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THE DEVELOPMENT OF A GROUNDWATER CLOSURE AND REHABILITATION PLAN IN A TYPICAL GOLD MINE ENVIRONMENT

by

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DECLARATION

I hereby declare that this dissertation submitted for the degree Masters in the Faculty of Natural and Agricultural Sciences, Department of Geohydrology, University of the Free State, Bloemfontein, South Africa, is my own work and has not been submitted to any other institution of higher education. I further declare that all sources cited or quoted are indicated and acknowledged by means of a list of references.

P.F. Labuschagne

12 March 2004

ABSTRACT

The generation of waste material associated with Gold Mining is a known fact. Research on these waste materials has currently expanded worldwide in an attempt to scientifically characterise and understand their interaction with the natural environment. These materials contain certain amounts of sulphide minerals and other harmful substances, associated with the exploited ore bodies and the beneficiation processes. It is even more important to understand certain impacts and to develop a logical approach to assess the impacts on receiving water bodies, towards mine.

The increase in awareness of environmental issues and a desire for a cleaner environment by the public has caused gold mining companies to place greater emphasis on the continuous rehabilitation of deleterious effects caused by mining operations. Ongoing rehabilitation is also a requirement of the Government Departments involved in mining in South Africa. The biggest concern for the relevant Government Departments is the possible uncontrolled pollution of water resources in the vicinity of these mines, after they have closed.

Investigations have shown that receiving water bodies, which mainly include rivers, streams, and the more complicated geohydrological system, are part of the primary end-receivers of harmful contaminants from identified waste bodies. The need for a cost effective method to assess site hydrology and geohydrology, to understand the associated legal responsibility of contaminated streams and aquifers, is recognised.

In the compilation of this thesis, the unique nature of the South African situation has been considered – this refers to a legally acceptable approach towards current legislation and policies. Throughout this document, the emphasis falls on what can reasonably be achieved, without compromising on information that would lead to early detection of water pollution.

This study leads to the construction of a logical approach towards mine closure specifically in the field of groundwater assessments. The final product of this approach should ultimately give more clarity on:

- The principles followed to identify objectives for mine closure and groundwater assessment,
- The adopted philosophy of mine closure as a geohydrological concept. Key words like; 'rules of the game', 'key uncertainties', 'options' and ' decisions' were highlighted.
- Key steps to follow when assessing site geohydrology and to determine related impacts and risks,
- Overview of methods that could be used for the mitigation of polluted aquifers and a brief site-specific application.

The key deliverable is therefore focussed on methods to scientifically assess 'sources', 'receivers' and 'options'. Ultimately this process has led to the development of a logical approach towards mine closure for groundwater assessment and remediation in a typical gold mine environment.

EKSERP

Die produksie van afvalstowwe, as by-produkte gedurende die myn van goud, is 'n bekende feit. Tans word die navorsing van hierdie afval materiaal as baie belangrik beskou sodat moontlike interaksies tot die natuurlike omgewing beter verstaan kan word. Die materiaal bevat sulfied minerale asook ander elemente wat moontlik nadelig kan wees vir die natuurlike omgewing. Die graad en hoeveelheid van die spesifieke elemente hang grootendeels af van die tipe erts liggaam wat gemyn word asook die prosessering van die erts. Soos wat 'n myn neig na sluiting raak dit dus belangrik om moontlikke impakte op natuurlikke water bronne te bepaal.

'n Toenemende bewustheid oor omgewings kwesies vanuit 'n publieke oogpunt, en 'n groter drang na 'n skoner natuurlike omgewing, het veroorsaak dat goud myne meer klem op grondwater rehabilitasie en omgewings bestuur lê. Staats Departemente, betrokke in die goudmyn bedryf, verreis ook die voortdurende rehabilitasie van besoedelde areas. Die grootste besorgdheid vir die Staats Departemente is dus die potensiaal vir onbeheerbare besoedeling van water bronne, deur myne wat sluiting in die oog staar.

Studies het gewys dat dit oorwegend riviere, strome en grondwater is wat die ergste deurloop onder besoedeling afkomstig van goud myne. Dit is as gevolg hiervan dat die behoefte ontstaan om 'n koste-effektiewe manier te ontwikkel en saam te stel om hierdie water bronne wetenskaplik te ondersoek en ook om die grondwater probleme vanuit 'n wetlike oogpunt te verstaan.

Gedurende die samestelling van hierdie verhandeling is die uniekheid van die Suid Afrikaanse wetgewing en beleidspunte deurentyd in ag geneem – dit verwys grootliks na die wetlike aanvaarbare benadering wat gevolg is. Die klem word deurentyd gelê op redelike en praktiese oplossings tot grondwater besoedeling sonder om die insameling van inligting te beperk.

Hierdie studie lei tot die samevoeging van 'n logiese benadering om grondwater te ondersoek tydens die sluiting van 'n goud myn. Die finale produk poog dus om meer duidelikhed oor die volgende te verskaf:

- Beginsels wat gevolg word om die doelwitte te formuleer,
- Die filosofie rakende groundwater en myn sluiting wat aangeneem is. Sleutel woorde soos: 'reels van die spel', 'hoof onsekerhede', opsies' en'besluitnemings' word deurentyd beklemtoon,
- Belangrikke stappe wat gevolg moet word tydens die grondwater ondersoek,
- Oorsig van grondwater rehabilitasie tegnieke.

Die primere produk is dus om te fokus op metodes om wetenskaplik 'oorsake', 'ontvangers' en 'opsies' te ondersoek. Ten slotte, hierdie proses lei tot die ontwikkeling van 'n logiese benadering vir grondwater ondersoeke in die proses van myn sluiting in 'n tipese goud myn omgewing.

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SECTION 1: OVERVIEW OF ADOPTED PHILOSOPHY & APPROACH

1 Background

Historically, South Africa has been the largest producer of gold in the world (Atomic Energy Corporation of South Africa, 1990). In 1996 alone, a total volume of 377 million tons of mine waste was produced, accounting for 81% of the total waste stream in South Africa (Chamber of Mines of South Africa, 2001). These mine wastes contain large amounts of sulphide minerals (10-30 kg per ton), which give rise to the generation of acid mine drainage (AMD) and salt transport. As the mining activities and industrial activities in South Africa increased from the turn of the century, so did the contamination of the Vaal River and other important surface water bodies. Water can be regarded as a scarce commodity in South Africa and the discovery of new water resources to meet the ever-increasing demands cannot be solely relied on. It is therefore important for mining companies to contain pollution within boundaries and away from these receiving water bodies. Mining, as the name implies, is a non-renewable activity and the inevitable fact of starting a mine is that mining will cease some time in the future (Hodgson, 2001). It is even more important to understand certain impacts and to develop a logical approach to assess these impacts towards mine closure. Many elements toxic to humans, animals and vegetation occur in surface effluent water and leachates from the mine waste storage facilities. It is important that these be quantified in terms of time and distance from the pollution source, as they tend to move into the groundwater. Monitoring the effect that waste facilities (such as waste rock and tailings dams) have on the water quality of surface and groundwater resources is a complex and multidisciplinary task. Numerous methodologies exist for monitoring of this kind. Facilities required for a specific situation will depend on the:

- Type of waste material – specific ore bodies mined, metallurgical processes, etc
- Amount of waste – volumes dumped per day on waste stockpile or storage facilities. This could also refer to underground seepage,
- Potential for leachate formation – the site-specific geological characteristics need to be understood,
- Vulnerability of groundwater resources - the site-specific geohydrological characteristics need to be understood,
- Vulnerability of surface water resources – downstream users, quality of effluent and current legislation will determine exemption on discharges, etc

This investigation and thesis will be compiled by applying extensive literature studies, environmental research and specifically, geohydrological studies that have been done from 2001 to 2003. These investigations provided valuable information on the geometry and behaviour of the groundwater systems in terms of groundwater flow and contaminant migration rate/s and direction/s. The technical information obtained from the previous groundwater investigations was used as a basis to perform this thesis. A database containing historical groundwater monitoring data and other environmental related data would be used as the basis of the study.

1.1 *Area of investigation*

For the purpose of this document and investigation the goldfields area adjacent to the Vaal River within the KOSH area (Klerksdorp, Orkney, Stilfontein and Hartebeesfontein) was selected. More specifically, the investigation area consists out of the northwestern portion of the current AngloGold mining area. This includes 4 shafts and associated metallurgical operations, situated to the east of Orkney, north of the Vaal River. Specific reference to the Eastern and Southern lease areas will also be made. Many of the possible pollution sources have been present in the area since mining commenced in the early fifties. The following map gives an overview of the regional location of the area:

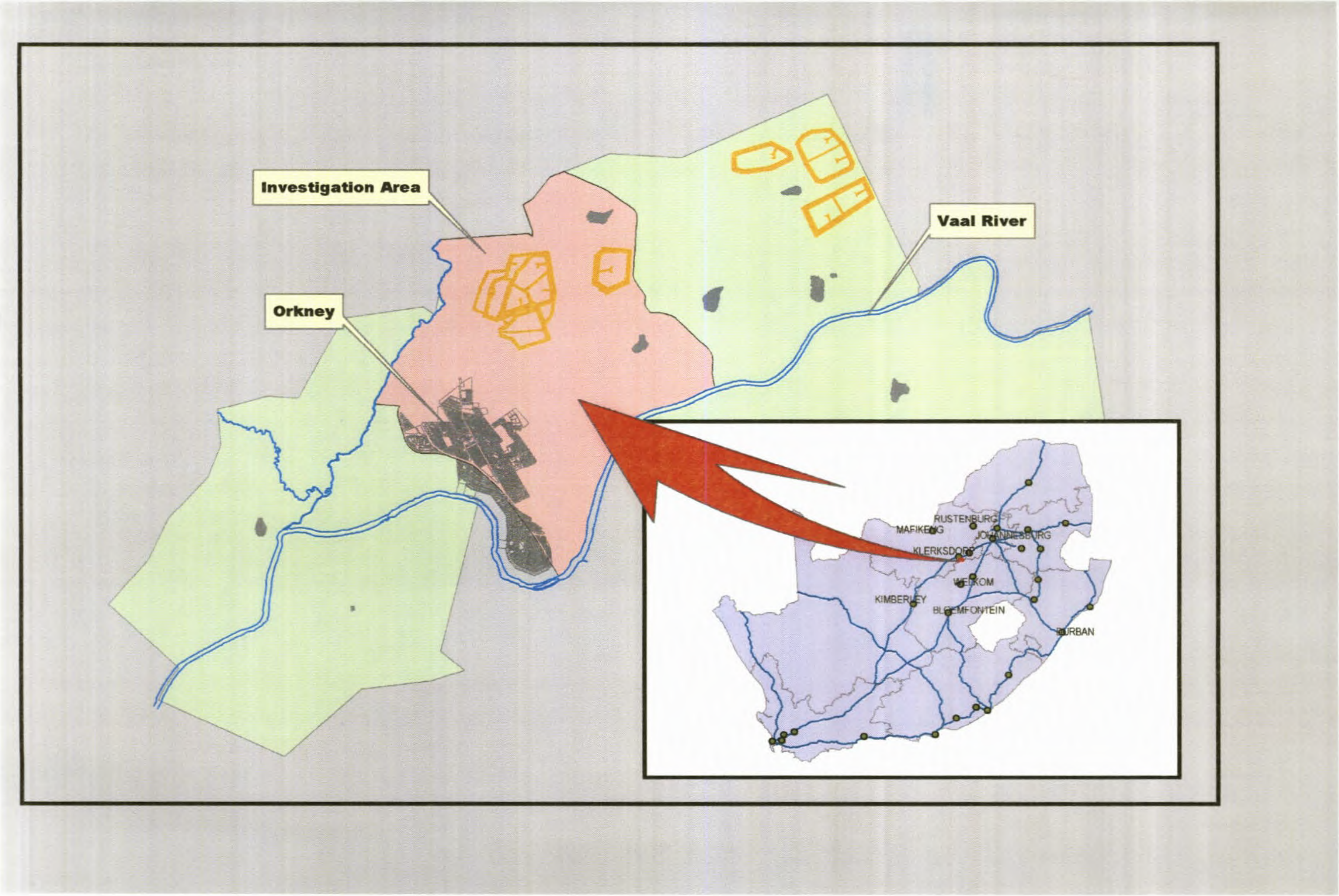


Figure 1: Regional setting of investigation area.

2 *Introduction & Approach*

2.1 *Scope and Objectives*

The main objectives of this thesis are:

i. To develop logical and practical steps that a gold mine can use during operations towards closure of the mine or selected sites. These steps will specifically be focused on geohydrological issues and remediation of polluted aquifers.

ii. To develop a methodology for an initial impact assessment of possible contamination sources;

iii. The establishment of a sufficient groundwater and surface water monitoring network and programme;

iv. To describe geological and geohydrological concepts and develop a conceptual model of the relevant aquifer system;

v. The construction of a database of key parameters – this will be focussed on cost effectiveness;

vi. The establishment of logical and practical steps to evaluate and characterize the identified "higher impact" sites on an initial screening based level;

vii. To identify typical closure objectives and possible rehabilitation options;

viii. To develop methods to evaluate these options for legal compliance, feasibility and cost benefit, and

ix. Ultimately to construct a user friendly and practical format for the compilation of a Strategic Groundwater Management Plan.

These objectives could be applied as management tools within an Environmental Management System (EMS), towards closure planning in a gold mining environment.

This research project will be divided into three sections and will ultimately focus on the following issues:

Section 1 – Generic Approach, Development of protocol, Methodology, Current Legislation, etc:

Section 2 – Overview of case study and methodology:

Section 3 – Application of protocol:

Apart from the 9 points above, the secondary aim of this research project is to look at affordable and practical groundwater remediation methods and management of the identified point sources. To reach these objectives, it is important to focus the approach on methods to integrate geological, hydrological and geohydrological characteristics and understand the interaction between these natural disciplines and man made features such as a tailings storage facility and other identified mining activities.

In the compilation of this thesis, the unique nature of the South African situation has been considered – this refers to a legally acceptable approach towards current legislation and policies. Throughout this document, the emphasis is on what could reasonably be achieved, without compromising on information that would lead to early detection of water pollution.

2.2 *Adopted Principles*

Clarity concerning the relevant issues and processes are necessary to achieve the operational and closure objectives in a reasonable, proactive and practicable manner.

The granting of a closure certificate, from a Water Management perspective, must be the result of a structured holistic approach. This in short will include assessments of possible pollution sources, groundwater regime and receiving water bodies.

i. The principle of "batneec" (best available technology, not entailing excessive cost) will be considered throughout this document – this is not particularly part of legislation but an important principle to follow,

ii. Consideration is also given to existing policy documents by governmental departments. Examples of the latter are the:

  - Environmental Conservation Act, Act 73 of 1989, dealing with general and hazardous waste and activities under the Environmental Impact assessment (EIA) regulations,
  - The Environmental Management Program Report (EMPR) regulations of the mining industry,
  - General requirements for mine closure Reg. 42(1), Minerals and Petroleum Resources Development Act & Regulations, No.28 of 2002,
  - New Water Act (Act No. 36 of 1998) - Water Services Act and Water Resources Act.

iii. It is critical that the environmental risk assessment (ERA) process that is followed when developing a mine closure strategy should pursue a consistent and structured process. The basic principle incorporated into the proposed approach is that the level of detail of ERA should be appropriate to the risks that exist, i.e. minor risks need not be subjected to a detailed quantitative risk assessment process, while significant risks should not stop at a simple qualitative assessment.

iv. The process and management of the site during operations and de-commissioning must comply with all relevant environmental legislation,

v. The time frame of the entire Risk Based Approach process depends on the life of mine and time of proposed de-commissioning.

vi. The EMS (environmental management system) should be in compliance with accepted best practice which can be motivated or have been approved by duly authorised persons within the relevant government departments,

vii. A final detailed closure plan for the identified sites or identified geographical areas should be prepared before the planned de-commissioning phase *(DME, 1992)*,

viii. In the absence of reliable data, consciously conservative assumptions must be made when undertaking any risk assessment or cost-estimate,

ix. The focus of a groundwater liability assessment should pay particular attention to long-term water quality issues and legal compliance,

x. Long term predictions on pollution, migration rates and loads to receiving water bodies must be calibrated according to field monitoring data. This should be started before actual de-commissioning phase.

2.3 *Adopted Philosophy*

The holistic approach and planning towards closure is based on a matrix developed by Sunter & Ilbury, 2002 (refer to Figure 2). This matrix could simply be utilized to understand the approach of holistic geohydrological assessment and nature of a real world scenario. The matrix has two axes: the horizontal one portrays certainty and uncertainty and the vertical one, control and the absence of control. These two axes yield four quadrants: the bottom right-hand one represents things that are certain but outside our control. Then going clockwise, the bottom left-hand one encompasses things that are both uncertain and outside our control; the top left-hand one things which are uncertain but within our control; and the top right-hand one things which are certain and within our control.

This matrix represents the philosophy, in this context, the environmental state and issues of a gold mine in time. Most of the South African Gold mines find themselves in one of the quadrants in a certain time frame or in more than one simultaneously. The most obvious reasons for the rotation around the matrix, over time, are:

- Fluctuations in gold price and subsequent life of mine,
- Environmental contamination from gold mining operations,
- Environmental legislation,
- Public perspectives, etc.

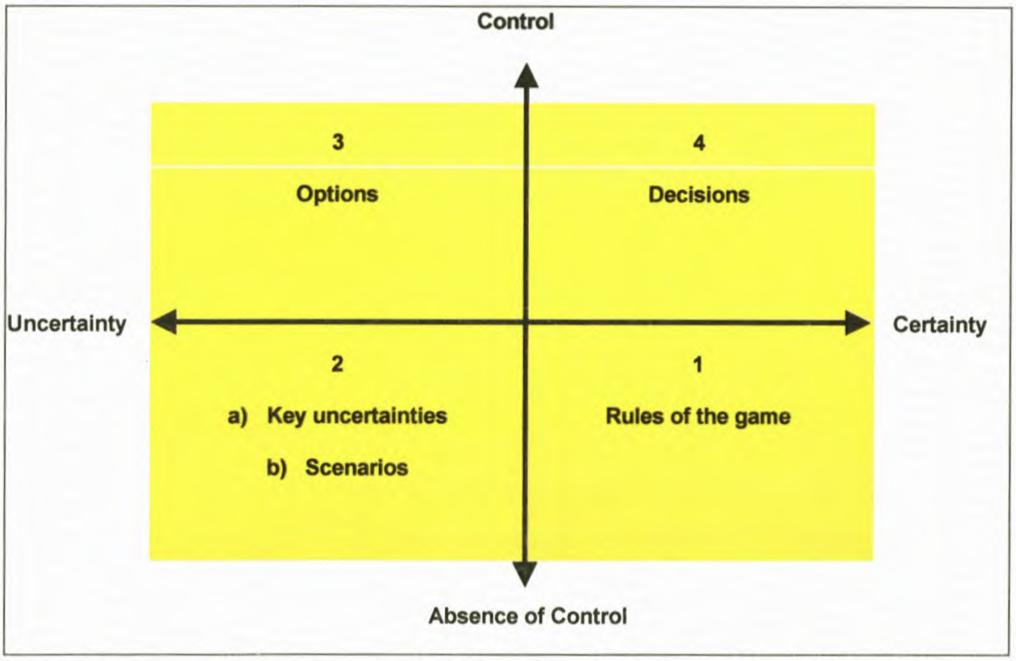
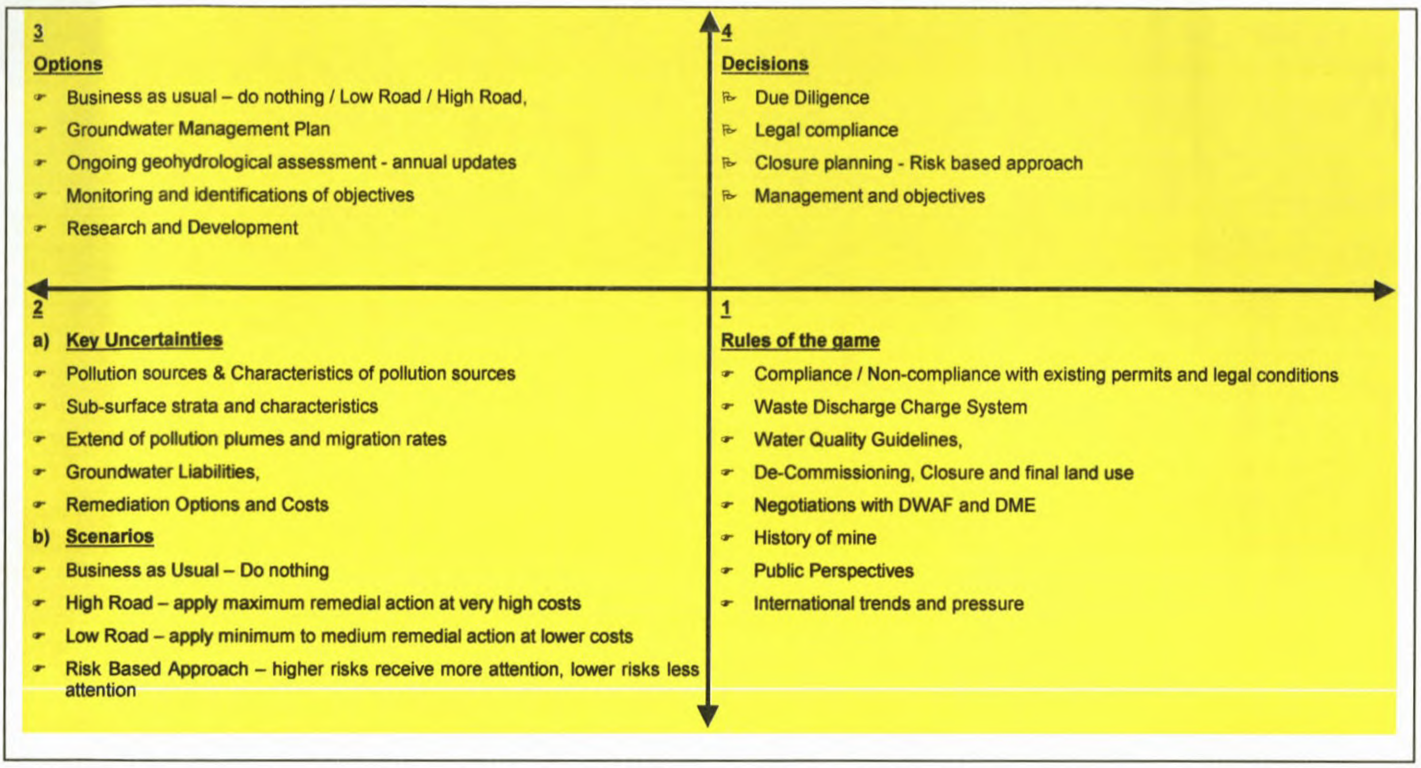


Figure 2: Matrix illustrating factors in Strategic Planning (Sunter & Ilbury, 2002)

For these reasons the matrix needs to be customized. The most important aspect of the newly constituted matrix follows Sherlock Holmes's line of thinking: first eliminate the impossible before concentrating on the possible.

The first quadrant now represents the rules of the game-things that are certain and over which we have no control. The second quadrant has two components: key uncertainties over which we also have no control; and plausible and relevant scenarios derived from these uncertainties, though the scenarios must be vivid and different enough to take us out of the comfort zone. The third quadrant is now identified with the options presented by the scenarios. The formulation of options is crucial and allows us to operate with more control in an uncertain environment. The fourth quadrant is the area where decisions are made based on the preferred scenario and linked to the preferred option. *It is also the quadrant where strategic plans and programmes of action should be located, as these are really decision paths formulated in advance.*

To achieve the final objectives within the scope of this thesis the above matrix could be updated and customized to give a better picture of strategic planning within the gold mining environment and especially Groundwater Management Plans. The following matrix represents the real world scenario of the day-to-day issues of a gold mine in South Africa (Figure 3).



3

Options

- Business as usual – do nothing / Low Road / High Road,
- Groundwater Management Plan
- Ongoing geohydrological assessment - annual updates
- Monitoring and identifications of objectives
- Research and Development

4

Decisions

- Due Diligence
- Legal compliance
- Closure planning - Risk based approach
- Management and objectives

2

a) Key Uncertainties

- Pollution sources & Characteristics of pollution sources
- Sub-surface strata and characteristics
- Extend of pollution plumes and migration rates
- Groundwater Liabilities,
- Remediation Options and Costs

b) Scenarios

- Business as Usual – Do nothing
- High Road – apply maximum remedial action at very high costs
- Low Road – apply minimum to medium remedial action at lower costs
- Risk Based Approach – higher risks receive more attention, lower risks less attention

1

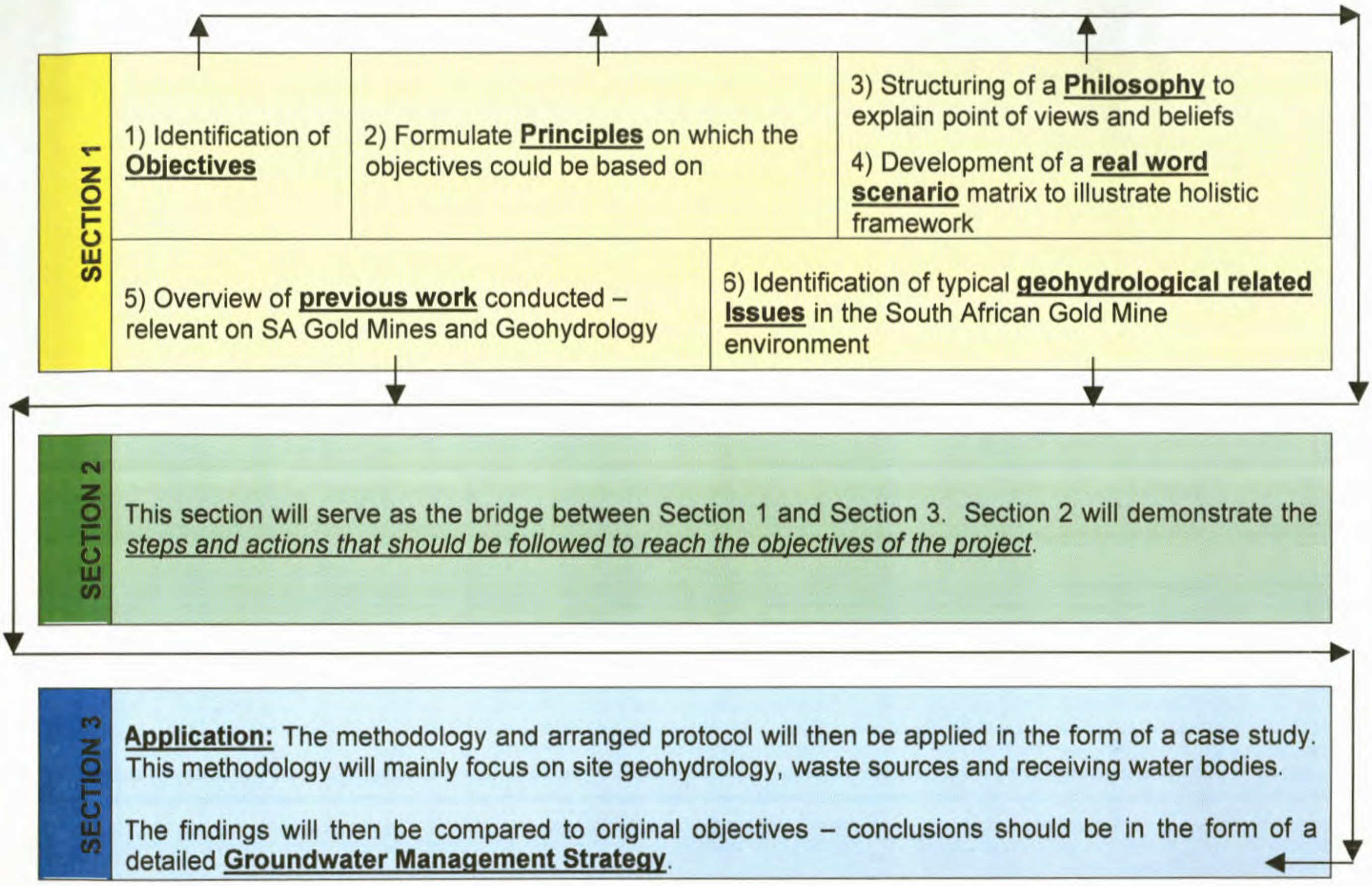
Rules of the game

- Compliance / Non-compliance with existing permits and legal conditions
- Waste Discharge Charge System
- Water Quality Guidelines,
- De-Commissioning, Closure and final land use
- Negotiations with DWAF and DME
- History of mine
- Public Perspectives
- International trends and pressure

Figure 3: Matrix illustrating factors in Strategic Groundwater Planning

2.4 Adopted Approach

The proposed approach and layout of this thesis could be explained by means of the following flow diagram.



1) Identification of **Objectives**

2) Formulate **Principles** on which the objectives could be based on

3) Structuring of a **Philosophy** to explain point of views and beliefs

4) Development of a **real word scenario** matrix to illustrate holistic framework

5) Overview of **previous work** conducted – relevant on SA Gold Mines and Geohydrology

6) Identification of typical **geohydrological related Issues** in the South African Gold Mine environment

This section will serve as the bridge between Section 1 and Section 3. Section 2 will demonstrate the *steps and actions that should be followed to reach the objectives of the project*.

Application: The methodology and arranged protocol will then be applied in the form of a case study. This methodology will mainly focus on site geohydrology, waste sources and receiving water bodies.

The findings will then be compared to original objectives – conclusions should be in the form of a detailed **Groundwater Management Strategy**.

The steps illustrated in the case study were developed for the specific site and information from studies compiled by several geohydrological consultants was also used. These could certainly be applied to typical South African conditions. At this early stage of the thesis it has become necessary to explain the current thinking of the Department of Water Affairs and Forestry (DWAF). This will simultaneously provide the concept of closure and guideline for mine closure in general. Therefore as one of the objectives, the following generic, guideline was used and followed as far as possible:

The following is an extract from an unpublished draft report that the Department of Water Affairs compiled for interim guidance towards closure:

The M5.0 Operational Guideline (Operational Guideline for the DWAF to assist the DME with EMP's in terms of the Minerals Act) states that the delegated responsibility of recommendation for approval of Closure Plans and Closure Certificates to the DME for all Category A mines lies with the Director: Water Quality Management (now Manager: Waste Discharge and Disposal). This operational guideline does not give guidance on the procedure for closure. Presently there are a number of Gold mines approaching the decommissioning phase, with quite a number of them already within this phase. A number of Closure EMPR's (or Closure Plans) and a number of requests for assistance with the closure process have been received by the regulators (specifically DME and DWAF). The mining industry (and consultants) is looking for guidance. In the past it was stated that the DME Closure Policy along with the EMPR process had to be followed, with specific references to risk assessment, future predictions, use of suitably qualified persons, consultative processes, etc. It seems as if this guidance was too vague, leaving it mostly in the hands of "suitably qualified persons", and the resultant quality and depth of investigations differed tremendously from application to application.

DWAF decided that some guidance was required urgently, to assure a measure of consistency in the mine closure process. The WRC has commenced with a project called: The development of an appropriate procedure for the closure of deep underground gold mines. The closure methodology proposed in this project is generic enough to be used for all Category A mines. A draft document has been compiled setting out the closure methodology (see Figure 4). This document has not yet been workshopped by the regulators to make it officially their own, but can be used in the mean time to assist DWAF personnel, the mining industry and the consultants. The proposed methodology has been through the normal WRC consultative process, by having select specialists from the mining industry and the regulators on the steering committee and a specialist workshop.

As the mine closure process essentially involves the application of significant financial resources for final environmental management actions followed by the transfer of residual environmental liability to the State, it is considered critical that the environmental risk assessment (ERA) process that is followed when developing a mine closure strategy, should follow a consistent and structured process. The basic principle incorporated into the proposed approach is that the level of detail of ERA should be appropriate to the risks that exist, i.e. minor risks need not be subjected to a detailed quantitative risk assessment process, while significant risks should not stop at a simple qualitative assessment.

The specific procedure that is proposed for mine closure risk assessment is shown in Figure 4 below. In many cases, the mine may wish to start the process with a screening-level ERA where not all the Steps shown in Figure 4 are undertaken. In particular, the more detailed and quantitative assessments shown in Steps 2, 4, 9 etc are not undertaken. For such a screening level ERA, the identification and assessment of alternative strategies is based on professional judgement rather than quantitative data. Subsequent more detailed studies will aim to review the appropriateness of the alternative strategies and provide quantitative assessments as the basis for closure costing.

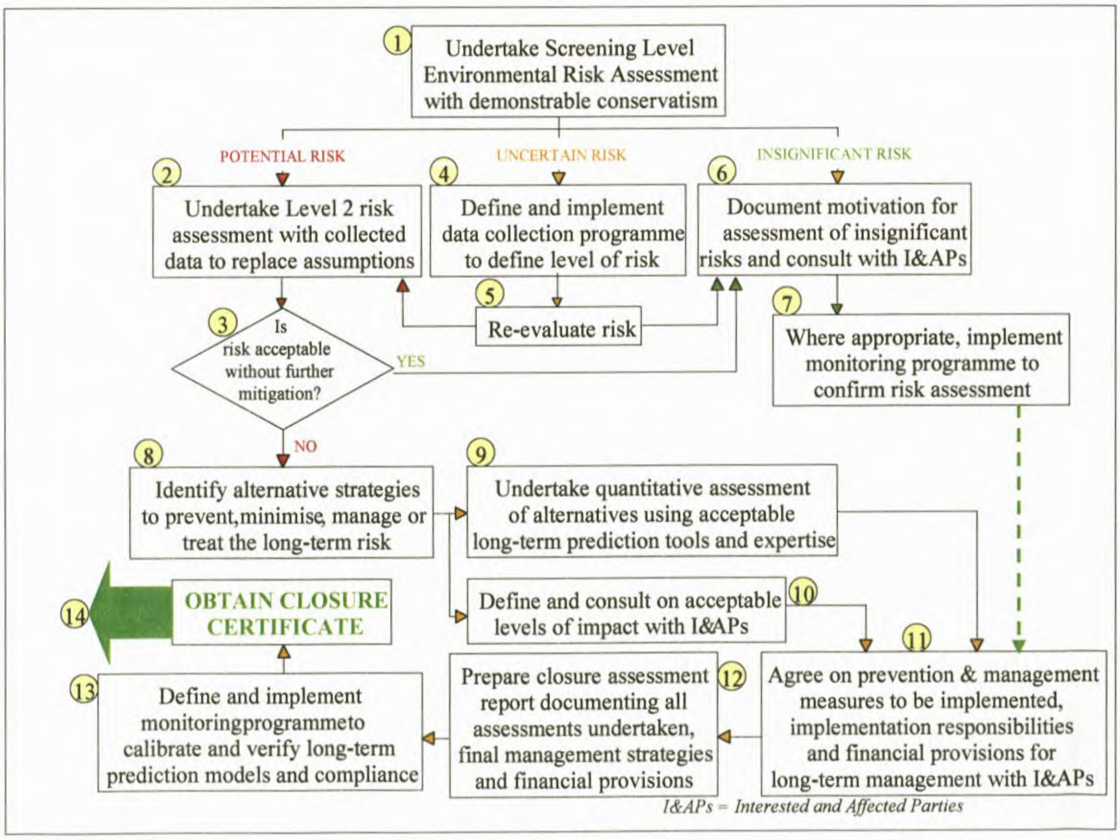


Figure 4: Flow Diagram of the Mine Closure Risk Assessment Process (Pulles et al, 2002)

3 Previous work & Discoveries in South Africa

The following will give a brief overview of some of the work previously conducted on the effect of mining activities on both ground- and surface water. The reason for the inclusion of this overview is to give us an idea of different discoveries, opinions and research over a period of time. It must be noted that not all the work is relevant on the selected investigation area or the scope and objectives of this thesis, but rather provide an overview on the broader South African environment. It is important to discover history and to apply the lessons learnt in current and future operations. It will also give us an idea of the awareness of typical issues in South Africa:

- In 1965, James and Mrost stated that pyrite oxidation in slimes dams is confined to a surface layer of about 2m in depth and that oxidation is limited to the depth to which oxygen can gain access. These results were verified by Mrost and Lloyed (1970).
- Thomas (1970) states that the mineral pollution of the streams in the Witwatersrand catchments area arising from run-off from slimes dams is probably South Africa's major pollution problem.
- Verhoef (1982) investigated the pollution of groundwater, due to the activities of the Buffelsfontein mine in the North Western Province. He concluded that high levels of Sulphate, ammonia and heavy metals (especially manganese) are found in polluted groundwater.
- Funke (1984) investigated the impact of mining wastes on the water quality of the Vaal catchment and of the Vaal Barrage. The author found that the contribution of AMD from the dumps and slimes dams towards a high salinity of the Vaal Barrage water is approximately 2% compared to the pollution load originating from underground mine effluents which are pumped to the surface and discharged into the rivers.
- According to Marsden (1986), the resultant release of sulphate, due to the oxidation of pyrite, is negligible in old slimes deposits, mainly due to the fact that oxidation does not proceed below a depth of 2 to 3 m in slime and 10 m in sand dumps.
- Jones et al (1988) stated that direct surface run-off is not a significant source of the salts that can be found in the stream water in the upper Vaal catchment area, but that the recharge of the streams by groundwater is of more significance. They also concluded that the hydro geological aspects proved to be more important than had first been expected.
- Funke (1990), *reports on the water requirements and pollution potential of South African gold and uranium mines* (WRC project KV9/90). The 43 larger South African gold and uranium mines in 1989 disposed of approximately 120 x 10^6 t of milled and processed ore and about 30 x 10^6 t of mined waste rock.
- Cogho, van Niekerk, Pretorius and Hodgson (1992) compiled a document for the Water Research Commission with the title: *The development for the evaluation and effective management of surface and groundwater contamination in the Orange Free State Goldfields.* They stated that contamination of groundwater resources is generally contained within close proximity of the disposal site, depending on the age of the site as well as the local groundwater gradients in the vicinity of the site.
- Cogho *et al* (1992) also explain the results from research of flow in the unsaturated and saturated parts of tailings dams: Neutron access tube above the phreatic surface shows that up to a depth of 1,5m, there is vertical movement of moisture, after which the moisture has to move horizontally, either to the centre of the slimes dam or to the side, where it can evaporate, explaining the precipitation of sulphates on the slimes dam surface. It furthermore means that there is no vertical flow past the depth of 1.5m, at specific tube locations. This limits the influx of water as pyrite oxidation.
- Pulles, Howie, Otto and Easton (1995), compile *a manual on Mine Water Treatment & Management in South Africa.* The main objective of the project was to define water

management and treatment practices and developments in the South African gold and coal mining industries.

- The Institute for Groundwater Studies (Scott, 1995), investigated Flooding of Central and East Rand Gold Mines: An investigation into controls over the inflow rate, water quality and the predicted impacts of flooded mines.

- Wates *et al* (1997) investigated the environmental aspects related to the design and construction of tailings dams with regard to the recent environmental legislation in South Africa. The authors concluded that failures such as the Merriespruit disaster have led to intensified public awareness of the safety and environmental hazards associated with mine dumps. This will be reflected in the promulgation of existing legislation such as the new Water Act and the establishment of a new set of guidelines; *The Code of Practice for Mine Residue Deposits* was developed under the guidance of the South African Bureau of Standards.

- James, A.R. (1997) compiled a document for the Water Research Commission with the title: *The Prediction of Pollution Loads from Coarse Sulphide-Containing Waste Materials*. Given the importance and significance of the contaminant load which emanates from coarse wastes in South Africa, the WRC and the mining industry identified the need to review the current status of prediction modelling and develop a method which can be used with a reasonable or useful degree of accuracy, to predict the drainage characteristics from coarse waste piles.

- The Use of Vegetation in the Amelioration of the Impacts of Mining on Water Quality – an Assessment of Species and Water Use – DB Versfeld, CS Everson and AG Poulter (1998). This project was commissioned by the WRC to assess the degree to which vegetation can be effective in utilizing rain and surface water, thus preventing its movement through, and leaching of, mining waste piles, replaced or fractured profiles, resulting in acidified or otherwise polluted ground and surface waters.

- Pilson, van Rensburg and Williams (2000), work on a WRC project named An Economic and Technical evaluation of regional treatment options for point source Gold Mine Effluents entering the Vaal Barrage Catchment. One of the conclusions was that, conventional methods of desalination needs to be modified to ensure that the production of by-products receives as much if not more attention, than the production of potable water. The importance of reducing the ingress of runoff and seepage into mine workings was highlighted.

- Rösner, Boer, Reyneke, Aucamp and Vermaak (2001) compiled a document for the Water Research Commission with the title: A preliminary assessment of the pollutions contained in the unsaturated and saturated zone beneath reclaimed gold-mine residue deposits. One of their concluding remarks was: "Groundwater quality beneath and in close vicinity to the investigated tailings dams is dominated by the Ca-Mg-SO4 type, indicating acidic seepage. High TDS (up tp 8000 mg/l) values occur mainly as a result of high salt loads (SO42- and Cl-) in the groundwater system. In most of the samples, groundwater pH values are fairly neutral due to the acid neutralising capacity of the dolomitic rock aquifer".

- Hodgson, et al, 2001, compiled a report for the Water Research Commission with the title – Prediction Techniques and Preventative measures relating to the post-operational impact of underground mines on the quality and quantity of groundwater resources. The report mainly concentrated on the design of reliable tools for the prediction of water qualities and quantities during the post-closure phase, to provide information for closure and to assess the applicability of these tools to South African conditions.

4 Challenges in a Typical South African Gold Mining Environment towards Closure Planning – a Geohydrological Perception

4.1 Introduction

Groundwater affected by mining is commonly subdivided into shallow and deep systems – they amount to a natural near-surface system and a deep mining induced system. Fractures and partings in the rock sequence, natural or enhanced by mining, convey water into the mine openings from where it must be pumped to allow mining to continue, Hodgson, 2001.

The shallow systems are usually recharged directly from rainfall and the water is of good quality. It is the influence of major mining activities on this aquifer system that needs to be understood and assessed towards the decommissioning and closure of mining operations.

This section provides an overview of typical groundwater related challenges or aspects that create challenges in the South African Gold Mining Environment. The challenges could be linked to one of the following categories:

- Potential Sources of groundwater pollution – Type and Characteristics, Commissioning and De-commissioning dates and related construction technologies,
- Contaminants contained in pollution sources,
- Water Balance – sufficiency and water reticulation
- Impact Locations, risk points and aquifers,
- Legislation and Legal Compliance – Permit Applications and Waste Discharge Charge System.

4.2 Potential sources of groundwater pollution

The sources of groundwater pollution are listed to determine where the major contributors of seepage are. The main focus will be on surface pollution sources. Due to the nature of the Gold Mining Industry, it has vast quantities of residue, which have to be disposed of. The bulk of the residue will, however, always be disposed of on the surface, posing an immediate pollution threat to the surrounding area.

The residues mainly consist of:

- Residues – material from beneficiation or metallurgical processes, which is structured in the form of slimes dams or tailings storage facilities as waste material.
- Excess mine and plant water – water pumped from deep mine workings and water from metallurgical processes the water is pumped to return water dams to be recycled for re-use or pumped into big evaporation ponds,
- Waste rock – rock material which is mined with gold ore or due to sinking of mining shafts and development of stopes – the rock does not have economic value due to insignificant or no gold content and is then stockpiled as waste rock. Other uses such as road building, etc. exist.

The nature and pollution hazard of each of the above structures will be discussed subsequently.

4.2.1 Tailings Storage Facilities (Slimes Dams)

Previously only the paddock system was used in the investigation area, but the cyclone system was recently applied on the West Extension Tailings Storage Facility (WE-TSF), which was originally built in the paddock system. The West Complex Tailings Storage Facility (WC-TSF), which is situated in the investigation area, as well as most other gold tailings dams in South Africa, is constructed using the upstream semi-dry paddock method. The construction of this dam will be briefly explained (refer to Figure 5 for layout of the WC-TSF and the WE-TSF):

The daywall (outer paddocked wall) impounding walls are generally raised mechanically (by tractor-plough) and shovel packing is only used when conditions are to wet for the tractor to gain access. The complex is constructed through 26 delivery stations at an average spacing of approximately 300m. Under normal conditions deposition cycles are irregular as the dam complex consists of four active compartments and the fact that this dam is operated together with the West Extension dam. Currently approximately 241 967 tons of dry slimes is deposited per month with an average relative dry density of 1.27.

The solid to water ratio in the wet slime varies from 1:1 for gold tailings up to 1:4.5 in slimes dams generated from the combined recovery of gold, uranium and pyrite. Some of the operating tailings dams store large volumes of surplus water from the plant in pond systems for evaporation purposes on top of the dam.

The residues contained in slimes dams consist essentially of slime from the gold- and/or uranium extraction processes. The grain size of this slime is between 65 and 80% minus 75um and the gold values vary between 0.1 and 0.5 g/t (Stanley, 1987). The maximum rate of deposition in South Africa is 2.5m/y, which, according to Funke, (1990) is on conventional paddock built dams. Cyclone dams could be developed up to 4 m/y.

When designing an effective water management system, the mining industry tries to meet two important objectives, namely:

- Minimizing the loss of water, which minimizes the water costs,
- Eliminating pollution caused by discharge of effluent, not complying with the statutory requirements.

The cost of water will potentially reached the level where it is a significant portion of the cost of gold production. This implies that the objectives must be accepted as a responsibility, which could be justified economically.

4.2.1.1 Tailings Storage Description in Investigation area

Details of the *Tailings Storage Facilities* are given in the following tables.

Table 1: Slimes Deposited

	West Float, Acid and Uranium Plant	**No. 1 Gold Plant**
No. of days discharged in a year	365	
Seasonal discharge	Discharge does not fluctuate with the seasons, but is based on deposition policy and maintenance requirements	
Average Slimes Deposited (dry t/day)	3908	8288
• West Complex *Tailings Storage Facilities* (Compartment 1 & 2, Grass Dam, Ariston Gully)	2391	5071
• West Extension *Tailings Storage Facility*	1517	3217
Slimes deposited (t/month)		
• West Complex *Tailings Storage Facilities* (Compartment 1 & 2, Grass Dam, Ariston Gully)	72714	154235
• West Extension *Tailings Storage Facility*	46138	97865

Note: Figures are based on production from April 1999 to March 2000

Table 2: Details of WC-TSF

Description	**West Complex *Tailings Storage Facilities*** West Compartment 1 & 2, Grass Dam, Ariston Gully, *West Pay Dam, Compartment 3, Abandoned Dam, Emergency Dam*
Height to date (m)	51.50
Planned final height (m)	Dam 1 East Compartment 60m - Others 45m
Top area between July and September 1998 (ha)	Compartment 1, Compartment 2, Grass Dam, Ariston Gully - 149.35
Foot print area (ha)	Compartment 1, Compartment 2, Grass Dam, Ariston Gully - 229.46
Annual Rise	2.23
Slope of walls (degrees)	30
Overall slope (degrees)	22 – 26
Terraced (stepped)	Yes
Berm width	7m
Breakaways	Yes (abandoned compartment)
Damage	Seepage on Eastern wall

Table 3: Details of WE-TSF

Description	**West Extension *Tailings Storage Facilities***
Height to date (m)	26.04
Planned final height (m)	60
Top area in January 2000 (ha)	75.44
Foot print area (ha)	90.08
Annual Rise	1.71
Slope of walls (degrees)	30
Overall slope (degrees)	22 – 28
Terraced (stepped)	Yes
Berm width	7m
Breakaways	nil
Damage	nil

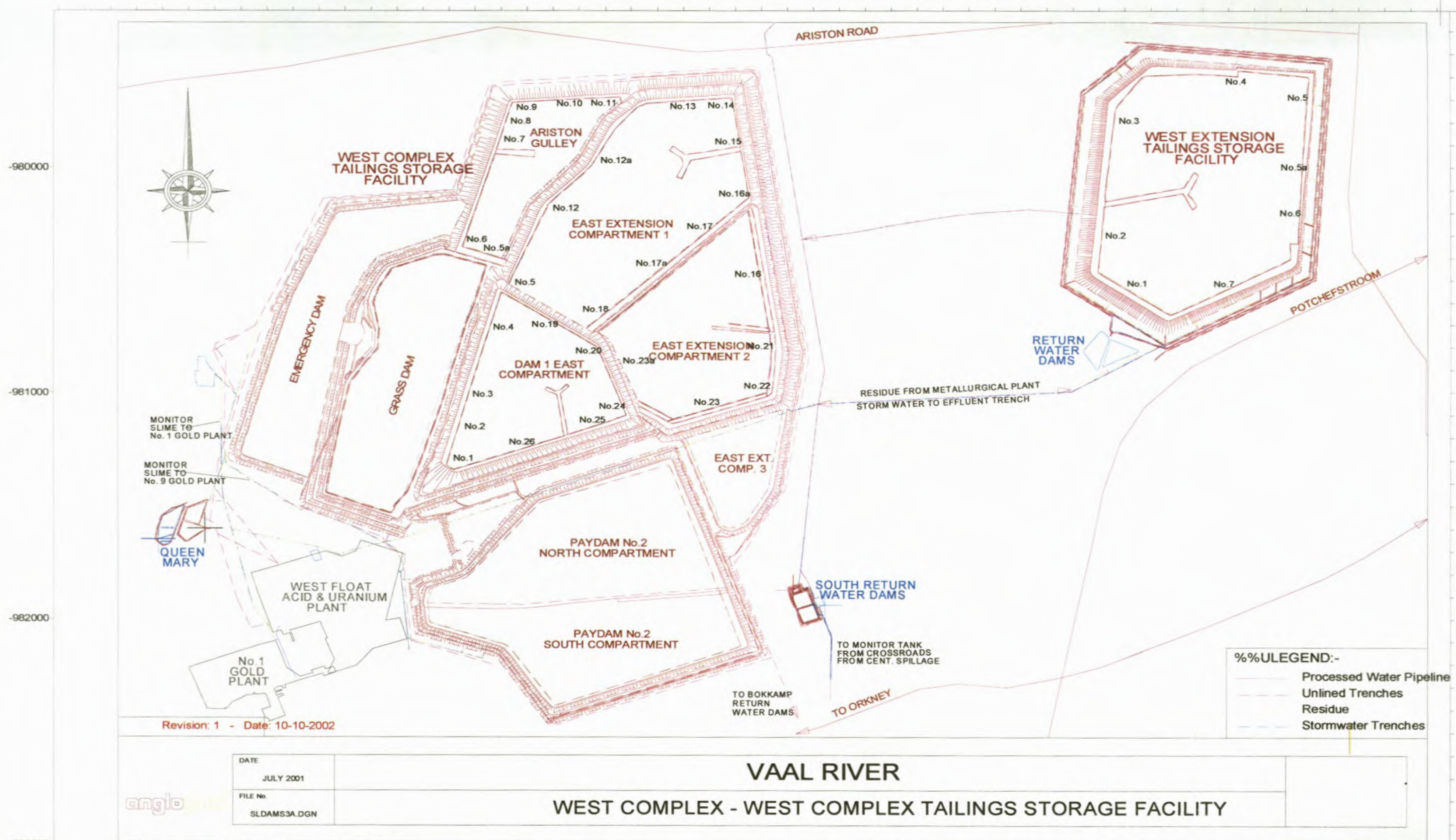


Figure 5: Layout Plan of the West Complex (WC-TSF) and West Extension Tailings Complex (WE-TSF) with the Metallurgical plants in the south western corner of the plan

4.2.1.2 Geohydrological conditions of tailings dams

According to *Funke (1990)*, pollution of groundwater by seepage is unlikely, particularly if gold slimes deposits have been built on impermeable soil, since about:

- 30% of the original water is returned to the gold plant via toe channels;
- 20% interstitial water retained, and
- The large surface area combined with the high net evaporation loss on the Witwatersrand of 850 mm/a assures high evaporation losses.

However, this ideal situation of minimal seepage and groundwater pollution is not always possible and does not always occur. Visual inspections of the two tailings storage facilities, mentioned above, indicate leaching as water percolates through the structure. The type of geological formations below the dam and the associated geohydrological characteristics will play a large role on seepage and water losses – this issue will be discussed in more detail in Section 3. The statement of Funke is therefore very idealistic and definitely not site specific but rather more in general.

See photo's below for a typical seepage plume at the toe of a tailings storage facility.

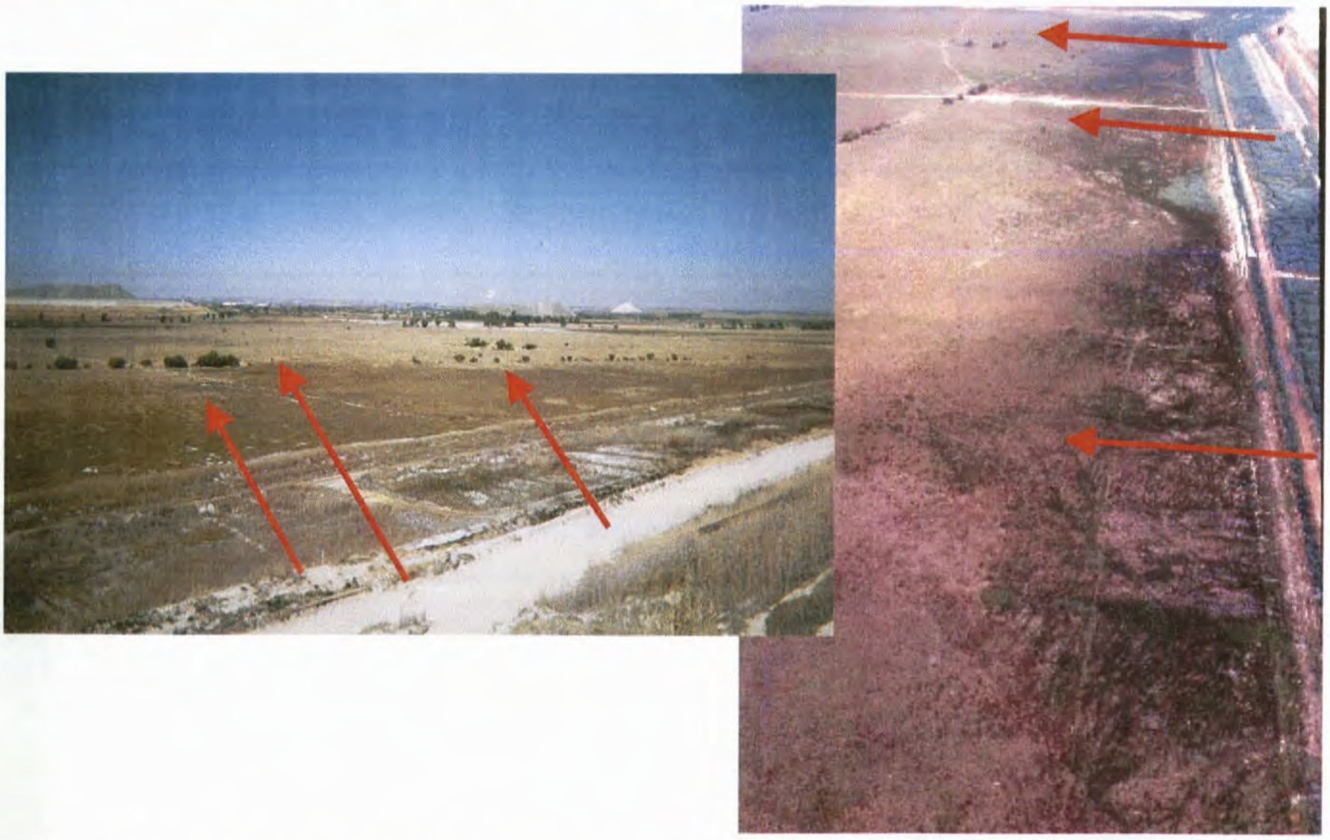


Figure 6: Identified seepage plume to the east of the West Complex Tailings Dam

The tailings dam remains almost saturated during the operational phase, as well as for the period after decommissioning of the impoundment. This is mainly due to the particle size distribution (fine sand and coarse to medium silt particle sizes) of gold-mine tailings, which enables water retention by capillary forces. After a tailings dam has been decommissioned, the phreatic surface slowly subsides, at a rate, which depends on the conditions of the under-drainage system and the size of the impoundment (Rosner, *et al*, 2001). Reported subsidence of the phreatic surface (line of zero pore water pressure) varies between 0.3m/y and more (Blight & Du Preez, 1997).

