. bathing))
 - Plant foods
- Exposure pathways are:
 - Dermal contact
 - Soil ingestion

- Children and adults are directly exposed to chromium in soil when they consume soil that has adhered to their hands (EPA, 1998). It may sound unfamiliar to others, but some women, particularly in black community in South Africa, tend to eat soil, particularly at their pregnancy stages.
- Soil ingestion rates in children are based on studies that measure the quantities of non-absorbable tracer minerals in the feces of young children. Indoor dust and outdoor soil may both contribute to the total daily ingestion (EPA, 1998).

Risk assessment related to human health should be performed with considerations of exposure assessment. Felter and Dourson, (1997) also maintain that the following routes have relevance to human exposure:

- Dermal
- Oral (Ingestion of food crops (edible vegetation))
- Inhalation:
 - There is insufficient evidence that indicates the concern about airborne pollution of chromium. The World Health organization (WHO), (1988) has also demonstrated that general population living in the vicinity of ferro-alloy plants and exposed to ambient air concentrations of up to 1 $\mu\text{g}/\text{m}^3$ did not show increased lung cancer mortality.
 - However, worker working inside the plant may be affected by chromium in the air or by direct contact during working.

For most people eating food that contains chromium(III), it is the main route of chromium uptake, as chromium(III) occurs naturally in many vegetables, fruits, meats, yeasts and grains. Various ways of food preparation and storage may alter the chromium contents of food. When food is stored in steel tanks or cans chromium concentrations may rise (Enzler, 2005).

2.4.6. Response to health effects from chromium

Similarities existing between human being and certain animals such as rats make it possible to conduct experiments on these animals (rats) and extrapolate the results to humans. Pedersen (1997) and Daugherty (1992) confirm that some animals exhibit a specific type of response and distribution patterns that are very similar to humans. In the absence of human data, it is assumed that effects observed in animals have the potential to occur in humans.

Results obtained from animal studies play pivotal role in terms of predicting response of human being to a certain ingested, inhaled or contacted chemical. Animal studies provide quite precise information about the adverse response to a substance because the studies are controlled in a lab.

After determining the critical Non-Observed Adverse-Effect Level (NOAEL) the dose is extrapolated to humans with the assumption that humans can be 10 times more sensitive than the most sensitive study species. Scientifically, a defensible dose-response relationship for end points of concern is applied. In most occasions, the end points in human being are as follows:

- Respiratory organs (e.g. lungs).
- Urinary system (e.g. kidneys).
- Immune systems.

Dose-response relationship demonstrates relationship between the amount of concentration exposed and the proportion of specific biologically significant changes in incidence and/or in degree of changes (EPA, 2005). It is therefore, likely that a dose response assessment be conducted. Dose response assessment to chromium will incorporate but not limited to the following:

- The amount of concentration that is to be exposed daily (i.e. reference concentration (RfC)).
- Lethal dose.
- Response/diseases.
- Target organs (end-points).

A generic form of explanation for the response of human health related to the increased dose has been established in **Figure 2.10** below. A class 0 (ideal) concentration of 0.05 mg/L, guideline for South African Drinking Water Standard (2001), has been used to assess the dose response curve in **Figure 2.10** below.

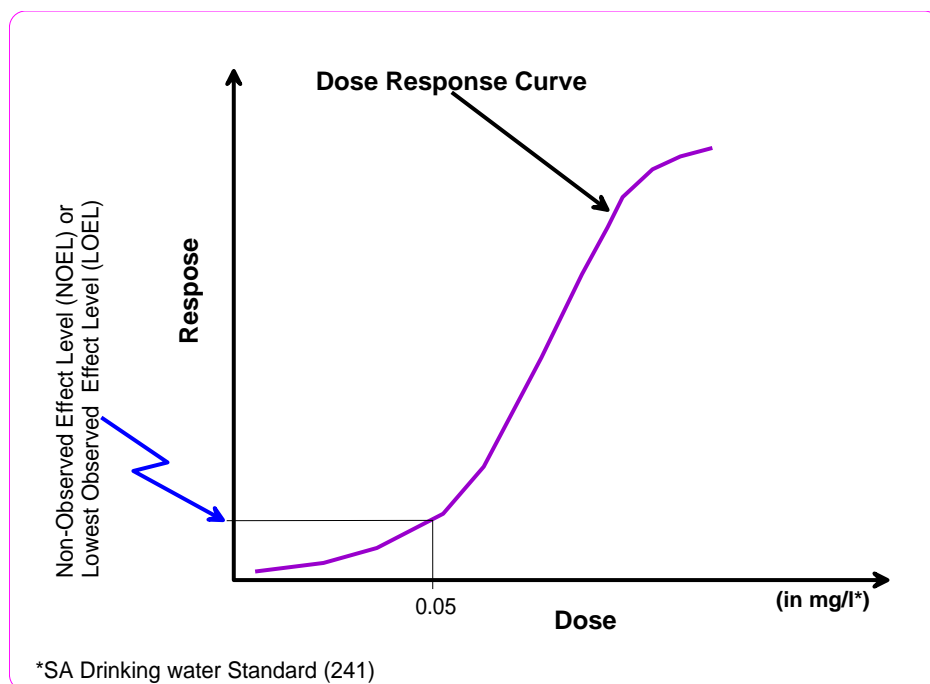


Figure 2-10: Generic representation of chromium Dose Response Curve

The response to dose exceeding the recommended maximum values will be manifested by certain diseases depending on target organs. Although, concentrations (dose) between 0.05 and 0.1 mg/l are still acceptable to human consumption, it can, however, start to cause environmental and human health problems if exposed to a very long period (in years). Maximum allowable (Class II) dose of between 0.1 and 0,5 mg/l can be consumed for a period of not more than 3 months according to South African Drinking Water Standards-SANS: 241 (2001).

Permissible concentrations are calculated and set as standards based on the Oral Reference Dose (RfD). However, it must be explicitly stated that the dose must have a Non-Observed Adverse-Effect Level (NOAEL) or Lowest Observed Effect Level (LOEL). Therefore, RfD is calculated with the consideration of uncertainty factors and focusing on hypersensitive individuals.

A chronic oral reference dose (RfD) of 0.003 mg chromium(VI)/kg/day has been derived and verified by EPA for soluble salts of chromium(VI) (e.g., potassium chromate, sodium chromate, potassium dichromate, and sodium dichromate) (ATSDR, 2000). Mackenzie et al. (as cited in ATSDR, 2000) concludes that this RfD, is based on a NOAEL for systemic effects in rats exposed to 2.5 mg chromium(VI)/kg/day as potassium chromate in the drinking water for 1 year.

2.4.6.1. Acute toxicity

Most of acute effect by chromium involves hexavalent chromium compounds.

Short-term, high level exposure to Cr (VI) produces irritation at the site of contact, including ulcers of the skin, irritation of the nasal mucosa, perforation of the nasal septum, irritation of the gastrointestinal tract, impairment of olfactory sense, and discoloration (yellowing) of teeth and tongue (ATSDR, 2000).

Compounds containing hexavalent chromium are responsible for the acute toxicity. This is confirmed by a 14 year old boy who has been reported dead after 8 days of administering (ingesting) approximately 1.5 g of potassium dichromate (WHO, 1998).

Acute toxicity of chromium has been reviewed by the World Health Organization (WHO, 1988). In adult human, the lethal oral dose is considered to be between 50 – 70 mg soluble chromates/kg body weights.

2.4.6.2. Chronic toxicity

Generally, population is exposed to chromium by eating food or food supplements, drinking water, and inhaling air that contain chromium (ATSDR, 2000). World Health Organization (1988) suggests that doses of hexavalent chromium greater than 10 mg/kg diet affect mainly the gastrointestinal tract, kidneys, and probably the haematopoietic system.

The following chronic inhalation for reference exposure levels in **Table 2.6** has been established (OEHHA, 2000)

Table 2.4.6: Chronic Inhalation RELs – Batch 2A (OEHHA, 2000)

Substance	Chronic REL ¹ (µg/m ³)	Hazard index target(s)
Chromium, hexavalent: soluble compounds except chromic trioxide	0.2	Respiratory system
Chromic trioxide (as chromic acid mist)	0.002	Respiratory system

¹Chronic Reference Exposure Levels

2.4.6.3. Oral risk assessment

Chronic human exposure to high levels of chromium (VI) by inhalation or oral exposure may produce effects on the:

- Liver
- Kidney
- Gastrointestinal tract
- Immune systems, and
- Possibly the blood (ATSDR, 1998).

An experiment tested on rat studies indicated that, following inhalation exposure, the lung and kidney have the highest tissue levels of chromium (U.S. EPA and WHO, 1998). These imply that, the end point of affected body parts are mainly lungs and kidneys. World Health Organization (1998) suggests three aspects for human health exposure assessment:

- Duration
- Magnitude
 - In this case, concentration of chromium is paramount
- Frequency

ATSDR (2000) classifies exposure periods of chromium to human effect into three categories. These three categories are listed in table 2.7 below.

Table 2.7: Categorization of diseases (ATSDR, 2000)

Disease category (severity)	Duration (days)
Acute	14
Intermediate	15 - 365
Chronic	≥ 365

2.4.7. Conclusions

Processes involved in Environmental Impact Assessment and Risk Assessment cannot be accomplished by solemnly specialist (e.g. groundwater consultant) but integration of other specialists with a sound knowledge of the contaminant's property and the type of aquifer in which it interact, is essential. The outcome of a risk assessment is either a set of chemicals, pathways, media, and/or scenarios of concern for which an appropriate action must be undertaken or a determination that no action is required.

2.5. RISK MANAGEMENT

Risk management refers to the development and implementation of a strategy to control, mitigate or manage the risk.

When performing risk assessment all possible alternatives (or information) to mitigate the impact require to be clearly stated. Selected alternatives from risk assessment can be implemented in risk management as to lessen the risk that might be imposed on the environment by chromium. Minimization of the future risk to both environment and human health will include (EPA, 1991):

- Data collection and site history information.
- Processing of gathered information (data evaluation).
- Data review.
- Selection of appropriate and/or reasonable measures (from risk assessment).
- Implementation of all possible strategies.

- Monitoring of the executable strategies.

The process of selection of reasonable measures is similar to the process of decision making. Decision making is the most crucial part in the assessment of the environmental risk management. These decisions will be mostly based on the following:

- A scientific integrity and judgemental approach,
- Severity of the problem,
- Future land use purposes and
- Standard guidelines or protocols required by the legal authorities

Identification of land use purpose is very important when remediation of contaminated sites requires reaching a certain clean up goal. Since, it is almost difficult to revert the contaminated site to the pristine environment, it is therefore, important, to set up clean goals based on the future land use purposes.

It should be clearly stated that, decisions taken after analysis results may not be accurate due to uncertainties.

Therefore, those uncertainties should be explicitly indicated within the documentation process. It is therefore, imperative to have monitoring process of the implemented results as to mitigate an unexpected breakthrough contamination (EPA, 1991). Changes of the chemical property such as re-oxidation of chromium (C(III) to Cr(VI)) may lead to breakthrough of hexavalent chromium contamination.

Risk management should be driven by the degree of conservatism and prioritization of human risk protection. Therefore, selection, evaluation and presentation of scientific results must be done without consideration of issues such as cost, feasibility or political purposes.

Once there is consideration of cost, feasibility and political interests, there might be possible restriction and/or elimination of valuable information. Therefore, reaching the desirable goals will be hampered by the aforementioned factors.

However, the accuracy and significance of the results which leads to the sustainable risk management can be achieved if sufficient and pertinent information (or data) has been collected and analyzed successfully.

The result can be presented and submitted to the risk managers. Risk managers are people responsible for decision making. The risk managers use the results of the risk characterization, other technological factors, and non-technological social and economic considerations in reaching a regulatory decision (EPA, 1991). Thereafter, implementation of the results from risk assessment can take place. However, risk assessment with itself should entail some mitigation alternatives in order to prevent unfeasibility of the implementation process.

2.5.1. Toxicity effect on environment

The toxicity of hexavalent chromium in biodiversity is due to its oxidizing property within the living cell.

Cr is mostly found in trivalent form (Cr^{+3}), but due to weathering of chromite (FeCr_2O_4), trivalent chrome may be oxidized by manganese oxides (MnO_2) (in the presence of moisture) to toxic hexavalent chrome.

Manganese dioxide (MnO_2) is predominant under strongly oxidizing conditions (McKenzie, 1977). According to World Health Organization (WHO) (1998), toxicity in aquatic environment is known to be affected by the following parameters:

- Water hardness,
- The pH,
- Temperature,
- Oxidation state and
- Organism size.

Temperature, oxidation states and the pH are discussed in chapter 3. Alkalinity is believed to be a co-factor for toxicity than water hardness (WHO, 1988). It will be recalled that, chromates mostly exist in high levels of pH or alkaline solutions.

Cooper (2002) further revealed that chromium toxicity has been suspected in ultramafic rocks which comprises of large amounts of total soil chromium. Chromite is present in serpentinized rocks and with less pronounced amount of nickel. Therefore, soils associated with ultramafic or serpentine are generally infertile owing to Cr toxicity.

Experiments performed by Cooper (1978), indicated that maize grown in ultramafic soils has been dehydrated (oxidized). Other symptoms of chromium toxicity to plants (e.g. maize) are stunted growth and purple colour to leaves (Soane and Saunder, 1959).

Cooper (2002) has concluded that any ultramafic subsoil with appreciable clay content and containing high total Chromium is likely to contain labile Cr(III) capable of oxidation to toxic Cr(VI). The toxicity of Chromium in natural soils will possibly depend on wetting-drying cycles and for which, if small amounts of Cr(VI) are produced, it will be negligible to consider soils to be toxic to annual crop.

Anthropogenic sources such as slag dumps and scrubber ponds are possibly the main sources of toxic chromium to subsoil. In fact, poorly drained soils with fluctuating water table may aggravate the situation, because drop of water table lead to air entry (dissolved oxygen) which eventually oxidizes Cr^{+3} to Cr^{+6} . It follows that; a similar oxidation may take place in those anthropogenic sources and lead to toxicity of the soil. Hexavalent chrome concentrations of lower levels as 0.5 ppm in solution and 5 ppm in solid are reported to be toxic to plants (Turner and Rust, 1971; Fendorf, 1994).

Hewitt (1953) explains that during the smelting of chromite, considerable quantities of waste are produced, which contain soluble chromates. Gemmell (as cited in Hewitt, 1953) has observed an inhibition of germination and growth in white mustard plants (*Sinapis alba*) in soils with high pH (waste heaps). Hewitt (1953) also pointed out that the main feature of chromium intoxication is chlorosis, which is similar to iron deficiency.

Therefore, the preceding facts (*inhibition of plant germination & growth and chlorosis intoxication*) are the manifestation of chromium impact on the environment. It is therefore

imperative to assess the presence of manganese on site (Fendorf and Zasoski, 1992) when predicting speciation and hazard of chromium (Fendorf, 1994).

However, in clay minerals or sediments which have greater influence in cation exchange capacity (CEC), it is therefore anticipated that chromium concentrations be reduced and thereby reducing the chromium toxicity. Environmental Protection Agency (US EPA, 1992) attributed to clay effect on toxicity as the function of cation exchange capacity, type and concentration of clay.

It should be clearly emphasized that immobilization of hexavalent chromium within groundwater systems does not alter its toxicity but does, however, decrease the risk imposed to the environment.

2.6. HAZARDOUS WASTE CLASSIFICATION FOR CHROMIUM

Classification of Hazardous Waste requires following all procedures of Minimum Requirements (DWAF, 2005). Minimum Requirements is defined as the minimum procedures, actions and information from the permit applicant before a waste disposal site permit can be issued. A generic approach based on Minimum Requirements procedures has been used to classify chromium hazardousness.

Minimum requirements for the handling, classification and disposal of Hazardous Waste sets out a systematic framework for identifying a hazardous and classifying it in accordance with the degree of risk that it poses to the environment (DWAF, 1998).

Hazardous waste is defined as an inorganic or organic element or compound that, because of its toxicological, physical, chemical or persistency properties, may exercise detrimental acute or chronic impacts on human health and environment (DWAF, 1998).

Hazardous Rating (HR) is normally used to classify Hazardous Waste into four categories:

- Hazard Rating (HR) 1 → Extremely hazardous waste
- Hazard Rating (HR) 2 → High risk hazardous waste
- Hazard Rating (HR) 3 → Moderate risk hazardous waste
- Hazard Rating (HR) 4 → Low risk hazardous waste

2.6.1. Explanation of Hazard Rating groups (DWAF, 1998)

The following are relevant for explanation of Hazard Rating groups:

❖ Hazard Rating 1 (Extreme Hazard)

- ↳ Defined as the waste of first priority concern, containing significant concentrations of extremely toxic substances, including certain carcinogens, teratogens and infectious wastes.

❖ **Hazard Rating 2 (High Hazard)**

- ↪ This is the waste of second priority with highly toxic characteristic or extremely toxic substances, which are not persistent, including certain carcinogens.

❖ **Hazard Rating 3 (Moderate Hazard)**

- ↪ Is a waste of third priority concern, which is moderately toxic or which contains substances that are potentially highly harmful to human health or to the environment but not persistent.
- ↪ Hazard Rating is mainly performed for the classification of an appropriate landfill of a substance.

❖ **Hazard Rating 4 (Low Hazard)**

- ↪ This is waste that often occurs in large quantities and which contains potentially harmful substances in concentrations that in most instances would represent only a limited threat to human health or to the environment.

2.6.2. Determination of Minimum Requirements

Chromium is classified based on its physical and chemical properties. The fate of hexavalent chromium within the environment or groundwater systems is characterized by the following properties:

- Its mobility,
- Very strong oxidizing agent,
- Carcinogenicity and
- Toxicity.

Chromium falls into the following classes (DWAF, 1998):

- **Class 5** (5.1, Oxidising agents)
- **Class 6** (6.1, Toxic substances), based on aforementioned characteristics (physical and chemical properties).

Class 5

Wastes falling in this class are oxidizing substances (i.e. class 5.1). Since hexavalent chromium [Cr(VI)] is considered as a very strong oxidizing agent.

Class 6

This class contains toxic and infectious substances. Hexavalent chromium is toxic to both plants and human life and thus falls into this class. Within class 6 substances, a further subdivision exists, which is as follows:

- Class 6.1 Toxic substance.
- Class 6.1 Infectious substances.

Chromium being a toxic substance as mentioned in the previous sections falls into class 6.1. With regard to this study, there is insufficient evidence to declare chromium either as Cr³⁺ or Cr⁶⁺ as infectious substance (class 6.2). Infectious substances are believed to be pathogenic or contain pathogens

With regard to principle of minimum requirement, substances categorized as oxidizing substances (class 5) must proceed to class 6 after treatment to neutralize oxidation potential.

Furthermore, Hazardous Waste such as hexavalent chromium emanated from mining or industrial processes must be tested against class 6 in order to allocate its Hazard Rating. Hazard Rating suggests taking into account of the following properties prior to exposure:

- Biodegradability.
- Persistence.
- Bioaccumulation.
- Chronic toxicity.
- Concentration.
- Production volume.
- High dispersion.
- Leakage to the environment.

The Department of Water Affairs and Forestry (DWAF) (1998) has established a table which contain a list of hazardous Waste substance. Chromium is one of Hazardous Waste listed in **Table 2.8**.

Thus, Minimum Requirement has classified Hazardous Waste such as chromium in the following manner (see **Table 2.8** below):

Table 2.8: Categorization of diseases (ATSDR, 2000)

Waste stream	Industrial group (source)	SABS 0228 Class/Danger group	HR	Acceptable environ. Risk (ppm)	Disposal Allowed (g/ha/m)	Preferred Technology	Allowed Technology	Unacceptable Technology
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7	Column 8	Column 9
Cr ³⁺	B2	-	3	4.7	7121	RCY	CTR	LWT
Cr ⁶⁺	D4	8(II)	1	0.02	30	RCY	RCR	LWT, pH < 6
Legend								

B2 = Mining Extraction in Mining & Quarrying of Metallic Minerals process.
D4 = Metal Manufacture in Metal Finishing and Electroplating process.
(II) = Danger Group (in brackets)
RCY = Recovery
RCR = Reduction then landfill codispose residues
CTR = Chemical Treatment then landfill codispose residues
LWT = Landfilling without treatment
ppm = Parts per billion
g/ha/m = Gram per hectare per meter

2.6.3. Interpretation of waste classification from table 2.8

Not all columns have been interpreted for classification but selected those related to chromium classification. The following columns were selected:

Column 2 (Industrial group (source))

Two types of industrial groups processing chromium have been established:

- B2 → Mining Extraction in Mining & Quarrying of Metallic Minerals process.
- D4 → Metal Manufacture in Metal Finishing and Electroplating process.

In the perspective of groundwater impact, D4 has more considerably significant impact than B2. It will be recalled that B2 normally produces chromium ore process residue (COPR). However, D4 produces considerable ferrochromium slag and chromate quantities which pose environmental concerns.

Column 5 (Acceptable environmental Risk)

This is the maximum concentration in parts per million (ppm) which cannot be exceeded. This concentration is based on determination of Estimated Environmental Concentration (EEC, in *g/ha/m*). Estimated Environmental Concentration (EEC) is the dose, or amount of a substance that can be disposed off in *g/ha/month* (DWAF, 2005). If EEC exceeds the Acceptable Risk Level (ARL), then that substance must remain in the toxic class. Nevertheless, if EEC is less or equals to ARL then it can be delisted from toxic class. The ARL for Cr⁶⁺ is given as 0.02 mg/l in which most assessed boreholes at the study area showed to exceed this limit.

Column 8 (Allowed Technology)

This is the technology which is believed to successfully lessen or mitigate the degree of substance's hazardousness. Allowed technology must by all possibilities achieve desired state (e.g. immobilization, solid or precipitation) or reach certain level of concentration of a substance in subject. Two technologies which are allowed for chromium clean-up goals are (DWAF, 1998):

- Reduction then landfill co-dispose residues (RCR) for Cr(III).
- Chemical Treatment then landfill co-dispose residues (CTR) for Cr(VI).

The above methods have been utilized in chapter 4 dealing with remedial approaches. However, combinations of methods to achieve improvement were included. This was in line with the requirements of RBCA (tier III).

Column 9 (Unacceptable Technology)

These are technologies that cannot achieve the clean-up goals. The use of unacceptable technologies may increase or accelerate the groundwater pollution (even surface or air pollution, depending on the chemical and unacceptable technology applied). A technology such as Landfilling without Treatment (LWT) is not allowed for chromium clean-up goals.

2.6.4. Landfill Classification for Chromium

According to *Minimum Requirements for the Handling, Classification and Disposal of Hazardous Waste*, published by the Department of Water Affairs and Forestry (DWAF, 1998), chromium [Cr(VI)] compounds are listed as mutagens and carcinogens (class A). Therefore, appropriate measures pertaining to the hazard rating and pre-treatment is a prerequisite prior to chrome disposal in a selected landfill.

After overall minimum procedures, actions and information gathered or performed, an appropriate landfill must be classified. This landfill should be classified with the consideration of all factors such as delisting processes performed in the Minimum Requirement procedures. However, toxic substance (class 6.1) with Hazard Rating 1 or 2 must be disposed at permitted **H:H** sites.

Therefore, landfill disposal suitable for hexavalent chromium (Cr^{6+}) (as toxic substance), according to Hazard Rating classification, can be as follow:

- Hazard Rating 1 (extreme risk) → **H:H** Landfill (permitted)

And for trivalent chromium (Cr^{3+}) can be as follow:

- Hazard Rating 3 (moderate risk) → **H:H or H:h** Landfill (permitted)

H:H landfill is more stringently designed, operated and monitored than an **H:h** landfill (DWAF, 1998).

2.7. SUMMARY

The aim of this chapter was to solicit input all factors to be considered when performing chromium impact assessment. The information gathered in chapter 2 was used to accomplish objectives of this study. DWAF (2005) defines Environmental Impact Assessment (EIA) as an investigation to determine the potential detrimental or beneficial impact on the surrounding communities, flora, fauna, water, soil and air arising from the development or presence of a waste disposal site. Within this chapter, factors such flora, fauna, water, soil and air have been generally assessed and encompasses the EIA requirements.

The Department of Water Affairs and Forestry (1998) has established a principle of Best Practicable Environmental Option (BPEO) → adopted in order to provide affordable environmental protection.

BPEO consists of:

- Waste avoidance.
- Correct classification.
- Minimum requirements for the safe handling, treatment and disposal of hazardous waste.
 - EIA is necessary before landfill is issued with a permit to operate.

3. CHAPTER 3: CASE STUDY

3.1 INTRODUCTION

Production of ferrochrome commenced in 1964 in the town of Middelburg which was produced entirely from South African raw material.

In July 1995 *Company A (main study area)* started to produce Low Carbon Ferrochrome and Ferrosilicochrome. In 2005, *Company A* has merged with *Company B* to have a full strength of ferrochrome production which made them to be the world leaders in chromium alloy technology. They supply approximately 10 per cent of world's ferrochromium needs. United States, Western Europe, Japan and South Africa are amongst the countries which provide the bulk production of stainless steel such as ferrochromium.

3.2 STUDY AREA

3.2.1 REGIONAL SETTING

The study area is situated about 5km south-east of Middelburg town in South Africa and also in the Quaternary Sub-Catchment B12D (WRC, 1990) and B12C. Middelburg falls within the Steve Thswete Local Municipality in the Mpumalanga Province (see **Figure 3.1**)

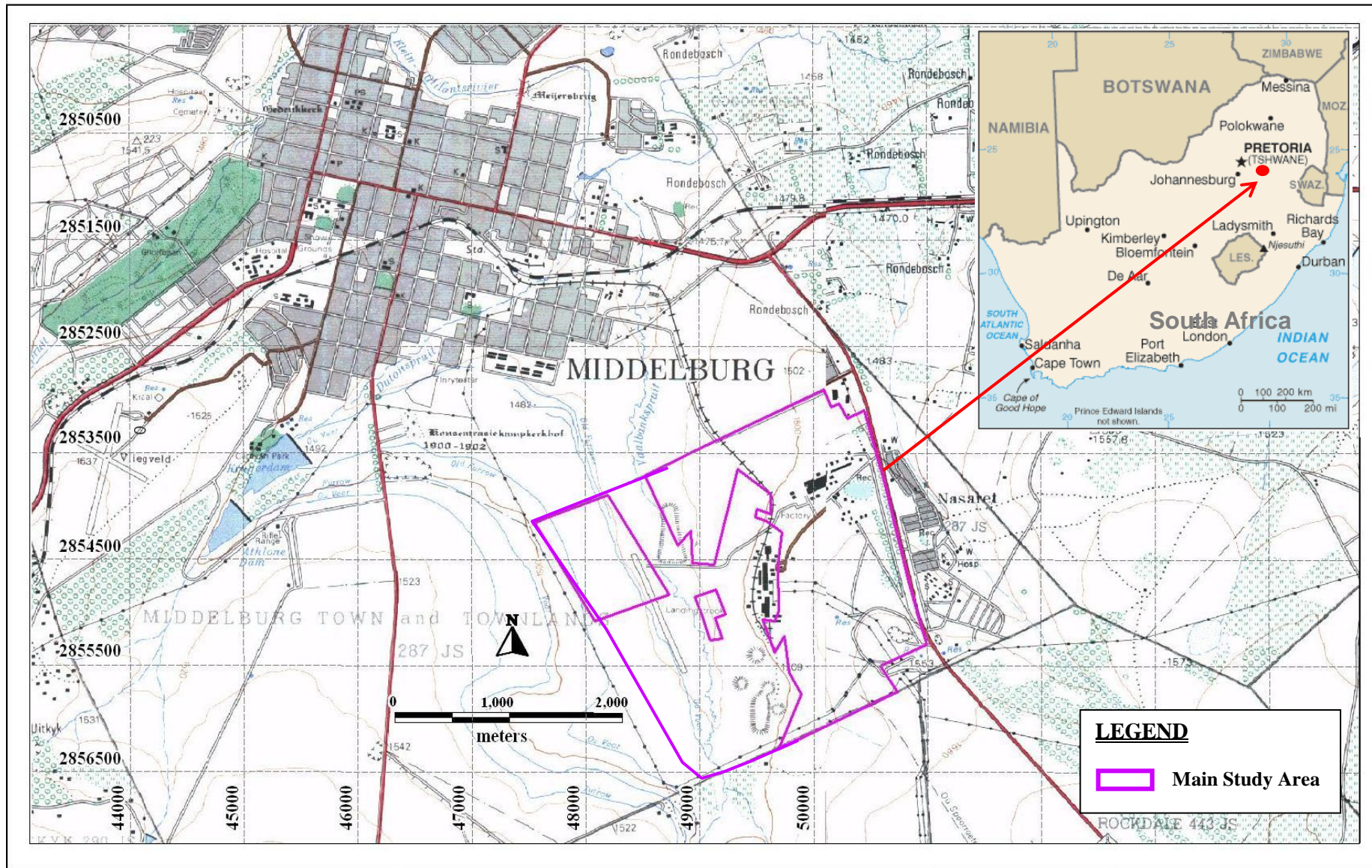


Figure 3-1: Regional topographical map of the study area

3.2.2 TOPOGRAPHIC SETTING

Figure 3.2 below indicates the site layout. Indicated in the layout of the study area on an aerial photo

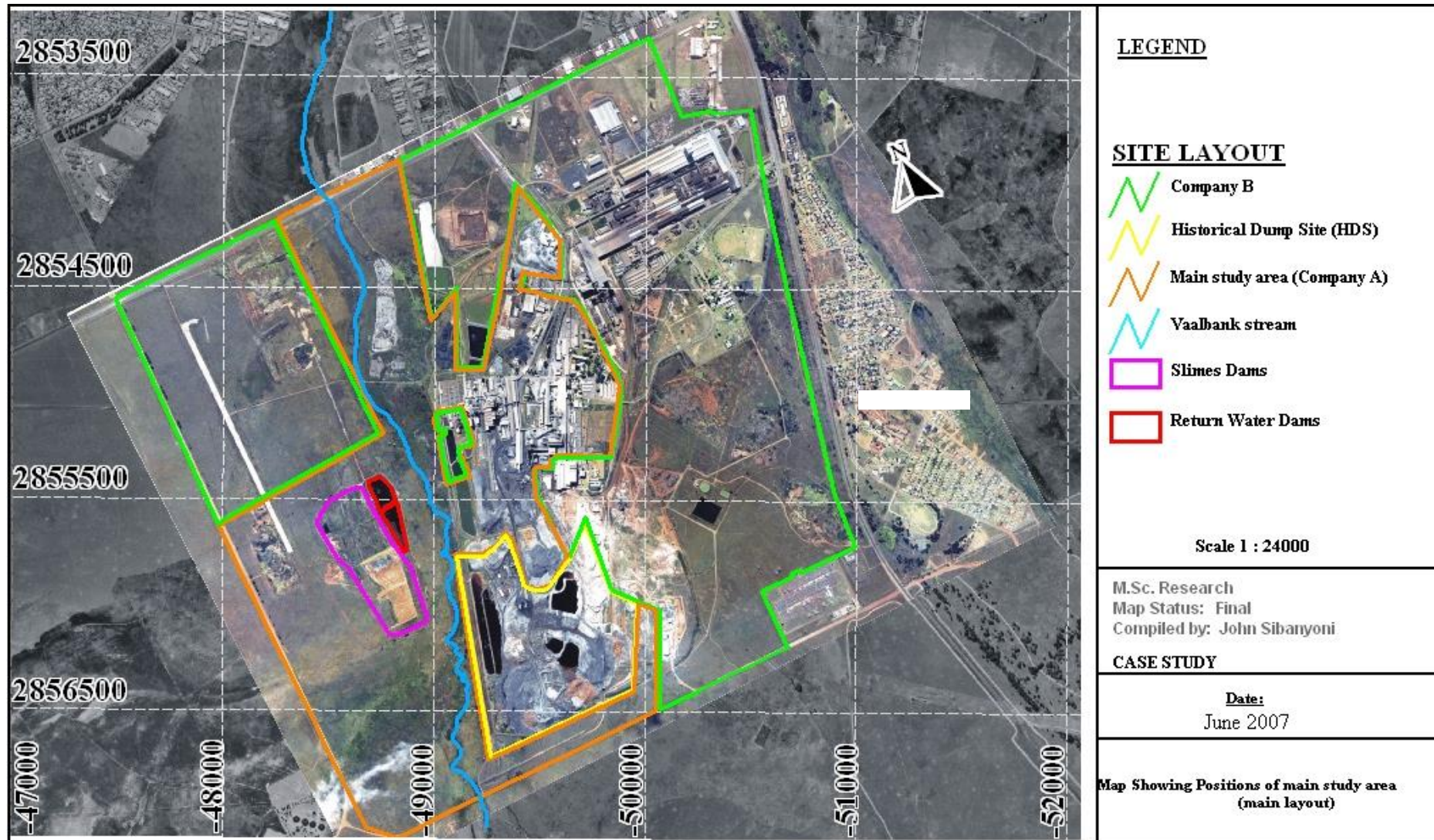


Figure 3-2: Local aerial photo map of the study area

The site is almost flat on top the western part is sloping to north-western side and part of the eastern part is sloping to north-eastern side (see **Figure 3.3** below).

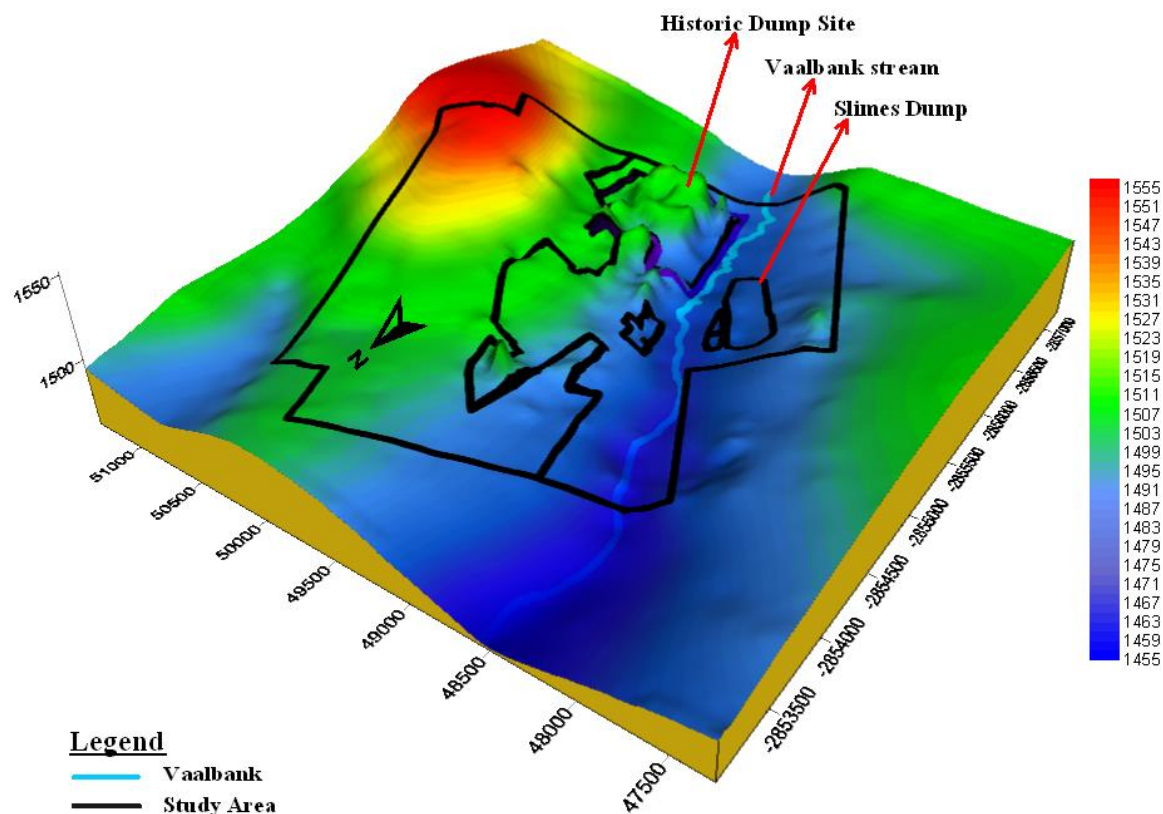


FIGURE 3-3: Topographical (3D) map showing surface contour lines and Vaalbank stream

3.2.3 METEOROLOGY

The climatic data give on this section are based on the availability of data obtained from Weather South Africa (WeatherSA). The major climatic components obtained during the study were:

- Rainfall
- Temperature

Evaporation for the study area is between 1500 and 1600 mm (WRC, 1990).

Temperature

Data for both averages of monthly rainfall and temperature (max & min) was plotted to observe the pattern of rainfall in the region against minimum and maximum temperatures. It was observed that events of rainfall regionally follow the pattern of temperature and more especial the maximum temperatures recorded throughout the year. It was also recorded that during winter (June and July) the area receives lowest rainfall while high rainfalls are observed in summer (Nov, Dec and Jan). Unfortunately weather station, WS_0516076 7 was closed in 1998 which is the reason to have limited data.

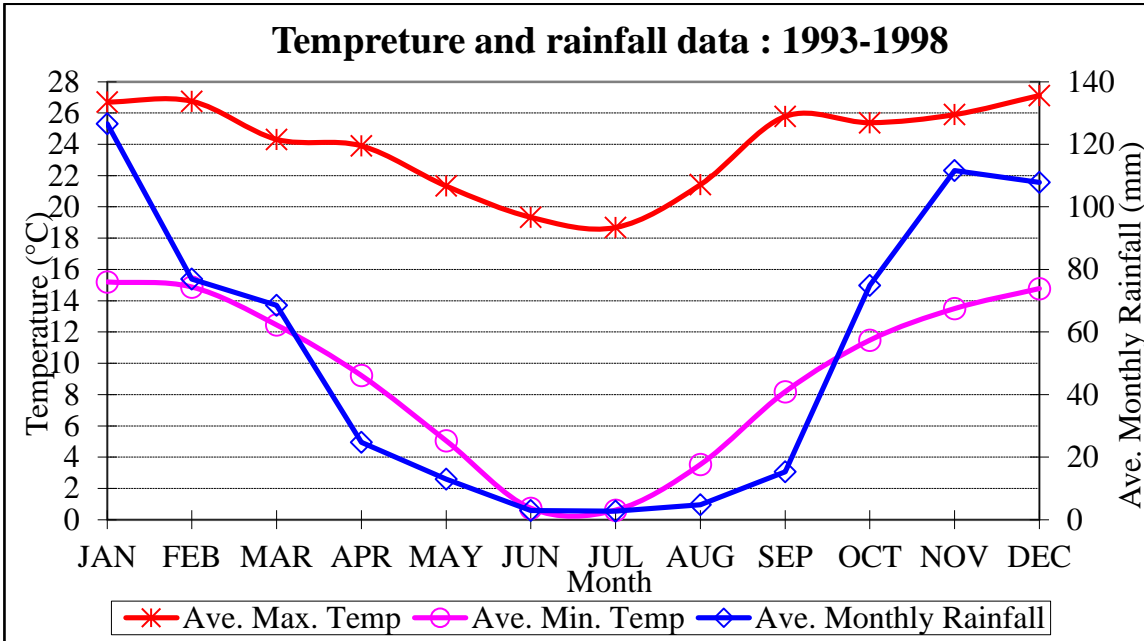


FIGURE 3-4: Average monthly temperature (max & min) and rainfall data for station [0516076 7] between 1993 and 1998 – MIDDELBURG DAM

Rainfall

Groundwater Resources of the Republic of South Africa, Sheet 1 & 2 (1995) map from the Department of Water Affairs (DWA) indicates a mean annual precipitation (MAP) between 600 – 800 mm with mean annual recharge (MAR) between 50 – 75mm (approx. 6 – 8% of MAP). This also corresponds to value 50 – 75mm for the mean annual recharge observed in Figure 6.8 on sub-section 3.4.

Two weather stations located in the vicinity of the study area were examined for climatological data analysis. Weather stations number 0515826 X, is located some ~4 km north-west, of the study area.. The second weather station (WS_0516076 7) is located 5.4 km north-east of the study area (see **Figure 3.5** below).

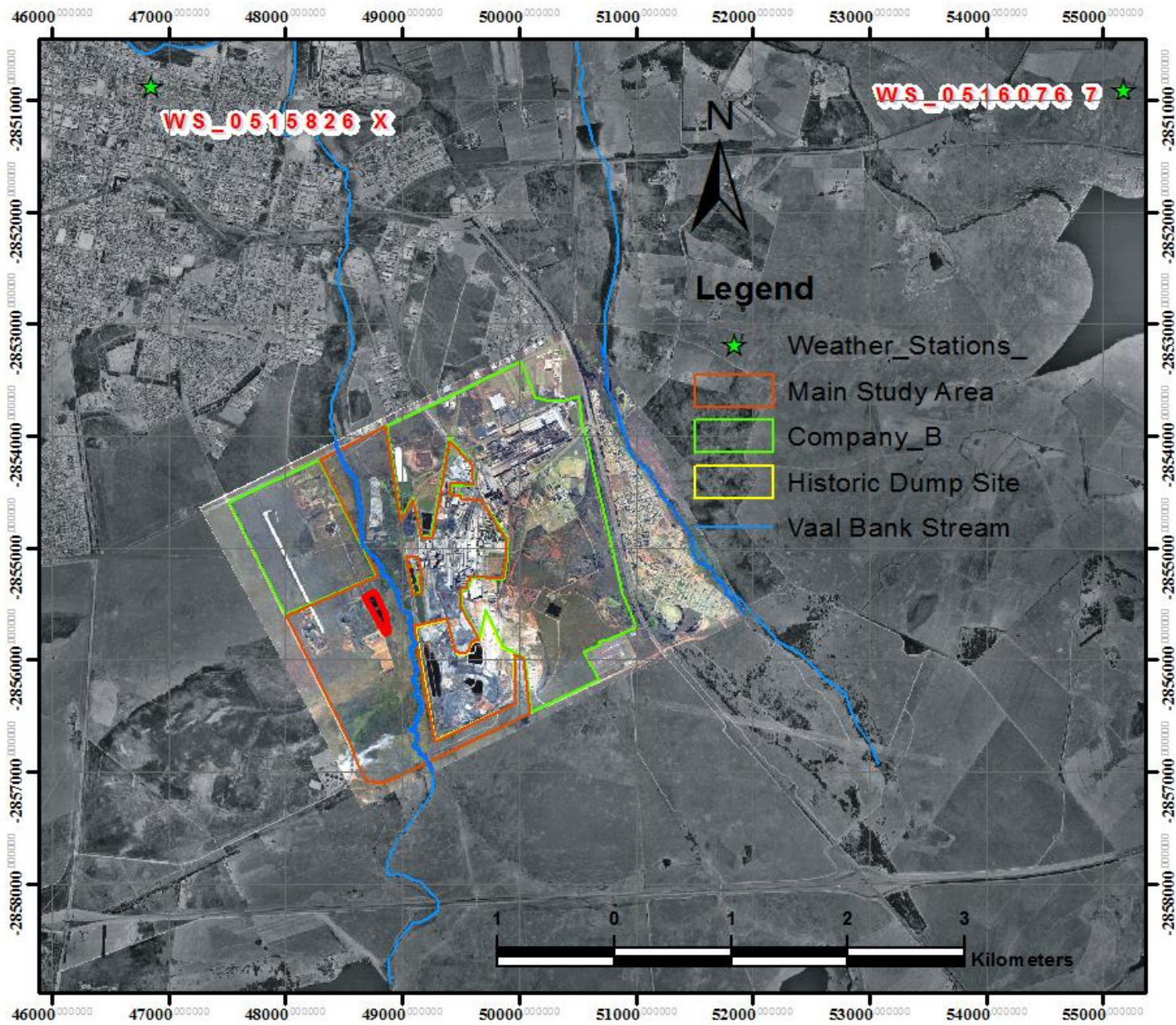


Figure 3-5: Positions of the weather stations near the study area

The rainfall obtained from the weather station WS_0516076 ranges from 1995 to 2006. Total accumulated rainfall from weather station WS_0515826 X and average monthly rainfall were plotted for the abovementioned period (i.e. **Figure 3.6 & 3.7**).