It is important to note that the majority of tailings dams in South Africa were constructed without seepage collection systems. In general, seepage escapes from tailings impoundments through two typical pathways, through the embankment structure and through the foundation materials on the floor. From experience of tailings dams in different areas the conclusion could be made that seepage regime of tailings dams is mainly controlled by:

- The anisotropy factor (ratio between horizontal and vertical permeability in porous media),
- Characteristics of underlying geology and geohydrological concepts, and
- Density of material itself.

4.2.2 Effluent - canals and earth trenches

The majority of the water will nevertheless reach the solution (toe collection) trenches on its way to the return water dam. The fact that the trenches are earth and not concrete trenches and almost constantly filled with water, will further propagate seepage into the underlying strata. The effluent canals, specifically the unlined earth trenches acts as linear sources of pollution. The canals have a high potential for groundwater pollution because it contains a head that acts as a driving force for seepage and pollution. The contribution of the effluent canals is generally less well defined than the primary pollution sources such as the tailings dams.

The following series of photos show typical earth trenches from tailings storage facilities, which transport tailings effluent to the return water dams. Note the condition of the trenches.

Figure 7: Photos of typical earth effluent trenches

4.2.3 *Return Water Dams*

Return water dams (RWD) are provided in all modern slimes dam complexes. These small water dams provide a service of great importance to the long-term stability of the slimes dam. In South Africa, the slimes dams is not usually designed as a water-holding structure, but in terms of DWAF regulations, it has to retain all water falling on it, including a 1:100 year storm. This water and the usual excess pool water, as well as possible overflows from the toe paddocks cannot be released into the nearest watercourse, but is generally stored in the RWD. The ideal is to re-use the water and retain it in a close water cycle.

It is evident from the above discussion that the water reaching the RWD will have a very high salt load. Since water is stored in the dam and the dam contains water most of the time, a constant seepage of water into the ground will occur, as the older dams are not usually lined. The amount of water penetrating will be determined by the status of dam linings and the permeability of the underlying strata.

By law, return water dams must have a 0.5m freeboard for a 1:100 year storm event. The following photo represents a typical tailings effluent RWD. It can be seen from this image that the dam is quite silted up. This dam is lined with a plastic engineered liner. The pump-station below the dam pumps water back to the plants for re-use.

Figure 8: Photo of Bokkamp Dam RWD within the investigation area

4.2.4 *Evaporation Dams*

Evaporation dams are large surface are dams which are relatively shallow and contain large amounts of redundant water. The dams need to be relatively shallow to increase the temperature of the water and consequently the evaporation rate. The majority of this water will have the same composition as that of the slimes dams and RWD.

4.2.5 *Rock Dumps*

Waste rock originates from two main sources, namely sorting and underground development. Rock pieces rejected by sorting are those mineralised to a lesser extent than the cut-off grade for gold extraction. With the traditional practice to stabilize waste rock dumps for geotechnical purposes, unknown volumes of low-grade water are sprayed onto the dumps during the construction phase (Funke, 1990).

The pyrite content of these rocks is generally less than that of the ore. Because rock dumps are very permeable to air and water, the oxidation of pyrite and the leaching of soluble oxidation products by rainwater can proceed freely. Although the rock dump as a whole is very permeable, the individual rock pieces are mostly impermeable. Most of the oxidation will therefore take place on the outer surface of the rock pieces, excluding the majority of pyrite from the oxidation process. It should also be mentioned that a considerable quantity of the rock dump is crushed to a relatively fine material, making more pyrite available for oxidation.

Figure 9: Example of typical Waste Rock Dump (WRD) – 3# WRD in investigation area

4.2.6 *Mineral processing plants*

On average, only five parts per million of every ton of ore mined is actually gold. It is therefore necessary to separate the precious metal from the more than 100 million tons of ore milled each year in South Africa (Chamber of Mines, 2002). This is carried out in the mine's gold plant. Initially, ore hoisted from the mine is broken into smaller pieces by a primary crusher; secondary crushers break it down further, followed by a milling stage to produce a fine rock dust. At this point most of the tiny particles of gold contained in the ore have been exposed. A cyanide solution chemically dissolves away the exposed gold particles and the resultant liquid follows one of two routes to recover the gold now held in solution.

The mineral processing plants where the beneficiation of the ore takes place, could pose groundwater pollution potential from the aqueous processes and chemicals that is used in the beneficiation process. Pollution may occur from on site spillages and leakages from the process containers and waste water ponds. The groundwater pollution from these sites is generally less well delineated or understood.

On the whole, metallurgical plants use about 50% of the total water intake of the mines.

According to *Funke (1990)*, typical water intake figures at surface plants are:

Gold recovery only:	0.9 to1.4 m^3/t of processed ore
Gold and uranium recovery:	2.5 m^3/t of processed ore
Gold, uranium and pyrite recovery:	3.0 m^3/t of processed ore
Gold, uranium, pyrite recovery and production of sulphuric acid:	4.0 to 4.5 m^3/t of processed ore
H2SO4 plant, scrubber/cooling water in circulation	11.0 to 14 m^3/t of acid

4.2.6.1 Plant Description in Investigation area

A brief description of the processes involved in the beneficiation plants within the investigation area is supplied in Appendix A. The West Float Acid and Uranium Plant and the No.1 Gold Plant are situated to the west of the west tailings Complex (refer to Figure 5)

The West Uranium Plant, later known as No. 9 Uranium Plant followed by No. 9 Flotation and Acid Plant and now known as West Float, Acid and Uranium Plant commissioned in the 1950's, was originally designed to process 260 000 tons per month. The No.1 Gold Plant was built in the early 1990's to replace an old gold plant in the area.

Basically four processes are involved to treat ore originating from the gold mines in the area. These include floatation processes for acid generation, acid generation, processes to refine uranium and then gold extraction processes. It could therefore be seen from Appendix A that the metallurgical processes involved in gold mining, is not simple but include rather complicated processes. All these beneficiation processes was implemented and developed to optimise the return of gold mining.

It can be seen from Appendix A that several processes require several reagents and these supply a number of by-products. For example, sulphuric acid is generated from pyrite, in the roasting processes of the pyrite calcine is the by-product. Calcine is an iron-oxide and is further processed to extract uranium. Sodium cyanide, copper sulphate and manganese are some of the reagents added to the ore pulp in the extraction processes. It is therefore apparent that a good understanding of these processes and associated by-products is required when assessing the impact on groundwater.

4.2.7 Domestic waste sites

The domestic waste sites originated from the office complexes, hostels and villages. These sites contain household wastes, which may comprise heavy metals. The domestic waste sites are a concern for the operational period and can be rehabilitated at the closure phase. Leachate generation and hence groundwater pollution from these sites may continue into the post-closure phase.

4.2.8 Sewage plants

The sewage plants are used to treat the sewage from the office complexes, hostels and villages. The groundwater pollution potential from the sewage plants is nitrate pollution from the wastewater ponds and canals. The purified sewage effluent (PSE) is treated to the required water quality specifications to be discharged or re-used.

4.2.9 Diffuse sources

Diffuse sources of groundwater pollution are smaller in scale and not continuous. Examples of diffuse sources are localized spillages and burst pipes, especially tailings pipelines. These kind of environmental hazards are usually handled as incidents.

4.2.10 Underground water

The primary source of water contamination in the gold mining industry has been shown to be pyrite oxidation in the underground stopes. In order to minimise the contamination of water, the water entering the underground workings (fissure water or mine service water) should be routed away from the workings as quickly as possible.

The typical underground sources of water contamination are pyrite oxidation, inadequate underground settling, fissure water, waste explosive and faecal contamination. The understanding of geology, hydrogeology and chemistry of the underground mine environment is important, since these parameters determine the water pollution potential from underlying geological formations, reaction rates and flow of contaminants within the aquifer. Moreover, if the area comprises rocks with high porosity, the mine area will be subjected to fissure water ingress and this can increase the volume of water and contaminant load from the mine.

Apart from the fact that underground water could obtain contaminants, which could end up in the mine make-up water circuit, it could also pose a threat to mine safety.

4.3 Contaminants contained in pollution sources

The contaminants that are contained in the wastewater sources, determines the severity of the impact on the neighbouring environment. The contaminants that are contained in the gold tailings, wastewater dams and waste rock dumps can be classified as:

1) Inorganic macro chemicals: Sulphate, nitrate, chloride, sodium, etc.

2) Inorganic micro chemicals and heavy metals: Iron, manganese, cadmium, cyanide, etc.

3) Radionuclides: Uranium and thorium decay series and radon.

The solubility, mobility and toxicity of these contaminants determine the environmental risks that are posed to humans and the environment. Most of the heavy metals and radionuclides are soluble at low pH conditions and are in soluble form inside the waste sources where low pH conditions exist. In general, these contaminants precipitate out in the proximity of the source due to the buffering capacity of the groundwater, especially dolomitic groundwater. However, there may be species such as manganese, aluminium and uranium complexes that can be mobile at higher pH levels.

4.3.1 Radio Activity

The radionuclide risks are less well defined and although it is not the primary focus of this investigation, it is important to note that there are radionuclides with very long half-lives, such as ^{238}U that has a half-life of $4.47E+10^9$ years. The assessment of these radionuclides should be done according to the international safety assessment methodologies, which involves time-dependant assessments on the migration rate and direction of the radionuclides and exposure assessments via primary and secondary pathways (Vivier, 2001).

4.3.2 Pyrite oxidation in slimes dams and waste rock dumps

The gold-bearing conglomerate encountered in South Africa is always intimately associated with a matrix and therefore crushing and grinding are essential for the recovery of gold. According to Forstner and Wittmann (1976), the conglomerate essentially consists of the following minerals: quartz (70 – 90%), phyllosilicates (10 – 30%) and primary minerals (1 – 2%). The pyrite (sulphide) content of the gold ore varies between 0.85 and 1.60%.

Acid is generated at mine sites when metal sulphide minerals are oxidised. The oxidation of sulphide minerals consists of several reactions. Each sulphide mineral has a different oxidation rate. For example, marcasite and framboidal pyrite will oxidise quickly while crystalline pyrite will oxidise slowly. For discussion purposes the oxidation of pyrite (FeS2) will be examined (Manaham, 1991).

$$2FeS_2(s)+2H_2O+7O_2 \rightarrow 4H^++4SO_4^{2-}+2Fe^{2+}$$

In this step, S_2^{2-} is oxidised to form hydrogen ions and sulphate, the dissociation products of sulphuric acid in solution. Soluble Fe2+ is also free to react further. Oxidation of ferrous ion to ferric ion occurs more slowly at lower pH values:

$$4Fe^{2+}+O_2+4H^+ \rightarrow 4Fe^{3+}+2H_2O$$

At pH levels between 3.5 and 4.5, iron oxidation is catalysed by a variety of *Metallogenium*, a filamentous bacterium. Below a pH of 3.5 the same reaction is catalysed by the iron bacterium *Thiobacillus ferrooxidans*. If the ferric ion is formed in contact with pyrite the following reaction can occur, dissolving the pyrite (Thompson, 1988):

$$2FeS_2(s)+14Fe^{3+}+8H_2O \rightarrow 15Fe^{2+}+2SO_4^{2-}+16H^+$$

This reaction generates more acid. The dissolution of pyrite by ferric iron (Fe^{3+}), in conjunction with the oxidation of the ferrous ion constitutes a cycle of dissolution of pyrite. Acid mine drainage impacts stream and river ecosystems in several ways through acidity, ferric ion (Fe^{3+}) precipitation, oxygen depletion and release of heavy metals associated with gold mining. Ferric iron precipitates as hydrated iron oxide as indicated in the following reaction (Thompson, 1988):

$$Fe^{3+}+3H_2O < \rightarrow Fe(OH)_3(s)+3H^+$$

$Fe(OH)_3$ precipitates and is identifiable as the deposit of amorphous, yellow, orange, or red deposit on stream bottoms ("yellow boy") (Thompson, 1988).

The above-mentioned reactions are major contributors to the fact that mine drainage has a low pH and high sulphate content. A consequence of the low pH of mine drainage is the fact that metal salts become very soluble at low pH. This is the result of heavy metal enrichment in the water.

According to Marsden (1986), the maximum depth of oxidation into a slimes dam is 3m, due to its very fine and highly compacted structure. He states that the oxidation interface lies between 2 – 3m horizons and that at the 3m horizon, sulphur is still present as sulphide, which means that oxidation has not occurred.

It is necessary to stress that the residue deposits contain tens of millions of tons of sulphur. However, owing to the inability of oxygen to penetrate more than 2 to 3m into the deposits, the rate of oxidation and pollution are low. Other buffering sources could be dolomitic aquifers with high calcium and magnesium content.

4.4 *Water Balance*

The gold mines in South Africa produce large amounts of tailings and waste rock material each month. If a ratio of 1:1 water to solids is accepted, it is evident that large volumes of water are pumped onto the slimes dams every month. A certain fraction of this water will reach the groundwater table by seeping through the unsaturated zone directly beneath the slimes dam.

In order to run an effective water management program, a clear understanding of the effluent generation and mine reticulation must be obtained. This can be achieved by using hydrological models, comprising elements such as:

i. Inflow: tailings water, precipitation and disposals such as sewage or concentrated effluents,

ii. Outflow: re-use of return water, evaporation, seepage losses and interstitial water.

In general, the water balance systems of Gold mines in South Africa consists of:

i. Intake of water with economic variables, depending on the source;
ii. De-watering of underground workings and pumping to surface;
iii. Use of water in underground mining operations;
iv. Use of water in metallurgical operations;
v. Use of water in other operations such as sewage and sanitation;
vi. Potable water;
vii. Effluent transfer by pipes, earth trenches or lined channels;
viii. Disposal of mining effluent on tailings storage facilities and RWD;
ix. Evaporation;
x. Seepage.

In-sufficient water balance systems could cause major economic and/or environmental implications for a gold mine operation.

4.5 Impact Locations, risk points and aquifers

Groundwater is seldom stagnant and generally flows slowly but surely. Subsurface pollution plumes migrate in the order of 10-200 m per year, depending on the hydraulic and transport properties. Apart from the contaminant mass flux to the environment, the receiving areas are very important. For example, if the receiving environment is a water user or a wetland, the implications are more severe than if the closest neighbour is tens of kilometres away.

Political and legal issues may cause technically comparative groundwater problems to be more sensitive than others and it could override technical issues. It is therefore important to incorporate the potential political/people issues into the risk assessment.

The impact risk points were considered in this assessment to determine where there are sensitive neighbouring environmental or human areas.

4.5.1 Aquifer classification

The reason for the inclusion or the mentioning of aquifer classification, is to highlight:

- The high value of sole source aquifers in South Africa, and
- The need for a pragmatic approach, which allows for special factors to be considered,

The aquifer system management classification developed by Parsons, 1995, is based on the British Geological Survey aquifer vulnerability classification, and recognises the need to consider the two important management aspects listed above. The need to assess the particular vulnerability of a specific aquifer should be a further crucial part of groundwater management.

According to Parsons, 1995, the definition for aquifer vulnerability is: a relative measure of the susceptibility of a groundwater body to be contaminated by anthropogenic activities, governed by the physical, chemical and biological properties of the soil and rock.

A wide range of geohydrological related factors could be used in classifying aquifers to create a better understanding of the vulnerability of a specific aquifer. A list of some of the factors used is presented in Table 4 (Parsons, 1995).

Table 4: Factors used to classify aquifers

Hydrological characteristics	Water Quality Issues	Usage
▪ aquifer material, ▪ lithostratigraphic unit, ▪ aquifer yield, ▪ borehole yield, ▪ borehole prospect map, ▪ depth to water table, ▪ time to travel	▪ present quality, ▪ current extent of contamination, ▪ potential for successful clean-up, ▪ degree of water treatment, ▪ required for potable use	▪ current and potential users, ▪ designated beneficial use, ▪ current and planned land tenure and use
Susceptibility	**Integrated Approach**	**Value**
▪ vulnerability to contamination ▪ assimilative capacity, ▪ time to travel	▪ hydraulic relationship with other resources, ▪ availability of alternative sources	▪ social value ▪ economic value ▪ environmental value

4.6 Legislation and Legal Compliance

4.6.1 Background on closure applications

This section deals with the existing legal regulations from the Department of Water Affairs and Forestry (DWAF) and the Department of Minerals and Energy (DME). The Government has turned down many applications for closure, especially in the last 10 years. The biggest concern is the possible uncontrolled pollution of water resources in the vicinity of these mines, after they closed and some filled up with water. Most of the mines that applied for closure were required to monitor the water conditions at the mine for a number of years. In spite of this period of monitoring and the data so generated, the Government was still not in a position to grant closure with confidence. The lack of confidence is due to:

- A lack of information or a lack of understanding of the system with respect to its long-term behaviour,
- A lack of understanding of the possible regional impact,
- Reluctance on the part of the Government to accept responsibility for these mines,
- A lack of specifically formulated evaluation techniques and procedures that can be applied to ensure that closure can be granted with confidence.

Mine closure planning and liability assessments are a critical process that may have significant financial implications for the mines. Uncertainties with regards to the legal requirements and standards, time aspects, environmental impacts, costs, etc. are all factors currently hampering closure planning.

Legislation in South Africa does not have a specific Act governing mine residue deposits. The provisions of a number of Acts such as the Mineral and Petroleum Resources Development Act, Mine Health and Safety Act and Water Act apply, either directly or indirectly. Various government departments have an interest, under the various laws, in protecting the environment affected by mining operations. In an effort to simplify compliance with the legal provisions, these departments have adopted a holistic, coordinated approach in order to achieve a common goal.

The following gives an overview of the current legislation in South Africa and opinions of interested and affected parties (I&AP's).

Most of the mine operations and hence the groundwater pollution are historical and developed under the old Water Act 54 of 1956, which stated that groundwater was "private" water. The National Water Act (NWA) 36 of 1998 became effective in September 1998. According to the NWA, groundwater is not private water and requires that all water uses be licensed in terms of section 21 of the act. The historical water uses that are still regulated under the old Water Act (54 of 1956) are likely to become compulsory for licensing under the NWA.

An important regulatory factor of the NWA is section 19 that deals with the prevention of pollution. It requires that the person, who owns, controls, occupies or uses the land in question, is responsible for taking measures to prevent pollution of water resources. In sections 19 (a) and (b), it is required that all reasonable measures should be taken to prevent water pollution from occurring, continuing or recurring. If these measures are not taken, the Catchment Management Agency may do whatever is necessary to prevent the pollution or remedy its effects and recover the costs from the person responsible for the pollution.

Pollution is defined (according to NWA) as the direct or indirect alteration of the physical, chemical or biological properties of a water resource to make it:

- Less fit for any beneficial purpose for which it may reasonably be expected to be used; or
- Harmful or potentially harmful –
    - To the welfare, health or safety of human beings;
    - To any aquatic or non-aquatic organisms;
    - To the resource quality; or
    - To property.

Under the NWA, DWAF will become a management agency on national level and the Catchment Management Agencies (CMA's) are likely to regulate the water aspects in future. The CMA's will be self-funded and a fee will be imposed on the use (per m^3) of water from a resource and addition of mass (contaminants) to water. Under the CMA's the waste discharge charge system is also likely to become effective between 2005-2010. In terms of this system, a water use will be charged for mass or volume of wastewater that is discharged. The value of the fees is currently in consideration and planning phases. Penalties will be imposed on violations of water use license conditions.

A mine can be considered closed once a certificate as contemplated in section 12 of the Minerals Act 1991, has been issued by the Regional Director concerned. A certificate is issued if the results of the final assessment indicate that all the provisions of the Act have been complied with and that all closure objectives stipulated in the EMP or closure plan have been met. If residual impacts have been identified, these must also be described in the EMP or closure plan.

The Regional Director (DME), after consultation with the relevant government departments and the mine, shall seek to have negotiated and finalised, adequate and irrefutable arrangements in terms of which the State and the mine are satisfied that these impacts will be adequately dealt with, before a certificate is issued.

4.6.2 DME Mine Closure Policy - Residual impacts after closure

The following section was abstracted from the Aide-Memoire for the Preparation of Environmental Management Programme Reports for Prospecting and Mining (DME, 1992).

There may be some significant residual impacts resulting from the construction, operational or decommissioning phases that persist after these activities have ceased and a closure certificate has been issued.

Where possible, these impacts should be identified at least qualitatively so that they can be accommodated when the closure objectives are being defined and when the environmental management programme is being devised.

The environmental impact assessment done in accordance with paragraphs 5.1 to 5.3 of Part 5 of the Aide-Memoire will have highlighted the major issues on which to focus. However, the potential impacts resulting from the closed operation, listed below, should be considered in any event. It is nevertheless recognised that quantification of these impacts could be imprecise, or even unfeasible.

1. *The potential for acid mine drainage or poor quality leachates emanating from the mine or residue deposits.*
2. *The long term impacts on groundwater,*
3. *The long-term stability of rehabilitated ground and residue deposits. Consider the use to which the land will be put when considering long-term stability,*
4. *The long-term impacts arising from river diversions.*

4.6.3 DWAF

Also refer to section 2.4 – 'Adopted Approach'.

The current hierarchy for mine water management from DWAF, is based on a precautionary approach and sets the following order of priority (BPG 1.1, DWAF):

1. *Pollution Prevention,*
2. *Water reuse / reclamation*
3. *Water treatment,*
4. *Discharge*

This hierarchy is valid whether the mine is preparing an EMPR, water licence, undertaking closure planning or motivating for an exemption from regulations GN704.

4.6.3.1 Groundwater Management Policy

In 2000, DWAF published their policy and strategy for groundwater quality management. The logical unit for groundwater quality management is an aquifer. The identification of surface water catchments and associated groundwater management was adopted as the approach for groundwater management.

Groundwater quality management cannot be carried out without intimate knowledge of the nature, extent, potential yield and vulnerability of the resource. The relationship between groundwater and surface water must also be understood in order to facilitate effective management.

4.6.3.2 Damage to aquifers by waste disposal and related activities

DWAF will follow a differentiated approach to the control of waste and wastewater disposal activities. Activities, which will receive specific attention, include: mining and industrial residue disposal (waste deposits); irrigation with wastewater, evaporation and storage of mining and industrial effluent and sludges and stockpiles of potentially polluting substances.

5 Groundwater Management in South Africa

5.1 Introduction

Groundwater management within Environmental and Groundwater resources Management in South Africa is a relatively new field. Currently more resources and effort has been applied to the field of water supply and the utilisation of groundwater. Groundwater by itself is a very important source of water in a dry country such as South Africa. When considering groundwater management within the industry and more specific gold mining environment, an even bigger shortcoming is experienced.

At this point of discussion and progress towards the case study, it was felt necessary to summarise all the identified issues in a more realistic and functioning manner with reference to the related mining environment. The main reason for this section is therefore to list current groundwater related challenges in a day-to-day gold mine scenario.

The following discussion is based on the matrix developed in paragraph 2.3 'Adopted Philosophy', and more specifically the first quadrant – "the rules of the game". The emphasis will however be on geohydrology.

5.2 Overview of challenges in groundwater management - day to day SA gold mine scenario

Geohydrology and the awareness thereof in the Gold Mine industry is relatively new and not 100% adopted. Although the implementation of strategic groundwater management plans is required by the Department of Water Affairs and Forestry, the level of assessments are usually generic and of poor standard. The time frame and costs are usually a big constraint. To understand site-specific geohydrology and to conduct sufficient groundwater investigations, projects require extensive information, research and field work.

5.2.1 Manpower and expertise

Internal and external communication is also one of the big issues that have hampered successful groundwater management. Communication within a gold mining company becomes a complex issue because of the size and complex structure of typical companies in South Africa. Environmental management and coordination is usually not communicated to operations and bottom line management.

Sufficient manpower in the form of environmental managers and coordinators on operational and worker level is a further problem within South African gold mine companies. In the past people with technical and mining backgrounds were employed as environmental managers. Lack of sufficient knowledge and experience regarding environmental management was experienced. Currently top management is becoming more aware of environmental management and the need for expertise.

5.2.2 Guidance from the relevant State Departments

5.2.2.1 Communications to State Departments

Discussions and negotiations with the government departments regarding water issues are very important. It is important to work with the regional as well as the national authorities from the start of a project. This will ensure a good relationship as well as understanding of both organizations.

5.2.2.2 Concluding remarks on current legislation

Legislation and guidelines regarding the closure of gold mines is not totally finalised yet. South Africa is currently in a process of research and development and no definite guidelines on requirements relevant on gold mine closure exist. It is therefore important that this issue of closure, based on current regulatory constraints, be placed in context.

The Department of Minerals and Energy (DME) and the Department Water Affairs and Forestry (DWAF) have placed certain requirements on mines before a closure certificate is granted. The main requirement is the EMP, which is compulsory for any mine (Moolman, 1997). EMP's are compiled in accordance with the requirements of the *Aide-Memoire* for the Preparation of Environmental Management Programme Reports for Prospecting and Mining (DME, 1992), which provides for the decommissioning and closure of a mine in Section 5 and Section 6 respectively. The DME is the lead agent in terms of issues concerning the granting of a closure certificate but interested and affected parties (including other governmental departments) are also involved in the approval of the EMP and mine closure process (section 39, Minerals act 1991).

It is important to remember that liability on mine closure is transferred to the State. In many instances government and Sate have inherited and have been burdened with poor legacies from old abandoned mines. It is therefore significant to understand the history and stigma associated with mine closure.

Within the present timeframe of South African gold mining industry, which could be characterised by either downscaling of operations or closure, the existing *Aide-Memoire* concepts seems to be out-dated. Closure of a gold mine could therefore no be guaranteed if the former process of EMPR is followed and a closure document submitted to the relevant State Departments.

The interactions of these closure issues could therefore be seen as the main driving force behind this thesis.

5.2.2.3 Assistance from and Internal problems within the State Departments

At present very little guidance from the State Departments is available for mine closure and more specifically groundwater related closure issues. Current guidance is based on Figure 4: Flow Diagram of the Mine Closure Risk Assessment Process (Pulles et al, 2002). It is therefore also important that mining companies negotiate guidelines and approaches with the State Departments.

One of the major problems within the South African State Departments, and more specifically DME (Department of Minerals and Energy) and DWAF is the lack of efficient manpower. More and more officials are being enticed into the private sector due to better working environments and better salaries. A good working relationship is no sooner established between a state official and a mine than that person resigns and a new less experienced person is brought in to fill his/her place. Lots of experience and site specific knowledge is lost for the particular state department and the process starts all over again.

5.2.3 Compliance with existing permits and legislation

At present a mine needs to apply for a licence under the M4. Operational guideline (Mine Water/ Effluent Discharge Permits) for general and operational water use, or if water needs to be discharged into a natural stream and into facilities that have been built for the purpose. An exemption is granted for special discharges if impacts on streams are accepted.

The permitting and approval of discharges, quantities of water used, quantities of water evaporated, etc. will become stricter. Although this will become a bigger headache to the mines, better catchment management and environmentally friendly operations will be the result. It is however important for a mine to negotiate with the DWAF to find practical and cost effective solutions.

5.2.4 *History of the mine*

"The sins of our fathers" as identified are certain legacies from the past. For example, old (1940 – 1970's) tailings storage facilities were built with the purpose of 'losing' excessive water and no under-drain systems were installed. Today highly polluted aquifers have resulted due to great seepage losses. Another classic example is the historical evaporation dams or evaporation fields; large areas were allocated for polluted underground or plant water to be evaporated. These areas were not lined and in some cases were located on vulnerable aquifer systems. Again accumulated salts in the soils and polluted aquifer systems have resulted. Many other cases exist of historical operations that did not take the natural environment into account

Figure 10: Example of salt precipitation near old evaporation field

The bottom line is that current mine management needs to understand these old operations and associated impacts on the environment. This could require a lot of time and resources.

5.2.5 *Contamination*

Cases of soil and groundwater contamination have had, and are having, great impacts on business. Groundwater needs to be protected for the better survival of current and future civilizations. Business should also be protected for same reasons. "A reasonable balance could and should be achieved between these sometimes seemingly opposing ingredients of survival. It is the opinion of the undersigned that a reasonable balance is achievable" (Ami Adini Environmental Consultants, USA, 2002)

5.2.6 *De-commissioning and Closure*

Currently more and more gold mines face closure – the reason being that either the ore resources are depleted or it is not economically feasible to mine the residual ore. This indicates social-economic as well as environmental implications. The mine needs to apply for closure under the current EMP regulations (DME, 1991). The mines need to know their groundwater liabilities and sufficient money needs to be allocated for environmental clean-ups.

5.2.7 *Underground water*

The gold mines in South Africa are generally grouped together very tightly, resulting in hydrological interconnections between adjacent mines. This makes it difficult, if not impossible, to consider the water related closure risks in isolation and consequently, a number of distinct hydrological groupings of mines has been defined, each of which should develop a regional mine closure strategy within which individual mine closure plans can be assessed.

It is important that both the aspects of water contamination as well as mine safety be considered when looking at underground water management. Underground mine working will fill up with water over time (slow or fast depending on the geohydrological setting) and this water will be contaminated (either for a limited time or in perpetuity). A key element influencing the risk that these processes pose to the water resource is whether or not this contaminated water will decant into the underground aquifers or into the surface water resource and to what extent the natural water resource can assimilate this contamination. The underground workings must, therefore, be considered to pose a potential water related risk until shown otherwise by way of a suitable semi-quantitative or fully quantitative geohydrological and geo-chemical assessment, Pulles *et al*, 2003.

The following aspects are relevant to the Vaal Reefs mining area (area of investigation), and was obtained from the WRC project relevant on deep mine closure by Pulles, *et al*, 2003.

- The Vaal Reefs mines within the KOSH area are mining at deeper levels than the hydraulic up-gradient Stilfontein mines. If mining ceased in the Stilfontein mines before the Vaal Reefs mines, the threat of down-gradient sub-surface flooding exists. This aspect needs to be managed on a holistic and integrated level between the relevant mining groups.
- Until the mined out volume is flooded, oxidising conditions will exist and groundwater quality deterioration will occur. This process will stop when the workings are completely flooded. Water with an additional salt load could therefore end up within the Vaal reefs underground workings.
- Upon complete flooding of the mine workings, interaction between the contaminated water and perched aquifers will occur, particularly along the southern borders of the Vaal River.

Although this thesis, according to the specific scope of work, does not include a detail study regarding specific conditions in deep underground workings and associated groundwater problems, a brief overview of recommendations for assessment are listed in paragraph 8.3 Strategic Groundwater Management Concept for deep underground water.

5.2.8 *Public Perspectives*

In most cases it is the down-stream groundwater users that are affected by the deterioration of groundwater qualities over mining boundaries. This could create certain risks and legal liabilities for a mine and have an effect on the public perspectives and relationships between the mine and IAP's.

Again, the mine needs to understand the underlying aquifer system and possible impacts of the waste facilities. The requirement for certain pre- assessments before a waste facility is built and operated will ensure more environmental friendly mining operations.

5.2.9 International trends and pressure

Gold mines in South Africa could face increased pressure to upgrade environmental management systems. This could come from stakeholders or be due to stock exchange policies. Mines in first world countries usually operate in line with this trend but mines in poorer third world countries could experience difficulties to live up to these standards.

SECTION 2: METHODOLOGYY AND CASE STUDY OVERVIEW

1 Introduction

Based on the information from Section 1 and by understanding the typical South African scenario, a methodology to address the identified groundwater issues, can now be formulated. The main objective of Section 2 is therefore, to formulate the approach and objectives into a workable methodology. (See paragraphs 2.1 Scope and Objectives and 2.4. – Adopted Approach). This methodology, based on findings from Section 1, will consequently be explained and applied in Section 3.

The approach will be explained by means of a case study, the sequence of steps will form an understandable and practical methodology, which could be used by a gold mining company towards closure. Figure 11 illustrates this proposed sequence of actions.

1.1 Methodology

Monitoring and determining the effect that waste facilities (such as waste rock and tailings dams) have on the quality of surface and groundwater resources is a complex and multidisciplinary task. The following flow chart (Figure 11) illustrates the uncertainties regarding waste facilities:

Figure 11: Flow Chart illustrating uncertainties regarding Gold Mining related waste

In order to develop an assessment for remedial purposes, field data is commonly entered into a predictive model to allow simulations to be developed for given field conditions. The outcome of these simulations is used as a guide during the decision making process. The reliability of these models and consequent understanding of site hydrological behaviour is, however, influenced by the quality and quantity of data available for consideration. Thus, in an ideal case, data should be available for all variations in site conditions, be they geological, chemical, hydrological or physical. In reality, though, it is either not possible or cost-effective to account for all possible variations, particularly where there has been a significant disruption to the natural environment from human activities on a large scale. In this instance, a cost-benefit approach was taken to the investigation by complimenting existing data with previously undetermined site parameters. Therefore, the scope of this thesis was controlled to accommodate the following work.

To explain the adopted approach, and to ultimately develop a Strategic Groundwater Management Plan, the following logical steps in groundwater assessment will be followed. As the following table only list the phases, a detail description is provided in Section 3 for each task in the different phases:

Table 5: Phases and assignments to be followed for compilation of Strategic Groundwater Plan

PHASE 1: Overview of physical geography
PHASE 2: Pre-Evaluation and Initial Impact Assessment
PHASE 3: Understand site monitoring requirements
PHASE 4: Formulating Geohydrological settings and concepts
PHASE 5: Impact Analysis and Risk Assessment
PHASE 6: Aquifer remediation and technical feasibility

1.2 Case Study Background

Table 5 above; list the identified steps, which should be included in a typical groundwater site assessment and also in this case study. These steps will be discussed in more detail in the next section.

The AngloGold Environmental Management Department – Water Management, is currently busy with investigations and action plans for long-term remediation. For the purpose of detail investigation and aquifer contamination delineation, the Vaal River operations were subdivided into three areas. This report will mainly deal with the north-western portion of the mining operations (Refer to Figure 12).

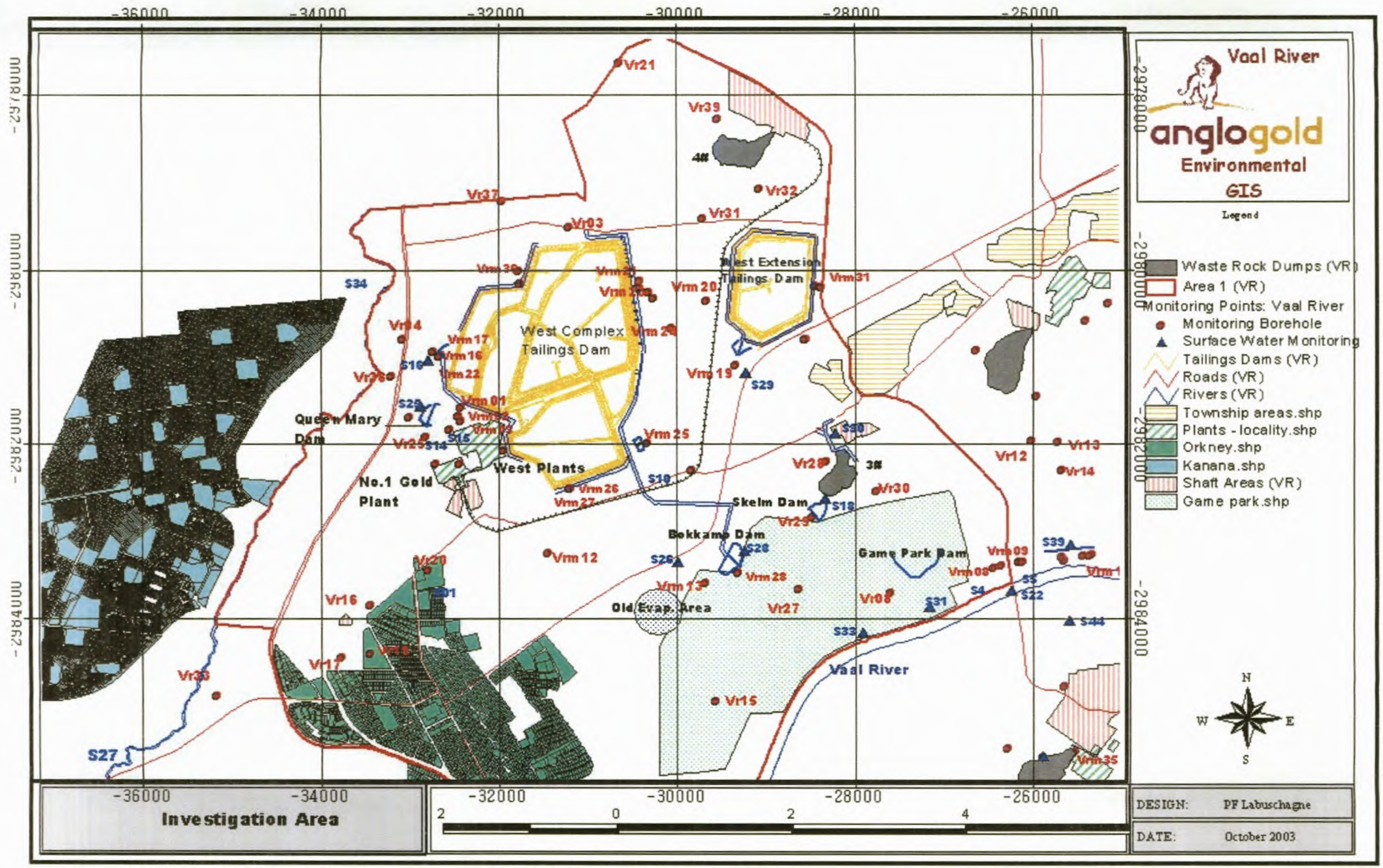


Figure 12: Map of Investigation Area & localities of groundwater monitoring sites

2 Overview of physical geography

2.1 Introduction

Now that we are familiar with the required input for the case study and the methodology, which will be applied for the geohydrological assessment, the physical geography of the site could be explained. This part of the investigation needs to supply very important geographical data, which will be used during the development of the site assessment. It must be noted that the better the background geographical data and the understanding thereof, the better the end results of the geohydrological assessment. The geography of the area, to be listed, should be focussed on groundwater-related issues and aspects. For example, air quality, wind directions, animal life, noise, etc. are not directly related to groundwater and the data will be irrelevant to the purpose of this thesis. It is therefore important to list geographical features that could be used and which will contribute to the final objective of the assessment. The following should be included in an overview discussion of the physical geography.

Table 6: Explanation of the tasks required

Task	Description / Overview
Topography and Drainage	The topography must be mapped to identify main surface run-off flow paths and local catchment divides and boundaries. The hydrology of a given area should be mapped and understood.
Geological Settings	The explanation of the local, site-specific geology of the area is very important and will form the foundation for the construction of a geohydrological conceptual model. Geological maps from the Geological Survey and Geology department of the mine should be consulted. Physical field mapping could give more credibility to this exercise.
Infrastructure and man-made features	The EMPR (Environmental Management Plan Report, DME 1992) could be consulted to list all infrastructure and man-made features, which could be connected or related to geohydrology.
Vegetation	Vegetation could be an indicator of salt migration, wetland conditions and could also be used for certain groundwater remediation options. A field survey, rather than a detailed discussion will be more than sufficient.
Climate	Rainfall and evaporation figures need to be listed. Temperature, wind data and other rain-event data could be ignored for the purpose of this study.

2.2 Topography and surface drainage

The topography of the area is flat, which influences the surface water drainage and occurrence of wetlands during the rainy seasons (see Figure 13). Topographic maps of the area show a recurring block type drainage pattern that seems particularly well developed to the south and west of the investigation area, characterized by the Vaal River and Schoon Spruit. Drainage of this type is often structurally controlled, and thus may provide some insight into the orientation of regional and convergent stresses.

Two natural wetland systems were identified in the area of investigation. Apart from these two, several smaller wetlands were identified. The smaller wetland systems were mainly formed as a result of tailings dams and waste rock dumps and also local geological contact zones. The manmade structures were built in the way of surface run-off and main flow paths and not constructed with under-drain systems. The result is therefore impeding and the forming of localized wetland or wet surface systems. The following table described the two main and smaller identified wetlands:

Table 7: Description of Wetlands

	Name	***Description***
1	Game Park Wetland	The wetland stretches from the No 3 waste rock dump in the north to the Vaal River basin in the south. This wetland is well developed and currently blocked in by the Game Park dam.
2	Old Evaporation area / semi wetland	The wetland is the result of the old evaporation facility, which was built in the main flow path west of the Bokkamp dam. Dirty run-off was contained for evaporation purposes.
3	Wet areas between the West Tailings Complex and West Extension Tailings Complex	Wet areas were identified between and next to the two tailings dams. This is the result of impeding of surface flow but also due to surfacing of shallow groundwater.
4	Wet areas up-gradient of the No. 3 and No. 4 Waste Rock dumps	Wet areas were identified up-gradient next to the two waste rock dumps. This is the result of impeding of surface flow.

- The West Tailings Dam Complex is situated on a watershed between the Schoonspruit in the west and the Vaal River in the south-east, but locally it drains into the Bokkamp Dam via canals.
- The West Extension Dam is situated in the Vaal River catchment, but locally, surface run-off drains towards the Game Park Wetland System and currently impeded by the Game Park Dam.

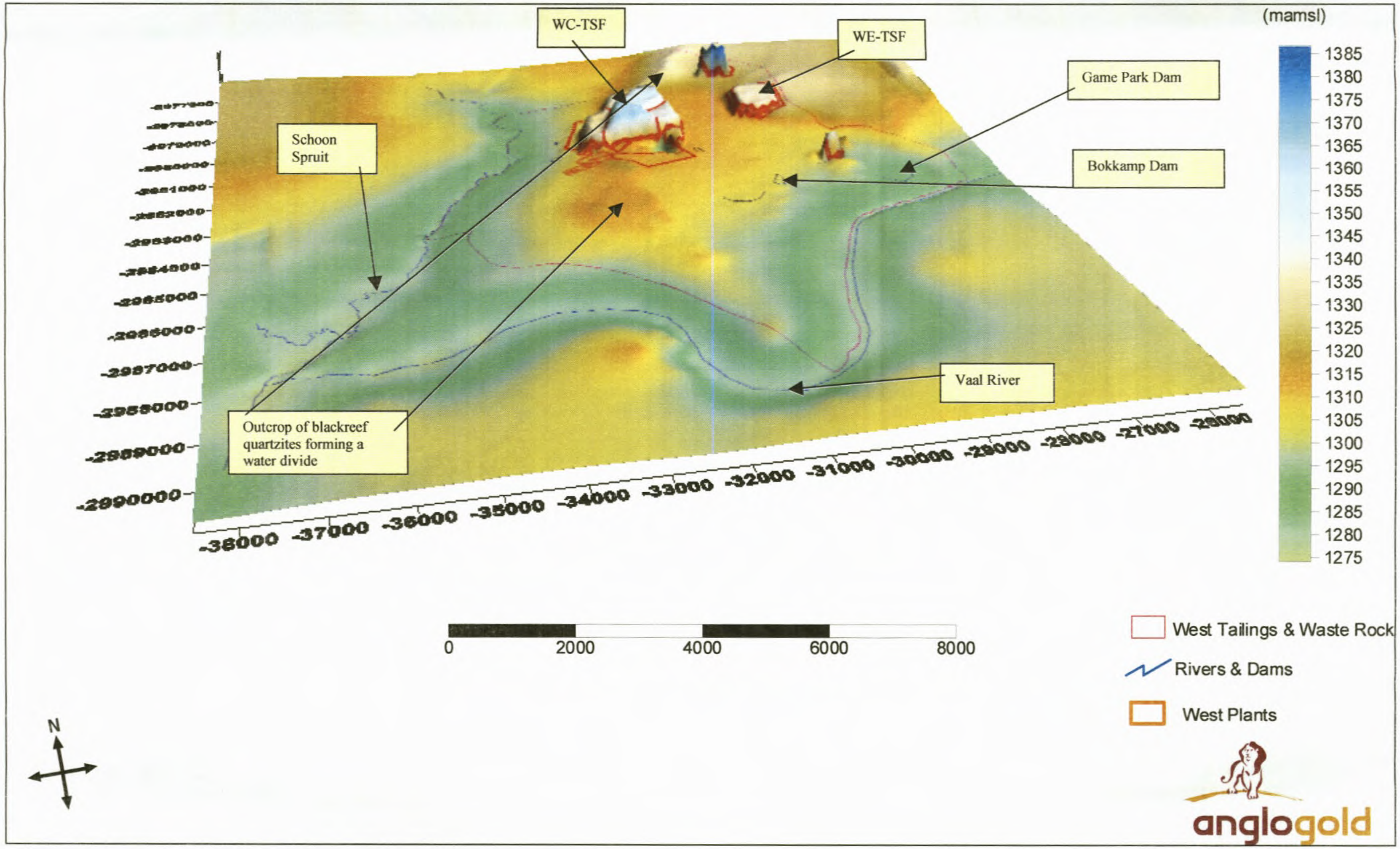


Figure 13: 3-Dimensional view of the Topography

2.3 *Geological Setting*

The following discussion on the site geology is a product of data collation, which was obtained from several reports, efforts from current site-specific field investigations and national surface geology maps (refer to Table 11, for sources of data).

2.3.1 *Local geology*

Three major rock units crop out on surface in the area (see Figure 14). These are, stratigraphically from bottom to top the Ventersdorp Supergroup, the Black Reef Formation and the Malmani Subgroup of the Transvaal Sequence.

The strata in the area generally dip 15° to 20° eastwards but are affected by extensive folding and faulting. Two dykes, possibly of Karoo Age, strike north-south across the area.

Along the banks of the Vaal River and Schoonspruit, river alluvium overlies bedrock and is dealt with as a separate engineering geological unit.

2.3.1.1 Ventersdorp Supergroup

The Ventersdorp Supergroup is a sequence of andesitic to basaltic lavas and tuffs with subordinate quartzites, agglomerates and conglomerates, and is found mainly in the western part of the investigation area. A maximum thickness of 2500 meters is developed in the area.

The Ventersdorp lavas are cut by a number of steeply dipping, east-west striking block faults. A major, north-south striking fault with a minimum down-throw of 400 meters to the west causes partial duplication of the Black Reef Formation outcrop in the Ariston Siding Area.

The weathering of the Ventersdorp lavas in the area is characterized by the formation of a blanket of residual soils up to 10 meters thick. Some residual outcrops and loose boulders of un-weathered lavas do occur. These residual soils are formed by the chemical action of groundwater on the lavas, which produces clay minerals such as kaolinite, montmorillonite and chlorite *(Jones & Wagener, 1982)*.

2.3.1.2 The Black Reef Quartzite

The Black Reef Quartzite Formation consists of a broadly fining upward sequence of grits, quartzites and sub-ordinate shales of up to 30m thickness. The upper contact with the Malmani dolomite is transitional and conformable. A basal conglomorate, which occurs towards the north west of the outcrop was extensively prospected and mined for gold in the previous century between 1887 and 1914.

The Black Reef Quartzite forms an elongated ridge in the western part of the study area due to its resistant nature. The interbedded shales are generally soft and manganiferous and often weather to a waddy material. The Western Tailings Dam Complex overlies the Black Reef Quartzite with the outcrop line running in a north-eastern direction through the western half of the slimes dam. Two sets of joints cut the quartzites, the major set striking north-south and the minor set striking east-west. These joints may be related to the folding. An inlier of Black Reef quartzites, caught up in faulting and folding, crops out between 3# and Orkney.

Smaller outcrops of the Black Reef Quartzite occur in the central part of the study area – in-between the east and west extension slimes dams, as well as in the vicinity of Bokkamp Dam in the south. These outcrops are assumed to be inliers of quartzite, wedged within the folding and faulting. In the Bokkamp dam outcrop, the Black Reef Quartzite dips at an angle of approximately 43° to the north. In the central outcrop – in between the two slimes dams, chert breccia is found in conjunction with the quartzite outcrop – possibly associated with the faulting and inhomogeneities in the area. The Black Reef Quartzite occurs here associated with a fault striking approximately 40°.

In general, the Black Reef Quartzite occurs at a depth of 160 m below surface, at a point directly between the two dams. This depth increases to approximately 220 m at a point directly south of the eastern slimes dam. Drilling in this formation during earlier exploration for gold has proven the formation to be a poor target for groundwater abstraction. Water is however stored in the old stopes, developed in the quartzite underneath the project area.

The Black Reef outcrop forms much of the watershed between the Schoonspruit and the Vaal River.

2.3.1.3 Malmani Sub-Group Dolomites

The dolomites in the study area are represented by a number of chert-rich and chert-poor formations of the Chuniespoort Group. The specific area of investigation – in between the two slimes dams – is characterised by the two bottom formations of this sequence of dolomitic rocks, which is known as the Monte Christo Formation and the Oaktree Formation. These two formations comprise a total thickness of 450m of dolomite, with the lower 200 m being the dark brown, manganiferous, chert-poor dolomite of the Oaktree Formation and the upper 250 m being the recrystallized light grey, chert-rich dolomite of the Monte Christo Formation. The upper part of the Monte Christo Formation typically becomes more chert-poor towards its top.

The general dip of the dolomite in the study area varies from less than 10° to 15° in places. This results in the general geological section in the study area – along an east-west line, to be as indicated in.

The formation of the local landscape has been dominated by the Vaal River in combination with the local geology. Varying chert contents and other differences between the two dolomite formations that are present, caused two different weathering profiles in the study area. They are:

- Elevated areas of chert gravel associated with the Monte Christo Formation in the east where the rock outcrop is highly irregular and solution cavities and slots may be found between pinnacles. Slots are expected to be up to 30 m deep.
- Shallow outcrop and sub-outcrop pinnacle dolomite developed partly also because of the scouring of the chert-poor residual soils by the southerly migrating Vaal River.
- The dolomites weather by solution in percolating groundwater. The presence of chert bands affects the style of weathering and the formation of underground cavaties in the dolomites considerably.
- A residual blanket of chert rubble overlies the dolomite in these areas. The eastern slimes dam overlies such chert gravel beds and is therefore seen as mostly overlying the lower Monte Christo Formation.
- The West Plants is situated partly on the chert-poor dolomite of the Oaktree Formation and Black Reef Quartzites of the Transvaal Sequence with the western parts of the No1. Gold plant on the Ventersdorp lavas.

2.3.1.4 Alluvium

Up to 10 meters of alluvial sands and clays overlie bedrock in a strip 0.5km wide on either sides of the Vaal River. These are sediments deposited by the Vaal River by channel migration and flooding.

The sands are usually loose, porous, light grey fine and silty and may be collapsible. The clays are usually soft, light and yellowish grey and are highly expansive.

The alluvial sands and clays usually contain large amounts of groundwater especially in abandoned channels, which form the best target for drilling.

2.3.2 *Faulting, Fracturing & Jointing*

A relatively large amount of faulting appears to have occurred throughout the area. Analysis of the plans of the underground workings indicated numerous faults, but as the majority of these pre-Transvaal in age they do not affect the present-day surface (Jones & Wagener, 1976). The large Kromdraai Fault has been projected to surface, as well as the continuation of the Kervel Road dyke/fault intrusion, and no surface evidence of either of these features was noted. According to Jones & Wagener, 1976, the main fault zones within the mapping area showing some form of surface evidence, either fault breccia, vein quartz or narrow shallow linear depressions, are listed below:

1. A group of three faults in the SW corner of the mapping area where the Ventersdorp lavas and Black Reef Quartzites have been up-faulted and exposed on surface.

2. A group of three (approximate) NNW-SSE faults in the center of the mapping area, the center main fault having a spring or "eye" located on it close to the Vaal River.

3. A group of five faults; three approximately WSW-ENE and two trending approximately NE-SW, located in the eastern section of the mapping area.

In general the larger fault zones appear to be zones of weakness, where prior erosion has taken place to depth and later filling by sand (and gravel) has occurred. Hence, certain of these may be termed major zones of water movement, in both the vertical and horizontal directions.

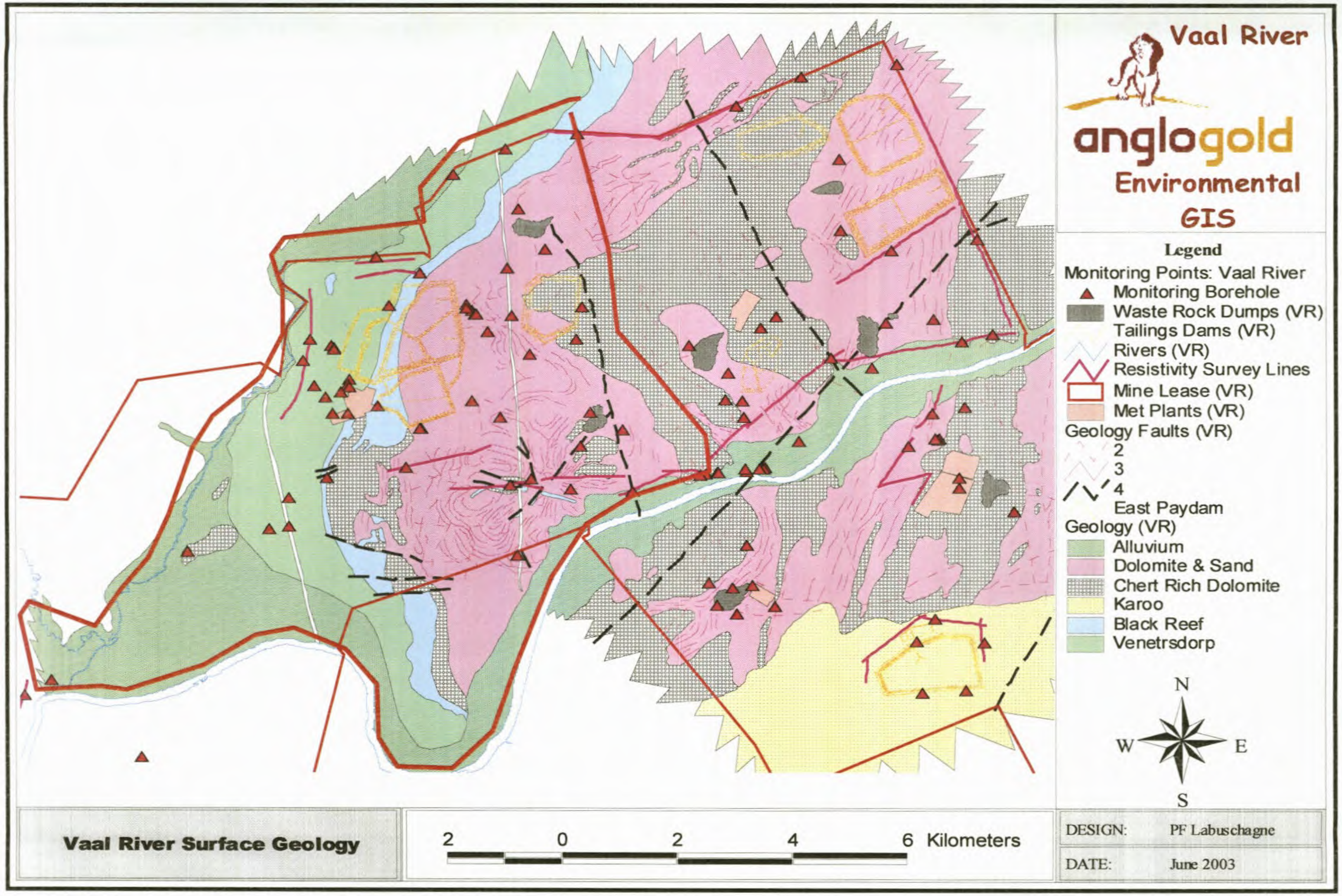


Figure 14: Surface Geology of the Investigation Area

2.4 *Infrastructure and man-made features*

Several dams and other drainage facilities have been constructed for various purposes; the most obvious of which are the tailings dams. An extensive hydraulic system has been developed to dispose of tailings from the respective gold, uranium and acid plants. Tailings are pumped to the tailings storage facilities via a network large diameter steel pipes several kilometres long. Shallow unlined earth trenches installed around the perimeter of the tailings dams themselves intercept water derived from the tailings dam, drain under gravity to the Bokkamp dam, from where water is pumped back to the plants for re-use as make-up water. The following table describes the dam facilities:

Table 8: Description of Tailings, Return Water and Containment Dams

	Name	***Description***
1	WC-TSF	Conventional paddocked type tailings storage facility, built out of several compartments. Dam was started in the 1950's and still in operation
2	WE-TSF	New cyclone type tailings storage facility. Dam was started in 1985 and still in operation.
3	Bokkamp Dam	Return water dam south of the west complex tailings dam
4	Game Park Dam	Dam constructed within the Game Park wetland system – originally for bird watching and wild life.
5	Return water dam east	Dam not currently in operation – originally built to contain penstock water for re-use
6	Queen Mary Dam	Pollution control dams west of the west extension tailings dam and plant areas
7	Skelm Dam	Dam built at the south western toe of the No. 3 waste rock dump – originally built to contain effluent water.
8	No. 1 Gold Plant Effluent Dam	Pollution control dam to contain run-off from plant area
9	No 3 # Sewage effluent dam	Redundant sewage effluent dams at 3#

Mines and associated plants in the vicinity of the project area are supported by an extensive infrastructure that includes workshops and offices. Gold ore is currently transported via railway, from certain AngloGold shafts inside and outside the investigation area, to the West Plants. Gold ore is also transported via road by means of truck from Tau Lekoa Gold Mine, which is situated to the west outside the investigation area. A stockpile area south of the west plants is constructed for the truck transportation system.

Significant proportions of the total mine staff is housed on site in hostels containing essential amenities and serviced by sewage treatment works. Most water used during the daily operations of the mines and associated infrastructure is piped into the site from the Midvaal Water Company. River water is also used as make up in the plants. Several roads have been constructed within the investigated area. Generally, all roads exposed to continual vehicular access between each of the facilities and public roads and within the respective mines.

2.5 *Vegetation*

Within the respective mining compounds and surrounds vegetation is restricted to lawn grasses, veld, small shrubs, and occasional trees, while invader plants species be identified at certain areas. Small patches of eucalypts are also visible. Reeds and Sedge (*Schoenoplectus Corymbosus*) occur across each of the sites in areas with a high groundwater table, or where surface water of shallow depth stands. It seems that the Sedge grass correlate with the occurrence of salt and radio-active anomalies in the soils (Viljoen, 2002).

2.6 Climate

The area of investigation falls in a summer rainfall area with an average annual precipitation of about 630 mm. The rainfall is almost exclusively due to showers and thunderstorms and falls mainly in summer, from October to April with the maximum falls occurring in January. The mean monthly and annual rainfall figures of the area, for the period 1975 to 2002, are given in Table 9, the yearly figures is presented graphically in Figure 15.

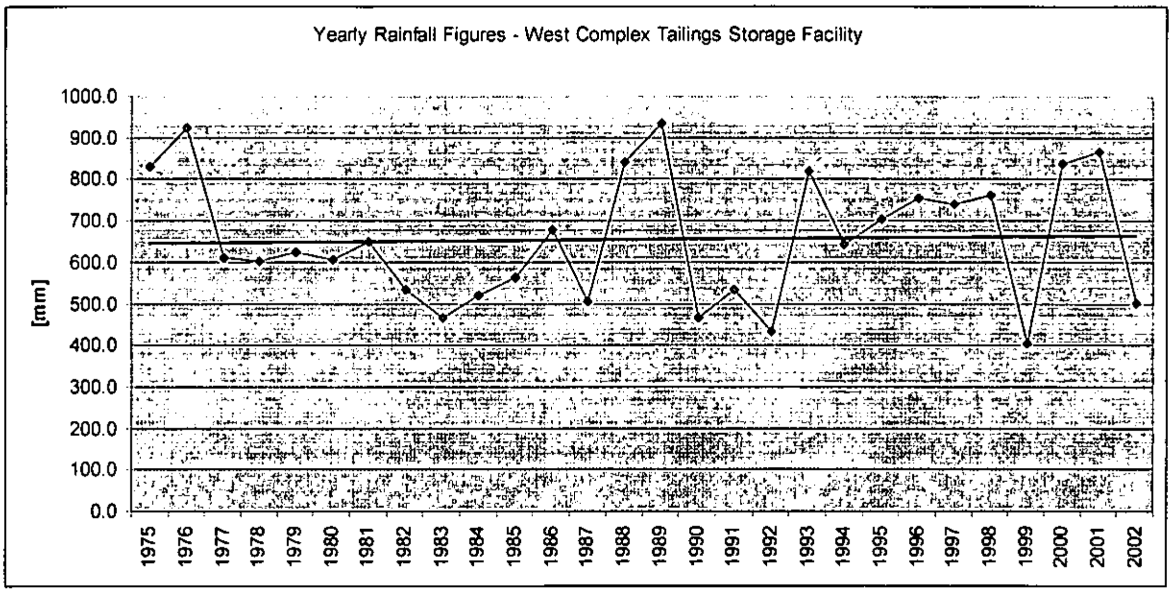


Figure 15: Rainfall Figures over time

Table 9: Climate data for Vaal River (average values for the period 1975 – 2001)

Month	Rainfall (mm)	Evaporation (mm)
January	114	210
February	86	155
March	90	153
April	50	112
May	19	72
June	6	94
July	4	129
August	7	147
September	22	176
October	74	212
November	80	194
December	102	227
Total	***654***	***1881***

It could be seen from the table above that the evaporation of the area is more than double than the yearly precipitation. This has definite impacts on evapo-transpiration values and accumulation of salts in topsoil. Aquifers is still recharged with 3-10% of the rainfall (this will be explained in more detail later on in this thesis), but due to high evaporation figures and in the case of shallow perched aquifers, polluted water is "sucked" out of the system by means of evapo-transpiration and capillary forces and salt remain in the topsoil zones. On the other hand, this will have positive impacts on post-closure water balance on decommissioned tailings dams. This will ensure a negative water balance on tailings; the infiltration of water will be reduced through high evaporation rates, and phreatic surface within tailings will drop eventually.

3 Pre-Evaluation and Initial Impact Assessment

3.1 Introduction

After the geographic features of the investigation area is studied and understood, the next phase of Geohydrological Assessment could be undertaken. This part of the investigation entails the gathering of as many as possible geological and geohydrological historical reports and background information as possible. Current monitoring data should be assessed and a preliminary impact assessment or impact rating should be compiled. Physical field investigations should be incorporated. The sequence of this part of the assessment should be more or less like follows:

Table 10: Explanation of the Pre-Evaluation and Preliminary Impact Assessment part of the thesis.

Task	Description / Overview
List of historical Investigations and Available Data	Numerous hydrological investigations have been undertaken at respective sites, most generally being conducted to provide site-specific geo-technical information or related to generic water related issues. The main reason for the compilation of this list is to provide a summary of water related reports and to give an idea of what are available in the Environmental Management library. This will also assist in the planning of future groundwater investigations and the intention is to overcome duplication of work and to use historical data in the best possible manner. It must be noted that not all the work is relevant on the selected investigation area or inline with the scope and objectives of this thesis, but rather provide an overview of historical main focus points and water related issues. It is important to discover history and to apply the lessons learnt in current and future operations.
Identification of possible pollution sources	All the possible pollution sources should be identified and listed – from the historical data, it could be possible to discover sources, which is not that obvious at all. It must be remembered that this is an preliminary exercise and require not to much time and effort – as the assessment progresses the list could be evaluated and adjusted according to findings and risks.
Groundwater Monitoring Sites	All the available groundwater monitoring sites should be listed and XYZ coordinates be updated. As the assessment progresses additional boreholes must be drilled according to the identification of information gaps.
Surface water monitoring sites	All the available surface water monitoring sites should be listed and XYZ coordinates be updated. As the assessment progresses additional sites must be included according to the identification of information gaps.
Identification of major seepage areas	To identify major seepage areas at this early stage, various methods could be used. Topography, airborne surveys, and assessment of groundwater levels were used for this task. The local geology map should also be consulted. Physical field inspections should be undertaken at this stage.
Groundwater Quality	Hydro-chemical monitoring results must be listed in an appropriate database. The database must be able to assist in the interpretation of the data. Contour maps, hydro-chemical imaging, water quality trend, etc could be compiled for interpretation purposes. It is however very important to apply water standards and benchmarks. This part of the assessment must be done on a regional scale (investigation area) but also on site specific level
Surface Water Quality	
Preliminary Impact Rating	At this stage of the geohydrological assessment a preliminary impact assessment and rating should be done. This will enable one to rate all the identified pollution sources and identify the sites with the highest impacts. As the assessment progresses additional information will be available and the assessment could be revised and updated.

3.2 *List of Historical Investigations and Available Data*

The following extractions summarise these reports; groundwater related issues are listed accordingly.

Table 11: Description of desktop study

	Title of Document	Author(s)	Date	Objectives and key findings
1	Control of Industrial Water and Stormwater and the Disposal of these Waters	Stewart, Svirodov & Olivier	May 1977	☞ This first report is confined to the area as far east as No.3 shaft only, which has the most pressing problems – this is an indication that the current investigation area correlates with the report of Stewart, et. al, 1977. It is an indication that issues such as the disposal of polluted effluent water also occurred as early as the 70's. ☞ The slimes dams to the north east of Western Reefs Gold Mine No.7 shaft are particularly large and situated at a fairly low part of the catchment with the consequence that seepage from the slimes dam tends to mix with stormwater runoff from the catchment and cause water-logging of the ground to the south and south east of the slimes dam, ☞ Groundwater seepage has arisen at the Boat Club. The alluvial ground is gradually slipping into the Vaal River largely due to ground water seepage forces.
2	Report on the Slimes Dam gravity survey and comment on other gravity surveys at Vaal Reefs South	Biesheuvel, K	Nov 1977	☞ This report contains comments on the results of the gravity survey carried out over the Slimes Dam area at Vaal Reefs South. Additional comment on previous surveys in the area has also been made in the light of information, which was received from the Geological Survey concerning geophysical investigations of dolomite terrain as well as the results of some theoretical model studies, which were carried out.
3	Geological Maps provided by the Vaal River operations	Geology Dept. Anglo American	1978	☞ Delineation of local surface geology
4	Hydrogeological investigation of proposed slimes dam – east of no.5#, Vaal Reefs.	Martenelli and Associates – Jones & Wagener.	1978	☞ "the dam is to be founded on dolomite of the Transvaal system and the Consulting Engineer for the project are concerned the effect this leakage may have on the natural groundwater regime in the area. This is of particular importance to the design and construction of drainage ditches around the dam."
5	The 1:250000 2626 (West Rand) geological map	Geological Survey	1979	☞ Delineation of surface geology
6	Vaal Reefs Exploration & mining Co. LTD. Water Seepage Investigation (Report no. CED/5/80)	Furman, MA – Anglo American Civil Engineering	June 1980	☞ From the work of previous investigators, it would appear that some 109 000 m^3 of water per day were being lost in seepage. 110 m3 of water per day were reaching the Vaal River in the form of seepage. ☞ It would appear that the worst seepage was taking place in the following area: - the two underlined area are in the current investigation area, substantial quantities of seepage were identified already 23 years ago. 1. West slimes dams and evaporation dam area (approximately 1 300m3 per day) 2. Area south of No.3 Shaft (approximately 8 600m3 per day), 3. The evaporation dam south of No.1#, adjacent to the Vaal River (Bird Dam) (approximately 16 000m3 per day), 4. The area surrounding the "Eye" south of No.2# (unknown quantity), 5. The east residue dam area (approximately 84 000 m3 /day)

	Title of Document	Author(s)	Date	Objectives and key findings
7	Effluent and Groundwater Study	Jones & Wagener,	1982	☞ This investigation was undertaken by Jones & Wagener to carry out a preliminary study of the quality of effluents and groundwater on the Vaal Reefs Complex. The report contains a description of the investigation done to that date and present the results of the quality analysis carried out on the major effluent streams and groundwater around the slimes dams. Some of the important finding will be listed later on in this document ☞ A total of 11 back actor pits and 6 percussion holes were profiled and water samples were recovered.
8	Geothechnical investigation for proposed slimes dam: West Extension.	Jones & Wagener Inc	1984	☞ This report was compiled to give an overview of the geothechnical investigation, which was done, in the West Extension tailings dam area – this data is very important for the preparation of geological concepts. ☞ There is a shallow artificial water table at an elevation of about 1310 masl (approximately 2-3 meters below ground level) in the area east of the West Division Dam (refer to boreholes 4, 5 & 6). The water table has developed in response to seepage losses from the dam in conjunction with shallow dolomite rockhead – this phenomenon could still be observed and seems to be part of various groundwater problems. ☞ The groundwater below the proposed dam has already being polluted over the years by seepage losses from the existing West Complex
9	Water Conservation and Pollution Control Project – Pilot De-watering Scheme on Vaal River North Bank Phase 1	Wates and Wagner	1990	☞ The pilot dewatering report concerns the confirmation of the geohydrological models developed during the previous study and to assess the pilot-dewatering scheme as a permanent pollution control measure – this is a good example of a groundwater remediation project and various geohydrological lessons could be learnt. The question could be asked; is this interception field not to far from the pollution source and what is the possibility of pumping river water as well? ☞ Fifteen large diameter dewatering wells and six small monitoring boreholes were installed in the alluvial and weathered deposits during this project. The boreholes were extended some 3m to 5m into the underlying dolomitic aquifer where possible.
10	Integrated hydrological assessment incorporating a geohydrological study for slimes dam M	Wates, Meiring & Barnard	1992	☞ Objectives were: define the geohydrological regime of the site and its environs, ☞ Assess the impact of the proposed slimes dam on the surface and groundwater resources of the area, ☞ Propose conceptual remediation measures should these be found to be necessary and give recommendations for the environmental management of the slimes dam.
11	Klerksdorp Mine Managers Association – Klerksdorp regional groundwater Baseline study	LW & Consulting Environmentalists	1994	☞ To provide baseline information and a regional groundwater model both of which will be required for the EMPR's, which are to be submitted, by Vaal Reefs, Hartebeesfontein, Buffelsfontein and Stilfontein. ☞ Information on regional borehole census, regional groundwater settings, dolomite compartments, effect of mining, interaction between surface and groundwater, seepage into the Vaal River, etc. ☞ The estimated quantity of polluted groundwater entering the Vaal River from compartment A is estimated to fall into the range 520 – 1720 Ml/ month.
12	The impact of diffuse load reductions from the mines in the Orkney/Stilfontein area on the water quality in the Vaal River	IWQS	Nov 1995	☞ The IWQS study was commissioned by DWAF: Pollution Control (Highveld Region) in order to develop water quality objectives for this stretch of the Vaal River ☞ Based on this modelling exercise, IWQS have calculated that it would be necessary to reduce the volume of diffuse seepage from the mines to 0.5 m^3/s in order to achieve 95% compliance with the recommended downstream water quality objective of 250 mg/l sulphate. IWQS recommend that the intercepted seepage be pumped to lined dams for re-use on the mines or disposed of via evaporation to avoid the re-circulation of poor quality water to the underlying aquifer.

	Title of Document	Author(s)	Date	Objectives and key findings
13	Klerksdorp Mine Managers Association – Phase 1 Investigation into the impact of diffuse seepage from gold mines in the Klerksdorp region on water quality in the Vaal River	Anglo American Civil Engineering	1996	☞ This study was prompted by a report by the Institute for Water Quality studies (IWQS, 1995) which identified that the seepage of contaminated water from the dolomitic aquifer which underlies the Klerksdorp Goldfields was adversely impacting on the quality of water within the Vaal River ☞ Prominent zones of seepage have been identified along the north bank of the Vaal River, and it is assumed that similar seepage zones also occur along the southern bank. Seepage is particularly pronounced along the section of the bank between 8# and 9# bridges on the Vaal River property and has developed in association with the complex geological condition, ☞ Rest water levels indicate that the piezometric surface becomes progressively closer to surface with increasing proximity to the river. This is of considerable significance as it indicates that groundwater in areas close to the river is more vulnerable to contamination from a surface source, particularly in areas where the dolomite aquifer outcrops at surface.
14	Klerksdorp Mine Managers Association – Phase 2 Investigation into the impact of diffuse seepage from gold mines in the Klerksdorp region on water quality in the Vaal River.	Anglo American Civil Engineering	1996	☞ In the light of the findings of the Phase 1 groundwater investigation, the objectives of this project was to undertake numerical modelling of the dolomitic aquifer over the Klerksdorp gold field, ☞ The situation modelled considers a situation 33 years after the start of slimes deposition, which should equate to the present day situation. The model indicates that the groundwater system is approaching steady state, and is therefore considered unlikely that the contaminant plumes will migrate much further, having already reached the river, which is the lowest topographic point of the system. However, it is probable that the intensity of contamination within the existing plumes will continue to increase with time. - It currently seems if mass builds up along the clayey alluvium banks of the Vaal River. ☞ Seepage volumes have been estimated for key areas in which the surface and groundwater systems can be seen to interact. Seepage volumes have been calculated by conducting flow budget calculations; a total flow of 73.1 Ml/day was calculated. The seepage volumes are of similar order of magnitude to the total seepage volume of 108 Ml/day estimated by the IWQS during their investigation into the impact of seepage from the Klerksdorp gold field. ☞ Modelling indicates that a salt load of approximately 211 tones per day of TDS is entering the Vaal River system as a result of contaminated seepage from the Klerksdorp gold field.
15	Establish guidelines and procedures to assess and ameliorate the impact of gold mining operations on the surface water environment – Case Study 3: Klerksdorp.	Heath R., CSIR	1995	☞ Strategy 6: Reduction in nitrogen in water pumped from underground – very high concentrations of nitrate is currently identified to the west of the investigation area. ☞ Install and manage passive treatment systems for excess effluent
16	Vaal Reefs Environmental Risk Assessment of the Water Dams,	Envirolink	1996	☞ Critical overview of the current status of the return water and evaporation dams in the area was supplied with risk ratings.
17	Technical Economic review of the assets of Vaal Reefs Exploration and Mining Company Limited, - Water treatment requirements to meet the Water Quality objective in the Vaal River	Steffen, Robertson and Kirsten CE (PTY) LTD	1997	☞ Intensive monitoring in the Vaal River over the previous six years had shown that salinity of the river increases by up to 40% as it flows through this mining area, due largely to seepage into the river. Sulphate was identified as the constituent with the biggest impact on the downstream users, leading to the setting of 250 mg/l SO_4 as the interim water quality objective in this stretch of the river. ☞ The division of responsibility of water treatment costs does not appear to have been defined for the KOSH area, but discussions with DWAF indicate that up to 55% of the costs may need to be borne by the VaalReefs group. ☞ Assuming an abstraction borehole every 50 m along the 20km front, the capital cost of installing an infiltration gallery was estimated from experience elsewhere at about R3 million per km, or R60 million for the 20km system. Cost estimates for desalination was also supplied.

	Title of Document	Author(s)	Date	Objectives and key findings
18	Results of the Westrand Airborne Multispectral Scanner Acid Mine Drainage Survey	Courtnage and Van den Berg	1998	☞ Remote sensing was done by Anglo Gold in 1997 using airborne geophysics, which included thermal, hyperspectral and radiometric surveys. This data was interpreted, integrated and reported by Mr Harald vd Berg from Environmental Investigation Technologies CC. ☞ The thermal image was obtained by flying over the area at night while recording the thermal radiation. At night, the water is warmer than the earth's surface and the warmer zones adjacent to the tailings dams can be mapped out, which should indicate the areas where shallow seepage takes place, ☞ The hyperspectral image confirms the findings of the thermal survey, except that it shows additional sulphate pollution to the west of the Eastern Extension ☞ Flow paths and seepage zones were identified,
19	Geophysical Investigation groundwater Pollution Control Study	KLM Consulting Services	1999	☞ This report details the ground resistivity geophysical survey that was undertaken across the anomalies that were identified during the airborne AMS work undertaken by Courtnage and Van den Berg (1998). ☞ A secondary objective was also to identify potential drilling targets for additional monitoring boreholes. ☞ Tritium water samples were also taken from 36 monitoring boreholes that existed at the time of the investigation
20	Remediation of Sulphate Generation by Mining operations in the Vaal River Catchment – Proposal & Background Report	KLM Consulting Services	1999	☞ To access conditions and sources of dissolved sulphates and other compounds potentially entering the Vaal River from AngloGold Vaal River operations. ☞ Discuss factors related to the hydrogeology of tailings facilities and demonstrates the importance of understanding the detailed settling of a particular tailings impoundment. ☞ Remedial options were mentioned – chemical, physical and hydraulic controls.
21	Results of the Pump Tests Conducted at Vaal River Operations	Geotechnical Services	1999	☞ This report details the results of the pumping tests undertaken on four of the monitoring boreholes in the Vaal River operational area. The results of the pumping tests indicate a ydrogeologis ranging from 0.2m^2/day to 1.58m^2/day
22	Groundwater Monitoring boreholes – Drilling reports	Hippo borehole and Pump Services	2000	☞ The ydrogeologis results for the monitoring boreholes ranged from 1.3m^2/day to 142m^2/day. These monitoring borehole results are considered to be more realistic for dolomitic aquifers than those quoted by Wates and Wagner (1990).
23	Northern Wellfield Status Report	Barnard, S.	2001	☞ This report details the current status of the northern wellfield as a pollution control measure of groundwater contamination migration through the shallow weathered aquifers into the Vaal River. ☞ The abstraction at the time of writing the report was 6456 Kl/day with a slightly increasing trend. Seepage from the boat club and the 9# bridge areas that is also pumped into the holding tank constitutes some 10% of the total abstraction volume
24	Bokkamp Study Aquifer Characteristics	GeoCon	2001	☞ The main objective of this project was to characterize and determine the groundwater status between the West Complex Tailings Dam and West Extension Tailings Dam, ☞ Nine additional monitoring boreholes were drilled, ☞ The highest salt load that impacts on the Vaal River is from the Western and Eastern Extension Tailings Dams, via the surface water pathway to the Bokkamp Dam and then to the Vaal River. A salt load in the order of 22,000 t/y is currently flowing into the Vaal River via this pathway
25	Clean and Dirty Water Separation Bokkamp dam Catchment	Keeve Steyn (Pty) Ltd	2001	☞ Deals with the separation of clean and dirty water and results of run-off calculations.
26	AngloGold Vaal Reefs Operations 8# bridge	Rison	2002	☞ Undertake a desktop feasibility study for the 8# bridge seepage.

	Title of Document	Author(s)	Date	Objectives and key findings
	Remedial Simulations			☞ A simple groundwater MODFLOW model was used to evaluate the various remedial options.
27	Drilling and aquifer testing of monitoring boreholes in Vaal River Area 1	AngloGold Water Management	2002	☞ Drilling and testing of 10 monitoring boreholes
28	Routine ground- and surface water monitoring and quarterly interpretation reports	AngloGold Water Management	2002	☞ Interpretation of groundwater level and hydrochemical data on a quarterly basis, ☞ List and discuss main "problem" areas with recommendations on possible solutions.
29	Routine updating of the groundwater Data Base with the GIS and associated PIVOT system	AngloGold Water Management	2002	☞ Updating of groundwater level and hydrochemical data into the local database.
30	Class 0 Groundwater Liability Project	Geocon	2002	☞ The assessment of the potential groundwater liabilities was conducted within defined criteria. The aim was to use the current information on groundwater pollution to determine the potential costs that could be associated with the management of the pollution. ☞ A checklist should be compiled of all the groundwater pollution sources, areas, volumes, spatial extent of groundwater pollution plumes, contaminants contained in the plumes with a remediation plan and costs per waste source.
31	Screening Geochemical Investigation on selected waste dumps (, 2002)	PHD	2002	☞ To evaluate the potential of selected tailings and waste rock dumps to impact on the water resources and implications of this in terms of mine closure and rehabilitation.
32	Preparation of Geohydrological Conceptual Models for the Vaal River (VR) areas.	AG	2002	☞ Gathering of available geotehcnical, geohydrological and geological data to compile conceptual groundwater models to be used in further numerical ydrogeol.

3.3 Identification of possible pollution sources

All identified waste sources must be listed in this section. At this stage of the investigation the known sources or definite polluters as well as the potential sources must be identified. The following sites (also refer to Figure 12), which could have possible impacts on site hydrology and geohydrology, were identified.

Table 12: List of potential pollution sources

No	Site	No	Site
1	West Complex Tailings Dam	12	Skelm dam – old evaporation dam at toe of No.3# Waste Rock Dump
2	Bokkamp dam – final return water dam for tailings effluent	13	No.3# Waste rockdump
3	Open unlined tailings effluent earth trenches – at toe of tailings dams and towards Bokkamp Dam	14	Old Calcine Dams – north of West Float & Acid Plant
4	West Extension Tailings Dam	15	Queen Mary Dams – West Metallurgical return/evaporation dam
5	Game park dam – current dam wall build with tailings material and accumulation of salts due to up-gradient contamination	16	No.4 # Waste rock dump
6	Old evaporation area west of Bokkamp – historical discharge of tailings effluent	17	No.1 Gold Plant & effluent dams
7	West Monitoring System and Pump Station – current reclamation system	18	No 3# Washing Plant Pump house & Dams
8	West Float Acid and Uranium Plant – Stockpile areas and containment facilities	19	Redundant West Extension Storm Water Dam
9	10# Ore loading Area – current ore stockpile area south of No.1 Gold Plant	20	No 3# Concrete Stormwater Channel
10	No. 9 Gold Plant effluent dams	21	3# sewerage plant area
11	Old Blackreef treatment Plant	22	6# and 7# Waste rock footprints
		23	Ellaton Mine – Black Reef Area

3.4 Groundwater Monitoring Sites

It must be noted that the following table represents an already upgraded groundwater-monitoring network. The preliminary site inspection was based on only the un-highlighted boreholes in Table 13. The upgrading and filling of information gaps will be discussed at a later stage.

Table 13: List of monitoring boreholes

Qty	BH No.	Y Co	X Co	Description	Date Drilled
Monitoring Boreholes NORTH & hydraulically up-gradient of the West Complex Tailings Dam					
1	vr/03	31227.35	2979428.20	Along Ariston road.	2000
2	vr/07	28511.28	2976736.66	VR / Harties boundary, east of Vaal River / Klerksdorp road.	
3	Vr21	30659.59	2977526.76	North of ARM, No. 4#.	
4	vr/31	29710.00	2979326.54	Downstream of 4# waste rock dump, just north of Arriston Road.	2002
5	vr/37	31998.93	2979125.71	North of Ariston Road, in plots.	
Monitoring Boreholes WEST of the West Complex Tailings Dam					
6	vr/04	33131.624	2980728.89	Along main Klerksdorp / Orkney road.	1999
7	vr/38	33252.53	2981147.93	Pony Club, west of Orkney / Klerksdorp road.	
8	vrm/16	32716.16	2980909.13	West Pay Dam Monitoring pump station.	2000
9	vrm/17	32718.82	2980926.72	West Pay Dam Monitoring pump station.	2000
10	vrm/22	32786.18	2980859.84	West Pay Dam Monitoring pump station.	1996
11	vrm/01	32465.32	2981514.21	West Complex Slimes Dam - in area of old calcine dams	1997
12	vrm/02	32494.20	2981605.83	West Complex Slimes Dam - in area of old calcine dams	1997
13	vrm/03	32461.14	2981667.98	West Complex Slimes Dam - in area of old calcine dams	1997
14	vrm/38	31,785.50	2,980,071.95	West of Ariston Gully Tailings Dam at old plant	
Monitoring Boreholes EAST of the West Complex Tailings Dam					
15	vrm/21	30425.96	2980042.46	West of West Extension Dam, South of Ariston road.	2001
16	vrm/23	30428.57	2980049.37	West of West Extension Dam, South of Ariston road.	2001
17	vrm/24	30063.10	2980587.04	Between West Dam Complex and West Extension Dams.	2001
18	vrm/42	30431.89	2980124.33	**West of West Extension Dam, Woodlands mon BH	2003
19	vrm/43	30324.76	2980173.55	**West of West Extension Dam, Woodlands mon BH	2003
20	vrm/44	30277.61	2980248.90	**West of West Extension Dam, Woodlands mon BH	2003
21	vrm/45	29840.71	2982249.78	**West of West Extension Dam, Woodlands mon BH	2003
22	vrm/46	28532.95	2980724.89	**West of West Extension Dam, Woodlands mon BH	2003
Monitoring Boreholes SOUTH of the West Complex Tailings Dam					
18	vrm/25	30336.17	2981934.64	East of West Pay Dam, North of No 9 Shaft Return Water Dams.	2001
19	vrm/26	31221.94	2982468.12	South of West Dam Complex, north of Orkney / No3 Shaft road	2001
20	vrm/27	31230.51	2982466.30	South of West Dam Complex, north of Orkney / No3 Shaft road	2001
21	vrm/12	31473.45	2983220.58	South of road from 3 # to Orkney, near old clay pigeon shooting club.	2000

Qty	BH No.	Y Co	X Co	Description	Date Drilled
Monitoring Boreholes at No 1 Gold Plant					
22	vr/25	32868.79	2981858.85	North of No 1 Gold Plant in Stone and Allied complex.	
23	vrm/36	32738.59	2982181.3	Downstream of 1 gold plant effluent dams	2002
24	vrm/37	32514.98	2982259.08	Upstream of 1 gold plant - inside plant area	2002
Monitoring Borehoels at the West Float Acid & Uranium Plant					
25	vrm/39	33,064.52	2,981,629.55	Below Queen Mary Dam	2002
26	vrm/40	32,597.73	2,981,768.94	West of Plant	2002
27	vrm/41	31,975.68	2,982,023.11	East Of Plant	2002
West Extension Monitoring Boreholes					
28	vrm/19	29330.50	2981030.79	South of West Extension Dam, and North of Orkney / Potchefstroom roa	2001
29	vrm/20	29660.59	2980269.37	West of West Extension Dam, but East of West Dam Complex.	2001
30	vrm/31	28416.20	2980098.97	east of west extension tailings dam	2001
Bokkamp Area Monitoring Boreholes					
31	vrm/13	29675.92	2983559.42	Below Bokkamp Dam, in Bob Williams Game Reserve.	
32	vrm/28	29296.44	2983454.50	In Bob Williams Game Reserve, below Bokkamp Dam	2001
33	vr/27	28617.05	2983631.29	In game park about 500m downstream of Bokkamp dam	2002
Game Park Dam					
34	vr/08	27558.112	2983681.912	In Bob Williams Game Reserve.	2000
35	vr/15	29559.021	2984934.307	In Bob Williams Game Reserve.	
ARM 3# Area - Groundwater Monitoring					
36	vr/28	28291.96	2982149.19	upstream of 3# waste rock dump	2002
37	vr/29	28453.94	2982801.45	downstream of skelm dam	2002
38	vr/30	27723.91	2982502.64	downstream of 3# waste rock dump	2002
ARM 4# Area - Groundwater Monitoring					
39	vr/32	29058.18	2978975.53	downstream of 4# waste rock dump	2002
40	vr/39	29531.29	2978183.11	upstream of 4# waste rock dump	2002

The table above listed all the monitoring boreholes within the investigation area – Vaal River north-western aquifer system (also refer to the locality map – Figure 12). Boreholes are currently sampled on either a quarterly, twice yearly or yearly basis – the objective of sample frequencies will be discussed in Section 4.3.

3.5 Surface water monitoring sites

The following table listed the surface water sample sites applicable to the area of investigation (*refer also to Figure 12: Map of Investigation Area*).

Table 14: List of surface water sample sites.

	Site No.	Description	Type of Monitoring	
		VAAL RIVER WESTERN AREA - SURFACE WATER MONITORING POINTS	Routine	Incident
1	S03	Vaal River - sample at Railway Bridge at Pelgrims Estate	x	
2	S04	Seepage at Boat Club - take sample west of No.9 Shaft Bridge on northern bank of Vaal River	x	
3	S05	Seepage at No. 9 Shaft Bridge - take sample west of No.9 Shaft Bridge on northern bank of Vaal River - Routine	x	
4	S06	Vaal River - sample at no. 9 Shaft Bridge	x	
5	S10	West Residue Dam Effluent Return - sample in channel next to tar road.	x	
6	S14	No.1 Gold Plant Containment dams - sample run-off from No.1 Gold Plant towards Queen Mary Dam	x	x
7	S15	West Uranium and Acid Plant - routine sampling of spillages and dirty run-off from Plant	x	x
8	S16	West Monitoring System Overflow - sample effluent overflow towards Orkney graveyard		x
9	S18	Skelm Dam and seepage from 3# waste rock dump	x	
10	S21	Sample of surface run-off from Game Park Dam Area if occurs	x	x
11	S25	Bokkamp Dam - routine sampling of dam water.	x	
12	S27	Schoon Spruit down stream - sample at weir next to tar road	x	
13	S28	Queen Mary Dam - routine sampling of dam water and overflow if occurs	x	x
14	S30	Sample surface run-off in concrete channel that outflows in wetland north east of No.3 waste rock dump.	x	
15	S31	Flow towards old evaporation area - sample effluent run-off directly north of tar road	x	
16	S32	Jag Spruit - sample at bridge	x	
17	S33	Sample of surface run-off from Bokkamp Dam at Vaal River, if occurs		x
18	S34	Schoon Spruit up stream	x	
19	S35	Vaal River - sample at southern boundary	x	
20	S44	West Extension Complex, sample surface run-off at culvert under tar road.	x	
	🟥	*- Radiation Monitoring Sites - Indicator, Background and Incident monitoring*		

3.6 *Identification of major seepage areas*

The obtain a general idea of areas where possible seepage of contaminated water could occur, the following aspects were considered:

- Evaluation of surface topography – determination of main surface water drainage paths and to identify areas where surface run-off is hampered by means of industrial interference
- Local geology and generic aquifer characteristics,
- Depth of groundwater table below ground surface – identification of unsaturated zone
- Depth of groundwater table below mean sea level – identification of flow
- Sources of artificial recharge and head differences,
- Height of phreatic water levels within the tailings dams,

The following information and historical data was utilized:

- Geo-technical studies,
- Air photography and topography maps,
- Data obtained from groundwater monitoring sites,
- Thermal Images

3.6.1 *Elevation data*

An elevation grid was created (also refer to Figure 13: 3-Dimensional view of the Topography) using a 2m contour interval dataset that was combined with elevations obtained from the World Geoscience radiometric survey. The resulting grid therefore has more detail especially in the Bokkamp dam area, which is relatively flat having no more than a 2m vertical variation. The data was then processed to produce a drainage grid that indicates the most likely position of surface streams. This stream data set, similar to a flow accumulation grid with an applied threshold value, must be checked against more accurate data when that becomes available from for example a ground survey or elevation mapping from detailed aerial photography. Figure 16 shows a colour elevation grid generated from the elevation data and also the calculated streams (van den Berg, 1998). The red areas show the topographical highs (approximately 1340 meters above mean sea level (mamsl)), the yellow the intermediate topography (around 1300 mamsl) and the green presents the lower Vaal River basin (approximately 1280 mamsl). The light blue lines illustrated the main surface drainage paths.

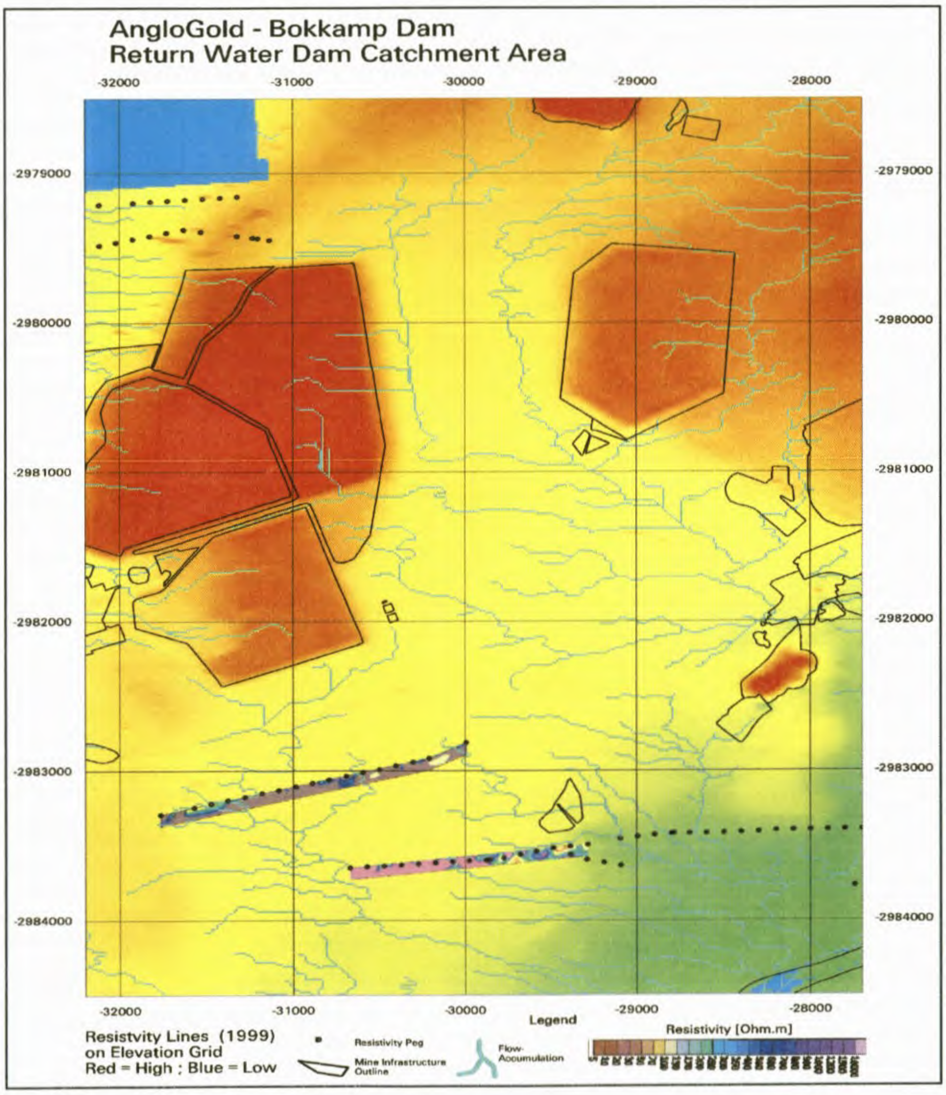


Figure 16: Colour elevation grids

3.6.2 *Groundwater Level observations*

Groundwater levels should be measured on a routine basis at least twice a year, but preferably quarterly. It is essential that a proper water level electrical contact meter be used and that the water table be measured up to a accuracy of 1 – 2 cm. Groundwater level interpretations must be done in conjunction with local geology and site-specific mining operations. The following gives an overview of typical groundwater level findings and also in relation to local geology:

3.6.2.1 Geology Background

When studying Figure 14: *Surface Geology of the Investigation Area*, it could be seen that the pink coloured area, which represents solid dolomite, shallow bedrock, underlying the majority of the western aquifer system (area within red block). The area to the west, towards the Schoon Spruit is underlined by Ventersdorp lava (refer to green areas). The spotted green areas represent clay alluvium deposits. The white spotted areas represents chert rich dolomite and red sands with deeper bedrock.

It is typical in this area that shallow groundwater levels will occur on the more impervious solid bedrock dolomites (pink areas) and deeper groundwater levels in the chert rich dolomites (white spotted areas).

3.6.2.2 Unsaturated thickness

The following contour map graphically illustrates the groundwater levels in meters below ground surface. This indicates basically zone above the saturated rocks and soils. This further gives a good idea of the thickness of the barrier zone. The barrier between a waste pile (tailings storage facility, waste rock dump, etc.) and an aquifer is represented by the unsaturated zone. It is within this zone that much attenuation of leachate occurs. Important processes in leachate attenuation include chemical precipitation, adsorption, dilution, dispersion and biodegration. The time that leachate would take to travel from the base of the waste pile to the top of the aquifer can be used to quantify the ability of the barrier zone to separate the waste from the aquifer. The data required for this calculation is depth to water and hydraulic conductivity and porosity of the vadose zone (buffer zone) *(Parsons et al, 1994)*. This calculation is usefully applied for site selection purposes and to identify sites, which is underlain by an efficient buffer zone. In the case of the tailings storage facilities in the investigation area, all these parameters indicate a site with an insufficient buffer zone, e.g. shallow bedrock, shallow groundwater table, high permeabilities, etc.

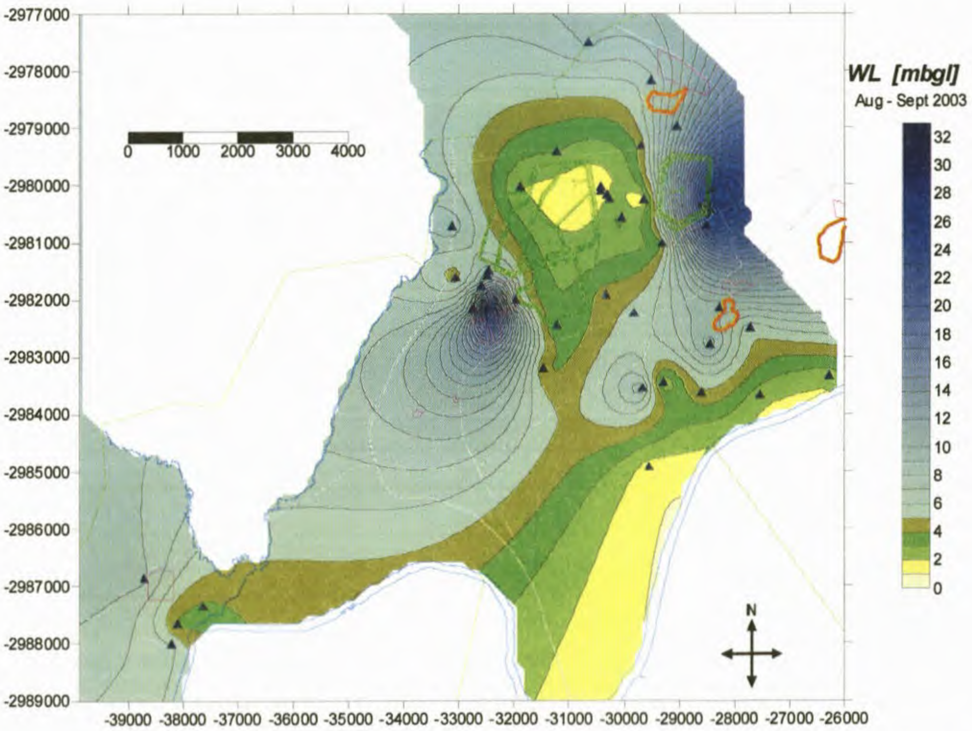


Figure 17: Groundwater level contour Map for September2003 – in meters below ground level (mbgl).

3.6.2.3 Groundwater levels above mean sea level (mamsl) and projected flow directions

The following contour map illustrates the groundwater levels of the area in meters below mean sea level. By doing this, groundwater flow directions could be delineated. Primary flow is towards the Vaal River in the south and Schoon Spruit in the west. The red line indicates the occurrence of a ridge (aquifer divide), which is formed by an outcrop of blackreef quartzites.

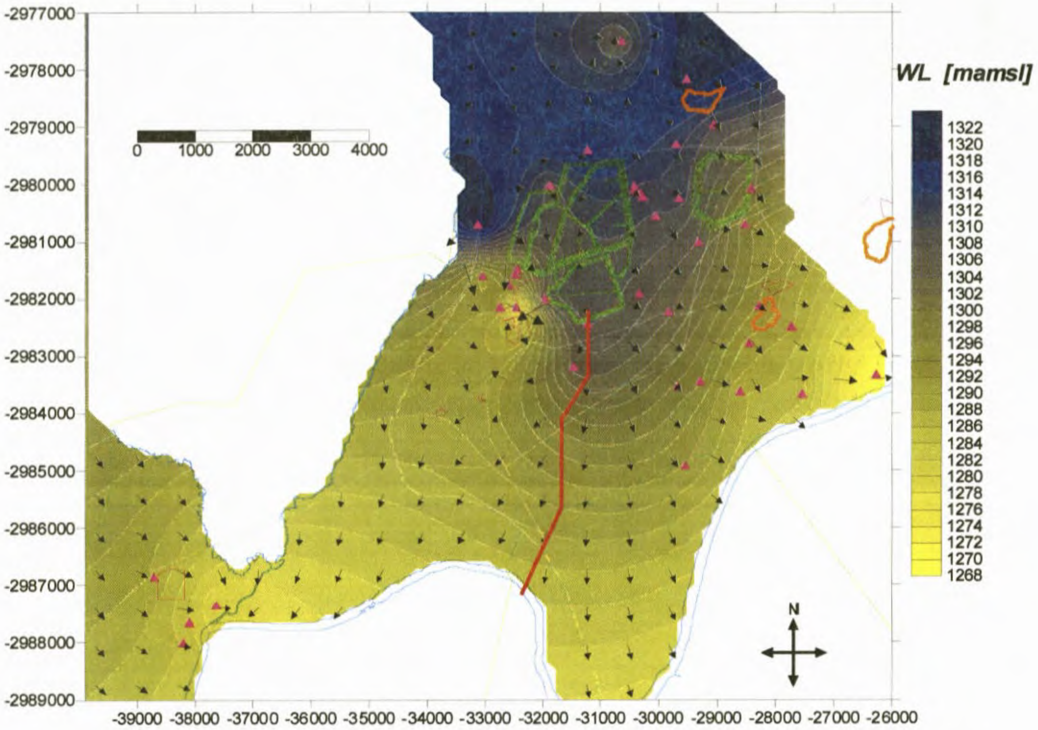


Figure 18: Groundwater levels and flow directions – in meters above mean sea level (mamsl)

3.6.2.4 Groundwater level trend over time

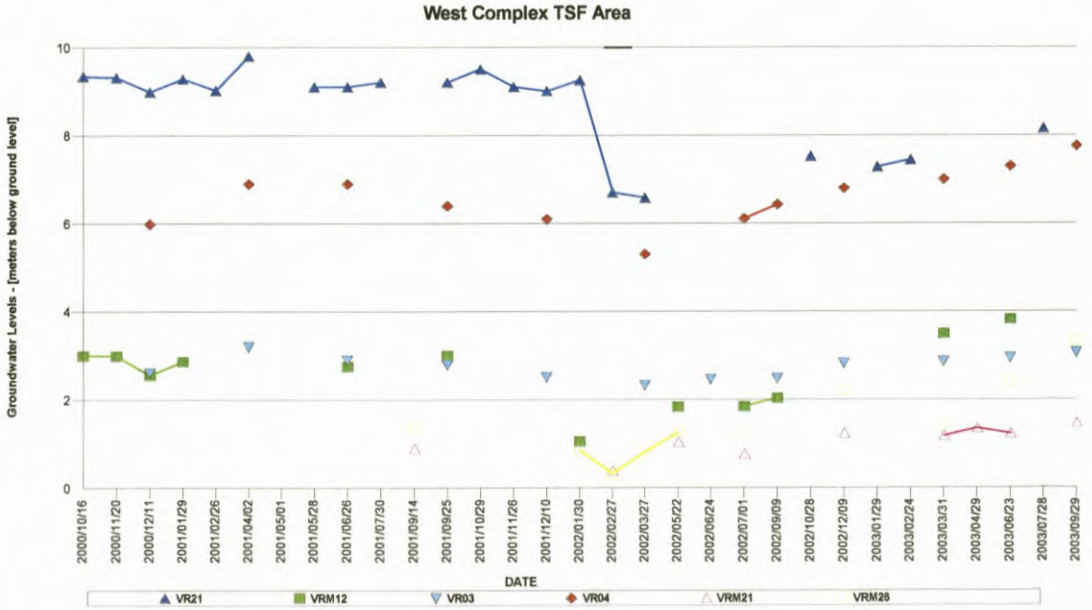


Figure 19: Groundwater level trends for monitoring boreholes up-gradient (Vr21, Vr03), East (Vrm21), South (Vrm12) and West (Vr04) of the West Complex Tailings Storage Facility.

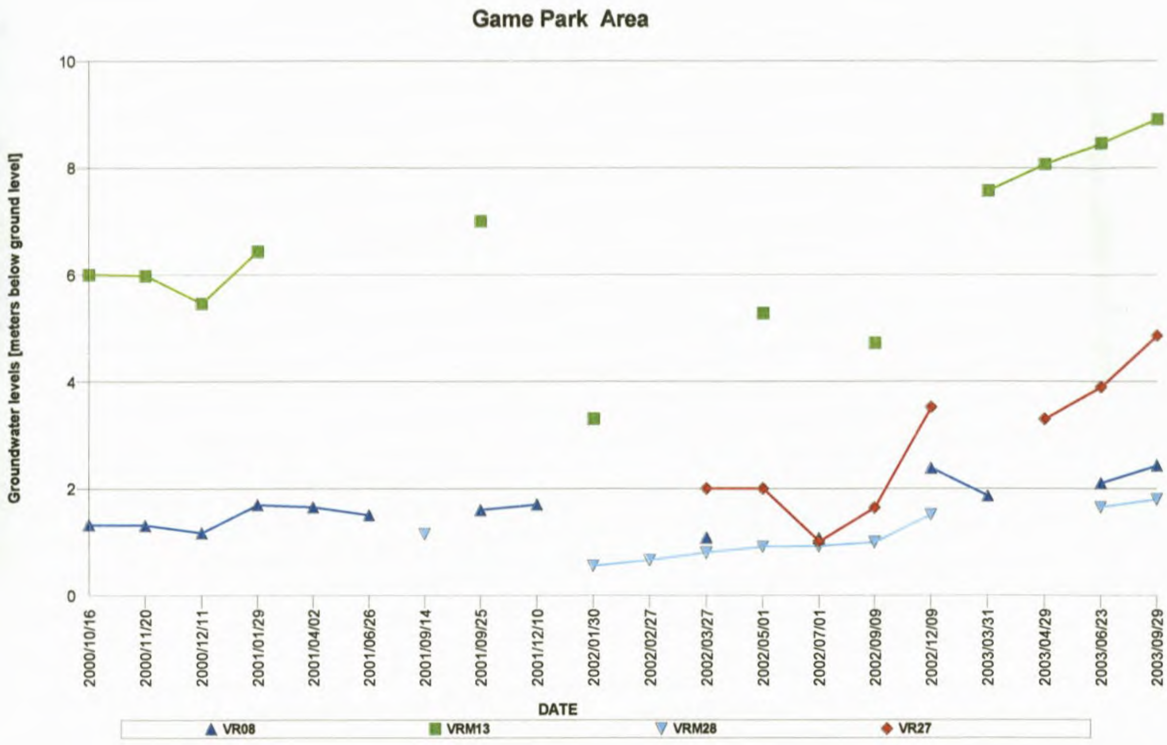


Figure 20: Groundwater level trends for monitoring boreholes below Bokkamp Dam (Vrm13, Vrm28, Vr27) and below Game Park Dam (Vr08)

3.6.2.5 Discussion

After studying Figures 17 – 20 the following conclusions could be made:

- It is typical in this area that shallow groundwater levels will occur on the more impervious solid bedrock dolomites (pink areas as represented on Figure 14) and deeper groundwater levels in the chert rich dolomites (white spotted areas).
- Figure 17, indicates a very small (1-3 meters below ground surface) unsaturated zone at certain areas and therefore a limited buffer capacity between the tailings storage area and groundwater table – this compared well with the "pink areas" of Figure 14.
- In most cases where the slimes dams overlay sub-outcrop or outcrop dolomite the phreatic surface does create wet conditions for a variable distance away from the toe of the tailings facility
- Conceptual groundwater flow model shows that where the depth to solid dolomite is greater the apparent seepage becomes less. Where the dolomite is deep enough no seepage will be seen to emerge around the toe of the dams. Low perched groundwater levels in the region of 0.3 to 3 meters below ground level could be observed. This perched aquifer zone primarily occurs below the eastern portion of the West Extension Tailings dam and stretch all the way to the Vaal River.
- In general groundwater flow is towards the lower Vaal River basin to the south and to the Schoon Spruit to the west (Figure 18).
- In general, stable groundwater level trends with slight seasonal variations occur. It is however visible from Figure 19 and Figure 20 that groundwater levels tend to be deeper in the last year. This is a definite reflection of dryer conditions that was experienced the pat year, especially water levels at boreholes Vr27 and Vrm13.