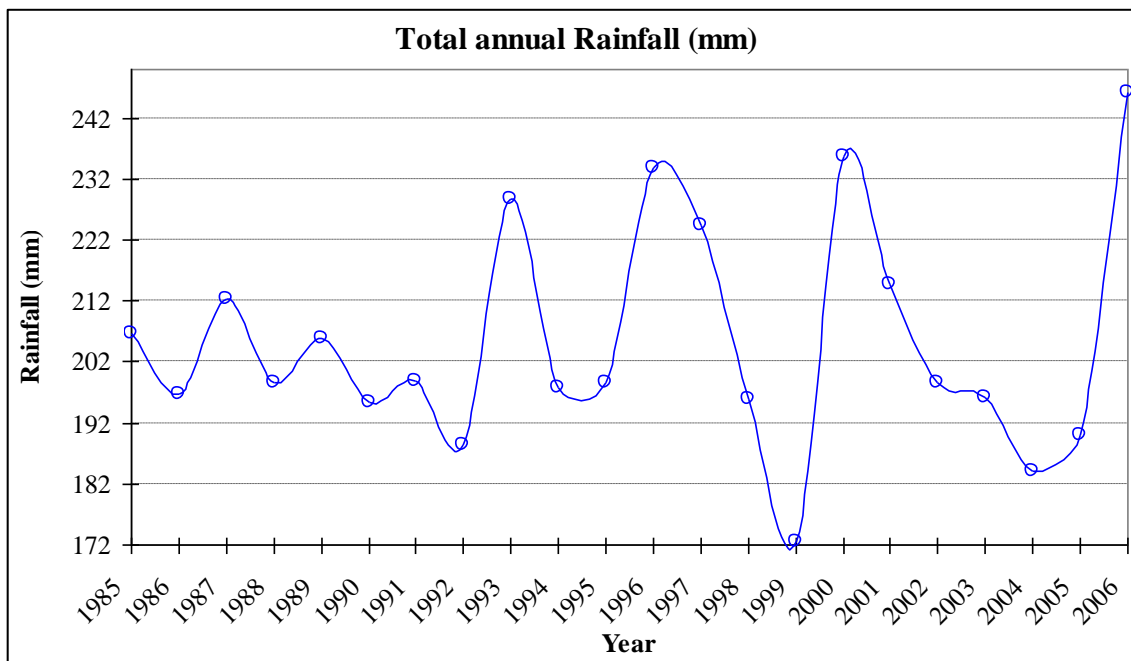


FIGURE 3-6: Total annual rainfall (mm) data from 1985 to 2006 for station [0515826 X] - MIDDELBURG - TNK Measured at 08:00 (Lat:-25.7670 Long: 29.4670 Height: 1447 mamsl)

The observation made on total accumulation rainfall from 1995 to 2006 indicates the following:

- Highest rainfall in years 2006, 2000 and 1996 exceeding 232mm.
- Lowest rainfall (dip cycle) are observed in 1999, 1992 and 2004.
- There is increasing fluctuation of rainfall data since 1992 to 2006.

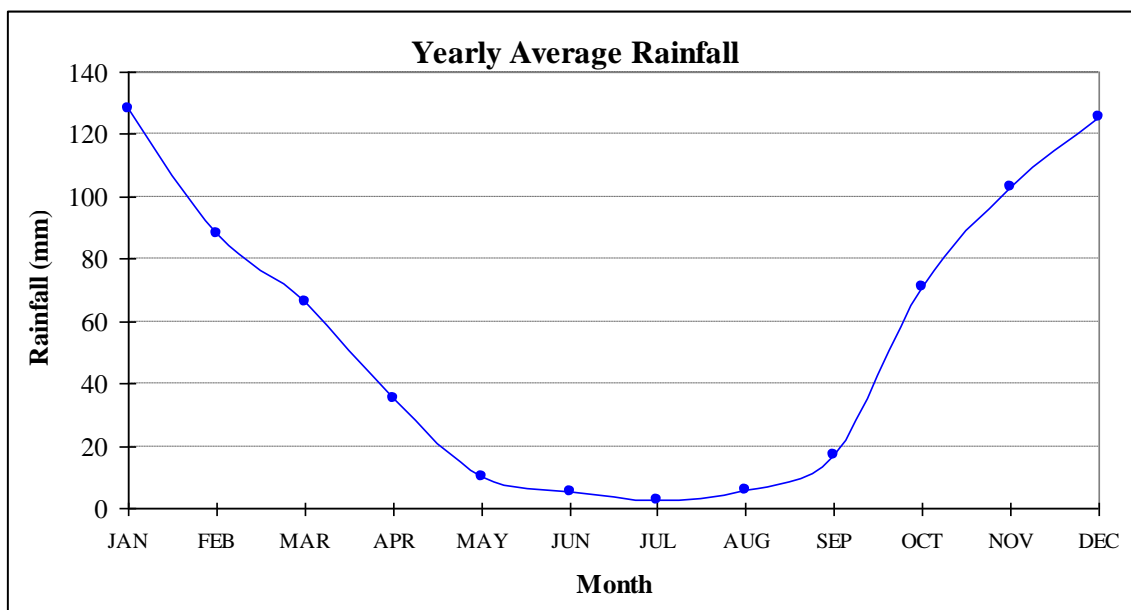


FIGURE 3-7: Average monthly rainfall (mm) data from 1985 to 2006 for station [0515826 X] - MIDDELBURG - TNK Measured at 08:00

A recent study by DWAF (2004) shows that groundwater recharge of the study area is 50 – 75 mm/a (see **Figure 3.8** below).

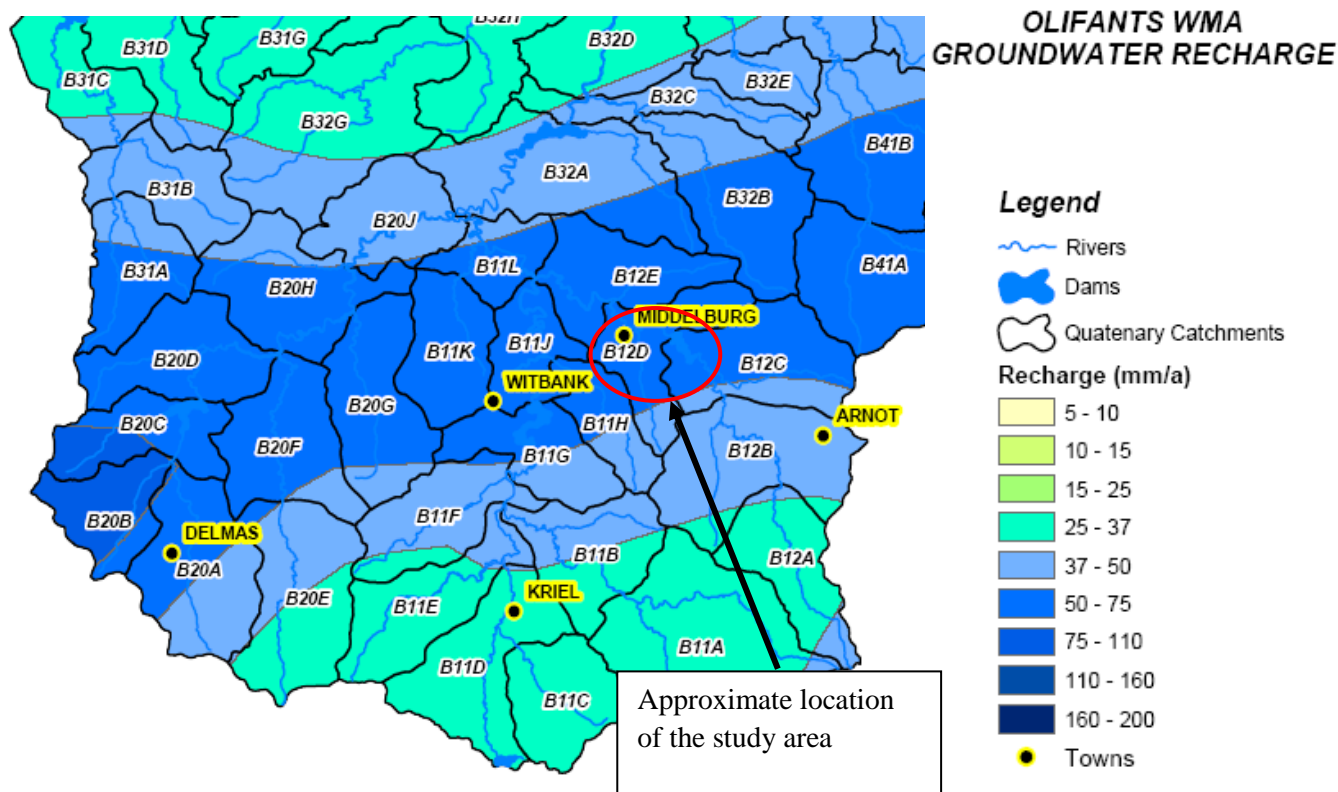


FIGURE 3-8: Map representing groundwater recharge in the Olifants Water Management Area (DWAF, 2004)

3.2.4 Land use

The land use activities of the area are predominately coal mining and agriculture.

The north-western part of the study area is dominated by light and heavy industrial activities. However, it has been noted in the recent two years (2009 & 2010) that both residential and light industrial is cropping in the far western part of Middelburg.

Between Hendriana Road and the site lies a grazing area with Vaalbank Water purification Works at far south western corner of the area. It is more likely that the grazing land will be invaded by light industrial activities or possible residential area as signs of new development were observed.

3.2.5 Detailed Description of site layout

The description of site study will be discussed at the hand of the plant and historic dump site.

The area consists of the following types of furnaces:

- Submerged Arc Furnace (2 × 10 MVA) (M1 & M2)
- Open Arc Furnace (1× 18 MVA) at company B
- DC Plasma Arc Furnace (1× 62 MVA) (M3 - closed furnaces)

Furthermore, the existence of the following equipments is relevant:

- Chrome Direct Reduction (CDR) Kiln (2 × 48 MVA)
- Crushing and screening plant
- Two Metal Recovery Plant (MRP)

The slag and chrome dust produced from the process are dumped at the historic dump site. The hot slag is always cooled through jet-water spray. However, it should be noted that part of the dump site is being cleared of fine dust containing chrome six and transported to Holfontein (hazardous waste dump, an H:H site).

3.2.6 Overview of the ferrochromium production process at the study area

An overview of the study area has been inserted here as to further reveal the original source of chromium contamination to both surface and groundwater. The inclusion of this process is nowhere a duplication of the previous explained process in chapter 2 (sub-section 2.3.3.2) as this one is specifically to this case study rather than a general process. However, the flow process diagram below has been simplified for the indication of final products discharge purposes.

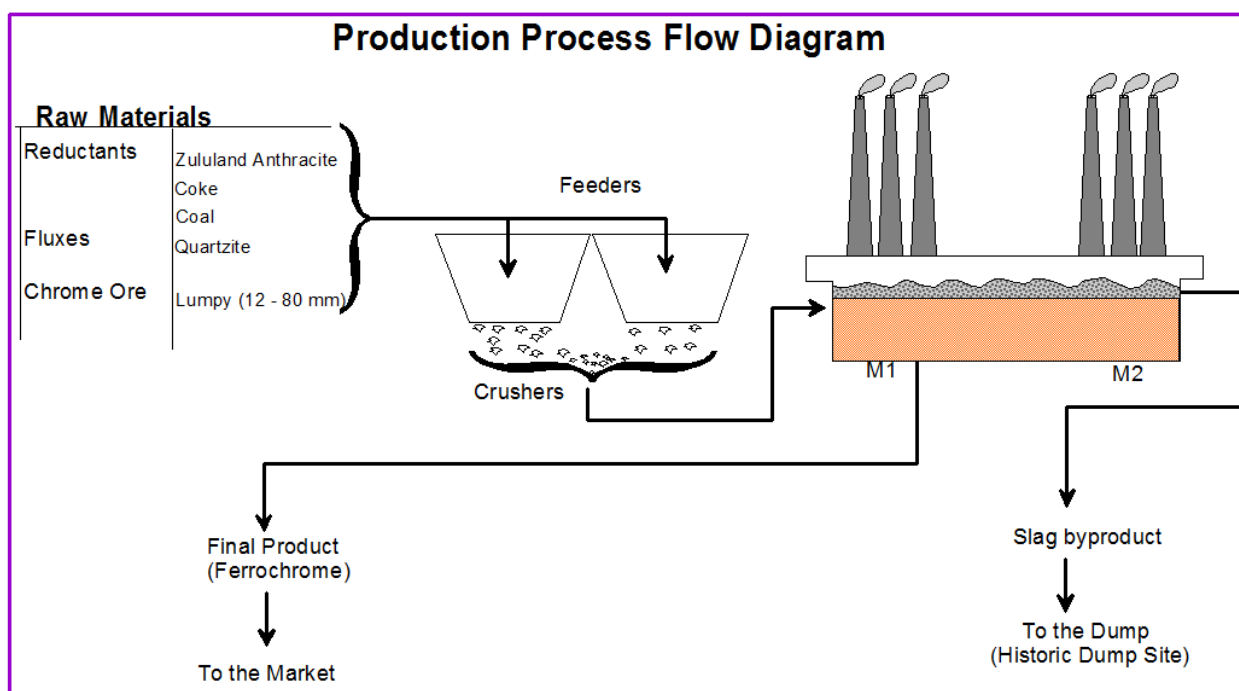


Figure 3-9: Ferrochromium process flow diagram

Figure 3.9 above illustrates all input materials (raw material) used in the process and the final major products namely:

- Ferrochromium
- Slag

However, other byproducts which contain chromium six are:

- Fine dust from open arc furnace
- Filter cake

The slag is dumped at the Historic Dump Site (HDS) and cooled down with the use of water. Although the slag is mostly inert in Cr^{3+} state, the process of water spraying to the slag may change the chemical state from Cr^{3+} to Cr^{6+} in the old underlying slag. Chromium (III) needs moisture (water) and air be oxidized to chromium (VI) which is carcinogenic and a contaminant to groundwater.

3.3 RESEARCH PROBLEM

Current problem in the study area (Research problem) is both surface and groundwater contamination by chromium. Early between 1960s and 1987 all waste materials were dumped at the Historic Dump Site (HDS) randomly. Therefore, there was no cohesive environmental management plan to mitigate the future impact. The HDS consisted and may still contain the mixture of the following (see **Figure 3.10** below):

- Phenols
- Electric Arc Furnace slag (EAF Slag)
- Low Carbon (LC) dust from submerged Arc furnace
- Effluent Treated Plant (ETP) filter/ filter cake, neutralized filter cake, ash, mould sands etc)
- Miscellaneous waste from *Company C* rolling mill process (e.g. steel shot,
- General waste (i.e. tyres, steel strapping, wooden pallets etc)

The following products are generated by the furnaces; M1 and M2 (see Figure 3.9):

- Fine dust
- Course dust
- Slag

The course dust is further supplied to the Chrome Direct Reduction (CDR) Kiln for further processing. However, fine dust contains hexavalent chromium and as a result it is collected and transported to Holfontein (hazardous waste dump, an H:H site).

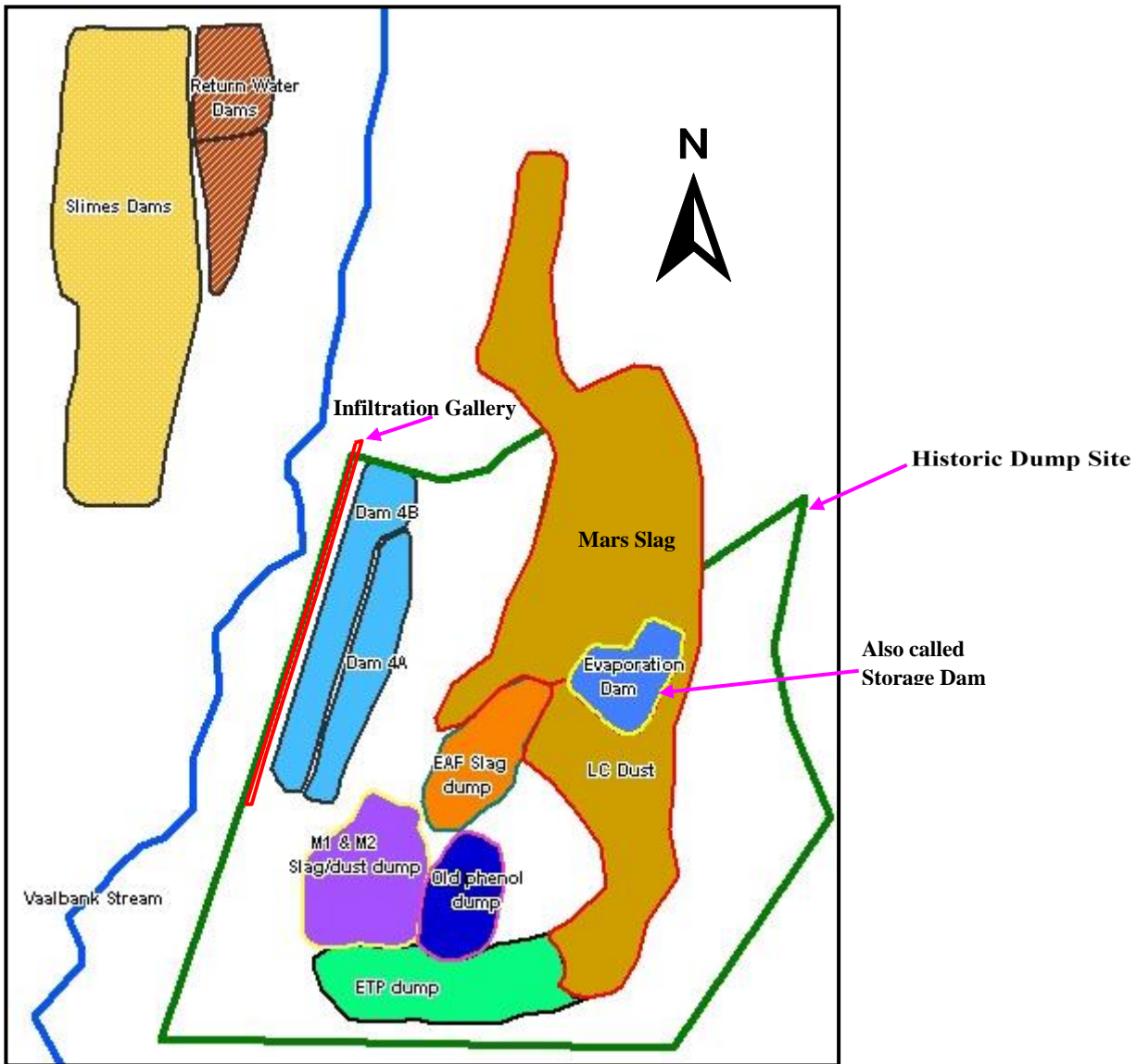


FIGURE 3-10: Composition of Historic Site Dump with locality of possible groundwater contamination

Large-scale application of concentrated Cr(VI) solutions in the metal finishing, tanning, and wood preserving industries over the last century has resulted in a widespread environmental problem. At many locations, Chromium has been released to the environment via leakage, poor storage, or improper disposal practices (Palmer and Wittbrodt, 1991).

Figure 3.11 illustrates general flow sheet for production of ferrochromium and possible chromium release to the environment (Vanhanen, 1999).

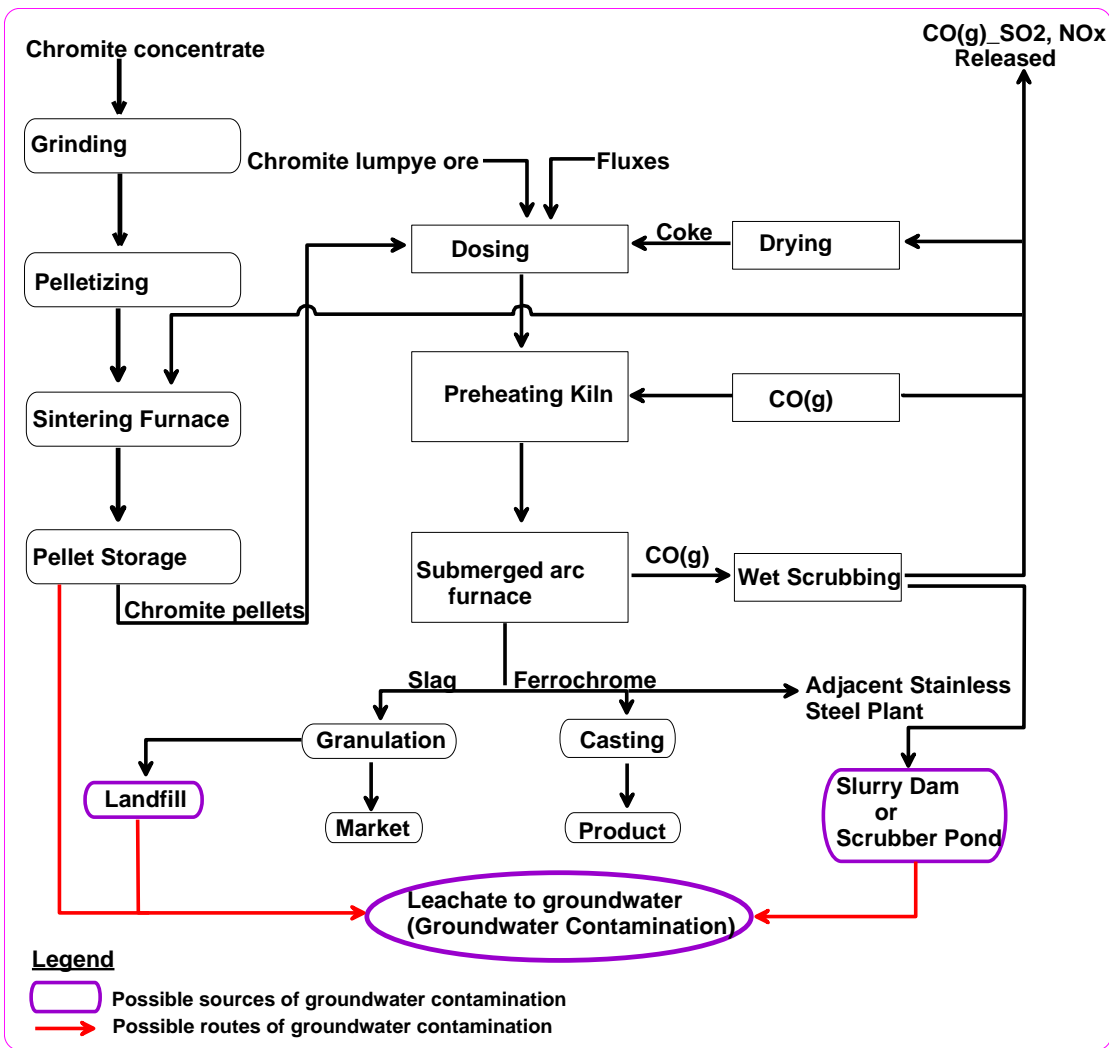


Figure 3-11: General flow sheet of ferrochromium process with possible routes to groundwater contamination

As indicated on **Figure 3.11** above, possible contamination to subsurface is from HDS by leaching of old deposits of slag and capturing or storage dams (i.e. Dam 4A & 4B)

An aerial photo from HDS depicting all infrastructure and dump material is shown in **Figure 3.12** below



Figure 3-12: Aerial photo of the historical site dump of the study area

3.4 REGIONAL GEOLOGY

3.4.1 Description of the regional geology

The regional geology of the study area comprises of the Loskop and Wilge River Formation of the Transvaal Sequence. This formation is characterized by the presence of pyroclastics, lava, quartzite, conglomerate, sandstone, shale, siltstone, grit, mudstone, and diabase sills. The central part of the main study area has been cross-cut by the Dwyka Formation of the Karoo Supergroup. Dwyka Formation comprises of the following:

- Tillite with subordinate sandstone
- Mudstone and
- Shale intruded by dolerite dyke and sheets.

Detailed geologic log description is provided in **APPENDIX II**.

Both Dwyka and Loskop and Wilge River Formations consist of compact, dominantly arenaceous, and argillaceous strata.

Furthermore, southern and eastern outskirts of *Company B* and occasional in *Company A* are underlain by the Selons River Formation.

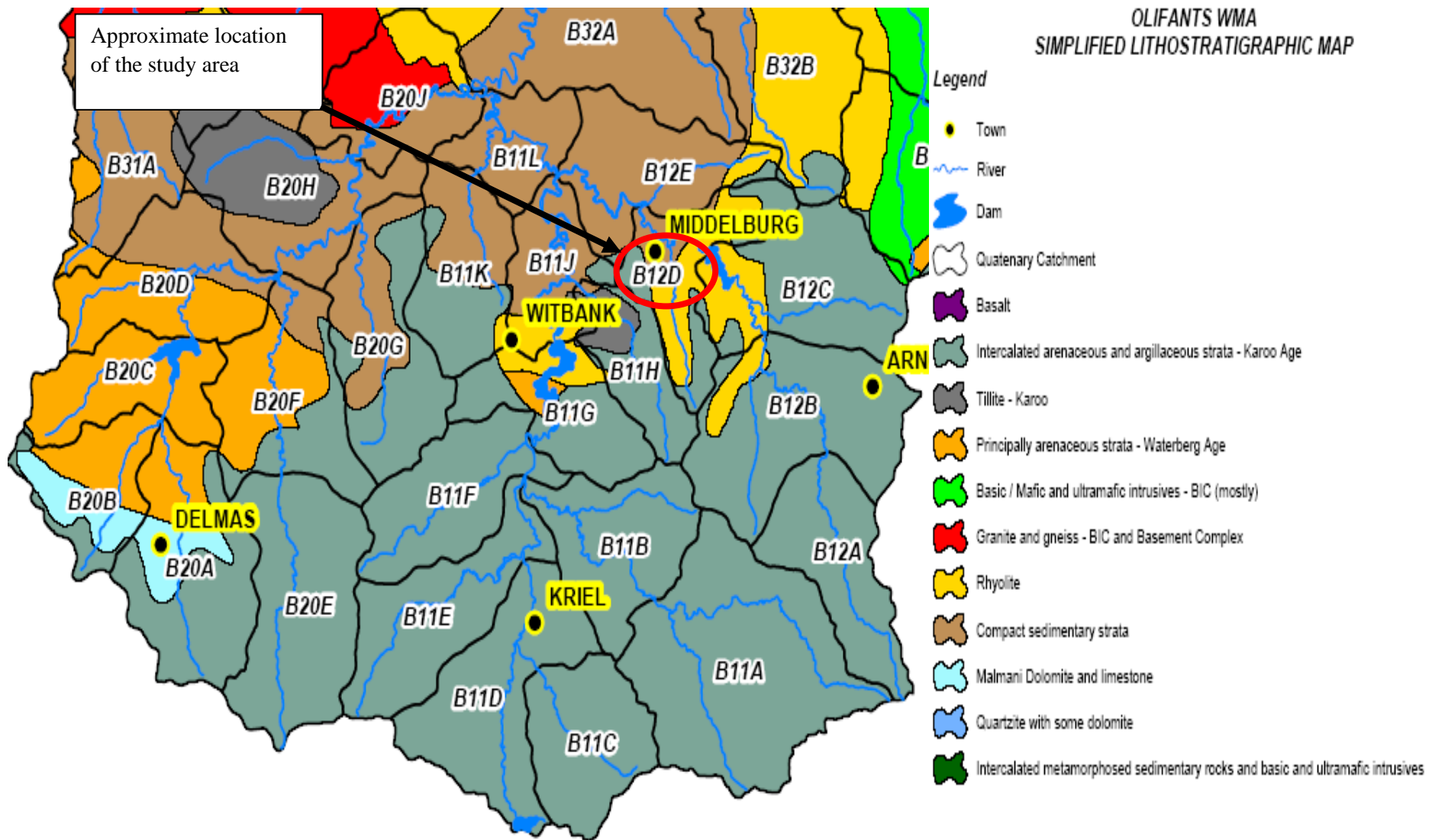


Figure 3-13: Map illustrating the regional geology of the study area in the Olifants Water Management Area (DWAF, 2004)

The Waterberg Group covers a part of the Transvaal Sequence in the Kwamhlanga, Witbank and Middelburg districts. This stratum was formed between 90 and 2 050 million years ago. **Figure 3.13** above indicates predominantly existence of rhyolite and intercalated arenaceous and argillaceous strata (Karoo Age) in the south-eastern part of the study area.

3.5 DESCRIPTION OF LOCAL GEOLOGY

3.5.1 Description of the local geology

Borehole logs (**APPENDIX II**) obtained during geotechnical work done at Company A in 1987 and further drilling work undertaken by Company B in 2005 provided clear understanding about local geology of the study area. It is therefore, important to explain the local geology of the study area at the hand of borehole logs obtained during geotechnical survey.

3.6 DESCRIPTION OF LOCAL GEOHYDROLOGY

3.6.1 GENERAL DESCRIPTION

Groundwater Resources of the Republic of South Africa; Sheet 1 & 2 by DWAF (1995) indicates the following regional information regarding groundwater:

- Recommended drilling depth below groundwater level is 20-30 *m*. formation mainly comprises of sedimentary rocks excluding dolomite and limestone. Drilling success rate is 40-60%.
- The nature of water bearing rock (aquifer) is compact, predominantly arenaceous strata.

3.6.2 LOCAL DESCRIPTION

Borehole prospects

The probability of drilling a success borehole (accessibility) is 40-60%. Probability of a successful borehole yielding is less than (<) 2 *l/s* (exploitability is 10-20%

3.6.3 Physical Aquifer Properties

Hydraulic Aquifer Properties

The engineering geotechnical investigations performed by WLPU (1989) in the study area revealed that sediments of the Loskop Formation consist of laminated, fissured, micro-shattered, closely jointed and fractured

properties. The fractures are reported to be almost vertical and the movement of groundwater is expected to be sub-vertical and lateral. However, it was noted from site geological logs provided in APPENDIX II that the geology of the area has marked varying degree which will influence the movement of groundwater at various strata.

Three types of permeability were performed and they are as following:

- Falling head test
- Constant discharge test
- Recovery test

The results from the permeability testing program are presented in **Table 3.1** below.

Table 3.2: Pump and permeability testing program (WLPU, 1987)

BH NO.	New BH Name	Depth of BH (m)	water strike (mbgl)	Blow yield (l/s)	Aquifer type	Pump testing details			Permeability testing details	
						Duration (min)	Yield (l/s)	Max. Drawdown (m)	Water level (m)	Type of test
MSA 1	CSD 22	30	25 & 27	0.01	Fractured shale				4.28	Falling Head
MSA 1A	CSS 5	4	-	-	Weathered shale				1.45	Falling Head
MSA 2	-	30	24-27	1.11	Fracture shale	90	1.90	17.03	3.58	Recovery
MSA 2A	-	7	-	-	Weathered shale				1.23	Falling Head
MSA 3	CSD 23	30	11-15, 19, 30	0.30	Fractured shale				2.15	Pump Out
MSA 3A	CSS 6	8	-	-	Weathered shale				2.15	Falling Head
MSA 4	-	30	21, 25, 27	1.11	Fractured shale	60	1.60	14.14	10.70	Recovery
MSA 4A	-	8	8	M	Weathered shale				No level	Falling Head
MSA 5	-	30	28	M	Fractured shale				2.20	Falling Head
MSA 5A	-	7	-	-	Weathered shale				2.16	Falling Head
MSA 6	-	30	15 & 20	0.01	Fractured shale				2.24	Falling Head
MSA7	-	30	15	M	Fractured shale				0.25	Pump Out
MSA 7A	-	6	-	-	Weathered shale				0.70	Falling Head
MSA 8	-	30	19	M	Fractured shale				3.52	Falling Head
MSA 8A	-	6	-	-	Weathered shale				1.90	Falling Head

BH NO.	New BH Name	Depth of BH (m)	water strike (mbgl)	Blow yield (l/s)	Aquifer type	Pump testing details			Permeability testing details	
						Duration (min)	Yield (l/s)	Max. Drawdown (m)	Water level (m)	Type of test
MSA 9	CSD 24	30	16 & 25	1.00	Fractured shale	45	1.90	14.82	0.17	Recovery
MSA 9A	CSS 7	6	-	-	Weathered shale				0.90	Pump Out
MSA 10	-	17	5 & 14	1.10	Fractured diabase				0.02	Pump Out
MSA 10A	-	7	6	M	Weathered diabase				0.00	Pump Out
MSA 11	-	20	4	0.40	Weathered-fractured diabase contact zone				0.00	Pump Out
MSA 12	-	25	18	2.20	Weathered-fractured diabase contact zone	80	1.90	6.17	1.80	Recovery
MSA 12A	-	14	-	-	Weathered diabase				1.90	Falling Head
MSA 13	-	20	12	0.60	Fractured shale-diabase contact zone				0.30	Pump Out
MSA 14	-	20	14	0,4	Fractured diabase				0.12	Pump Out
MSA 15	-	20	8 & 17	0.60	Fractured diabase				1.15	Pump Out & Falling Head
MSA 16	-	10	5	M	Weathered-fractured diabase contact zone				0.24	Pump Out
MSA 17	-	30	16 & 21	0.10	Fractured shale				2.43	Falling Head
MSA 18	-	30	-	-	Fractured shale				0.76	Falling Head

BH NO.	New BH Name	Depth of BH (m)	water strike (mbgl)	Blow yield (l/s)	Aquifer type	Pump testing details			Permeability testing details	
						Duration (min)	Yield (l/s)	Max. Drawdown (m)	Water level (m)	Type of test
M/SHOP-N	CSD 26	20	17	0.40	Weathered-fractured diabase contact zone				3.82	Falling Head
M/SHOP-S	CSD 27	13	7 & 10	0.20	Weathered-fractured diabase contact zone				4.00	Falling Head

The results of the above tests indicate that the top layer (residual) as well as shale have lower permeabilities ranging from 1.39×10^{-7} to 3.92×10^{-5} m/s as compared to the fractured diabase contact with permeability of ranging from 1.39×10^{-6} to 3.92×10^{-4} m/s. **Table 3.2** below represents details of the overall permeability test results.

Table 3.2: Generalised summary of permeabilities on the site (WLPU, 1987)

geology	Range of permeability (m/s)	Typical permeability (m/s)	m/d
Weathered shale	1.39×10^{-7} - 3.92×10^{-5}	-	0.012 - 3.387
Fractured diabase	3.84×10^{-6} - 1.00×10^{-4}	3.14×10^{-5}	2.713
Weathered diabase	-	1.00×10^{-4}	8.64
Fractured contact zone	7.67×10^{-6} - 3.92×10^{-4}	1.00×10^{-4}	8.64

3.6.4 Aquifer Dynamics

Ground water flow direction

The general groundwater flow, as observed in **Figure 3.14** above, is towards north-west in east of Vaalbank stream and towards north-east on west of the stream. However, the flow eventually converges towards north.

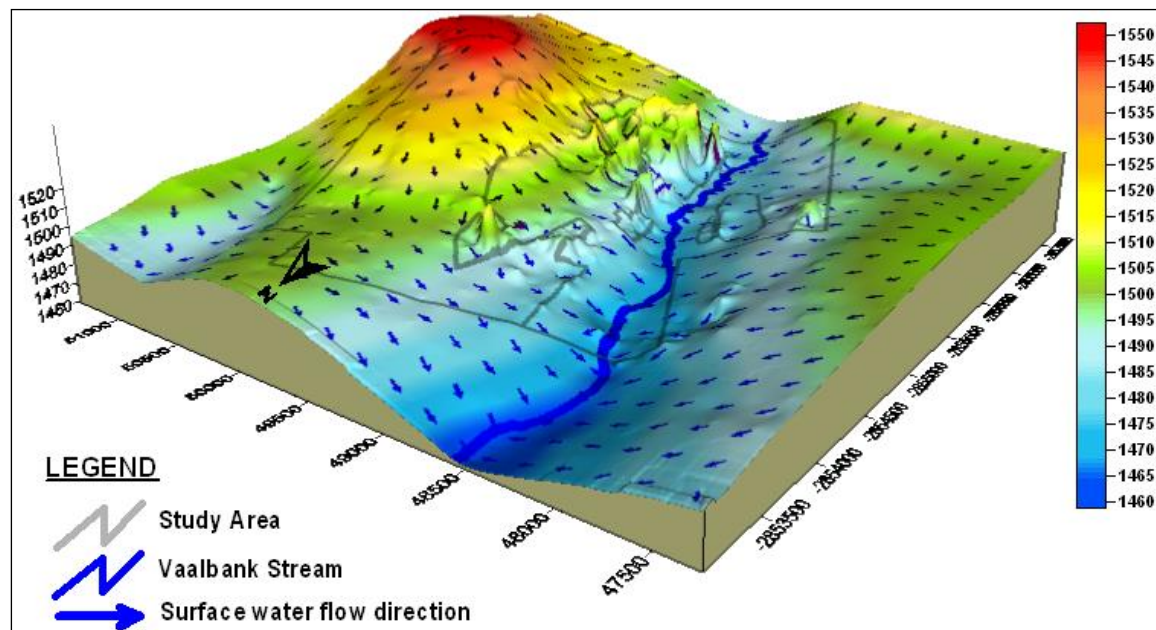


FIGURE 3-14: Surface water flow direction 3D model of the study area

Groundwater flow is general to the north in the main catchment area. At the study area (HDS) is towards the Vaalbank stream (west) before it flows to the north.

3.7 AQUIFER CLASSIFICATION

3.7.1 Aquifer Types

The drilling investigation conducted by WLPU (1987) and by JMA (2006) revealed better description of the local geology and better understanding of the types of the aquifers contained in the study area. There are mainly four types of the aquifer found in the study area:

- Weathered shale
- Fractured diabase
- Weathered diabase
- Fractured contact zone

The average thicknesses of the classified layers drilled up to 30 *m* depth are tabulated below. Overburden overlaying the area is approximately 3.5 *m*.

Table 3.3: Description of aquifer types

Strata	Ave. Thickness (m)	Total depth (m)
Overburden	3.5	
Weathered rock	10	
Fractured rock	11.5	
Fresh rock	5	30

3.8 HYDROCHEMISTRY AND IMPACT ASSESSMENT

3.8.1 Assessment of groundwater impact

The hydrochemistry of the study area was assessed with the aid of available data from monitoring points for both surface and groundwater. Localities of monitoring points are indicated in **Figure 3.15** below

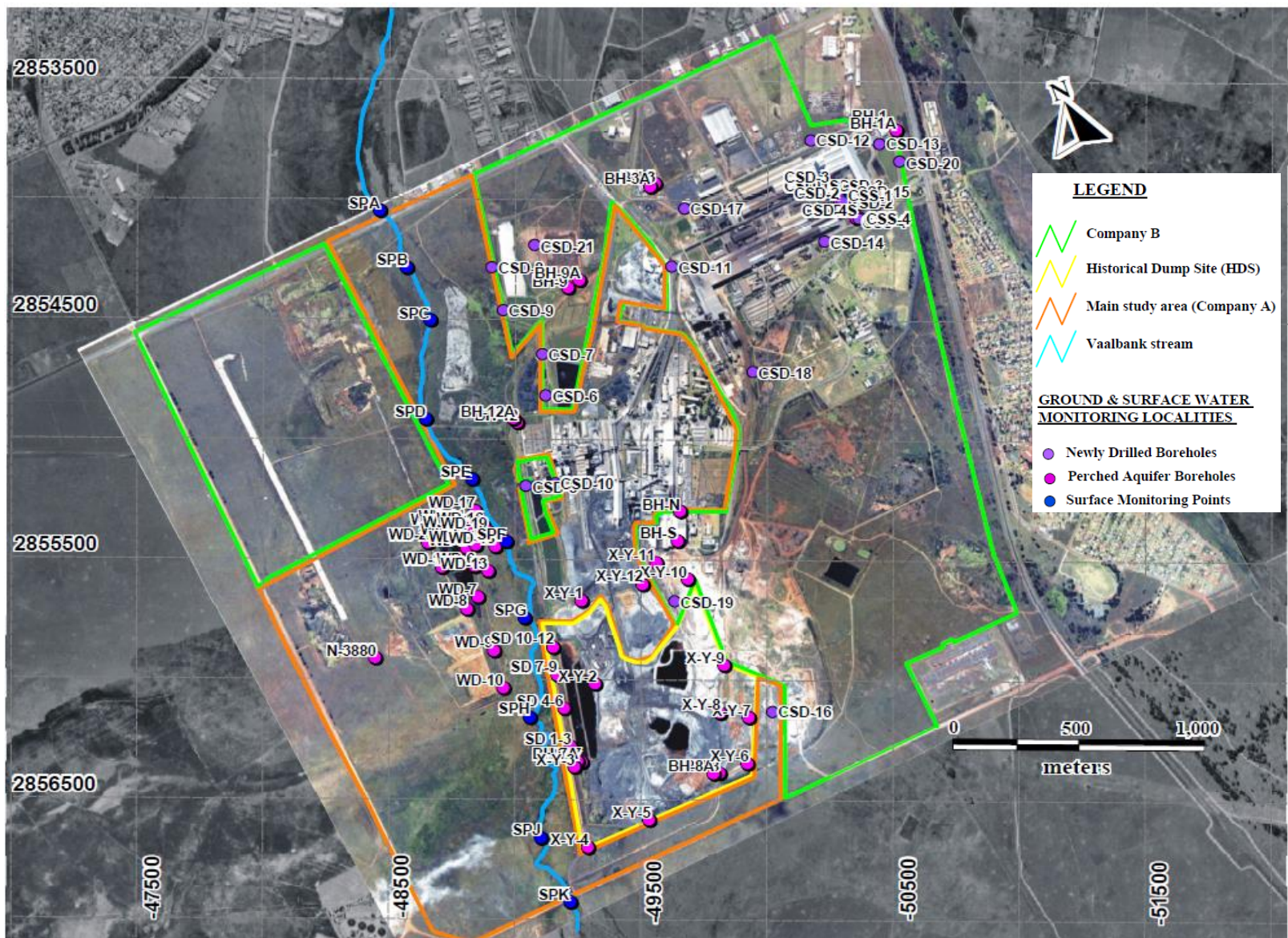


Figure 3-15: Monitoring localities and positions of dump areas (X-Y points)

From the list of monitoring points, APPENDIX III, a refinement of more relevant boreholes was made by selecting boreholes on east and west of Vaalbank stream. The selected boreholes are perceived as boreholes located to capture

any possible contamination to groundwater based on the direction of groundwater flow and background information. Please see **Figure 3.16** below for selected areas (boreholes) for impact assessment.

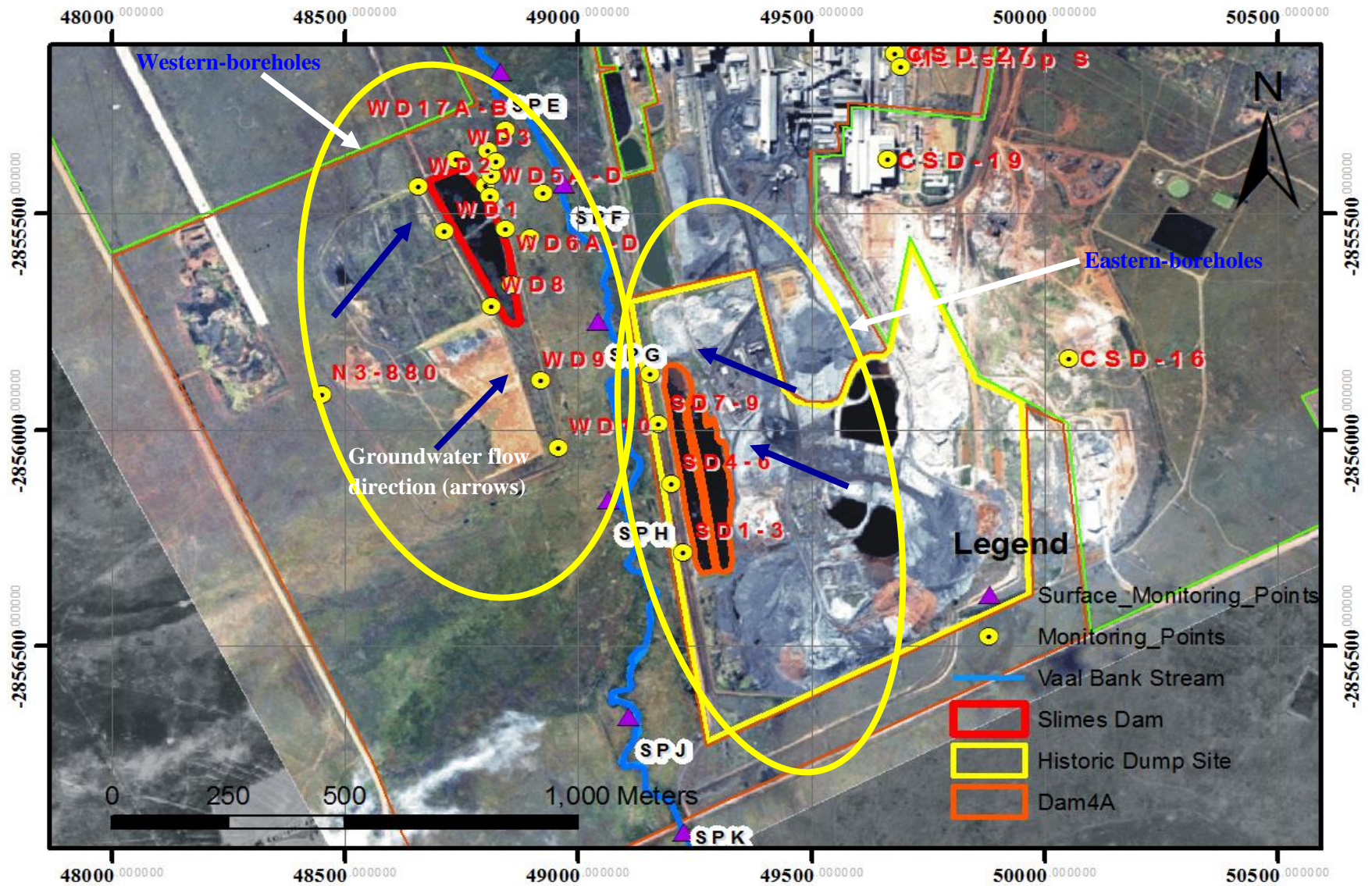


Figure 3-16: Position of selected monitoring boreholes (yellow circle) on the possible pathways (East and West of Vaalbank stream)

3.8.2 EASTERN-BOREHOLES

The eastern part of Vaalbank stream represents capturing location of contamination from the HDS with boreholes SD 1-12 located between the HDS and the stream. Borehole CSD-16 was used as the available background monitoring point to compare other borehole results on the capturing location. Monitoring results for SD1-12 indicate some contamination predominantly by sulphates and chromium. However, CSD 16 on the upper-gradient does not indicate pollution by the abovementioned contaminants which is a good indication that HDS play a very important role in the source of groundwater contamination. All water quality data was assessed against South African (SA) Drinking Water Standard: SANS 241 (2001 & 2011).

Background boreholes

CSD16 was used as background borehole to compare with chemistry results from boreholes below the HDS (source of contamination). However, boreholes SD1-3 were also included in this list as these boreholes are located at just upper gradient of the collection dams (i.e. Dam 4A & 4B shown in **Figure 3.10 & 3.16** on previous, section 3.6) and flushing from Vaalbank stream is expected to play role in terms of dilution if any contamination might occur. **Figure 3.17** displays a plot of electrical conductivity (EC) and SO₄ for borehole SD1. Unfortunately there were only two samples for CSD 16 with values of 1.58 and 0.63 mg/l for SO₄ which are far below the maximum limit. This can be attributed to the fact that CSD 16 is on upper gradient of the HDS and no contamination related to components found in the HDS site.

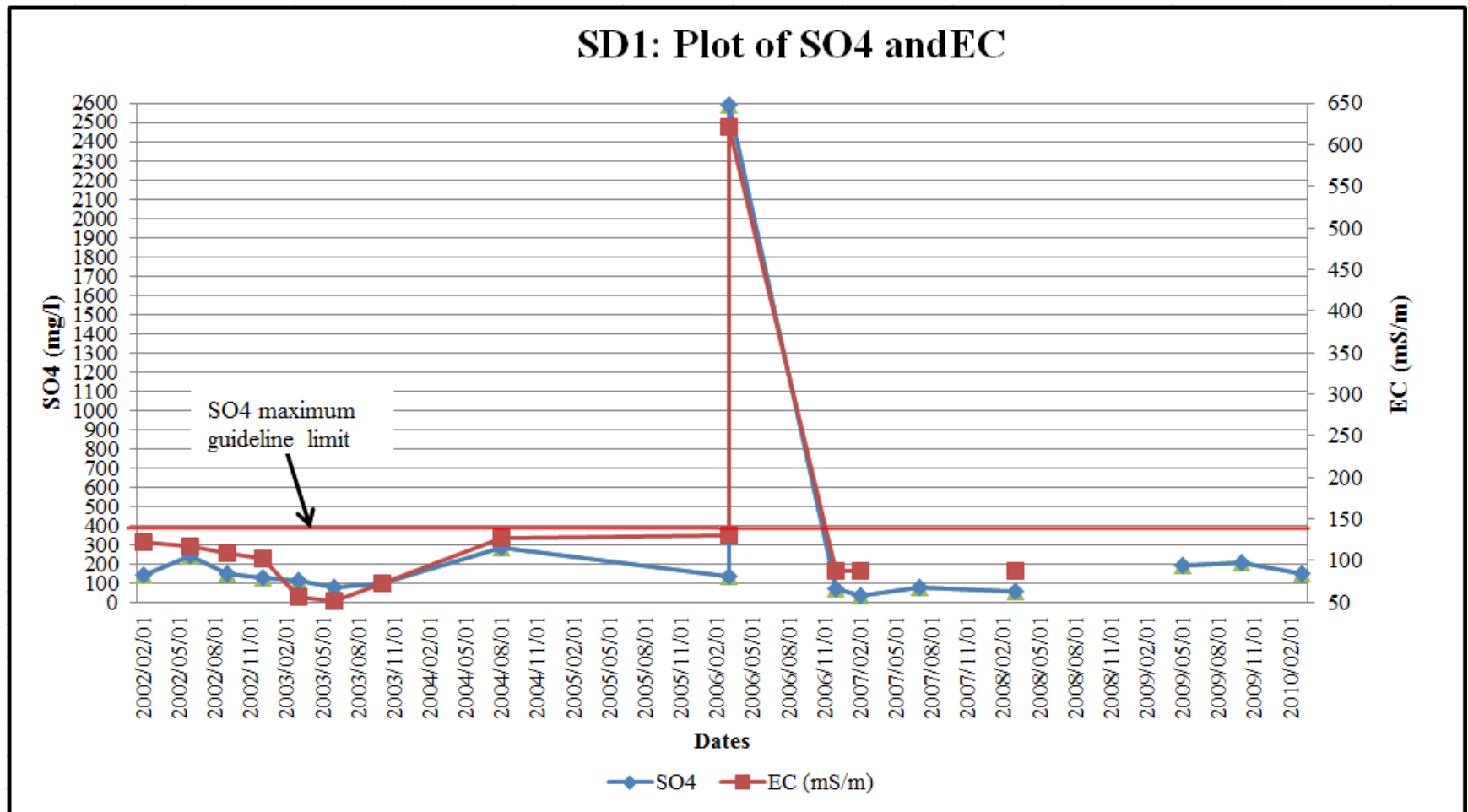


Figure 3-17: Borehole SD1 with Plot of SO4 and EC

An outlier has been observed on sample results of March 2006 for SD1. It is unlikely that the spike is related to typing error as both EC and SO4 has the same trend. Possible cause of outlier can be cross-contamination during sampling or once-off spillage caused by as outlier was an average of four samples taken on same day (30 March 2006). The graph shows good correlation of electrical conductivity (EC) and sulphates (SO₄)

Boreholes below HDS

These are boreholes located immediate below the HDS and just before the stream. Boreholes SD4-9 are in this category and SD7 was selected for assessment of impact because of insufficient data as compared to others. **Figure 3.18** below indicates plot (in logarithm scale) of SO₄ and Cr(VI) for samples results between 2001 and 2009. Red line showing maximum guideline limits for SO₄ and Cr(VI) was also inserted for reference purposes. It can be observed that SO₄ has exceeded the maximum guideline limit (400mg/l) when using SA Drinking Water Standard SANS (2001). Furthermore, Cr(VI) show some exceedance in March 2002, with high jump in March 2003 and almost throughout the year of 2009. The plot of Cr(VI) between June 2003 and August 2008 is constant at value of 0.02 mg/l which can be related to lower detection limit.

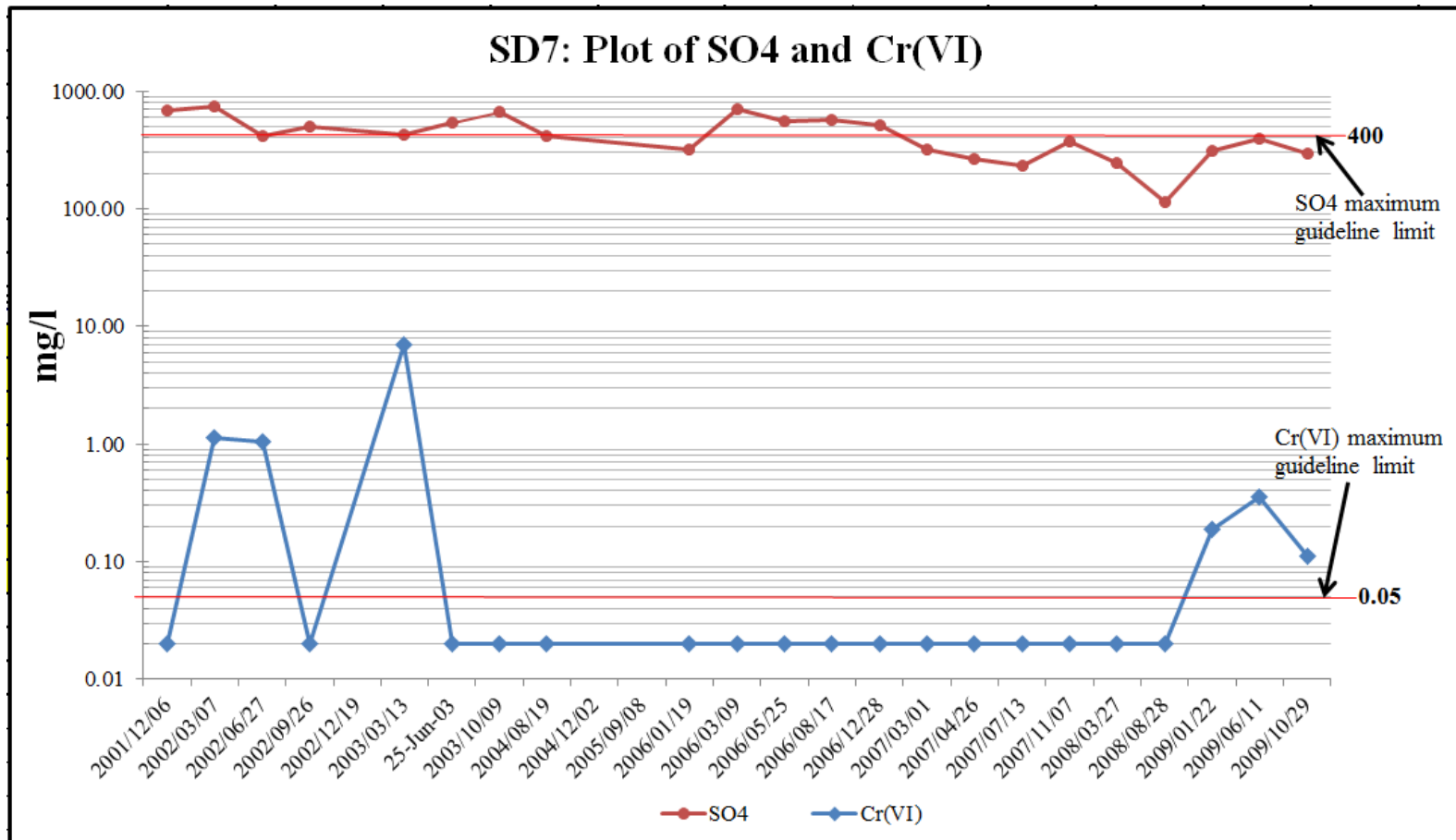


Figure 3-18: Borehole SD7 with Plot of SO₄ and Cr(VI) on logarithmic scale

Boreholes below the capturing dams (dam 4A & 4B)

Boreholes SD 10-12 represents monitoring points located just below the two capturing dams (dam 4A & 4B) and the HDS. It was anticipated that these boreholes should be picking up most components of the contaminants. The selection of two (SD10 & 11) of these boreholes was based on information available to assess, with SD 11 having most data to analyze. The plot of SO₄ in **Figure 3.19** below indicates that 19 samples of the total 23 samples were exceeding the limit with highest values of 779 mg/l in May 2006. This implies that 82.6% of total sampled water has been exceeding the limit since 2001 up to 2009. Although not plotted in the graph, Cr(VI) indicated some exceedance on SD11 by 0.41 mg/l in June 2002 and still high by 0.14 mg/l in October 2009.

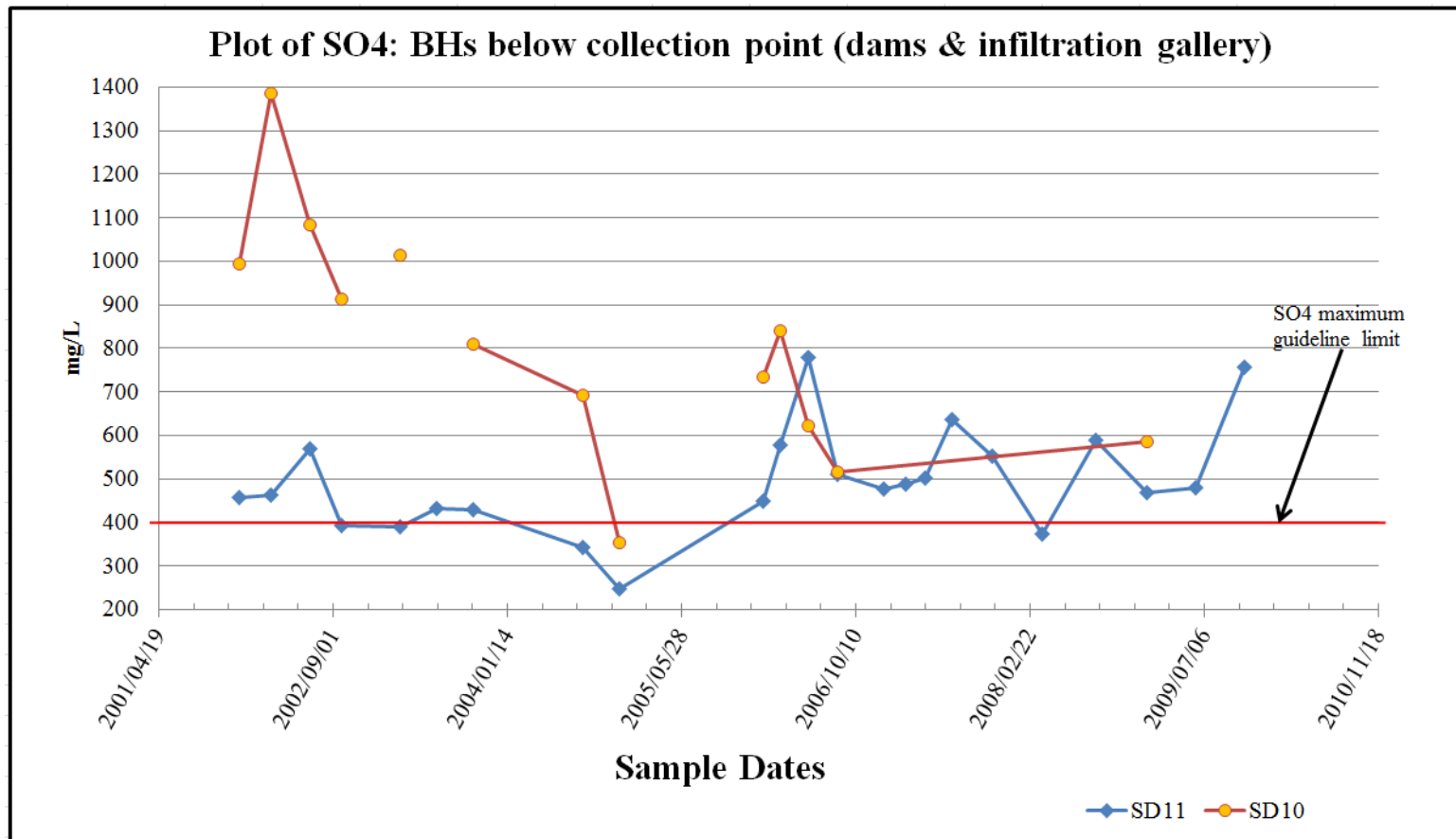


Figure 3-19: Plot of SO₄ for boreholes SD 10 & 11 below infiltration gallery and dam 4A & 4B

3.8.3 WESTERN-BOREHOLES

Western boreholes were selected based on the fact that they represent impact on western part of study area to assess slimes dam impact to groundwater

Background boreholes

Borehole N3-880 was selected to represent background monitoring point as it is located at the upper gradient of the slimes dam and return water dam. Although N3-880 was the most suitable background borehole, other monitoring points WD9 & 10 were also included in this category as they are located upper and parallel to the flow through slimes dam.

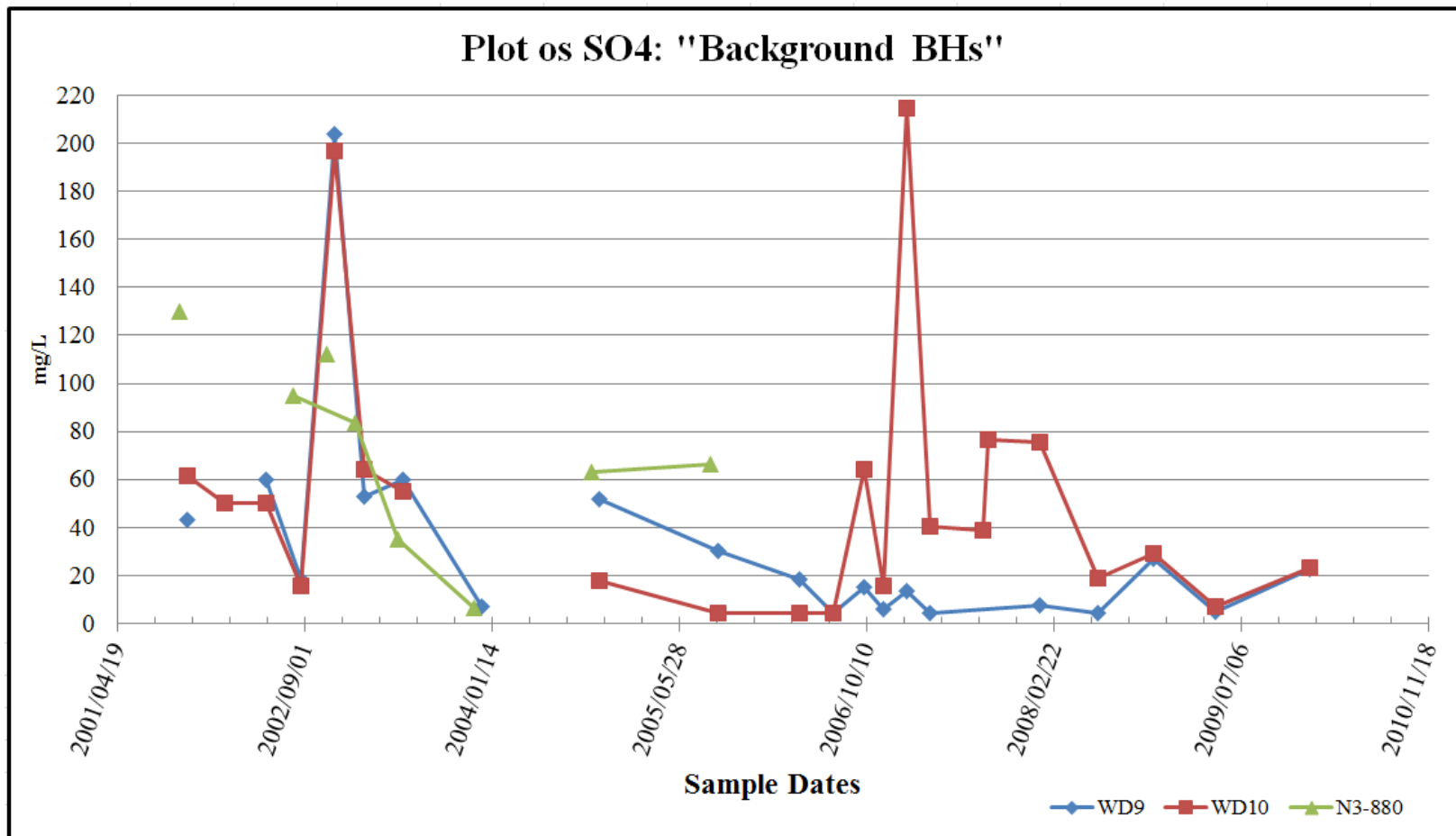


Figure 3-20: Plot of SO4 for background boreholes (i.e. WD9, WD10 & N3-880)

As it was theoretically anticipated, that borehole N3-880 is the most suitable monitoring point, the graph (data) on **Figure 3.20** above indicates SO₄ below 140 mg/l in total sample results which is far below the maximum guideline limit. It was unfortunate that there was no geological log information for western boreholes, but of observed data plotted for both WD9 and WD10 shows same trend, particularly first and last leg of the graph.

The only information which was helpful in terms of understanding the aquifer depth was some available depth borehole information found on boreholes, N3-880 and WD5D as depicted on **Figure 3.22** below.

Boreholes in the vicinity of slimes dam

These are immediate boreholes are those selected in the vicinity just below (<20m) the dam. Boreholes WD5D, WD6C and WD7 were selected based on reasonable or sufficient data to analyze. These boreholes were plotted for chemical of concern in this case SO₄ (see **Figure 3.21** below). Borehole, WD5D indicates a steady increase of SO₄ from 2002 to 2007 which can be attributed to fact that is closest borehole to the return water dam (source) and shallow borehole (5m deep). WD5D is in the vicinity of the discharge point of return water dam which might be the cause of increased trend.

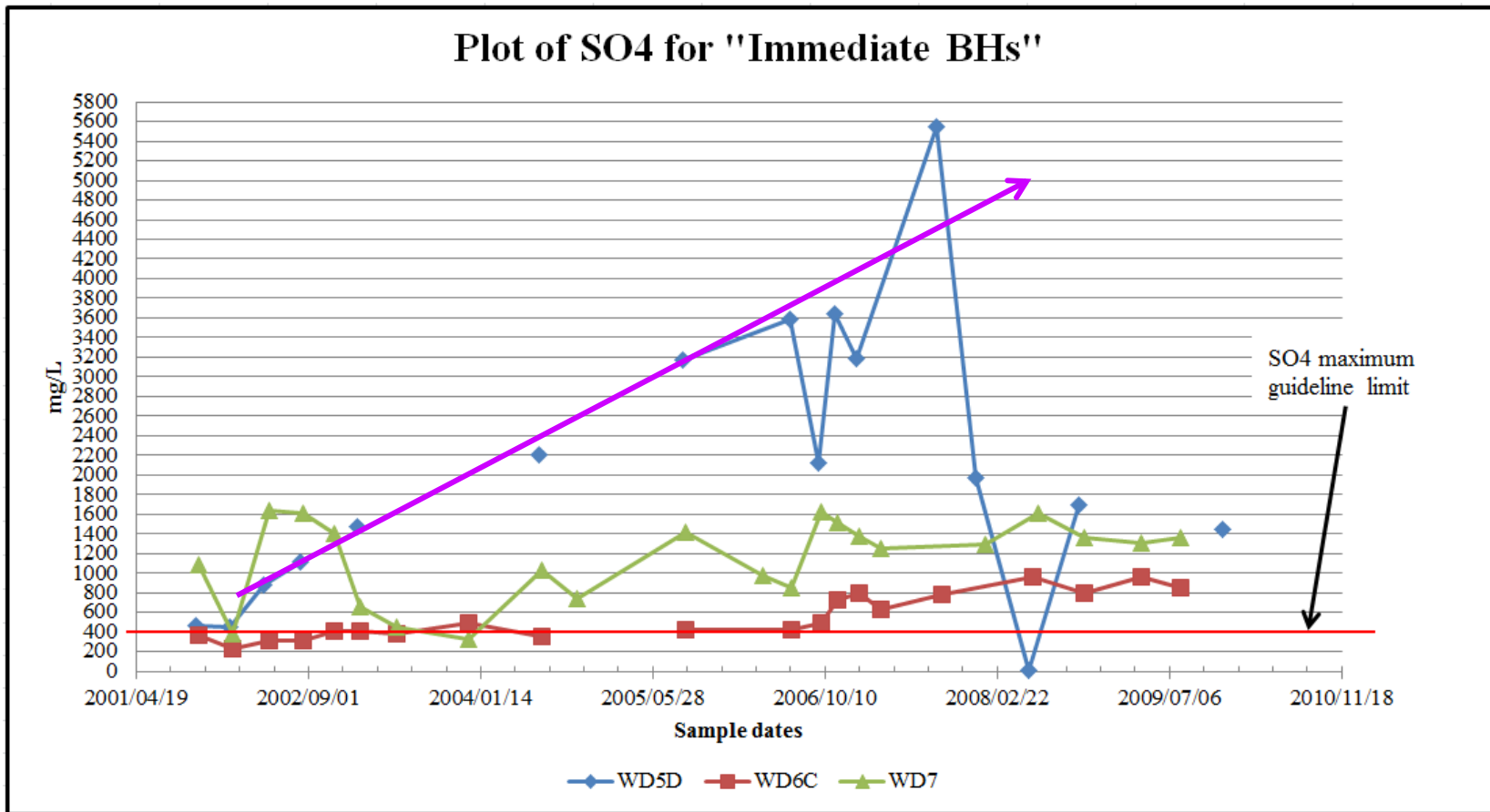


Figure 3-21: Plot of SO4 for boreholes immediate below the slimes dam

Borehole WD5D shows high exceedance of guideline limit (400mg/l) with hith highest values 5543 mg/l in August 2008. WD5D is a shallow boreholes (5m deep, see **Figure 3.22** below) as compared to WD7 with likely depth of between 15 and 25 m. This is good indication difference between shallow and perched or saturated borehole regarding the impact. The high fluctuation of WD5D results observed on the **Figure 3.21** above can be attributed to flushing or mixing of rainfall recharge as compared to data from deeper boreholes WD7 and WD6C with depth approximately 16m deep.

The impact of acidic conditions in shallow boreholes was observed by corroded steel casing on those boreholes (see **Figure 3.23** below). This impact will then challenge the continous monitoring on the area if replacement boreholes with PVC casing are not planned for near future



Figure 3-22: Boreholes in vicinity (approx. <10m) of the return water dam corroded /deteriorated due to acidic water by SO₄

Boreholes below slimes dam

Boreholes WD11B, WD17A, WD17B and WD18A were selected to represent this category located at down-gradient between 90 and 200m away below the slimes and return water dams. These boreholes are also located near the Vaalbank stream downgradient. Boreholes WD17A and WD17B are coupled boreholes about 1-2m apart but with different depth such as 5m and 30m. As observed on **Figure 3.23**, the two boreholes have opposite response (plotting) which can be attributed to their depths. Shallow boreholes will respond quickly to contamination while deeper holes will have lag time.

The migration of the plume (SO₄) shows to be advanced to Vaalbank stream as those boreholes (WD17A & WD18A) is less than 50m to the stream. Again February 2008 indicates high contamination which might be attributed to overflow of return water dam possible by high rain season.

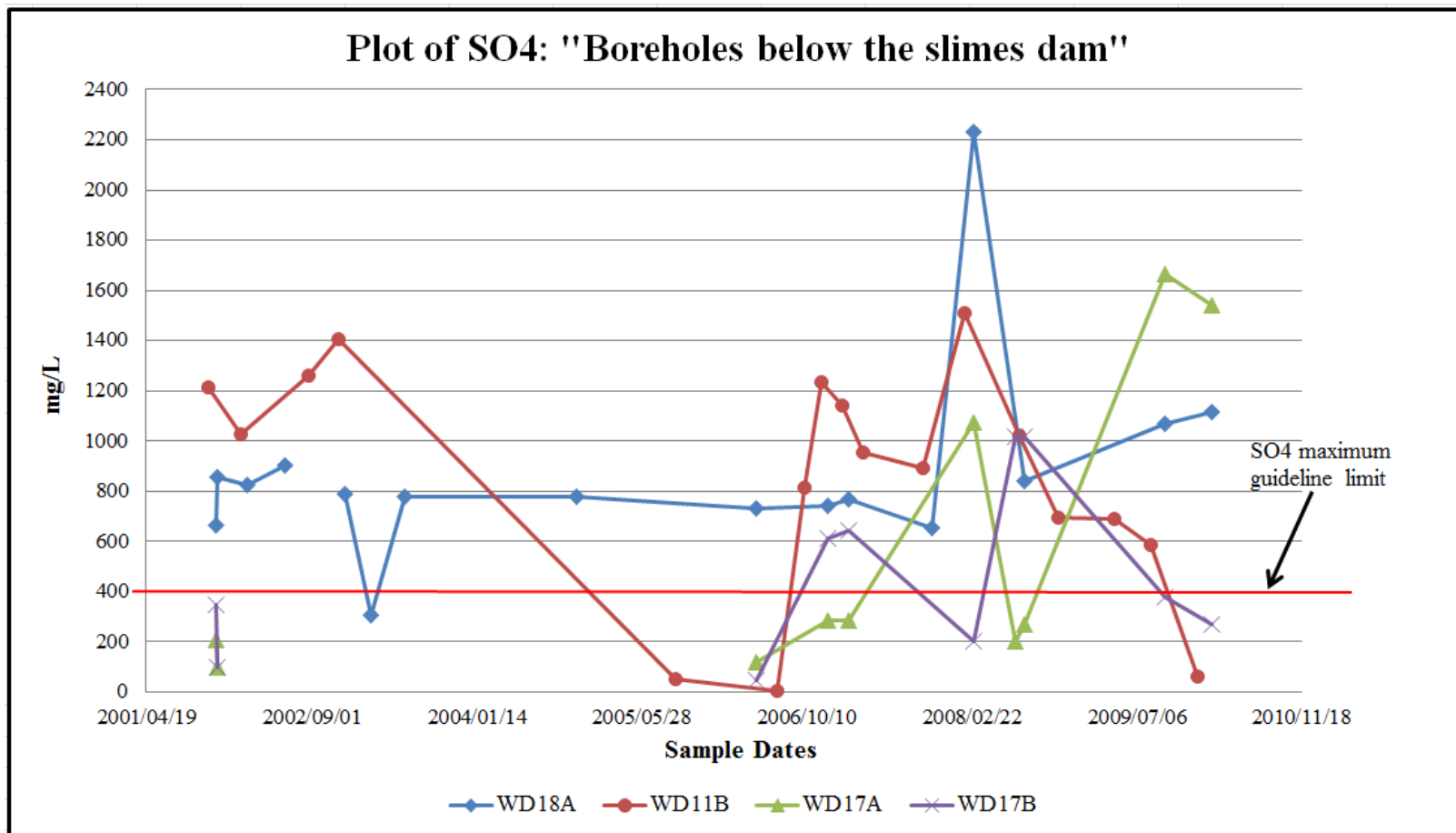


Figure 3-23: Plot of SO₄ for boreholes below the slimes dam

The selected boreholes (WD11B, WD17A, WD17B & WD18A) in **Figure 3.24** below were also plotted for hexavalent chromium results. As indicated in **Figure 3.24** below, Cr(VI) results were always below the guideline limit. This clearly shows evidence of kind of pollutants encountered on western part of the study area as compared to the eastern part with slag dump. Western part indicates to have no pollution by Cr.

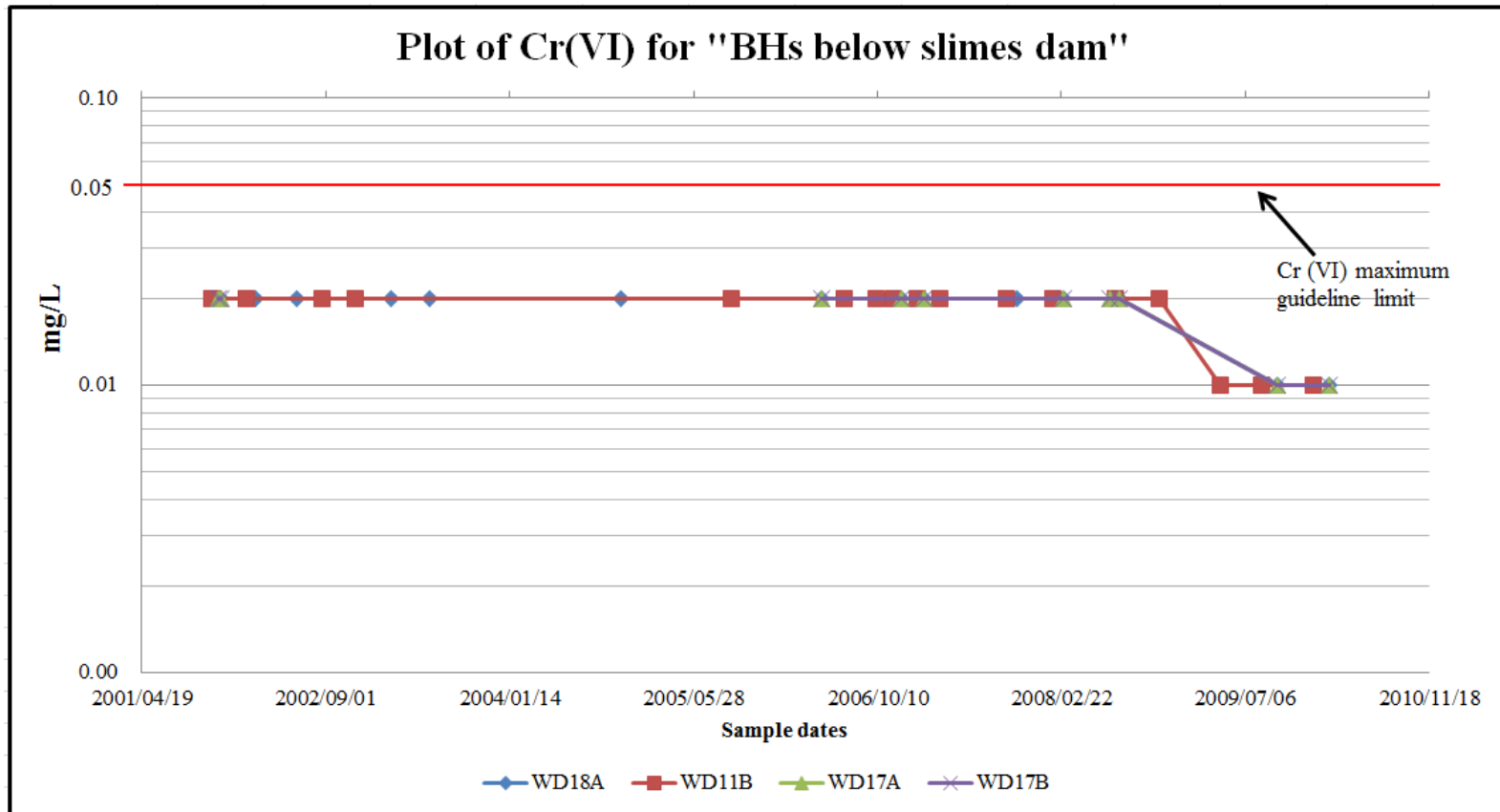


Figure 3-24: Plot of Cr(VI) for boreholes below the slimes dam

The above figure also indicates constant sample results (0.02 mg/l) between 2001 and 2008 of Cr(VI) which can be attributed to lower detection limit of the instrument. However, results of 2008 to 2010 indicate some decrease which is likely to be the change of equipment used.

3.8.4 TRILINEAR PLOTS

The above selected boreholes, (i.e. east and western boreholes) were also plotted on piper diagram for assesemnt of water type and origin. The classification of hydrochemical facies using piper diagram helps in terms of identifying mixing of waters and origin of water

3.8.4.1 Eastern boreholes

These boreholes were represented by background (CSD16), immediate (SD7) and below HDS boreholes (SD10 &11). The plot (**Figure 3.25** below) of background borehole, CSD 16, shows background water quality dominated by Ca and Mg cations and bicarbonate anion species (**Type B** water, see legend on **Figure 3.25**). Both immediate and below HDS boreholes (SD 7, 10 & 11) indicate to have poor water quality dominated by Ca + Mg and Cl + SO₄ (type A water).

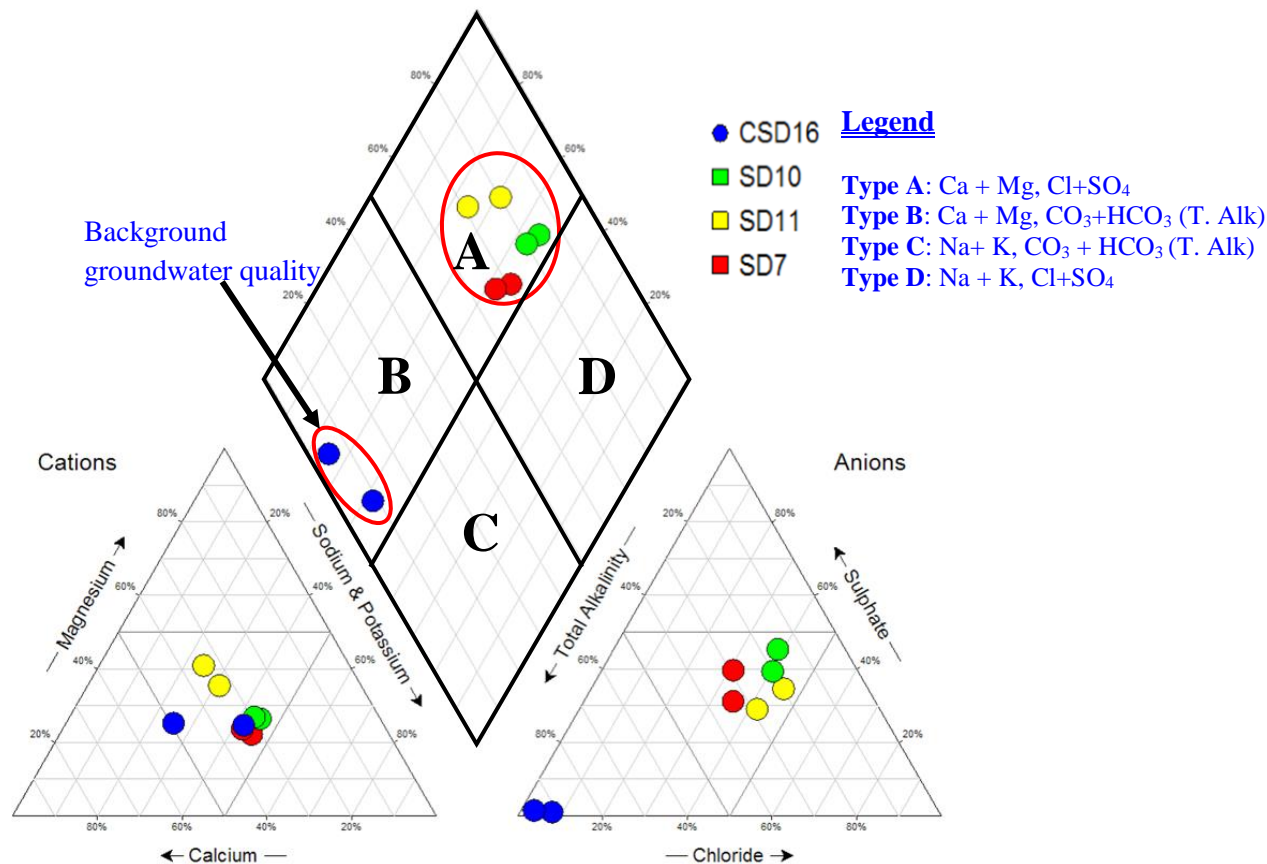


Figure 3-25: Piper plots for eastern boreholes on HDS area

Western boreholes

Background boreholes (WD9 & WD 10) indicate the sodium-bicarbonate type of water (i.e. **Type C** water as illustrated on **Figure 3.26**). It was unfortunate that borehole, N3-880, could not plot on piper due to lack of all required data such as total alkalinity (or HCO_3^-). Background monitoring boreholes did not show indication of contamination by contaminants such as sulphate from slimes dam and return water dam. Although, WD18A is not immediate to slimes dam has water type as those immediate which can be attributed to depths of boreholes.

Boreholes (WD5D, WD7 & WD 18A) in the vicinity or immediate slimes dam indicate sodium-sulphate water type (i.e. **Type A** water). WD18A is a shallow borehole as WD5D (5m deep, see **Figure 3.22** above) which might be vulnerable to immediate contamination due to spillage of the dam during rain seasons.

Monitoring points (WD 6C, WD11B, WD17A) located below the return water dam have magnesium-sulphate water type (**Type D** water).

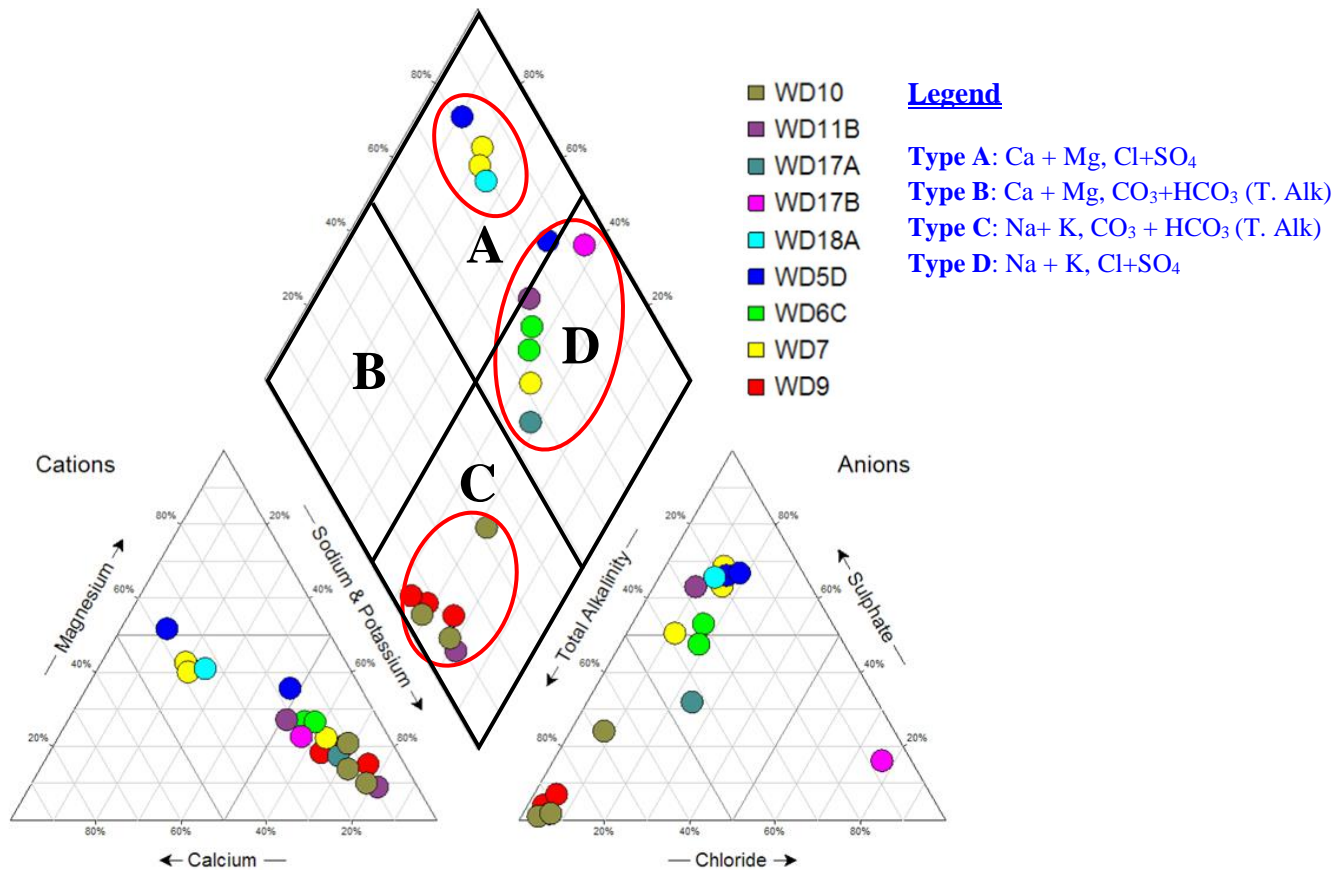


Figure 3-26: Piper plots for western boreholes around slimes dam

3.8.5 CONCLUSIONS FOR GEOCHEMICAL AND IMPACT ASSESSMENT OF THE STUDY AREA

The assessment of the impact of the contaminants in the study area was based on available monitoring results. The following comments are relevant:

Eastern boreholes

Results from eastern boreholes indicates that groundwater contamination are predominantly by two major contaminants namely:

- Sulphates
- Cr(VI)

The impact indicates that the main source of contamination is the HDS based on the fact that background borehole, CSD 16, is having no contamination of SO₄ and Cr(VI) except manganese (Mn), 0.28 mg/l, and Iron (Fe) 0.333 mg/l, which might be related to natural of other unknown activities not related to HDS.

Immediate boreholes and boreholes downgradient were all showing contamination by both SO₄ and Cr(VI) (see **Figure 3.21**)

Western boreholes

The following comments have been made for western boreholes:

- Boreholes on the western part show contamination with predominant sulphates. No significant Cr(VI) was observed in these boreholes (see **Figure 3.24** above). However it was noted that contamination by sulphates were higher than in the eastern counterparts.
- Borehole N3-880 used as background monitoring point indicated good water quality followed by WD9 and WD10 as they were located at upper gradient.
- Boreholes immediate below slimes dam and far below (near Vaalbank stream) indicated high impact of sulphates. It was therefore, concluded that slimes dam is the major source of the contamination.
- Contaminated boreholes below slimes dam with no contamination by Cr(VI) indicated that the area was not used for slag dumping as observed at the HDS.