- It could be assumed that shallow groundwater levels historically occurred in this area if historical data, the site-specific geology and relative distance to the Vaal River were considered. The current situation, however, is definitely worsened by the occurrence of a constant head within the tailings storage facility and associated seepage. *The following issues regarding this situation appear to be of relevance*:
- The West Extension Tailings dam is not equipped with an under-drain system, seepage from the tailings dam that is not captured by the toe trenches seeps directly into the underlined dolomitic aquifer system,
- Shallow groundwater levels could impact on dam stability,
- Earth trenches which transport effluent towards the Bokkamp dam are practically built within this shallow water table – that's why effluent and groundwater qualities correlates almost 100% in the direct vicinity of the trenches. Seepage from the trenches will increase when the regional water-table lowered, which tend to be the current situation. On the other hand, when the regional water level rises again, the earth trenches could actually intercept the groundwater table.

3.6.3 Remote sensing information

AngloGold did remote sensing surveys in 1997, using airborne geophysics, which included thermal, hyper spectral and radiometric surveys.

3.6.3.1 Night Time Thermal data

The thermal image was obtained by flying over the area at night while recording the thermal radiation. At night, the water is warmer than the earth's surface and the warmer zones adjacent to the tailings dams can be mapped out, which should indicate the areas where shallow seepage takes place.

The thermal image was used to delineate the zones where potential seepage areas occur (Figure 21). The thermal image delineation indicates that there are three main potential areas where seepage occurs namely:

- To the south of the Western Tailings Dam Complex, Paydam no 2, southern compartment.
- To the east of the Western Tailings Dam Complex, east of compartments 1, 2 and 3.
- To the west and south of the Western Extension.

However, it should be emphasised that this method of seepage identification should not be used on its own, it is important to understand site-specific geological, geohydrological and hydrological concepts. It could be a dangerous method if someone who do not know the site attempt to interpreted the images and come up with certain conclusions.

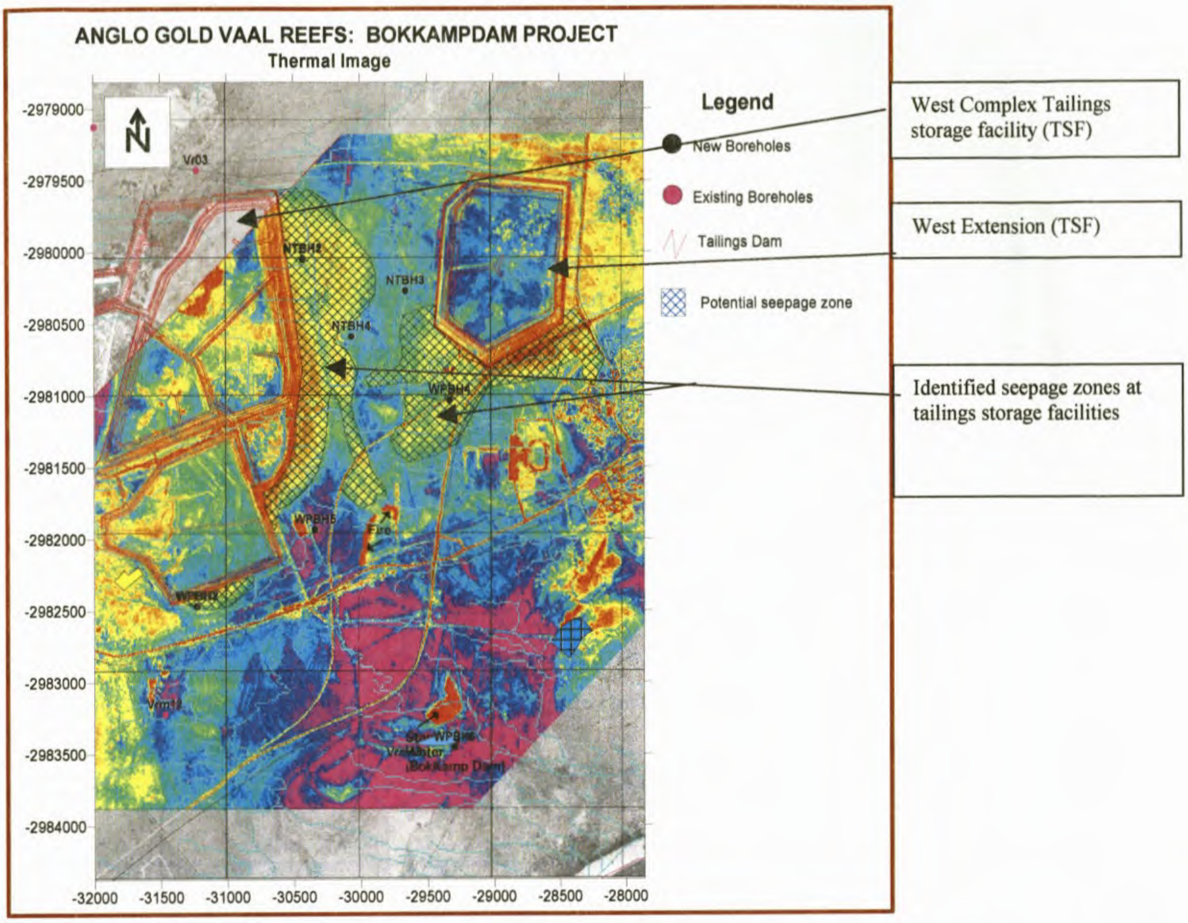


Figure 21: Thermal Image Of the investigation area – note seepage plume to the east and south of the West Complex and to the South west of the West Extension Tailings Storage Facilities

3.7 Water Quality Assessment

3.7.1 Overview

Groundwater qualities should be determined to evaluate site conditions and current state of the aquifers. This section will provide a broad overview of site groundwater quality by means of contour maps and site-specific discussions. It must be noted that this is a preliminary site assessment and available data should be used, the monitoring system needs to be upgraded if information gaps is experienced – the next step in the assessment will address this issue.

The following background information was obtained from the geo-technical feasibility study for the West Extension Tailings Dam, compiled by Jones & Wagener in 1984. This data is essential in such a study, it gives a fine overview of historical conditions – this could be compared to the current situation.

- In order to assess the likely magnitude of pollution after construction the properties of typical slimes effluent are compared with those of water samples taken from four boreholes on the north west site and from earlier boreholes drilled well away from any existing slime dam.
- Though the slimes effluent is moderately acidic (pH 5 to 7) the groundwater (both natural and polluted) has a neutral to slightly alkaline pH of 7 to 8.
- Total dissolved solids in the natural groundwater are about 8 times less than that of the polluted groundwater and effluent.

- Calcium content is of the same order in the effluent and polluted groundwater and some 10 times less in the natural groundwater.
- Sulphates are variable being least in natural groundwater and 10 times and 20 times greater in polluted water and effluent respectively,
- It is also noteworthy that the water obtained from boreholes in the immediate vicinity of, and up to 700 metres from the existing slimes dam had some properties similar to those of the effluent (TDS, Cl and Ca) whilst other properties (pH, T-Alk, Mg and SO_4) varied significantly. This may be due to variations in slimes effluent properties or in dilution and/or reactions within the rock and soil masses over even short distances.
- The groundwater below the proposed dam has already being polluted over the years by seepage losses from the existing West Complex Tailings Dam. TDS values of up to 10 000 mg/l were detected from boreholes east of the current West Complex Tailings Dam

3.7.2 Groundwater Hydro-chemical Contour Maps

The following contour maps were constructed by using the April and September 2003 hydro-chemical data, respectively. *The Kriging interpolation method was applied with the Surfer 8 software program.* ***It must be noted that the contour maps are only constructed to give a broad overview of groundwater quality – contours in areas where <u>no</u> groundwater sample sites exist must be ignored.***

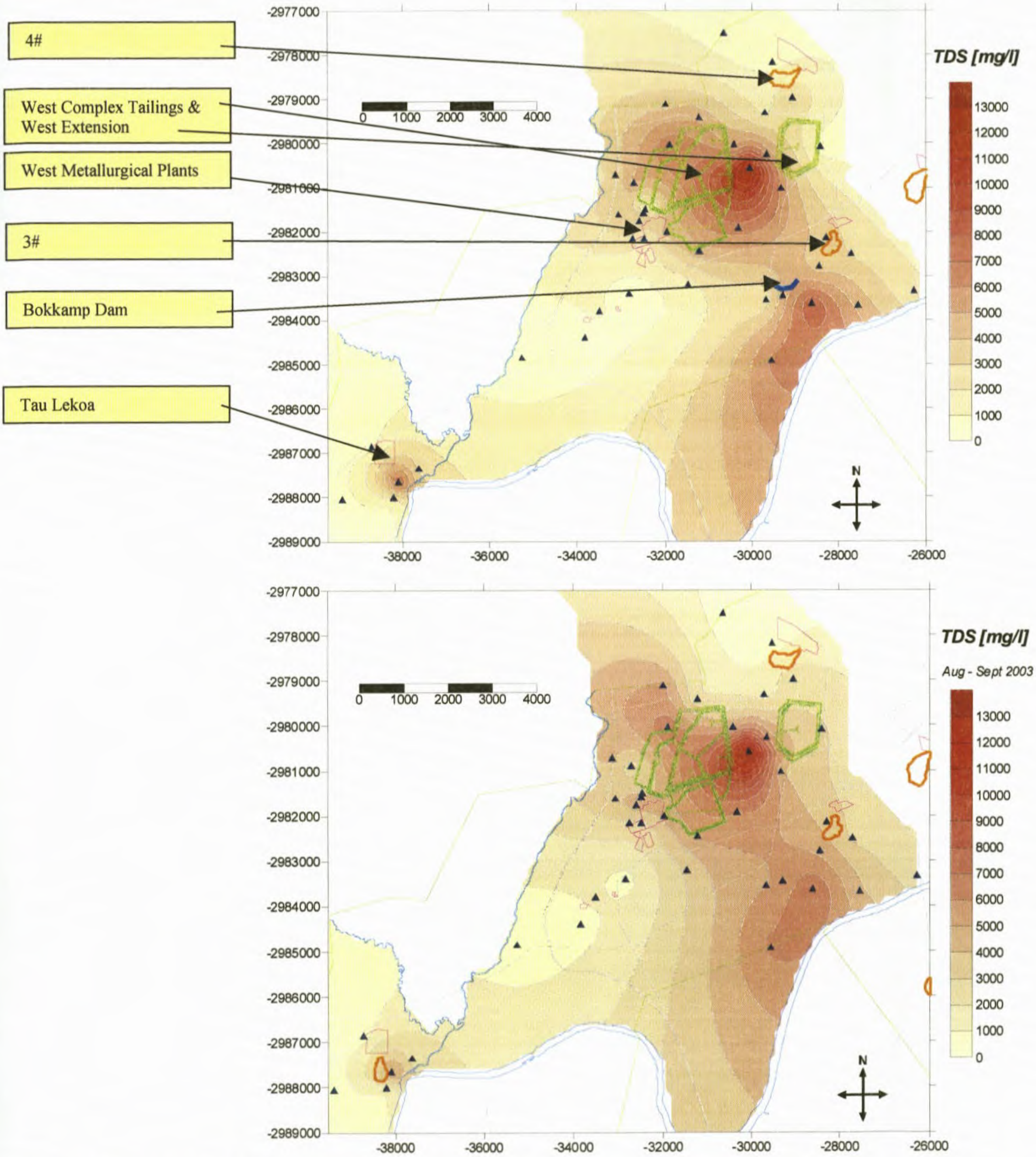


*Figure 22: Groundwater **TDS** contour maps – Vaal River West – Comparison between the April and September 2003 TDS Contour Maps*

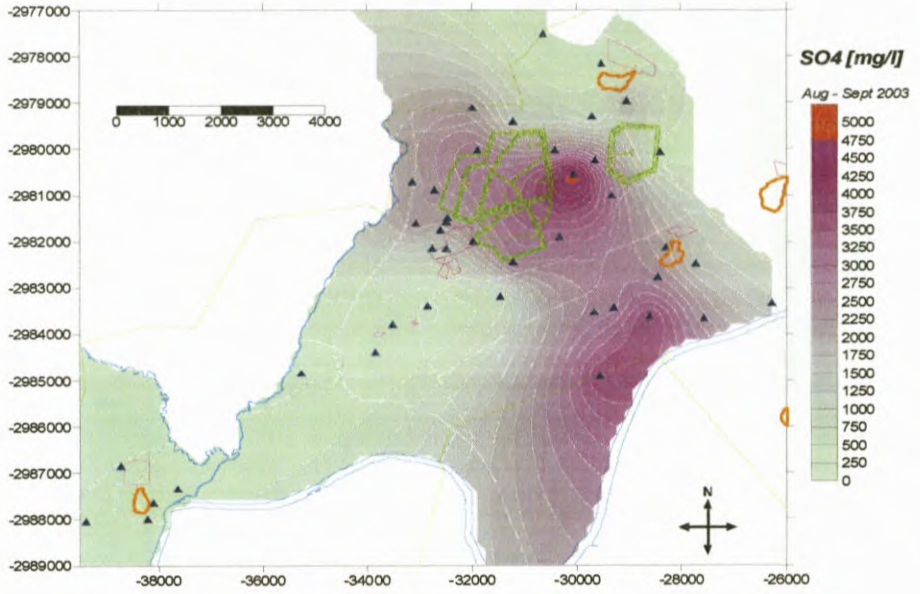


Figure 23: Groundwater ***Sulphate*** *contour map – Vaal River West*

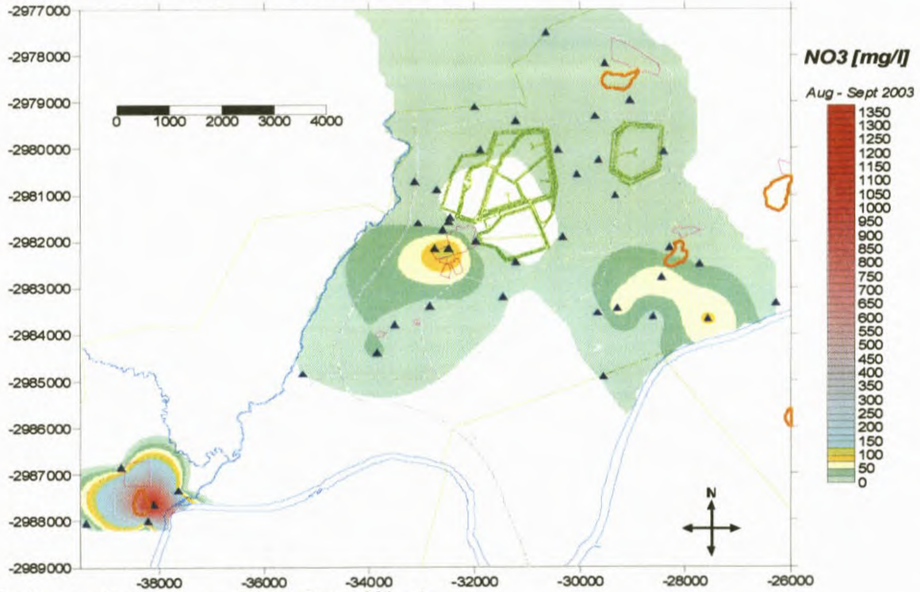


Figure 24: Groundwater ***Nitrate*** *contour map – Vaal River West*

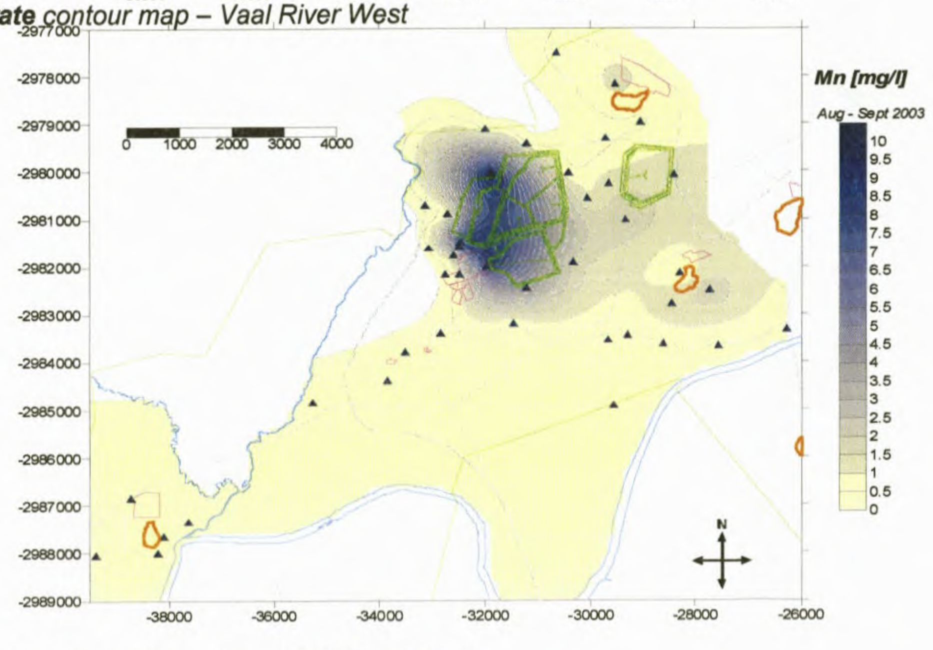


Figure 25: Groundwater ***Manganese*** *contour map – Vaal River West*

3.7.2.1 Discussion

After studying Figure 22 – Figure 25, the following conclusions could be made:

- The TDS contour map (Figure 22) indicates high concentrations in the area between the West Complex Tailings Dam and the West Extension Tailings facility. TDS values, almost in the same order, occurred also to the south, in the RF Williams Game Park.
- The conclusion could be made that high concentrations of dissolved salts in the groundwater and the occurrence of shallow groundwater levels (Figure 17) correlates with magnitude and locality. The main reason for this trend seems to be associated to the accumulation of salts in the unsaturated zone (zone above groundwater level, usually topsoil – 0-3m below ground surface). The reason for the accumulation of salts further down-gradient, closer to the Vaal River is due to flow against the more impermeable alluvial clay layer along the Vaal River,
- The accumulation of salts in this zone seems to be accelerated by a combination of the following:
  - Shallow bedrock and flat topography – which constraint good groundwater flow,
  - Shallow groundwater levels
  - High evapo-transpiration,
  - Dry winter months

Figure 23 – Figure 25 represents the SO_4, NO_3 and Mn contour maps respectively. These elements were used as indicator constituents. Other dominant ions in groundwater are Ca, Mg, Cl and Na. High metal concentrations usually occurred with lower pH values.

Although the area is not part of this investigation area, note the abnormal high NO_3 plume hydraulic-down gradient of the Tau Lekoa waste rock dump (shaft in south western corner of map) (Figure 24). High nitrate values seem to directly associate to waste rock operations in general.

Elevated Mn levels could observed in the direct vicinity of the Tailings Storage facility and West Plants (Figure 25). High Mn concentrations in groundwater seems to be linked to older metallurgical processes in the extraction of uranium. This tendency needs to be investigated in more detail, for the interim it is advised that plant managers look into historical and current use of Manganese.

3.7.3 Hydro-chemical Imaging

The Piper diagram represents the concentrations as percentages, this is achieved by working the percentage that each represents of the major cations (Ca, Mg and Na+K). Analyses are plotted on the basis of the percent of each cation (or anion). Each apex of a triangle represents a 100% concentration of one of the three constituents. As water flows through an aquifer it assumes a diagnostic chemical composition as a result of interaction with the lithological framework (Fetter, 1998). For example the calcium percentage of the major cations in an analysis would be determined by (meq/l):

$\frac{Ca}{Ca \quad Mg \quad (Na \quad K)}\%$ using the same technique the percentage contribution of each of the other species is calculated and the results are plotted as one point in the cation trilinear field, Scott, 1996.

The term hydro-chemical facies is used to describe the bodies of groundwater, in an aquifer, that differ in their chemical composition. The facies are a function of the lithology, solution kinetics, and flow patterns of the aquifer (Back, 1966). It must however be noted that pollution from gold mining operations tend to indicates dominant SO4 type, it is thus important to consider the effect of cultural noise on identified aquifer facies. The Schoeller semi-logarithmic diagram shows the total concentrations of the cations and anions and also allows us to make a visual comparison of the compositions of different waters. The concentrations are plotted in meq/L. The diagram has been used to directly determine the saturation indices of groundwaters with respect to minerals such as calcite and gypsum. The following Figures represent and explained Piper and Schoeller diagrams of certain boreholes.

- Figure 26: Vr04, situated to the west, between West Complex Tailings and Schoon Spruit. The diagram indicates polluted water with dominants Ca/MgSO_4 content,
- Figure 27: Vrm24, situated in close proximity east of the West Complex Tailings dam. Also dominant Ca/MgSO_4 content is visible. This water could also be classified as stagnant (Back, 1966)
- Figure 28: Vr21, situated up-gradient on the northern lease boundary. The water indicates an initial Ca/Mg $(HCO_3)_2$ content but tends towards Ca/MgSO_4 content.
- Figure 29: Vrm13, is situated down-gradient of the Tailings dam and return water dam. Dominant Ca/MgSO_4 content is visible. It is also visible from the Scholler diagram that Mg is the major cation. Mg will therefore dominate precipitation of SO_4.

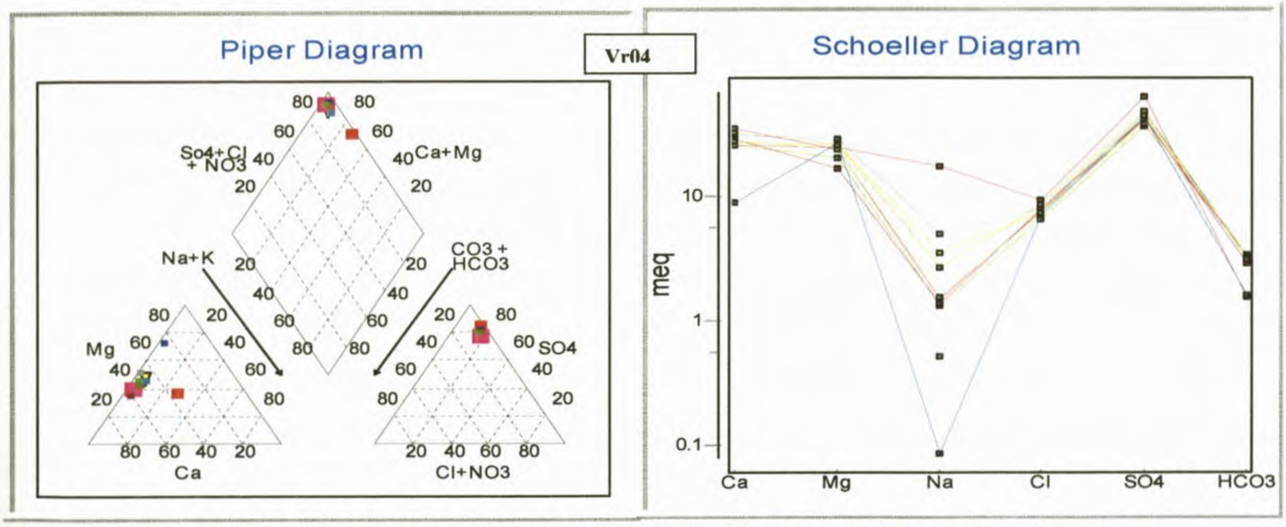


Figure 26: Piper & Schoeller diagrams of Vr04 – west of WC-TSF towards Schoon Spruit

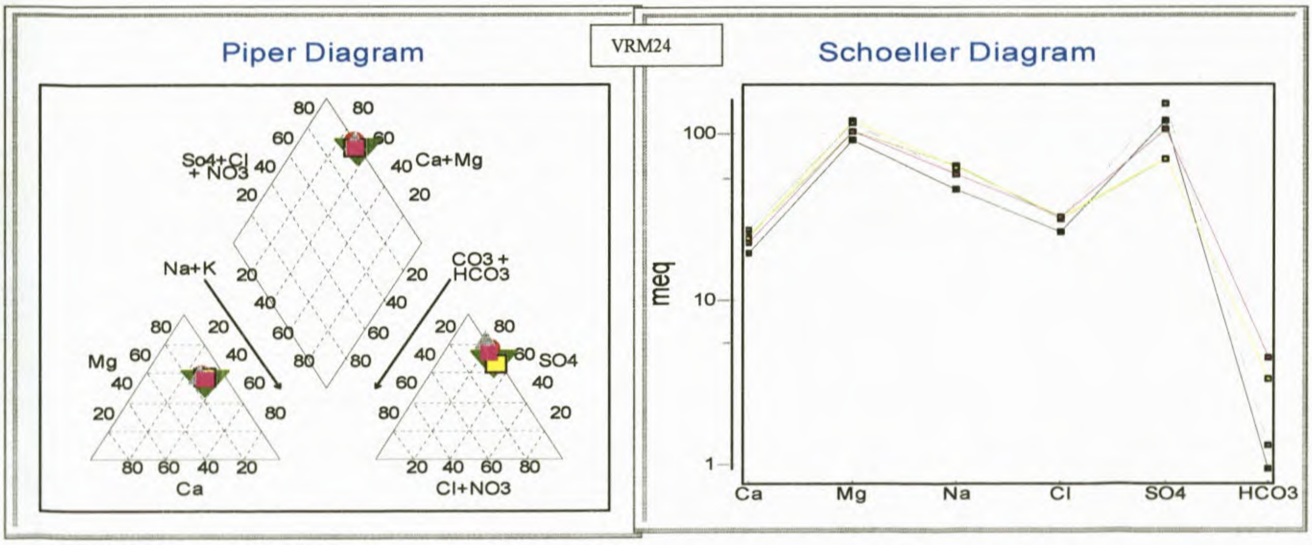


Figure 27: Piper & Schoeller diagrams of borehole Vrm24 – Between WC-TSF and WE-TSF

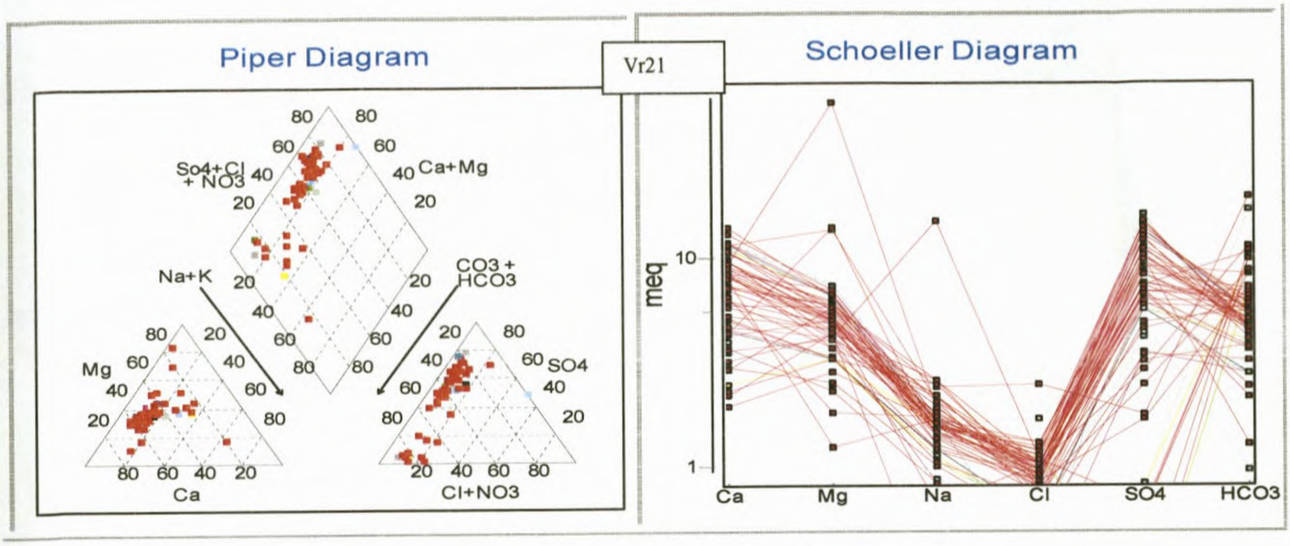


Figure 28: Piper & Schoeller diagrams of Vr21 – north up-gradient of WC-TSF

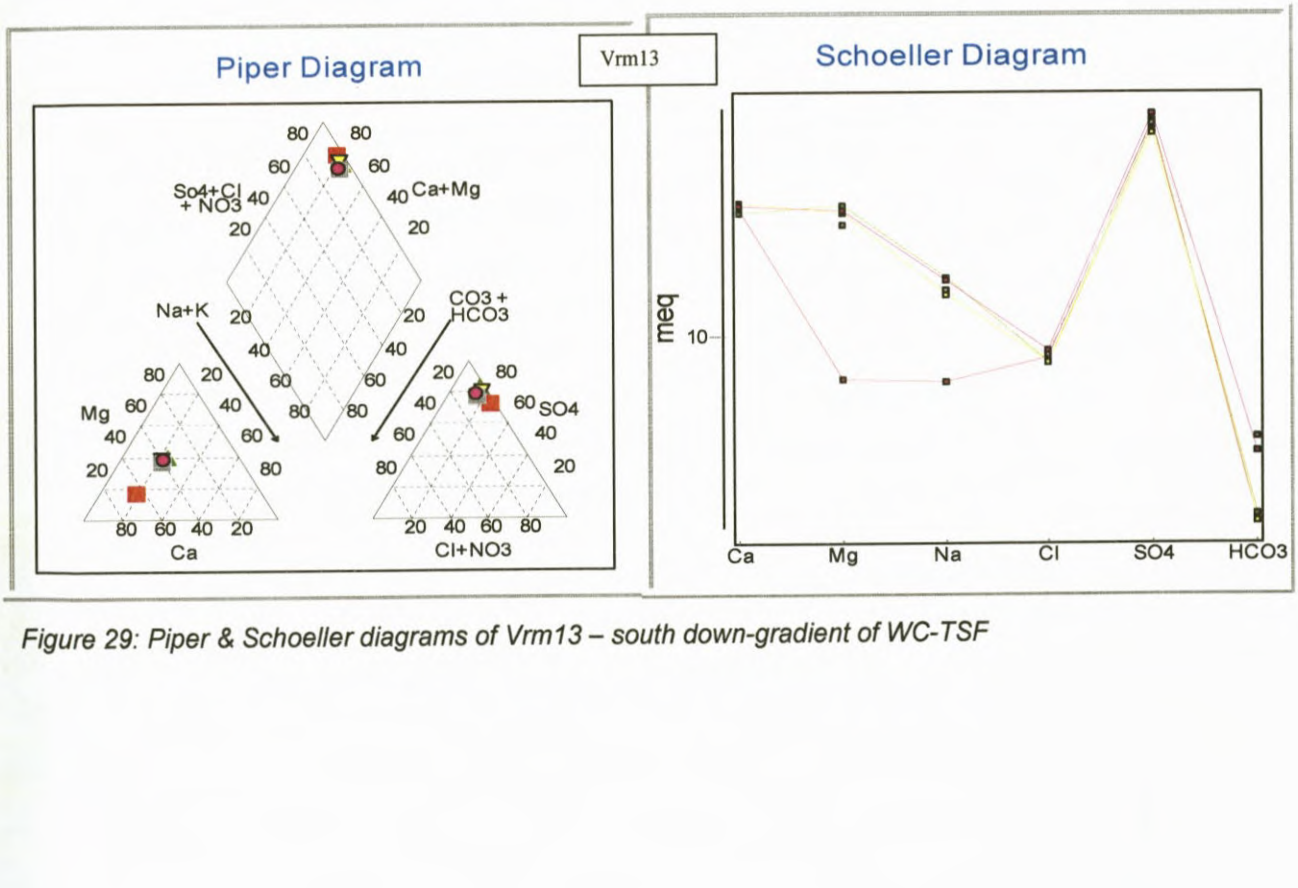


Figure 29: Piper & Schoeller diagrams of Vrm13 – south down-gradient of WC-TSF

3.7.4 Site specific Discussion

The following provide an overview of site-specific water qualities. This will be illustrated through tables of the latest chemical results and time graphs.

Note: the values above the limit for livestock watering (sheep) were coloured dark **red**, the values above the maximum limit for human consumption were coloured dark **blue** (DWAF Water Quality Standards, 1996). None of the groundwater is currently used for domestic use. The guideline limits were only used as an indicative and data interpretation tool. Only recent data is presented – the database could be consulted for further investigative purposes.

Time graphs are constructed so that temporal changes in water quality can be identified. The following trend figures illustrate the groundwater quality of the area over time. Unfortunately no reliable data exist for the period pre-1998. Currently it could be seen from the figures that the majority of the TDS levelled of and stable trend could be observed. Plots in the west suggest that there is some attenuation in indicator contents as polluted water migrates from surface water bodies (tailings dams and return water dams), through the unsaturated zone, and into underlying aquifers.

3.7.4.1 West Complex Tailings Area

Table 15: West Complex Tailings Area and Monitoring Sites and latest data

Groundwater Monitoring sites		**Monitoring Data for last sample runs**												
BH No	***Site Description***	**Date**	**pH**	**TDS**	**CN Tot**	**Cl**	**NO3**	**SO4**	**Fe**	**Mn**	**Ca**	**Mg**	**Na**	**Water Level**
Vr03	North - Along Ariston road	23-Jun-03	6.4	5078	<0.5	320	1	3000	17	41	554	308	426	2.95
		29-Sep-03	7.8	2152	<0.5	154	1	1184	<0.5	<0.4	201	130	209	3.06
Vr04	West - Along main Klerksdorp / Orkney road.	23-Jun-03	7.4	3804	<0.5	270	8	2163	<0.5	<0.4	602	288	34	7.3
		29-Sep-03	7.3	4200	<0.5	278	11	2106	<0.5	<0.4	600	309	60	7.76
Vr21	North Up gradient borehole.	28-Jul-03	8.1	528	<0.5	24	3	25	<0.5	0.7	45	37	45	
Vr37	North - Along Ariston Road, in plots	28-Jul-03	7.4	5181	<0.5	244	12	2158	<0.5	0.4	606	300	802	
Vrm21	East - Shallow Aquifer (5m)	29-Apr-03	7.0	4574	<0.5	330	1	2539	<0.5	1.9	509	206	516	1.35
		23-Jun-03	7.2	4472	<0.5	320	1	2614	<0.5	1.3	510	190	468	1.23
		29-Sep-03	7.0	4690	<0.5	320	3	2514	<0.5	0.6	483	157	460	1.47
Vrm23	East - Deep Aquifer (35m)	29-Apr-03	7.7	4320	<0.5	298	2	2493	<0.5	<0.4	557	158	486	1.27
		23-Jun-03	7.6	4327	<0.5	312	1	2580	<0.5	<0.4	548	148	462	1.16
		29-Sep-03	7.3	4504	<0.5	320	1	2509	<0.5	<0.4	505	127	460	1.43
Vrm24	Between West Dam Complex and West Extension Dams.	29-Apr-03	7.5	14600	<0.5	1140	14	3418	<0.5	0.6	466	1463	1460	3.32
		23-Jun-03	7.8	14138	<0.5	1094	21	7382	<0.5	0.9	530	1450	1330	3.2
		29-Sep-03	7.7	14412	<0.5	1140	10	5114	<0.5	1	449	1283	1340	3.35
Vrm25	East of West Pay Dam, at Return Water Dams.	23-Jun-03	7.1	6227	<0.5	524	3	3459	<0.5	2	496	372	696	4.08
		29-Sep-03	7.1	5953	<0.5	522	1	2990	<0.5	1.8	425	332	662	4.62
Vrm26	South - Deep aquifer (35m)	23-Jun-03	7.2	4731	<0.5	366	1	2819	0.9	2	480	172	610	2.44
		29-Sep-03	7.1	5148	<0.5	356	1	2619	<0.5	0.8	508	161	584	3.31
Vrm27	South - Shallow aquifer (5m)	23-Jun-03	7.0	5461	<0.5	388	1	3137	<0.5	5.7	548	216	690	2.18
		29-Sep-03	7.0	5136	<0.5	386	1	2804	<0.5	3.9	428	175	624	2.58
vrm/12	South of road from 3 # to Orkney, near old clay pigeon shooting club.	23-Jun-03	7.1	1308		110	5	653	<0.5	<0.4	196	98	57	3.82
		29-Sep-03	7.2	3160	<0.5	106	1	583	<0.5	<0.4	171	80	70	4.04
Surface Water Monitoring Sites														
Site	***Site Description***	**Date**	**pH**	**TDS**	**CN Tot**	**Cl**	**NO3**	**SO4**	**Fe**	**Mn**	**Ca**	**Mg**	**Na**	**Au**
S10	No.9 Gold Plant Effluent Dams	17-Feb-03	7.9	4274	15.6	300	52	2405	0.5	11.8	533	154	470	0.015
		22-Apr-03	9.8	4774	13.1	308	117	2428	<0.5	<0.4	775	24	504	
		17-Jun-03	7.8	4905	13.5	326	87	2750	< 0.5	21*	935	139	448	

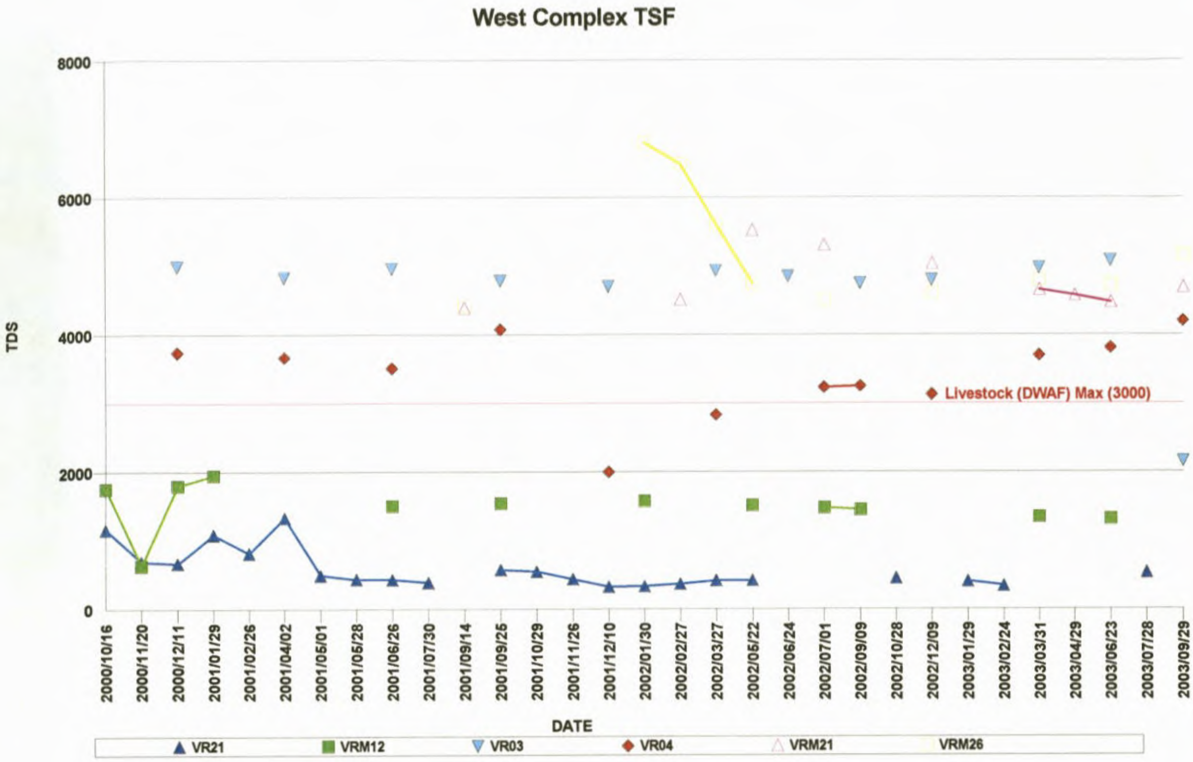


Figure 30: Groundwater TDS levels in [mg/l] – for monitoring boreholes up-gradient (Vr21, Vr03), East (Vrm21), South (Vrm12 and Vrm26) and West (Vr04) of the West Complex Tailings Storage Facility.

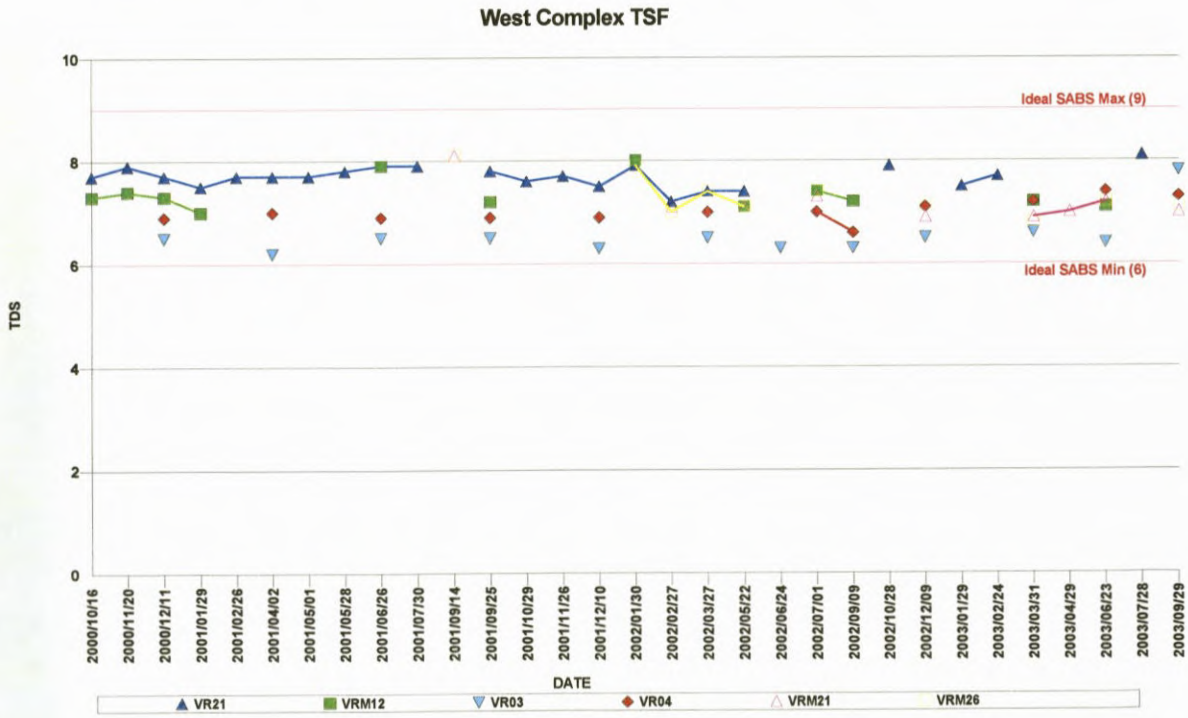


*Figure 31: Groundwater **pH** Time Graph –for monitoring boreholes up-gradient (Vr21, Vr03), East (Vrm21), South (Vrm12 and Vrm26) and West (Vr04) of the West Complex Tailings Storage Facility.*

Table 16: Conclusions & Required Actions for the West Complex Area

Identified Hydrological and Geohydrological Issues:	**Required Actions**
Perched Aquifer System Shallow groundwater levels occur in the direct vicinity of the West Complex Tailings Dam – especially at the eastern and southern walls. The water table has developed in response to seepage losses from the dam in conjunction with shallow dolomite rockhead.	The occurrence of the shallow perched groundwater, to the east and south of the West Complex Tailings dam, needs to be minimized and managed. The following actions needs to be considered: Optimization of vegetation and trees – this could drain a portion of groundwater via root uptake and evapo-transpiration. The occurrence of shallow bedrock, however, will complicate the plant of trees. The minimization of seepage from the source, which is dominantly the tailings dam and earth trenches, should also be considered. Although this is a difficult and impractical suggestion, it will be functional to concrete the earth trench at certain portions where low bedrock and associated groundwater occur.
Pollution Migration: Contaminated water that seeps from the tailings dams with a salt load in the order of 3,500 mg/L. The water infiltrates into the upper, soil and weathered dolomite zone under the driving force of the head in the dams. The monitoring boreholes around the West Complex Tailings dam indicate very high SO4, Ca, Mg, Cl and Na content. No major anomalies were identified from the trend graphs. – this is a definite indication of steady state conditions.	The introduction and spread of pollutants within site aquifers can be expected to continue unless remedial actions are taken. The long-term objective towards final closure and decommissioning will be to bring the system back into a more natural flow environment with minimal cultural impact on natural groundwater flow. The separation of clean and dirty surface run-off water will play a big roll together with the ydrogeologi of natural vegetation and long-term groundwater plume management. Other groundwater remediation options, like borehole drilling, etc. will be considered as an option during future investigations.
Contaminated Soils The seepage water reaches the areas adjacent to the dam where the piezometric heads are lower; it seeps towards the topographic surface. When it reaches the level of the plant root zone between 1.0-0.5 m depths, the water is taken out of the system by transpiration and evaporation and the salts precipitate. Over a period of decades, the salt may build up to high levels in the soil zone. This could be one explanation for the high salt content at borehole Vrm24 in the central part between the West Complex and West Extension dams.	Accumulation of salts needs to be reducing by applying remediation methods, which will lower the level of the perched water table. Methods like the optimisation of vegetation and or physical transformation of the aquifer needs to be applied. Physical aquifer transformation refers to something like interception boreholes or cut-off trenches. This issue needs further investigation to determine the feasibility of different proposed remedial actions.

3.7.4.2 West Metallurgical Plants

Table 17: Monitoring Sites and latest data

Groundwater Monitoring sites		**Monitoring Data for last sample runs**												
BH No	***Site Description***	**Date**	**pH**	**TDS**	**CN Tot**	**Cl**	**NO3**	**SO4**	**Fe**	**Mn**	**Ca**	**Mg**	**Na**	**Water Level**
vrm01	North west of old calcine dams	29-Apr-03	8.4	128	<0.5	6	1	58	<0.5	<0.4	17	3	3	5.88
		26-May-03	8.4	42	< 0.5	4	1	35.0	<0.5	<0.4	16	3	3	6.63
		29-Sep-03	7.0	3154	<0.5	184	1	1908	<0.5	9.1	480	83	258	8
vrm02	West of old calcine dams	31-Mar-03	6.6	4018	<0.5	190	45	2098	<0.4	25	498	213	332	6
		23-Jun-03	6.3	4414	<0.5	202	49	2608	<0.5	22	576	204	262	8.08
		29-Sep-03	6.8	5897	<0.5	194	2	2301	<0.5	7.5	462	180	286	9.35
Vrm39	Down-gradient of Queen Mary Dam	24-Mar-03	7	3769	0.007	247	79.74	1834	0.09	0.03	316	232	328	3.51
		10-Jul-03	6.5	3995		224	18	2201	0.07	0.08	405	214	285	4.42
Vrm40	Down-gradient of West Float Acid & Uranium Plant operations	24-Mar-03	7	4102	0.015	241	119.61	1923	0.16	3.2	352	272	244	5.67
		10-Jul-03	6.5	4487		231	28	1721	0.02	1.7	500	280	225	6.33
Vrm41	Up-gradient of West Float Acid & Uranium Plant operations	24-Mar-03	7.1	4384	0.006	290	8.41	2053	0.18	6.5	368	220	384	6.17
		10-Jul-03	6.5	4359		286	2.4	2153	0.02	8.4	490	200	365	6.69
Surface Water Monitoring Sites														
Site	***Site Description***	**Date**	**pH**	**TDS**	**CN Tot**	**Cl**	**NO3**	**SO4**	**Fe**	**Mn**	**Ca**	**Mg**	**Na**	**Au**
S15	Down-gradient of the West uranium and Acid Plant													
S28	Queen Mary Dam	7-Apr-03	10.9	3996	11.8	108	25	1959	<0.5	<0.4	705	1	434	<0.002

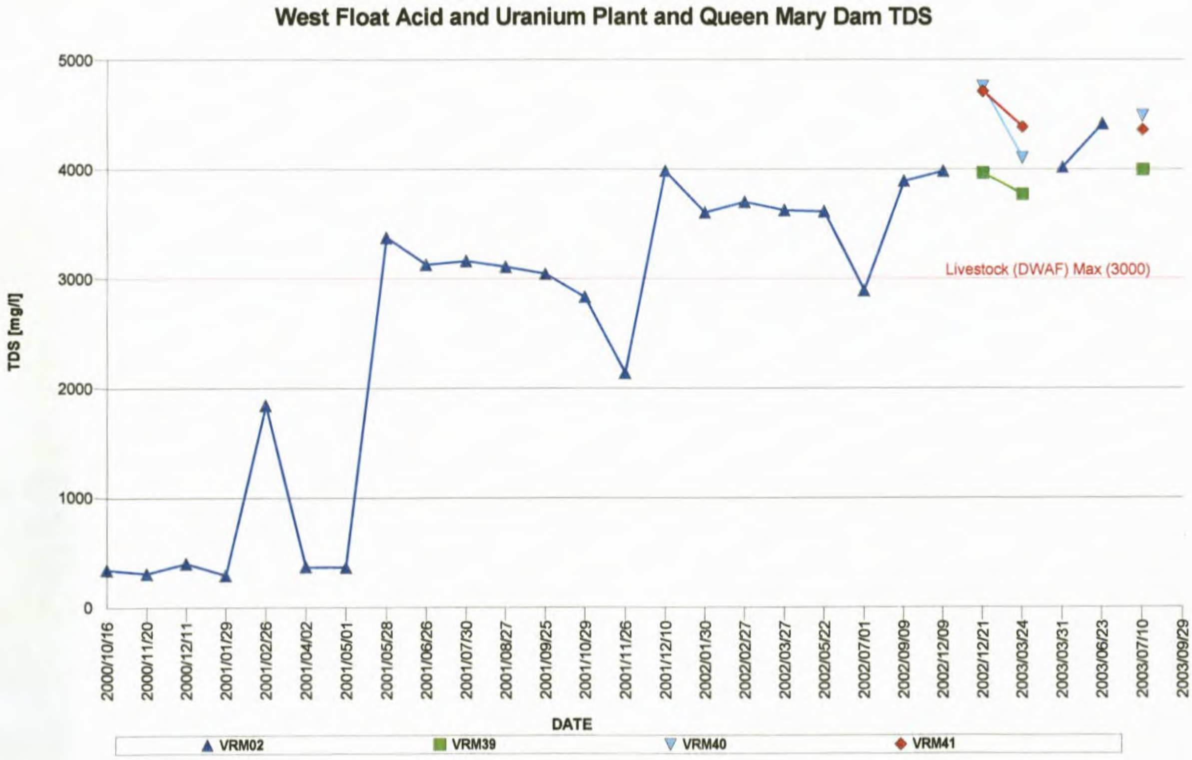


*Figure 32: Groundwater **TDS** Time Graph [mg/l] – for monitoring boreholes up-gradient (Vrm41) and Down-gradient (Vrm40) of the <u>West Float Acid & Uranium Plant</u>, west of ydroge dams (Vrm02) and below Queen Mary Dam (Vrm39)*

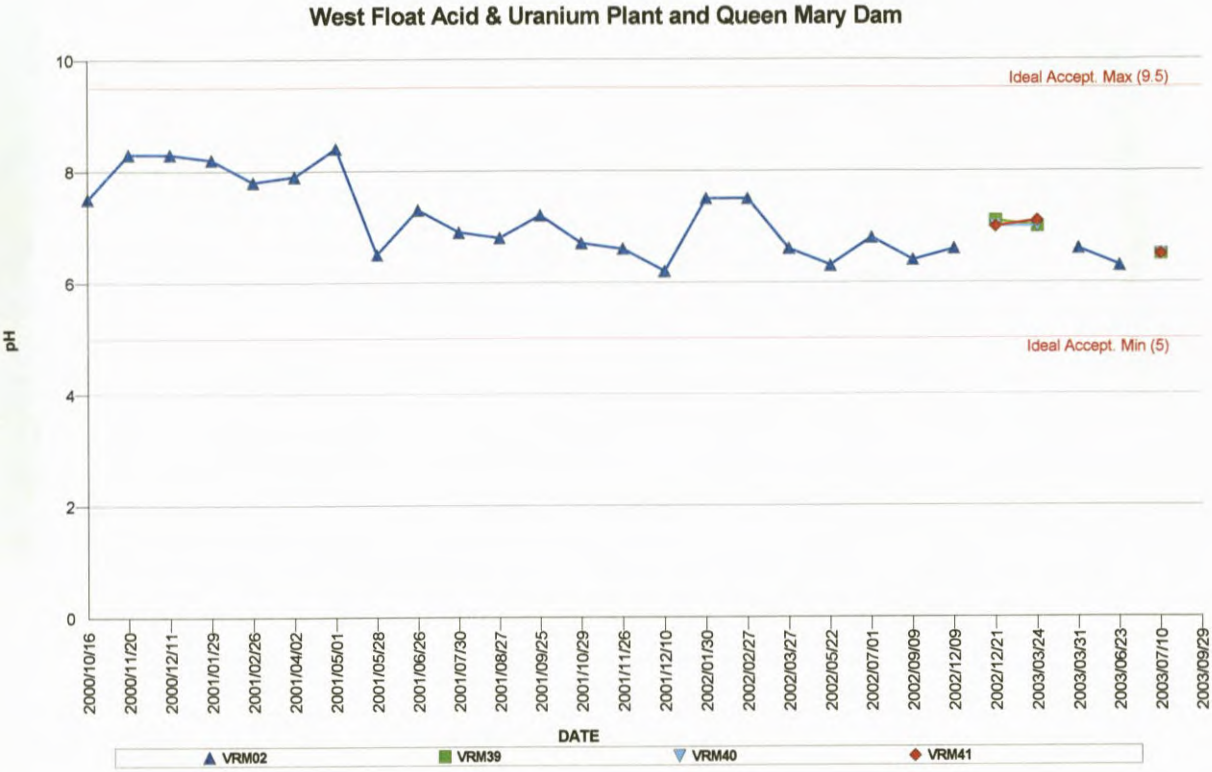


Figure 33: Groundwater ***pH*** *Time Graph*

Table 18: Conclusions & Required Actions for the West Float Acid & Uranium Plant

Identified Hydrological and Geohydrological Issues:	**Required Actions**
Groundwater Quality The deteriorating trend, visible from borehole Vrm02, needs to be investigated in more detail. The most obvious reason seems to be the impact from the newly built trench. This trench was built at the end of 1999 and transport tailings from the reclamation operations at the West Pay dam to the west pump-station. Visual inspections suggest flow on exposed bedrock and result in direct horizontal migration of salts on top of the bedrock zone. The three newly drilled monitoring boreholes indicate high SO4, Ca, Mg, Na, Cl and Mn content in the local aquifer system. This is a typical indication of mining and specifically metallurgical originated groundwater contamination. VRM39 was drilled below the Queen Mary Dams, VRM41 situated hydraulic up-gradient of the plant, VRM40 situated down-gradient of the plant. VRM41 however, shows slightly higher concentrations for the indicator elements. The long term slimes spills and earth trenches in this area could be the reason for these higher concentrations	It must be noted that groundwater pollution in this area was accumulated over a long period of time. To clean such an aquifer will be a long process of rehabilitation and improvement of surface operations. Surface drainage and the separation of clean and dirty run-off water needs to be upgraded. Slimes spillages, which occur over the last 10 – 20 years, needs to be cleaned up. The long-term use of the Queen Mary dam needs to be finalized and the environmental impact needs to be assessed. Tailings material needs to be cleaned up in and around the Queen Mary dams.