3.9 SOURCE DESCRIPTION

Sources of groundwater contamination were identified during site visit and also from notes provided from personnel involved. The following were noted:

- Identification of possible sources
- Contribution of sources to groundwater
- Types of disposed material and possible contaminants
- Extent of the source area

A source-pathway-receptor principle has been used to assess the study area. The diagram below (Figure 3.27) illustrates general groundwater flow at the site with its associated source-pathway-receptor principle

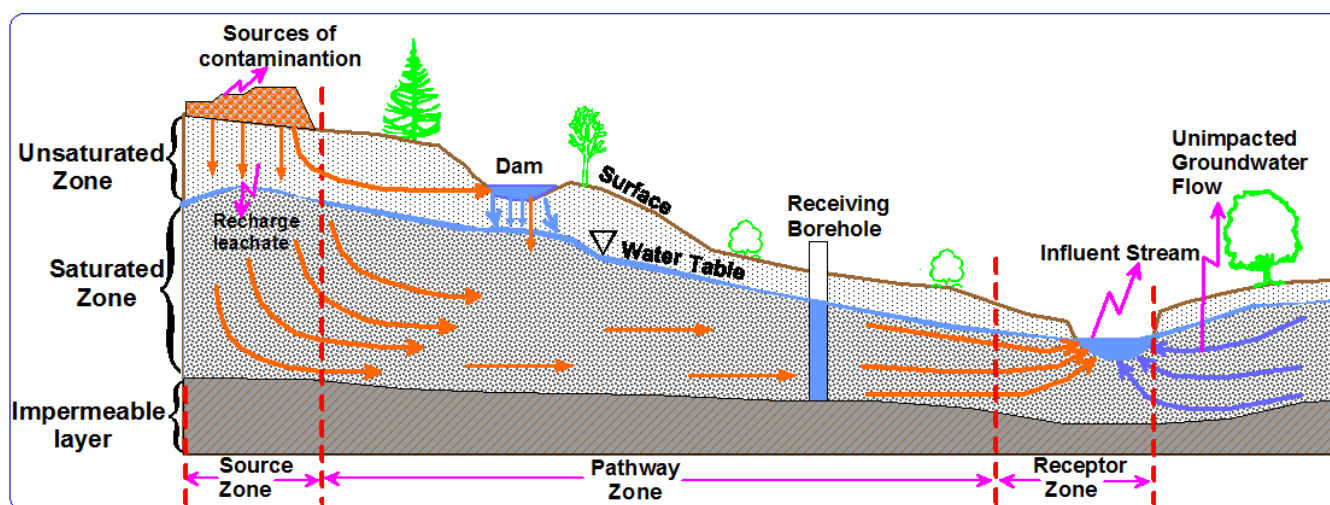


Figure 3-27: Schematic of groundwater flow representing Source-Pathway-Receptor principle

3.9.1 Identification of possible source of contamination

Identification of chromium contamination at study area was based on the literature reviews and laboratory investigations results from previous studies which used redox reactions as indicators of hexavalent chromium. The general redox indicators theory was brought below for better understanding before fieldwork identification

3.9.1.1 General Redox Indicators

Generally, oxidation/reduction indicators are substances that change colour upon being oxidized or reduced (Skoog et al., 1996). Because of this chromium's property, it is thus an advantageous for a pilot site characterization of chromium contaminated sites. **Table 3.4** (below) has been compiled in attempt to use chromium's properties particularly that of colour change, for characterization of its oxidation state in both liquid and solid state.

Studies by US EPA (1994) demonstrated that, monomeric species (CrO_4^{2-}) imparts a **yellow** colour to the water when concentration of C(VI) is greater than 1 mg/L. Water that contains

high levels of dichromates ($\text{Cr}_2\text{O}_7^{2-}$) has an orange colour (see **Table 3.4** below). Because colour depiction mainly depends on concentration level (>1 mg/L), it therefore requires that one must be cautious when no colour may be visible when concentrations are less than 1 mg/L.

Hence acceptable environmental risk concentration for Cr(VI) is 0.02 ppm (DWAF, 1998). Therefore visibility of the colour may only be significant for concentration above 1 mg/L and thus only assist on type of chromium specie or oxidation state (Cr(III) or Cr(VI)) to be analyzed in the laboratory.

Table 3.4 Appearance and solubility of some chromium compounds

<i>Substance</i>	<i>Chemical Compound</i>	<i>Oxidation state</i>	<i>Colour</i>	<i>Solubility</i>	<i>Reference:</i>
Chromic acid (Chromium (VI) oxide)	CrO_3	+6	Bright orange solid	Dissolves readily in: <ul style="list-style-type: none"> Water. Very strong acid (H_2SO_4). Oxidizing agent. In NaOH forming chromate (CrO_4^{2-}). 	Lee, 1996 & EPA, 1984
calcium chromate	CaCrO_4	+6	Yellow crystals	Practically insoluble in water, soluble in dilute acids	ATSDR, 1993
Calcium chromate (VI) dihydrate	$\text{CaCrO}_4 \cdot \text{H}_2\text{O}$	+6	Yellow	Soluble in water	WHO, 1988
Lead chromate	PbCrO_4	+6	Orange yellow	Insoluble in water; soluble in strong acids (e.g. HCl & HNO_3).	EPA, 1984
Chromium (VI) fluoride	CrF_6	+6	Yellow solid	Unstable	Lee, 1996
Dichromate	$\text{Cr}_2\text{O}_7^{2-}$	+6	Orange	Less soluble in water.	EPA, 1994
Potassium chromate	$\text{K}_2\text{Cr}_2\text{O}_7$	+6	Red brown	Very unstable, decomposes to Cr(+III) and Cr(+VI).	Lee, 1996
Chromium fluoride	CrF_5	+5	Red solid	-	Lee, 1996
Chromium (IV) oxide	CrO_2	+4	black	Made from hydrothermal reduction. Very rare compounds	Lee, 1996
Chromic (III) oxide	Cr_2O_3	+3	Green solids	Insoluble in acid, but oxidized to Cr(VI) in alkaline solution.	Lee, 1996 & EPA, 1984
Chromic (III) chloride	CrCl_3		Red-violet flakes (solids)	Insoluble in H_2O , but soluble in presence of Cr^{2+}	EPA, 1984 & ATSDR, 1993
Chromic (III) fluoride	CrF_3		Green	-	##
Calcium chromium (III) oxide	CaCr_2O_4	+3	Olive-green	insoluble	WHO, 1988

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World Health Organization (WHO, 1988), also obtained that, gradual reduction of hexavalent chromium to the trivalent state, is demonstrated by the colour change of the conventional chromate cleaning solution, in the laboratory from bright orange to green, in the presence of organic matter. Groundwater impact by chromium, particularly Cr(VI) with concentration > 1 mg/L can be visualized by the colour property of chromium.

3.9.2 Field identification of chromium contamination

A field visit was undertaken during the study to identify possible cause of contamination and visual impacts that will assist to assess the study area.

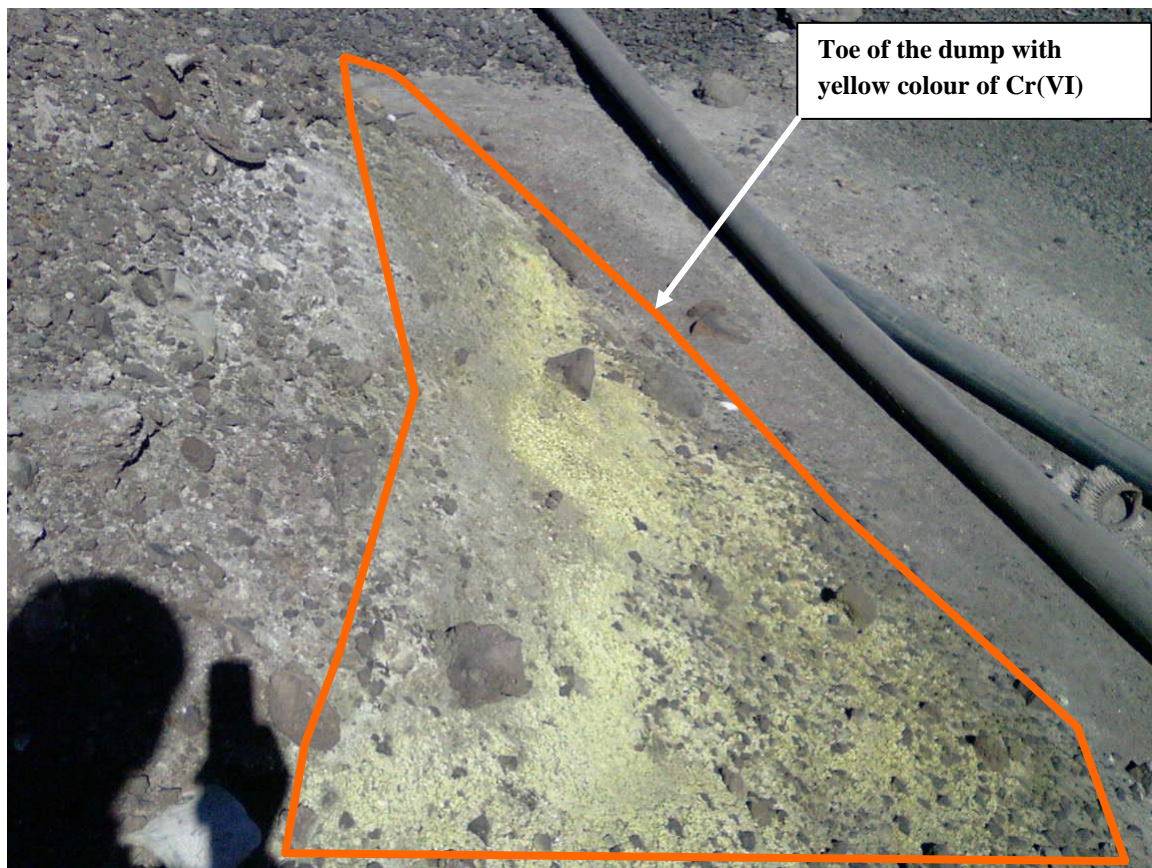


Figure 3-28: Photo taken from HSD (June 2006) indicating evidence of the presence of Cr(VI) at the toe of the dump.

It was earlier highlighted in **section 3.12.1.1** of this chapter, that the presence of hexavalent chromium is observed or can be characterized by its yellow colour if Cr(VI) exceeds 1 mg/l. Furthermore, this colour is more evident in moist soils. Therefore, **Figure 3.28** illustrates the toe of the dump where the soil is moist and presence of Cr(VI) can be observed by its yellow colour at the HDS.

Both groundwater seepage and surface water crosses at two dams called Dam 4A and 4B. Water samples of Dam 4B indicates to have elevated (above the limit) of Cr(VI).

3.10 GROUNDWATER PATHWAYS

3.10.1 PATHWAY DESCRIPTION

Identification of possible groundwater pathways

Surface water flow at the study area is mainly to the south-westerly direction. However, groundwater flow at the HDS is predominantly to the west. Information on the assessment of possible groundwater flow barriers such as dyke and sills has not been obtained for this particular study.

However, any preferential groundwater flow such as fractures could be seen as possible and immediate pathway to the stream, Vaalbank. It has been reported that during high rainfall overflow of contaminated water at Dam 4A & 4B, which is collection point for contaminated water, occurs and is quickly reaching Vaalbank stream in the vicinity.

The challenge with the assessment and prevention of pathway at the HDS is that the storage facility is not lined to prevent leaching of material to subsurface. The current existing preventative measure is canal/trench capturing all surface with dosing of ferrous sulphate and shallow groundwater flow. However, this does not give a guarantee that no further contaminant can possibly escape through seepage in to the subsurface, flow through preferential pathways such as fractures to the stream below.

A quick snapshot **Figure 3.29** was taken to illustrate position of HDS, boreholes (SD 1-12) between stream and collection dams (Dam 4A & 4B) and stream. Sample results taken on boreholes during year 2007 indicated highest sulphates (SO_4) contamination of 1125 mg/l for SD10. Furthermore, SD 7 indicated Cr(VI) of as high as 0.357 mg/l for sample result of 2009. These results have exceeded maximum limit of 0.05 mg/l (total Cr) for drinking water for US EPA and SA Drinking water Standards (SANS 241 of 2011). Results from boreholes SD4 did not indicate some observed contamination as they are upper gradient and expect them to serve as background monitoring points.

The observed contamination from boreholes SD 7-12 between HDS and stream are indication of possible pathway between source and receptor.



Figure 3-29: Photo taken from HSD (June 2006) indicating evidence of the presence of Cr(VI) at the toe of the dump.

Figure 3.30 below indicates a cross-section cut from south-east (point AA) through the Historic Dump Site (HDS) to the north-west (point BB) of the study area in order to illustrate the flow gradient of the site. The distance covered in this cross-section cut is 2000m

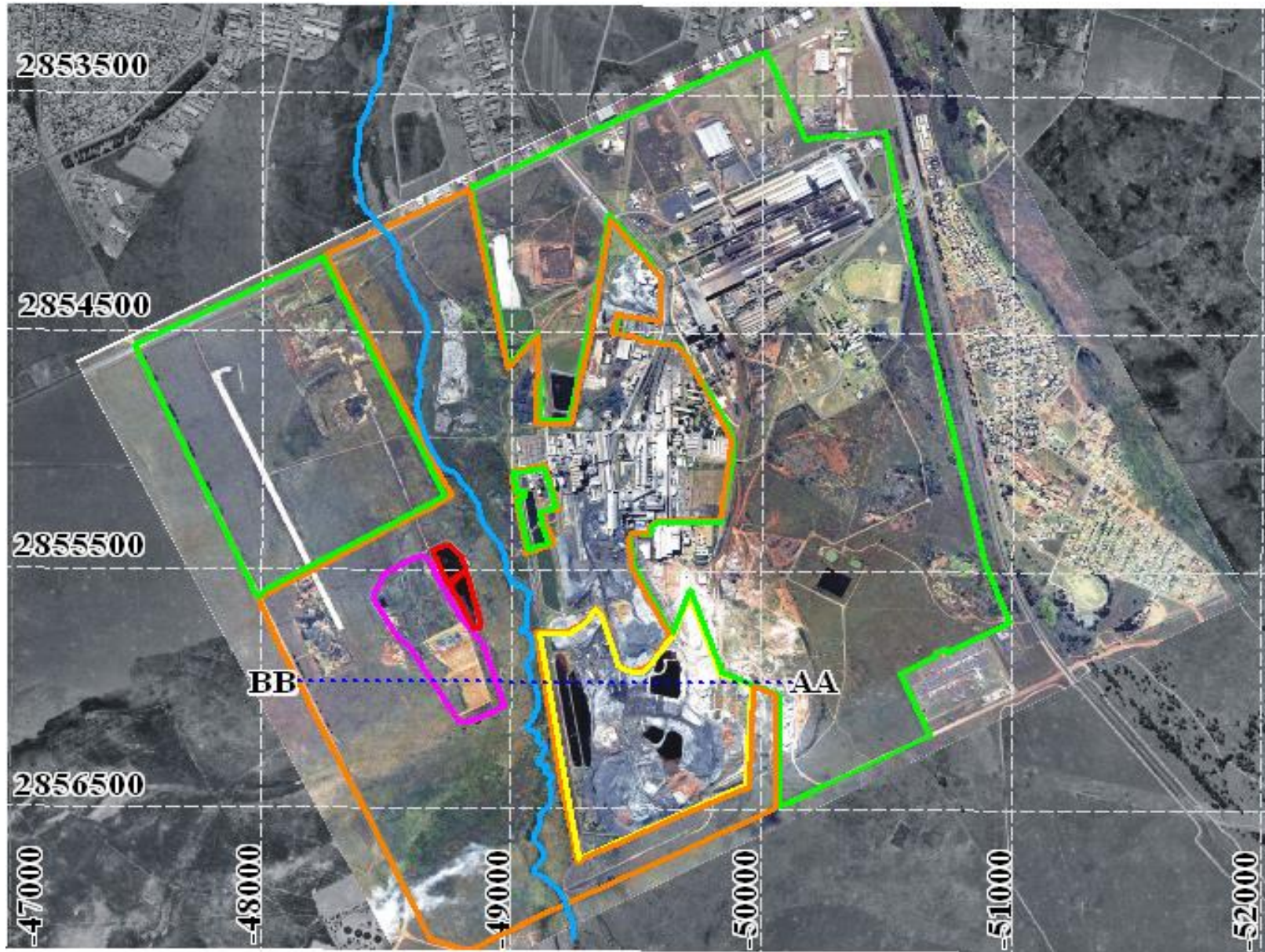


Figure 3-30 FIGURE 3.30: Cross-sectional cut from point AA (SE) through the HDS to point BB (NW).

The plot below (**Figure 3.31**) indicates the cross-section illustrated above which is used to analyze the flow situation in the area.

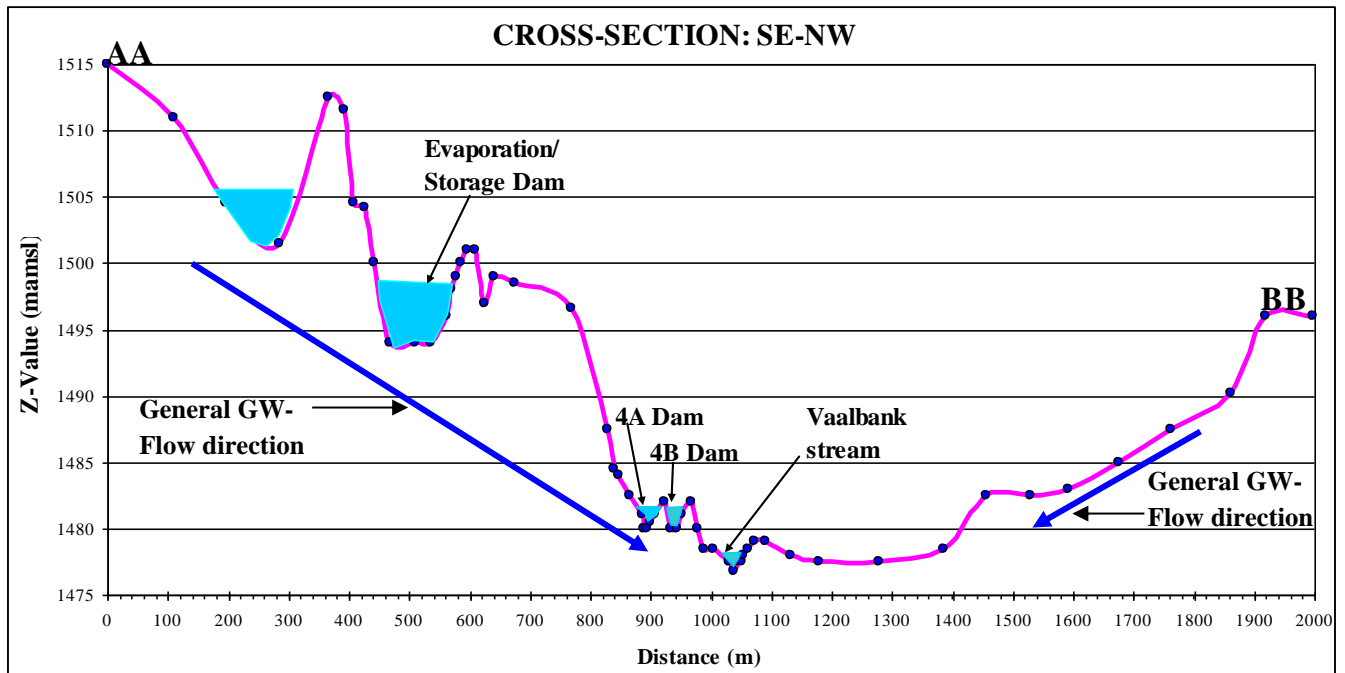


Figure 3-31: Cross-sectional cut and from point AA (SE) through the HDS to point BB (NW) and possible groundwater flow directions.

3.11 RECEPTORS

3.11.1 Identification of receptors

The most crucial stage in the process of identification of immediate receptors is identification of nearest receptors which are likely to have adverse impact during receiving the contaminant. Vaalbank stream lies approximately 70m west of HDS is the source of contamination. There is no drinking water supply borehole between HDS and Vaalbank stream which could be perceived as critical receptor for possible impact in water supply to community.

The major receptor in this area is the Vaalbank stream which runs from south to the north of the study area. The source of contamination as mentioned earlier is about 70m to the stream. Any overflows due to high rainfall or possible preferential groundwater flow will eventual reaches the stream.

Several monitoring points for stream at within the study area has indicated degree of exceeding guideline limits for sulphates (SO_4) and chromium (Cr^{3+} and Cr^{6+}) for certain occasion. This is an indicator of contamination reaching the stream.

However, monitoring points below and outside the study area have indicate some decrease in contamination which can be attributed to dilution during mixing in the flow process. Similarly background samples on stream did not show and contamination as anticipated.

3.12 IMPACT ASSESSMENT

The description of impact has been described fully in sub-section 3.13 & 14 dealing with the pathways and receptors. The mechanism of impact has been identified as through overflow of collection dams (4A & 4B) located at the HDS. However, it is worth to note that the process of cooling the slag by spraying water onto it is possible the main course of regeneration of chromium six. As the water infiltrates the old slag with more dissolved oxygen, the slag can then change from Cr^{3+} to Cr^{6+} .

The impact on the stream especially when going down stream for few kilometres is difficult to assess as water is diluted and quick to be predicted as the model used is for groundwater.

3.12.1 Modelling of the study area

It is always a good practice to create a conceptual model of the area as to indicate better understanding of geologic complex and hydrogeologic system of the study area prior modeling. This will help to guide and to adjust the model where there is a misrepresentation of the field situation.

However, conceptual model representation is illustrated on **Figure 3.14** on sub-section 3.9. Modflow was selected as the modeling code for this study and the package is called Groundwater Modeling System (GMS 8.1). Modflow is a modular three-dimensional finite-difference groundwater model of the U. S. Geological Survey, to the description and prediction of the behaviour of groundwater systems have increased significantly over the last few years). The GMS interface was developed by the Environmental Modeling Research Laboratory of Brigham Young University in partnership with the U.S. Army Engineer Waterways Experiment Station.

3.12.2 Model Construction

A three layer model was constructed to represent, weathered shale (layer 1), fractured rock (layer 2) and weathered diabase (layer3).

The following table (**Table 3.5**) presents information used during model setup

TABLE 3.5: MODEL INPUT INFORMATION

No.: of layers	3	Remarks
Dimensions	72 rows & 68 columns	
Refinement	Around contamination source and well in the same location	High convergence around source and pumping well
Maximum elevation	1558	
Permeabilities (JMA, 2007 & WLP, 1987)	Layer 1 = 0.012 m/d Layer 2 = 0.032 m/d Layer 3 = 0.078 m/d	
Rotation angle for grids/model	28°	
Recharge	5.75×10^{-5} m/d	Based on 700mm/a and 3% groundwater recharge

3.12.3 Boundary conditions

Boundary conditions are very important in terms of representation of field conditions. Both south and northern parts of the model (Vaalbank Stream) were given specified heads as these values were available.

The Vaalbank and unknown stream were specified as drain throughout the model area (see **Figure 3.32** below).



Figure 3-32: Model setup for the study area

3.12.4 Model Calibrations

The model was calibrated for flow scenario in steady state period since 1995 to 2011. **Figure 3.33** indicates the initial heads before any pumping to any borehole. The observed modelled hydraulic heads indicate to correspond with the pre-conceptual model provided earlier in section 3.9.

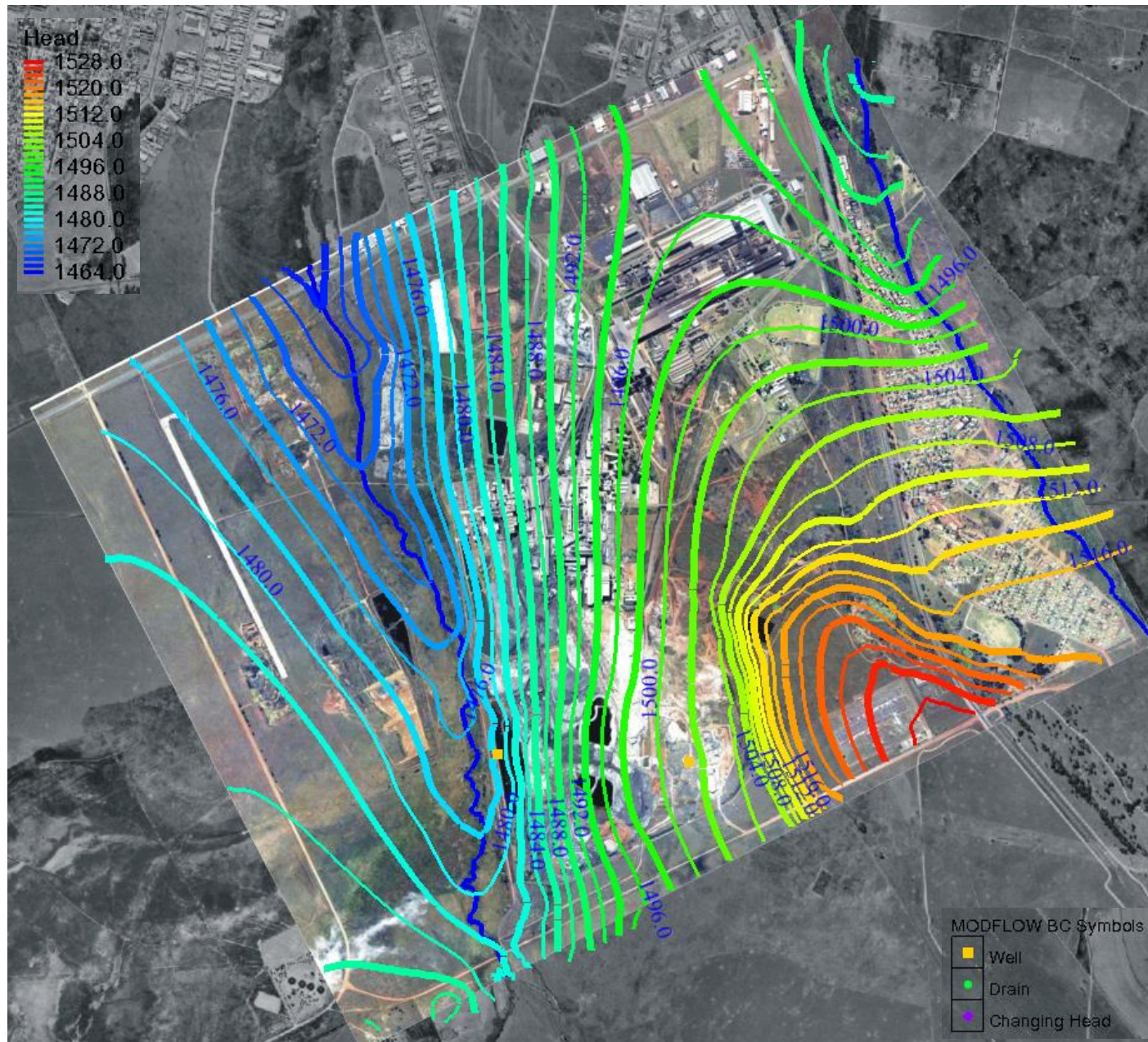


Figure 3-33: Model starting heads within the study area

Initial groundwater level elevations were generated through general knowledge of groundwater level depths in the study area, followed by interpolating depth of groundwater table for the model domain. The results were then subtracted from the surface topography. Shallow groundwater table (0-3m) are located along the Vaalbank stream while deepest groundwater table ($\pm 15\text{m}$) is in the high lying areas

3.12.5 Mass transport calibration

After flow calibration, mass transport model was also calibrated for both SO_4 and Cr as they are the major contaminant from sample results. The model was calibrated from year 1995 to 2011. The current predicted plume for SO_4 is indicated in **Figure 3.34** below

The input parameters are provided in **Table 3.6** below.

TABLE 3.6: MASS TRANSPORT INPUT PARAMETERS

Locality	Specie/ package	Initial values (mg/l)	Comments or assumptions
HDS	SO_4	2734	Based on Dam 4A highest values assumed to recharge or leach into subsurface
	Cr	17.8	Maximum value obtained from monitoring (Dam 4A) during Oct 2001
Slimes dam & return water dam	SO_4	5534	Based maximum record on monitoring data (WD5D Aug 2007 results)
	Cr	0.14	Maximum monitoring values at slimes dam
Porosity		0.3	
Model Package	MT3D		

Furthermore, the source of contamination to groundwater which mainly originate from collection point, Dam 4A and dam4B was taken into consideration. Dam 4A and 4B recorded highest values for both chromium (max. 17.8 mg/l, 2001) and sulphate (max. 2734 mg/l) and therefore were used as recharge/leachate area.

Chromium (VI) was plotted for Dam 4A to indicate trend of monitoring results since 2001 up to 2005 (see Figure 3.31 below)

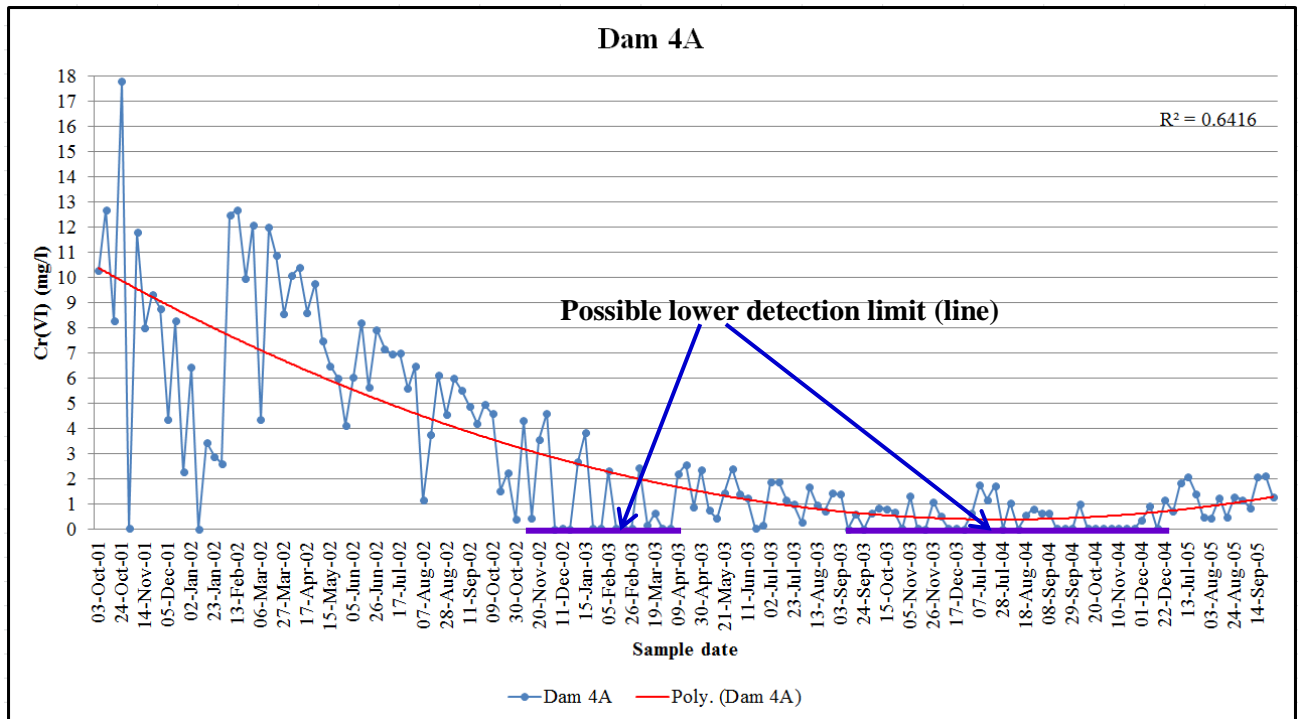


Figure 3-34 Chromium (VI) monitoring results since 2001 to 2005

The trend indicates high contamination in 2001 and 2002, but some improvement in 2003 and 2004. This can be attributed period where dosing of ferrous sulphate at infiltration gallery for reducing Cr(VI) to Cr(III). However, the plot of polynomial trend line indicates another increase of Cr(VI) in 2005.

Contamination in the upper-gradient during dump and water cooling of slag, is collected at Dam4A & 4B which is the main reason to use it as the main source or contamination recharge area in the mass transport model.

Both SO₄ and Cr(VI) were used for the assessment of the plume extent during mass transport modelling.

Three scenarios were assessed for both SO₄ and Cr(VI). The following comments for these scenarios are relevant:

- First scenario assessed the initial conditions and plume extent
- Second scenario assess 10-11 years after dumping commenced
- Third scenario assess 17 years which is current scenario

Please see **Figure 3.35** for the calibration results for sulphates for both HDS and the slimes dam.

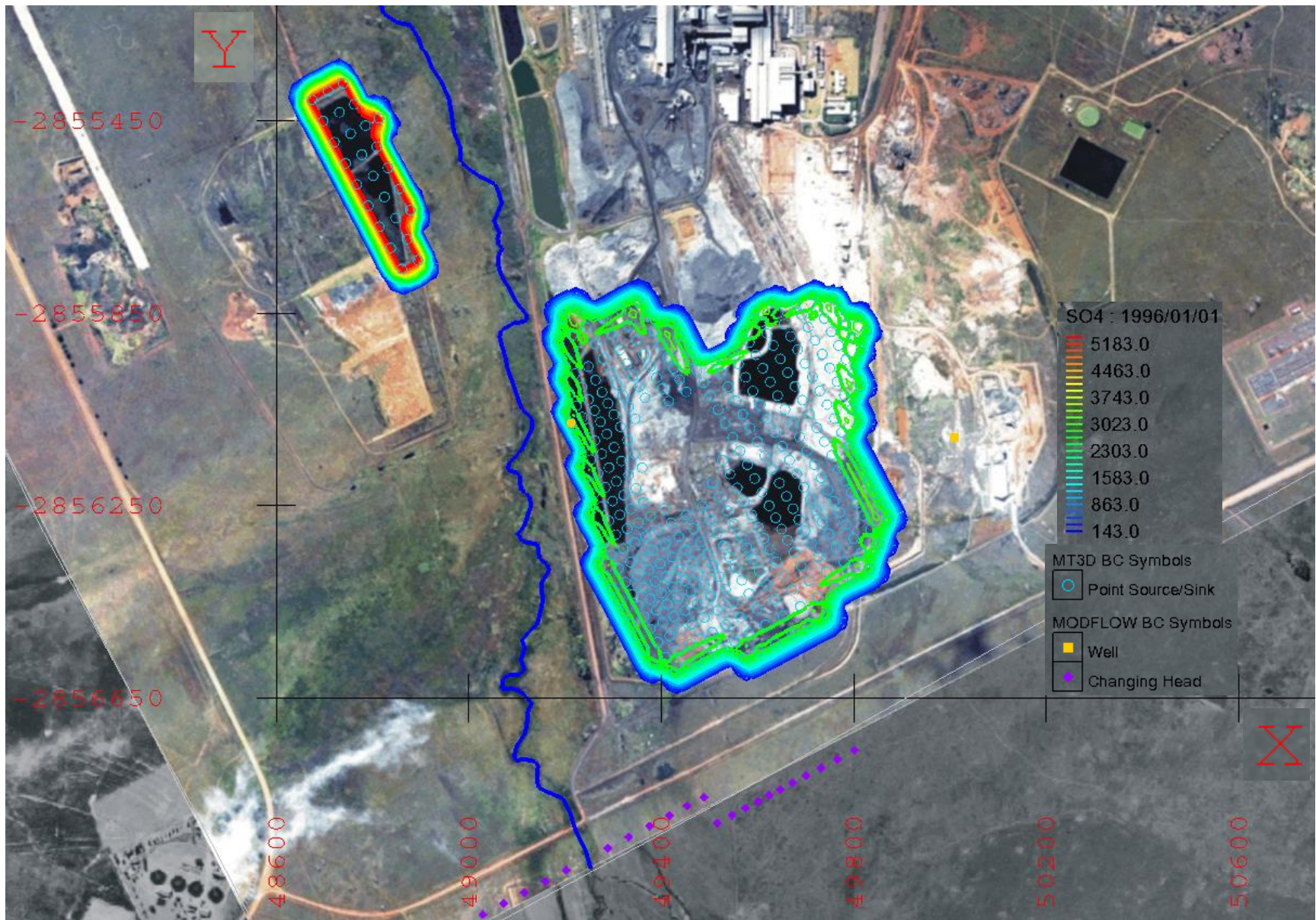


Figure 3-35: Plume extent for SO4 for the HDS and Slimes Dam (1 year)

The initial SO₄ values for slimes dam and HDS were 5534 mg/l and 2734 mg/l respectively. Slimes dam recorded highest contamination of sulphates as compared to the HDS as it can be observed on the intense of SO₄ concentration on Figure 3.35 above.

Further SO₄ assessment of 11 years was performed.

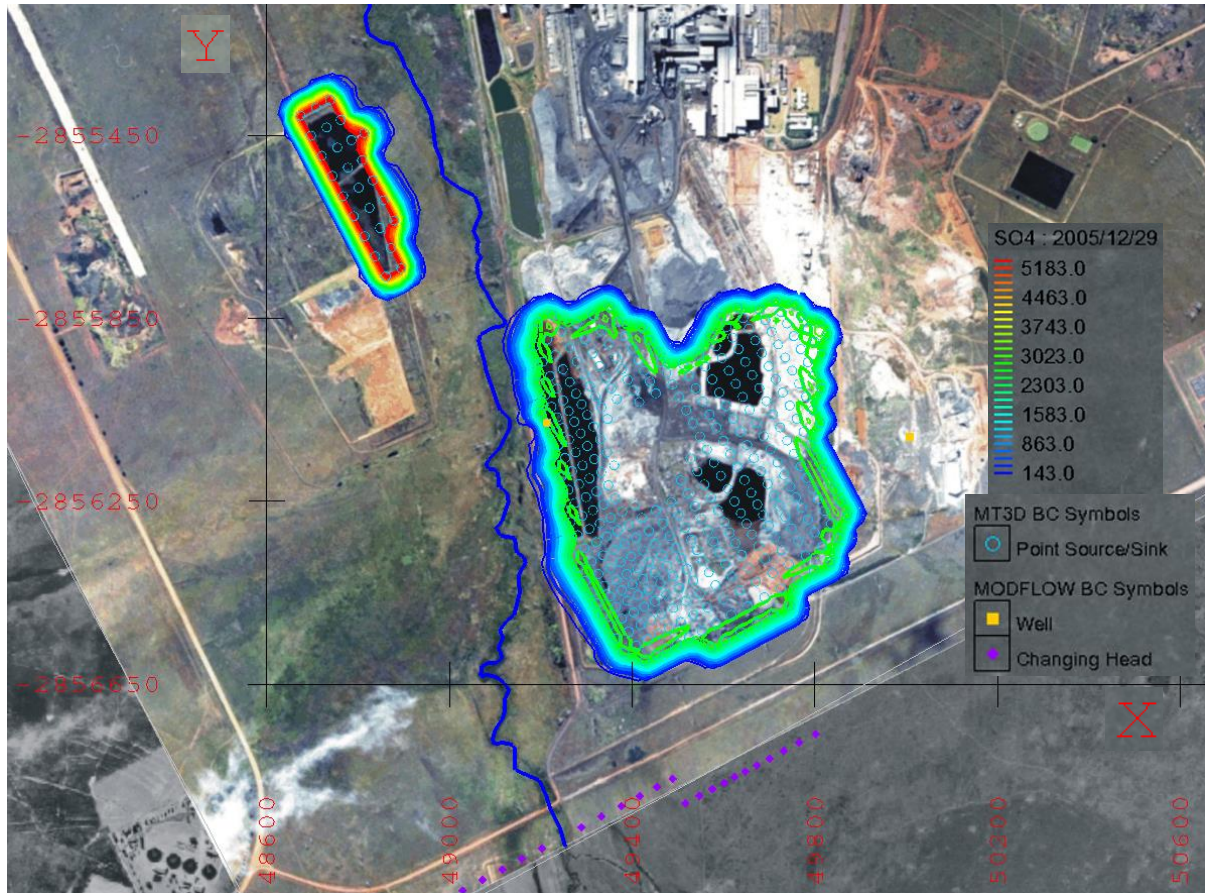


Figure 3-36: Plume extent for SO₄ for the HDS and Slimes Dam (11 year)

The plume indicates to have reached the Vaalbank stream with values estimated between 143 – 700 mg/l.

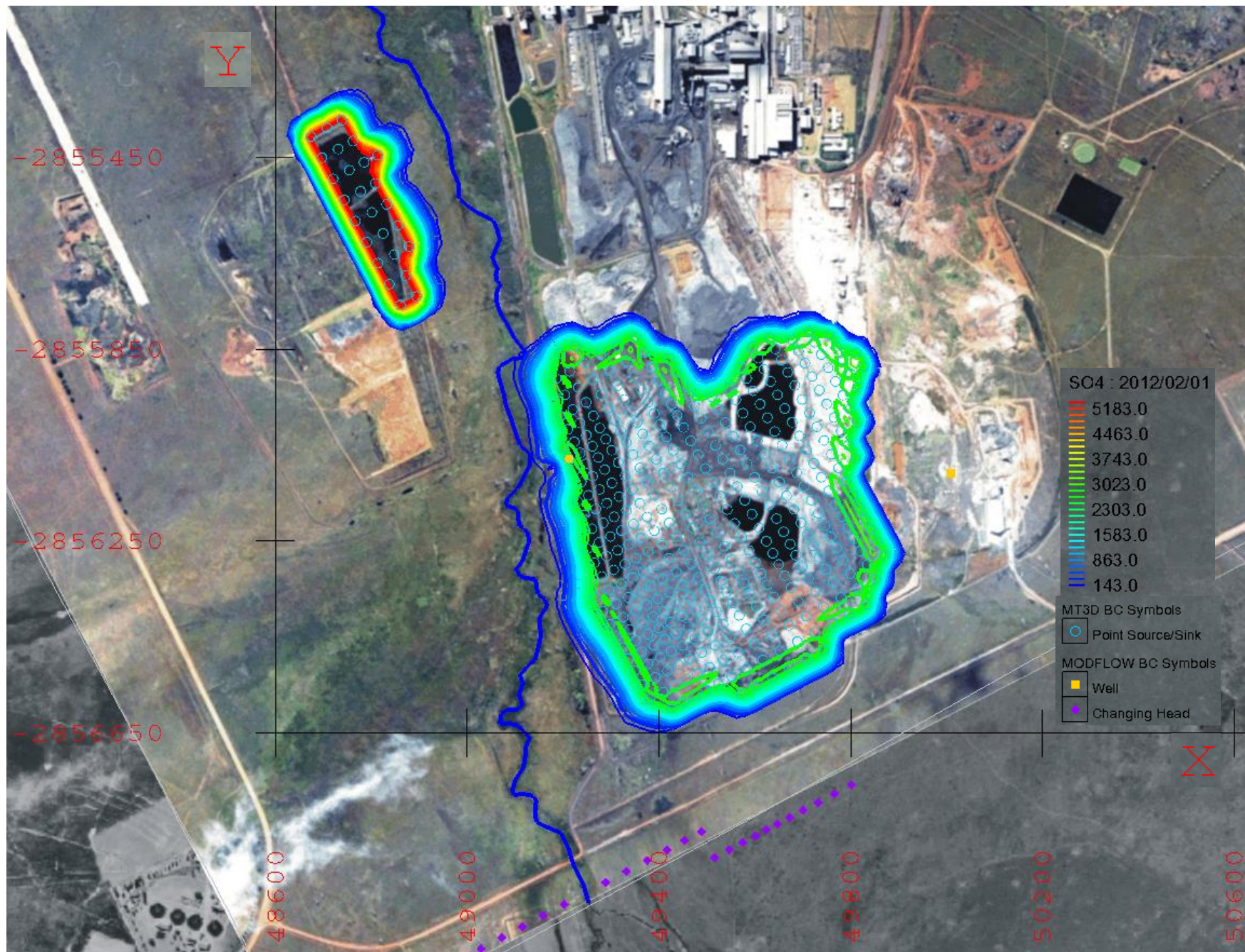


Figure 3-37: Plume extent for SO4 for the HDS and Slimes Dam (17 years)

Chromium (Cr^{6+}) was also assessed for plume extent in the study area. The following figure illustrates Cr (VI) plume model for both HDS and the slimes dam

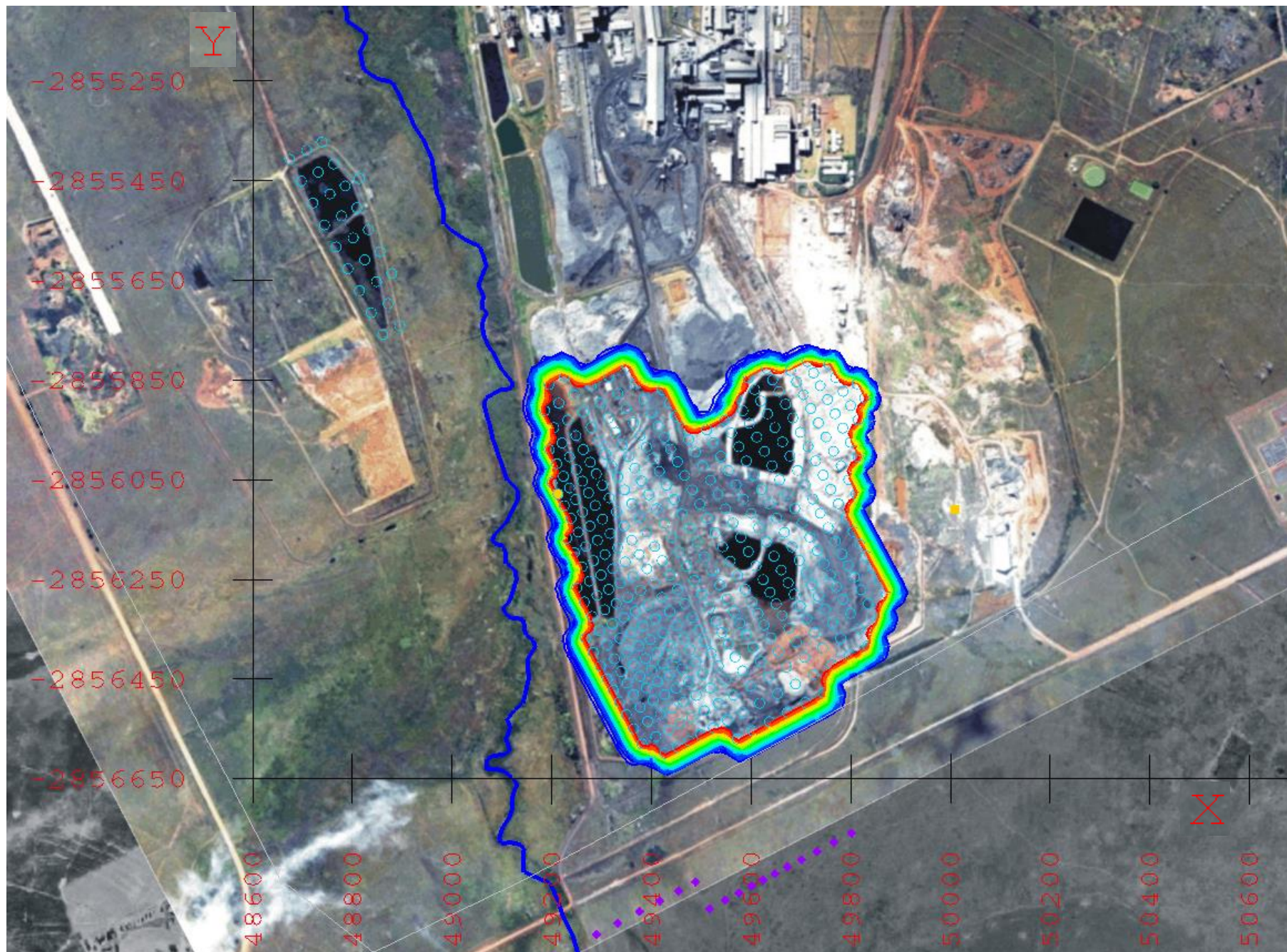


Figure 3-38: Plume extent for Cr(VI) for the HDS and Slimes Dam (1 year)

It is observed that there is insignificant impact in the vicinity of of the slimes dam and HDS. Slimes dam does not indicate any plume extent as it will be recalled that slimes dam did not indicate any record of chromium slag dump. As a result (from monitoring data) slimes dam was given maximum initial value of 0.14 mg/l which will hardly show any extent as it was once off.

A 10 year plume assessment was also performed to observe the extent (see **Figure 3.39** below)

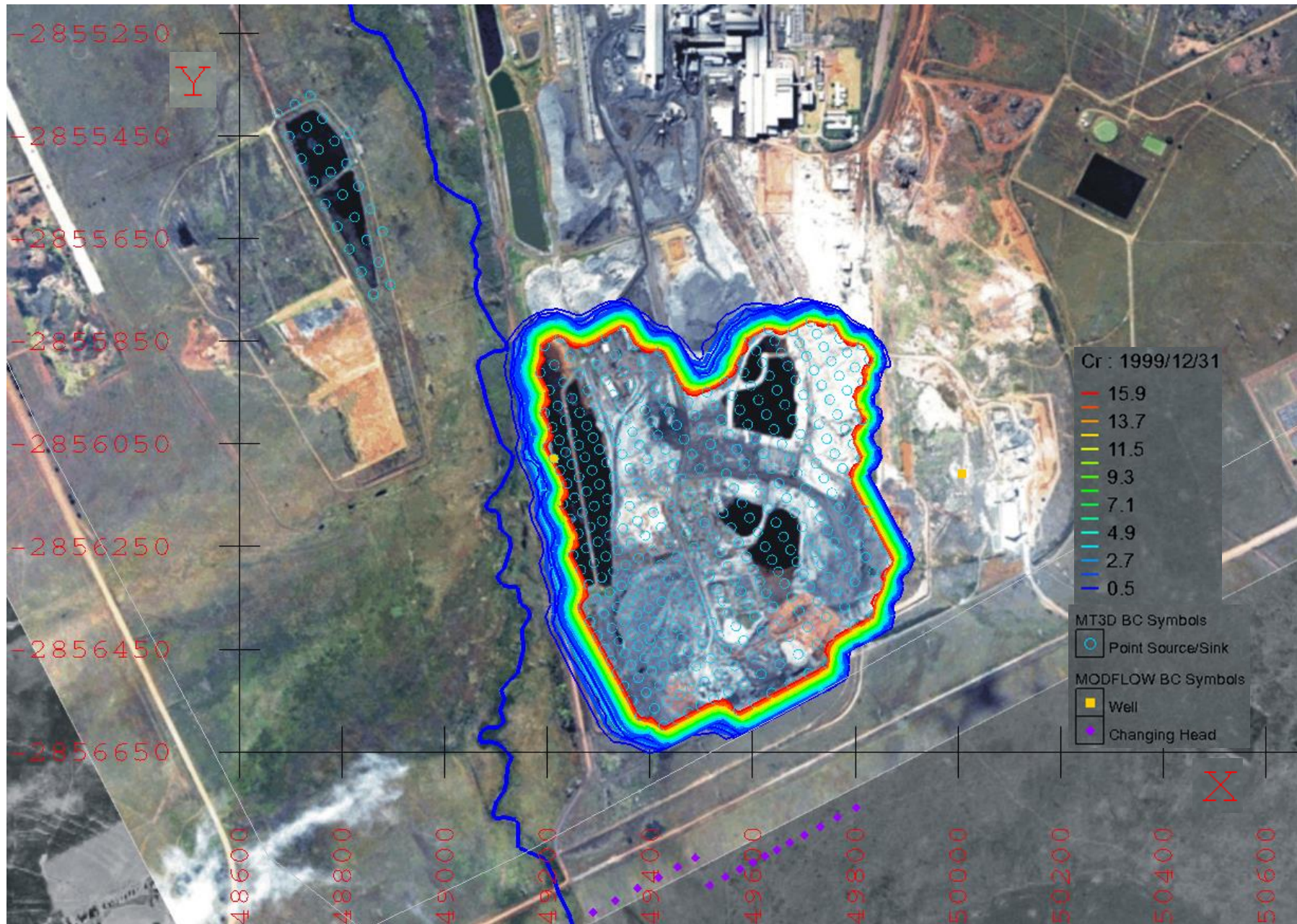


Figure 3-39: Plume extent for Cr(VI) for the HDS and Slimes Dam (10 years)

HDS was given initial Cr(VI) of 17.8 mg/l based on maximum value obtained from monitoring data from Dam4A. This was used as initial value as it is believed that leachate from the dam will reach groundwater system and eventually reach Vaalbank stream.

The final scenario of the assessment of Cr(VI) was to assess the current situation which is 17 years since activities commenced (see **Figure 3.40** below)

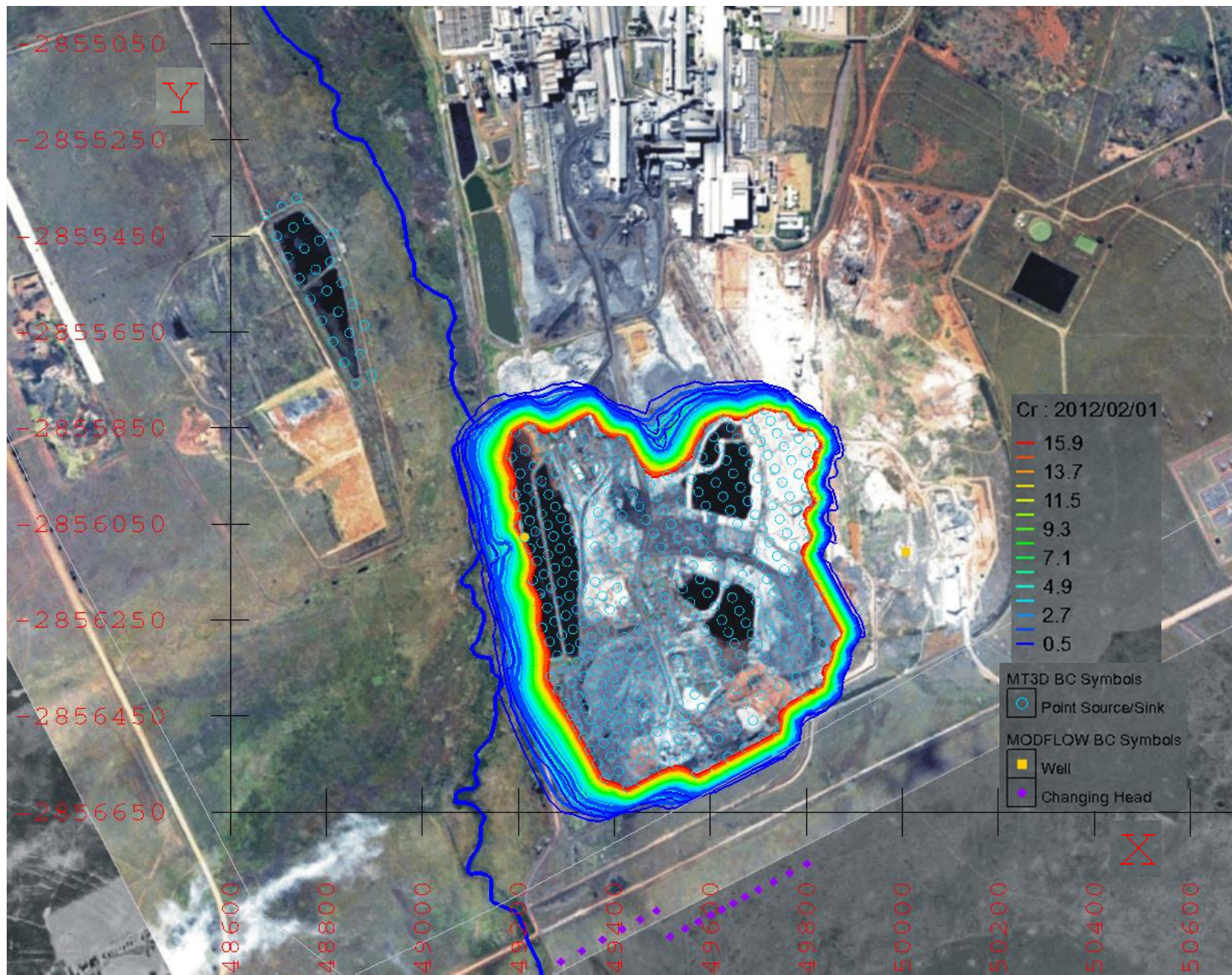


Figure 3-40: Plume extent for Cr(VI) for the HDS and Slimes Dam (17 years)

The slimes dam does not indicate any contamination by chromium when compared to the HDS which indicate an advanced plume to the Vaalbank stream.

SUMMARY

The plume indicates to have reached the Vaalbank stream. The western part of the model is contaminated by SO_4 according to the monitoring data. This can be attributed to the existing slimes dam as all boreholes at the down-gradient of the slimes dam are contaminated. In particular, shallow boreholes (5m deep) indicate major impact compared to deeper boreholes (30m deep). The observed high contamination on the shallow boreholes can be attributed to fluctuation of water table in the capillary fringe with presence of dissolved oxygen and moisture. As indicated in the previous sections, oxidation of Cr(III) to Cr(VI) requires moisture and dissolved oxygen which is almost similar case to generation of SO_4 . However, oxidation of Cr(III) can also be increased by presence of manganese dioxide (MnO_2). Samples from CSD 16 indicated some marked increased (see appendix III) on Mn which in turn may oxidize Cr(III) to Cr(VI)

However, HDS site is contaminated by both chromium and sulphates. Chromium is generated from filter cake, fine dust and possible oxidized Cr^{3+} to Cr^{6+} . Although contamination by SO_4 seems to be peculiar, the usage of ferrous sulphates (FeSO_4) for neutralization of chrome six at Dam 4A (trench) is one of the reason there is high SO_4 contamination in groundwater samples.

3.12.6 Model assumptions

The following assumptions were made for the model:

- For steady state, input concentration will remain constant
- Chemical reactions or adsorption on sediment is negligible due to very low reducing capacity as the contamination occurred many years (± 17 years)

4. CHAPTER 4: RECOMMENDATIONS AND CONCLUSIONS

4.1. REMEDIAL APPROACHES AND DISCUSSIONS

4.1.1. Remedial approaches

Various methods exist for the remedial of sites contaminated by chromium. Amongst those methods the following are relevant:

- In Situ remediation
 - In Situ soil flushing
 - Solidification/Stabilization In situ
 - Electrokinetic treatment
 - Natural Attenuation

- Ex Situ Remediation
 - Pump and treat
 - capping

Table 4.1 below illustrates the applicability and effectiveness of each method for chromium

Table 4.1: Classification of remedial methods for chromium (derived from: Dzombak and Evanko, 1997)

Remedial technology	cost	Long-term Effectiveness/ Permanence	Commercial Availability	General Acceptance	Applicability to High Metals Concentrations	Applicability to Mixed Waste (metals & organics)	Toxicity Reduction	Mobility Reduction	Volume reduction
In Situ remediation									
In Situ Soil flushing	+	«	+	+	+	+	«	«	+
Natural Attenuation /biological treatment	+	«	•	•	«	-	+	+	«
Solidification/Stabilization In Situ	+	•	+	+	+	+	«	+	«
Electrokinetic treatment	•	+	+	+	+	-	«	«	+
Ex Situ Remediation									
Pump and treat/chemical treatment	+	•	•	•	+	-	+	+	«
Capping	+	«	+	+	«	+	«	+	«
Physical Separation	•	+	+	+	+	«	«	«	+
Solidification/ Stabilization Ex situ	•	•	+	+	+	+	«	+	«

• denotes average; + denotes positive; « denotes Marginal; - denotes inadequate information

Table 4.1 above provides various range of chromium remediation methods. However, selection of the method will depend mainly on factors not limited to the following:

- Cost of such method
- Effectiveness to permanently reduce/stabilize Cr(VI)
- General acceptable by given legislation of that country
- Availability of equipment or chemicals used

Treatment of hexavalent chromium for huge scale and long term processing might be challenged by high costs. Few methods have been applied in the study are. These methods include:

- Partial physical separation whereby dust containing Cr(VI) has been collected and dumped at permitted landfill which in this case is Holfontein (**H:H** site)
- Chemical treatment (ex situ) whereby the infiltration gallery has been continuously dosed with ferrous sulphate as a reducing agent.

These methods have reduced the high impact of chromium from previous legacy of random dumping without consideration of taking the dust to Holfontein site. However, the effectiveness of these methods has proved to be partial addressing the issue at site. Observation from monitoring data indicates that contamination still exist at site. As a result further investigation to improve the treatment of contaminated aquifer is envisaged.

The main challenge which is the source (re-generation of Cr(VI) which should be the main focus starting point as addressing the problem without removing the source will be infective and long term costs to the company.

During the study, Cr(VI) contaminated seepage was treated with ferrous sulphate (FeSO_4) as a reducing agent for Cr(VI) at the infiltration gallery before re-entering to Dam4B (collection point). Although this process might seem to be effective, on the other hand sulphates are released to groundwater unintentionally. As a result, monitoring boreholes between dam 4A & 4B and Vaalbank stream indicate high sulphates.

In terms of remediation approach a combination of various methods might work effectively rather a single method. For example pump and treat will only reduce certain amount and other amount will remain in sediment. Again the Natural Attenuation method which utilises soil organics such as fluvic and humic acids may not work effectively on such site with low Potential Aquifer Reduction Capacity (PARC). The low capacity of intake of sediment can be attributed to long term contamination which has already utilised the adsorption of the sediment. This then challenges that coupled methods are required to effectively mitigate the impact. The following methods recommended:

- Pump and treat and then followed by in situ flushing
- Finally injection of sodium dithionite for reduction and stabilization/immobilization on sediments/aquifer

However, the above recommended methods will only work effectively if human activities such as fluctuation of water table by spraying water are controlled on a designed banded area (i.e. lined area of about 200 X 200 m).

4.1.2. Discussions

The challenge faced on this study was availability of consistence record for thorough assessment of the study area. For example there was no continuous record for water levels which could have assisted better to understand its influence or relationship with induced hexavalent chromium. Furthermore certain boreholes were either dry or demolished during operational road maintenance.

However, with such limited data trend analysis on groundwater impact was assessed. Literature review indicated that colour change of chromium on various oxidation states could be utilised on field assessment to identify chrome contaminated sites with concentrations above 1 mg/l. This approached was used successful to identify chrome-contaminated areas at the study area (i.e. Historic Dump Site). Furthermore, the geologic logs of borehole MSA 3 (now called CSD 23) indicated some fractured plane which is indication of possible preferential flow.

4.2. CONCLUSIONS

The successful of the purpose of the study is mainly based on the achievement of the results aimed in the study objectives. The main objective of the study was to assess both impact and risk to environment and human health. In this case the main component of this study was based on the available field results (case study), technical analysis and possible mitigation as this should be helpful in future assessment and remedial of chromium contaminated sites.

The selected cased study with ferrochromium process and slug dump represented most suitable environment for the purpose of this study. However, it must be noted that most detailed analysis were limited due to lack of available data and that fact that it would be out of the scope or objective of the study.

The study focused mainly on the source, pathway receptors and impact assessment to groundwater. Literature studies detailed in chapter 2 have been utilised and was valuable to assess the field data. Sources of contamination have been identified successful as the HDS locate at the south of the study area and the defunct slimes and return water dam in west of the study area. Objectives were successful achieved as the application of theory (literature) was practical feasibly to identify presence or source of hexavalent chromium on the dump site. Furthermore, both groundwater and surface water monitoring results confirmed the impact of groundwater by mainly sulphates and hexavalent chromium

The following conclusions have been made regarding the outcome of the assessment:

- The spraying of water onto the hot slag for cooling purposes need to consider alternative method as this might be likely to be possible main cause for regeneration of hexavalent chromium owing to fluctuation of water levels and moisture which oxidizes Cr(III) to Cr(VI).

- Dam4A & 4B chemical results indicate non-compliance to almost all monitored variables (see Appendix VI). This can be seen as a source of contamination recharging into the subsurface.
- The use of infiltration gallery may serve as capturing point for contamination but it is more likely that escape through overflow during storm rainfall and seepage is also the cause of contaminated water at below monitoring points (i.e. SDs boreholes).

4.3. RECOMMENDATION

The recommendations provided below are mainly based on the outcome of the study. The following recommendations are relevant:

- Monitoring of ground water levels should be performed monthly. This will help to have record of groundwater table fluctuation and eventual confirm the cause of re-oxidation of Cr(III) to Cr(VI)
- Although borehole CSD 16 was used as background monitoring hole, there is a need for one good representative background groundwater monitoring borehole on south of the HDS
- Dam 4A & 4B need to be kept at lower levels to avoid possible spillage/overflow during storm rains.
- A small designed slag cooling area with liner system should be constructed as an alternative for random dumping and spraying. The containment should be designed in a manner that percolated water can be collected (as seepage) to sealed collection point then pump and treated.
- Boreholes such as WD5A-D, with steel casing were deteriorating in terms of corroding and need to be replaced with PVC casing to avoid further corrosion by acidic conditions particularly at toe of slime dam and return water dam.
- Destroyed boreholes below the HDS during haulage road maintenance need to be replace for continuous monitoring
- There should be consistence in terms of monitoring parameters whereby in some results, critical parameters such as SO₄ were missing. The following variables should be always be at least part of monitoring as they assist in assessment of Cr(VI) causes:
 - EC, pH, SO₄, Mg, Ca, K, TDS, Cr⁶⁺, total Cr, NO₃, Fe, Mn and Total Alkalinity,
- Pump and treat can be used in dam 4A & 4B while injecting sodium dithionite which will act as detoxificant and immobilizer of Cr(VI).
- Good database for all monitoring results should be creating for information/records to be available for future investigations

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6. APPENDICES

6.1. APPENDIX I: DEFINITIONS AND ACRONYMS

3.12.7 Definitions of terms

- ❖ **Anaphylaxis** = refers to a rapidly developing and serious allergic reaction that affects a number of different areas of the body at one time. It is caused by exposure to a foreign substance after a preliminary exposure.
- ❖ **Apoptosis** = Disintegration of cells into membrane-bound particles that are then eliminated by phagocytosis or by shedding. It is thought some forms of cancer may result when this process of cell death is somehow interrupted, allowing cells to grow unchecked, with the result being a cancerous tumor.
- ❖ **Briquetting** = the process of agglomerating chrome ore fine and concentrates with binding material such as *Bentonite*.
- ❖ **Coke** = Solid residue of impure carbon obtained from bituminous coal and other carbonaceous materials after removal of volatile material by destructive distillation. It is used as a fuel and in making steel. Coke is the residual solid product obtained upon carbonisation of coking coal. Depending upon property, coke is known as Hard Coke, Soft Coke and Metallurgical Coke.
- ❖ **Crocoite** = Geologic mineral chemically named lead chromate (PbCrO_4).
- ❖ **Carbothermic reduction** = Reduction reaction between carbon and chromite which involves heat.
- ❖ **Ferrochromium** = Mixture of both of chromium (Cr) and iron (Fe) used in the production of stainless steel.
- ❖ **Fluxes** = material that promotes fusing of metals and otherwise aids physical and chemical processing (Papp, 2000).
- ❖ **Gangue** = is worthless rock or other material in which valuable minerals are found.
- ❖ **Chromite ore** = is a rock containing a high concentration of useful minerals (chromium) which can be recovered at a profit. An ore also contains materials without value called gangue.

- ❖ **Coprecipitation** = the simultaneous *precipitation* of a normally soluble component with a macro-component from the same solution by the formation of mixed crystals, by *adsorption*, occlusion or mechanical entrapment.
- ❖ **Slag** = Remaining material of ferrochromium process.
- ❖ **Gangue** = worthless rock or other material in which valuable minerals are found
- ❖ **Green pellets** = Iron-rich powder rolled into balls and fired in a furnace to produce strong, marble-sized pellets. The "green" pellets are then formed in rotating drums or on rotary discs. Green pellets are made by rolling fine grained moist ore with an addition of a binder and fine grained coke breeze into balls in a rotary drum or on a disc.
- ❖ **Sintering** = means heating pelletized chromite up to a high temperature for binding together chromite grains in the pellets with molten quartz (silicates).
- ❖ **Retort process** = a vessel where substances are decomposed or distilled by heat.
- ❖ **Refractory** = Hard, heat resistant substances such as fire clay, bricks or blocks. The refractory protects a furnace shell from abrasion, heat and oxidation
- ❖ **Wet Scrubber** = Apparatus used to remove impurities from a gas with the aid of water. Slurry or slime is emitted from this process.
- ❖ **Reference concentration (RfC)** = Reference concentration (RfC) means a value representing a daily exposure level for the human population, including sensitive subpopulations, that is not likely to cause deleterious and non-reversible adverse noncancer health effects during a chronic or subchronic exposure period. Reference concentration is generally expressed in the unit of milligram per cubic meter (mg/m³).
- ❖ **Reference dose (RfD)** = Reference dose (RfD) means a value representing a daily exposure level for the human population, including sensitive subpopulations, that is not likely to cause deleterious and non-reversible adverse noncancer health effects during a chronic or subchronic exposure period. Reference dose is generally expressed in the unit of milligram per kilogram body weight (mg/Kg/day).

3.12.8 Acronyms, Abbreviations and Symbols

❖ ACD	=	Allergic Contact Dermatitis
❖ NRS	=	Non-Recovery Slag
❖ RS	=	Recovery Slag
❖ POE	=	Point Of Exposure
❖ PARC	=	Potential Aquifer Reduction Capacity
❖ Cr	=	Chromium
❖ Cr (III)	=	Trivalent chromium
❖ Cr (VI)	=	Hexavalent chromium
❖ Cr ₂ O ₃	=	chromium (III) oxide
❖ Al	=	Aluminium
❖ Mg	=	Magnesium
❖ Ca	=	Calcium
❖ PAH	=	Polycyclic Aromatic Hydrocarbon
❖ DNA	=	Deoxyribonucleic acid
❖ RfC	=	Reference concentration.
❖ RfD	=	Reference dose.
❖ RNA	=	Ribonucleic acid; a polymeric constituent of all living cells
❖ U.S. EPA	=	United State Environmental Protection Agency

6.2. APPENDIX II: GEOLOGICAL LOG INFORMATION

BH Name/No	Date drilled	Date Sampled	Water level (m)	Casing depth m (all plain steel with 165 mm)	Depth (m)	Water strike (l/s)	Water Strike Depth (m)	Layer description (m)	Geological Description
MSA 1	01-09-87	22-09-87	8.58	6.00	30	<0.01	23	0-5	Light brown and grey highly weathered shales
								5-11	Dark grey and purple slightly weathered shales
								11-30	Purple and purplish grey shales, mudstones and quartzites
MSA 1A	17-09-87	22-09-87		1.00	4			0-4	Light brown and grey to dark and purple highly weathered shales and mudstones
MSA2	02-09-87	22-09-87	4.94	15.00	30	0.07	1.11	0-7	Light grey and brown to purple brown and purple weathered shales and mudstones
								7-9	Purplish brown and dark purple mudstones
								9-14	Light grey and purple quartzites with intercalated shales and mudstones
								14-30	Dark purple mudstones with thin intercalated quartzites
MSA 2A	17-09-87	22-09-87	6.88	1.00	7			0-7	Light grey and brown to purple brown and purple weathered shales and mudstones
MSA 3	02-09-87	22-09-87	3.82	18.00	30	0.1	0.25	0-3	Moist dark reddish brown clayey silt and moist to wet
								3-10	Light brown and yellow to green highly weathered diabase
								10-18	Weathered and fractured diabase
								18-30	Dark blueish and purple shales, mudstones and quartzites stained brown and yellow on bedding and fracture planes

BH Name/No	Date drilled	Date Sampled	Water level (m)	Casing depth m (all plain steel with 165 mm)	Depth (m)	Water strike (l/s)	Water Strike Depth (m)	Layer description (m)	Geological Description
MSA 3A	17-09-87	22-09-87	3.21	1.00	8			0-8	Moist dark reddish brown clayey silt. Light brown and yellow green highly weathered diabase.
MSA 4	03-09-87	22-09-87	2.87	18.00	30	0.20 & 1.11	25 & 26	0-12	Slightly moist to moist, dark reddish brown clayey silt. Moist to slightly wet, reddish brown becoming yellowish brown to greenish brown highly weathered diabase.
								12-30	Light green and greyish green weathered mudstones and shales. Alternating layers of shales and fine grained hard rock quartzite.
MSA 4A	17-09-87	22-09-87	Dry	1.00	4			0-4	Slightly moist to moist dark reddish brown clayey silt.
								4-10	Moist to slightly wet, reddish brown becoming yellowish brown to greenish brown highly weathered diabase.
MSA 5	03-09-87	22-09-87	6.61	10.00	30		27	0-4	Slightly moist reddish brown silty sand. Dark blueish grey and chocolate brown weathered shales and mudstones.

BH Name/No	Date drilled	Date Sampled	Water level (m)	Casing depth m (all plain steel with 165 mm)	Depth (m)	Water strike (l/s)	Water Strike Depth (m)	Layer description (m)	Geological Description
								4-9	Dry, purple and blueish grey mudstones and hard rock quartzite.
								9-15	Purple mudstones and shales and fine grained hard rock quartzite.
MSA 5A	17-09-87	22-09-87	Dry	1.00	7			0-1	Slightly moist, reddish brown silty sand.
								0-7	Dark blueish grey and chocolate brown weathered shales and mudstones.
MSA 6	03-09-87	22-09-87	12.56	15.00	30	<0.01	15 & 20	0-3	Slightly moist light brown silty sand.
								3-6	Moist purplish weathered shales and mudstones.
								6-10	Slightly moist to dry, dark blueish and purple shales and mudstones.
								10-18	Wet purple shales and mudstones, seeps noticed.
								18-24	Wet, light brown and brown to chocolate brown and greyish green mudstones and shales fractured and jointed.
								24-27	Dark purple shales and mudstones.
MSA7	04-09-87	22-09-87	0.94	10.00	30		15	0-5	Slightly moist light brown sand; alluvium and yellowish brown weathered shales.
								5-9	Slightly moist, purplish brown weathered shales and mudstones.
								9-20	Dry to slightly moist, purple mudstones and shales; thin alternating light greenish grey mudstones.
MSA 7A	17-09-87	22-09-87	1.70	1.00	5	No	N/A	0-2	Slightly moist light brown sand, alluvium.
								2-5	Slightly moist yellowish brown weathered shale becoming purplish brown.

BH Name/No	Date drilled	Date Sampled	Water level (m)	Casing depth m (all plain steel with 165 mm)	Depth (m)	Water strike (l/s)	Water Strike Depth (m)	Layer description (m)	Geological Description
MSA 8	07-09-87	22-09-87	6.58	18.00	30			0-8	Dry to slightly moist dark red brown silty sand
								8-13	Dry to slightly moist light green and brown slightly weathered mudstones and shales.
								13-30	Wet to purplish red and greyish red mudstones and shales, thin intercolated hard rock quartzite.
MSA 8A	17-09-87	22-09-87	6.66	1.00	6			0-3	Dry to slightly moist dark red brown silty sand
								3-6	Dry to slightly moist light green and brown slightly weathered mudstones and shales.
MSA 9	17-09-87	22-09-87	2.26		30			0-6	Slightly moist to dry, brown to chocolate brown and purple highly weathered mudstones and shales.
								6-12	Moist to wet, purple to dark greyish blue and light brown mudstones and shales, weathered and fractured with thin intercolated hard rock dark red and purple quartzites.
								12-30	Fresh hard rock quartzite and mudrock
MSA 9A	17-09-87	22-09-87	0.98	1.00	6	No		0-5	Slightly moist to dry, brown to chocolate brown and purple highly weathered mudstones and shales.
MSA 10	08-09-87	22-09-87	0.24	8.00	17	0.2 and 1.1	5 & 14	0-2	Moist, fill and light brown silty sand

BH Name/No	Date drilled	Date Sampled	Water level (m)	Casing depth m (all plain steel with 165 mm)	Depth (m)	Water strike (l/s)	Water Strike Depth (m)	Layer description (m)	Geological Description
								2-5	Wet, light brownish yellow silt clay residual diabase.
								5-13	Wet, blueish green weathered and fractured diabase
								13-17	Blueish green, very hard rock diabase

6.3. APPENDIX III: GEOCHEMICAL MONITORING RESULTS

Red highlight means values exceeded limit for SANS 241 (2005)

Borehole ID	Coordinates		Date Sampled	PH	EC	Ca	Na	Cr(VI)	Cr (total)	SO ₄	Cl	Mn	Mg	TDS	NO ₃ as N	Fe	F	Total Alkalinity
Units →	X_Coord	Y_Coord	-	-	mS/m	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
N3-880	2855917	-48450	2001/10/04	7.38	52.80	2.48	19.20	0.02		130.00	10.00							
N3-880	2855917	-48450	2002/02/07															
N3-880	2855917	-48450	2002/10/31	7.56	13.80	7.21	10.30	0.02		112.00	420.00	0.44						
N3-880	2855917	-48450	2002/04/11															
N3-880	2855917	-48450	2002/08/01	7.16	9.90	4.75	8.38	0.02		95.10	100.00	0.51						
N3-880	2855917	-48450	2003/01/16	7.42	18.00	5.41	15.00	0.02		83.60	10.00	0.20						
N3-880	2855917	-48450	2003/05/07	7.95	19.30	8.63	10.90	0.02		34.80	10.00	0.40						
N3-880	2855917	-48450	2003/11/27	7.60	15.20	7.68	14.70	0.02		6.55	10.00	0.36						
N3-880	2855917	-48450	2004/08/26															
N3-880	2855917	-48450	2004/10/07	3.60	61.50	8.44	6.57	0.02		63.10	10.00	0.82						
N3-880	2855917	-48450	2005/08/18	7.98	54.50	104.00	9.60	0.02		66.20	18.00	0.70						
Mellsho p N	2855022	-49678	2001/10/04	7.42	119.00	9.64	26.70	0.02		115.00	18.00							
Mellsho p N	2855022	-49678	2002/01/10	7.70	26.80	29.80	5.70	0.02		54.50	140.00							
Mellsho p N	2855022	-49678	2002/04/04															
Mellsho p N	2855022	-49678	2002/08/01	7.73	45.00	54.20	24.90	0.21		56.70	30.00	1.21						

Borehole ID	Coordinates		Date Sampled	PH	EC	Ca	Na	Cr(VI)	Cr (total)	SO ₄	Cl	Mn	Mg	TDS	NO ₃ as N	Fe	F	Total Alkalinity
Mellsho p N	2855022	-49678	2002/10/31	7.89	38.90	38.60	24.80	0.02		94.40	390.00	0.09						
Mellsho p N	2855022	-49678	2003/01/16	8.60	29.00	26.60	10.70	0.02		197.00	13.00	0.07						
Mellsho p N	2855022	-49678	2003/05/07	12.00	73.90	86.60	29.30	0.28		124.00	34.00	0.61						
Mellsho p N	2855022	-49678	2003/11/27	11.10	40.00	32.50	13.40	0.52		24.10	22.00	0.06						
Mellsho p N	2855022	-49678	2004/07/08															
Mellsho p N	2855022	-49678	2004/10/07	7.60	57.80	52.30	21.30	0.02		61.60	22.00	0.15						
Mellsho p N	2855022	-49678	2005/08/18	9.15	33.70	17.60	9.60	0.02		53.50	16.80	0.00						
Mellsho p N	2855022	-49678	2007/02/22	9.49	22.30	36.90	7.06	0.02	2.71	24.70	4.29	1.13	11.60	145.00	0.50	19.10	6.20	
Mellsho p N	2855022	-49678	2007/03/08	7.51	53.60	36.10	23.30	0.02	0.03	51.00	17.10	0.07	20.90	347.00	0.50	0.19	0.47	
Mellsho p N	2855022	-49678	2007/07/30	8.85	33.00	35.40	10.60	0.02	1.19	51.80	11.60	0.15	10.80	208.00		7.68	9.13	
Mellsho p N	2855022	-49678	2007/11/22	9.13	26.40	34.70	5.64	0.27	2.32	33.60	2.54	0.38	8.09	334.00	0.50	8.09	16.00	
Mellsho p N	2855022	-49678	2008/01/31	8.71	21.50	20.70	5.38	0.09	0.41	22.30	5.33	0.04	6.42	139.00	0.50	1.13	6.45	
Mellsho p N	2855022	-49678	2008/03/13	9.20	32.30	33.90	6.34	0.02	0.45	52.30	7.91	0.15	9.75	208.00	0.50	1.38	11.80	
Mellsho p N	2855022	-49678	2008/04/10	8.98	26.90	29.30	4.64	0.07	0.94	31.10	2.78	0.13	9.08	170.00	0.50	1.55	11.80	
Mellsho p N	2855022	-49678	2008/05/08	8.26	39.90	48.30	10.60	0.55	6.55	58.20	7.53	0.15	15.90	252.00	4.76	2.43	1.30	
Mellsho p N	2855022	-49678	2008/06/03	8.57	41.60	38.70	12.00	1.26	3.32	45.40	9.25	0.13	14.70	265.00	2.47	5.61	10.70	
Mellsho p N	2855022	-49678	2008/07/03	8.48	45.10	57.20	16.40	0.14	1.36	45.00	12.30	0.10	17.60	290.00	0.50	0.21		

Borehole ID	Coordinates		Date Sampled	PH	EC	Ca	Na	Cr(VI)	Cr (total)	SO ₄	Cl	Mn	Mg	TDS	NO ₃ as N	Fe	F	Total Alkalinity	
Mellsho p N	2855022	-49678	2008/09/18	7.90		62.10	19.50	0.59	0.90	128.00	23.00	0.22	24.90	366.00		0.79	7.36		
Mellsho p N	2855022	-49678	2009/02/05	8.92		19.10	1.81	0.40	0.92	7.17	1.97	0.22	4.70	82.00		7.53	6.98		
Mellsho p N	2855022	-49678	2009/06/25	8.90		33.40	24.60	0.01	0.21	26.30	6.01	0.20	18.70	158.00		0.10	5.22		
Meltsho p S	2855158	-49694	2001/10/04	6.64	49.30	3.78	28.80	0.02		114.00	16.00								
Meltsho p S	2855158	-49694	2002/01/10	7.60	48.30	40.60	29.30	0.02		58.20	100.00								
Meltsho p S	2855158	-49694	2002/04/04																
Meltsho p S	2855158	-49694	2002/08/01	7.47	50.00	43.00	24.90	0.02		45.60	50.00	0.62							
Meltsho p S	2855158	-49694	2002/10/31	7.03	53.80	47.10	37.60	0.02		89.90	310.00	1.30							
Meltsho p S	2855158	-49694	2003/01/16	7.63	51.00	33.10	21.20	0.02		103.00	27.00	0.19							
Meltsho p S	2855158	-49694	2003/05/07	8.17	64.30	65.70	25.70	0.02		124.00	38.00	0.22							
Meltsho p S	2855158	-49694	2003/11/27	7.40	56.80	46.60	28.50	0.03		95.50	28.00	0.26							
Meltsho p S	2855158	-49694	2004/07/01																
Meltsho p S	2855158	-49694	2004/10/07																
Meltsho p S	2855158	-49694	2005/08/18	7.89	54.50	49.70	26.60	0.02		66.20	18.00	0.30							
Meltsho p S	2855158	-49694	2007/02/22	7.48	51.90	38.60	22.40	0.02	0.13	41.30	19.00	0.39	22.60	334.00	0.50	2.73	0.35		
Meltsho p S	2855158	-49694	2007/03/08	8.71	24.40	16.80	8.64	0.02	0.10	26.10	6.98	0.03	6.19	158.00	0.50	0.20	9.15		

Borehole ID	Coordinates		Date Sampled	PH	EC	Ca	Na	Cr(VI)	Cr (total)	SO ₄	Cl	Mn	Mg	TDS	NO ₃ as N	Fe	F	Total Alkalinity
Meltsho p S	2855158	-49694	2007/07/30	7.56	49.70	38.10	21.50	0.02	0.02	44.90	18.70	0.02	19.90	315.00		5.03	0.35	
Meltsho p S	2855158	-49694	2007/11/22	7.65	51.90	41.70	24.90	0.02	0.02	38.40	15.60	0.02	21.90	19.00	0.50	0.79	1.35	
Meltsho p S	2855158	-49694	2008/01/31	7.39	50.20	41.10	27.20	0.02	0.02	34.30	14.40	0.02	21.90	334.00	0.50	0.28	0.40	
Meltsho p S	2855158	-49694	2008/03/13	7.41	48.40	35.20	20.00	0.02	0.06	35.60	18.90	0.04	18.60	315.00	0.50	0.65	0.57	
Meltsho p S	2855158	-49694	2008/04/10	7.58	49.90	44.10	27.30	0.02	0.06	33.90	17.40	0.06	22.90	315.00	0.50	0.87	0.63	
Meltsho p S	2855158	-49694	2008/05/08	7.45	47.90	44.80	25.90	0.02	0.20	54.50	27.00	0.03	23.80	303.00	6.44	1.90	1.10	
Meltsho p S	2855158	-49694	2008/06/03	7.55	51.80	33.70	27.90	0.02	0.06	36.10	16.20	0.02	19.40	334.00	1.68	1.04	0.90	
Meltsho p S	2855158	-49694	2008/07/03	7.41	47.30	36.70	24.10	0.02	0.02	18.50	16.50	0.02	18.80	303.00	0.50	0.15		
Meltsho p S	2855158	-49694	2008/09/18	7.43		34.50	18.20	0.02	0.02	93.90	17.80	0.06	19.20	303.00		0.16	0.50	
Meltsho p S	2855158	-49694	2009/02/05	7.36		35.00	20.80	0.01	0.05	34.90	15.30	0.12	21.90	290.00		1.83	0.50	
Meltsho p S	2855158	-49694	2009/06/25	7.34		25.30	9.66	0.01	0.21	35.90	15.60	0.20	8.81	290.00		0.10	3.56	
WD1	2855538	-48714	2001/10/04	7.66	52.80	8.69	40.40	0.02		113.00	21.00							
WD1	2855538	-48714	2002/01/10	7.90	20.10	18.30	8.99	0.02		33.20	80.00							
WD1	2855538	-48714	2002/04/11	7.69	35.20	29.00	28.20	0.02		56.60	11.00	0.02						
WD1	2855538	-48714	2002/08/01	7.96	48.30	36.20	35.90	0.02		61.30	60.00	0.71						
WD1	2855538	-48714	2002/10/31	7.65	41.30	28.00	41.30	0.02		93.80	310.00	0.18						
WD1	2855538	-48714	2003/01/16	7.87	21.00	23.20	25.30	0.02		73.10	19.00	0.09						

Borehole ID	Coordinates		Date Sampled	PH	EC	Ca	Na	Cr(VI)	Cr (total)	SO ₄	Cl	Mn	Mg	TDS	NO ₃ as N	Fe	F	Total Alkalinity
WD1	2855538	-48714	2003/05/07	8.06	42.30	33.60	21.30	0.02		63.90	13.00	0.02						
WD1	2855538	-48714	2003/11/27	7.60	40.50	25.90	28.90	0.02		69.10	18.00	0.18						
WD1	2855538	-48714	2004/07/01															
WD1	2855538	-48714	2004/10/07															
WD1	2855538	-48714	2006/03/16	7.27	43.50	30.90	8.44	0.02	0.09	15.70		0.11	15.00	277.00		1.12	0.10	212.00
WD1	2855538	-48714	2006/06/22	7.61	46.10	25.00	17.60	0.02	0.02	53.30		0.19	14.50	303.00		0.45	0.88	180.00
WD1	2855538	-48714	2006/09/14	7.46	310.00	116.00	394.00	0.02	0.02	1096.00		2.18	105.00	1950.00	9.80	70.40	3.87	356.00
WD1	2855538	-48714	2006/11/02	7.45	49.00	33.70	32.30	0.02	0.02	63.20		0.23	21.80	315.00		0.91	1.18	
WD1	2855538	-48714	2007/01/04	7.77	31.50	25.50	17.20	0.02	0.02	31.00		0.16	14.10	202.00		1.59	1.47	
WD1	2855538	-48714	2007/03/08	7.37	195.00	60.30	153.00	0.02	0.03	537.00		0.86	47.00	1260.00		7.46	4.12	
WD1	2855538	-48714	2007/06/22	7.56		30.60	35.60			91.20	17.40		21.40	265.00				
WD1	2855538	-48714	2007/11/22	7.75	45.50	65.80	32.10	0.02	0.02	79.80		0.19	19.40	290.00		1.65	0.96	
WD1	2855538	-48714	2009/07/09	7.65		75.30	49.00	0.01	0.21	229.00		0.50	51.00	694.00		0.11	0.92	
WD1	2855538	-48714	2009/11/26	7.50		61.90	52.20	0.01	0.10	147.00		0.10	33.80	1010.00		0.05	2.54	
WD2	2855436	-48658	2001/10/04	7.61	301.00	10.50	557.00	0.02		1043.00	210.00							
WD2	2855436	-48658	2002/01/10	7.60	56.80	14.40	96.60	0.02		146.00	60.00							
WD2	2855436	-48658	2002/04/11	7.17	78.00	26.60	101.00	0.02		225.00	23.00	1.22						
WD2	2855436	-48658	2002/08/01	7.11	50.10	20.20	52.60	0.02		137.00	100.00	0.45						
WD2	2855436	-48658	2002/10/31	7.18	74.20	24.30	96.50	0.02		167.00	530.00	0.25						
WD2	2855436	-48658	2003/01/16	7.72	70.00	14.80	55.30	0.02		59.60	33.00	0.33						
WD2	2855436	-48658	2003/05/07	7.87	77.20	29.20	84.80	0.02		195.00	35.00	0.66						