3.7.4.3 Bokkamp Dam Area

Table 19: Monitoring Sites and latest data

Groundwater Monitoring sites		**Monitoring Data for last sample run**												
BH No	***Site Description***	**DATE**	**pH**	**TDS**	**CN Tot**	**Cl**	**NO3**	**SO4**	**Fe**	**Mn**	**Ca**	**Mg**	**Na**	**WL**
vrm/13	Below Bokkamp Dam, in Bob Williams Game Reserve.	23-Jun-03	7.5	**4588**	<0.5	278	12	**2662**	<0.5	2.2	558	320	288	8.46
		29-Sep-03	7.3	**4962**	<0.5	270	9	**2601**	<0.5	<0.4	514	289	296	8.9
vrm/28	In Bob Williams Game Reserve, below Bokkamp Dam	23-Jun-03	7.1	**5073**	<0.5	370	71	**2745**	<0.5	<0.4	662	180	538	1.65
		29-Sep-03	7.3	**5270**	<0.5	372	67	**2633**	<0.5	0.4	601	167	530	1.8
vr/27	In game park about 500m downstream of Bokkamp dam	23-Jun-03	7.2	**8104**	<0.5	600	6	**4430**	<0.5	<0.4	565	**635**	35	3.9
		29-Sep-03	7.2	**7040**	<0.5	506	9	**3870**	<0.5	<0.4	480	**585**	780	4.86
vr/15	Windmill in Bob Williams Game Reserve.	31-Mar-03	7.3	**6124**	<0.5	176	1	**3249**	<0.5	<0.4	490	**550**	452	equipped
		23-Jun-03	7.5	**6203**	<0.5	228	1	**3771**	<0.5	<0.4	540	**540**	434	equipped
Surface Water Monitoring Sites														
Site	***Site Description***	**DATE**	**pH**	**TDS**	**CN Tot**	**Cl**	**NO3**	**SO4**	**Fe**	**Mn**	**Ca**	**Mg**	**Na**	**Au**
S25	Bokkamp Dam	4-Aug-03	8.0	**5172**	**17.00**	316	**125**	**2910**	<0.5	**9.8**	621	86	556	
		1-Sep-03	7.4	**4904**	<0.5	302	**114**	**2790**	<0.5	0.7	745	96	784	
		22-Sep-03	7.4	**4710**	<0.5	304	**240**	**2698**	<0.5	**11.1**	761	88	704	
		9-Oct-03	7.1	**4948**	<0.5	348	**101**	**2897**	<0.5	4.0	659	108	490	
S31	Flow towards old evaporation area	Dry - no flow observed												
S33	Overflow from Bokkamp into Vaal	Dry - no flow observed												

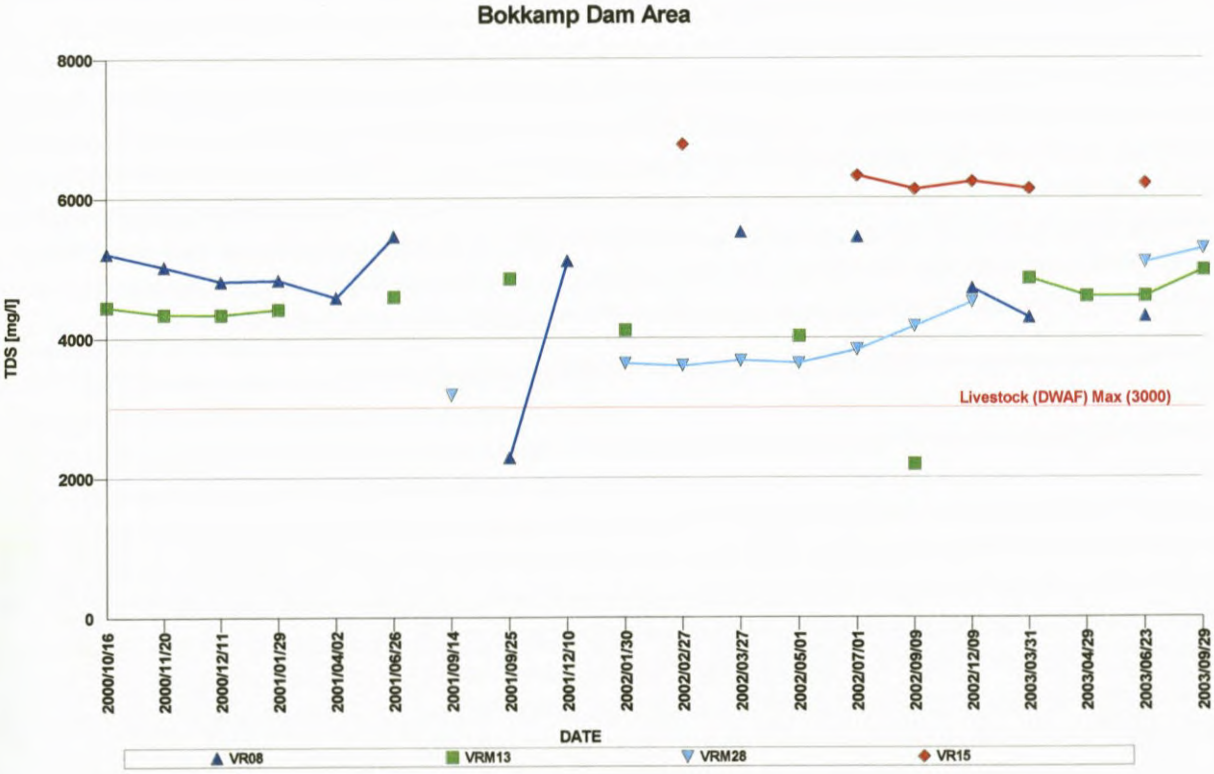


*Figure 34: Groundwater **TDS** Time Graph – Bokkamp Dam Area*

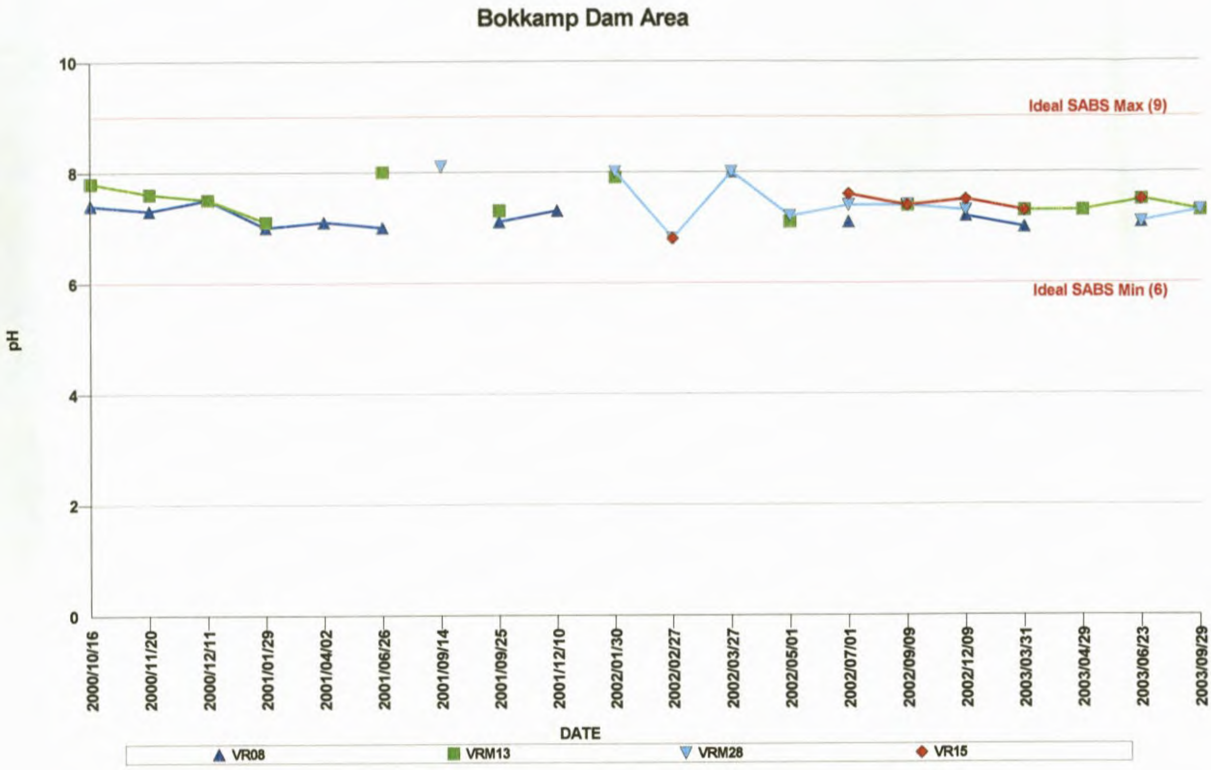


*Figure 35: Groundwater **pH** Time Graph – Bokkamp Dam Area*

Table 20: Conclusions & Required Actions for the Area

Identified Hydrological and Geohydrological Issues:	**Required Actions**
Contaminated groundwater and plume migration It is visible from the chemical analysis that salt migration and the associated plume, from the Bokkamp dam, Old Evaporation area and trenches, reached the aquifer to the south, which is intercepted by monitoring borehole Vr15 in that area. Available evidence suggests that the salt precipitate observed on the site surface, as well as the occurrence of the invader plants, hydraulic down-gradient of this area, defines the maximum extent of a shallow groundwater table, and plume migration.	The mobilization of salts from the Bokkamp Return water dam, Old Evaporation area, area down-gradient of the Bokkamp Dam towards the Vaal River and associated effluent trenches can be managed and reduced if the system is managed in a more environmental friendly manner. The current condition of the effluent trenches towards the return water facility is not up to standard and contaminated water is currently seeps from the trenches directly into the saturated groundwater zone. The workability of the existing liner system of the Bokkamp Dam should be evaluated and inspected. As mentioned in the section regarding the West Complex Tailings Dam, the installation of proper concrete trenches at certain critical portions will benefit in a number of ways. This will ydrogeo water reclamation and minimize water seepage The effort to ydrogeo the clean/dirty water separation along this effluent trench, through the construction of berms, is a positive environmental management performance.

3.8 River water Quality

3.8.1 Pollution load estimation on the Vaal River

A reference site is chosen for each of the investigated water bodies. The selected site is located upstream and outside of the Mine's sphere of influence. The concentrations of the indicator constituents of the selected site are then used as a standard for comparison. Comparison is made between these values and the values of the sites within the Mine's sphere of influence. This method provides an effective survey to gauge the impact of the mining activities on the water quality of the surrounding streams.

The index value is calculated by dividing the concentration of each monitoring site by the concentration of the reference site. Generally, index values greater than one indicate that the water quality is been impacted on.

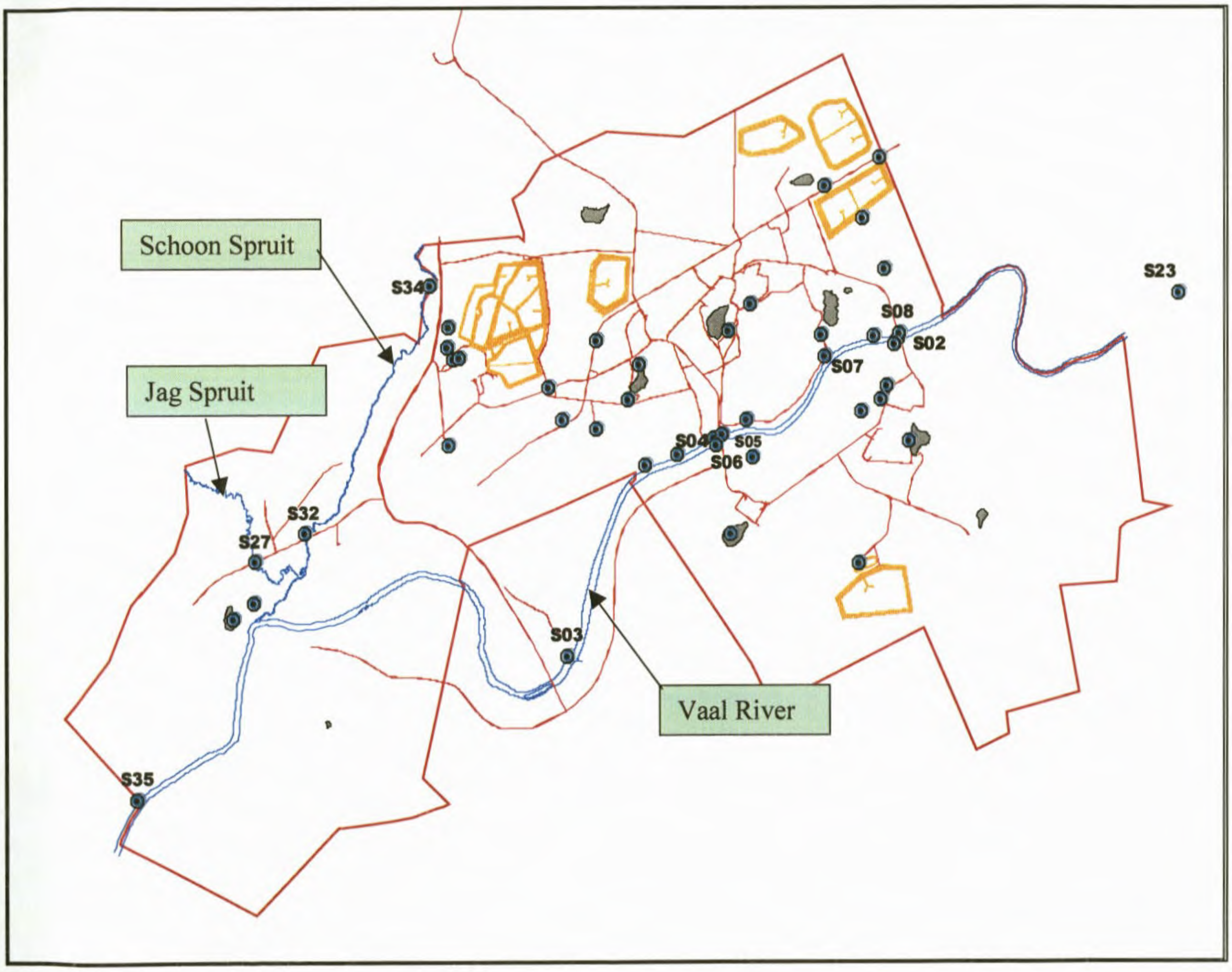


Figure 36: Vaal River Monitoring Sites

Currently the following surface water monitoring points exists in the Vaal River (also refer to Figure 36)

Table 21: Current Vaal River Monitoring Sites

Site	**Description**	FLOW DIRECTION ↓
S23	Vaal River Upstream – sample Eastern boundary at Vermaas Drift	
S2	Vaal River – sample at No.8 Shaft Bridge	
S6	Vaal River – sample at N0.9 Shaft Bridge	
S3	Vaal River – sample at Railway Bridge at Pelgrims Estate.	
S35	Vaal River – sample at southern boundary	
S24	Vaal River – Regina Bridge – down stream of southern boundary	

Table 22: Pollution index for the Vaal River – as measured on the 9th of October 2003

	Reference Site	Vaal River - East to West			Sources	
Site no.	S23 - Vermaas drift	S02	S03	S35	S07 - Eye seepage	S04 - Boat seepage
TDS	612	674	720	720	3002	2445
TDS Index	1.00	1.10	1.18	1.18	4.91	4.00
Cl	82	86	90	94	268	182
Cl Index	1.00	1.05	1.10	1.15	3.27	2.22
Na	76	78	85	30	356	312
Na Index	1.00	1.03	1.12	0.39	4.68	4.11
SO4	220	226	256	256	1656	1246
SO4 Index	1.00	1.03	1.16	1.16	7.53	5.66

- Table 22, indicates the pollution index as measured on this specific day. The impact on the Vaal River water quality was the most obvious at the Pelgrims Estate Bridge. The up-stream (S23) and down-stream (S35) samples show similar water quality.
- Figure 37 shows the seasonal fluctuation in salt content in the Vaal River; the effect of summer rainfall dilution could be seen. Figure 38 shows the salt contents of the down-stream monitoring sites in comparison with the upstream monitoring sites. It could be seen that the TDS content of the downstream samples is most of the time between 0 to 50 mg/l higher than the upstream monitoring site.

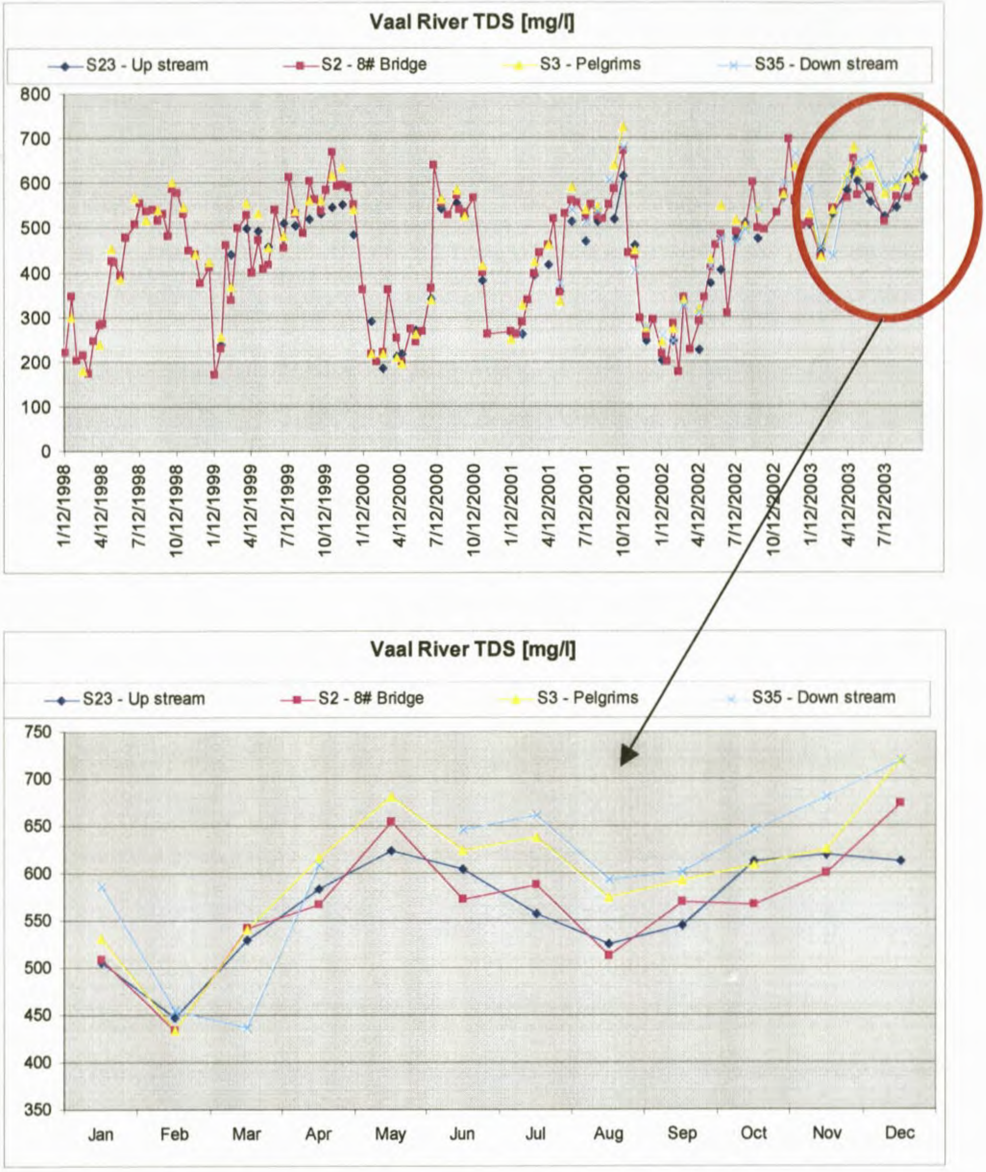


Figure 37: TDS values over time for the Vaal River Monitoring Sites.

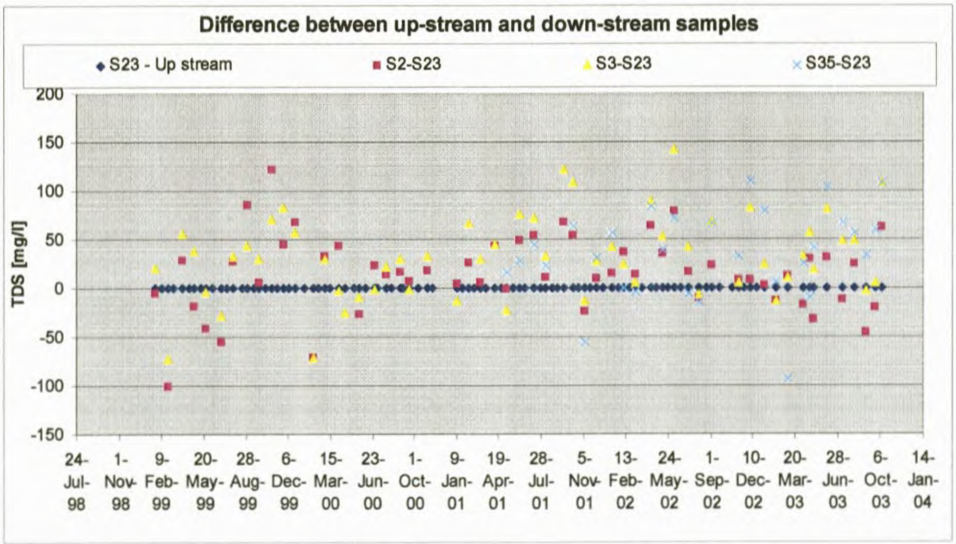


Figure 38: Differences in TDS [mg/l] of the downstream samples against upstream S23

3.8.2 Schoon and Jagspruit water quality over time

Table 23: Current Schoon Spruit and Jag Spruit Monitoring Sites

S27	Schoon Spruit down stream – sample at weir next to tar road
S32	Jag Spruit – sample at bridge
S34	Schoon Spruit up stream

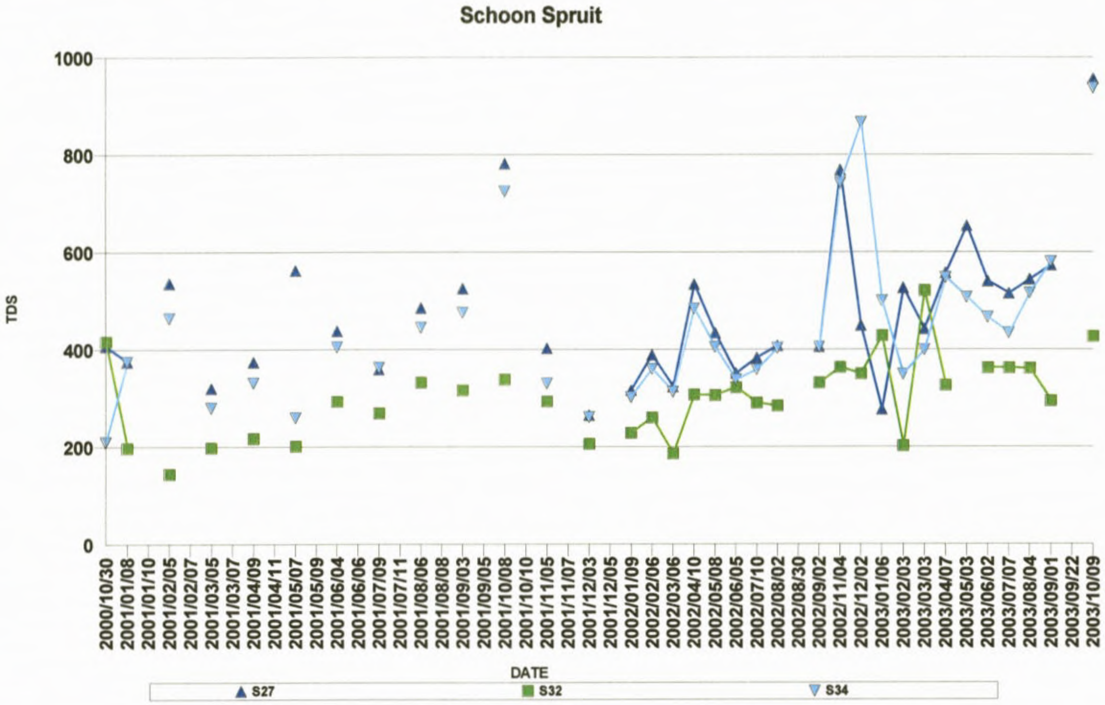


Figure 39: TDS values [mg/l] over time for the Scoon Spruit

3.9 *Preliminary Impact Rating*

A Geohydrological Impact Rating of the identified pollution sources serves as an incentive for monitoring focus. The *80/20 principle* was adopted and applied; this means that 20% of the sites, which cause 80% of the pollution will be classified as "problem areas" and will receive priority attention. The preliminary impact rating must therefore be used as a tool to:

- ensure that the time and money is spending on more important areas,
- to advice responsible managers on groundwater liabilities,
- serve as a basis for future predictions and strategic groundwater management.
- assess site hydrology according to "Rules of the Game",
- to supply answers on "Key Uncertainties" which were highlighted in Figure 3: Matrix illustrating factors in Strategic Groundwater Planning

This geohydrological impact rating was constructed to focus on the following aspects: quantity of waste, potential for leachate generation, toxicity of leachate, potential for infiltration, potential mass flux to the environment, depth to groundwater, aquifer vulnerability, possibility of litigation, possibility of plume spread, contravention of legislation, downstream users and impact after closure (refer to Table 24).

The format of this matrix is simple and easy to use. There are 10 aspects to be rated, each aspect had a likelihood and severity counting, which counts out of 5 each. After a number out of 5 is awarded, according to the likelihood and severity of that specific aspect, it is added up to count out of 10. After each aspect is rated out of ten all is added up to count out of 100. Each identified pollution source will therefore have a rating out of 100. For the purpose of this investigation it was decided that every site above 65 would be rated as priority as high impact sites. Every site between 65 and 55 will be rated as medium impact site and below 55 as low impacts site.

It must be emphasised that this is a preliminary impact rating exercise and that it is essential to upgrade the rating exercise to a more advanced level. This must be done after the detail geohydrological site assessment is completed and should then be updated on a yearly basis. At this proposed advanced stage it should be important to include a weighting factor into the rating method to ensure more credibility. For the purpose of this preliminary exercise it is however important to have a general to good idea of the following site specific aspects:

- geological, geohydrological and hydrological concepts,
- the waste material and the general composition thereof,
- the history of the site, and
- the operations.

The following table (Table 24) lists the identified pollution sources and each site is rated according to the important aspects:

Table 24: List of Initial Impact Rating

Environmental Impact Rating: Vaal River Projects

(L = Likelihood, S = Severity, T = Total)

No	Project/Aspect	Quantity of Waste			Leakage potential & Liner			Toxicity of leakage			Infiltration Potential (n)			Pollution migration (K, T)			Depth to groundwater			Aquifer vulnerability			Downstream users			Legislation & Contravention			Closure Implications			Total
		L	S	T	L	S	T	L	S	T	L	S	T	L	S	T	L	S	T	L	S	T	L	S	T	L	S	T	L	S	T	
1	West Tailings Dam Complex	5	5	10	4	5	9	3	5	8	4	5	9	5	5	10	4	5	9	4	5	9	1	2	3	3	3	6	4	4	8	81
2	Bokkamp dam - final return water dam for tailings effluent	4	4	8	2	5	7	3	4	7	3	4	7	3	4	7	4	4	8	4	4	8	5	5	10	5	5	10	4	5	9	81
3	Open unlined tailings effluent trenches - at toe of tailings dams and towards Bokkamp Dam	4	4	8	4	4	8	4	4	8	4	4	8	3	4	7	4	5	9	4	4	8	4	4	8	3	4	7	4	4	8	79
4	West Extension Tailings Dam	4	4	8	4	5	9	3	5	8	4	5	9	5	5	10	4	4	8	4	5	9	1	2	3	3	3	6	4	4	8	78
5	Game park dam - current dam wall build with tailings material and accumulation of salts due to up-gradient contamination	3	4	7	4	4	8	3	3	6	3	4	7	3	4	7	4	4	8	4	4	8	5	5	10	4	4	8	4	4	8	77
6	Old evaporation area west of Bokkamp - seasonal recharge of tailings effluent	3	3	6	4	3	7	3	3	6	3	4	7	3	4	7	4	4	8	3	4	7	4	4	8	3	4	7	4	4	8	71
7	West Monitoring System and Pump Station - current reclamation system	3	3	6	4	3	7	3	3	6	3	4	7	3	4	7	4	4	8	3	4	7	4	4	8	3	4	7	4	4	8	71
8	West Float Acid and Uranium Plant - Stockpile areas and containment facilities	3	5	8	4	4	8	5	5	10	3	3	6	3	3	6	3	4	7	3	3	6	3	4	7	3	4	7	3	3	6	71
9	10# Ore loading Area - current ore stockpile area south of No.1 Gold Plant	3	3	6	4	4	8	5	4	9	3	4	7	3	4	7	3	3	6	3	3	6	3	3	6	4	5	9	2	3	5	69
10	No. 9 Gold Plant effluent dams	4	4	8	2	3	5	4	4	8	3	4	7	3	4	7	5	5	10	3	3	6	2	2	4	3	3	6	4	3	7	68
11	Skelm dam - old evaporation dam at toe of No.3# Waste Rock Dump	2	4	6	4	3	7	3	4	7	3	4	7	3	4	7	3	3	6	4	3	7	3	4	7	4	3	7	4	3	7	68
12	No.3# Waste rockdump	4	5	9	4	4	8	4	5	9	3	4	7	3	4	7	3	3	6	3	3	6	2	3	5	3	3	6	3	2	5	68
13	Old Calcine Dams - north of West Float & Acid Plant	2	2	4	4	3	7	4	4	8	3	4	7	3	4	7	4	4	8	3	3	6	4	3	7	3	3	6	3	3	6	66
14	Queen Mary Dams	2	4	6	4	3	7	3	4	7	3	3	6	3	3	6	3	3	6	3	3	6	3	2	5	3	3	6	3	3	6	61
15	No.4 # Waste rock dump	4	3	7	4	5	9	3	5	8	3	3	6	3	3	6	2	3	5	2	3	5	1	2	3	3	2	5	3	3	6	60
16	No.1 Gold Plant effluent dams	2	5	7	1	3	4	5	5	10	2	3	5	3	3	6	2	2	4	3	2	5	3	2	5	2	3	5	3	3	6	57
17	No 3# Washing Plant Pump house & Dams	2	2	4	1	3	4	4	4	8	3	4	7	3	4	7	3	3	6	3	3	6	2	2	4	2	3	5	2	3	5	56
18	Redundent West Extension Storm Water Dam	2	2	4	1	3	4	4	4	8	3	4	7	3	4	7	3	3	6	3	3	6	2	2	4	2	3	5	2	3	5	56
19	No 3# Concrete Stormwater Channel	2	2	4	1	3	4	3	3	6	3	4	7	3	3	6	3	3	6	3	3	6	2	2	4	2	3	5	3	3	6	54
20	3# sewerage plant area	2	3	5	2	2	4	2	2	4	4	3	7	2	2	4	3	3	6	3	3	6	2	1	3	3	2	5	2	2	4	48
21	6# and 7# Waste rock footprints	2	2	4	2	2	4	3	4	7	2	3	5	2	3	5	2	2	4	2	2	4	2	3	5	2	2	4	2	2	4	46
22	Ellaton Mine - Black Reef Area	2	3	5	2	2	4	2	2	4	2	3	5	2	2	4	2	3	5	2	3	5	2	2	4	2	2	4	2	3	5	45

Scoring of an aspect/ site:

Severity + Likelihood = Impact Score (use highest possible score, e.g.: Severity = 5, Likelihood = 3, Thus score = 8, or
Severity = 2, Likelihood = 2, Thus score = 4, use score rating = 4
Then Score + Score = Total aspect/site Score out of a 100
Then >65 = High Risk; >55 and <65 = Medium Risk and <55 = Low Risk

4 Understand site monitoring requirements

4.1 Introduction

The geohydrological impact rating exercise is now completed and the critical areas identified, the assessment could continue and start to focus on the water monitoring network and programme. This part of the investigation will mainly focus on the optimisation of the current ground- and surface water-monitoring network. A technical assessment will be undertaken and include the identification of information gaps, siting of additional boreholes, drilling of boreholes, aquifer testing and field sampling exercises.

The progression of this part of the assessment should be more or less as follows (detail discussion follow):

Table 25: Description of tasks required for 'Understand site monitoring requirements'

Task	Description / Overview
Identification of information / monitoring gaps	This will give an overview of site-specific conditions and identification of information gaps. To understand the monitoring requirements of a certain area the site geology, geohydrology and hydrology needs to be known. The type, quantity and characteristics of the waste are also very important.
Siting of additional boreholes	Additional monitoring sites must be sited to fill information gaps. The siting process will be based on scientific based methods.
Drilling of additional monitoring boreholes	The drilling of additional boreholes must follow. This must be done according to certain specifications and site-specific conditions.
Aquifer testing	Boreholes must then be tested to identify aquifer parameters and characteristics
Monitoring programme	The monitoring programme must be updated to insure that boreholes are sampled at the correct frequencies and analysed for suited parameters. Groundwater levels must also be included.
Routine Monitoring Reports	The findings of routine monitoring field exercises must be discussed and monitoring results be interpreted.

All these steps will then be feeded into the next level of the geohydrological assessment.

4.1.1 Overview of monitoring

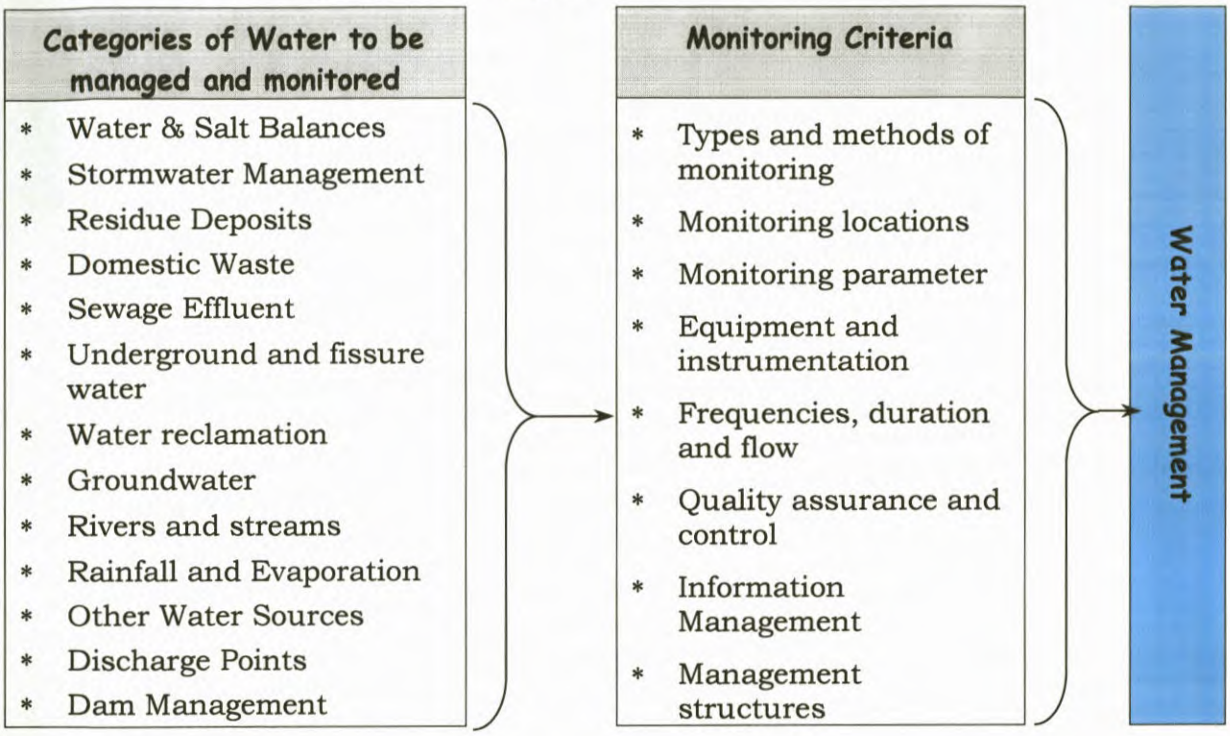
In order to ensure that this Monitoring Program achieves the required result, it is appropriate to restate the main objectives of the program:

- To serve as an exclusive guideline for region specific water management teams, based on environmental management requirements and site-specific operations.
- To assist the region specific water management teams in their current operations and water management strategy.
- The results or deliverables from an efficient water monitoring program should be:
- Assist and ensure efficient environmental management,
- Assist in risk assessments,
- Identify shortcomings
- Major anomalies will be identified and subsequently be brought to the attention of management. Recommendations will also be made to improve water quality characteristics to ensure that operations adhere to Department of Water Affairs and Forestry requirements.

- Serve as an information base during management decisions
- Serve as verification of good practices and good management decisions

The following diagram illustrates the identified categories, which must be included in the water-monitoring program. Each category must be managed according to a specified range of monitoring criteria. Note: This is only included for discussion purposes – refer to paragraph 4.2. (Potential sources of groundwater pollution), in Section 1, for descriptive notes on some of the categories.

Table 26: Water Monitoring Programme Categories & Criteria



4.2 *Identification of information / monitoring gaps*

4.2.1 *Overview*

To optimise the groundwater monitoring network to such a stage that it could serve as an appropriate indicative and management tool certain questions needs to be answered:

- What is the ultimate objective of monitoring – is it only to satisfy in minimum requirements set out by DWAF (refer to Minimum requirements for monitoring at Waste Disposal Sites, 1996), or is it to serve as a good groundwater management tool to ultimately assisted in aquifer characterisation, model calibration and decision making processes?
- How could one be sure that 'enough' groundwater monitoring sites is installed and what is the optimal frequencies to sample the monitoring sites
- The following will attempt to give some answers:

The term 'Information gap' becomes applicable when one realise that, to answer certain questions, or to solve certain problems, more information will be needed. This could either be information regarding groundwater levels, geological characteristics, boundary conditions or groundwater qualities and identification of indicative chemical parameters.

The quantity of groundwater monitoring sites will therefore ultimately depend on the type of information that is needed and the site-specific conditions. For the purpose of this investigation, the location and number of groundwater monitoring sites were based on the following:

- Geology: The heterogeneous nature of the local geology, which includes complex dolomitic aquifers, black reef quartzites, alluvial clays and Ventersdorp lavas, make groundwater monitoring a complicated function, which needs accurate planning and siting. It is therefore understandable that a number of boreholes be required to at least cover all the geology types.
- Type of waste and operations: On a typical gold mining site various types of waste and a number of operational sites exist. It could become a very complex exercise to distinguish between certain wastes and indicative chemical parameters. For instance; a tailings storage facility is located adjacent to a very big Gold and Uranium Plant, and on the other side of the gold plant is a shaft with a very big waste rock dump. These facilities are all situated in line along the topography; the tailings dam is situated up gradient, then the plant and then the shaft hydraulic down gradient. Monitoring boreholes should be sited to fingerprint contamination from each source, with associated possible seepage or leakage of containment facilities. Also refer to paragraph 4.2. – Section 1: Potential sources of groundwater pollution,
- History of sites and operations: On old aerial photo's unknown sites, trenches and ponds were identified, these sites were visited and the placement for groundwater monitoring sites, at some were requested,
- Water quality contour maps and Numerical modelling: The following contour map of the TDS values shows over interpolation at areas where no monitoring sites exists. This could supply wrong impressions of pollution migration or extents of plumes. The **red circles** indicate areas where more information is still needed for model calibration purposes. Boreholes within the **blue circles** indicate newly drilled monitoring boreholes (refer to Table 13: List of monitoring boreholes – the green and blue highlighted sites on this table indicated newly drilled monitoring boreholes). These boreholes were drilled to overcome information gaps:

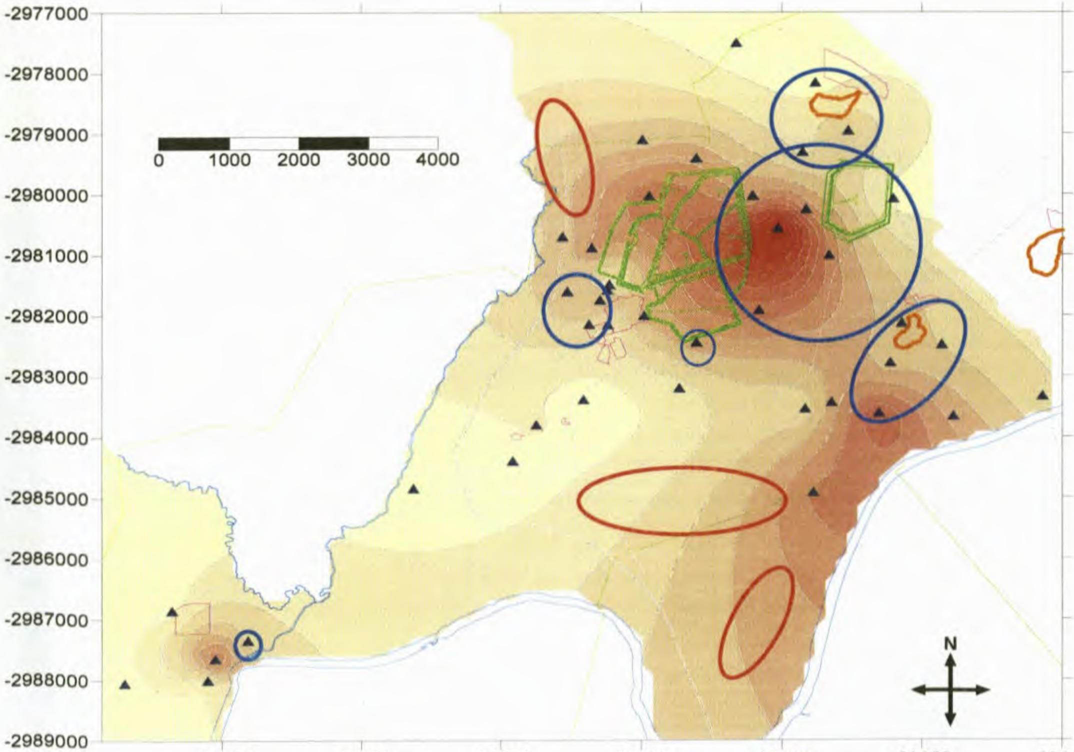


Figure 40: Map indicating information gaps and newly drilled monitoring boreholes.

4.2.2 *Siting of additional boreholes*

The following discussion gives an overview of the methods used to site the monitoring boreholes indicated in the blue circles above:

Geophysics was one of the methods, which were applied for the sitting of the drilling positions for the proposed monitoring boreholes. Topography, surface drainage, visual seepage, etc. were also considered during the sitting process.

The investigation required additional surface geophysical surveys, which were aimed at delineating structures and lineaments, identified from surface mapping, remote sensing as well as from existing information sources. This was necessary due to limited information being available in the target area in between the slimes dams, from previous surveys. Previous surveys had a regional approach and only information captured between the tailings dams is directly applicable to this investigation.

Several techniques were used at different profiles depending on the targets identified and character of the site. These were:

1. Geomagnetic profiling
2. Resistivity profiling
3. Frequency domain Electromagnetic (EM) Max-Min profiling
4. Very Low Frequency (VLF) Electromagnetic (EM) profiling

Geomagnetic profiling was done extensively to locate dyke intrusions. These profiles were carried out across the target area in an east-west direction to locate and define possible north-south trending dyke intrusions. The presence of several high-tension electrical power lines, as well as several pipelines, hampered these surveys. The main power line running in a north-south direction in between the two slimes dams caused major problems due to it running right across the Black Reef Quartzite outcrop in the central part of the study area where complex faulting occurs – thus preventing detailed geophysical surveys in this area. Most major anomalies noted on geophysical profiles were caused by power lines and pipelines and analyses of geophysical data had to take it into account.

Electromagnetic profiling was done using the Max-Min EM due to its effectiveness in poor conductive shallow topsoil occurring in the target area. Resistivity profiling was done in conjunction with EM profiling where surface conditions allowed it. VLF profiling was done along certain profiles to evaluate its effectiveness in the dolomitic terrain in conjunction with the EM and magnetic data.

4.2.3 *Geophysical survey results*

Fifteen geophysical profiles were carried out across the target area, as indicated in Table 27. Profiles were numbered as 1 to 15. The following techniques were applied at the different profiles:

Table 27: Geophysical profile sections and method used.

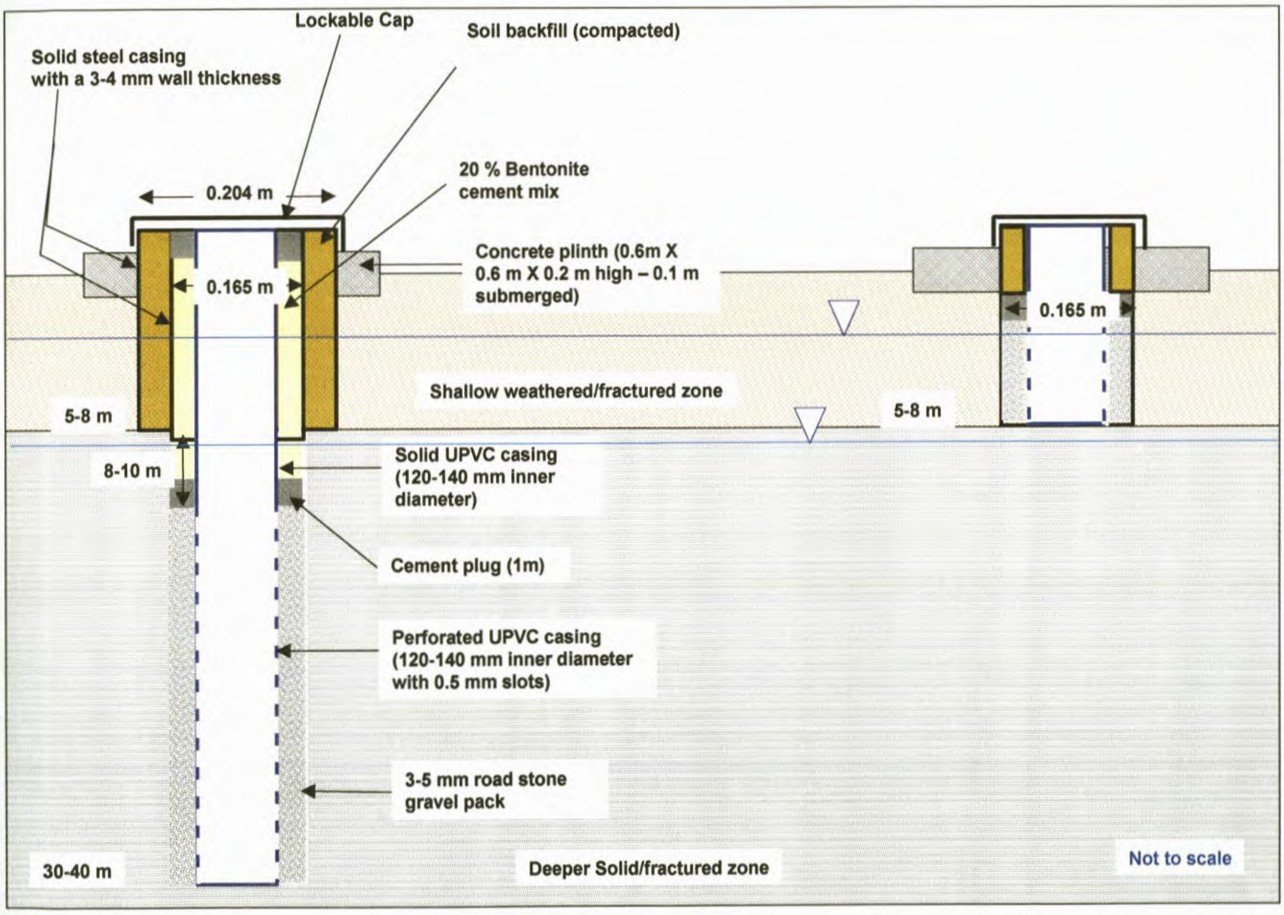
PROFILE NUMBER	GEOPHYSICAL TECHNIQUE APPLIED	PROFILE NUMBER	GEOPHYSICAL TECHNIQUE APPLIED
Profile 1	Geomagnetic – Resistivity	Profile 9	VLF EM
Profile 2	Geomagnetic – MaxMin EM – Resistivity	Profile 10	Geomagnetic
Profile 3	Geomagnetic	Profile 11	Geomagnetic
Profile 4	Geomagnetic – Resistivity	Profile 12	Geomagnetic
Profile 5	Geomagnetic – Resistivity	Profile 13	Geomagnetic
Profile 6	Geomagnetic – MaxMin EM – Resistivity	Profile 14	Geomagnetic
Profile 7	Geomagnetic – Resistivity	Profile 15	Geomagnetic
Profile 8	Geomagnetic – VLF EM		

Another 6 lines were walked in 2002 for the drilling of additional boreholes: Geophysical results indicate that the dolomite in the target area is medium heterogeneous with minor deeply weathered structures encountered. Little indication of major north-south trending structures – possibly associated with dyke intrusions could be identified. Geophysical data indicated that the dolomite could best be described as outcrop and sub-outcrop, pinnacle dolomite with water bearing slots and occasional mega joints. Borehole siting was concentrated on deeper weathered areas and channel like depressions within bedrock.

4.2.4 *Drilling of additional monitoring boreholes.*

Altogether 16 additional monitoring boreholes were drilled in 2002 and 2003 (see Table 13). The boreholes drilled in 2003 were constructed in multiple form – one deep and one shallow hole next to each other to differentiate between shallow and deeper aquifer conditions (see Figure 41).

Figure 41: Schematic representation of the monitoring borehole construction (source: Geocon, 2002)



Borehole drilling and the construction of the boreholes must be according to certain specifications. A good guideline to follow is the Waste Management Series of DWAF, 1998. Site-specific conditions must also be considered when boreholes are drilled and constructed. If site specific geological and geohydrological concepts are ignored it could cause things like cross-contamination through impermeable clay layers, etc.

The boreholes vary in depth between 5.00 – 40.00 m. The purpose of the boreholes was to determine the geology and geohydrological conditions in the area between the two tailings dams, in the Game Park below the Bokkamp Dam, at 3 Shaft WRD, 4 Shaft WRD and to the west at the metallurgical plants. The boreholes were developed to serve as future monitoring boreholes. The geological borehole profiles are listed in Table 31 and Figure 43 and will be discussed in more detail later on.

4.2.5 *Aquifer testing*

Pumping tests were conducted on the boreholes that were drilled to determine the hydraulic parameters of the subsurface. The purpose of the pumping tests was to derive hydraulic parameters for the upper, weathered and the fractured bedrock hydraulic zones. Refer to paragraph 5.4.1 Aquifer Tests to obtain Transmisivity and Hydraulic Conductivity for a detailed discussion in Section 3 of this document.

4.3 *Monitoring programme*

After a detailed evaluation of the current Vaal River water monitoring network and associated monitoring system, it was decided to upgrade and compile an official water-monitoring programme. The following table explains the different types and frequency of monitoring necessary for the efficient monitoring and data collection of individual sites according to DWAF. This will serve only as a guideline to establish more site specific and detailed monitoring plans.

Table 28: Minimum monitoring requirements at various types of waste management facilities (DWAF, 1998)

	At or near surface monitoring								Within waste or unsat. Zone						Groundwater Monitoring							
MONITORING REQUIREMENTS → ↓ WASTE ENVIRONMENT	Rainfall	Evaporation	Run-off (volume, quality)	Water infiltration on waste	Toe seepage from waste	Soil cover on waste	Vegetation on waste or soil	Bioassaying	Pressure vacuum lysimeters	Gas samplers	Electrical conductivity probes	Leachate collectors	Temperature within waste	Special detectors	Special monitoring holes	Other holes	Groundwater levels	Groundwater chemistry	Borehole yield	Groundwater usage	Fountain seepage	Water balance
Mines – Reactive Environment	d		d																			m
Tailings Dams				m	m	y	y					m			yes	yes	m	3m	y	y	m	m
Ore Discard			d	m	m	y	y					m			yes	yes	m	3m	y	y	m	m
Waste Rock Dumps (opencast)				m	m	y	y								yes	yes	m	3m	y	y	m	m
Waste Rock Dumps (other)					m	y	y								yes	yes	y	y	y	y	y	y
Mine Water (impoundment)				m	m										yes	yes	3m	3m	y	y	m	m
Mine Water (discharged)			d					y														w
Hazardous Waste	d	d	d	m	m	m	m	y	m	m		m		m	yes	yes	m	m	y	y	m	y
Domestic Waste Sites	d		d		m	y	y			m					yes	yes	3m	3m	y	y	m	m
Sewage – Unlined maturation ponds			d												yes	yes	y	3m	y	y	m	
Radioactive waste	As specified by the CNS in collaboration with the DWAF																					
Explanation of codes: d = daily monitoring; w = weekly monitoring; m = monthly monitoring; 3m = 3-monthly monitoring; y = yearly monitoring																						

(Minimum Requirements for Water Monitoring at Waste Management Facilities, 2^nd^ Edition 1998, 6-3)

Monitoring at the following sites/areas where considered, this was used as a guideline and was followed where practicable possible:

- Monitoring boreholes to be drilled and sampled in order to effectively determine and monitor the impact (quality and quantity and extent) of the mining activities on the groundwater system;
- All borehole siting activities must be based on scientific investigations;
- The hydrogeologist must approve the positions of all boreholes (in writing), before drilling commences;
- Additional monitoring points as requested by the Regional Director of DWAF must be adhered to;

- Sampling must be performed at points where groundwater seepage intercepts the surface;
- Monitoring points at rehabilitation sites are of essence as it is an indication of the success of the project.

Table 29: Recommended monitoring distances for different types of waste environments. (DWAF, 1998)

Environment	No. Holes	Distance From Waste	Monitoring Frequency
Mines – Reactive Environment			
Tailings facilities	1-3	50-250 m downstream	Samples from boreholes every 3 months. Sample monthly from streams above and below mine. If pollution from mine occurs, install recorders in streams above and below mine measure daily flow, EC and pH. Sample farmers' boreholes1-5 km radius, initially and when problems are expected.
Ore discards	2-5	50-500 m downstream and above	
Rock discards (opencast)	1/250 ha	into water accumulations	
Rock discards (other)	1-3	50-200 m downstream	
Mine water (impoundment)	2-6	50-1000 m downstream	
Framers' boreholes		Within 1-5 km from mine workings	
Hazardous Waste	5-10	10-200 m surrounding	Site specific constituents at frequencies recommended by impact study

Ultimately the sample frequencies depend on locality, information required and certain aquifer characteristics. The site groundwater monitoring system (see Table 13) measures up to the recommended minimum requirements for borehole siting and monitoring. The required areas for additional borehole siting (see Figure 40) will therefore supply information on a more advanced level as what is essentially expected from the authorities. This is an important factor, which could impact on the credibility of site assessments, mine management must therefore use their own discretion for decisions like this.