Borehole ID	Coordinates		Date Sampled	PH	EC	Ca	Na	Cr(VI)	Cr (total)	SO ₄	Cl	Mn	Mg	TDS	NO ₃ as N	Fe	F	Total Alkalinity
WD2	2855436	-48658	2003/11/27	7.50	40.40	28.80	32.90	0.02		74.00	18.00	0.20						
WD2	2855436	-48658	2004/07/01															
WD2	2855436	-48658	2004/10/07															
WD2	2855436	-48658	2005/08/18	7.79	30.70	15.10	28.00	0.02		61.80	13.90	0.40						
WD2	2855436	-48658	2006/03/16	6.77	47.50	19.70	25.10	0.02	0.04	107.00		0.67	11.10	303.00		0.14	0.36	138.00
WD2	2855436	-48658	2006/06/22	6.66	36.00	19.30	24.40	0.02	0.02	77.80		1.41	11.50	227.00		2.55	0.36	102.00
WD2	2855436	-48658	2006/09/14	7.45	312.00	115.00	398.00	0.02	0.02	1159.00		2.11	101.00	2020.00	9.80	58.00	3.76	357.00
WD2	2855436	-48658	2006/11/02	6.54	37.40	21.30	29.40	0.02	0.02	74.40		1.21	12.30	240.00		3.49	0.33	
WD2	2855436	-48658	2007/01/04	6.68	36.30	17.60	18.80	0.02	0.02	57.80		0.37	9.87	233.00		0.63	0.46	
WD2	2855436	-48658	2007/03/08	7.65	44.80	24.60	21.80	0.02	0.02	44.40		0.21	15.50	290.00		0.66	1.43	
WD2	2855436	-48658	2007/06/22	7.59		23.00	39.40			78.50	16.60		15.20	235.00				
WD2	2855436	-48658	2007/11/22	6.86	53.30	26.90	42.60	0.02	0.02	126.00		0.91	14.50	1510.00		17.40	0.91	
WD2	2855436	-48658	2009/07/09	6.78		27.20	36.60	0.01	0.21	91.30		1.03	19.80	334.00		0.25	2.83	
WD2	2855436	-48658	2009/11/26	6.84		33.70	44.80	0.01	0.10	98.20		0.96	21.30	347.00		0.05	0.50	
WD3	2855372	-48740	2001/10/04	7.70	604.00	5.73	1174.00	0.02		2213.00	420.00							
WD3	2855372	-48740	2002/01/10	7.80	267.00	70.40	565.00	0.02		528.00	340.00							
WD3	2855372	-48740	2002/04/11	7.72	403.00	109.00	754.00	0.02		1225.00	230.00	2.22						
WD3	2855372	-48740	2002/08/01	7.60	460.00	146.00	7223.00	0.02		1758.00	340.00	2.05						
WD3	2855372	-48740	2002/10/31	7.21	538.00	119.00	1370.00	0.02		1032.00	590.00	1.96						
WD3	2855372	-48740	2003/01/16	7.99	104.00	144.00	1058.00	0.02		2405.00	369.00	0.39						
WD3	2855372	-48740	2003/05/07	7.78	557.00	215.00	807.00	0.02		993.00	355.00	0.75						

Borehole ID	Coordinates		Date Sampled	PH	EC	Ca	Na	Cr(VI)	Cr (total)	SO ₄	Cl	Mn	Mg	TDS	NO ₃ as N	Fe	F	Total Alkalinity
WD3	2855372	-48740	2003/11/27															
WD3	2855372	-48740	2004/10/07															
WD3	2855372	-48740	2005/08/18	7.63	272.00	78.00	390.00	0.02		1120.00	10.00	0.50						
WD3	2855372	-48740	2006/03/16	7.11	218.00	43.70	171.00	0.02	0.05	804.00		0.27	37.30	1390.00		12.70	2.77	207.00
WD3	2855372	-48740	2006/09/14	7.57	312.00	106.00	408.00	0.02	0.02	1040.00	9.80	2.25	107.00	2020.00	9.80	87.20	3.75	367.00
WD3	2855372	-48740	2006/11/02	7.18	232.00	80.20	280.00	0.02	0.02	764.00		1.08	68.80	1510.00		28.20	3.99	
WD3	2855372	-48740	2007/01/04	7.30	219.00	71.90	191.00	0.02	0.02	753.00		1.24	58.40	1390.00		14.00	3.72	
WD3	2855372	-48740	2007/03/08	6.76	31.70	16.20	20.00	0.02	0.03	39.50		0.49	9.49	202.00		0.41	0.59	
WD3	2855372	-48740	2007/06/22	7.10		23.90	40.80			71.90			15.30	237.00				
WD3	2855372	-48740	2007/11/22	7.50	240.00	67.70	257.00	0.02	0.02	694.00		0.88	64.80	170.00		24.20	3.99	
WD3	2855372	-48740	2009/07/09	7.33		99.60	240.00	0.01	0.21	820.00		1.88	98.30	1640.00		0.10	3.31	
WD3	2855372	-48740	2009/11/26	7.90		54.90	184.00	0.01	0.10	414.00		1.09	53.30	473.00		0.05	3.57	
WD4A	2855433	-48801	2001/10/11	6.80	253.00	173.00	166.00	0.02		686.00	86.00							
WD4A	2855433	-48801	2002/01/17	8.00	22.30	17.30	13.00	0.02		129.00	10.00							
WD4A	2855433	-48801	2002/04/24	7.42	83.00	59.30	47.00	0.02		355.00	110.00	0.52						
WD4A	2855433	-48801	2002/08/08	6.80	355.00	326.00	175.00	0.02		1157.00	640.00	0.57						
WD4A	2855433	-48801	2002/11/07	7.08	292.00	245.00	239.00	0.02			205.00	0.41						
WD4A	2855433	-48801	2003/01/23	6.70	243.00	204.00	206.00	0.02		1193.00	188.00	0.58						
WD4A	2855433	-48801	2003/04/17															
WD4A	2855433	-48801	2003/12/04															
WD4A	2855433	-48801	2004/07/01	7.21	386.00	119.00	281.00	0.02		1228.00	202.00	0.71						

Borehole ID	Coordinates		Date Sampled	PH	EC	Ca	Na	Cr(VI)	Cr (total)	SO ₄	Cl	Mn	Mg	TDS	NO ₃ as N	Fe	F	Total Alkalinity
WD4A	2855433	-48801	2004/10/14															
WD4A	2855433	-48801	2005/08/25	7.17	382.00	248.00	347.00	0.02		1432.00	336.00	0.90						
WD4A	2855433	-48801	2006/03/23	7.19	151.00	68.30	102.00		0.02	481.00		0.23	48.10	1010.00	2.21	24.90	0.46	169.00
WD4A	2855433	-48801	2006/06/29	7.18	463.00	265.00	456.00	0.02	0.02	2635.00		1.08	223.00	3030.00	2.20	17.00	0.59	862.00
WD4A	2855433	-48801	2006/09/21	8.43	209.00	92.90	114.00	0.02	0.02	690.00		0.02	73.60	1320.00	2.20	0.25	3.54	307.00
WD4A	2855433	-48801	2006/11/09	6.80	426.00	434.00	259.00	0.02		1974.00		1.22	366.00	2770.00	0.50	97.90	0.48	
WD4A	2855433	-48801	2007/01/11	6.95	422.00	288.00	171.00	0.02	0.02	1850.00		0.76	245.00	2770.00	3.50	11.40	0.49	
WD4A	2855433	-48801	2007/03/15	7.02	225.00	204.00	297.00	0.02	0.03	917.00		0.39	152.00	1450.00	0.30	11.90	0.91	
WD4A	2855433	-48801	2007/08/16	7.14	332.00	288.00	287.00	0.02	0.02	1529.00		0.44	242.00	2140.00	10.30	17.10	0.60	
WD4A	2855433	-48801	2007/12/06	7.13	274.00	148.00	161.00	0.02	0.02	977.00		0.42	117.00	1770.00	3.30	229.00	2.76	
WD4A	2855433	-48801	2008/05/08	7.14	327.00	215.00	164.00	0.02	0.02	766.00		0.50	137.00	2080.00	3.00	17.70	0.85	
WD4A	2855433	-48801	2008/10/16	6.99		192.00	407.00	0.02	0.12	1163.00		0.50	168.00	2400.00	0.90	23.40	0.66	
WD4A	2855433	-48801	2009/03/05	7.04		168.00	429.00	0.01	0.20			0.48	139.00	2210.00		46.70	0.93	
WD4B	2855433	-48801	2001/10/11															
WD4B	2855433	-48801	2002/01/17	7.50	355.00	142.00	499.00	0.02		816.00	129.00							
WD4B	2855433	-48801	2002/04/24	7.69	390.00	183.00	459.00	0.02		1262.00	284.00	3.38						
WD4B	2855433	-48801	2002/08/08	7.80	379.00	180.00	527.00	0.02		1144.00	450.00	5.24						
WD4B	2855433	-48801	2002/11/07															
WD4B	2855433	-48801	2003/01/23															
WD4B	2855433	-48801	2003/04/24															
WD4B	2855433	-48801	2003/12/04															

Borehole ID	Coordinates		Date Sampled	PH	EC	Ca	Na	Cr(VI)	Cr (total)	SO ₄	Cl	Mn	Mg	TDS	NO ₃ as N	Fe	F	Total Alkalinity
WD4B	2855433	-48801	2004/07/01	7.29	550.00	259.00	605.00	0.02		1630.00	244.00	1.93						
WD4B	2855433	-48801	2004/10/14															
WD4B	2855433	-48801	2005/08/25	7.76	433.00	89.30	567.00	0.02		1691.00	226.00	0.30						
WD4B	2855433	-48801	2006/03/23	7.01	601.00	338.00	649.00		0.02	2260.00	543.00	3.24	316.00	3970.00		193.00	0.96	367.00
WD4B	2855433	-48801	2006/06/29	7.07	548.00	499.00	325.00	0.02	0.02	3364.00	452.00	0.15	359.00	3470.00	20.80	3.72	0.31	20.00
WD4B	2855433	-48801	2006/09/21	8.44	209.00	7.52	20.10	0.02	0.02	660.00	51.20	0.02	6.35	1320.00	9.80	0.02	3.52	307.00
WD4B	2855433	-48801	2007/01/11	6.91	374.00	411.00	356.00	0.02	0.02	1562.00	207.00	0.74	320.00	2400.00		9.07	0.60	
WD4B	2855433	-48801	2007/08/16	7.38	331.00	242.00	429.00	0.02	0.03	1499.00	208.00	0.30	197.00	2140.00		98.20	0.56	
WD4B	2855433	-48801	2007/12/06	7.12	308.00	165.00	343.00	0.02	0.02	1036.00	163.00	0.53	141.00	1950.00		85.40	2.25	
WD4B	2855433	-48801	2008/05/08	7.17	358.00	321.00	20.80	0.02	0.05	1023.00	118.00	1.00	238.00	2270.00		403.00	1.90	
WD4B	2855433	-48801	2009/12/09	7.14		103.00	343.00	0.01	0.30	786.00	104.00	0.17	90.60	1640.00		0.07	1.28	
WD4C	2855433	-48801	2001/10/11	7.00	384.00	332.00	158.00	0.02		1274.00	312.00							
WD4C	2855433	-48801	2002/01/17	7.50	15.10	45.10	22.90	0.02		143.00	25.00							
WD4C	2855433	-48801	2002/04/24	7.74	213.00	177.00	92.60	0.02		697.00	158.00	0.55						
WD4C	2855433	-48801	2002/08/08	6.90	343.00	287.00	245.00	0.02		1094.00	560.00	0.68						
WD4C	2855433	-48801	2002/11/07	7.24	326.00	324.00	182.00	0.02			255.00	0.56						
WD4C	2855433	-48801	2003/01/23	7.10	326.00	223.00	139.00	0.02		1284.00	251.00	0.54						
WD4C	2855433	-48801	2003/05/08															
WD4C	2855433	-48801	2003/12/04															
WD4C	2855433	-48801	2004/07/01	6.97	495.00	318.00	554.00	0.02		1519.00	236.00	1.92						

Borehole ID	Coordinates		Date Sampled	PH	EC	Ca	Na	Cr(VI)	Cr (total)	SO ₄	Cl	Mn	Mg	TDS	NO ₃ as N	Fe	F	Total Alkalinity
WD4C	2855433	-48801	2004/10/14															
WD4C	2855433	-48801	2005/08/25	7.15	425.00	402.00	283.00	0.02		1717.00	331.00	1.20						
WD4C	2855433	-48801	2006/03/23	7.16	452.00	201.00	296.00		0.02	1515.00	259.00	1.47	200.00	2900.00	2.21	27.50	0.40	304.00
WD4C	2855433	-48801	2006/06/29	7.17	570.00	610.00	392.00	0.02	0.02	3326.00	392.00	0.47	439.00	3660.00	4.90	15.20	0.29	20.00
WD4C	2855433	-48801	2006/09/21	6.94	555.00	630.00	119.00	0.02	0.02	2405.00	308.00	0.32	437.00	3660.00	2.20	16.10	0.51	863.00
WD4C	2855433	-48801	2007/01/11	6.97	381.00	324.00	449.00	0.02	0.02	1438.00	189.00	0.38	231.00	2460.00	2.00	10.00	0.67	
WD4C	2855433	-48801	2007/03/15	6.89	332.00	471.00	227.00	0.02	0.02	1756.00	237.00	1.39	385.00	2140.00	1.10	0.42	0.57	
WD4C	2855433	-48801	2007/08/16	6.98	378.00	410.00	248.00	0.02	0.02	2630.00	258.00	0.45	400.00	2400.00	10.60	23.50	0.59	
WD4C	2855433	-48801	2007/12/06	6.92	403.00	346.00	309.00	0.02	0.02	1383.00	240.00	1.23	315.00	2650.00	1.50	18.60	2.00	
WD4C	2855433	-48801	2008/05/08	7.06	364.00	454.00	14.90	0.02	0.02	770.00	101.00	1.72	363.00	2330.00	4.30	40.60	0.90	
WD4C	2855433	-48801	2008/10/16	7.02		247.00	327.00	0.02	0.02	1070.00	128.00	0.78	188.00	2140.00	0.80	1.15	0.69	
WD4C	2855433	-48801	2009/03/05	6.98		205.00	304.00	0.01	0.20			0.58	163.00	2020.00		3.30	0.80	
WD4C	2855433	-48801	2009/12/09	7.30		133.00	267.00	0.01	0.30	761.00	82.90	0.31	102.00	1640.00	0.27	0.05	1.56	
WD4D	2855433	-48801	2001/10/11	7.10	341.00	277.00	135.00	0.02		1183.00	298.00							
WD4D	2855433	-48801	2002/01/17	7.50	26.80	25.20	10.70	0.02		139.00	10.00							
WD4D	2855433	-48801	2002/04/24	7.40	208.00	175.00	94.20	0.02		1420.00	148.00	0.25						
WD4D	2855433	-48801	2002/08/08	6.90	379.00	367.00	201.00	0.02		1309.00	310.00	0.91						
WD4D	2855433	-48801	2002/11/07	7.05	339.00	354.00	185.00	0.02			251.00	0.72						
WD4D	2855433	-48801	2003/01/23	6.90	324.00	297.00	155.00	0.02		1345.00	224.00	0.67						
WD4D	2855433	-48801	2003/05/15															

Borehole ID	Coordinates		Date Sampled	PH	EC	Ca	Na	Cr(VI)	Cr (total)	SO ₄	Cl	Mn	Mg	TDS	NO ₃ as N	Fe	F	Total Alkalinity
WD4D	2855433	-48801	2003/12/04															
WD4D	2855433	-48801	2004/07/01	6.98	508.00	215.00	440.00	0.02		1502.00	230.00	1.37						
WD4D	2855433	-48801	2004/10/14															
WD4D	2855433	-48801	2005/08/25	7.08	503.00	487.00	147.00	0.02		2333.00	330.00	1.80						
WD4D	2855433	-48801	2006/03/23	7.08	260.00	147.00	144.00		0.02	1037.00	128.00	0.70	114.00	1640.00	2.21	25.70	0.74	248.00
WD4D	2855433	-48801	2006/06/29	7.67	769.00	185.00	862.00	0.02	0.02	3632.00	678.00	3.42	276.00	4920.00	6.10	20.90	1.39	372.00
WD4D	2855433	-48801	2006/09/21	7.74	775.00	287.00	113.00	0.02	0.02	2954.00	571.00	3.40	453.00	4920.00	2.20	219.00	1.67	907.00
WD4D	2855433	-48801	2006/11/09	6.91	424.00	324.00	536.00	0.02		1826.00	202.00	1.37	253.00	2770.00	0.50	388.00	0.60	
WD4D	2855433	-48801	2007/03/15	6.85	334.00	338.00	286.00	0.02	0.02	1478.00	188.00	1.10	264.00	2140.00	8.10	18.70	0.54	
WD4D	2855433	-48801	2007/12/06	7.24	460.00	342.00	539.00	0.02	0.02	1940.00	304.00	2.29	419.00	2900.00	1.30	119.00	2.35	
WD4D	2855433	-48801	2008/05/08	7.34	494.00	338.00	26.20	0.02	0.06	1549.00	215.00	1.71	517.00	3150.00	4.90	113.00	2.00	
WD4D	2855433	-48801	2008/10/16	6.87		404.00	209.00	0.02	0.02	1434.00	196.00	1.24	328.00	2520.00	0.33	0.93	0.51	
WD4D	2855433	-48801	2009/03/05	6.91		330.00	264.00	0.01	0.20			0.90	298.00	2400.00		1.47	0.94	
WD4D	2855433	-48801	2009/12/09	7.06		317.00	265.00	0.01	0.30	1502.00	220.00	1.04	276.00	2460.00	3.93	0.20	0.60	
WD5A	2855458	-48812	2001/10/11															
WD5A	2855458	-48812	2002/01/17	7.60	144.00	75.20	186.00	0.02		301.00	77.00							
WD5A	2855458	-48812	2002/04/24	7.86	311.00	117.00	391.00	0.02		1056.00	208.00	2.57						
WD5A	2855458	-48812	2002/08/08	7.80	343.00	93.80	602.00	0.02		731.00	310.00	1.53						
WD5A	2855458	-48812	2002/11/07															
WD5A	2855458	-48812	2003/01/23															
WD5A	2855458	-48812	2003/05/07															

Borehole ID	Coordinates		Date Sampled	PH	EC	Ca	Na	Cr(VI)	Cr (total)	SO ₄	Cl	Mn	Mg	TDS	NO ₃ as N	Fe	F	Total Alkalinity
WD5A	2855458	-48812	2003/12/04															
WD5A	2855458	-48812	2004/07/01	6.65	613.00	852.00	270.00	0.02		1985.00	542.00	1.78						
WD5A	2855458	-48812	2004/10/14															
WD5A	2855458	-48812	2005/08/25	7.75	488.00	148.00	706.00	0.02		1422.00	477.00	0.50						
WD5A	2855458	-48812	2006/06/29	7.04	500.00	311.00	547.00	0.02	0.03	2699.00	360.00	1.25	267.00	3150.00	10.50	31.10	0.52	639.00
WD5A	2855458	-48812	2006/09/21	7.01	554.00	629.00	119.00	0.02	0.02	2364.00	299.00	0.29	437.00	3660.00	9.80	63.20	0.46	869.00
WD5A	2855458	-48812	2007/01/11	7.02	527.00	454.00	270.00	0.02	0.02	2324.00	301.00	0.20	301.00	3340.00		14.20	0.26	
WD5A	2855458	-48812	2007/03/15	6.96	413.00	559.00	331.00	0.02	0.02	2151.00	285.00	0.58	385.00	2650.00		27.40	0.29	
WD5A	2855458	-48812	2007/08/30	7.08	506.00	618.00	335.00	0.02	0.07	2404.00	311.00	0.45	417.00	3340.00		17.50	1.10	
WD5A	2855458	-48812	2007/12/20	6.85	484.00	598.00	455.00	0.02	0.02	1976.00	219.00	0.22	431.00	3150.00		3.57	0.79	
WD5A	2855458	-48812	2008/05/22	6.98	465.00	400.00	229.00	0.02	0.02	4.00	168.00	0.18	281.00	3030.00		6.46	3.61	
WD5A	2855458	-48812	2008/10/16	6.86		246.00	615.00	0.02	0.02	1944.00	251.00	0.83	253.00	3340.00		2.49	0.54	
WD5A	2855458	-48812	2009/03/05	6.84		222.00	667.00	0.01	0.20			0.80	234.00	3340.00		72.60	0.55	
WD5B	2855458	-48812	11-Oct-01															
WD5B	2855458	-48812	2002/01/17	7.60	74.70	30.50	94.00	0.02		188.00	34.00							
WD5B	2855458	-48812	2002/04/24	7.44	175.00	53.90	188.00	0.02		531.00	130.00	0.16						
WD5B	2855458	-48812	2002/08/08	7.20	211.00	54.10	343.00	0.02		482.00	310.00	0.45						
WD5B	2855458	-48812	2002/11/07	7.02	260.00	78.80	451.00	0.02			232.00	0.59						
WD5B	2855458	-48812	2003/01/23	6.90	258.00	77.00	419.00	0.02		944.00	194.00	0.32						
WD5B	2855458	-48812	2003/05/07															
WD5B	2855458	-48812	2003/12/04															

Borehole ID	Coordinates		Date Sampled	PH	EC	Ca	Na	Cr(VI)	Cr (total)	SO ₄	Cl	Mn	Mg	TDS	NO ₃ as N	Fe	F	Total Alkalinity
WD5B	2855458	-48812	2004/07/01	7.16	293.00	146.00	409.00	0.02		723.00	216.00	0.60						
WD5B	2855458	-48812	2004/10/14															
WD5B	2855458	-48812	2005/08/25	7.01	399.00	204.00	484.00	0.02		1285.00	405.00	1.10						
WD5B	2855458	-48812	2006/06/29	7.25	553.00	522.00	322.00	0.02	0.02	3330.00	364.00	0.16	383.00	3660.00	10.20	10.50	0.28	838.00
WD5B	2855458	-48812	2006/09/21	8.44	209.00	85.20	112.00	0.02	0.02	714.00	53.00	0.02	66.50	1320.00	9.80	0.08	3.49	308.00
WD5B	2855458	-48812	2006/11/09	6.84	524.00	660.00	468.00	0.02		2342.00	348.00	0.22	480.00	3340.00		38.80	0.29	
WD5B	2855458	-48812	2007/01/11	6.95	520.00	523.00	322.00	0.02	0.02	2341.00	301.00	0.09	371.00	3340.00		19.40	0.24	
WD5B	2855458	-48812	2007/03/15	6.98	406.00	464.00	269.00	0.02	0.03	1966.00	242.00	0.23	330.00	2650.00		1.98	5.82	
WD5B	2855458	-48812	2007/08/30	7.16	514.00	617.00	363.00	0.02	0.02	2565.00	266.00	0.16	453.00	3340.00		30.50	0.23	
WD5B	2855458	-48812	2007/12/20	6.98	542.00	184.00	511.00	0.02	0.02	2026.00	313.00	1.02	187.00	3470.00		0.85	0.97	
WD5B	2855458	-48812	2008/05/22	7.24	535.00	243.00	489.00	0.02	0.02	4.00	243.00	0.81	237.00	3470.00		69.30	3.12	
WD5B	2855458	-48812	2009/03/05	7.60		234.00	714.00	0.01	0.20			4.78	330.00	3660.00		3.03	1.99	
WD5B	2855458	-48812	2009/12/09	7.04		202.00	657.00	0.01	0.30	1865.00	200.00	0.57	197.00	3030.00		0.27	0.60	
WD5C	2855458	-48812	2001/10/11	7.10	196.00	130.00	119.00	0.02		441.00	174.00							
WD5C	2855458	-48812	2002/01/17	6.90	206.00	161.00	141.00	0.02		375.00	91.00							
WD5C	2855458	-48812	2002/04/24	7.29	252.00	208.00	122.00	0.02		1044.00	176.00	0.02						
WD5C	2855458	-48812	2002/08/08	6.80	324.00	305.00	163.00	0.02		904.00	380.00	0.21						
WD5C	2855458	-48812	2002/11/07	7.04	348.00	326.00	180.00	0.02			272.00	0.33						
WD5C	2855458	-48812	2003/01/23	6.90	383.00	330.00	203.00	0.02		1260.00	287.00	0.51						
WD5C	2855458	-48812	2003/05/15															

Borehole ID	Coordinates		Date Sampled	PH	EC	Ca	Na	Cr(VI)	Cr (total)	SO ₄	Cl	Mn	Mg	TDS	NO ₃ as N	Fe	F	Total Alkalinity
WD5C	2855458	-48812	2003/12/04															
WD5C	2855458	-48812	2004/07/01	7.68	231.00	37.30	237.00	0.02		718.00	178.00	0.13						
WD5C	2855458	-48812	2004/10/14															
WD5C	2855458	-48812	2005/08/25	6.92	748.00	759.00	522.00	0.02		3671.00	598.00	1.00						
WD5C	2855458	-48812	2006/06/29	7.19	550.00	653.00	415.00	0.02	0.02	3261.00	333.00	0.45	472.00	3470.00	10.20	6.88	0.27	20.00
WD5C	2855458	-48812	2006/09/21	8.47	209.00	89.20	113.00	0.02	0.02	679.00	53.70	0.02	68.90	1320.00	9.80	0.06	3.43	309.00
WD5C	2855458	-48812	2006/11/09	6.78	527.00	333.00	784.00	0.02		2152.00	396.00	1.79	292.00	3340.00		611.00	0.43	
WD5C	2855458	-48812	2007/01/11	6.86	509.00	383.00	629.00	0.02	0.02	2142.00	373.00	1.01	329.00	3340.00		112.00	0.61	
WD5C	2855458	-48812	2007/03/15	6.73	430.00	364.00	463.00	0.02	0.04	2118.00	332.00	0.66	293.00	2770.00		31.60	0.44	
WD5C	2855458	-48812	2007/08/30	7.12	535.00	383.00	555.00	0.02	0.02	2977.00	324.00	0.97	307.00	3470.00		364.00	1.21	
WD5C	2855458	-48812	2007/12/20	7.36	755.00	191.00	704.00	0.02	0.02	3232.00	497.00	1.22	268.00	4920.00		0.26	2.03	
WD5C	2855458	-48812	2008/05/22	6.99	447.00	397.00	226.00	0.02	0.02	4.00	163.00	0.25	272.00	2900.00		3.39	3.10	
WD5C	2855458	-48812	2008/10/16	6.93		437.00	295.00	0.02	0.02	1648.00	172.00	0.23	313.00	2770.00		2.63	0.50	
WD5C	2855458	-48812	2009/03/05	6.88		335.00	270.00	0.01	0.20			0.20	239.00	2650.00		0.26	1.54	
WD5C	2855458	-48812	2009/12/09	7.18		316.00	326.00	0.01	0.30	1486.00	130.00	0.19	221.00	2460.00		0.22	0.50	
WD5D	2855458	-48812	2001/10/11	7.20	213.00	164.00	121.00	0.02		463.00	199.00							
WD5D	2855458	-48812	2002/01/17	6.90	228.00	204.00	122.00	0.02		453.00	112.00							
WD5D	2855458	-48812	2002/04/24	7.33	305.00	310.00	126.00	0.02		877.00	258.00	0.02						
WD5D	2855458	-48812	2002/08/08	6.80	373.00	388.00	163.00	0.02		1109.00	320.00	0.05						
WD5D	2855458	-48812	2002/11/07	7.19	397.00	403.00	220.00	0.02			310.00	0.16						

Borehole ID	Coordinates		Date Sampled	PH	EC	Ca	Na	Cr(VI)	Cr (total)	SO ₄	Cl	Mn	Mg	TDS	NO ₃ as N	Fe	F	Total Alkalinity
WD5D	2855458	-48812	2003/01/23	6.80	396.00	229.00	165.00	0.02		1466.00	298.00	0.14						
WD5D	2855458	-48812	2003/05/15															
WD5D	2855458	-48812	2003/12/04															
WD5D	2855458	-48812	2004/07/01	6.77	761.00	1169.00	402.00	0.02		2204.00	694.00	1.82						
WD5D	2855458	-48812	2004/10/14															
WD5D	2855458	-48812	2005/08/25	7.21	689.00	698.00	388.00	0.02		3168.00	544.00	0.40						
WD5D	2855458	-48812	2006/06/29	7.84	731.00	232.00	766.00	0.02	0.02	3579.00	724.00	3.37	303.00	4730.00	13.10	37.50	1.40	829.00
WD5D	2855458	-48812	2006/09/21	6.82	531.00	351.00	117.00	0.02	0.02	2116.00	367.00	1.39	295.00	3470.00	9.80	128.00	0.64	608.00
WD5D	2855458	-48812	2006/11/09	7.45	849.00	290.00	1690.00	0.02		3635.00	804.00	2.85	562.00	5360.00		292.00	1.67	
WD5D	2855458	-48812	2007/01/11	7.56	740.00	308.00	1137.00	0.02	0.02	3191.00	616.00	1.81	457.00	4730.00		185.00	1.25	
WD5D	2855458	-48812	2007/08/30	7.63	844.00	436.00	1366.00	0.02	0.02	5543.00	816.00	2.44	640.00	5360.00		584.00	1.04	
WD5D	2855458	-48812	2007/12/20	6.91	484.00	577.00	428.00	0.02	0.02	1971.00	225.00	0.40	399.00	3150.00		5.62	0.75	
WD5D	2855458	-48812	2008/05/22	7.66	699.00	215.00	717.00	0.02	0.03	4.00	348.00	1.25	324.00	4410.00		37.70	3.15	
WD5D	2855458	-48812	2008/10/16	7.08		424.00	250.00	0.02	0.03	1698.00	163.00	0.46	278.00	2650.00		7.52	0.50	
WD5D	2855458	-48812	2009/03/05	6.90		368.00	276.00	0.01	0.20			0.28	252.00	2520.00		4.38	0.57	
WD5D	2855458	-48812	2009/12/09	7.15		314.00	296.00	0.01	0.30	1445.00	129.00	0.28	212.00	2330.00		0.15	1.98	
WD6A	2855534	-48845	2001/10/18															
WD6A	2855534	-48845	2002/01/23	8.00	173.00	19.60	238.00	0.02		321.00	72.00							
WD6A	2855534	-48845	2002/05/09															
WD6A	2855534	-48845	2002/08/15															
WD6A	2855534	-48845	2002/11/14															

Borehole ID	Coordinates		Date Sampled	PH	EC	Ca	Na	Cr(VI)	Cr (total)	SO ₄	Cl	Mn	Mg	TDS	NO ₃ as N	Fe	F	Total Alkalinity
WD6A	2855534	-48845	2003/01/30	8.00	93.00	15.30	214.00	0.02		431.00	47.00	0.33						
WD6A	2855534	-48845	2003/05/15															
WD6A	2855534	-48845	2003/12/04															
WD6A	2855534	-48845	2004/07/08															
WD6A	2855534	-48845	2004/10/21															
WD6A	2855534	-48845	2005/09/01	8.47	198.00	11.70	865.00	0.02		219.00	86.80	0.00						
WD6A	2855534	-48845	2006/06/26	8.29	78.30	11.50	95.80	0.02	0.02	25.10	95.50	0.02	2.91	505.00	2.21	0.05	9.24	204.00
WD6A	2855534	-48845	2006/07/06	8.02	325.00	107.00	497.00	0.02	0.02	890.00	142.00	0.16	92.60	2080.00	3.40	1.85	2.54	671.00
WD6A	2855534	-48845	2006/09/28	8.10	360.00	110.00	575.00	0.02	0.02	1092.00	159.00	1.11	92.60	2270.00	0.70	464.00	1.95	688.00
WD6A	2855534	-48845	2006/11/16	7.68	459.00	14.90	957.00	0.02	0.02	1643.00	296.00	0.02	99.30	2900.00	2.30	5.67	1.86	
WD6A	2855534	-48845	2007/01/18	7.64	413.00	73.50	591.00	0.02	0.02	1234.00	232.00	0.35	73.50	2650.00	0.23	106.00	3.92	
WD6A	2855534	-48845	2008/06/05	8.23	448.00	51.00	1015.00	0.02	0.05	1278.00	253.00	0.58	188.00	2900.00	0.90	182.00	1.92	
WD6A	2855534	-48845	2008/10/30	6.91		156.00	371.00	0.02	0.02	875.00	129.00	1.39	172.00	1700.00	0.33	46.60	1.72	
WD6A	2855534	-48845	2009/04/16	7.07		335.00	342.00	0.01	0.21	1041.00	25.10	0.48	255.00	1950.00	18.40	1.69	0.63	
WD6A	2855534	-48845	2009/08/06	7.96		119.00	1474.00	0.01	0.21	2352.00	411.00	0.47	268.00	4410.00	0.84	0.10	2.03	
WD6B	2855534	-48845	2001/10/18	7.65	158.00	25.30	345.00	0.02		403.00	160.00							
WD6B	2855534	-48845	2002/01/23	7.30	161.00	50.30	169.00	0.02		349.00	98.00							
WD6B	2855534	-48845	2002/05/09	7.30	165.00	51.40	241.00	0.02		388.00	107.00	1.47						
WD6B	2855534	-48845	2002/08/15	7.70	162.00	40.30	250.00	0.02		388.00	270.00	1.17						
WD6B	2855534	-48845	2002/11/14	7.45	108.00	26.40	255.00	0.02		403.00	110.00	1.01						

Borehole ID	Coordinates		Date Sampled	PH	EC	Ca	Na	Cr(VI)	Cr (total)	SO ₄	Cl	Mn	Mg	TDS	NO ₃ as N	Fe	F	Total Alkalinity
WD6B	2855534	-48845	2003/01/30	7.50	154.00	23.70	263.00	0.02		281.00	103.00	1.07						
WD6B	2855534	-48845	2003/05/15	7.40	78.70	57.60	224.00	0.02		423.00	105.00	0.77						
WD6B	2855534	-48845	2003/12/04															
WD6B	2855534	-48845	2004/07/08	7.35	193.00	49.90	211.00	0.02		530.00	110.00	0.19						
WD6B	2855534	-48845	2004/10/21															
WD6B	2855534	-48845	2005/09/01	7.27	178.00	31.20	580.00	0.02		398.00	97.30	0.70						
WD6B	2855534	-48845	2006/07/06	7.15	224.00	215.00	146.00	0.02	0.02	664.00	117.00	0.64	157.00	1450.00	2.30	0.11	0.73	382.00
WD6B	2855534	-48845	2006/09/28	7.37	222.00	203.00	133.00	0.02	0.02	782.00	109.00	0.71	137.00	1450.00	0.50	113.00	0.42	346.00
WD6B	2855534	-48845	2006/11/16	7.00	182.00	19.90	504.00	0.02	0.02	481.00	123.00	0.06	79.90	1200.00	0.80	11.50	0.33	
WD6B	2855534	-48845	2007/01/18	7.03	199.00	51.20	120.00	0.02	0.02	562.00	122.00	0.83	42.80	1260.00	0.23	64.60	0.99	
WD6B	2855534	-48845	2007/03/22	7.17	188.00	51.20	136.00	0.02	0.02	396.00	90.40	0.72	49.20	1200.00	1.30	115.00	0.84	
WD6B	2855534	-48845	2007/09/13	7.20	268.00	364.00	184.00	0.02	0.06	328.00	43.30	0.81	250.00	1700.00	1.70	110.00	0.34	
WD6B	2855534	-48845	2008/06/05	6.95	287.00	281.00	130.00	0.02	0.02	1046.00	122.00	0.51	200.00	1830.00	1.70	27.20	0.79	
WD6B	2855534	-48845	2009/08/06	6.87		163.00	330.00	0.01	0.21	862.00	113.00	0.44	158.00	1830.00	0.29	0.23	0.50	
WD6C	2855534	-48845	2001/10/18	7.31	130.00	65.60	199.00	0.02		364.00	120.00							
WD6C	2855534	-48845	2002/01/23	7.50	121.00	58.10	88.80	0.02		227.00	78.00							
WD6C	2855534	-48845	2002/05/09	7.20	151.00	107.00	128.00	0.02		305.00	91.00	0.16						
WD6C	2855534	-48845	2002/08/15	7.30	153.00	100.00	124.00	0.02		305.00	270.00	0.48						
WD6C	2855534	-48845	2002/11/14	6.99	157.00	87.90	0.56	0.02		404.00	116.00	0.02						
WD6C	2855534	-48845	2003/01/30	7.50	135.00	60.70	194.00	0.02		411.00	83.00	0.56						

Borehole ID	Coordinates		Date Sampled	PH	EC	Ca	Na	Cr(VI)	Cr (total)	SO ₄	Cl	Mn	Mg	TDS	NO ₃ as N	Fe	F	Total Alkalinity
WD6C	2855534	-48845	2003/05/15	7.20	70.30	102.00	132.00	0.02		386.00	114.00	0.55						
WD6C	2855534	-48845	2003/12/11	7.05	193.00	109.00	118.00	0.02		494.00	122.00	61.00						
WD6C	2855534	-48845	2004/07/08	7.74	137.00	69.40	77.00	0.02		349.00	78.00	0.05						
WD6C	2855534	-48845	2004/10/21															
WD6C	2855534	-48845	2005/09/01	7.03	171.00	104.00	145.00	0.02		422.00	105.00	0.40						
WD6C	2855534	-48845	2006/07/06	7.55	182.00	54.60	238.00	0.02	0.02	417.00	119.00	0.62	57.70	1200.00	2.20	1.16	0.68	310.00
WD6C	2855534	-48845	2006/09/28	7.26	186.00	65.10	235.00	0.02	0.02	495.00	115.00	1.75	59.70	1200.00	0.50	231.00	0.50	293.00
WD6C	2855534	-48845	2006/11/16	6.99	214.00	63.70	119.00	0.02	0.02	728.00	123.00	0.02	98.40	1390.00	0.50	4.94	0.32	
WD6C	2855534	-48845	2007/01/18	6.94	242.00	188.00	146.00	0.02	0.02	792.00	124.00	0.17	139.00	1580.00	0.23	72.60	1.07	
WD6C	2855534	-48845	2007/03/22	7.00	233.00	147.00	116.00	0.02	0.23	633.00	97.30	0.23	105.00	1510.00	0.90	16.20	0.30	
WD6C	2855534	-48845	2007/09/13	7.05	253.00	287.00	199.00	0.02	0.02	778.00	124.00	0.29	208.00	1640.00	3.50	95.40	0.32	
WD6C	2855534	-48845	2008/06/05	6.95	275.00	274.00	175.00	0.02	0.04	956.00	123.00	0.29	207.00	1770.00	2.00	15.60	41.10	
WD6C	2855534	-48845	2008/10/30	6.99		237.00	191.00	0.02	0.02	796.00	111.00	0.31	184.00	1700.00	1.00	21.80	0.50	
WD6C	2855534	-48845	2009/04/16	6.88		208.00	319.00	0.01	0.21	956.00	21.50	0.60	197.00	1830.00	4.47	0.54	0.50	
WD6C	2855534	-48845	2009/08/06	6.95		233.00	256.00	0.01	0.21	856.00	107.00	0.20	172.00	1830.00	1.08	0.10	0.50	
WD6D	2855534	-48845	2001/10/18	7.41	124.00	66.50	196.00	0.02		393.00	110.00							
WD6D	2855534	-48845	2002/01/23	7.70	113.00	30.40	101.00	0.02		217.00	182.00							
WD6D	2855534	-48845	2002/05/09	7.35	133.00	87.70	119.00	0.02		297.00	84.00	0.36						
WD6D	2855534	-48845	2002/08/15	7.G	155.00	114.00	118.00	0.02		297.00	250.00	0.61						

Borehole ID	Coordinates		Date Sampled	PH	EC	Ca	Na	Cr(VI)	Cr (total)	SO ₄	Cl	Mn	Mg	TDS	NO ₃ as N	Fe	F	Total Alkalinity
WD6D	2855534	-48845	2002/11/14	6.91	138.00	78.80	134.00	0.02		394.00	104.00	0.60						
WD6D	2855534	-48845	2003/01/30	7.70	156.00	89.30	187.00	0.02		413.00	103.00	0.67						
WD6D	2855534	-48845	2003/05/15	7.30	99.60	109.00	113.00	0.02		329.00	118.00	0.67						
WD6D	2855534	-48845	2003/12/11	7.05	197.00	130.00	105.00	0.02		474.00	133.00	441.00						
WD6D	2855534	-48845	2004/07/08	7.18	152.00	105.00	72.00	0.02		412.00	70.00	0.25						
WD6D	2855534	-48845	2004/10/21															
WD6D	2855534	-48845	2005/09/01	7.19	179.00	113.00	134.00	0.02		466.00	102.00	0.50						
WD6D	2855534	-48845	2006/07/06	7.23	183.00	63.20	267.00	0.02	0.02	429.00	120.00	1.11	65.00	1200.00	2.40	1.07	0.60	306.00
WD6D	2855534	-48845	2006/09/28	7.45	222.00	400.00	132.00	0.02	0.02	783.00	109.00	0.64	271.00	1450.00	0.50	27.10	0.39	341.00
WD6D	2855534	-48845	2006/11/16	7.16	216.00	99.70	172.00	0.02	0.02	777.00	124.00	0.10	158.00	1390.00	0.50	3.20	0.29	
WD6D	2855534	-48845	2007/01/18	7.05	240.00	264.00	155.00	0.02	0.02	799.00	121.00	0.28	180.00	1510.00	0.23	22.80	1.28	
WD6D	2855534	-48845	2007/03/22	7.12	227.00	108.00	91.50	0.02	0.02	678.00	96.00	0.40	97.60	1450.00	1.00	8.42	0.34	
WD6D	2855534	-48845	2007/09/13	7.12	203.00	96.40	205.00	0.02	0.02	98.00	15.40	2.34	88.20	1320.00	1.70	209.00	0.79	
WD6D	2855534	-48845	2008/06/05	6.90	268.00	173.00	249.00	0.02	0.02	880.00	121.00	1.37	170.00	1700.00	0.70	83.00	0.79	
WD6D	2855534	-48845	2008/10/30	7.01		259.00	232.00	0.02	0.02	996.00	122.00	0.60	213.00	1830.00	0.90	21.30	0.50	
WD6D	2855534	-48845	2009/04/16	7.01		258.00	224.00	0.01	0.21	931.00	25.80	0.22	191.00	1770.00	7.03	0.38	0.50	
WD6D	2855534	-48845	2009/08/06	7.12		235.00	225.00	0.01	0.21	915.00	102.00	0.48	173.00	1890.00	0.76	0.10	0.50	
WD7	2855662	-48858	2001/10/18	7.48	324.00	372.00	338.00	0.02		1087.00	420.00							
WD7	2855662	-48858	2002/01/23	7.30	180.00	143.00	98.90	0.02		384.00	230.00							