4.4 Monitoring Parameters – Analytical Variables

The water permit prescribes the frequency of analyses as well as constituents to be analysed for of specified monitoring points.

For sites presently not regulated by permit conditions, the following guidelines may be used: The range of elements that may be found by analysis of a waste environment is very extensive. For the purpose of this document, the required analysis are grouped under two headings:

- Comprehensive analysis
- Indicator analysis

It is important to note that all monitoring performed for cyanide should be done according to the AngloGold cyanide code, which was developed in accordance to the international cyanide code.

4.4.1 Comprehensive Analyses

For all new sites and first time monitoring at existing sites, a comprehensive analysis is required. It is essential that accurate background levels, for as wide a range of constituents as possible, be established at the outset. This will usually include a complete macro analysis as well as an analysis for the trace elements that could reasonably be expected to be present within the environment tested.

4.4.2 Indicator analysis

Indicator analysis may be performed once comprehensive analyses have been completed. This process may continue until undesirable trends are uncovered. This will keep analytical costs to a minimum, but still provide enough information upon which further action can be initiated, if necessary. Depending on the type of waste handled, so-called "pollution indicators" for each of these environments may be identified. Examples are:

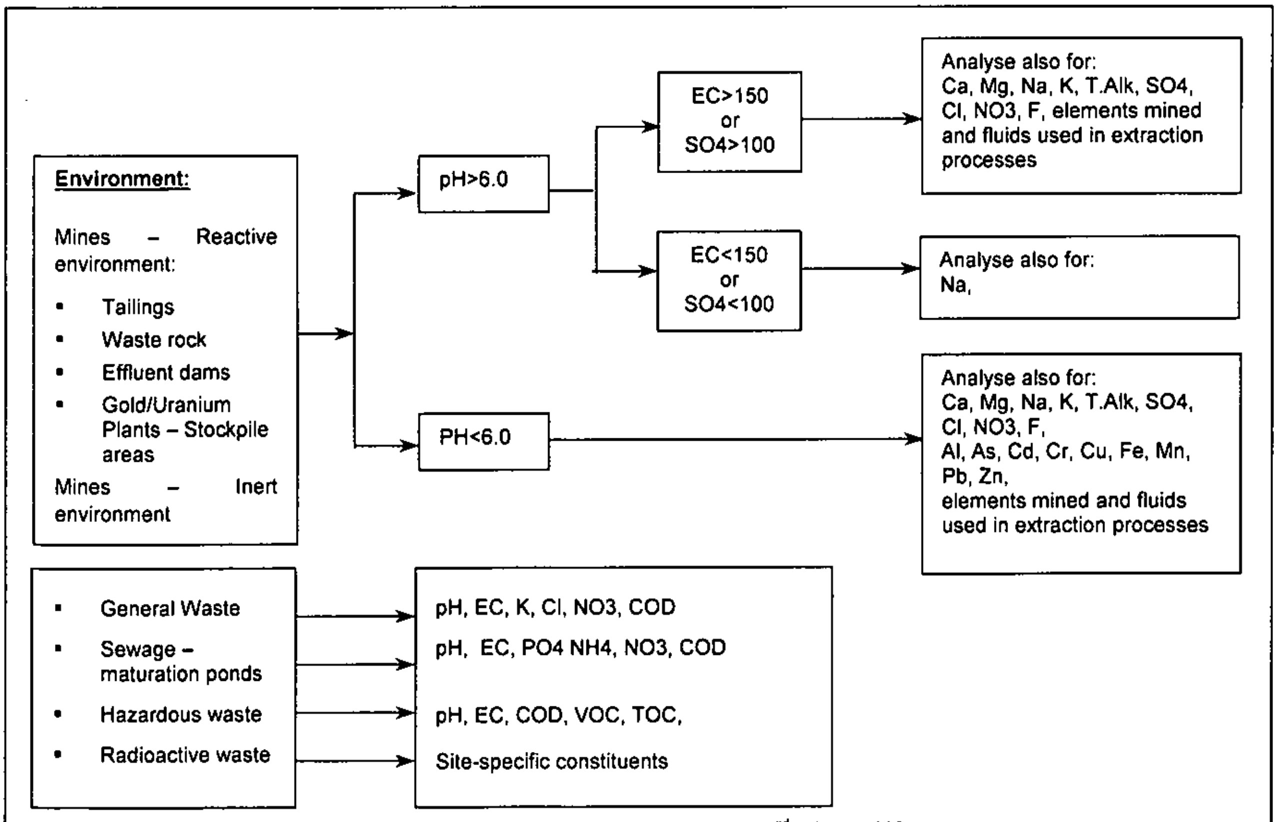
- General and special variables for discharge of industrial effluent into public streams, such as electrical conductivity (EC), Na, SO_4.
- The so-called sewage variables, such as COD, NH4, PO_4.
- Hazardous waste disposal variable, such as VOC, THM, Cr_{6+}
- General waste disposal variables, such as COD, Cl, NO_3, NH_4.
- Mine pollution variables, such as pH, EC, Mn, SO_4.

Apart from this distinction according to the type of waste environment, another dimension can be introduced by classifying contaminants into four classes, namely:

- Physical, such as pH, EC, alkalinity and acidity.
- Aesthetic, such as iron, manganese, odour and taste.
- Other inorganic, such as high TDS and heavy metals.
- Other organic, such as toxic or carcinogenic compounds.

Analysis of physical, aesthetic and inorganic variables is easily performed. Qualitative and quantitative analysis of organic constituents are extremely complex. In view of these complexities and the high cost associated with chemical analyses, the list of variables to be tested for under these minimum monitoring requirements, should be kept as short as possible. Once pollution is detected, more elaborate tests may be performed. The following table suggests minimum monitoring requirements for chemical analyses:

Table 30: Monitoring Parameters – Analytical Variables



Minimum Requirements for Water Monitoring at Waste Management Facilities, 2nd Edition 1998, It is up to the discretion of the individual, which other parameters are to be analysed for. E. Coli should be analysed for in instances where biological contamination is expected. Ammonia, nitrate and nitrite are meaningful parameters to analyse for in all environments of human and animal waste. Many modern analytical laboratories are using multi-element analytical techniques such as ion chromatography. In these instances, the full chromatographic spectrum should be considered, on condition that this is available at the same price as the required indicator constituent.

4.5 Routine Monitoring Reports

At least two monitoring reports should be compiled on a yearly basis; one after the rainy season and one after the dry season. This will create a good database of findings and seasonal trends. These reports should summarise findings made during routine water monitoring field exercises. The reports needs to include comments on the current state of the site monitoring system, groundwater level discussions and observed trends in ground- and surface water quality over time, mainly through the use of graphical interpretation methods. These methods include:

- Water level fluctuations
- Time Graphs
- Contour Maps – of groundwater levels and groundwater quality
- Data Tables

The reports further needs to gives a detail discussion on site-specific groundwater issues and supplies the following information:

- Identified site, or Business Unit,
- Table of existing groundwater monitoring sites, date last sampled, chemical and water level data of latest sample run,
- Time graphs of selected chemical parameters,
- Table, which summarises identified, site-specific groundwater issues and required actions.

The various site concentrations can be compared by means of a colour to a certain water quality standard. This method is useful because an unchanging standard is always used. The South African Water Quality Guidelines for Human Consumption and Livestock Watering (Department of Water Affairs and Forestry, 1996) were used.

5 *Formulating Geohydrological settings and concepts*

5.1 *Introduction*

This part of the investigation is very important and will serve as input data for the next step of the assessment, which will be flow and transport modelling.

Prior to the development of a flow model, the hydrology of the study area must be understood conceptually. See section 5.4, Hydraulic variables and constraints, which illustrate technical data required for the modelling process. Transferring the real world situation into an equivalent model system, which can then be solved using existing program codes, is a crucial step in groundwater modelling. The proposed numerical model will therefore be a summary of:

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

5.2 *Background Information*

The following data was obtained from the *Jones & Wagener Inc., 1978 and 1984, Geotechnical reports for the West Reef Area and West Extension Tailings dam. This data is deliberately included under a separate heading to again put the emphasis on historical findings and reports – this should form the basis of the conceptual framework.*

- The variation in the chert and rock components of the Monte Christo and Oaktree Formations is strikingly illustrated on site where the area on Monte Christo is defined by a surface strewn with abundant chert rubble (angular boulders and gravel) whereas within the area on the Oaktree shallow sub-outcrop, floaters and outcrop are present.
- As the rocks of the Monte Christo Formation are rich in chert and poor in manganese weathering results in a fairly thick residuum of sandy material with chert, below a capping of chert rubble. In contrast the rocks of the Oaktree Formation are chert poor and the protective capping of chert rubble is not developed. This result in the removal of the weathered soil residuum and the occurrence of outcrop and/or shallow sub-outcrop of dolomite.
- The Vaal River acts as a major source of groundwater recharge. If dewatering of the dolomite rock mass should occur in the vicinity of the Vaal a loss of water from this river system could be expected probably sufficiently high as to affect volume. That volumes have not been affected is a strong indication of the negligible influence of de-watering.
- The occurrence of diabase dyke intrusions is limited and the formation of groundwater compartments restricted as a result.
- Sinkholes forming within the main dam area will not affect the stability of the dam. They could however result in direct channelling of polluted water and slime from the dam to the underlying water table.
- According to data obtained from permeability tests in shallow soil test pits it was discovered that water would move vertically downwards in the soil profile until it encounters either the groundwater table or bedrock.

- Dolomite and chert from the impermeable rock material and movement of water must take place either along joints in the rock-mass, or when above the groundwater table, along the interface of the overlying soil and dolomite, in a direction governed by the slope gradient of the rock-head.
- Flow directions affected by pinnacle/slot rock head morphology (which become more complex) are still governed by general gradient, and locally, by the more deeply weathered major slots or fault lineations. There would thus be a tendency for water at the residuum/rock head contact to concentrate in these features.
- Observations on elevation of the water table recorded in current and earlier percussion boreholes indicate that:
- There is a shallow artificial water table at an elevation of about 1310 masl (approximately 2-3 meters below ground level) in the area east of the West Division Dam (WC-TSF). The water table has developed in response to seepage losses from the dam in conjunction with shallow dolomite rockhead.
    - This observation is in contras with findings made by *Funke (1990)*, which stated that pollution of groundwater by seepage is unlikely, particularly if gold slimes deposits have been built on impermeable soil:
    - This ideal situation of minimal seepage and groundwater pollution is not always possible and does not always occur. Visual inspections of the two tailings storage facilities indicate leaching as water percolates through the structure. The type of geological formations below the dam and the associated geohydrological characteristics will play a large role on seepage and water losses – The statement of Funke is therefore very idealistic and definitely not site specific but rather more in general.
- There is a permanent natural water table at a depth of about 1300 masl. The elevation of this table was noted in other boreholes during an earlier study, which were separated by distances of up to 5 km.
- The free water surface in the Vaal River is at an elevation of 1280 masl. On the basis of all available water table elevations both north and south of the Vaal River it was found that the hydraulic gradients are fairly consistent at about 6% (range from 4% to 7%).
- In most cases where the slimes dams at Vaal Reefs overlay sub-outcrop or outcrop dolomite the phreatic surface does create wet conditions for a variable distance away from the toe of the tailings facility.
- Conceptual groundwater flow models shows that where the depth to solid dolomite is greater the apparent seepage becomes less. Where the dolomite is deep enough no seepage will be seen to emerge around the toe of the dams.

5.3 *Site Aquifers*

The area under investigation is underlain by different and complex aquifers systems. The following discussion provides and overview of site aquifers.

5.3.1 *Dolomite Aquifer*

The dolomite aquifer consists of solid chert-poor formations on the western part of the aquifer, which is followed, in the east by chert-rich dolomites. The chert-poor dolomites have a low general permeability and the chert-rich dolomites are expected to have a higher permeability. Higher permeability zones may occur along geological structures.

The main hydraulic zones are determined by the upper, weathered dolomite and soil zones and the lower solid fractured bedrock dolomite. The bedrock dolomite consists of fracture and matrix zones. These hydraulic zones have important influences on contaminant transport by providing preferred pathways for transport and adsorption for retardation. Other important hydraulic zones are the dyke zone and the properties of the dyke and its contact zones – which are not well defined and the quartzite-dolomite contact in the west.

Little or no surface runoff occurs in dolomitic terrain and most rainwater percolates down through solution enlarged fractures to the water table. This zone of vertical groundwater movement is termed the vadose zone. At the water table, horizontal flow predominates over vertical flow and the groundwater migrates down-slope. This zone of horizontal movement is termed the phreatic zone.

5.3.1.1 Weathered Dolomitic Aquifer

The weathered aquifer consists of both alluvium and weathered dolomitic material. According to the geological logs, the depth of weathering ranges from 5m to 20m below surface. The groundwater rest level is relatively shallow and generally lies within the weathering profile itself. Water strikes are mostly commonly associated with changes in the subsurface such as at the contact between alluvial clays and the dolomitic bedrock, at the base of the cherty weathering profile or within solution cavities and joints within the dolomites themselves.

The weathered aquifer is the most vulnerable to contamination from pollution sources. A potentially important aquifer is being contaminated where thick accumulations of cherty gravel occur.

5.3.1.2 Solid/Fractured Dolomitic Aquifer

The top of the fractured dolomitic aquifer is generally located at the base of the weathering profile some 5m to 20m below surface. The primary porosity of dolomite is negligible. Percolating water, which forms carbonic acid dissolves the dolomite to form solution cavities. Although solution cavities and fractures were intersected during drilling, the area is not characterized by large wad filled solution cavities at present.

Pumping tests undertaken during previous investigations have indicated that the transmisivity for the fractured dolomitic aquifer ranges 1.3m^2/day to 140m^2/day. This relatively wide range of values is to be expected in an anisotropic medium such as fractured dolomite.

The water strikes within the fractured dolomite commonly occur within solution cavities and fractures. However, previous investigations undertaken within dolomitic terrain has indicated that the dolomitic aquifer and any overlying cherty transitional zone may act as a single hydrogeological unit (Krantz, 2001). The degree of this hydraulic interconnection would be determined by the drilling of shallow monitoring boreholes.

Previous investigations have suggested that there is minimal interconnection between the dolomitic aquifer and the Vaal River. However, such investigations are based on the groundwater levels within the monitoring boreholes at the northern well field – this could be misleading because of the active production activities currently in progress.

The dolomitic aquifer has always been recognised as an important water resource that has the potential for large-scale water supply projects. The prevention or containment of the pollution within this aquifer is therefore an important priority.

5.3.2 Alluvium & Vaal River Aquifer

The north bank of the Vaal River is underlain by solid to fractured dolomite. Alluvial sands and clay beds directly overlie the dolomite with surficial deposits compromising essentially levee and backswamp deposits. Previous investigations by Wates and Wagner (1990) indicate that alluvial clay deposits within the vicinity of the Vaal River result in perched groundwater levels. These perched groundwater levels may result in shallow seepage that may rapidly migrate to the Vaal River.

Three distinct geological and geohydrological zones have been identified along the length of the current well field on the northern bank of the Vaal River. These zones could be applied to the rest of the Vaal River's riverbank and conceptually it looks as follows:

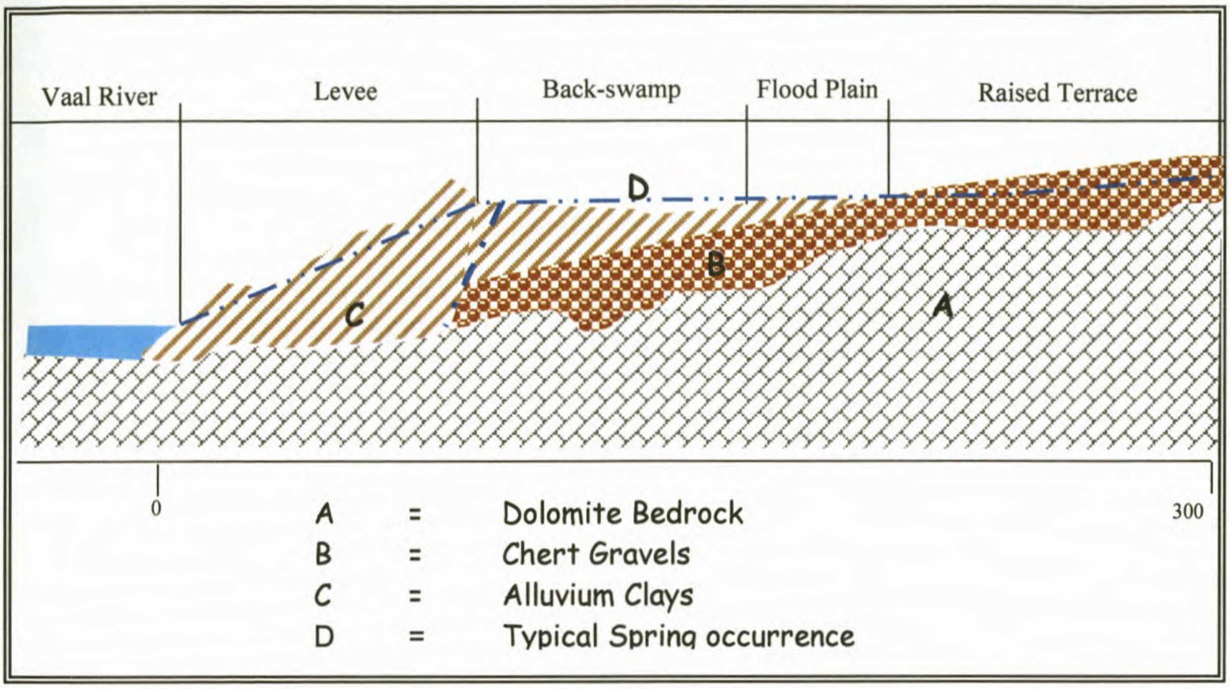


Figure 42: Cross section of Vaal River Model (based on model created by Wates and Wagner (1990))

5.3.3 The Ventersdorp Lava Aquifer

The occurrence of groundwater in the Ventersdorp lavas is controlled by the depth and degree of weathering and fracturing of the lava itself. A general water-bearing horizon is present, as evidenced by the number of boreholes drilled between Orkney and Klerksdorp. This water-bearing horizon is relatively shallow, boreholes were reported to be between 10m and 30m deep, and the water table was measured as less than 10m. The hydraulic gradient is westwards towards the Schoonspruit. The Ventersdorp lava groundwater is susceptible to pollution from effluent seepage because of the relatively high permeability of the topsoil and developed fractures.

5.4 Hydraulic variables and constraints

This part of the formulation of the geohydrological concepts is very important and will be translated into numerical terms during the modelling process. Previous experience and knowledge of the host lithologies are also reflected in the groundwater concepts especially where there is limited available field data or time-dependent observations. The geohydrology of the investigation area was systematically assessed to ultimately undertake numerical modelling of the relevant aquifer systems with a view to achieving the following:

- Identify areas in which the surface and groundwater systems interact,
- Quantifying the volume of flow from the groundwater system into the Vaal River,
- Identifying areas in which remedial action should be concentrated for closure planning.

Variables and constraints that act upon the movement of pollutants through an aquifer are typically:

- The transmisivity and hydraulic conductivity of the underlying strata.
- The storativity and effective porosity of the underlying strata.
- Recharge from rainfall and mining operations,
- The hydraulic gradient of groundwater levels,
- Dispersion and convection characteristics of the aquifer.
- Boundaries such as dykes, rivers, constant heads of artificially recharge zones, catchment boundaries and topography.
- Other sources of water in the area such as streams, pans, dams and lakes.
- Sinks within the area where groundwater is abstracted or naturally emanates on surface in the form of fountains.

5.4.1 *Aquifer Tests to obtain Transmisivity and Hydraulic Conductivity*

Pumping tests were conducted on the boreholes that were drilled to determine the hydraulic parameters of the subsurface. The purpose of the pumping tests was to derive hydraulic parameters for the upper, weathered and the fractured bedrock hydraulic zones. The pumping tests consisted of calibration tests of 1-3 steps that lasted for 15 min each, followed by multi-rate tests that consisted of 1-4 steps of 60 min with recovery tests in between. After that a constant rate discharge test was conducted for either 6, 12 or 24 hours (depending on yielding rates), followed by recovery again.

Most of the boreholes had very low yields and were pumped dry within short time periods, however boreholes Vr28, Vr30 and Vr31 are high yielding boreholes (see Table 31). The methods of Cooper-Jacob and Theis & Jacob recovery were used for the calculation of the hydraulic parameters.

The average range of hydraulic conductivities derived from the pumping tests are as follows:

- Fractured dolomite = 0.1 – 1 m/d
- Weathered dolomite = 0.5 – 2 m/d
- The shallow boreholes in the upper, weathered soil and weathered zone had hydraulic conductivity values of (Vrm21) 0.42 m/d and (Vrm27) 0.33 m/d, which is higher than the average value. This indicates that the upper, weathered zone is more permeable than the bedrock dolomite and would explain the preferred shallow seepage surrounding the tailings dams. These values compares well with other literature and previous investigations.

The following table summarises the localities and geohydrological characteristics of the newly drilled monitoring boreholes. These boreholes were drilled during the Vivier, 2001 investigation and the AngloGold, 2002 investigation.

The hydraulic conductivity was determined from pumping tests. The tests showed that the upper weathered zone is more permeable than the bedrock dolomite with an average hydraulic conductivity of 1.5 m/d. The average hydraulic conductivity of the bedrock dolomite was 0.4 m/d.

Table 31: Results of aquifer tests done on certain boreholes.

BH No.	Description	Geology	BH Depth (m)	Main Water Strike (m)	Water level (m)	BH Yield (l/s)	Avg. pump rate (L/s)	Pump Duration (min)	CR - Late Time T (m2/d)	CR - K (m/d)	Rec - T (m2/d)	Rec - K (m/d)	Comments
vrm23	East of West Complex	Fractured dolomite	35	13	0.80	0.30	0.72	40	0.630	0.018	0.342	0.010	
vrm21	East of West Complex	Fractured dolomite	5	5	0.90	0.10	0.72	10	1.730	0.049			
vrm20	West of West Extension	Chert Rich/ Fractured dolomite	30	30	0.80	0.10	0.77	15	0.257	0.007			
vrm24	Between West Complex and West Extension	Fractured dolomite	25	25	2.15	0.10	0.56	30	0.187	0.005	0.064	0.002	
vrm26	South of West Pay Dam	Fractured dolomite	30	9	1.37	0.20	0.61	30	0.289	0.008	0.226	0.006	
vrm27	South of West Pay Dam	Fractured dolomite	5	5	1.15	0.10	0.33	15	1.260	0.036			
vrm19	South of West Extension	Chert Rich/ Fractured dolomite	35	35	1.50	0.10	0.75	20	0.270	0.008	0.815	0.023	
vrm25	East of West Pay Dam	Fractured dolomite	30	30	2.30	0.10	0.97	30	0.593	0.017	0.550	0.016	
vrm28	50m South East of Bokkamp Dam	Chert Rich/ Fractured dolomite	30	30	1.15	0.10	1.89	20	1.750	0.050	1.140	0.033	
Vr27	500m South East of Bokkamp Dam	Chert Rich/ Fractured dolomite	30	16	1.64	1.00	0.70	1440	12.900	0.369	25.704	0.734	Fractured zone @ 16m
Vr28	50m North of 3# waste rock dump	Chert Rich/ Fractured dolomite	30	10	2.50	3.80	2.65	720	21.450	0.613	59.616	1.703	Water strike in fractures
Vr29	Below Skelm Dam	Chert Rich, Wad/ Fractured dolomite	30	14	2.40	0.90	0.60	360	7.200	0.206	16.000	0.457	Water strike in fractures
Vr30	250m below 3# waste rock dump	Fractured dolomite	30	8	1.80	4.20	4.20	720	261.360	7.467	260.000	7.429	Cavity @ 8m
Vr31	500 m south of 4# waste rock dump	Fractured dolomite	40	31	2.30	4.20	4.20	1080	47.520	1.358	80.700	2.306	Fractured zone @ 31m
Vr32	250m south east of 4# waste rock dump	Fractured dolomite	40	37	4.50	0.50	0.28	72	2.290	0.065	2.700	0.077	
Vr39	North of 4# waste rock dump	Fractured Dolomite	30	30	2.50	0.10	~	~	~	~	~	~	
Vrm31	East of West Extension Tailings Dam	Clay/ Fractured dolomite	40	40	27.00	0.10	~	~	~	~	~	~	
Vrm36	No 1 Gold Plant	Lava	40	40	8.00	0.20	~	~	~	~	~	~	
Vrm37	No 1 Gold Plant	Lava	40	40	33.00	0.10	~	~	~	~	~	~	
		Soil/Overburden	2							20.000			Historical Inf
		chert								8.000			Historical Inf
AVG for Fractured Dolomite					**2.00**	**0.87**	**1.18**	**204.70**	**7.62**	**0.22**	**18.13**	**0.52**	
AVG for weathered Dolomite					**1.55**	**1.07**	**1.49**	**429.17**	**47.29**	**1.35**	**60.73**	**1.74**	

BH = Boreholes; *CR = Constant Rate pumping test;* *Rec = Recovery*

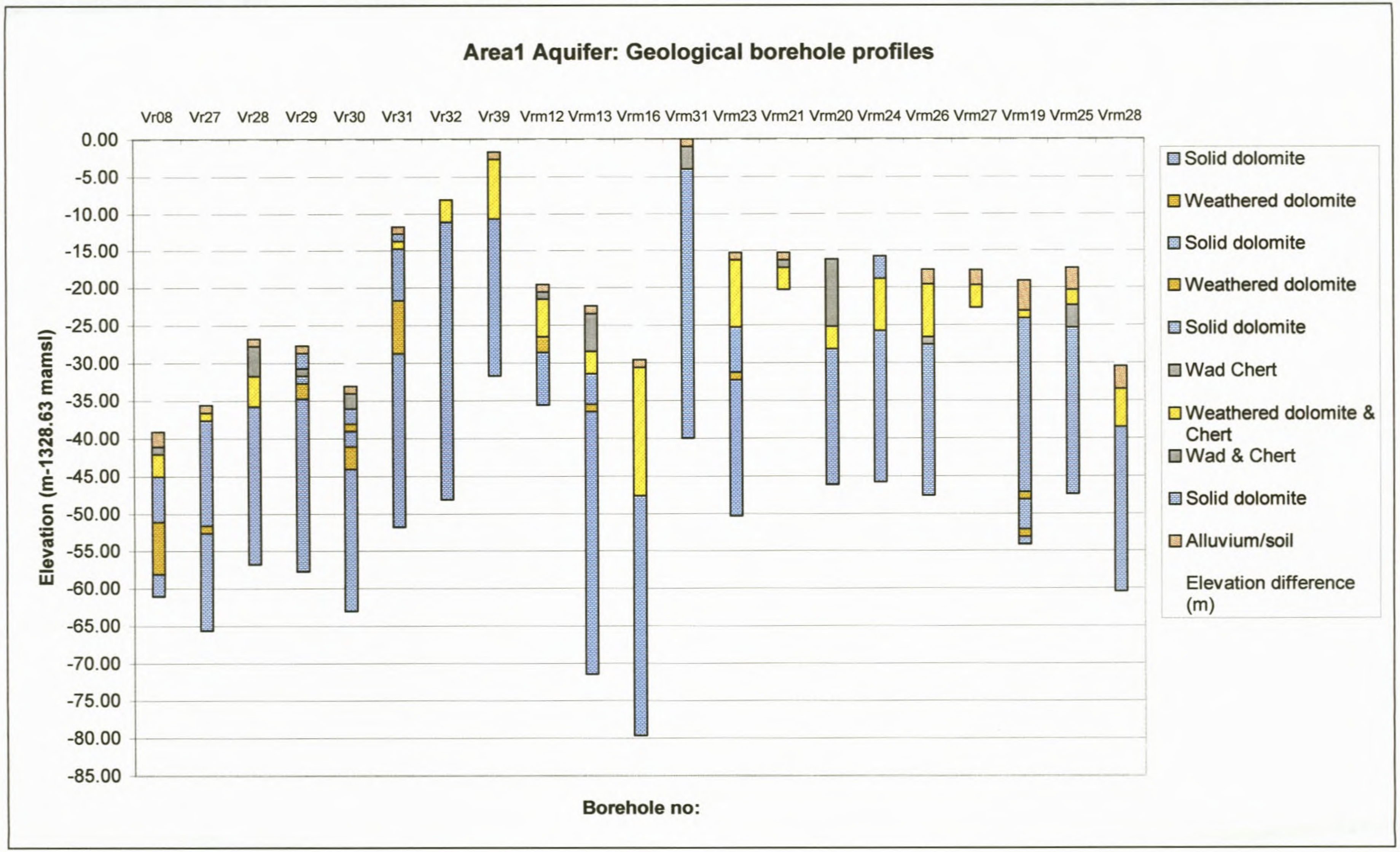


Figure 43: Geological Logs of Monitoring Boreholes

5.4.2 Understand hydraulic characteristics of tailings material

It is important to understand the hydraulic characteristics of the tailings material within the tailings storage facilities. These two structures needs to be incorporated and will be handled as constant heads within the model domain. It is further important to understand the occurrence of the phreatic surface within the dams and the drop of this surface after de-commissioning. Hydraulic conductivity values for tailings are estimated in a range of 0.001 and 0.1 m/day as quoted by some authors as:

- 0.01 m/day (Woyshner et al, 1997) for waste rock and fine tailings mixed,
- 0.004 – 0.17 m/day by Yanful et al, 1990 – for fine grained tailings,
- 0.056 m/day (international Atomic Energy Agency, 1990).

According to Cogho, *et al*, (1992) an average saturated hydraulic conductivity (Ks) value of 1 x 10^{-7} m/s (0.008 m/d) was obtained by means of laboratory experiments, as well as Cambell's formula. This value also compared favourably with values obtained from Steffen, Robertson & Kirtsen in Welkom, as well as values published by James and Mrost (1965) and Mrost and Lloyd (1971). Calibration and evaluation of the monthly neutron density readings yielded an estimated flux (q) of 1,7 x 10^{-11} m/s for the paddock area (unsaturated area), while a value of 1 x 10^{-7} m/s was obtained for the pool area.

A hydraulic conductivity of 0.001 m/day for tailings will be used as an initial estimate in the model runs.

The hydraulic conductivity of the weathered zone directly underneath a tailings dam is assumed to be lower than reported, due to compaction by the weight of the tailings. This could however be influenced by outcropping dolomites.

5.4.3 Storativity and Effective Porosity

The storativity of an aquifer (S) is an essential parameter in the estimation of groundwater recharge (RE) and cannot be determined easily because of the interdependence between S and RE in the water level response, (Bredenkamp, *et al*, 1995). The storage coefficient of aquifers in the investigation area has been tested by pumping test methods, and an average value of 0.01 – 0.001 can be assumed for the fractured aquifer. The reason for this relatively low storativity value lies in the fact that only a small proportion of the pores and fractures in the un-weathered aquifer partake in water flow.

In the upper, weathered aquifer the effective porosity is one or two orders higher and a value of 0.01 or 0.1 can be achieved. This higher value is a result of the fact that almost all calcium and magnesium that normally binds the sedimentary grains together, has been leached from this horizon. Water can therefore permeate into and through the weathered matrix.

5.4.4 Sources and sinks

Sources and sinks can be defined as points of recharge and abstraction from the aquifer. Sources can be precipitation and inflow from surface water and recharging boreholes, while sinks can be abstraction boreholes, springs, evapo-transpiration, and outflow to surface water Recharge

Infiltration of groundwater in chert poor dolomites occurs along numerous solutions enlarged joints and faults, which extend down to the water table. These fissures form an extensive, interconnected reservoir and act as routes for the downhill migration of groundwater. Eventually where the water table reaches surface, as near the Vaal River, small springs occur.

In chert rich dolomites areas, groundwater infiltration occurs downwards through the chert rubble and is concentrated along fault planes, which act as major groundwater migration routes. Unlike the fissures in chert free dolomites, these fault-controlled cavities can contain large amounts of groundwater.

The recharge to the aquifers underlying the site originates from rainfall and mining infrastructure. The amount of rainfall recharge will vary across the site depending on the weathering profile. Greater recharge is thought to be associated with the chert gravels (7.5% of MAP) while the dolomites are thought to be in the order of 4% of MAP. Recharge in the immediate vicinity of the Vaal River is thought to be relatively low (1%) given the alluvial clays and the groundwater discharge that occurs in this area as a result of groundwater convergence from the opposite banks of the river. The Ventersdorp aquifer will also be in the region of 3%.

The following table listed some related references of recharge estimates elsewhere, this will be used for confirmation purposes:

Table 32: Estimates of recharge, and related references – source: Bredenkamp, et al, 1995.

Authors and references	Title	S-Value	Recharge (mm/a)	Comments
Bredenkamp, D.B., Schutte,J.M. and du Toit, Proc.Simp. Vienna 1974	Recharge of dolomitic aquifer as determined from tritium profiles	Not required	Grootfontein 25-35mm 5.3% Rf_{av}	Based on 13 profiles in the Bo Molopo area,.
Bredenkamp, D.B., (1988).	Quantitative estimation of groundwater recharge in dolomite	0.028	Bo Molopo 78 mm Rieton 54 mm	Based on hydrograph interpretation
Fleisher, J.N.E, (1981). Univercity of the OFS	Geohydrology of the dolomite aquifers of the Malmani Subgroup of the SW Transvaal	0.0175	54.6 mm	Gemsbokfontein compartment
Enslin J.F. and Kriel J.P. (1959). Internal report to DWAF	Some results obtained from a study of dolomitic catchment in the Transvaal	8.9% for Vent/post comp.	70.4 mm – .105 Rf_{av} 87.8 mm - .13 Rf_{av} 36.8 mm - .058 Rf_{av}	Steenkoppies Zuurbekom Bank compartment

The effect of artificial recharge has been taken into account by increasing the recharge coefficient assigned to cells in the immediate vicinity of slimes dams. The amount of artificial recharge assigned to decommissioning dams has been reduced.

Sinks in the form of evapo-transpiration was considered.

5.4.5 *Artificial Water*

The normal water additions to the groundwater table in the form of rainfall recharge can be calculated by standard methods, once the infiltration-runoff ratio has been accurately determined.

Artificial additions of water, except from the main tailings dams are unlikely to be known, i.e. incidents (leaking pipes, etc.), garden irrigation, irregular water used for washing, cleaning, etc., in general these should infiltrate and supplement the natural perched water tables, but not have a marked effect on the overall sub-surface water tables and water movement.

The regular additions of water to certain areas in the mapping area, namely the tailings dams, effluent earth trenches, unlined effluent dams, dam overflows, etc. areas has resulted in existing or new perched water tables being extended onto surface surrounding these features. A zone of surface and sub-surface flow often extends from the tailings dams towards the Vaal River (Jones & Wagener, 1978). It is clear that these areas were noted in the 1970's; current (2003) borehole data suggest even further migration of these perched zones.

For this reason, large-scale regular surface flow of artificial water on the permeable dolomite materials will occur once the natural perched and/or the permanent water tables have been raised to existing ground level and maintained at this level. Therefore if:

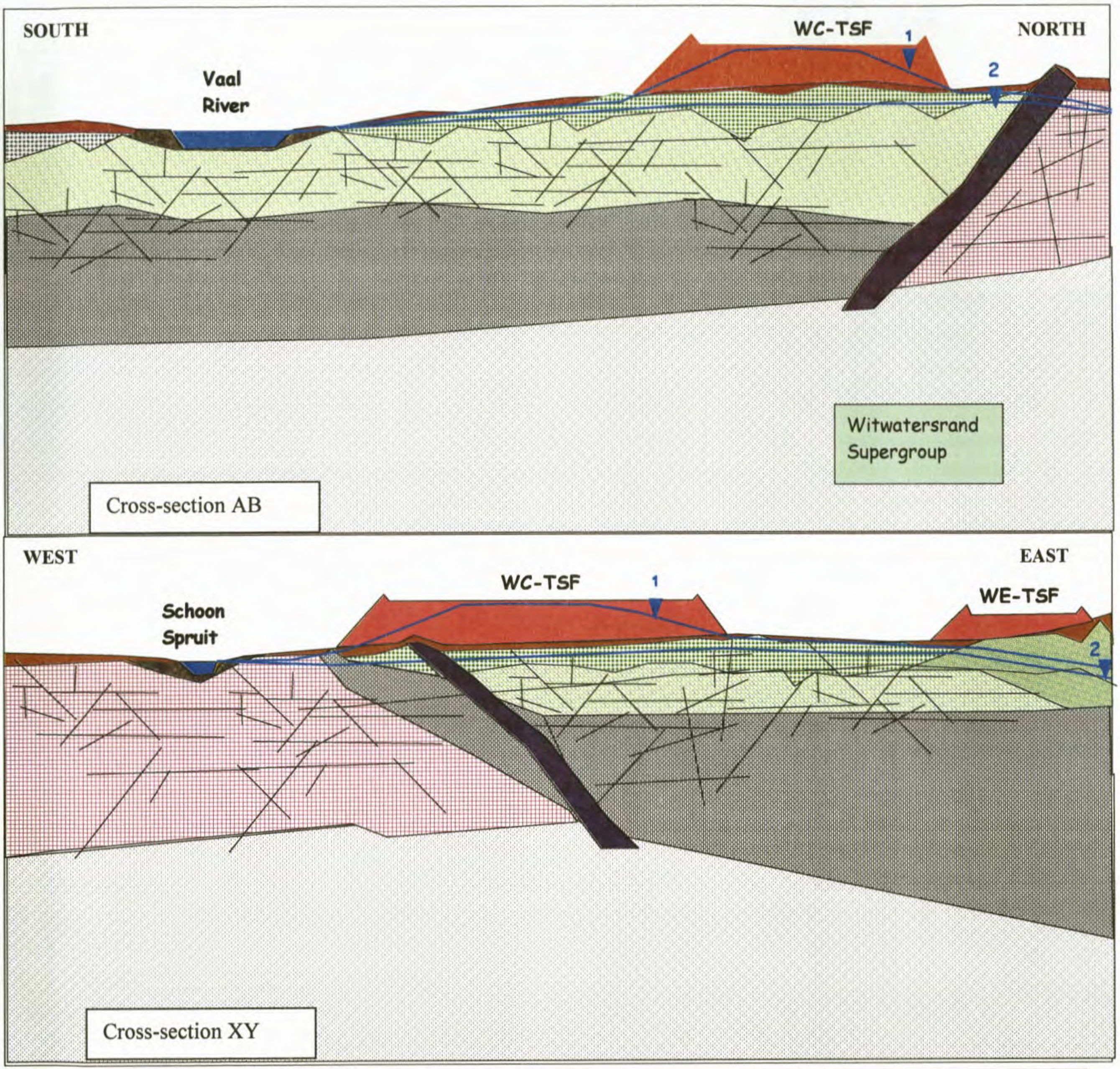
- The ratio of shallow sub-surface (i.e. perched water table flow in the soil horizon) flow to deep sub-surface flow (i.e. permanent water table flow from fractured dolomite zone) can be determined, and
- The zones of influence and main directions of flow of both the individual perched water tables related to each slimes dam and the permanent water table flow could be ascertained and controlled, then the artificial water additions can be treated and controlled by on-surface structures.

One of the most likely areas to be able to control the shallow sub-surface flow of artificial water, will be at the alluvial zone contact with the dolomite, adjacent to the Vaal River, however, this imply rehabilitation work closer to the receiving water body and further away from the source, which is not always good practice.

5.5 Concluding Remarks

The geometry of the West Dolomite Aquifer and its physical properties will determine the migration rate and direction of contaminants in the groundwater. The available information suggests that, also refer to Figure 44 for geological and geohydrological conceptual model:

- Groundwater gradients broadly mimic the topography from North to South towards the Vaal River. Localized groundwater elevation variations are expected particularly between the chert gravel accumulations and the weathered dolomite.
- Because the dolomite fracture network is discontinuous it is unlikely that all water entering the dolomite system will flow towards a unique discharge point. The main water bearing fractures are those trending North South following the regional groundwater gradient.
- The bed of the Vaal River is reported to be cut into the dolomite. Springs could be associated with these north south trending fractures extending below the River.
- Seepage water present in the weathered zone above the dolomite is preventing from entering the Vaal River by a belt of clay alluvium fringing the river channel. This result in a zone of seepage of the water table where the sub-surface flow has been "impounded" by the relatively impervious alluvial material. At this stage there is therefore no evidence of any direct hydraulic continuity between the dolomite aquifer, the perched water table aquifer and the Vaal River (Jones & Wagener, 1982).
- Diffuse groundwater seepage will mainly discharge into the Vaal River via the perched water table aquifer which surfacing all along the Vaal River in the form of springs and then flowing as surface run-off into the Vaal River. Secondary recharge will be as baseflow.
- The seepage water reaches the areas adjacent to the dam where the piezometric heads are lower, it seeps towards the topographic surface. When it reaches the level of the plant root zone between 1.0-0.5 m depth, the plants start to abstract the seepage, which can be at a rate of 500-800 mm/m^2 per annum. The water is taken out of the system by transpiration and evaporation and the salts precipitate.
- Over a period of decades, the salt may build up to high levels in the soil zone. This could be one explanation for the high salt content at borehole Vrm24 in the central part between the tailings dams.
- According to Biesheuvel (1977), gravity results show that, but for minor possible exceptions, the mean bedrock depth over the entire area, which has been surveyed to date, is less than 15 meters. This correlates with the logs in Figure 43: Geological Logs of Monitoring Boreholes



	K(x,y)	K(z)	n		Depth
	(m/d)		%		(m)
Tailings	0.05	0.005	30	🟥	0-40
Soil	0.5-1	0.1	20	🟫	0-2.5
Alluvial Clay	0.01	0.001	30	⬛	2.5-10
Transvaal: Fractured / Weathered Dolomite with sporadic cavities	2-4	0.4	25	▨	2-10
Transvaal: Solid / Fractured Dolomite	0.2 - 0.4	0.02	10	▨	20-40
Transvaal: Impervious Dolomite	0.001	0.0001	1	▩	40-500
Chert rich dolomite, weathered	3-5	0.5	30	🟩	15-30
Black Reef Quartsites	0.01	0.001	10	⬛	10-30
Ventersdorp Lava	0.01	0.001	10	▦	10-40

Porosity values (n) is Based on Driscoll, 1986)

1 ▼ = artificial water table *2 ▼ = regional water table*

Figure 44: Graphical Illustration of Geological and Geohydrological Concepts – NOTE: NOT TO SCALE

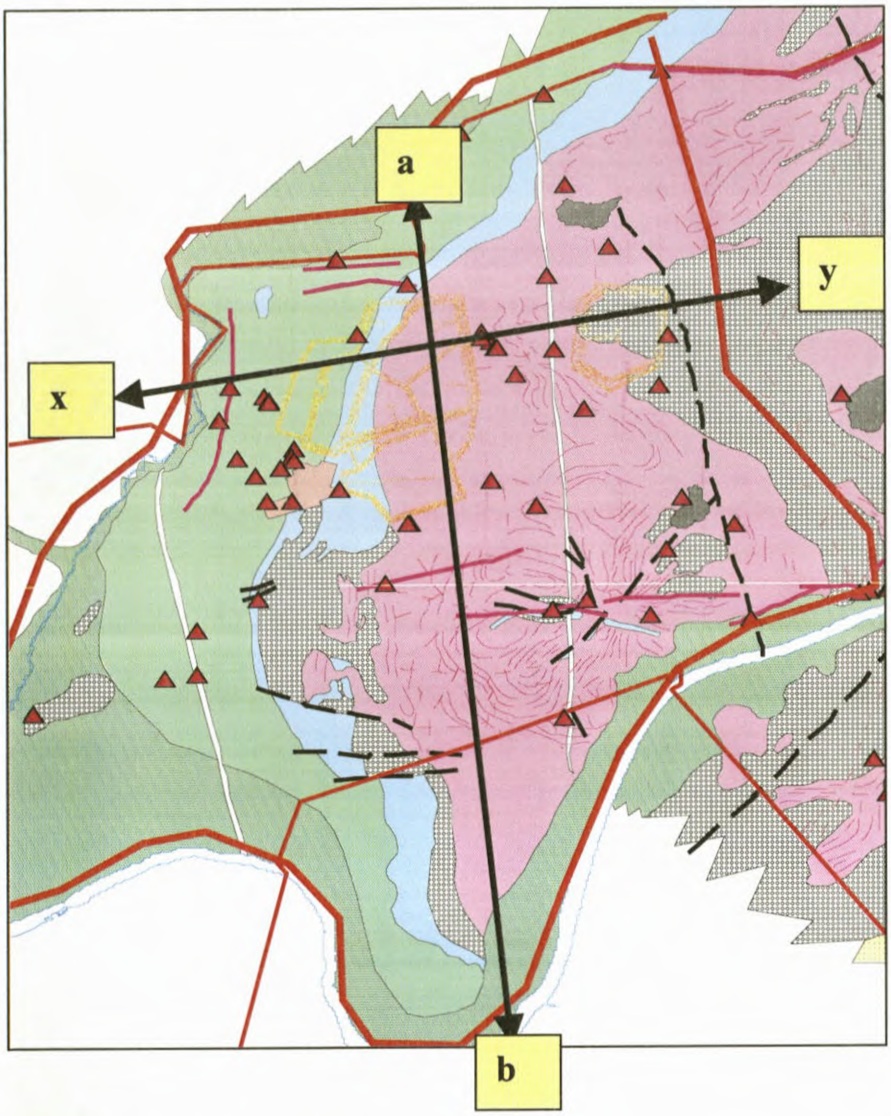


Figure 45: Cross sections used for conceptual model

6 Impact Analysis and Risk Assessment

6.1 Introduction

The main objective of this part of the assessment is to collate all the data that are listed and discussed before. At this time of the assessment there should be a list of critical identified aspects that needs more physical field investigations. This includes the main "uncertainties" which comprises out of aspects that usually require more attention. Tailings storage facilities, waste rock dumps, polluted soils and other unknown aspects could be listed. There may be some significant residual impacts resulting from the construction, operational or decommissioning phases that persist after these activities have ceased and a closure certificate has been issued. A more compressive scientific approach for experiments and analysis are therefore required. Where possible, these impacts should be identified qualitatively as well as quantitatively so that they can be accommodated when the closure objectives are being defined and when the environmental management programme is being devised. The geohydrological impact assessment done in accordance with paragraphs 3.9 of Section 3 will have highlighted the major issues on which to focus. However, the potential impacts resulting from the closed operation, listed below, should be considered in any event. It is nevertheless recognised that quantification of these impacts could be imprecise, or even unfeasible.

- The potential for acid mine drainage or poor quality leachates emanating from the mine or residue deposits.
- The long term impacts on groundwater, (DME, 1992)

The sequence of this part of the assessment should be more or less like follows:

Table 33: Explanation of the Impact analysis and risk assessment as part of the thesis.

Task	Description / Overview
Test Pits and soil profiles	Test pits must be constructed for physical observational purposes. Soils samples needs to be collected at areas where more information is required. Accumulation of salts in topsoil could be the driving force behind this and to understand the magnitude. This information will later be used for modelling purposes and to identify areas, which should be targeted for physical remediation.
Screening Acid base accounting (ABA) and geo-chemical modelling	At this stage only a screening type of ABA exercise is required. This entails sampling of tailings and rock material and lab analysis. This again, is necessary to supply a first order quantification of magnitude of possible acid and neutralising potential of the material. If definite out layers on samples be identified a next sample run should be consider. This data will be used as input concentrations into mass transport modelling – the two tailings storage facilities will be applied as constant sources of contamination into the mass transport model. The geo-chemical modelling exercise will supply concentration over time figure to be applied as input parameter for mass transport modelling purposes.
Numerical modelling	This entails the collation of data into a mathematical groundwater model. Answers on groundwater flow and behaviour of mass transport should be identifies and explained. The real value of geohydrological modelling should be optimised and needs to be utilised for managing purposes.
Salt balance	Water budget data obtained from numerical model simulations needs to be translated into a salt balance. This will ultimately provide answers for the risk assessment on receiving water bodies.
Understand impacts of contamination on receiving water bodies	The ultimate destination of the salt migration plumes must be identified – this must then be translated into a site-specific impact and risk assessment. The direct impact on receiving water bodies needs to be determined. This exercise must therefore include the identification of receiving water bodies and associated water users. As part of the closure application process, the answers of this exercise needs to be explained and demonstrated to the applicable Government departments and interested and affected parties (I&AP's).

6.2 *Test pits and soil profiles*

The groundwater seepage from the tailings dams follows the upper soil and weathered zones, which varies between depths of 0.5-5.0 m. The water flows due to the driving head gradient in the dam and seeps beneath the cut-off trench. When the saline water reaches the plant root zone, it is taken up by transpiration and evaporation processes. The water evaporates and the salts precipitate. This process is visible in some areas on the ground surface (Figure 46) and in the test pits. Note that in the test pit, Figure 47, the upper part of the soil profile in the root zone is considerably drier than the deeper parts.

This process has taken years to accumulate salts in the upper soil zone and in the aquifer underneath. Therefore, the soil zone might act as a source for contamination and even be more saline than the tailings dam water *(Vivier, 2001, Bokkamp Report for AngloGold)*.

Figure 46: Photograph of salt precipitation in the soil in east of the WC – TSF.

Figure 47: Photograph of the eastern face of a test pit east of the west of the WC – TSF.

During January 2002, Viljoen from Golder Associates performed an assessment of the amplitude and impact of inorganic soil contamination on certain identified areas within the investigation area. See Figure 48 for sample locations.

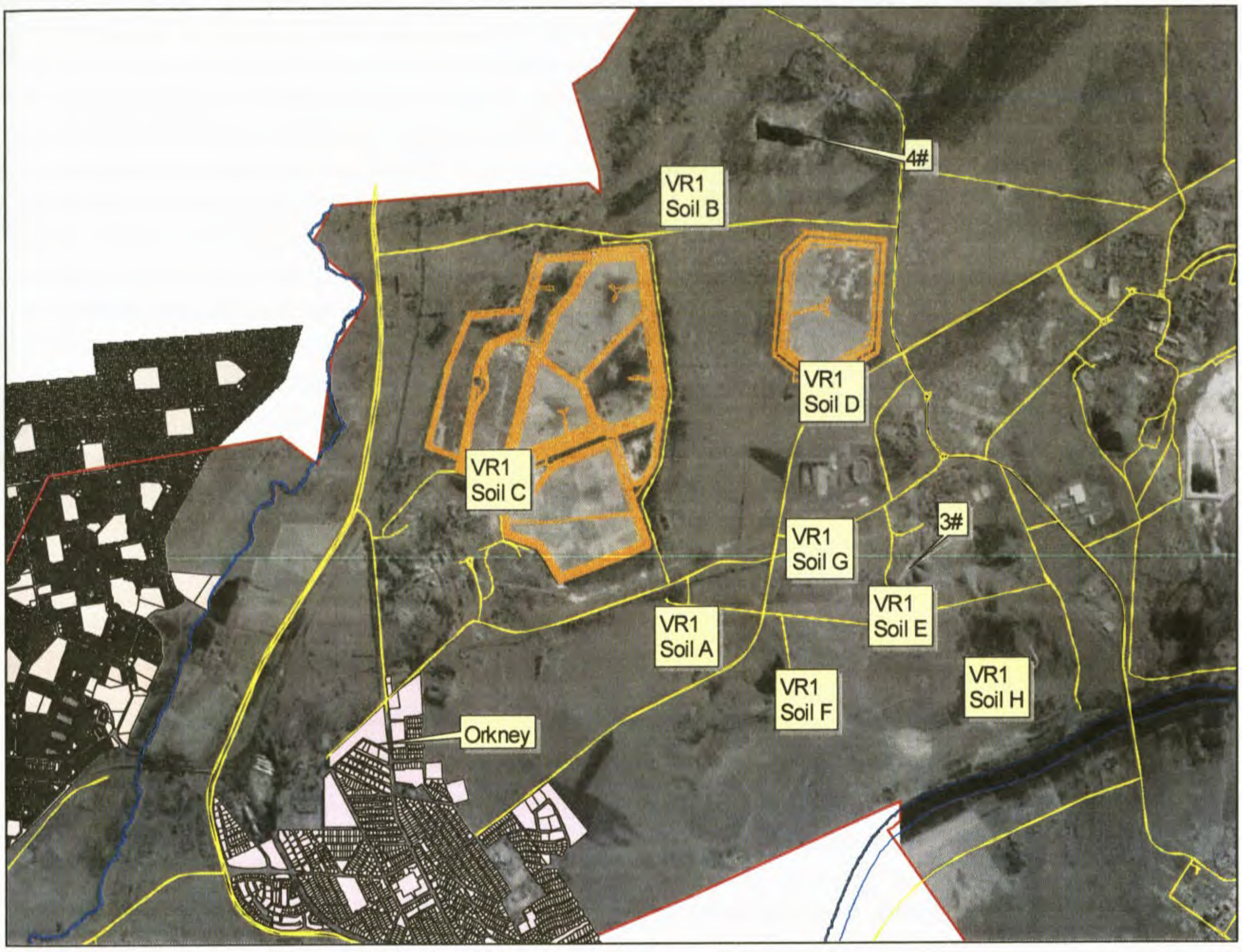


Figure 48: Different areas of soil investigated in Area VR1.

The target areas were selected according to the findings form the preliminary impact assessment and associated field investigations. Table 34 list the description of the selected areas and results from soil sample analysis. The soils are contaminated with a combination of spilled gold tailings material and contaminated seepage water and it was required to assess the amplitude and impact of soil contamination to the surrounding environment. From the assessment soil remediation strategies were formulated for rehabilitation of the area for closure purposes. It was conclusive that the driver of soil contamination was the oxidation of pyrite forming sulphuric acid and the precipitation of excess quantities of sulphur in the soil solution.

From the conclusions and recommendations of the soil investigations Anglogold Vaal River Operations had to assess and demonstrate with a high confidence level the cost and benefit of the proposed soil remediation strategies of the contaminated sites for closure purposes. It is obvious from the results in Table 34 that the soils is heavy polluted with accumulated salts (2 orders higher than background values), very high SO_4 contents is visible. The major soil remediation option is to isolate the source of pollution and to apply organic material. Isolation of source refers to physical clean-up work and site rehabilitation. The clean-up and treatment of these soils will have a definite positive impact on site groundwater qualities.

Table 34: Summary of the different areas in terms of the dominant soil types, effective depth, rehabilitation potential, prevailing soil contamination and proposed soil remediation. Soil types, effective depth, rehabilitation potential, prevailing inorganic soil contamination and required soil remediation.