Borehole ID	Coordinates		Date Sampled	PH	EC	Ca	Na	Cr(VI)	Cr (total)	SO ₄	Cl	Mn	Mg	TDS	NO ₃ as N	Fe	F	Total Alkalinity
WD7	2855662	-48858	2002/05/09	7.06	354.00	364.00	245.00	0.02		1631.00	292.00	0.02						
WD7	2855662	-48858	2002/08/15	7.20	355.00	324.00	248.00	0.02		1610.00	450.00	0.05						
WD7	2855662	-48858	2002/11/14	7.18	350.00	396.00	253.00	0.02		1406.00	300.00	0.02						
WD7	2855662	-48858	2003/01/30	7.50	306.00	219.00	237.00	0.02		659.00	273.00	0.07						
WD7	2855662	-48858	2003/05/15	7.60	65.90	208.00	184.00	0.02		446.00	251.00	0.02						
WD7	2855662	-48858	2003/12/11	7.11	199.00	98.40	233.00	0.02		325.00	220.00	0.05						
WD7	2855662	-48858	2004/07/08	7.16	326.00	289.00	137.00	0.02		1028.00	270.00	0.12						
WD7	2855662	-48858	2004/10/21	7.40	294.00	180.00	108.00	0.02		734.00	268.00	0.05						
WD7	2855662	-48858	2005/09/01	7.13	390.00	695.00	289.00	0.02		1415.00	268.00	0.00						
WD7	2855662	-48858	2006/04/13	7.66	263.00	162.00	105.00	0.02	0.02	976.00	182.00	0.18	103.00	1700.00	2.21	1.15	5.80	332.00
WD7	2855662	-48858	2006/07/06	7.93	324.00	115.00	560.00	0.02	0.02	848.00	140.00	0.17	105.00	2080.00	2.90	0.02	1.98	666.00
WD7	2855662	-48858	2006/09/28	7.13	383.00	406.00	245.00	0.02	0.02	1625.00	240.00	0.02	280.00	2460.00	0.50	9.65	0.40	434.00
WD7	2855662	-48858	2006/11/16	7.01	368.00	194.00	251.00	0.02	0.02	1515.00	268.00	0.02	233.00	2330.00	1.00	0.95	0.29	
WD7	2855662	-48858	2007/01/18	7.22	367.00	462.00	284.00	0.02	0.02	1372.00	246.00	0.03	322.00	2330.00	1.60	11.50	4.86	
WD7	2855662	-48858	2007/03/22	6.93	363.00	305.00	167.00	0.02	0.10	1250.00	213.00	0.13	210.00	2330.00	0.60	16.30	0.27	
WD7	2855662	-48858	2008/01/17	7.15	337.00	281.00	299.00	0.02	0.02	1289.00	251.00	0.24	206.00	2140.00	0.60	1.28	24.90	
WD7	2855662	-48858	2008/06/19	6.95	386.00	343.00	187.00	0.02	0.02	1604.00	6.10	0.11	238.00	2460.00	4.20	1.31	0.50	
WD7	2855662	-48858	2008/10/30	7.10		372.00	311.00	0.02	0.02	1360.00	235.00	0.09	287.00	2400.00	0.33	3.83	0.50	
WD7	2855662	-48858	2009/04/16	7.03		324.00	218.00	0.01	0.21	1305.00	2.70	0.20	225.00	2140.00	6.91	0.24	0.50	

Borehole ID	Coordinates		Date Sampled	PH	EC	Ca	Na	Cr(VI)	Cr (total)	SO ₄	Cl	Mn	Mg	TDS	NO ₃ as N	Fe	F	Total Alkalinity
WD7	2855662	-48858	2009/08/06	7.10		374.00	306.00	0.01	0.21	1366.00	229.00	0.20	265.00	2460.00	0.48	0.10	0.50	
WD8	2855712	-48814	2001/10/18	7.73	198.00	57.50	364.00	0.02		296.00	370.00							
WD8	2855712	-48814	2002/01/23	8.10	281.00	140.00	277.00	0.02		1042.00	190.00							
WD8	2855712	-48814	2002/04/04															
WD8	2855712	-48814	2002/08/15	7.50	312.00	124.00	422.00	0.02		363.00	400.00	0.48						
WD8	2855712	-48814	2002/11/14	7.45	274.00	122.00	391.00	0.02		734.00	268.00	0.02						
WD8	2855712	-48814	2003/01/30	7.60	290.00	136.00	365.00	0.02		775.00	294.00	1.26						
WD8	2855712	-48814	2003/05/15	7.60	146.00	278.00	310.00	0.02		622.00	310.00	2.62						
WD8	2855712	-48814	2003/12/11	7.25	319.00	197.00	262.00	0.02		1114.00	336.00	2.40						
WD8	2855712	-48814	2004/07/08	7.37	311.00	192.00	219.00	0.02		931.00	238.00	0.34						
WD8	2855712	-48814	2004/10/21	7.60	312.00	171.00	204.00	0.02		793.00	273.00	0.81						
WD8	2855712	-48814	2005/09/01	7.40	352.00	230.00	677.00	0.02		1169.00	248.00	0.10						
WD8	2855712	-48814	2006/04/13	7.47	221.00	112.00	157.00	0.02	0.02	820.00	101.00	0.13	87.80	1450.00	2.21	6.95	6.30	290.00
WD8	2855712	-48814	2006/07/06	8.39	322.00	105.00	442.00	0.02	0.02	811.00	133.00	0.09	81.90	2080.00	2.20	0.07	1.96	660.00
WD8	2855712	-48814	2006/09/28	7.20	383.00	400.00	239.00	0.02	0.02	1642.00	241.00	0.02	271.00	2460.00	0.50	20.10	0.39	437.00
WD8	2855712	-48814	2006/11/16	6.84	397.00	282.00	438.00	0.02	0.02	1642.00	332.00	0.24	286.00	2520.00	0.50	1.84	0.57	
WD8	2855712	-48814	2007/01/18	7.05	419.00	369.00	392.00	0.02	0.02	1722.00	259.00	0.80	251.00	2650.00	3.50	25.80	2.59	
WD8	2855712	-48814	2007/03/22	6.83	407.00	411.00	294.00	0.02	0.06	1347.00	249.00	1.04	296.00	2650.00	1.00	17.50	0.60	
WD8	2855712	-48814	2008/01/17	7.28	350.00	257.00	362.00	0.06	0.40	1348.00	110.00	0.05	180.00	2210.00	1.10	6.03	18.70	

Borehole ID	Coordinates		Date Sampled	PH	EC	Ca	Na	Cr(VI)	Cr (total)	SO ₄	Cl	Mn	Mg	TDS	NO ₃ as N	Fe	F	Total Alkalinity
WD8	2855712	-48814	2008/06/19	6.87	444.00	385.00	266.00	0.02	0.07	1769.00	1.90	0.72	274.00	2900.00	4.40	19.30	0.71	
WD8	2855712	-48814	2008/10/30	6.91		452.00	296.00	0.02	0.08	1727.00	296.00	0.67	344.00	2900.00	0.40	11.30	0.62	
WD8	2855712	-48814	2009/04/16	7.04		332.00	462.00	0.01	0.21	1931.00	2.14	0.20	262.00	3030.00	2.89	0.31	1.29	
WD8	2855712	-48814	2009/08/06	7.11		368.00	503.00	0.01	0.21	1870.00	350.00	0.29	288.00	3150.00	0.58	0.10	0.96	
WD9	2855885	-48921	2001/10/25	7.93	49.70	8.00	68.80	0.02		42.90	10.00							
WD9	2855885	-48921	2002/01/30															
WD9	2855885	-48921	2002/05/23	7.90	49.00	5.45	77.60	0.02		59.60	17.00	0.22						
WD9	2855885	-48921	2002/08/22	7.96	48.70	8.71	86.20	0.02		18.00	30.00	0.49						
WD9	2855885	-48921	2002/11/21	7.90	54.50	6.59	77.70	0.02		204.00	10.00	0.32						
WD9	2855885	-48921	2003/02/06	7.70	49.50	4.48	62.60	0.02		52.50	11.00	0.21						
WD9	2855885	-48921	2003/05/21	8.18	46.30	10.20	71.10	0.02		60.00	10.00	0.23						
WD9	2855885	-48921	2003/12/18	7.89	37.80	2.48	47.90	0.02		6.94	10.00	0.06						
WD9	2855885	-48921	2004/07/15															
WD9	2855885	-48921	2004/10/28	8.20	56.60	6.09	62.00	0.02		51.50	10.00	317.00						
WD9	2855885	-48921	2005/09/08	8.07	47.60	5.20	74.10	0.02		29.80	10.00	0.20						
WD9	2855885	-48921	2006/04/13	7.66	53.40	7.28	74.90	0.02	0.02	18.10	10.00	0.20	7.89	347.00	2.21	0.67	9.80	233.00
WD9	2855885	-48921	2006/07/13	7.64	61.50	19.30	78.10	0.02	0.02	4.00	10.00	0.35	11.90	397.00	2.20	0.22	4.26	339.00
WD9	2855885	-48921	2006/10/05	7.84	64.80	14.60	104.00	0.02	0.02	15.20	10.00	0.72	16.50	410.00	0.50	1.63	4.36	350.00
WD9	2855885	-48921	2006/11/23	7.74	63.60	6.36	56.30	0.02	0.02	5.54	7.86	0.36	8.03	410.00	0.50	1.94		
WD9	2855885	-48921	2007/01/25	7.73	62.70	11.20	102.00	0.02	0.02	13.20	1.00	0.68	13.50	397.00	0.23	5.58	3.99	

Borehole ID	Coordinates		Date Sampled	PH	EC	Ca	Na	Cr(VI)	Cr (total)	SO ₄	Cl	Mn	Mg	TDS	NO ₃ as N	Fe	F	Total Alkalinity
WD9	2855885	-48921	2007/03/29	7.76	60.3 0	7.57	68.20	0.02	0.02	4.00	4.33	0.45	9.40	397.00	0.23	2.10	3.26	
WD9	2855885	-48921	2008/01/17	7.61	66.9 0	9.99	104.0 0	0.02	0.02	7.52	5.97	0.81	14.00	429.00	0.23	2.10	26.00	
WD9	2855885	-48921	2008/06/19	7.43	77.6 0	13.30	83.80	0.02	0.02	4.00	41.00	1.16	17.50	492.00	0.60	1.20	3.99	
WD9	2855885	-48921	2008/11/13	7.68		13.40	151.0 0	0.02	0.02	26.60	15.10	1.40	20.10	492.00	0.33	1.98	4.64	
WD9	2855885	-48921	2009/04/30	7.58		12.70	153.0 0	0.01	0.30	4.53	11.80	0.34	18.00	441.00	0.33	0.05	5.23	
WD9	2855885	-48921	2010/01/07	7.83		10.30	130.0 0	0.01	0.30	22.60	8.60	0.64	15.10	441.00	0.27	0.05	5.18	
WD10	2856040	-48959	2001/10/25	7.96	42.7 0	2.47	271.0 0	0.02		61.50	64.00							
WD10	2856040	-48959	2002/01/30	8.50	50.9 0	10.10	102.0 0	0.02		50.30	10.00							
WD10	2856040	-48959	2002/05/23	8.70	38.0 0	3.02	63.90	0.02		49.80	12.00	0.02						
WD10	2856040	-48959	2002/08/22	8.79	38.6 0	5.40	77.70	0.02		15.50	70.00	0.57						
WD10	2856040	-48959	2002/11/21	8.74	37.0 0	6.84	68.40	0.02		197.00	10.00	0.04						
WD10	2856040	-48959	2003/02/06	8.90	40.0 0	2.50	59.80	0.02		63.90	10.00	0.02						
WD10	2856040	-48959	2003/05/21	9.11	39.1 0	5.89	62.30	0.02		54.70	10.00	0.02						
WD10	2856040	-48959	2003/12/18															
WD10	2856040	-48959	2004/07/15															
WD10	2856040	-48959	2004/10/28	8.80	40.7 0	3.60	44.00	0.02		17.90	10.00	0.02						
WD10	2856040	-48959	2005/09/08	8.77	39.7 0	3.90	68.70	0.02		4.00	10.00	0.00						
WD10	2856040	-48959	2006/04/13	8.61	40.1 0	5.25	41.20	0.02	0.02	4.00	10.00	0.02	2.81	265.00	2.21	0.72	8.50	198.00
WD10	2856040	-48959	2006/07/13	7.76	61.0 0	9.93	74.90	0.02	0.02	4.00	10.00	0.47	12.00	397.00	2.20	1.58	4.36	338.00
WD10	2856040	-48959	2006/10/05	8.57	55.5 0	14.90	88.50	0.02	0.02	64.20	15.50	0.02	9.03	366.00	0.50	0.21	3.34	188.00

Borehole ID	Coordinates		Date Sampled	PH	EC	Ca	Na	Cr(VI)	Cr (total)	SO ₄	Cl	Mn	Mg	TDS	NO ₃ as N	Fe	F	Total Alkalinity
WD10	2856040	-48959	2006/11/23	8.70	40.9 0	4.52	49.60	0.02	0.02	15.60	4.05	0.02	2.41	265.00	0.50	0.24		
WD10	2856040	-48959	2007/01/25	7.99	88.8 0	30.10	119.0 0	0.02	0.02	215.00	2.27	0.25	17.70	568.00	0.23	1.77	5.25	
WD10	2856040	-48959	2007/03/29	8.59	51.0 0	11.00	78.30	0.02	0.03	40.10	3.47	0.09	6.60	334.00	0.90	2.53	6.43	
WD10	2856040	-48959	2007/08/16	8.70	41.4 0	9.17	70.30	0.02	0.02	38.70	4.42	0.02	4.59	265.00	10.20	0.57	3.17	
WD10	2856040	-48959	2007/08/30	8.67	51.0 0	11.50	68.90	0.02	0.02	76.40	16.70	0.02	6.04	334.00	0.23	0.32	3.51	
WD10	2856040	-48959	2008/01/17	8.41	60.0 0	12.00	91.10	0.02	0.02	75.70	21.10	0.08	7.90	378.00	0.23	4.21	24.90	
WD10	2856040	-48959	2008/06/19	8.51	42.6 0	4.87	49.60	0.02	0.02	18.90	4.96	0.03	2.96	277.00	0.33	0.92	3.27	
WD10	2856040	-48959	2008/11/13	8.38		8.01	62.70	0.02	0.02	29.20	5.69	0.08	5.35	277.00	0.33	0.34	3.17	
WD10	2856040	-48959	2009/04/30	8.74		8.30	89.90	0.01	0.30	7.07	6.32	0.05	3.43	246.00	0.33	0.05	4.14	
WD10	2856040	-48959	2010/01/07	8.49		7.21	79.00	0.01	0.30	23.20	6.30	0.20	4.71	277.00	0.27	0.13	3.06	
WD11A	2855352	-48808	2001/10/25	8.22	220.00	78.50	269.00	0.02		654.00	150.00							
WD11A	2855352	-48808	2002/01/30	8.50	221.00	73.60	337.00	0.02		529.00	158.00							
WD11A	2855352	-48808	2002/05/23	8.30	431.00	33.20	735.00	0.02		1084.00	180.00	0.02						
WD11A	2855352	-48808	2002/08/29															
WD11A	2855352	-48808	2002/11/21	7.99	261.00	53.50	328.00	0.02		940.00	172.00	0.36						
WD11A	2855352	-48808	2003/02/06	7.50	509.00	90.10	841.00	0.02		2266.00	298.00	0.73						
WD11A	2855352	-48808	2003/05/21															
WD11A	2855352	-48808	2003/12/18															
WD11A	2855352	-48808	2004/07/15															
WD11A	2855352	-48808	2004/10/28	8.60	230.00	38.60	272.00	0.02		320.00	169.00	0.56						
WD11A	2855352	-48808	2005/09/08	7.63	158.00	150.00	73.80	0.02		436.00	86.00	0.00						

Borehole ID	Coordinates		Date Sampled	PH	EC	Ca	Na	Cr(VI)	Cr (total)	SO ₄	Cl	Mn	Mg	TDS	NO ₃ as N	Fe	F	Total Alkalinity
WD11A	2855352	-48808	2006/07/13	8.77	40.40	6.25	65.60	0.02	0.02	4.00	10.00	0.02	3.77	265.00	2.20	0.37	3.94	201.00
WD11A	2855352	-48808	2006/10/05	8.52	363.00	114.00	435.00	0.02	0.02	1326.00	134.00	0.02	110.00	2330.00	0.90	0.36	2.14	396.00
WD11A	2855352	-48808	2006/11/23	7.86	236.00	52.00	146.00	0.02	0.02	785.00	94.50	0.44	36.40	1510.00	0.50	13.40		
WD11A	2855352	-48808	2007/01/25	7.82	245.00	79.80	292.00	0.02	0.02	781.00	76.80	0.43	61.40	1580.00	0.23	8.90	1.90	
WD11A	2855352	-48808	2007/03/29	7.60	234.00	71.60	197.00	0.02	0.02	648.00	76.40	0.03	56.00	1510.00	0.23	0.55	4.97	
WD11A	2855352	-48808	2007/09/13	7.72	206.00	87.20	309.00	0.02	0.02	265.00	34.40	0.70	53.90	1320.00	1.60	23.20	1.55	
WD11A	2855352	-48808	2008/01/31	7.71	214.00	67.50	269.00	0.02	0.02	644.00	87.10	0.62	55.30	1390.00	0.60	2.94	1.13	
WD11A	2855352	-48808	2008/07/17	7.62	212.00	95.70	229.00	0.02	0.08	543.00	54.90	0.10	79.10	1390.00	0.50	1.72	7.07	
WD11A	2855352	-48808	2008/11/13	7.91		80.50	265.00	0.02	0.03	435.00	45.60	0.13	69.40	1200.00	0.33	0.43	1.94	
WD11A	2855352	-48808	2009/04/30	8.24		79.10	238.00	0.01	0.30	550.00	61.30	0.05	62.50	1200.00	0.94	0.05	2.41	
WD11A	2855352	-48808	2009/08/20	8.19		67.20	263.00	0.01	0.21	456.00	53.40	0.20	58.80	1070.00	0.51	0.10	1.29	
WD11A	2855352	-48808	2010/01/07	8.88		3.47	239.00	0.01	0.30	107.00	111.00	0.05	1.02	725.00	0.93	0.05	0.78	
WD11B	2855352	-48808	2001/10/25	8.30	408.00	49.30	683.00	0.02		1214.00	200.00							
WD11B	2855352	-48808	2002/01/30	8.90	405.00	46.40	784.00	0.02		1027.00	240.00							
WD11B	2855352	-48808	2002/06/27															
WD11B	2855352	-48808	2002/08/22	8.36	451.00	44.60	942.00	0.02		1261.00	340.00	1.27						
WD11B	2855352	-48808	2002/11/21	8.05	470.00	57.70	632.00	0.02		1406.00	240.00	4.32						
WD11B	2855352	-48808	2003/02/06															
WD11B	2855352	-48808	2003/05/21															
WD11B	2855352	-48808	2003/12/18															
WD11B	2855352	-48808	2004/07/15															

Borehole ID	Coordinates		Date Sampled	PH	EC	Ca	Na	Cr(VI)	Cr (total)	SO ₄	Cl	Mn	Mg	TDS	NO ₃ as N	Fe	F	Total Alkalinity
WD11B	2855352	-48808	2004/12/02															
WD11B	2855352	-48808	2005/09/08	8.68	61.30	7.70	107.00	0.02		50.70	10.00	0.00						
WD11B	2855352	-48808	2006/07/13	8.78	38.10	7.21	72.00	0.02	0.02	4.00	10.00	0.02	4.22	246.00	2.20	1.06	3.95	207.00
WD11B	2855352	-48808	2006/10/05	8.01	256.00	87.30	237.00	0.02	0.02	814.00	94.10	0.40	66.70	1640.00	0.50	7.93	2.01	362.00
WD11B	2855352	-48808	2006/11/23	8.11	331.00	76.50	286.00	0.02	0.02	1236.00	124.00	0.10	75.60	2140.00	1.10	52.10		
WD11B	2855352	-48808	2007/01/25	8.41	325.00	80.00	401.00	0.02	0.02	1141.00	101.00	0.06	94.00	2080.00	0.23	47.40	1.79	
WD11B	2855352	-48808	2007/03/29	8.63	293.00	75.90	351.00	0.02	0.08	952.00	90.90	0.06	98.90	1890.00	0.23	3.71	26.90	
WD11B	2855352	-48808	2007/09/27	7.70	292.00	190.00	410.00	0.02	0.37	892.00	83.40	6.38	75.40	1890.00	0.90	3629.00	1.28	
WD11B	2855352	-48808	2008/01/31	8.14	435.00	79.30	621.00	0.02	0.02	1512.00	138.00	0.24	163.00	2770.00	10.60	5.80	0.89	
WD11B	2855352	-48808	2008/07/17	8.12	319.00	97.80	464.00	0.02	0.03	1022.00	90.00	0.05	142.00	2020.00	0.80	1.74	4.74	
WD11B	2855352	-48808	2008/11/13	8.12		60.20	352.00	0.02	0.02	696.00	61.50	0.12	84.00	1640.00	0.33	4.56	1.71	
WD11B	2855352	-48808	2009/04/30	8.31		44.50	342.00	0.01	0.30	691.00	66.50	0.05	72.40	1390.00	1.11	0.05	1.69	
WD11B	2855352	-48808	2009/08/20	7.99		89.50	284.00	0.01	0.21	585.00	50.80	0.20	75.50	1260.00	0.32	0.15	1.10	
WD11B	2855352	-48808	2010/01/07	8.87		4.92	341.00	0.01	0.30	61.10	234.00	0.05	6.61	1070.00	0.42	0.05	2.39	
WD12A	2855409	-48814	2001/11/01	8.00	165.00	306.00	166.00	0.02		1303.00	253.00							
WD12A	2855409	-48814	2002/02/07	8.15	316.00	313.00	141.00	0.02		1146.00	290.00							
WD12A	2855409	-48814	2002/05/30	6.70	226.00	194.00	75.40	0.02		234.00	171.00	0.36						
WD12A	2855409	-48814	2002/08/29	7.60	354.00	347.00	172.00	0.02		1712.00	420.00	0.02						
WD12A	2855409	-48814	2002/11/28	8.12	362.00	335.00	165.00	0.02		1518.00	327.00	0.08						

Borehole ID	Coordinates		Date Sampled	PH	EC	Ca	Na	Cr(VI)	Cr (total)	SO ₄	Cl	Mn	Mg	TDS	NO ₃ as N	Fe	F	Total Alkalinity
WD12A	2855409	-48814	2003/02/13	7.50	373.00	109.00	75.30	0.02		816.00	306.00	0.02						
WD12A	2855409	-48814	2003/05/29	7.11	406.00	369.00	177.00	0.02		972.00	400.00	0.21						
WD12A	2855409	-48814	2003/12/18															
WD12A	2855409	-48814	2004/07/22	7.85	128.00	131.00	42.00	0.02		273.00	70.00	0.14						
WD12A	2855409	-48814	2004/10/28															
WD12A	2855409	-48814	2005/09/15	7.50	497.00	461.00	211.00	0.02		2523.00	403.00	0.00						
WD12A	2855409	-48814	2006/07/20	7.42	503.00	1077.00	428.00	0.02	0.11	2461.00	402.00	0.02	526.00	3340.00	3.10	0.10	0.50	578.00
WD12A	2855409	-48814	2006/10/12	7.71	515.00	469.00	204.00	0.02	0.02	2202.00	325.00	0.02	451.00	3340.00	3.80	0.11	18.60	511.00
WD12A	2855409	-48814	2006/11/30	7.44	510.00	425.00	182.00	0.02	0.02	2486.00	372.00	0.02	394.00	3340.00	3.20	0.75	0.23	
WD12A	2855409	-48814	2007/02/01	7.36	811.00	493.00	446.00	0.02	0.02	2360.00	342.00	0.02	411.00	5230.00	13.20	0.50	0.29	
WD12A	2855409	-48814	2007/04/05	7.52	514.00	330.00	147.00	0.02	0.02	2021.00	288.00	0.02	271.00	3340.00	0.23	2.66		
WD12A	2855409	-48814	2007/09/27	7.63	484.00	518.00	265.00	0.02	0.02	1384.00	197.00	0.02	512.00	3150.00	0.90	41.80	0.29	
WD12A	2855409	-48814	2008/01/31	7.34	472.00	458.00	229.00	0.02	0.02	1824.00	238.00	0.02	446.00	3030.00	23.70	0.26	0.41	
WD12A	2855409	-48814	2008/11/27	7.44		446.00	218.00	0.01	0.05	2084.00	283.00	0.05	436.00	3030.00	0.33	0.36	0.50	
WD12A	2855409	-48814	2009/09/03	7.79		404.00	268.00	0.01	0.30	2015.00	272.00	0.05	413.00	2770.00	0.60	0.56	0.50	
WD12A	2855409	-48814	2010/01/21	7.66		392.00	296.00	0.01	0.10	1809.00	223.00	0.10	404.00	2770.00	0.27	0.34	0.50	
WD12B	2855409	-48814	2001/11/01															
WD12B	2855409	-48814	2002/02/07															
WD12B	2855409	-48814	2002/05/30															
WD12B	2855409	-48814	2002/08/29															
WD12B	2855409	-48814	2002/11/28															

Borehole ID	Coordinates		Date Sampled	PH	EC	Ca	Na	Cr(VI)	Cr (total)	SO ₄	Cl	Mn	Mg	TDS	NO ₃ as N	Fe	F	Total Alkalinity
WD12B	2855409	-48814	2003/02/13															
WD12B	2855409	-48814	2003/05/29															
WD12B	2855409	-48814	2003/12/18															
WD12B	2855409	-48814	2004/07/22															
WD12B	2855409	-48814	2004/10/28															
WD12B	2855409	-48814	2005/09/15															
WD13A	2855553	-48897	2001/11/01	8.10	92.00	120.00	69.80	0.02		459.00	68.00							
WD13A	2855553	-48897	2002/02/07	8.36	97.00	78.40	6.08	0.02		253.00	48.00							
WD13A	2855553	-48897	2002/05/30	7.40	124.00	69.70	71.40	0.02		488.00	73.00	0.19						
WD13A	2855553	-48897	2002/08/29	7.70	121.00	119.00	69.00	0.02		309.00	220.00	0.02						
WD13A	2855553	-48897	2002/11/28	8.26	117.00	89.90	62.90	0.02		378.00	69.00	0.02						
WD13A	2855553	-48897	2003/02/13	7.50	127.00	114.00	70.60	0.02		375.00	70.00	1.15						
WD13A	2855553	-48897	2003/05/29	8.21	129.00	113.00	69.10	0.02		443.00	90.00	0.17						
WD13A	2855553	-48897	2003/12/18															
WD13A	2855553	-48897	2004/07/22															
WD13A	2855553	-48897	2004/10/28															
WD13A	2855553	-48897	2005/09/15	7.71	155.00	119.00	71.60	0.02		493.00	91.80	0.00						
WD13A	2855553	-48897	2006/07/20	8.24	404.00	273.00	337.00	0.02	0.02	1610.00	171.00	0.02	48.90	2650.00	2.50	0.11	2.16	367.00
WD13A	2855553	-48897	2006/10/12	8.56	56.20	15.40	89.80	0.02	0.02	41.10	10.00	0.12	4.24	366.00	6.00	0.25	2.91	225.00
WD13A	2855553	-48897	2006/11/30	7.47	216.00	225.00	84.60	0.02	0.02	767.00	135.00	0.16	103.00	1390.00	0.50	0.29	0.31	
WD13A	2855553	-48897	2007/02/01	7.55	224.00	214.00	97.40	0.02	0.02	749.00	128.00	0.02	112.00	1450.00	6.50	0.40	0.39	
WD13A	2855553	-48897	2007/04/05	8.05	226.00	115.00	80.90	0.02	0.02	786.00	134.00	0.02	82.00	1450.00	0.23	0.70		

Borehole ID	Coordinates		Date Sampled	PH	EC	Ca	Na	Cr(VI)	Cr (total)	SO ₄	Cl	Mn	Mg	TDS	NO ₃ as N	Fe	F	Total Alkalinity
WD13A	2855553	-48897	2007/09/27	7.44	234.00	336.00	107.00	0.02	0.10	641.00	95.90	0.68	162.00	1510.00	1.30	2.78	0.40	
WD13A	2855553	-48897	2008/02/14	8.73	120.00	18.70	157.00	0.02	0.02	223.00	122.00	0.02	38.40	757.00	0.50	0.55	0.42	
WD13A	2855553	-48897	2008/07/17	7.40	249.00	339.00	126.00	0.02	0.02	748.00	112.00	0.06	148.00	1580.00	0.33	0.28	2.99	
WD13A	2855553	-48897	2008/11/27	7.60		303.00	91.40	0.01	0.05	934.00	135.00	0.05	166.00	1640.00	0.33	0.44	0.50	
WD13A	2855553	-48897	2009/05/13	7.65		263.00	103.00	0.01	0.21	898.00	128.00	0.20	145.00	1640.00	0.89	0.10	1.16	
WD13A	2855553	-48897	2009/09/03	7.47		326.00	125.00	0.01	0.30	903.00	116.00	0.08	157.00	1580.00	1.14	1.01	0.50	
WD13A	2855553	-48897	2010/01/21	8.79		20.70	259.00	0.01	0.10	191.00	113.00	0.10	14.40	820.00	0.27	0.13	0.81	
WD13B	2855553	-48897	2001/11/01															
WD13B	2855553	-48897	2002/02/07															
WD13B	2855553	-48897	2002/05/30															
WD13B	2855553	-48897	2002/08/29															
WD13B	2855553	-48897	2002/12/05															
WD13B	2855553	-48897	2002/12/05															
WD13B	2855553	-48897	2003/02/13															
WD13B	2855553	-48897	2003/05/29															
WD13B	2855553	-48897	2003/12/18															
WD13B	2855553	-48897	2004/07/15															
WD13B	2855553	-48897	2004/10/28															
WD13B	2855553	-48897	2005/09/15	8.67	60.00	8.40	103.00	0.02		54.50	10.00	0.00						
WD13B	2855553	-48897	2006/07/20	7.82	281.00	210.00	642.00	0.02	0.03	976.00	125.00	0.02	107.00	1830.00	2.20	0.62	1.61	241.00
WD13B	2855553	-48897	2006/10/12	7.52	214.00	194.00	95.10	0.02	0.02	673.00	113.00	0.04	112.00	1390.00	0.70	0.05	0.55	319.00
WD13B	2855553	-48897	2006/11/30	8.86	57.70	13.20	90.60	0.02	0.02	57.90	8.41	0.21	6.69	366.00	37.80	21.40	1.91	
WD13B	2855553	-48897	2007/02/01	8.75	60.70	15.60	98.10	0.02	0.02	51.40	1.00	0.02	3.02	397.00	8.30	0.12	1.66	

Borehole ID	Coordinates		Date Sampled	PH	EC	Ca	Na	Cr(VI)	Cr (total)	SO ₄	Cl	Mn	Mg	TDS	NO ₃ as N	Fe	F	Total Alkalinity
WD13B	2855553	-48897	2007/04/05	8.84	63.90	15.50	94.00	0.02	0.02	45.00	6.41	0.02	4.17	410.00	1.30	0.40		
WD13B	2855553	-48897	2007/09/27	8.85	75.40	33.00	147.00	0.02	0.07	44.50	4.83	0.97	17.60	492.00	1.30	94.40	2.57	
WD13B	2855553	-48897	2008/02/14	8.57	366.00	228.00	306.00	0.02	0.02	1035.00	332.00	1.18	160.00	2330.00	16.80	0.25	0.35	
WD13B	2855553	-48897	2008/07/17	8.80	88.80	7.49	190.00	0.02	0.02	79.00	13.70	0.02	2.94	568.00	0.40	0.53	2.67	
WD13B	2855553	-48897	2008/11/27	8.91		8.97	159.00	0.01	0.05	91.20	17.10	0.17	6.40	618.00	0.50	16.00	2.84	
WD13B	2855553	-48897	2009/09/03	8.97		4.71	140.00	0.03	0.30	100.00	24.60	0.05	2.73	694.00	0.94	1.27	2.69	
WD13B	2855553	-48897	2010/01/21	8.91		11.80	360.00	0.01	0.10	63.60	229.00	0.10	6.26	1070.00	0.27	0.07	2.40	
WD15A	2855376	-48825	2001/11/08	7.00	398.00	558.00	79.50	0.02		1661.00	270.00							
WD15A	2855376	-48825	2002/02/14	7.38	395.00	439.00	81.80	0.02		1131.00	310.00							
WD15A	2855376	-48825	2002/06/06	5.50	413.00	504.00	66.10	0.02		1681.00	440.00	0.02						
WD15A	2855376	-48825	2002/09/05	6.85	416.00	605.00	69.20	0.02		927.00	280.00	0.02						
WD15A	2855376	-48825	2002/12/05	6.80	420.00	688.00	104.00	0.02		3023.00	320.00	0.02						
WD15A	2855376	-48825	2003/02/20	6.70	409.00	565.00	81.60	0.02		1706.00	307.00	0.09						
WD15A	2855376	-48825	2003/06/05	7.06	408.00	580.00	861.00	0.02		1621.00	330.00	0.14						
WD15A	2855376	-48825	2003/12/18															
WD15A	2855376	-48825	2004/07/15															
WD15A	2855376	-48825	2004/11/04															
WD15A	2855376	-48825	2005/09/22	7.27	368.00	534.00	119.00	0.02		1494.00	337.00	0.10						
WD15A	2855376	-48825	2006/05/04	9.33	136.00	9.44	115.00	0.02	0.02	246.00	103.00	0.14	1.00	1022.00	2.21	16.20	0.90	277.00
WD15A	2855376	-48825	2006/05/04	9.13	187.00	15.00	117.00	0.02	0.02	143.00	89.70	0.02	11.00	1390.00	2.21	0.16	4.75	692.00

Borehole ID	Coordinates		Date Sampled	PH	EC	Ca	Na	Cr(VI)	Cr (total)	SO ₄	Cl	Mn	Mg	TDS	NO ₃ as N	Fe	F	Total Alkalinity
WD15A	2855376	-48825	2006/07/27	9.08	133.00	3.53	218.00	0.02	0.02	243.00	120.00	0.02	1.22	851.00	7.90	7.66	0.62	293.00
WD15A	2855376	-48825	2006/10/19	8.85	137.00	4.33	283.00	0.02	0.02	181.00	111.00	0.79	1.31	883.00	0.50	60.00	0.33	299.00
WD15A	2855376	-48825	2006/12/07	9.02	141.00	7.26	181.00	0.02	0.14	177.00	131.00	0.31	1.15	914.00	0.50	45.00	0.49	
WD15A	2855376	-48825	2007/02/08	8.70	141.00	9.52	224.00	0.02	0.06	24.90	23.90	1.82	5.66	914.00	0.23	172.00	1.55	
WD15A	2855376	-48825	2007/04/12	8.19	188.00	21.20	239.00	0.02	0.41	148.00	125.00	4.74	16.30	1200.00	0.23	468.00	0.60	
WD15A	2855376	-48825	2008/02/14	7.87	442.00	454.00	94.60	0.02	0.03	2041.00	362.00	0.02	372.00	2900.00	3.20	0.70	0.25	
WD15A	2855376	-48825	2008/07/03	7.51	264.00	147.00	161.00	0.02	0.02	588.00	392.00	0.17	282.00	1700.00	0.33	7.58		
WD15A	2855376	-48825	2008/12/11	6.93		729.00	137.00	0.01	0.05	2309.00	242.00	0.42	505.00	3030.00	0.90	6.57	0.50	
WD15A	2855376	-48825	2009/09/17	7.00		600.00	141.00	0.01	0.30	1980.00	188.00	0.26	436.00	2900.00	3.50	0.05	0.50	
WD15A	2855376	-48825	2010/02/04	7.06		503.00	141.00	0.01	0.07	25.50	23.30	0.20	387.00	2900.00	5.74	0.11	0.50	
WD15B	2855376	-48825	2001/11/08	8.50	82.90	44.10	60.00	0.02		60.20	87.00							
WD15B	2855376	-48825	2002/02/14	8.33	83.00	43.70	63.00	0.02		115.00	55.00							
WD15B	2855376	-48825	2002/06/06	7.70	95.20	59.50	66.10	0.02		170.00	230.00	0.27						
WD15B	2855376	-48825	2002/09/05	8.00	67.70	72.50	62.80	0.02		128.00	120.00	1.54						
WD15B	2855376	-48825	2002/12/05	7.60	122.00	70.80	63.90	0.02		273.00	170.00	3.97						
WD15B	2855376	-48825	2003/02/20															
WD15B	2855376	-48825	2003/06/05															
WD15B	2855376	-48825	2003/12/18															
WD15B	2855376	-48825	2003/12/18															
WD15B	2855376	-48825	2004/07/15															
WD15B	2855376	-48825	2004/11/04															

Borehole ID	Coordinates		Date Sampled	PH	EC	Ca	Na	Cr(VI)	Cr (total)	SO ₄	Cl	Mn	Mg	TDS	NO ₃ as N	Fe	F	Total Alkalinity
WD15B	2855376	-48825	2005/07/15	9.00	158.00	32.40	215.00	0.02		181.00	100.00	0.02						
WD15B	2855376	-48825	2006/07/27	9.07	192.00	9.16	320.00	0.02	0.02	102.00	123.00	0.02	11.50	1260.00	2.20	4.63	3.95	708.00
WD15B	2855376	-48825	2006/10/19	9.10	220.00	7.76	487.00	0.02	0.02	110.00	137.00	0.02	14.80	1390.00	0.50	0.88	3.37	821.00
WD15B	2855376	-48825	2006/12/07	9.39	225.00	8.33	459.00	0.02	0.02	124.00	174.00	0.02	12.60	1450.00	1.40	1.06	3.99	
WD15B	2855376	-48825	2007/02/08	9.29	225.00	7.68	410.00	0.02	0.02	141.00	185.00	0.17	13.20	1450.00	0.23	31.50	3.44	
WD15B	2855376	-48825	2007/04/12	9.18	296.00	8.19	408.00	0.02	0.02	124.00	168.00	0.02	10.80	1890.00	0.23	1.32	3.37	
WD15B	2855376	-48825	2008/02/14	8.25	247.00	130.00	110.00	0.02	0.02	557.00	395.00	0.06	156.00	1580.00	1.50	5.03	0.53	
WD15B	2855376	-48825	2008/07/03	7.52	264.00	81.60	98.00	0.02	0.05	627.00	397.00	0.11	183.00	1700.00	5.40	3.76		
WD15B	2855376	-48825	2008/12/11	7.26		162.00	137.00	0.01	0.05	759.00	452.00	0.11	284.00	1770.00	1.70	0.83	0.50	
WD15B	2855376	-48825	2009/09/17	7.10		144.00	122.00	0.01	0.30	826.00	383.00	1.42	258.00	1770.00	3.34	0.05	0.50	
WD15B	2855376	-48825	2010/02/04	7.06		133.00	127.00	0.01	0.07	989.00	425.00	3.74	245.00	1890.00	0.60	0.07	0.59	
WD17A	2855303	-48846	2001/11/15	8.60	85.80	12.10	161.00	0.02		207.00	85.00							
WD17A	2855303	-48846	2001/11/22	8.20	86.30	17.90	176.00	0.02		95.60	260.00							
WD17A	2855303	-48846	2006/05/11	8.51	80.70	15.70	85.60	0.02	0.02	121.00	68.70	0.02	11.60	523.00	2.21	0.26	0.67	171.00
WD17A	2855303	-48846	2006/12/14	8.27	155.00	31.30	141.00	0.02	0.08	286.00	136.00	0.29	32.70	1010.00	0.23	21.00	0.50	
WD17A	2855303	-48846	2007/02/15	7.96	325.00	28.40	185.00	0.02	0.02	282.00	136.00	0.02	37.60	2080.00	0.50	0.52	0.45	
WD17A	2855303	-48846	2008/02/28	8.09	347.00	241.00	370.00	0.02	0.02	1072.00	311.00	1.25	163.00	2210.00	10.80	0.14	0.53	
WD17A	2855303	-48846	2008/07/03	8.59	131.00	20.70	219.00	0.02	0.02	200.00	101.00	0.02	47.50	851.00	0.33	0.24		
WD17A	2855303	-48846	2008/07/30	8.80	144.00	16.00	165.00	0.02	0.02	267.00	110.00	0.02	31.80	914.00	0.33	0.54	0.86	

Borehole ID	Coordinates		Date Sampled	PH	EC	Ca	Na	Cr(VI)	Cr (total)	SO ₄	Cl	Mn	Mg	TDS	NO ₃ as N	Fe	F	Total Alkalinity	
WD17A	2855303	-48846	2009/10/01	7.71		384.00	386.00	0.01	0.30	1663.00	371.00	0.05	300.00	2900.00	2.22	0.05	0.50		
WD17A	2855303	-48846	2010/02/18	8.15		420.00	433.00	0.01	0.14	1540.00	345.00	0.10	269.00	2650.00	2.01	8.17	0.50		
WD17B	2855303	-48846	2001/11/15	7.40	150.00	21.30	141.00	0.02		349.00	90.00								
WD17B	2855303	-48846	2001/11/22	7.50	145.00	21.30	142.00	0.02		95.20	260.00								
WD17B	2855303	-48846	2006/05/11	7.94	285.00	51.40	164.00	0.02	0.02	45.20	159.00	0.72	34.60	1830.00	2.21	0.95	0.60	20.00	
WD17B	2855303	-48846	2006/12/14	7.89	310.00	103.00	172.00	0.02	0.02	613.00	229.00	0.66	66.30	1950.00	1.50	2.09	0.54		
WD17B	2855303	-48846	2007/02/15	8.67	147.00	155.00	266.00	0.02	0.02	643.00	245.00	1.04	109.00	946.00	0.90	0.94	0.45		
WD17B	2855303	-48846	2008/02/28	8.53	102.00	16.40	118.00	0.02	0.02	201.00	97.40	0.02	27.80	662.00	1.00	0.26	0.66		
WD17B	2855303	-48846	2008/07/03	7.67	387.00	273.00	365.00	0.02	0.02	1016.00	278.00	1.35	193.00	2460.00	7.50	0.18			
WD17B	2855303	-48846	2008/07/30	7.70	395.00	312.00	377.00	0.02	0.03	1015.00	264.00	1.40	201.00	2520.00	10.00	0.37	0.73		
WD17B	2855303	-48846	2009/10/01	8.49		23.20	205.00	0.01	0.30	378.00	136.00	0.05	74.20	1010.00	0.55	0.05	0.50		
WD17B	2855303	-48846	2010/02/18	8.69		634.00	258.00	0.01	0.24	271.00	101.00	0.09	58.00	757.00	0.27	6.34	0.94		
WD18A	2855451	-48926	2001/11/15	8.30	240.00	147.00	141.00	0.02		663.00	85.00								
WD18A	2855451	-48926	2001/11/22	7.70	208.00	173.00	172.00	0.02		858.00	220.00								
WD18A	2855451	-48926	2002/02/21	8.53	203.00	53.80	163.00	0.02		823.00	131.00								
WD18A	2855451	-48926	2002/06/13	8.09	221.00	62.20	249.00	0.02		904.00	290.00	0.08							
WD18A	2855451	-48926	2002/09/12																
WD18A	2855451	-48926	2002/12/12	7.24	244.00	149.00	196.00			787.00	111.00	5.56							
WD18A	2855451	-48926	2003/02/27	7.70	235.00	126.00	175.00	0.02		304.00	122.00	1.92							

Borehole ID	Coordinates		Date Sampled	PH	EC	Ca	Na	Cr(VI)	Cr (total)	SO ₄	Cl	Mn	Mg	TDS	NO ₃ as N	Fe	F	Total Alkalinity
WD18A	2855451	-48926	2003/06/12	8.50	228.00	83.30	150.00	0.02		779.00	160.00	0.05						
WD18A	2855451	-48926	2003/12/18															
WD18A	2855451	-48926	2004/07/22															
WD18A	2855451	-48926	2004/11/11	8.60	235.00	143.00	151.00	0.02		776.00	102.00	2.16						
WD18A	2855451	-48926	2005/09/29	8.09	231.00	135.00	109.00	0.02			130.00	0.00						
WD18A	2855451	-48926	2006/05/11	7.97	200.00	114.00	97.40	0.02	0.02	730.00	107.00	0.02	83.90	1260.00	2.21	0.15	0.37	246.00
WD18A	2855451	-48926	2006/12/14	7.38	220.00	126.00	70.90	0.02	0.05	739.00	119.00	0.30	68.30	1390.00	0.40	0.92	0.91	
WD18A	2855451	-48926	2007/02/15	7.76	238.00	130.00	436.00	0.02	0.02	767.00	126.00	1.47	113.00	1510.00	0.90	0.96	0.28	
WD18A	2855451	-48926	2007/10/25	7.39	99.40	332.00	160.00	0.02	0.02	651.00	112.00	0.94	172.00	631.00	2.20	0.37	3.52	
WD18A	2855451	-48926	2008/02/28	7.26	457.00	561.00	96.00	0.02	0.02	2230.00	358.00	0.02	428.00	2900.00	3.50	0.06	0.30	
WD18A	2855451	-48926	2008/07/30	7.47	272.00	340.00	172.00	0.02	0.02	838.00	107.00	1.28	144.00	1770.00	0.33	0.83	0.53	
WD18A	2855451	-48926	2009/10/01	7.34		318.00	168.00	0.01	0.30	1068.00	145.00	2.58	170.00	1830.00	0.86	0.05	0.50	
WD18A	2855451	-48926	2010/02/18	7.26		359.00	202.00	0.01	0.09	1113.00	136.00	1.22	189.00	1830.00	0.27	3.52	0.83	
WD18B	2855451	-48926	2001/11/15	7.80	190.00	66.80	247.00	0.02		877.00	225.00							
WD18B	2855451	-48926	2001/11/22	8.50	240.00	65.20	267.00	0.02		1017.00	380.00							
WD18B	2855451	-48926	2006/05/11	7.69	249.00	92.20	108.00	0.02	0.02	942.00	125.00	0.07	114.00	1580.00	2.21	0.23	0.32	341.00
WD18B	2855451	-48926	2006/12/14	8.03	236.00	116.00	144.00	0.02	0.02	939.00	135.00	0.06	161.00	1510.00	0.90	3.77	0.24	
WD18B	2855451	-48926	2007/02/15	7.74	222.00	100.00	463.00	0.02	0.02	872.00	130.00	1.09	190.00	1450.00	2.00	89.60	0.58	
WD18B	2855451	-48926	2007/10/25	7.83	182.00	177.00	162.00	0.02	0.02	744.00	120.00	0.38	189.00	1200.00	2.30	46.80	2.36	
WD18B	2855451	-48926	2008/02/28	7.86	251.00	160.00	108.00	0.02	0.02	683.00	376.00	0.02	178.00	1640.00	0.70	1.73	0.62	

Borehole ID	Coordinates		Date Sampled	PH	EC	Ca	Na	Cr(VI)	Cr (total)	SO ₄	Cl	Mn	Mg	TDS	NO ₃ as N	Fe	F	Total Alkalinity
WD18B	2855451	-48926	2008/07/30	7.85	293.00	174.00	165.00	0.02	0.05	915.00	127.00	0.12	155.00	1890.00	0.33	1.53	0.50	
WD18B	2855451	-48926	2009/10/01	7.63		224.00	207.00	0.01	0.30	1188.00	153.00	0.16	255.00	2020.00	0.51	0.05	0.50	
WD18B	2855451	-48926	2010/02/18	7.26		156.00	224.00	0.01	0.08	1215.00	153.00	0.09	247.00	1830.00	0.27	4.61	0.50	
SD1	2856283	-49226	2001/11/29															
SD1	2856283	-49226	2002/02/28	7.36	122.00	26.00	252.00	0.02		140.00								
SD1	2856283	-49226	2002/06/20	7.50	118.00	29.40	484.00	0.02		240.00	270.00	1.69						
SD1	2856283	-49226	2002/09/19	7.47	109.00	19.40	156.00	0.02		147.00	140.00	0.91						
SD1	2856283	-49226	2002/12/19	7.20	103.00	23.00	218.00	0.02		128.00	102.00	0.99						
SD1	2856283	-49226	2003/03/06	7.00	56.00	35.30	73.10	0.02		115.00	56.00	1.27						
SD1	2856283	-49226	2003/06/19	7.90	50.70	34.00	94.00	0.02		75.70	30.00	3.63						
SD1	2856283	-49226	2003/10/02	7.09	73.20	206.00	107.00	0.02		102.00	75.00	0.02						
SD1	2856283	-49226	2004/08/12	7.60	127.00	38.70	100.00	0.02		286.00	84.00	1.25						
SD1	2856283	-49226	2004/11/25															
SD1	2856283	-49226	2005/09/08															
SD1	2856283	-49226	2006/03/02	7.14	131.00	44.20	177.00	0.02	0.02	135.00	99.70	1.79	23.80	851.00		3.47	0.75	
SD1	2856283	-49226	2006/03/30	7.88	534.00	105.00	558.00		0.02	1544.00	435.00	0.77	140.00	3470.00	2.21	20.30	1.36	
SD1	2856283	-49226	2006/03/30	7.13	0.50	146.00	408.00		0.02	1327.00	285.00	1.02	142.00	3970.00	2.21	80.90	0.57	
SD1	2856283	-49226	2006/03/30	7.09	621.00	556.00	310.00		0.02	2587.00	382.00	0.27	346.00	3970.00	4.72	1.86	0.25	
SD1	2856283	-49226	2006/03/30	7.02	613.00	610.00	366.00		0.02	2371.00	384.00	0.14	406.00	3970.00	10.70	5.75	0.20	
SD1	2856283	-49226	2006/12/21	7.16	87.60	22.30	100.00	0.02	0.02	73.20	79.80	0.37	13.50	555.00	0.23	6.99	1.74	

Borehole ID	Coordinates		Date Sampled	PH	EC	Ca	Na	Cr(VI)	Cr (total)	SO ₄	Cl	Mn	Mg	TDS	NO ₃ as N	Fe	F	Total Alkalinity
SD1	2856283	-49226	2007/02/22	7.11	88.0 0	27.70	115.0 0	0.02	0.36	34.80	68.90	1.09	18.60	555.00	0.50	51.40	0.79	
SD1	2856283	-49226	2007/07/16	7.77		30.60	141.0 0		0.01	80.10			21.00	494.00				
SD1	2856283	-49226	2008/03/13	7.14	86.8 0	21.70	102.0 0	0.02	0.02	54.30	77.20	0.20	13.60	555.00	1.20	0.19	0.81	
SD1	2856283	-49226	2009/01/08	7.11		29.30	286.0 0	0.01	0.05		136.00	0.25	21.10	788.00	2.88	1.38	0.53	
SD1	2856283	-49226	2009/05/28	7.00		54.20	262.0 0	0.01	0.21	192.00	165.00	0.99	42.90	1390.00	0.38	0.10	0.50	
SD1	2856283	-49226	2009/10/15	7.23		40.10	227.0 0	0.01	0.30	207.00	173.00	0.05	28.90	3030.00	7.25	0.11		
SD1	2856283	-49226	2010/03/03			34.70	200.0 0	0.01	0.07	145.00	155.00	0.42	25.10	820.00	2.48	0.05	0.59	
		0																
SD2	2856283	-49226	2001/11/29	8.00	105 0.00	817.00	1095. 00	0.02		302.00	115.00							
SD2	2856283	-49226	2002/02/28	7.97	51.0 0	24.30	27.70	0.02		92.40								
SD2	2856283	-49226	2002/06/20	8.00	33.3 0	31.50	26.60	0.02		435.00	120.00	1.93						
SD2	2856283	-49226	2002/09/19	8.26	33.8 0	30.80	26.40	0.02		154.00	20.00	1.44						
SD2	2856283	-49226	2002/12/19	8.13	32.7 0	26.50	27.90	0.02		63.60	11.00	0.11						
SD2	2856283	-49226	2003/03/06	7.86	33.0 0	33.60	7.41	0.02		19.70	12.00	0.12						
SD2	2856283	-49226	2003/06/19	9.20	34.1 0	38.20	30.50	0.02		66.50	10.00	0.11						
SD2	2856283	-49226	2003/10/02	8.35	35.3 0	21.20	21.20	0.02		19.10	10.00	0.15						
SD2	2856283	-49226	2004/08/12	8.30	38.6 0	27.10	14.20	0.02		106.00	12.00	0.04						
SD2	2856283	-49226	2004/10/07															
SD2	2856283	-49226	2005/07/07															
SD2	2856283	-49226	2006/03/02	7.82	41.0 0	30.80	24.00	0.02	0.02	20.50	18.00	0.02	10.70	265.00		1.27	0.51	
SD2	2856283	-49226	2006/05/18	7.34	96.8 0	16.20	96.50	0.02	0.02	97.30	58.30	0.60	11.70	618.00	2.21	1.35	1.19	

Borehole ID	Coordinates		Date Sampled	PH	EC	Ca	Na	Cr(VI)	Cr (total)	SO ₄	Cl	Mn	Mg	TDS	NO ₃ as N	Fe	F	Total Alkalinity
SD2	2856283	-49226	2006/12/21	8.16	38.50	30.00	23.80	0.02	0.02	14.50	15.70	0.06	11.70	246.00	10.10	1.18	1.24	
SD2	2856283	-49226	2007/02/22	8.18	39.80	30.10	23.30	0.02	0.04	13.20	15.00	0.48	12.50	252.00	8.10	3.56	0.41	
SD2	2856283	-49226	2007/04/26	8.12	38.70	29.10	24.60	0.02	0.02	9.00	16.10	0.04	11.40	246.00	8.70	0.88	0.91	
SD2	2856283	-49226	2007/07/16	7.94		29.90	31.00		0.01	15.80			12.00	222.00				
SD2	2856283	-49226	2007/11/07	8.32	39.00	34.20	28.10	0.02	0.31	25.30	19.30	1.14	13.70	246.00	13.40	16.50	0.60	
SD2	2856283	-49226	2008/03/13	8.22	41.60	30.20	21.20	0.02	0.09	13.70	18.40	0.09	10.90	265.00	9.50	1.42	0.59	
SD2	2856283	-49226	2009/01/08	7.83		31.90	34.40	0.01	0.05		20.50	0.05	12.40	290.00	12.40	0.63	1.12	
SD2	2856283	-49226	2009/05/28	7.69		26.00	23.50	0.01	0.21	34.80	30.30	0.20	11.10	277.00	4.83	0.10	0.50	
SD2	2856283	-49226	2009/10/15	7.90		35.70	32.70	0.01	0.30	33.10	20.80	0.05	14.70	290.00	11.20	0.05		
SD2	2856283	-49226	2010/03/03			33.90	29.50	0.01	0.07	19.00	21.90	0.37	12.90	290.00	2.87	0.06	0.50	
		0																
SD3	2856283	-49226	2001/11/29															
SD3	2856283	-49226	2002/02/28															
SD3	2856283	-49226	2002/06/20															
SD3	2856283	-49226	2002/09/19															
SD3	2856283	-49226	2002/12/19															
SD3	2856283	-49226	2003/03/06															
SD3	2856283	-49226	2003/06/19															
SD3	2856283	-49226	2003/10/02															
SD3	2856283	-49226	2004/07/01															
SD3	2856283	-49226	2004/10/07															
SD3	2856283	-49226	2005/07/14															
SD3	2856283	-49226	2006/03/02	6.98	453.00	268.00	534.00	0.02	0.05	755.00	10.00	0.03	126.00	2900.00		3.23	2.93	
SD3	2856283	-49226	2006/05/18	8.32	37.80	24.00	23.90	0.02	0.02	23.40	15.50	0.02	9.41	240.00	15.10	1.69	0.49	
		0																
SD4	2856124	-49200	2001/11/29	9.10	235.00	45.00	4382.00	0.02		472.00	30.00							

Borehole ID	Coordinates		Date Sampled	PH	EC	Ca	Na	Cr(VI)	Cr (total)	SO ₄	Cl	Mn	Mg	TDS	NO ₃ as N	Fe	F	Total Alkalinity
SD4	2856124	-49200	2002/02/28	7.44	50.9 0	3.50	104.0 0	0.02		105.00								
SD4	2856124	-49200	2002/06/20	7.50	50.8 0	6.15	109.0 0	0.02		491.00	140.00	0.92						
SD4	2856124	-49200	2002/09/19	7.40	49.3 0	3.51	78.00	0.02		349.00	50.00	0.30						
SD4	2856124	-49200	2002/12/19	7.28	48.2 0	3.71	111.0 0	0.02		237.00	41.00	0.39						
SD4	2856124	-49200	2003/03/06	7.12	48.0 0	2.72	40.10	0.02		122.00	37.00	0.12						
SD4	2856124	-49200	2003/06/19	8.30	51.1 0	4.87	133.0 0	0.02		48.70	30.00	0.63						
SD4	2856124	-49200	2003/10/02	7.16	49.3 0	6.18	99.30	0.02		37.00	90.00	0.02						
SD4	2856124	-49200	2004/08/12	7.90	55.4 0	3.83	67.50	0.02		99.90	38.00	0.02						
SD4	2856124	-49200	2004/11/25	7.70	30.3 0	2.36	84.90	0.02		55.00	42.00	0.02						
SD4	2856124	-49200	2005/07/14															
SD4	2856124	-49200	2006/03/02	8.48	31.6 0	1.00	32.80	0.02	0.02	13.00	23.80	0.02	1.00	202.00		0.83	1.29	
SD4	2856124	-49200	2006/05/18	8.14	56.4 0	2.19	88.40	0.02	0.02	28.70	33.80	0.02	1.21	366.00	13.90	0.28	3.05	
SD4	2856124	-49200	2006/12/21	7.30	57.4 0	4.56	94.00	0.02	0.02	21.80	40.80	0.02	2.80	366.00	8.50	0.56	3.16	
SD4	2856124	-49200	2007/02/22	7.27	57.9 0	4.73	92.00	0.02	0.03	13.70	34.10	0.12	2.63	366.00	6.30	1.62	3.14	
SD4	2856124	-49200	2007/07/16	7.57		5.01	125.0 0		0.01	23.40			2.84	339.00				
SD4	2856124	-49200	2008/03/13	7.22	57.8 0	3.49	77.40	0.02	0.03	24.60	39.60	0.03	2.00	366.00	4.50	0.05	2.24	
SD4	2856124	-49200	2009/01/08	7.19		4.39	145.0 0	0.01	0.05		41.60	0.09	2.28	378.00	3.55	0.65	2.03	
SD4	2856124	-49200	2009/05/28	7.39		2.50	82.80	0.01	0.21	27.50	35.10	0.20	1.58	366.00	1.10	0.10	2.55	
SD4	2856124	-49200	2009/10/15	7.57		3.59	122.0 0	0.01	0.30	39.60	38.50	0.05	2.24	366.00	3.93	0.09		
SD4	2856124	-49200	2010/03/03			3.29	104.0 0	0.01	0.23	23.50	40.40	0.09	2.06	366.00	2.12	1.55	2.33	
		0																

Borehole ID	Coordinates		Date Sampled	PH	EC	Ca	Na	Cr(VI)	Cr (total)	SO ₄	Cl	Mn	Mg	TDS	NO ₃ as N	Fe	F	Total Alkalinity
SD5	2856124	-49200	2001/11/29	9.20	232.00	56.30	4080.00	0.02		485.00	26.00							
SD5	2856124	-49200	2002/02/28	8.80	29.90	3.00	69.40	0.02		105.00								
SD5	2856124	-49200	2002/06/20	7.60	33.40	9.84	63.20	0.02		271.00	140.00	0.95						
SD5	2856124	-49200	2002/09/19	9.15	30.30	2.79	57.80	0.02		17.40	30.00	0.02						
SD5	2856124	-49200	2002/12/19	9.09	29.80	2.56	76.40	0.02		51.20	11.00	0.04						
SD5	2856124	-49200	2003/03/06	8.69	30.00	2.41	24.00	0.02		13.60	10.00	0.03						
SD5	2856124	-49200	2003/06/19	10.00	30.40	3.15	66.20	0.02		53.60	10.00	0.02						
SD5	2856124	-49200	2003/10/02	9.20	31.50	3.76	70.70	0.02		13.50	10.00	0.02						
SD5	2856124	-49200	2004/08/12	9.50	30.70	2.67	29.50	0.02		107.00	10.00	0.02						
SD5	2856124	-49200	2004/11/25	9.00	33.60	2.63	52.10	0.02		43.70	10.00	0.02						
SD5	2856124	-49200	2005/07/14															
SD5	2856124	-49200	2006/03/02	7.14	58.00	3.91	96.40	0.02	0.02	18.00	10.00	0.02	2.15	366.00		1.28	2.52	
SD5	2856124	-49200	2006/05/18	9.02	29.90	7.68	40.50	0.02	0.02	21.30	10.00	0.02	1.00	189.00	4.40	0.58	1.59	
SD5	2856124	-49200	2006/12/21	8.96	30.70	2.69	48.90	0.02	0.02	4.00	2.61	0.02	1.41	195.00	0.23	0.18	2.17	
SD5	2856124	-49200	2007/02/22	8.89	33.60	6.44	56.10	0.02	0.08	9.97	3.12	0.08	2.32	214.00	1.90	2.52	1.50	
SD5	2856124	-49200	2007/04/26	8.75	34.40	6.22	58.50	0.02	0.14	14.50	5.63	0.02	2.46	221.00	1.80	2.00	1.44	
SD5	2856124	-49200	2007/07/16	8.15		3.11	75.10		0.01	6.41			1.50	203.00				
SD5	2856124	-49200	2007/11/07	9.17	32.90	4.30	69.40	0.02	0.02	18.70	3.76	0.02	1.13	208.00	3.30	1.21	2.07	
SD5	2856124	-49200	2008/03/13	8.21	35.00	4.88	58.50	0.02	0.02	7.03	4.35	0.18	1.56	221.00	0.23	0.50	1.27	
SD5	2856124	-49200	2009/01/08	8.74		4.92	77.80	0.01	0.05		3.75	0.05	1.39	221.00	0.44	0.26	1.20	
SD5	2856124	-49200	2009/05/28	8.47		3.15	50.50	0.01	0.21	26.00	20.50	0.20	1.45	214.00	0.91	0.10	1.40	

Borehole ID	Coordinates		Date Sampled	PH	EC	Ca	Na	Cr(VI)	Cr (total)	SO ₄	Cl	Mn	Mg	TDS	NO ₃ as N	Fe	F	Total Alkalinity
SD5	2856124	-49200	2009/10/15	9.11		3.55	73.70	0.01	0.30	25.40	3.80	0.05	1.50	202.00	0.27	0.16		
SD5	2856124	-49200	2010/03/03			3.54	65.50	0.01	1.73	5.80	2.90	0.11	1.28	208.00	0.27	11.80	1.31	
		0																
SD6	2856124	-49200	2001/11/29															
SD6	2856124	-49200	2002/02/28															
SD6	2856124	-49200	2002/06/20															
SD6	2856124	-49200	2002/09/19															
SD6	2856124	-49200	2002/12/19															
SD6	2856124	-49200	2003/03/06															
SD6	2856124	-49200	2003/06/19															
SD6	2856124	-49200	2003/10/02															
SD6	2856124	-49200	2004/08/19															
SD6	2856124	-49200	2004/11/25	7.50	111.00	20.00	132.00	0.02		141.00	81.00	0.70						
SD6	2856124	-49200	2005/07/14															
SD6	2856124	-49200	2006/03/02	7.04	134.00	36.40	265.00	0.02	0.05	121.00	173.00	0.16	13.90	851.00		4.57	2.08	
		0																
SD7	2855986	-49173	2001/12/06	6.90	140.00	1291.00	3603.00	0.02		686.00								
SD7	2855986	-49173	2002/03/07	7.20	938.00	618.00	1026.00	1.12		746.00	660.00							
SD7	2855986	-49173	2002/06/27	7.14	662.00	403.00	994.00	1.05		410.00	500.00	0.33						
SD7	2855986	-49173	2002/09/26	7.12	268.00	524.00	1015.00	0.02		500.00	570.00	0.41						
SD7	2855986	-49173	2002/12/19															
SD7	2855986	-49173	2003/03/13	6.80	122.00	926.00	1608.00	7.03		418.00	600.00	0.59						
SD7	2855986	-49173	2003/06/25	6.52	144.00	1097.00	1406.00	0.02		540.00	920.00	0.55						
SD7	2855986	-49173	2003/10/09	6.77	150.00	886.00	1234.00	0.02		665.00	1340.00	0.54						
SD7	2855986	-49173	2004/08/19	7.50	411.00	257.00	290.00	0.02		414.00	250.00	0.21						

Borehole ID	Coordinates		Date Sampled	PH	EC	Ca	Na	Cr(VI)	Cr (total)	SO ₄	Cl	Mn	Mg	TDS	NO ₃ as N	Fe	F	Total Alkalinity
SD7	2855986	-49173	2004/12/02															
SD7	2855986	-49173	2005/09/08															
SD7	2855986	-49173	2006/01/19	7.18	392.00	284.00	407.00	0.02	0.03	321.00	268.00	0.03	120.00	2520.00	244.00	0.16	1.18	389.00
SD7	2855986	-49173	2006/03/09	7.20	439.00	277.00	444.00	0.02	0.02	710.00	411.00	0.03	115.00	2770.00		2.52	1.67	524.00
SD7	2855986	-49173	2006/05/25	8.10	681.00	320.00	113.00	0.02	0.02	560.00	398.00	0.02	182.00	4410.00	445.00	0.18	0.50	359.00
SD7	2855986	-49173	2006/08/17	7.50	566.00	323.00	501.00	0.02	0.02	568.00	410.00	0.02	194.00	3660.00	394.00	0.16		545.00
SD7	2855986	-49173	2006/12/28	7.16	489.00	178.00	247.00	0.02	0.02	516.00	368.00	0.02	119.00	3150.00	262.00	0.30	2.40	
SD7	2855986	-49173	2007/03/01	7.33	370.00	222.00	364.00	0.02	0.80	322.00	232.00	1.08	114.00	2330.00	0.50	59.80	1.67	
SD7	2855986	-49173	2007/04/26	7.05	478.00	303.00	420.00	0.02	0.22	267.00	282.00	0.27	146.00	3030.00	346.00	14.10	0.99	
SD7	2855986	-49173	2007/07/13	7.28	468.00	273.00	338.00	0.02	0.32	231.00	279.00	0.37	112.00	3030.00	329.00	20.40	0.87	
SD7	2855986	-49173	2007/11/07	7.45	312.00	216.00	406.00	0.02	0.34	369.00	248.00	0.18	82.70	2020.00	139.00	8.98	2.62	
SD7	2855986	-49173	2008/03/27	7.38	250.00	82.10	182.00	0.02	0.22	246.00	156.00	0.13	27.90	1580.00	89.50	3.79	1.18	
SD7	2855986	-49173	2008/08/28	7.59	128.00	68.00	101.00	0.02	0.13	115.00	72.20	0.03	18.80	820.00	13.50	1.30	1.43	
SD7	2855986	-49173	2009/01/22	7.40		145.00	147.00	0.19	0.29	310.00	185.00	0.05	38.40	1830.00	11.60	0.57	1.30	
SD7	2855986	-49173	2009/06/11	7.50		196.00	351.00	0.36	0.70	390.00	243.00	0.20	54.20	2080.00	138.00	0.22	1.26	
SD7	2855986	-49173	2009/10/29	7.51		212.00	834.00	0.11	0.61	293.00	152.00	0.20	102.00	1320.00	43.40	0.81		
SD8	2855986	-49173	2001/12/06	7.90	1049.00	883.00	2826.00	0.02		805.00								
SD8	2855986	-49173	2002/03/07	7.85	1090.00	806.00	1081.00	0.02		1159.00	755.00							
SD8	2855986	-49173	2002/06/27	8.14	1210.00	866.00	1242.00	0.02		706.00	740.00	0.52						
SD8	2855986	-49173	2002/09/26	7.85	1170.00	967.00	1455.00	0.02		878.00	780.00	0.75						

Borehole ID	Coordinates		Date Sampled	PH	EC	Ca	Na	Cr(VI)	Cr (total)	SO ₄	Cl	Mn	Mg	TDS	NO ₃ as N	Fe	F	Total Alkalinity
SD8	2855986	-49173	2002/12/19															
SD8	2855986	-49173	2003/03/13	7.6	111.00	827.00	1568.00	0.02		699.00	610.00	1.00						
SD8	2855986	-49173	2003/06/25	7.84	112.00	827.00	1583.00	0.02		561.00	696.00	0.02						
SD8	2855986	-49173	2003/10/09	9.57	131.00	548.00	1120.00	0.02		698.00	655.00	0.02						
SD8	2855986	-49173	2004/08/19	7.20	132.00	770.00	620.00	0.02		458.00	792.00	0.02						
SD8	2855986	-49173	2004/12/02	7.80	118.00	817.00	995.00	0.02		241.00	810.00	0.21						
SD8	2855986	-49173	2005/09/08															
SD9	2855986	-49173	2001/12/06															
SD9	2855986	-49173	2002/03/07															
SD9	2855986	-49173	2002/06/27															
SD9	2855986	-49173	2002/09/26															
SD9	2855986	-49173	2002/12/19															
SD9	2855986	-49173	2003/03/13															
SD9	2855986	-49173	2003/06/23															
SD9	2855986	-49173	2003/10/09															
SD9	2855986	-49173	2004/08/19															
SD9	2855986	-49173	2004/12/02	7.30	477.00	184.00	457.00	0.02		300.00	283.00	0.07						
SD9	2855986	-49173	2005/09/08															
SD10	2855870	-49156	2001/12/06	7.40	929.00	3269.00	838.00	0.02		995.00								
SD10	2855870	-49156	2002/03/07	7.34	964.00	1127.00	229.00	0.02		1386.00	590.00							
SD10	2855870	-49156	2002/06/27	7.17	122.00	1197.00	355.00	0.02		1083.00	650.00	1.75						
SD10	2855870	-49156	2002/09/26	7.16	138.00	1479.00	517.00	0.11		913.00	850.00	1.26						
SD10	2855870	-49156	2002/12/19															
SD10	2855870	-49156	2003/03/13	6.90	117.00	9.62	9.42	0.02		1015.00	690.00	0.96						

Borehole ID	Coordinates		Date Sampled	PH	EC	Ca	Na	Cr(VI)	Cr (total)	SO ₄	Cl	Mn	Mg	TDS	NO ₃ as N	Fe	F	Total Alkalinity
SD10	2855870	-49156	2003/06/25															
SD10	2855870	-49156	2003/10/09	6.96	145.00	1022.00	6.29	0.02		811.00	845.00	2.28						
SD10	2855870	-49156	2004/08/19	7.00	149.00	1626.00	530.00	0.02		692.00	848.00	2.14						
SD10	2855870	-49156	2004/12/02	8.50	145.00	820.00	524.00	0.02		355.00	845.00	1.43						
SD10	2855870	-49156	2005/09/08															
SD10	2855870	-49156	2006/01/19	7.39	736.00	455.00	772.00	0.02	0.02	735.00	559.00	0.27	252.00	4730.00	608.00	0.27	0.42	364.00
SD10	2855870	-49156	2006/03/09	7.28	628.00	417.00	767.00	0.02	0.08	841.00	531.00	0.63	237.00	3970.00		0.25	0.65	381.00
SD10	2855870	-49156	2006/05/25	8.03	681.00	414.00	113.00	0.02	0.02	623.00	453.00	0.26	239.00	4410.00	517.00	2.74	0.50	390.00
SD10	2855870	-49156	2006/08/17	7.95	640.00	384.00	715.00	0.02	0.06	516.00	357.00	0.14	229.00	4100.00	416.00	2.03		307.00
SD10	2855870	-49156	2009/01/22	8.13		206.00	635.00	0.01	0.05	587.00	345.00	0.05	191.00	3470.00	5.63	0.62	0.53	
		0																
SD11	2855870	-49156	2001/12/06	6.90	980.00	1994.00	2242.00	0.02		458.00								
SD11	2855870	-49156	2002/03/07	7.66	448.00	447.00	197.00	0.02		464.00	385.00							
SD11	2855870	-49156	2002/06/26	7.30	863.00	532.00	623.00	0.41		568.00	590.00	0.31						
SD11	2855870	-49156	2002/09/26	7.76	723.00	417.00	388.00	0.22		393.00	610.00	0.07						
SD11	2855870	-49156	2002/12/19															
SD11	2855870	-49156	2003/03/13	7.00	438.00	378.00	193.00	0.02		391.00	300.00	0.12						
SD11	2855870	-49156	2003/06/25	7.35	595.00	583.00	392.00	0.02		433.00	440.00	0.34						
SD11	2855870	-49156	2003/10/09	7.60	895.00	401.00	585.00	0.02		429.00	600.00	0.06						
SD11	2855870	-49156	2004/08/19	7.70	461.00	595.00	126.00	0.02		343.00	420.00	1.45						
SD11	2855870	-49156	2004/12/02	7.30	430.00	188.00	88.00	0.02		248.00	408.00	0.30						

Borehole ID	Coordinates		Date Sampled	PH	EC	Ca	Na	Cr(VI)	Cr (total)	SO ₄	Cl	Mn	Mg	TDS	NO ₃ as N	Fe	F	Total Alkalinity
SD11	2855870	-49156	2005/09/08															
SD11	2855870	-49156	2006/01/19	7.52	522.00	370.00	304.00	0.02	0.02	449.00	479.00	0.31	267.00	3340.00	253.00	0.07	479.00	789.00
SD11	2855870	-49156	2006/03/09	7.72	568.00	494.00	528.00	0.02	0.03	577.00	560.00	0.77	318.00	3660.00		0.29	560.00	1209.00
SD11	2855870	-49156	2006/05/25	7.44	1280.00	736.00	114.00	0.02	0.02	779.00	724.00	1.20	531.00	8200.00	1161.00	1.62	724.00	465.00
SD11	2855870	-49156	2006/08/17	8.01	865.00	449.00	760.00	0.02	0.38	510.00	454.00	0.31	234.00	5550.00	578.00	0.90	454.00	345.00
SD11	2855870	-49156	2006/12/28	6.94	548.00	349.00	195.00	0.02	0.02	478.00	450.00	0.56	221.00	3470.00	422.00	0.13	450.00	
SD11	2855870	-49156	2007/03/01	7.21	793.00	522.00	707.00	0.02	0.40	488.00	484.00	0.51	298.00	5050.00	684.00	2.82	484.00	
SD11	2855870	-49156	2007/04/26	7.21	701.00	445.00	450.00	0.08	0.13	503.00	474.00	0.58	250.00	4600.00	543.00	2.96	474.00	
SD11	2855870	-49156	2007/07/13	7.55	898.00	552.00	865.00	0.19	0.32	637.00	544.00	0.21	258.00	5680.00	959.00	1.16	544.00	
SD11	2855870	-49156	2007/11/07	7.04	662.00	733.00	402.00	0.08	0.19	553.00	489.00	0.81	406.00	4290.00	731.00	0.56	489.00	
SD11	2855870	-49156	2008/03/27	7.30	491.00	248.00	194.00	0.02	0.13	373.00	382.00	0.19	155.00	3150.00	297.00	1.26	382.00	
SD11	2855870	-49156	2008/08/28	7.51	820.00	421.00	704.00	0.02	0.37	589.00	467.00	0.07	237.00	5230.00	550.00	0.75	467.00	
SD11	2855870	-49156	2009/01/22	7.23		375.00	322.00	0.01	0.05	467.00	371.00	0.58	236.00	3340.00	22.10	0.29	371.00	
SD11	2855870	-49156	2009/06/11	7.91		287.00	477.00	0.09	0.21	479.00	321.00	0.35	169.00	3340.00	268.00	0.38	321.00	
SD11	2855870	-49156	2009/10/29	7.35		215.00	875.00	0.14	0.58	757.00	417.00	0.20	103.00	3340.00	349.00	0.82	417.00	
		0																
SD12	2855870	-49156	2001/12/06															
SD12	2855870	-49156	2002/03/07	7.80	386.00	440.00	220.00	0.02		800.00	410.00							
SD12	2855870	-49156	2002/06/27															
SD12	2855870	-49156	2002/09/26															
SD12	2855870	-49156	2002/12/19															
SD12	2855870	-49156	2003/03/13															

Borehole ID	Coordinates		Date Sampled	PH	EC	Ca	Na	Cr(VI)	Cr (total)	SO ₄	Cl	Mn	Mg	TDS	NO ₃ as N	Fe	F	Total Alkalinity
SD12	2855870	-49156	2003/06/25															
SD12	2855870	-49156	2003/10/09															
SD12	2855870	-49156	2004/08/19															
SD12	2855870	-49156	2004/12/02															
SD12	2855870	-49156	2005/09/08															
SD12	2855870	-49156	2006/03/09	7.17	394.00	377.00	391.00	0.02	0.09	538.00	365.00	0.81	177.00	2520.00		1.90	1.16	519.00
SD12	2855870	-49156	2008/03/27	8.10	510.00	130.00	492.00	0.02	0.14	528.00	339.00	0.62	97.00	3340.00	204.00	4.53	0.57	
CA13			2001/12/13	7.70	132.00	125.00	111.00	0.02		253.00	40.00							
CA14			2001/12/13	9.00	119.00	89.70	145.00	0.02		283.00	140.00							
CA19			2001/12/13	8.70	48.00	380.00	68.40	0.02		469.00	310.00							
CA21A			2001/12/13	7.90	325.00	110.00	38.10	0.02		178.00	50.00							
CA22			2001/12/13	8.20	107.00	103.00	42.20	0.02		234.00	180.00							
CA26			2001/12/13	8.30	107.00	22.90	41.30	0.02		159.00	70.00							
WD1A			2001/11/08	8.50	122.00	5.54	214.00	0.02		130.00	156.00							
WD16B			2001/11/08	9.00	97.30	6.08	182.00	0.02		83.50	22.00							
WD19A			2001/11/08	8.70	77.30	17.20	138.00	0.02		30.50	20.00							

6.4. APPENDIX VI: SURFACE MONITORING RESULTS: DAM 4A

Date	pH	Conductivity	F	Cr ⁶⁺	Cl	NO ₃ - N	COD	Phenols	SO ₄	Ca	Cr	Fe	Mg	Mn	Na	K
Units		mS/m	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	
03-Oct-01	9.86	1880	1.67	10.3	1030	236	185	0.069	125	1782	14.4	0.931	22.7	0.298	2132	
10-Oct-01	9.99	2140	1.9	12.7	1100	263	135	0.056	393	259	12.7	0.057	9.29	0.02	315	
17-Oct-01	8.5	1810	0.1	8.27	1420	260	310	0.048	552	2712	7.04	0.178	137	1.25	3936	
24-Oct-01	9.29	1930	1	17.8	1030	108	136	0.072	531	2472	9.49	0.075	21.9	0.094	2067	
31-Oct-01	9.8	1970	2.6	0.02	1130	58.4	146	0.063	146	3085	11.5	0.081	14.7	0.088	3332	
07-Nov-01	9.73	1780	3.6	11.8	1600	179	197	0.044	466	2747	10.1	0.51	9.92	0.02	2265	
14-Nov-01	9.8	1720	2	8.015	29	21.7	192	0.083	683	2237	9.62	0.048	21.4	0.123	2518	
21-Nov-01	9.7	1850	18	9.34	1200	31.6	192	0.588	753	2086	14.1	0.02	8.31	0.02	2352	
28-Nov-01	9	1640	2.37	8.775	1400	440	70.28	0.084	849	2121	11.2	0.02	9.1	0.02	2286	
05-Dec-01	9	1560	1.67	4.35	1900	1911	63.7	0.033	688	2214	10.5	0.02	9.2	0.02	2311	
12-Dec-01	10.4	1660	2.29	8.265	13	1846	94.86	0.229	971	2072	10	0.02	6.35	0.024	2389	
19-Dec-01	10.1	1430	2.19	2.275	800	1788	102	0.081	2.9	1943	10.1	0.135	6.92	0.02	2374	
02-Jan-02	10.7	1370	2.5	6.44	1000	^1404	165	0.078	213	1717	12.9	0.15	1.53	0.02	2353	
09-Jan-02	11	1510	2		1800	1560	308	0.404	220	1930	17.7	0.035	1.48	0.02	2580	
16-Jan-02	11.4	1440	0.9	3.445	180	1904	81.2	0.381	200	1663	21.2	0.079	17.5	0.124	2079	
23-Jan-02	11.1	1500	0.77	2.89	910	1587	95.6	0.127	216	1952	14.7	0.02	2.93	0.02	1479	
30-Jan-02	11.4	1520	1.43	2.6	840	1967	398'	0.078	332	1574	11	0.184	1.94	0.02	1891	
06-Feb-02	11.2	1560	1.02	12.5	1000	2062	117	0.109	723	1767	14.4	0.02	1.94	0.02	2172	
13-Feb-02	11	1530	1.2	12.7	800	1103	184	0.089	339	2005	13.5	0.044	3.59	0.02	2454	
20-Feb-02	11	1430	1.16	9.95	750	572	95.6	0.056	360	1829	10.6	0.02	12.5	0.02	1758	
27-Feb-02	11.2	1520	1.02	12.1	845	2013	176	0.02	431	2267	13.85	0.02	2.98	0.02	3184	
06-Mar-02	11	1530	1.28	4.37	870	1402	375	0.085	732	2059	10.8	0.02	7.24	0.02	1807	
13-Mar-02	10.7	1590	0.846	12	890	678	139 .	0.087	415	2050	12.8	0.02	7.2	0.081	2179	
20-Mar-02	11.1	1470	1.28	10.9	910	709	510	0.059	389	1718	11.8	0.02	5.67	0.02	2180	
27-Mar-02	10.6	1490	1.44	8.55	790	667	123	0.057	622	1178	9.74	0.02	22.8	0.02	1761	
03-Apr-02	10.4	1520	0.563	10.1	890	305	141	0.032	188	3720	11.6	0.029	28.8	0.02	1471	

Date	pH	Conductivity	F	Cr ⁶⁺	Cl	NO ₃ - N	COD	Phenols	SO ₄	Ca	Cr	Fe	Mg	Mn	Na	K
Units		mS/m	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	
10-Apr-02	11	1330	1.09	10.4	840	755	127	0.358	417	4081	11.3	0.02	24.6	0.02	2008	
17-Apr-02	11	1520	0.859	8.615	980	790		0.059	436	4327	10.8 _n	0.203	23.1	0.02	1741	
24-Apr-02	10.8	1530	0.842	9.78	830	667		524	524	4090	11.3	0.02	18.7	0.02	2450	
fl-May-02	10.4	1620	0.75	7.5	980	1160	146	0.036	843	3113	10.2	0.073	33.4	0.02	2114	
15-May-02	10.3	1630	1.41	6.5	850	1364	176	0.031	800	6081	6.57	0.02	61.3	0.02	1927	
22-May-02	10.3	1620	1.1	6	945	1053	183	0.032	518	3276	8.43	0.02	32.8	0.02	1955	
29-May-02	9.8	1680	0.78	4.14	980	917	139	0.033	506	2778	7.17	0.079	32.9	0.02	1596	
05-Jun-02	10	1630	0.77	6.06	3100	40.7	175	0.013	516	3560	7.81	0.058	42.3	0.02	2364	
12-Jun-02	9.9	1620	1.34	8.22	1900	1366	63.2	0.516	672	3010	9.71	0.068	30.4	0.02	2510	
19-Jun-02	9.9	1620	1.2	5.64	1040	88	157	0.01	1035	4310	7.87	0.02	40.4	0.02	2297	
26-Jun-02	9.9	1650	1.39	7.94	2000	107	252	0.02	601	4519	11.3	0.02	43.1	0.02	3771	
03-Jul-02	9.6	1650	1.22	7.18	900	1589	160	0.07		5655	9.24	0.02	36.7	0.02	4252	1496
10-Jul-02	9.53	1690	1.07	6.95	1280	1763	153	0.01		4777	9.7	0.32	40.9	0.02	2739	1192
17-Jul-02	8.97	1720	1.13	7	980	588	206	0.04		4439	7.12	0.18	31.4	0.02	2109	783
21-Jul-02	9.4	1740	1.81	5.6	1700	1616	10	0.03		5023	7.26	0.18	22	0.02	2407	915
31-Jul-02	8.83	1760	1.47	6.48	2000	1583	541	0.43		4138	6.78	0.36	42.2	0.02	1883	807
07-Aug-02	9.1	1760	1.13	1.14	2900	1832	349	0.6		5180	7.8	0.09	56.1	0.02	2681	465
14-Aug-02	9.3	1790	1.2	3.75	2500	2205	430	0.09		5290	7.14	0.25	163	0.03	1695	695
21-Aug-02	9.29	1790	1.13	6.14	1900	2424	119	0.15		4861	7.67	0.19	57.7	0.06	2520	1009
28-Aug-02	8.8	1780	1.19	4.55	1400	2142	140	0.16		1750	6.5	0.33	27.7	0.06	1774	665
04-Sep-02	9.27	1840	1.41	6	1300	1687	160	0.46		1615	8.38	0.29	61.7	0.02	6060	2140
04-Sep-02	8.8	1810	1.29	5.54	1160	2478	449	0.04		4960	5.97	0.3	131	0.08	3067	1214
11-Sep-02	8.9	1820	1.22	4.9	1190	2818	202	0.07		3031	6.3	0.3	169	0.02	2564	1201
25-Sep-02	9.09	1930	1.32	4.2	1220	2543	625	0.05		5290	5.27	0.26	81	0.12	2160	631
02-Oct-02	8.49			4.96					651		7.1			0.16		
09-Oct-02	7.77			4.59					594		8.03			0.09		
16-Oct-02	9.17			1.53					1207		5.99			0.05		

Date	pH	Conductivity	F	Cr ⁶⁺	Cl	NO ₃ - N	COD	Phenols	SO ₄	Ca	Cr	Fe	Mg	Mn	Na	K
Units		mS/m	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	
23-Oct-02	8.41			2.25					1015		4.77			0.22		
30-Oct-02	8.44			0.393					447		5.34			0.21		
06-Nov-02	8.71			4.315							4.36			0.11		
13-Nov-02	8.33			0.439					1248		3.46			0.02		
20-Nov-02	8.8			3.55					1456		5.44			0.04		
27-Nov-02	8.7			4.61					1264		5.46			0.05		
04-Dec-02	8.52								1936		5.03			0.11		
11-Dec-02	8.49			0.02					1745		4.27			0.22		
18-Dec-02	8.27								11.4		4.09			0.17		
08-Jan-03	8.24			2.69					227		4.1			0.11		
15-Jan-03	8.23			3.83					2054		7.13			0.03		
22-Jan-03	8.1			0.02					1957		2.97			0.12		
29-Jan-03	8.2			0.02					1011		3.5			0.11		
05-Feb-03	8.3			2.31					2466		4.29			0.03		
12-Feb-03	8.3			0.02					1427		2.98			0.06		
19-Feb-03	8			0.02					1309		2.7			0.05		
26-Feb-03	8			0.02					1020		2.35			0.02		
05-Mar-03	8.36			2.43					860		2.36			0.08		
12-Mar-03	8.1			0.15					1303		1.77			0.29		
19-Mar-03	8.3			0.62					945		1.81			0.02		
26-Mar-03	7.8			0.02					1303		0.388			0.06		
02-Apr-03	8.3			0.02					1462		2.71					
09-Apr-03	8.04			2.18					1667		2.17					
16-Apr-03	8.3			2.57					1282		2.63					
23-Apr-03	8.4			0.88					787		2.21					
30-Apr-03	7.9			2.37					779		2.37					
07-May-03	8.27			0.74					1251		1.9					
14-May-03	8.1			0.42					771		1.67					

Date	pH	Conductivity	F	Cr ⁶⁺	Cl	NO ₃ - N	COD	Phenols	SO ₄	Ca	Cr	Fe	Mg	Mn	Na	K
Units		mS/m	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	
21-May-03	8.23			1.43					1057		1.53					
28-May-03	7.72			2.41					629		2.41					
04-Jun-03	8.2			1.41					632		1.42					
11-Jun-03	7.9			1.22					1542		1.35					
18-Jun-03	8			0.02					1102		1.87					
25-Jun-03	7.61			0.17					785		1.53					
02-Jul-03	8.21			1.86					1700		1.97					
09-Jul-03	7.8			1.89					1568		1.96					
16-Jul-03	7.9			1.16					2734		1.16					
23-Jul-03	7.83			0.99							1.64					
30-Jul-03	7.78			0.26					1327		1.13					
06-Aug-03	7.91			1.67					1388		1.88					
13-Aug-03	7.93			0.97					1003		1.75					
20-Aug-03	7.96			0.72					993		1.37					
27-Aug-03	8.28			1.42					1310		1.42					
03-Sep-03	8.2			1.39					1146		1.61					
10-Sep-03																
17-Sep-03	8			0.61					1146		0.913					
24-Sep-03																
01-Oct-03	7.64			0.62												
08-Oct-03	7.7			0.85												
15-Oct-03	7.4			0.8												
22-Oct-03	7.41			0.69												
29-Oct-03	7.9			0.02												
05-Nov-03	8.3			1.31												
12-Nov-03	8.18			0.02												
19-Nov-03																
26-Nov-03	8			1.09												

Date	pH	Conductivity	F	Cr ⁶⁺	Cl	NO ₃ - N	COD	Phenols	SO ₄	Ca	Cr	Fe	Mg	Mn	Na	K
Units		mS/m	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
03-Dec-03	9.7			0.5												
10-Dec-03	8.11			0.02												
17-Dec-03	7.31			0.02												
24-Dec-03																
31-Dec-03	7.33			0.63												
07-Jul-04				1.76												
14-Jul-04				1.16												
21-Jul-04				1.72												
28-Jul-04																
04-Aug-04				1.05												
11-Aug-04																
18-Aug-04				0.54												
25-Aug-04				0.8												
01-Sep-04				0.63												
08-Sep-04				0.65												
15-Sep-04				0.02												
22-Sep-04				0.02												
29-Sep-04				0.02												
06-Oct-04				0.99												
13-Oct-04				0.02												
20-Oct-04				0.02												
27-Oct-04				0.02												
03-Nov-04				0.02												
10-Nov-04				0.02												
17-Nov-04				0.02												
24-Nov-04				0.02												
01-Dec-04				0.36												
08-Dec-04				0.93												

Date	pH	Conductivity	F	Cr ⁶⁺	Cl	NO ₃ - N	COD	Phenols	SO ₄	Ca	Cr	Fe	Mg	Mn	Na	K
Units		mS/m	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
15-Dec-04				0.02												
22-Dec-04				1.14												
29-Dec-04				0.7												
06-Jul-05				1.83												
13-Jul-05				2.09												
20-Jul-05				1.39												
27-Jul-05				0.47												
03-Aug-05				0.45												
10-Aug-05				1.24												
17-Aug-05				0.47												
24-Aug-05				1.28												
31-Aug-05				1.17												
07-Sep-05				0.85												
14-Sep-05				2.06												
21-Sep-05				2.1												
28-Sep-05				1.27												