AREA	**SOIL TYPE**	**EFFECTIVE DEPTH (mm)**	**REHAB. POTENTIAL**	**SOIL CONTAMINATION**	**SOIL REMEDIATION**
VR1 Soil A – Old Evaporation Area (20ha)	Mispah	200	Low	1,083 mg/kg SO_4 (Background 21 mg/kg)	Isolate pollution source. Apply 80 t/ha/200mm organic material
VR1 Soil B (48ha) – Seepage plume east of WC-TSF	Mispah	300	Low	1,393 mg/kg SO_4 (Background 21mg/kg)	Isolate pollution source. Apply 80t/ha/200mm organic material
VR1 Soil C (5ha) – Seepage plume south of WC-TSF	Bainsvlei Mispah	>300 300	High Low	2,819mg.kg SO_4 (Background 21mg/kg), ESP*>15 (Background <15), 30mg/kg NO_3 (Background 2mg/kg)	Isolate pollution source. Apply 80t/ha/200mm organic material
VR1 Soil D (35ha) – Seepage plume west and south of WE-TSF	Mispah	300	Low	4,338mg/kg SO_4 (Background 21mg/kg), 50mg/kg NO_3 (Background 2mg/kg), 39mg/kg P (Background 4mg/kg)	Isolate pollution source. Apply 80t/ha/200mm organic material
VR1 Soil E (8ha) – Queen Mary Dam area	Bainsvlei	>300	High	2,950mg/kg SO_4 (Background 21mg/kg), ESP*>15% (Background <15%), 270mg/kg NO_3 (Background 2mg/kg)	Isolate pollution source. Apply 80t/ha/200mm organic material
VR1 Soil F (39ha) – Area below Bokkamp Dam	Mispah	300	Low	4,500mg/kg SO_4 (Background 21mg/kg), ESP*>15% (Background <15%), 47mg/kg P (Background 4mg/kg), 63mg/kg NO_3 (Background 2mg/kg)	Isolate pollution source. Apply 80t/ha/200mm organic material
VR1 Soil G (18ha) – Skelm Dam Area	Mispah	300	Low	592mg/kg SO_4 (Background 21mg/kg), 99mg/kg NO_3 (Background 2mg/kg)	Isolate pollution source. Apply 40t/ha/200mm
VR1 Soil H (112ha) – Game Park Dam Area	Mispah	300	Low	2,096mg/kg SO_4 (Background 21mg/kg), 39mg/kg NO_3 (Background 2mg/kg)	Isolate pollution source. Apply 80t/ha/200mm

*: Exchangeable Sodium Percentage

6.3 Screening Acid Base Accounting and Geo-chemical Modelling

6.3.1 Introduction

This part of the investigation includes the geo-chemical assessment of tailings and waste rock material. For the purpose of this thesis, it was decided to include a very brief discussion of the Acid Base Accounting and geo-chemical modelling exercise, rather than a detailed and complex report on techniques results and discussions. The objective of the inclusion is therefore to illustrate the concept and importance of the application and not to elaborate too much on technicalities of ABA and geo-chemical modelling. These two geo-chemical related exercises, and associated experiments, are complicated fields and are progressively more incorporated in geohydrological studies. What must come out of this is to illustrate the following:

- To identify target areas and material such as tailings and waste rock that could cause problems over the long term,
- The storage facilities, stockpiles or dumps need to be conceptually studied,
- The sampling protocol and quantities of sampling must be according to the objectives of the study and must be based on scientific methods,
- Data assessment must be simple and the data needs to be in a format so that it could be incorporated into the geohydrological assessment.
- It is very important that the uncertainties of the input data and results be discusses and explained. A range of possible concentrations of predicted SO_4 and TDS, and other modelled parameters, must be supplied. These values must then be compared to actual field data to understand the credibility and usefulness of the data. It could be seen from Table 35 and *Figure 52* that exact values were listed, for a screening type exercise this should rather be in range format with more efficient explanations.

Pulles Howard and de Lange Inc (PHD), 2002 undertook a screening level acid base accounting (ABA) and interim geo-chemical modelling exercise. ABA tests have been designed to measure the balance between potentially acid-generating minerals (maximum potential acidity) and acid-neutralizing minerals (neutralization potential) in a sample. This procedure, known as acid-base accounting, yields a figure known as Net Neutralization Potential (NNP), which determines whether a particular sample will theoretically generate acidity over time. In standard acid-base accounting, the maximum potential acidity (MPA) is calculated using the total sulfur value and assumes that all sulfur present is in the sulfide form and potentially convertible to acid. The neutralization potential (NP) is determined by treating the sample with an excess of standardized hydrochloric acid, heating to ensure complete reaction, then titrating the unconsumed acid with standardized base to a pH of 7.0. The difference between the MPA and the NP yields the Net Neutralization Potential (NNP), a figure, which may be reported as either positive or negative.

The main purpose of the study was to evaluate the potential of the following tailings dams and waste rock dumps, in the investigation area, to impact on the water resource and the implications of this in terms of mine closure and rehabilitation:

- Vaal River west tailings complex
- Vaal River west extension tailings dam
- Vaal River No 3 waste rock dump
- Vaal River No 4 waste rock dump

This project used the principles and methodologies set out in the BPG 1.5: Pollution Prediction from Mining Sites (Department of Water Affairs and Forestry, 2002).

6.3.2 Development of Conceptual Models

Conceptual models were developed for tailings dams and waste rock dumps. These conceptual models were used to develop the sampling programme, as well as to direct the water balance and geo-chemical modeling.

6.3.2.1 Tailings Dams

Tailings dams consist of fine-grained particles with the following characteristics:

- Particles are relatively uniform in size and exhibit a narrow size distribution.
- The water table within a tailings dam is typically elevated with a portion of the dump being in a saturated state.
- The proportion of seepage emanating from the toe of the dump relative to that seeping into the underlying aquifer is dependent on the permeability contrast between the waste material and the underlying geology and the difference between horizontal and vertical permeability of the tailings.

The environment within a tailings dam is less conducive to the production of acid mine drainage than that of a waste rock dump. This is primarily due to the fact that the penetration of oxygen is limited (mainly true for operating facilities receiving large regular inputs of water). However, this is counteracted by the fact that fine waste has a small particle size and consequently, a large surface area of reactive minerals.

The tailings dam consists of an unsaturated upper zone and a saturated lower zone. The unsaturated zone can typically be subdivided into three separate zones:

1. An uppermost oxidation zone where the bulk of the sulphide oxidation will occur;
2. A hardpan that effectively reduces the amount of vertical oxygen and water penetration and results in the lateral movement of infiltration water; and
3. A lower zone where the pore spaces are partially filled with water and where sulphide oxidation occurs at a reduced rate.

The saturated zone typically extends somewhat above the true water table due to the capillary rise of water into the pore spaces. This saturated zone does not allow for any significant sulphide oxidation although effective neutralisation by base minerals may still occur here.

For modelling purposes, a simplified conceptual model was used. Four zones were considered for water movement as shown below.

- Zone 1 – the unsaturated zone.
- Zone 2 – the saturated zone.
- Zone 3 – the slope zone (this zone will be assumed unsaturated).
- Zone 4 – the mixing zone for geochemical modelling.

The simplified water balance for the conceptual tailings model can be read from Figure 49 as follows:

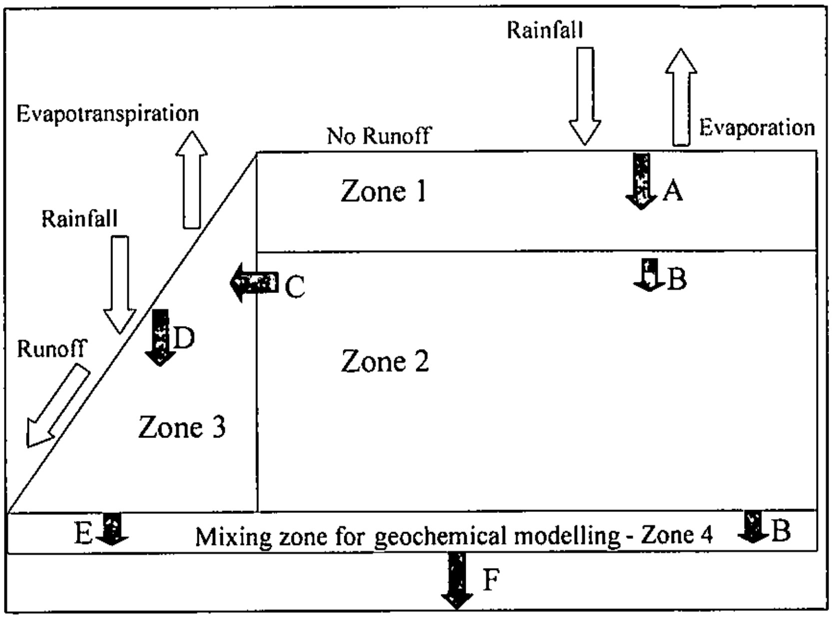


Figure 49: Conceptual model for tailings dams (PHD, Technical Report to AngloGold, 2002)

6.3.2.2 Waste Rock Dumps

Coarse waste residue deposits typically provide an environment that is very conducive to the production of acid mine drainage. This is primarily due to the fact that coarse waste deposits are very permeable and allow the ingress of oxygen to considerable depths. However, this is counteracted by the fact that, per definition, coarse waste has a large particle size, thereby ensuring that a large amount of the minerals that contribute to the change in water quality, are locked up within the larger particles. In these coarse waste deposits, water may flow in channels and macropores somewhat independently of the hydraulic conditions in the smaller pores. The saturated hydraulic conductivities of the macropore region can be up to several orders of magnitude higher than the hydraulic conductivity of the porous matrix (López *et al*, 1997).

Newman *et al* (1997) suggest that samples where the portion of fine material in a waste rock dump was larger than 40 % were capable of retaining water under negative pore-water pressures. This capacity to retain water was very small for samples with less than 40 % fine material.

The phreatic surface within the coarse waste residue deposit is dependent on the volume of water ingress on the dump surface and the permeability of the underlying weathered material/aquifer relative to that of the waste material. It is anticipated that the underlying lithologies generally have a lower permeability than that of coarse waste residue deposits. Since the permeability of the coarse waste material is relatively high, one would expect the phreatic surface within the dump to be relatively flat and located within the lower portion of the dump. This depressed water table has two very important effects that need to be considered (Department of Water Affairs and Forestry, 2002):

- Water flows vertically down through the dump along preferential flow paths – this means that some particles are fairly isolated from the water flow path.
- Oxygen penetrates deep into the dump and the spaces between particles are typically filled with air (and oxygen), while particles are surrounded by a thin layer of water.

Leachate from a coarse waste residue deposit is most likely to seep from the face of the dump in close proximity to the toe rather than percolate into the underlying aquifer. This is attributed to the relatively low permeability of the underlying material that cannot accommodate the seepage volume from the coarse waste residue for any given rainfall event.

Uncontrolled leachate that emanates from the coarse waste residue, as surface runoff will often flow down gradient until it percolates into the weathered soil profile. The distance that such a surface runoff covers before seeping into the underlying aquifers is dependant on the seepage volume, the permeability of the underlying material and the topographic slope in the immediate vicinity of the coarse waste residue. The vertical percolation of the leachate into the underlying aquifers may be hindered by the upward convergence of groundwater in the immediate vicinity of watercourses. However, relatively clean groundwater will come into contact with mine waste residue seepage as a result of the convergence process. This contaminated groundwater will usually enter the watercourses as baseflow (Department of Water Affairs and Forestry, 2002).

6.3.3 Sampling of Tailings Dams

Sample positions were planned at a frequency of one sample point per 10 hectares of tailings dam. The positions were marked on a plan of the dams and the co-ordinates of each position logged in a table. The sampling team used a Global Positioning System (GPS) to locate each position, and where positions changed for any reason (e.g. surface flooding) a new set of co-ordinates was logged.

Samples were taken using a Dutch auger and the auger bits had measurements marked on them to ensure that sampling occurred reproducibly at precise depths. All shallow holes were drilled to 2.5m and samples were taken at 50cm intervals. One deep hole was drilled at each tailings dam and it was planned to drill one hole to 10m at one of the decommissioned dams from those two areas, or to water table at the decommissioned ones and to 4m at the operational ones. Collected samples were placed in clearly labelled plastic bags, and sealed with cable ties ensuring that a minimum amount of air remained in the plastic bag.

6.3.4 Sampling of Waste Rock Dumps

Samples were taken using the Backactor at the toe of the dump. The sample positions were marked on a plan of the dumps and the co-ordinates of each position logged in a table. The sampling team used a GPS to locate each position, and where positions changed for any reason (e.g. inaccessibility due to berm) a new set of co-ordinates was logged.

The backactor accessed the sidewall of the dumps to approximately 3m. At each sampling point, 2 backactor scoops of material were screened through a coarse (25x13mm) screen. The coarse fractions were retained in 50kg polywoven plastic bags whereas fine fractions were placed into clear plastic bags. Sample bags were sealed using cable ties.

6.3.5 Data Assessment

The main purpose of this screening level exercise is to assess the ABA data by evaluating relationships between acid potential and neutralization potential as an indicator of the potential for the material to produce acid mine drainage. Because this is a very coarse assessment, as it does not consider reaction kinetics or the multitude of factors that affect the ability of the material to actually realize its acid and/or neutralization potential, it was decided to incorporate an interim geochemical modeling exercise. The interim geochemical modeling will give an indication if the material will become acidic or for how long such acid conditions may persist, or how pronounced the acidic conditions might be.

It must however be noted that this ABA and geo-chemical modeling attempts would have more credibility and practical value if it could be applied in conceptual models. This must then become workable tools for management decision purposes.

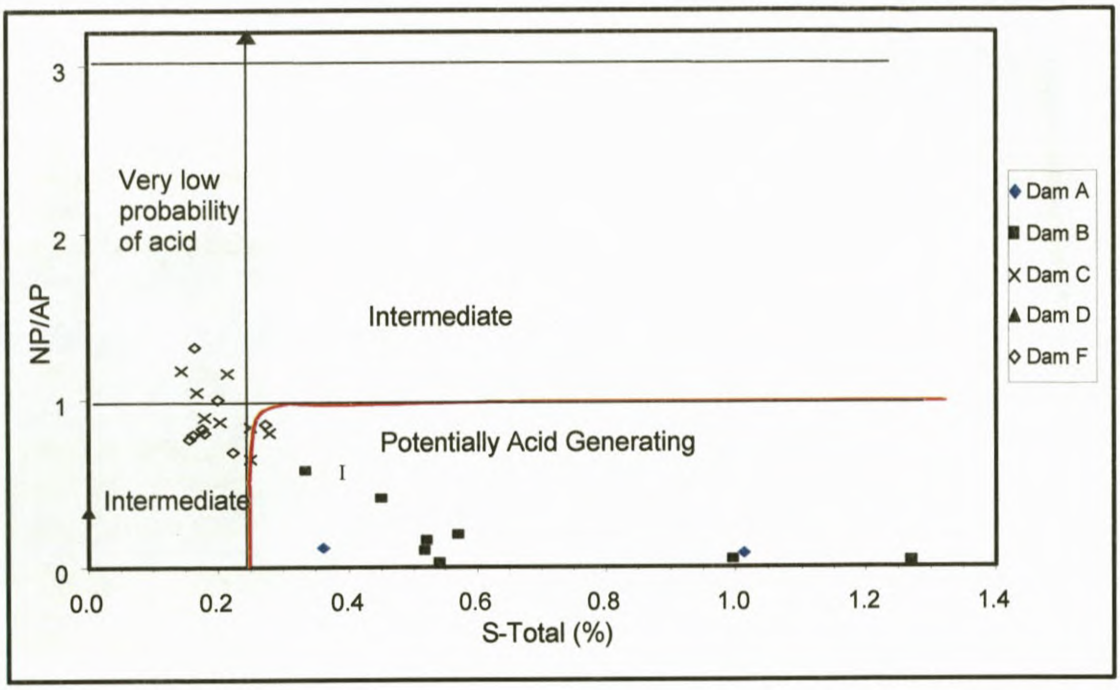


Figure 50: Classification of acid generating capacity based on Total S (%) vs AP/NP for Vaal River tailings dams (PHD, Technical Report to AngloGold, 2002).

The classification of the Vaal River tailings dams is shown above in Figure 50 (Dams A, B, C and D make up the West tailings complex while Dam F is known as the West extension tailings dam). Based on the ABA data the conclusion must be made that the Vaal River west tailings complex, with some uncertainty for the classification of the west extension tailings dam, has a strong tendency to turn acid.

The picture for the Vaal River waste rock dumps is less clear, as it can be seen from Figure 51, there is a fairly wide scatter of data. However, it does appear that the No 3 waste rock dump data plots more in the potential acid generating areas while the No 4 waste rock dump data plots more in the intermediate and non-acid generating areas.

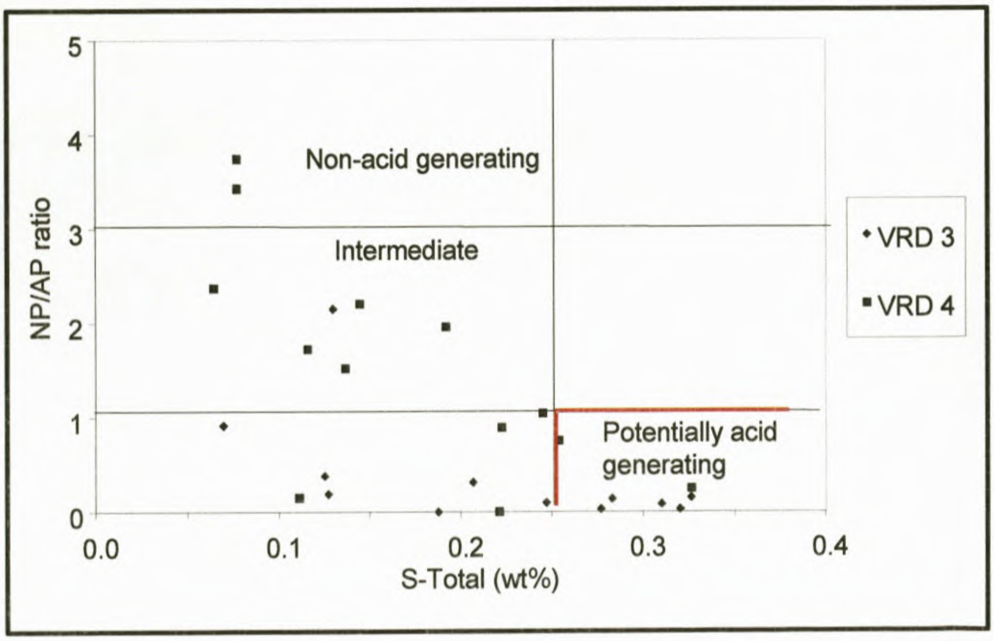


Figure 51: Classification of acid generating capacity based on Total S (%) vs AP/NP for Vaal River waste rock dumps (PHD, Technical Report to AngloGold, 2002).

6.3.6 *Geochemical modeling*

Base case or interim kinetic geo-chemical modeling was undertaken using the REACT model of Geochemist's Workbench developed by Bethke (1996). This is a popular commercially available model. The equilibrium modelling, i.e. speciation was carried by use of the computer model, PHREEQC 2.0 that was developed by Parkhurt & Appelo (1999).

It must again be emphasized that the objective of this study was to undertake a screening level evaluation of a number of facilities simultaneously. It was furthermore considered critical to construct the assessment process such that relative comparison could be made between different facilities and between different management options for each facility. It is however recommended that certain uncertainties regarding the output results (*Figure 52*) should be better explained and clarified. The absolute future water quality values presented in this report should therefore be viewed as indicative only.

The major results from the base case geo-chemical modelling are summarised in Table 35. It is clear from this table that there are large differences between the different facilities, highlighting the fact that these facilities cannot be evaluated on a generic basis. The differences in long-term water quality prediction are primarily due to differences in mineralogy, although the water balances also have significant effects. Although the long-term water quality characteristics of each facility are different, they can be grouped in the following ways:

pH classification

P1. Facilities predicted to turn and remain strongly acid (pH<5)
P2. Facilities predicted to turn and remain slightly acid (pH 5-6.5)
P3. Facilities predicted to remain neutral to alkaline (pH >6.5)
P4. Facilities with initial strongly acid conditions rapidly returning to slightly acid to neutral

Salinity classification

S1. Facilities with persistent very high salinity (TDS > 3000 mg/l)
S2. Facilities with persistent medium salinity (TDS 1000 – 3000 mg/l)
S3. Facilities with persistent low salinity (TDS < 1000 mg/l)
S4. Facilities with initial medium to high salinity declining to low salinity

Table 35: Summary of the results from base case modelling for long-term water quality prediction

Facility	pH Characteristics		Salinity Characteristics		
	Class.	Min. pH	Class.	Max TDS (mg/l)	Max salt load (t/a)
VR west tailings complex	P4	4.5	S1	6200	3000
VR west extension tailings dam	P2	4.7	S1	3300	380
VR No 3 waste rock dump	P1	3.6	S3	1000	50
VR No 4 waste rock dump	P3	7.2	S4	2700	86

The results in Table 35 are also colour coded from green (best case) to orange (intermediate case) to red (worst case). In assessing the results, it must be stressed that the geochemical modelling was undertaken as a screening level study and the absolute values shown here should not be taken as definitive but rather as indicative. The results show that the two tailings storage facilities are generally predicted to give rise to more saline conditions. It should also be noted that those facilities classed as P1 will probably give rise to elevated metal and radionuclide levels in the seepage while this may also occur to a lesser degree for the P2 and P4 classified facilities.

Figure 52 shows the results of the geo-chemical modelling; the third figure indicates SO_4, Mg and Ca predictions in mg/kg. For the purposes of the proposed numerical transport modelling exercise, a current SO_4 concentration of 4600mg/l, a 30-year of 4400 mg/l and a 60-year of 4000 mg/l constant concentrations could be used.

A fairly stable pH is predicted which indicates stable conditions with minimum metal oxidation occurrences.

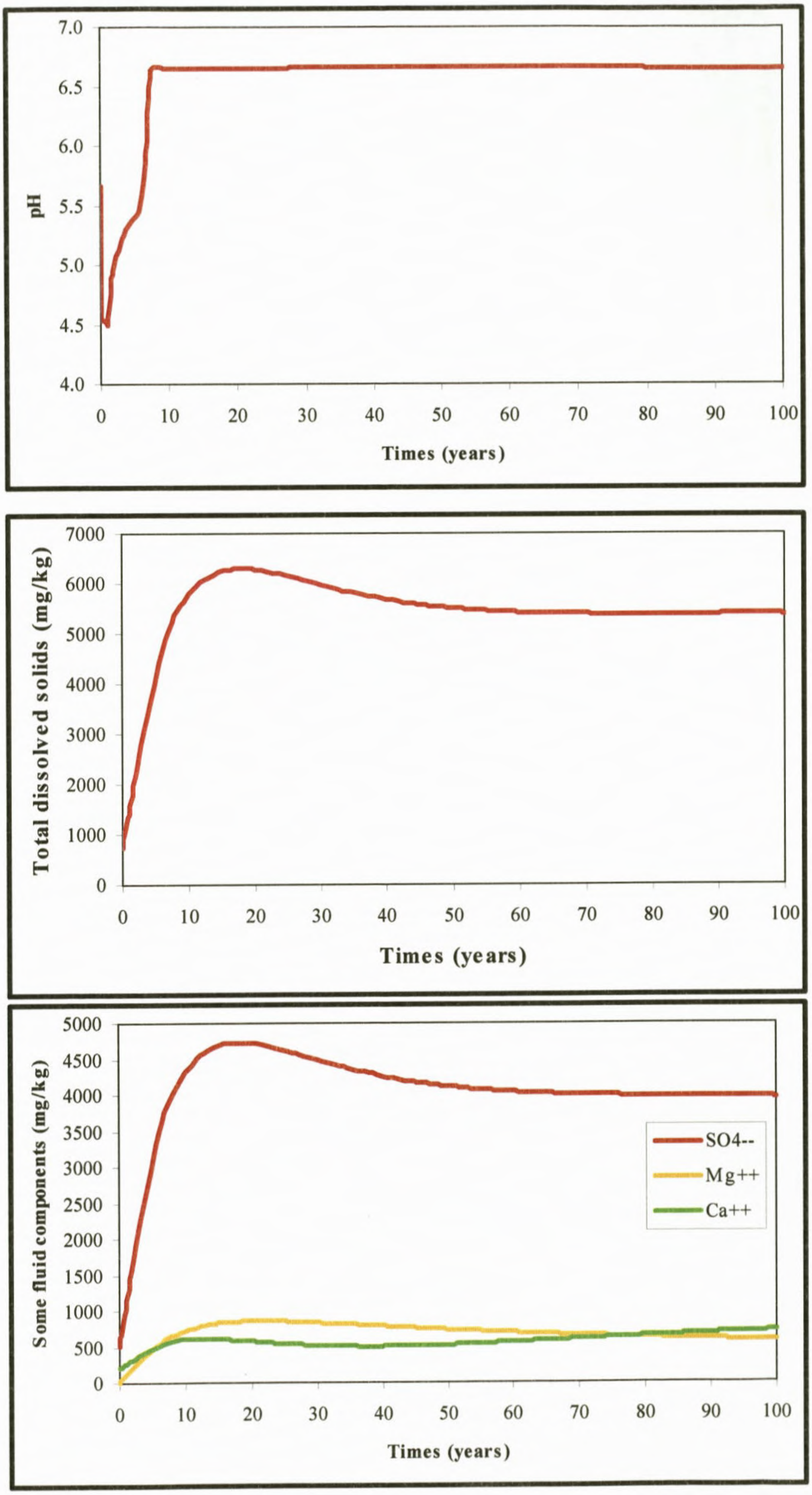


Figure 52: *Base case scenario for Vaal River west tailings complex*

6.4 *Numerical Modelling*

6.4.1 *Introduction to groundwater flow and pollution modelling*

Modelling of groundwater flow and pollution transport though the substrata is commonly done to predict the outcome of specific scenarios. There are two areas of geohydrology where we need to rely upon models of a real geohydrological system: to understand why a flow system is behaving in a particular observed manner and to predict how a flow system will behave in the future (Fetter, 1998). For the purpose of this investigation groundwater modelling was applied to give more clarity in this regard, but also to analyse hypothetical contamination and rehabilitation scenario's in order to gain generic understanding of typical behaviour and to identify different management options.

Groundwater modelling is based on a sound understanding of the geology, geohydrology and hydrochemistry of systems, also considering topographic variations and the amount of recharge to the groundwater system.

The first step in constructing a model is the subdivision of the area to be modelled into smaller areas (cells) within which the characteristics are similar. Considerations for subdivision of the investigation area were typically:

- The surface geometry, such as topography, streams and positions of waste management facilities.
- The hydraulic characteristics of the underlying aquifer.
- Current groundwater quality distribution.

It is important to note that a numerical groundwater model is only a representation of the actual system. It should therefore be regarded as an approximation, the level of accuracy dependent on the quality of the data that is available.

6.4.2 *Numerical Code used*

For this modelling exercise the computer software program Visual Modflow was used. Visual Modflow is an easy-to-use-modelling environment for practical applications in three-dimensional groundwater flow and contaminant transport simulations, using the finite difference mathematical application.

The following numerical codes or methods for groundwater modelling were used. A broad explanation and discussion follows:

6.4.2.1 *ModFlow and Modpath*

For this numerical model the saturated groundwater flow - partial differential flow equation using the finite difference method:

$$\frac{\partial}{\partial x}\left(Kxx\frac{\partial u}{\partial y}\right)+\frac{\partial}{\partial y}\left(Kyy\frac{\partial u}{\partial y}\right)+\frac{\partial}{\partial z}\left(Kzz\frac{\partial u}{\partial z}\right)=Ss\frac{\partial u}{\partial t}\pm Q$$

where

u = hydraulic head

Q = sources / sinks

The equation describes the three-dimensional flow of groundwater through the substrata, calculating the water table-response. The equation may be solved analytically for simple problems, though for this study, piece-wise approximation of the equation is usually obtained through the finite difference method, because of the complexity of the problem. Once the water-level distribution is available over the whole area in question, seepage velocities and seepage

$$v = k(\partial h / \partial l)/n$$

directions can be calculated according to the following equation.

Where:

v = seepage velocity (m/d)

k = Hydraulic conductivity (m/d)

n = effective porosity (%)

h/l = groundwater gradient (m/m)

The flow modelling is done based on the assumption that steady state has been attained for the water levels in the area. Realistically several of the factors should be varied over time, but currently the information available prevents these factors from being included.

6.4.2.2 MT3D-MS

Mass transport in the regions of the identified pollution sources will be simulated by means of the MT3D numerical code. The engine simulates 3-D advective-dispersive transport of dissolved solutes in groundwater using the following equation:

$$\underbrace{\frac{\partial}{\partial \chi i}\left(Dij\frac{\partial C}{\partial \chi j}\right)}_{Dispersion} - \underbrace{\frac{\partial}{\partial xi}(viC)}_{Advection} + \underbrace{qs\frac{Cs}{\theta}}_{Sink\,/\,Source} \underbrace{-\lambda\left[C + \rho b\frac{S}{\theta}\right]}_{\text{Reactions}} = \underbrace{R\left[\frac{\partial c}{\partial t}\right]}_{\text{Retardation}}$$

Data Needed:

- Dicretization in all directions $\partial xi, (\partial x, \partial y, \partial z)$
- Dispersivity: D $_{\text{longitudinal}}$, K $_{\text{transverse}}$
- Retardation, Decay, Transformations
- Boundary and Initial Conditions

6.4.3 Modelling the flow and groundwater levels of the area

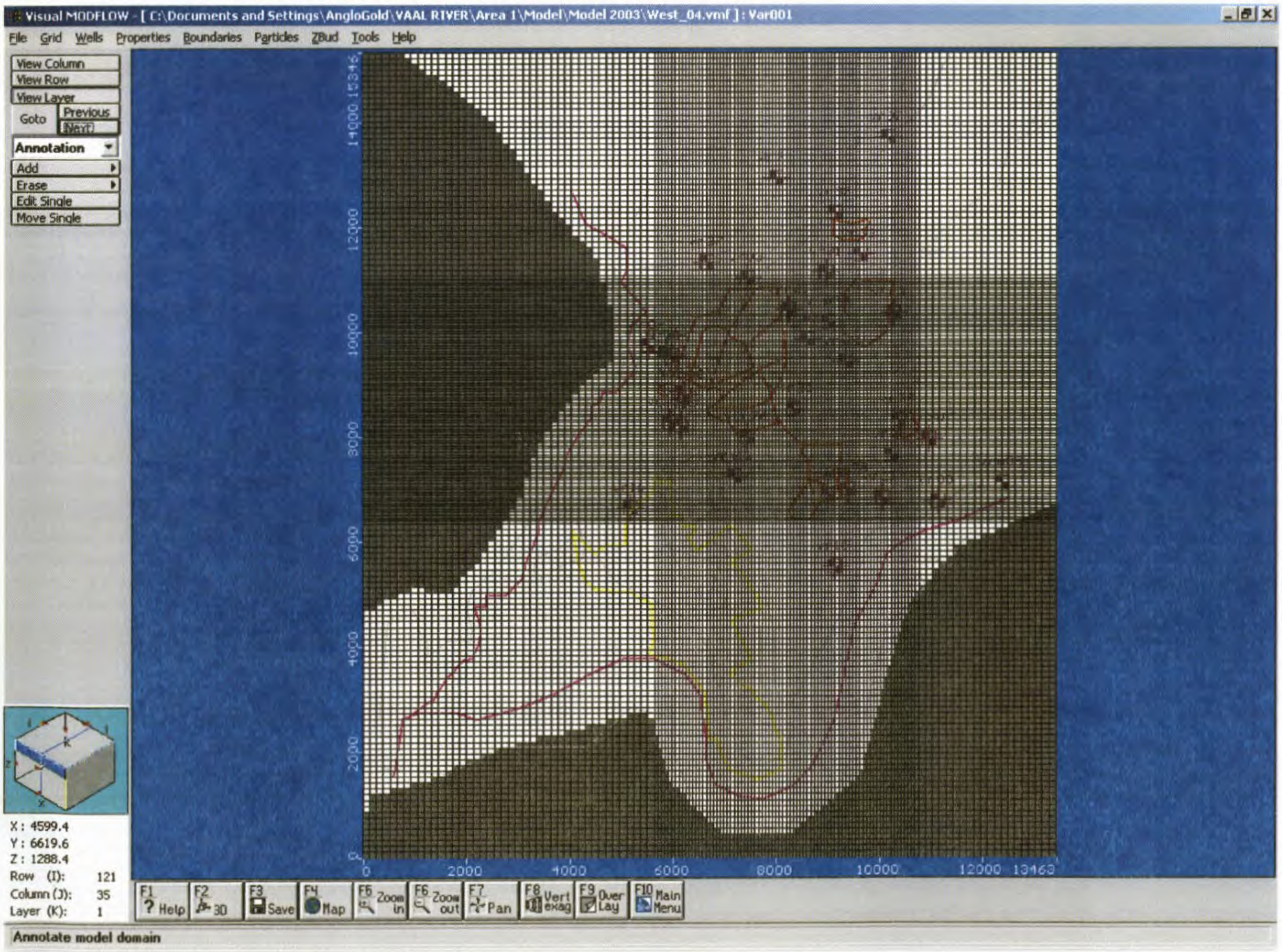
6.4.3.1 Generation of a finite-difference grid with multiple layers

MODFLOW (Harbaugh et al, 2000), an internationally accepted modelling package that calculates the groundwater flow equation using the Finite-Difference (FD) approach, was used during this investigation. The FD method was the first method to be used for the systematic numerical solution of partial differential equations (refer to section 6.4.2), where the user subdivides the total model area into rectangular cells using a regular grid. Parameters, such as water level, conductivity, and recharge are then assigned to each cell.

In this instance, the model network extends over a larger area than that under investigation so as to ensure that the boundary effects will not influence simulated results. In addition, the network has been refined in areas where more accurate answers are required, such as the Tailings dams and associated infrastructure (see Figure 53). A steady state calibration was then conducted to ensure the flow model has the same behaviour as the actual system under investigation once all necessary aquifer parameter and boundary conditions variables were considered (see Figure 56).

The following model components identified is based on the geological and geohydrological concepts defined before (see Figure 44), this could be graphically illustrated through the next two figures:

- The top layer, which represents all manmade structures, such as the tailings dam, effluent trenches and return water dams, the unsaturated zone (topsoil), and part of the weathered zone of the underlying geological formations.
- The second layer, which represents the bottom part of the weathered Transvaal Sub-Group sediments. This layer consists of weathered dolomite and usually extends to a depth of about 10 – 15 m. Aquifers in this layer are generally perched on less permeable in situ sediments, also in this layer is the Venetrsdorp lavas to the west of the investigation area,
- The third layer represents bedrock Transvaal Sub-Group sediments. This layer consists of solid hardrock dolomite and usually begins at a depth of 10 – 15 meters; in this case it extends to about 40 m. The aquifer itself varies according to the depth of less fractured dolomite and chert material, but generally occurs to in the upper 20 to 30 m of the profile; Deeper, confined aquifers within basement lithologies also form part of this layer.
- The 4th layer consists out of impermeable rock and is constructed from 50 to 60 m.
- The green areas west and south of the model grid indicates no=flow boundaries. The areas were selected as no flow because it is located on the other side of the two river boundaries and not necessary to be included in model simulations.



X : 4599.4
Y : 6619.6
Z : 1288.4
Row (I): 121
Column (J): 35
Layer (K): 1

Annotate model domain

Figure 53: Grid used during modelling.

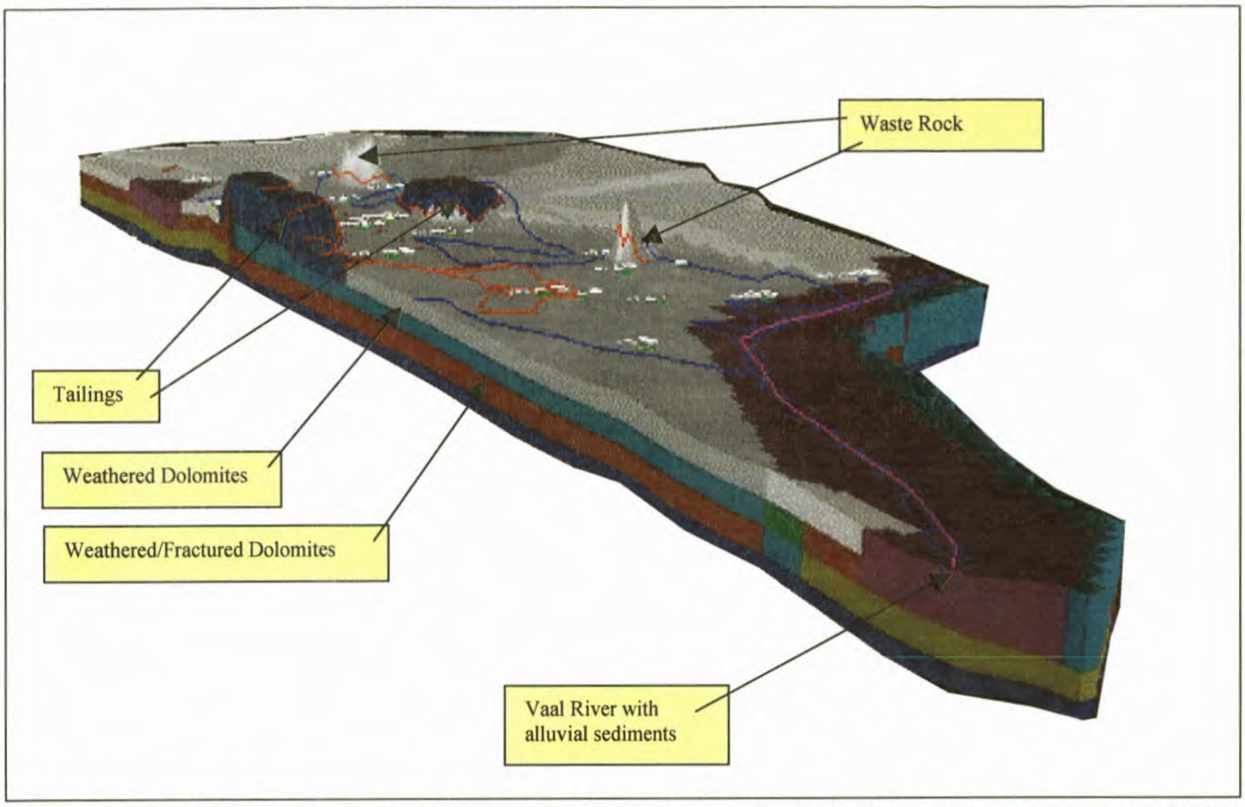


Figure 54: North South cross-section through model domain to illustrate different zones of permeabilities and aquifer conditions

6.4.3.2 Boundary conditions

One of the first and most demanding tasks in groundwater modelling is identifying the model area and its boundaries. Boundary conditions express the way the area under investigation interacts with the rest of the environment. Boundaries in groundwater models can be specified as:

- Dirichlet (also know as constant head or constant concentration) boundary conditions;
- Neuman (or specified flux) boundary conditions;
- Cauchy (or a combination of Dirichlet and Neuman) boundary conditions.

The southern and western boundaries were assumed to be river boundaries, these coincident with the Vaal River and Schoon Spruit respectively. The River boundary condition is used to simulate the influence of a surface water body on the groundwater flow. Surface water bodies such as rivers, streams, lakes and swamps may either contribute water to the groundwater system, or act as groundwater discharge zones depending on the gradient between the surface water body and the groundwater system. The MODFLOW River Package simulates the surface water / groundwater interaction via a seepage layer separating the surface water body from the groundwater system (see figure below).

The MODFLOW River Package input file requires the following information for each grid cell containing a River boundary;

- River Stage: The free water surface elevation of the surface water body. This elevation may change with time – the average water level for the Vaal River is 1280 mamsl (meters above mean sea level) and for the Schoon Spruit 1279 mamsl.
- Riverbed Bottom: The elevation of the bottom of the seepage layer (bedding material) for the surface water body – the elevation of the river bottom was between 1274 mamsl and 1276 mamsl.

- Conductance: A numerical parameter representing the resistance to flow between the surface water body and the groundwater caused by the seepage layer (riverbed) – an average conductance for the riverbed of 0.01 m/d was applied.

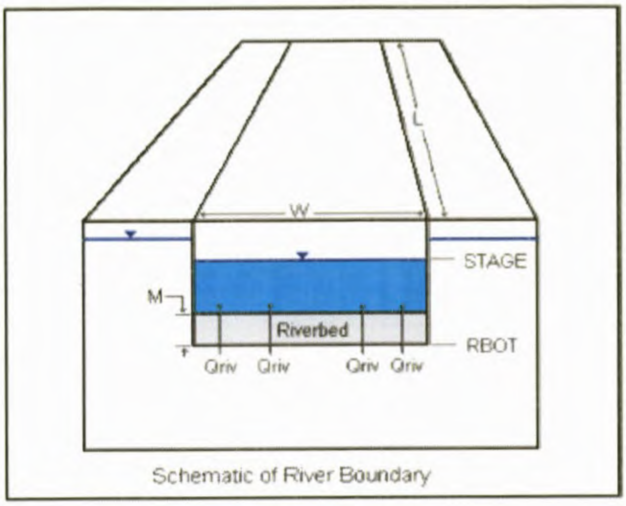


Figure 55: Schematic illustration of river boundary

Constant head boundaries were included within the 3-dimensional setting of the two Tailings Storage Facilities.

6.4.3.3 Initial conditions

Initial conditions must be specified for the entire area, with the initial piezometric head distribution generally the starting point for the numerical calculations. Unfortunately, the available groundwater head data is insufficient for this purpose in this instance. The model was constructed and run in steady state mode. The water table was then calibrated according to background water monitoring boreholes, away from artificial water sources and according to the level of the Vaal River. This had yielded a slight deeper water table, which is more a more realistic picture of pre-mining conditions. This water level was then used as input for initial conditions and the model was again run in transient mode.

6.4.3.4 Calibration of steady state flow model

The steady state head distribution is dependent upon the recharge, hydraulic conductivity, sources, sinks and specified boundary conditions. For a given recharge component and set of boundary conditions, the water level distribution across the aquifer under steady-state conditions can be obtained for a specific hydraulic conductivity value. The simulated head distribution can then be compared to the measured water level distribution, and K or recharge values altered until an acceptable head correlation is obtained. In this instance, K was varied (see Table 36) until an RMS (root mean square) value of <10% was returned (see Figure 56).

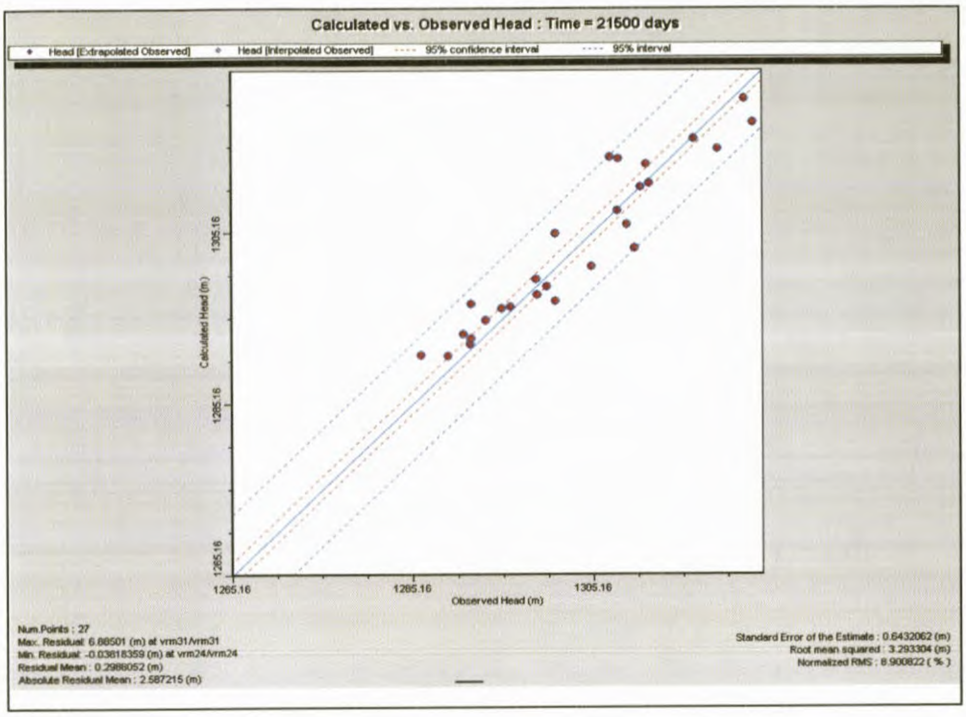


Figure 56: Steady state water level calibration.

Table 36: Varied K values for calibration purposes

	Initial K(x,y)	Initial K(z)	Calibration K(x,y)	Calibration K(z)
	(m/d)			
Tailings	0.05	0.005	0.05	0.005
Soil	0.5-1	0.1	**1.5**	**0.15**
Alluvial Clay	0.01	0.001	0.01	0.001
Transvaal: Fractured / Weathered Dolomite with sporadic cavities	2-4	0.4	**5**	**0.5**
Transvaal: Solid / Fractured Dolomite	0.2 – 0.4	0.02	**0.5**	**0.05**
Transvaal: Impervious Dolomite	0.001	0.0001	0.001	0.0001
Chert rich dolomite, weathered	3-5	0.5	**5**	**0.5**
Black Reef Quartsites	0.01	0.001	**0.05**	**0.005**
Ventersdorp Lava	0.01	0.001	0.01	0.001

6.4.3.5 Flow direction, vectors and other observations

Using the water level information as input, groundwater flow directions and seepage velocities have been calculated next. This is done for each of the nodes in the finite difference network. The results of these calculations are plotted in Figure 57 using arrows to indicate the directions (top part of figure) and velocity of flow range from 0.01 to 0.45 m/d (bottom part of figure). The lengths of the arrows are proportional to the seepage velocity at each point. The greater density of arrows in specific areas is due to the greater detail in the finite element network and does not signify more concentrated or faster seepage. Seepage in the tailings area occurs dominantly to the south towards the Vaal River and west towards the Schoon Spruit. For the determination of the regional transient state water-table gradient, measurement of static water levels in the monitoring boreholes is necessary. The piezometric levels and gradients for the Western Dolomite aquifer were obtained by using the water level elevation information of 9 new and 8 existing boreholes to determine the piezometric head distribution and gradients. The contour map, shows that:

- The maximum piezometric head elevation is north of the Western Tailings Dam Complex is at 1,318 mamsl at borehole VR03. The minimum piezometric head elevation is at 1,288 mamsl at borehole VR08 south-west of the Bokkamp Dam, north of the Vaal River boundary.

- The inflow boundaries from the tailings dams cause a flat plateau in the heads between the two dams. The piezometric level elevation here is limited by the topographic elevation. If the piezometric levels rise above this surface, the groundwater evaporates. Note that the influence of the aquifer in the upper, weathered zone controls the piezometric heads in this area. The average piezometric gradient from borehole VR03 (1,318 mamsl) to VR08 (1,288 mamsl) is 5.34E-03.

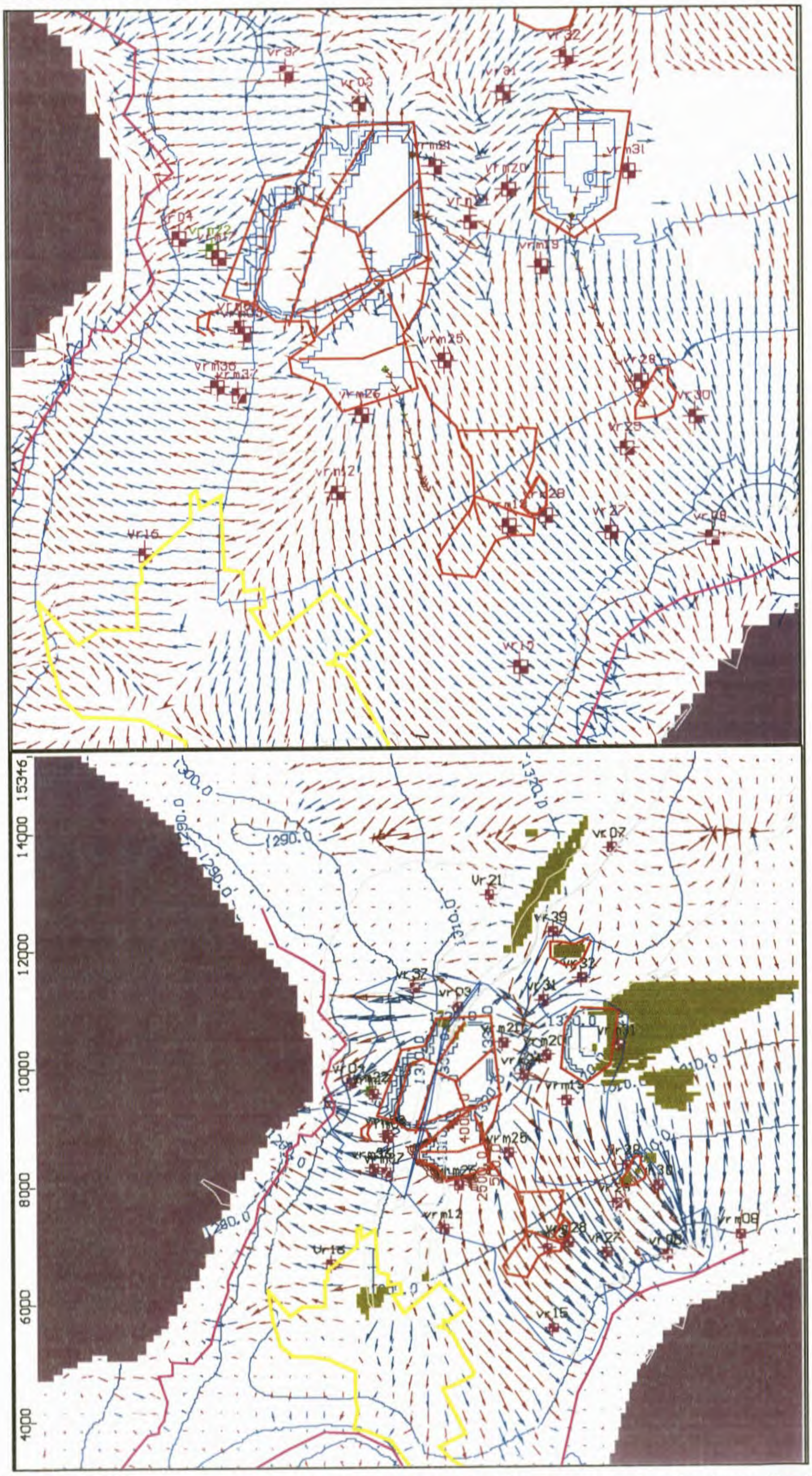


Figure 57: General groundwater flow directions and flow vectors for the investigation area.

6.4.4 Three dimensional mass transport model

6.4.4.1 Overview

Groundwater mass transport models attempt to simulate the movement of dissolved matter/mass (usually referred to as a pollutant or contaminant) that has accumulated in the aquifer. There are several factors that may affect the concentration distribution of a contaminant as it moves through an aquifer. There are two basic processes operating to transport solutes. Diffusion is the process by which both ionic and molecular species dissolved in water move from areas with higher concentration to areas of lower concentration. Advection is the process by which moving groundwater carries with it dissolved solutes. As solutes are carried through porous media, the process of dispersion acts to dilute and lower its concentration. Finally, there are chemical and physical processes that cause retardation of solute movement so that it may not move as fast as the advection rate would indicate (Fetter, 1998).

6.4.4.2 Dispersion

The mixing that occurs along the streamline of fluid flow is called longitudinal dispersion. Dispersion that occurs normal to the pathway of fluid is lateral dispersion. As groundwater flow proceeds in an aquifer, regions of greater than average hydraulic conductivity and lesser than average conductivity will be encountered. The resulting variation in linear groundwater velocity results in much greater hydrodynamic dispersion than that caused by the pore-scale effects. The greater the distance over which dispersivity is measured, the greater the value that is observed. This has been called the scale effect. The following table listed the used values:

Table 37: Summary of mass transport parameters used in the model (from Spitz and Moreno, 1996).

Sorption coefficient (L/mg)	**Molecular Diffusion (m2/s)**	**Longitudinal Dispersivity (m)**	**Transverse Dispersivity (m)**
0	0	10-100	5

6.4.4.3 Calibration

Calibration of mass transport models is usually difficult as contaminant concentrations at the sources are not available over a period of time. However, to overcome this problem, simulated and observed sulphate concentrations were compared to ensure the respective models were representative of field conditions, sulphate being the selected pollution indicator (Figure 58).

The history of the area (bear in mind that mining started already in the 1940's) was an important factor for calibration purposes. Old possible pollution sources were included as either initial concentrations or as constant sources of pollution. It must be noted that these sites were inspected and soil samples were obtained to confirm the assumptions where possible.

Refer to Figure 12 for localities of calibration boreholes.

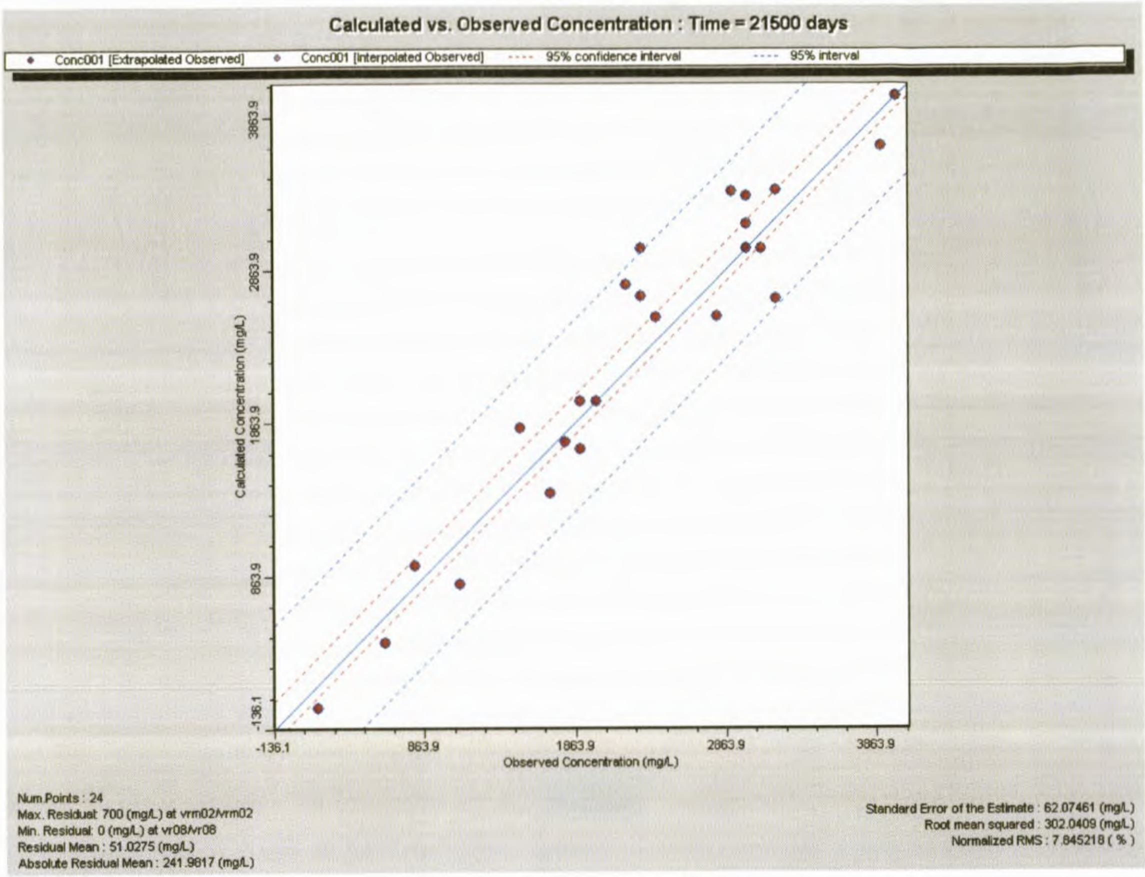


Figure 58: Mass-transport calibration. It should be appreciated that most of these boreholes are situated in the first layer of the model.

6.4.5 *Initial Conditions and results from model simulations*

Modelled scenarios are summarized in Table 38. This table also explains typical sulphate concentrations used for model simulations. These concentrations was loaded as constant sources of contamination.

Sulphate was used as the indicator element for geochemical purposes. It is introduced into the system as previously explained. Sulphate is a convenient constituent to study the movement of pollution, because: it is readily soluble, does not adsorb readily onto clay particles in the soil or the aquifer and it does not decay over time. Sulphate concentrations of several monitoring boreholes as well as chemistry data obtained from the geo-chemical modelling exercise, waste rock, in situ material, soils, etc were used to determine the different input concentrations.

The following figures indicate the sulphate concentration contours for the regional pollution migration for the shallow perched and deep regional aquifers. The calculated data for the different simulation time steps was export to the interpolation program "Surfer" for contouring purposes (Golden Software, Inc, 2002). The numerical mass transport model of the study area was done over a period of 60 years. All possible influences from the identified pollution sources were incorporated.

Table 38: Description of modelling simulations and assumptions.

Simulation description	Figure number	Comments
1) Current state (2003)	Figure 58	The current state flow model was calibrated using the available data set. The head within the tailings facilities was calculated according to current dam heights and side pizo's to obtain an optimal phreatic head – constant head (1355 mamsl within the WC-TSF and 1337 mamsl in the WE-TSF) and dry side slopes. The Vaal River and Schoonspruit were simulated with a constant level of around 1280 mamsl. The current pollution migration model was calibrated using the available data set. A constant concentration of between 4500 and 4000 for the West Complex and between 2500 and 2200 mg/L SO_4 for the West Ext. were assumed based on values obtained from the PHD (2002) investigation. **It must be noted that these values were efficient and the modelled plume compare well to field data.** Other sources like the old evaporation area and seepage areas were based on the results of the soil analysis (Viljoen, 2001). Typical SO4 concentrations of 2000 – 4000 mg/l were used
2) 17 years (2020)	Figure 59	Future 2020 prediction, from the assumptions listed above and it was assumed that the above conditions would continue up to about 2020.
4) 37 years (2040)	Figure 60	For conceptual purposes and for the sake of management options it is currently assumed that: ◆ Current operation will continue to about 2020, the tailings will then be closed and the phreatic heads will slowly reduce. ◆ At that moment in time only the Tailings and waste rock dumps will remain, a constant concentration ◆ All other contamination sources will be closed and rehabilitated. This simulation was therefore started with initial heads and initial concentrations from the previous 20-year simulation. The following sources of constant sulphate contamination was eochemic ignored: ◆ Queen Mary Dams, Old treatment plant west of the West Complex, Old Evaporation area, Skelm Dam, Game Park Dam and associated earth trenches. No further rehabilitation options were considered.
5) 57 years (2060)	Figure 61	Future 2060 prediction from the assumptions listed above.

It is clear from the simulations that polluted groundwater sampled at the site is derived from the Tailings storage facilities, unlined earth trenches, old evaporation dams and overflow from the Bokkamp dam. Modelling suggests that pollution will continue to migrate towards waterways located down-hydraulic gradient, with significant movement occurring along the shallow perched aquifer on top of the chert poor dolomite sequence.

Refer to Paragraph 6.6 for conclusions and unique findings obtained from these modeling simulations.

***Aquifer Depth**: 0 – 15 meters below ground level*
***Aquifer Type**: Weathered/ Perched/ high K (m/d)*

***Aquifer Depth**: 15 – 40 meters below ground level*
***Aquifer Type**: Weathered/ Fractured/ med. K (m/d)*

***Aquifer Depth**: 40 – 60 meters below ground level*
***Aquifer Type**: Solid/ Fractured/ low K (m/d)*

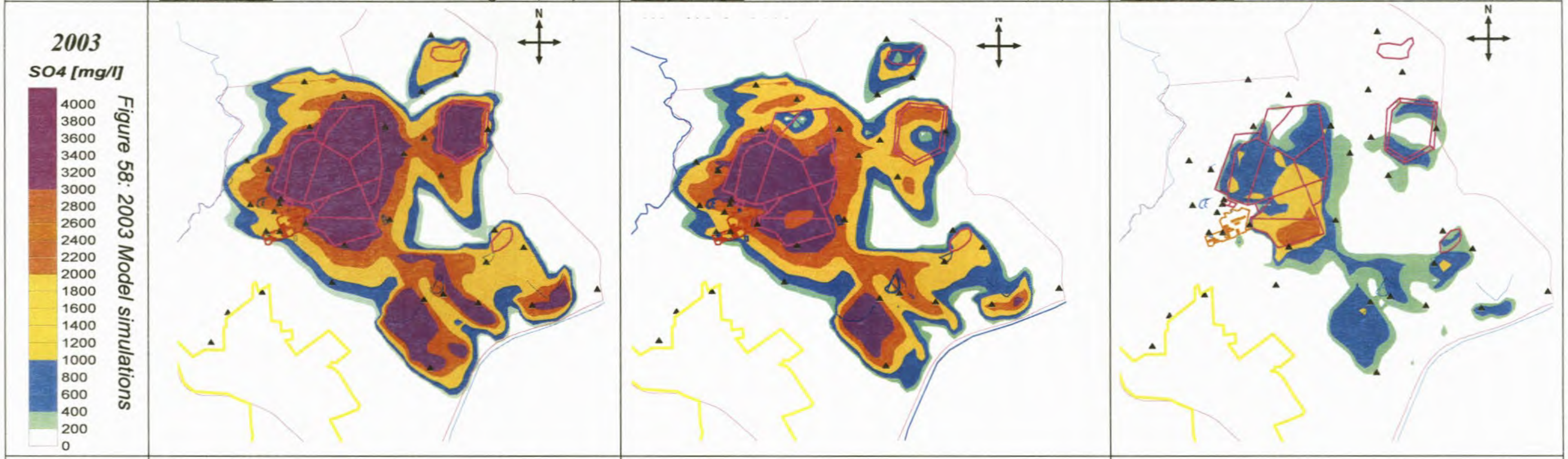


Figure 58: 2003 Model simulations

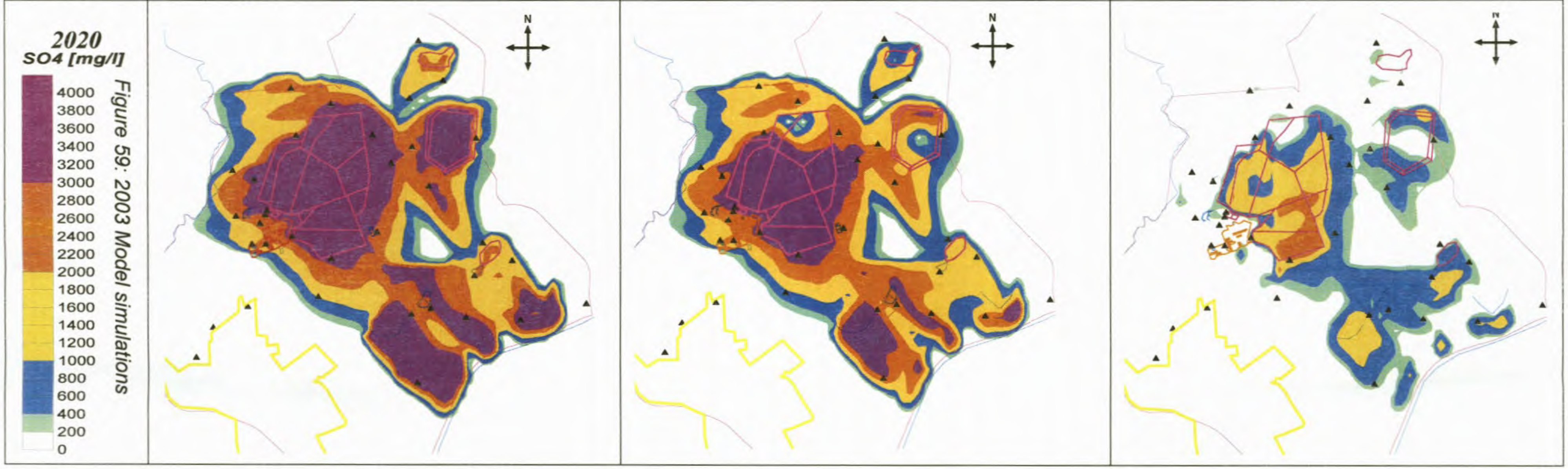


Figure 59: 2003 Model simulations

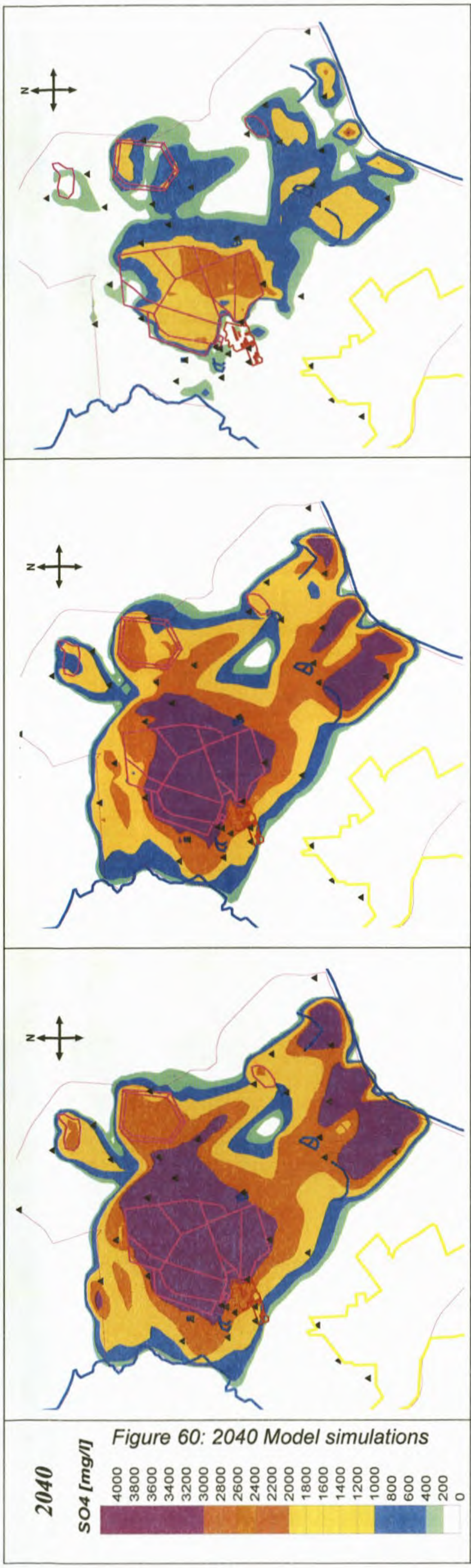


Figure 60: 2040 Model simulations

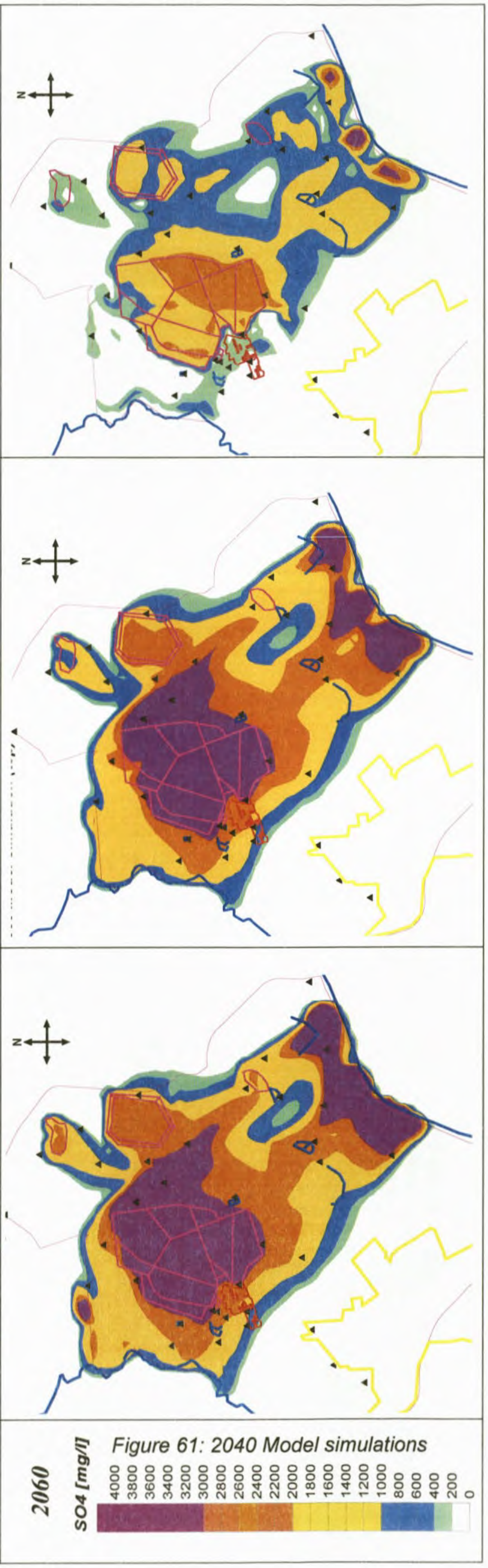


Figure 61: 2040 Model simulations

6.5 Understand impact and risk of pollution plumes on receiving water bodies

6.5.1 Introduction

The Water Act (1998) is based on a number of principles, one of which is that the quantity, quality and reliability of water required maintaining the ecological functions on which humans depend shall be reserved so that the human use of water does not individually or cumulatively compromise the long-term sustainability of aquatic and associated ecosystems. Currently no groundwater is used or will be used for domestic purposes, however the long-term land use of the area needs to be considered, currently the potential for future groundwater usage exist in the game park area and north west of the WC-TSF where small holdings exists. For this purpose a short overview of human health and groundwater use will be given. Experts in the field highlight the following components as important when performing a health risk assessment (EPA, 1994):

- Toxicity of the contaminant: When exposed to toxic chemicals there are numerous health effects that vary from mild headaches to death, all of which need to be considered;
- Carcinogenicity of a contaminant: Cancers traced to direct, involuntary exposure to environmental pollution are estimated to constitute about 2% of all cancer risks. However exposure to certain chemicals can cause some forms of cancer and therefore the carcinogenicity of a chemical needs to be accounted for;
- Exposure to a contaminant: This establishes whether exposure to a chemical or microbiological agent can cause harm. To determine exposure, it is necessary to combine an estimation of environmental concentrations of the hazards with demographic or behavioural descriptions of the exposed population;
- Population exposed to a contaminant: The population is composed of groups who differ in their vulnerability to health hazards. For example babies are more susceptible to infection because of their lack of immunity;
- Size of exposed population: The seriousness of health risks does not only depend on the hazardous agents but also on the size of the population affected. In general the bigger the population, the more cost and effort needed to treat the resulting health impacts.

6.5.2 Assessment of potential impacts

The contaminated seepage emanating from the WC-TSF and associated infrastructure, and later from the WE-TSF, over the time of existence, has had a high impact on the local weathered/fractured aquifer system as well as on soil. The duration of the impact will be long term, as indicated by the results of the modelling. The significance of the impact on the groundwater system could be assessed in light of potential targets, including local groundwater users. The impacts on the regional groundwater quality could also be assessed in light of mining activities and aquifer dewatering into the mine workings.

Seepage from the two tailings dams and other identified seepage areas has also had an impact on the Schoon Spruit and Vaal River, via migration through the perched aquifer system. This also severely impact on soil qualities, which started a seasonal circle of evapotranspiration of shallow groundwater during the winter months, precipitation of salts, and recharge of salts back into the aquifer after the rainy season.

The significance of the impact could however be assessed in terms of the overall impact on the major receiving water bodies. Four major receiving water bodies were identified which are the Vaal River, Schoon Spruit, Deeper Aquifer system and soils.

6.5.2.1 Salt balance

A water balance calculates the inflows to, and outflows from, a given groundwater system, by considering groundwater flow as a result of gradient differences, groundwater recharge and aquifer abstraction, and constant heads that have been used to depict surface water features. In complex geological systems, it is essential to develop a groundwater flow model that will be able to calculate a detailed water balance. Once this has been achieved, the mass of pollutants moving through the aquifer system can be calculated (refer to tables Table 40 and Table 41).

Stream flow records for the Vaal River and Schoon Spruit were obtained from DWA&F. The stream flow records used for the Vaal River and the Schoon Spruit, in the following calculations, was from the C2H007 Pilgrims Estate and C2H073 Goedgenoeg stations respectively. The Pilgrims Estate station is situated to the south of the investigation area and the Goedgenoeg station to the west of the area.

The following tables represent the flow data in numerical form:

Table 39: Annual mean flow in the Vaal River at station C2H007 (Pilgrims Estate) obtained from Department of Water Affairs and Forestry (HYANN V45) & Annual mean flow in the Schoon Spruit at station C2H073 (Goedgenoeg) obtained from Department of Water Affairs and Forestry (HYANN V45)

Vaal River Station C2H007 (Pilgrims Estate)		**Schoon Spruit Station C2H073 (Goedgenoeg)**	
Year starting October	**Annual Mean Flow (m^3/s)**	**Year**	**Annual Mean Flow (m^3/s)**
1979/80	24.3	1986/87	0.4
1980/81	29.2	1987/88	3.3
1981/82	9.2	1988/89	3.3
1982/83	7.2	1989/90	1.1
1983/84	15.8	1990/91	1.4
1984/85	18.5	1991/92	0.2
1985/86	17.9	1992/93	0.2
1986/87	25.4	1993/94	1.5
1987/88	70.2	1994/95	0.2
1988/89	100.3	1995/96	8.3
1989/90	15.9	1996/97	5.7
1990/91	18.5	1997/98	4.9
1991/92	11.4	1998/99	1.0
1992/93	19.8	1999/00	17.4
1993/94	29.6	2000/01	1.5
1994/95	27.1	2001/02	4.0
1995/96	248	***Minimum***	***0.2***
1996/97	145.6	***Maximum***	***17.4***
1997/98	74.5	***Mean***	***3.4***
1998/99	39.7	***Median***	***1.5***
1999/00	148.3		
2000/01	73.9		
2001/02	74.2		
Minimum	***7.2***		
Maximum	***248.0***		
Mean	***54.1***		
Median	***27.1***		

The salt balance was calculated with the results of the zone budget calculations obtained from the numerical model. Flow rates at selected areas were calculated and a sulphate load was calculated accordingly.

As sulphate was identified as the main indicator constituent for mass transport and migration, it was decided to use sulphate for the following calculations. The total dissolved solids (TDS) for each plume could also be calculated, but at this moment only SO_4 was calculated. The regional percentage of SO_4 in TDS was calculated and is about 52% of the total TDS, this could be used to obtained a rough idea of TDS loads.

Zone budget calculates sub-regional water budgets using results from steady-state or transient *MODFLOW* simulation. Zone budget calculates budgets by tabulating the budget data that *MODFLOW* produces using the cell-by-cell flow option.

Table 40: Flow rates and salt sulphate loads to the environment

Description of selected Zone	2003		2020		2040		2060	
	Flow (m3/d)	Load (kg/d)	Flow (m3/d)	Load (kg/d)	Flow (m3/d)	Load (kg/d)	Flow (m3/d)	Load (kg/d)
Eastern Part of West Complex Tailings Dam (on Transvaal)	1500	6000	1600	6400	1116	4464	701	2804
Western Part of West Complex Tailings Dam (on Ventersdorp)	500	2000	500	2000	173	692	131	524
West Extension Tailings Dam	500	1250	700	1750	389	972.5	184	460

Table 41 Estimated salt-balance (SO_4) for the Vaal River and Schoon Spruit using the numerical model. The current condition after almost 50 years of operation, and scenarios 17, 37 and 57 years into the future, are also shown.

	2003			2020			2040			2060		
	Flow (m3/d) as part of plume	**Load (kg/d)**	**Increase Concentartion (mg/l)**	**Flow (m3/d) as part of plume**	**Load (kg/d)**	**Increase Concentartion (mg/l)**	**Flow (m3/d) as part of plume**	**Load (kg/d)**	**Increase Concentartion (mg/l)**	**Flow (m3/d) as part of plume**	**Load (kg/d)**	**Increase Concentartion (mg/l)**
Plume facing the Vaal River as river leakage (Mean Vaal River Flow = 54.1m3/s)	218.4	655.2	0.140	249.6	748.8	0.160	280.8	842.4	0.180	311	933	0.200
Plume facing the Vaal River as river leakage (Minimum Vaal River Flow = 7.2m3/s)	218.4	655.2	1.053	249.6	748.8	1.204	280.8	842.4	1.354	312	936	1.505
Plume facing the Schoon Spruit as river leakage (Mean Schoon Spruit flow = 3.4m3/s)	154.4	154.4	0.527	540.4	810.6	2.767	694.8	1112	3.794	725	1233	4.206
Plume facing the Schoon Spruit as river leakage (Minimum Schoon Spruit flow = 0.2m3/s)	154.4	154.4	7.720	540.4	810.6	40.530	694.8	1112	55.584	726	1234	61.710

The loads and increases of SO_4 into the Vaal River and Schoon Spruit were calculated by using the sum of flows where the sulphate plume make contact with the water body as detected from the numerical simulations, the corresponding sulphate concentrations were applied. For example; in 2003 only 70% of the plume intercept the Vaal River and in 2060 100% of the plume, with an average quality of 1000 – 2000 mg/l. The input concentration of 3000 mg/l of SO_4 seems to be a conservative value for the calculations.

It is evident from the table above that the loads into the two receiving water bodies will increase over time. The reason for that, especially seepage into the Vaal River, is because of the current steady state nature of the plume and due to the fact that the sulphate plume is "damming-up" along the contact between the Transvaal dolomites and the clayey alluviums along the river system. For that reason a constant, relatively low base-flow from the aquifer, into the Vaal River occur. A significant amount of polluted groundwater also pushes out and surfaces as "eyes" or small fountains along this contact. It is therefore obvious that salts that daylights will accumulate through winter months and discharge into the river system via the first big rainstorms of the summer months. It is therefore expected that this portion of salt load into the Vaal River will be greater than the loads estimated in Table 41.

The following table gives an approximate idea of which percentage of groundwater enters the Vaal River through base flow and which will surface as little fountains. It seems that the amount of groundwater that daylights along the dolomite and alluvium contact is approximately 20 – 40 % of the shallow perched aquifer flow. The uncertainty regarding the day lighting of groundwater needs to receive more attention. If this phenomenon is better understood and assessed, efficient and practical remediation methods could be applied. Currently the 20 – 40% seems to be too high if it is compared to physical field measurements. Currently it seems if evapotranspiration (ET) dominates the actual surface flow of the day lighting water, in other words, negligible surface run-off occurred because of the domination of ET. The bigger impact is therefore on the soils due to the accumulation of salts and not directly on the Vaal River itself. ET values also need to be re-assessed and upgraded. Results of the model simulations suggest that ET and aquifer storage is the same – this is a definite indication of perched conditions.

Table 42: Results from Modflow Zone Budget for out flow of zone next to Vaal River

Flow Component	***m3/day***	***% of Total***
River leakage	312	20
ET	561	36
Storage	546	35
To deeper Aquifer	120	8
TOTAL	**1539**	**100**

6.6 *Concluding Remarks*

The following summarises unique findings, which were identified through the entire modelling process:

It is important to emphasize the value of such a modelling process; the interaction between the geological, geohydrological and hydrological environments could only be understood if detail modelling were done.

- The chemical results and other analysis on soil, water, tailings material and waste rock shows that over the last 50 years sulphates represents the greatest concern and that TDS is also generally a problem. TDS values are dominantly constituted out of SO_4 (55%), Ca (15%), Mg (12%), Na (9%), and Cl (8%) – Note: this is approximate and average percentages.
- The risk of transportation and identification of heavy metals in streams and groundwater seems to be low due to reasonable low pH values in groundwater. High natural Ca and Mg concentrations occur within the dolomitic aquifer, the Ca and Mg serve as buffer for pH.
- The salt balance and modelling simulations suggest diffuse seepage of approximately 600kg/d sulphates into the Vaal River and 150kg/d into the Schoon Spruit. Although this load shows an insignificant deterioration in river and stream water qualities and specific salt concentrations, the actual load in terms of mass unit per time unit is more relevant.
- Management should rather focus on specific load and not differences in up-stream and down-stream samples. To look only at the variations between up-stream and down-stream samples could be misleading and the actual impact on a major river like the Vaal River could be missed or wrongly interpreted.
- The current impact of contaminated shallow perched aquifers on soils seems to become a very important issue. Groundwater modelling suggests an evapotranspiration rate of approximately 36% of total aquifer flow. This hypothetically means that about 36% of salts will be transported to soil and soil surface. The accumulation of salts in soils is therefore a big issue and management needs to give more attention to this issue.
- No current groundwater users exist on the investigation area, but due to the fact that groundwater is not currently suitable for use, focus should be on diffuse seepage and possible long-term aquifer uses. The potential exist that certain portions of the aquifer will be used or the demand for use will increase.

- A detail health risk assessment should be part of long-term land use determination exercise. It is important that both soil and vegetation be incorporated in such an assessment. The reason for the proposed combination of soils and vegetation with groundwater is due to the occurrence of abnormal shallow perched aquifers, which contains high concentrations of salts. The interaction between these disciplines should be investigated in more detail.
- Modelling results further suggest daily water losses of approximately 2000m^3/day from the two tailings storage facilities. This, in turn, could be a long-term economic risk to the company. In economical terms, this suggests that if a cubic meter of water is purchased for R3, a total amount of R6000 is lost daily. Management should therefore also focus on improving tailings under drainage systems to optimise the return of water.
- Current field observations and river and stream water qualities compared well to the results of modelling. It must be remembered that the investigation area represents one of three major plumes, which could possibly impact on Vaal River quality.
- At this moment it is suggested that down-hole logging be done to identify the main pollution migration zones and different depths of pollution migration. The heterogeneous nature of the dolomite aquifer, caused by the sporadic occurrence of cavities and fractures in depth, complicates aquifer modelling and delineation of pollutants in depth.
- More emphasis will be given to scenario modelling now that the geohydrological concepts is understood. The focus should therefore be shift to closure planning and decommissioning of tailings storage facilities.

7 Aquifer remediation and technical feasibility

7.1 Introduction

This section of the assessment will consequently be focused on the outcome of the previous part. Possible aquifer remediation and other management options must be developed in accordance with major impacts on receiving water bodies. It is very important to focus resources on the more important issues. The following provides an overview of possible options that could be applied for groundwater remediation, it also discuss certain site-specific management options that could be considered. It must be noted that if a certain option is selected for remediation of an aquifer or for interception purposes, a detailed feasibility study and cost benefit analysis should be undertaken. It must further be noted that groundwater pollution in this area accumulated over a long period of time. Thus, to clean such an aquifer will be a slow and lengthy process of rehabilitation and improvement of surface operations.

The main objective of this section is therefore to identify possible options to remediate the identified plumes of salt migration within the aquifers. The idea is to look at practical site-specific options and the focus will be on the lowering of perched aquifers and the interception of high TDS groundwater.

7.2 Identification of remedial options in general

Aquifer cleanup frequently involves an initial emergency response to avoid, or reduce, an imminent health hazard in the case of production for human consumption or seepage into a vulnerable receiving surface body. This is generally aimed at:

- Eliminating the source of contamination; and
- Initiating some form of control on the further spread of the contamination plume.

The purpose of plume control, in turn, is to slow down the movement of, or if practical, completely isolate ("capture") the plume. A convenient and cost-effective way of doing this is by some form of hydro-dynamic control. The following section is based on conceptual options to remediate groundwater contamination. Although the scenario's is based on technical data and results from various modelling exercises, it still remains concepts and should be tested and monitored on micro-scale to optimise site-specific aspects.

Most of the remediation techniques and research are related to organic pollution such as petroleum from leaking underground tanks, but for the purpose to remediate salinity aquifers, much could be applied. However, limitations to remediation of contaminated groundwater became apparent in the mid 1980's as data from groundwater remediation projects in the US became available (Bell, 1999). The most common groundwater remediation strategy in the US has been the pump-and-treat approach (P&T technology), where contaminated groundwater is pumped to the surface, treated and returned to the aquifer. Because of growing concerns in the US that this approach was not likely to achieve target levels in many cases, and the predictions of clean-up times had been seriously underestimated, and independent assessment of the issues was conducted by the US National Research Council in 1994 (EPA, 1995). The survey revealed that only 8 out of the 77 sites reached the remediation clean-up level and in most cases the concentration of the target compounds in the extracted water had reach ed a constant level.

The low success of pump technologies is not surprising, because even in the case of an optimal design of the P&T approach, restoration of groundwater is limited by four factors which are inherent to the problem of removing contaminants from the subsurface (Bell, 1999). These factors are:

- Compounds strongly adsorbed to aquifer solids,
- Highly heterogeneous subsurface environments contain zones of low permeability (e.g. clay),
- Slow mass transfer of contaminants from aquifer solids to the bulk interstitial fluid,

- Widespread presence of non-aqueous phase liquids (NAPL's), particularly those that are dense than water. This factor does not account for inorganic trace element pollution, but for the purpose of this investigation the SO_4 plume did spread over almost 500ha, which is a very big area to clean up.

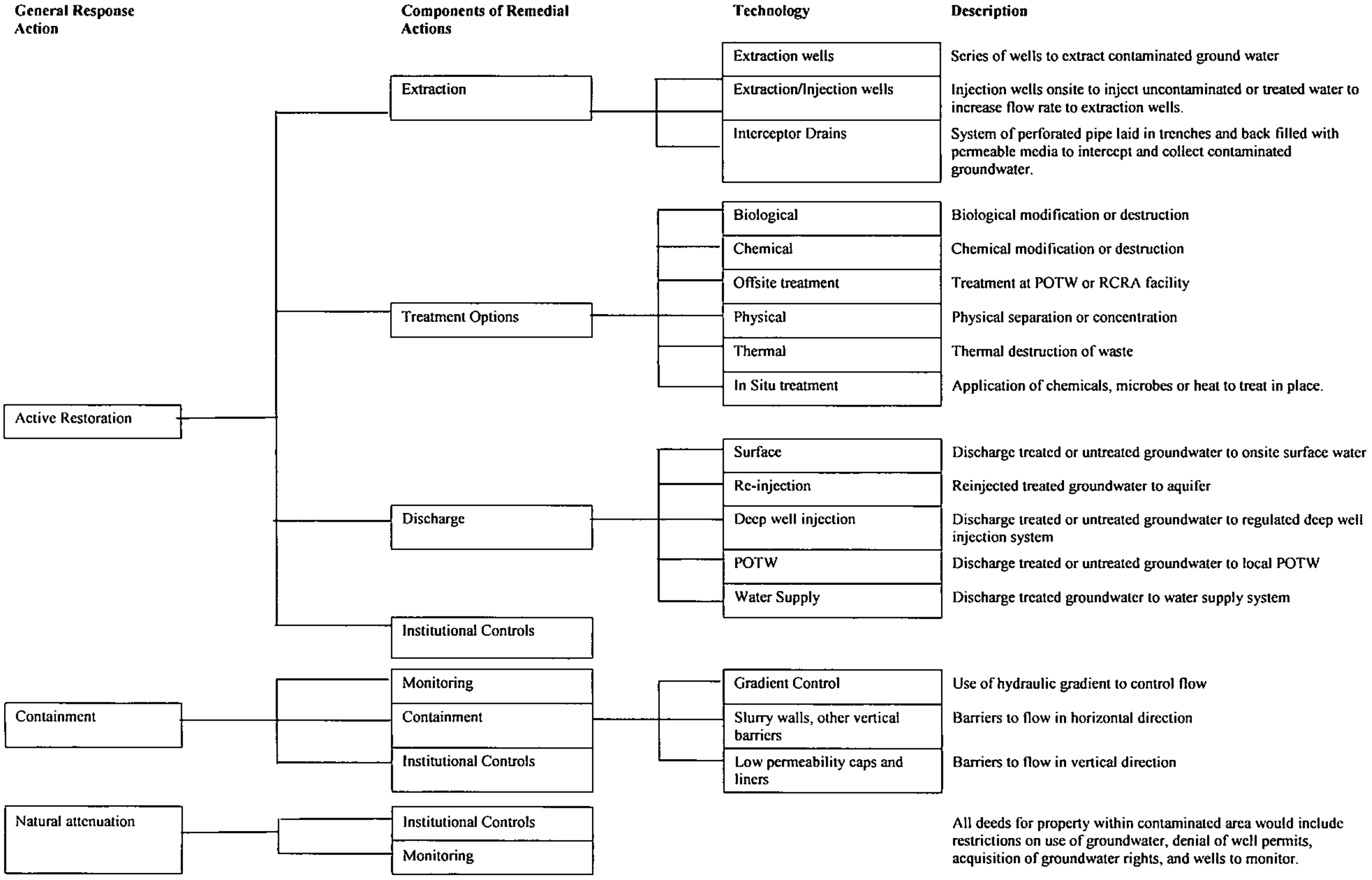
The options for the management of groundwater pollution are constraint by four aspects namely:

- The legal requirements,
- Social considerations such as down stream users or interested and effected parties,
- Financial viability,
- The technical feasibility.

The following list further groundwater remediation techniques. Some of these are not applicable to groundwater, if heavily affected by salts and heavy metal contamination.

- Bioremediation – indigenous sulphate reducing bacteria – also referred to as passive treatment systems,
- Permeable reaction wall (iron base catalyst),
- Treatment wall (gravel with pumping boreholes constructed within the wall),
- Surfactants,
- Permeable reactive barriers or hydraulic barrier
- In-situ flushing,
- Pneumatic fracturing extraction vacuum,
- Bentonite wall and pumping boreholes,
- Blast created trenches for groundwater Remediation,
- Phytoremediation of soils and Groundwater

The following table gives and overview of groundwater remediation options. It must be noted that water, which is reclaim from a polluted aquifer, must be dealt with in a proper way. Treatment of water could be necessary.



General Response Action	Components of Remedial Actions	Technology	Description
Active Restoration	Extraction	Extraction wells	Series of wells to extract contaminated ground water
		Extraction/Injection wells	Injection wells onsite to inject uncontaminated or treated water to increase flow rate to extraction wells.
		Interceptor Drains	System of perforated pipe laid in trenches and back filled with permeable media to intercept and collect contaminated groundwater.
	Treatment Options	Biological	Biological modification or destruction
		Chemical	Chemical modification or destruction
		Offsite treatment	Treatment at POTW or RCRA facility
		Physical	Physical separation or concentration
		Thermal	Thermal destruction of waste
		In Situ treatment	Application of chemicals, microbes or heat to treat in place.
	Discharge	Surface	Discharge treated or untreated groundwater to onsite surface water
		Re-injection	Reinjected treated groundwater to aquifer
		Deep well injection	Discharge treated or untreated groundwater to regulated deep well injection system
		POTW	Discharge treated or untreated groundwater to local POTW
		Water Supply	Discharge treated groundwater to water supply system
	Institutional Controls		
Containment	Monitoring		
	Containment	Gradient Control	Use of hydraulic gradient to control flow
		Slurry walls, other vertical barriers	Barriers to flow in horizontal direction
		Low permeability caps and liners	Barriers to flow in vertical direction
	Institutional Controls		
Natural attenuation	Institutional Controls		All deeds for property within contaminated area would include restrictions on use of groundwater, denial of well permits, acquisition of groundwater rights, and wells to monitor.
	Monitoring		

Table 43: Different Groundwater remediation options (EPA, 1995)

7.3 *Identification and Application to Investigation Area*

7.3.1 *Overview*

The following section summarise certain remediation options, which were focussed on the remediation of groundwater and the minimization of seepage. These mitigation and management options are solely focused on the investigation area, and will therefore represents site-specific conditions. There could be differentiating between indirect remediation and direct remediation.

- Indirect remediation refer to options that could be applied to improve the groundwater situation by doing something on contamination sources ir improve the management of these sources,
- Direct remediation refers to options that could be applied to the aquifer itself.

7.3.2 *Indirect Remediation*

The following list options that can be followed to "indirectly" remediate pollution plumes, this method of remediation is to be applied to identify pollution sources like the tailings and other identified seepage areas.

7.3.2.1 Physical site rehabilitation of tailings storage facilities and waste rock dumps

Physical methods like gladding with in-situ rock material, re-shaping, vegetation and engineered covers could be applied for long-term closure rehabilitation methods. The effects of the different management options in terms of facility water balance, oxygen balance and salt balance needs to be evaluated. It is recommended that two to three options is selected for each site and then assessed to identify the best long-term option. The best long-term options must therefore show benefits to both environmental management and economical expenses. The following table summarise different management option with possible effects on water balance and oxygen balance (Pulles *et al*, 2002).

Table 44: Effects of management options on water and oxygen balances

Management Option	**H_2O balance effect**	**O_2 balance effect**
Waste Rock Dumps		
Do nothing option	-	-
Remove source	N/A	N/A
Reshape, engineered cover & vegetate	Significant reduction	Significant reduction
Tailings Dams		
Do nothing option	-	-
Remove source	N/A	N/A
No reshaping, vegetate bare tailings	Not significant – slight decrease	Not significant – slight increase
No reshaping, rock clad, no vegetation	Increase infiltration	Not significant – slight decrease
No reshaping, armour and vegetation	Not significant – slight decrease	Not significant – slight increase
Reshape, vegetation on bare tailings	Increase due to larger footprint	Increase due to larger footprint
Reshape, rock cladding, no vegetation	Increase infiltration	Increase due to larger footprint
Reshape, armouring and vegetation	Increase due to larger footprint	Increase due to larger footprint
Reshape, engineered cover & vegetate	Reduce infiltration	Reduce infiltration
Dump Footprints		
Do nothing option	-	-
Remove source	N/A	N/A
Cover with 300mm soil & vegetate	Not significant	Not significant
Old Evaporation Dams		
Remove hazardous material en rehabilitate soils	N/A	N/A
Earth Trenches		
Line trenches with impermeable layer	Reduce infiltration	N/A

Each option could be geochemically modelled to identify the best option to optimise the following factors:

- Abundance of acid generation minerals such as pyrite;

- Abundance of neutralisation minerals such as calcite;
- O_2 diffusion rate;
- Pyrite surface area which strongly affects the mineral reaction rates; and
- Water infiltration rates.

It must be remembered that the option, which resulted the optimum levels of the 5 points above will usually be the most expensive option. It is therefore important to construct a cost benefit analysis. The outcome of the geochemical model and predicted loads to the environment could now be used in numerical groundwater models to predict groundwater behaviour against certain rehabilitation options.

The following figure illustrates the impact of the best remediation option on the area groundwater quality. All the options will have a minor impact on the plume over time expect for the engineering cover option. This option will give the best results over time but is obviously the more expensive option. It is therefore suggested that a cost benefit analysis be done. Woyshner *et al* (1997) examined a cover that was designed to minimize the exposure of tailings and waste rock to oxygen. This was achieved by alternating layers of coarse (sand) and fine (clay) material. The objective was to keep a clay layer near saturation point in order to control the ingress of oxygen. The clay layer, with a low hydraulic conductivity, also minimizes the entry of water into the tailings. In previous work undertaken by Pulles, various cover options were evaluated and modelled in terms of hydraulic permeability. Of these options, the following cover is specified as an engineered cover that will be used in this study for Anglogold: *The cover will consist of three layers, viz. 20 – 40 cm topsoil, 40 – 80 cm compacted and clay amended soil with high water retention ability and 30 – 50 cm coarse sandy material.*

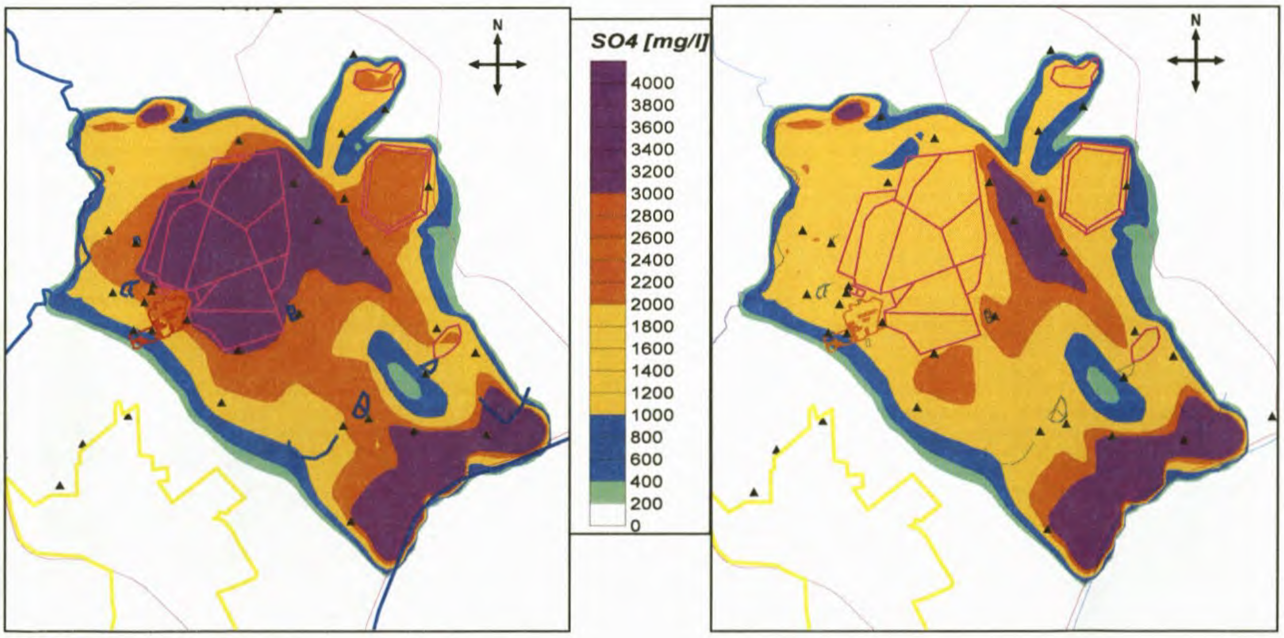


Figure 62: 2060 Model simulation for the Base Case and Engineering cover options

7.3.2.2 Rehabilitation of polluted soils

The Initial Conditions and results from model simulations in section 6.4.5 show the plume reduction from 2020 to 2040 by only rehabilitate polluted soil of old evaporation dams and earth trenches. The indication of polluted soils in areas, which were previously used as evaporation areas, old earth trenches and stockpile areas is evident as illustrated from a comprehensive soil sampling exercise. Refer to section 16.2 Test pits and soil profiles, Table 34. The SO_4 content is between 1000 and 4000 mg/kg. The load from this area could be reduced by simple soil rehabilitation techniques.

7.3.2.3 *Upgrading of operational activities*

When considering current deposition rates from metallurgical plants onto tailings storage facilities and associated densities of material, it could be comprehend what impact the ratio of water and solids could have on water balance and ultimate groundwater pollution.

Lets assume approximately 5000 tons of material is dumped on the West Complex tailings storage facilities per day – (refer to Table 1 in Section 1, 5000 tons/day is the magnitude of average of the current deposition).

When consider the percentage solids per mass, the following equation could be applied (personal communications with Steyn, 2003, manager of No. 1 Gold Plant):

$$SG\,(RD-1)\,/\,[RD\,(SG-1)]*100$$

Where:

- SG (specific gravity) of Witwatersrand ore body usually been accepted as 2.7 and the transport medium being water and the,
- RD (relative density) for this operation for tailings material is approximately 1.35.
- Therefore the % solids in the tailings material is 2.7 (1.35-1)/ [1.35 (2.7-1)]* 100=41%.
- Therefore 5000 tons of wet tailings material is 41% solids and 59% water,
- Therefore 2950 tons (m^3) water.

Figure 63: Comparisons of different RD's for Tailings material and associated water disposal

RD	***% Solids***	***% Water***	***m3/day***	***m3/year***
1.5	52.94	47.06	2352.94	858823.53
1.45	49.29	50.71	2535.50	925456.39
1.4	45.38	54.62	2731.09	996848.74
1.35	**41.18**	**58.82**	**2941.18**	**1073529.41**
1.3	36.65	63.35	3167.42	1156108.60
1.25	31.76	68.24	3411.76	1245294.12
1.2	26.47	73.53	3676.47	1341911.76
1	0.00	100.00	5000.00	1825000.00

7.3.3 *Direct Remediation options or Hydrodynamic Control*

The following discussion will explain methods, which could be directly applied to aquifer systems or identified seepage areas. The aquifer conditions and complex nature of the local geology in the investigation area will makes groundwater remediation, by means of interception or in-situ passive treatment, very difficult.

7.3.3.1 *Extraction Well System*

Under the circumstances where the water table is relatively deep or due to outcropping geological strata, the use of a recovery ditch is not practical and a well(s) must be employed. The principle is as follows:

- Installed wells is pumped at sufficient capacity to trap the contaminant plume within a cone of depression;
- Contaminated groundwater is pumped to the surface where it can be either treated or used as plant make-up water.
- If the groundwater is treated it could be re-circulated through the contaminated aquifer zone until an acceptable level of water quality is reached. Re-circulation could be done by means of injection wells or infiltration galleries.

The only area where interception boreholes will work is about 100 m – 300 m north of the Vaal River along the dolomite alluvium contact. The aquifer in this region supply higher yields for boreholes (Wates and Wagener, 1990).

The following concept was used:

When consider the distance to-boundary method, which was developed to determine the theoretical radius of influence of the hydraulic boundary, the following borehole spacing was determined: The method employs a modification to the Cooper-Jacob equation 2 where r is the radius of influence in the aquifer when boundary conditions are encountered.

If the transmisivity (T) of $20 m^2/d$, pumping time of 12-24 hours/day and a storativity (S) of 0.01 is used for the following calculation of radius of influence (r^2);

$r^2 = 2.25\ T\ t\ /\ S$ (*Kruseman, et al, 1989)*

then the radius of influence seems to be 200 – 250 m for the dolomite zones closer to the Vaal River.

This will require at least 10 boreholes over the 2000 m of river front. Previous borehole drilling in the area suggests an average borehole yield of 2l/s. The well field will therefore comprise out of a line of 10 interception boreholes, each with a projected yield of 2l/s. The boreholes will be drilled just to the top of solid bedrock, which is approximately 15 – 30 meters below ground surface for this area. The following give an overview of cost estimates and projected return in income for water savings and saving in waste discharge charge penalties:

Table 45: Summary of well field cost estimates for installation and operating costs and projected return of income

Installation Costs		**Teturn in Water Costs**	
GeoPhysics	R 20,000.00	Water Costs (R / m3)	R 2.30
Drilling	R 380,000.00	Estimated Water reclaimed (m3/d)	2000
Drilling	R 150,000.00	Water Reclaimed per year (m3/y)	730000
Testing	R 85,000.00	Total Cost if purchased from Midvall Water Company	**R 1,679,000.00**
Analysis	R 15,000.00		
Equiping & Reticulation to dam	R 500,000.00	**Return in future WDCS**	
Dam	R 450,000.00	Quantity of difuse discharge (m3/d)	300
Reticulation to operations (2500 m of pipe)	R 600,000.00	Quality of difuse discharge (mg/l)	2000
		Applicable penalty / m3	R 0.05
	R 2,200,000.00	Applicable penalty / kg	R 0.60
Electricity of Borehole Pumps			
Cost per Unit (R per kWh)	R 0.30		
Units per pump (kW)	5		
Running cost per pump over 24 hours	R 36.00		
Running costs for 8 pumps per year	**R 105,120.00**		
Electricity of Pumps in Pump House			
Cost per Unit (R per kWh)	R 0.30		
Units per pump (kW)	20		
Running cost per pump over 24 hours	R 144.00		
Running costs for pump house per year	**R 52,560.00**		

Figure 64 could be compared to Figure 62 to illustrate this concept. It could be seen from this figure that the built up of salts along the alluvial eoch is successfully intercepted and the aquifer plume will attenuate over time. This option is expensive and requires full-time maintenance.

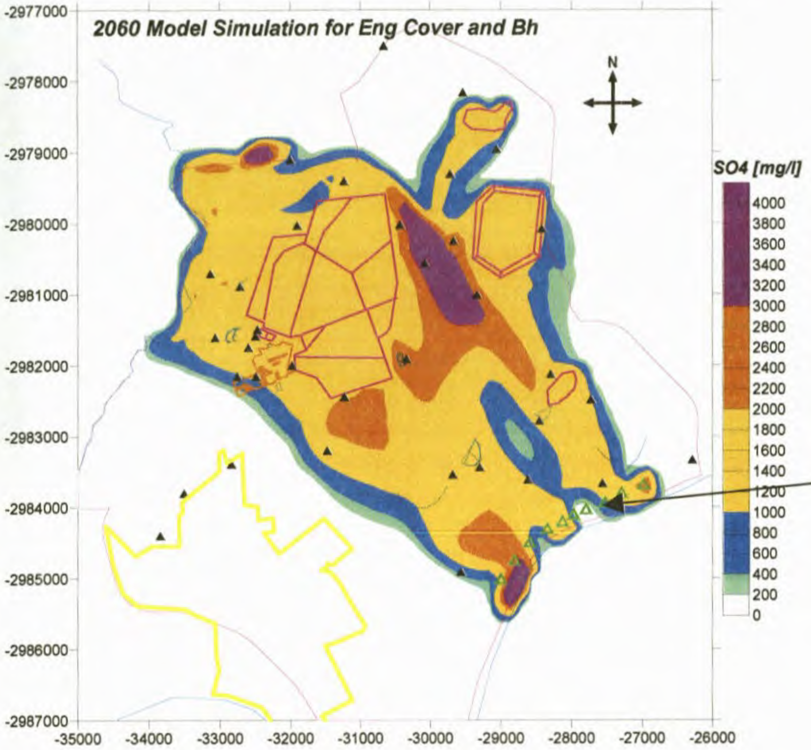


Figure 64: 2060 Model simulation for the Engineering cover option with an interception well field on the dolomite/alluvium contact. This well field was now in operation for 20 years

Proposed well field

- More to the north, closer to the pollution sources, low yielding aquifers exist and will not yield enough water for pumping purposes.
- Excavation of a cut-off trench closer to the pollution sources would be the ideal method for intercepting of the shallow polluted groundwater. The occurrence of shallow dolomite outcrops and pinnacles make this option almost impossible or very expensive.

7.3.3.2 Excavated Ditch

This might be used as both:

- An up-gradient means of intercepting both runoff (sheet flow), and upper portion of the groundwater flow, and diverting it away from the source; or/and
- A down-gradient means of intercepting the upper portion of the plume.

Recovery ditches have proved highly effective in recovering mass transport. A liner may be placed on the down-gradient side of the ditch to prevent intercepted salts re-entering the aquifer. Multiple-pumping systems may be effectively used for the reuse of the intercepted water. Pumping offers the advantages of (which could be disadvantages in certain cases):

- Inducing a steeper hydraulic gradient within the plume zone. This increases the rate of flow of contaminants towards the ditch.
- Reversing the hydraulic gradient down gradient of the ditch. This helps to trap contaminants and thus prevent further migration;

The area to the west along the Schoon Spruit needs to be investigated to determine the best option to reduce the plume in that area. The possibility occurs to de-water a current shallow underground mine working to establish a reverse groundwater gradient back to the tailings dam, but also to excavate a cut-off trench below the Queen Mary dams. This area seems to be sufficient for such an operation, but further work needs to be done.

Disadvantages from this could be:

- The bedrock could be to deep at certain places, this will then require a very deep trench, which will become very expensive and impractical to operate,
- The static groundwater level could reach a level below the bottom of the trench,
- The flow of water could be to slow and the remediation process will become to lengthy and unfeasible

All these need to be considered and assessed in more detail.

7.3.3.3 Passive treatment

The following briefly explains passive barriers, passive treatment walls, treatment walls, or trenches. An in-ground trench is backfilled with reactive media to provide passive treatment of contaminated ground-water passing through the trench. Treatment wall is placed at strategic location to intercept the contaminant plume and backfilled with media such as zero-valent iron, microorganisms, zeolite, activated carbon, peat, bentonite, limestone, saw dust, or other. The treatment processes, which occur within the treatment wall, are typically contaminant degradation, sorption or precipitation. Applicable to wide range of organic and inorganic contaminants; choice of media for treatment wall is based on specific contaminant. Hydrogeologic setting is critical to application; geologic materials must be relatively conductive and a relatively shallow aquitard must be present to provide a "basement" to the system. Ground-water flow should have a high degree of preference, and ground-water quality must support the desired reaction without imposing additional loading of the reactive media or creating undesirable by-products (EPA, 1995)

- In situ passive treatment was also considered for the site but find to be difficult to implement. For passive treatment systems diffuse seepage and low topographical gradients are negatives and will create difficulties. It normally works in areas where seepage is contained into a little stream and where flow through the system could be at a certain velocity.

The following describes important aspects of typical design criteria for passive treatment – this information was obtained from a technical feasibility study for passive treatment at the AngloGold Jerritt Canyon Mine Site, Navada, USA. Past experience with the design and operation of passive sulphate reducing facilities have yielded the following general design criteria:

- The pH range of the inflow should be 5 to 9
- Areal loading factors should range from 9.8 m^2/liter/min (for near neutral input) to 19.6 m^2/liter/min (for highly acidic input).
- In order to provide sufficient time for the required reactions to occur, the system should provide for a residence time of 2 to 6 days.
- If compost is to be the source of soluble organic carbon, then a shorter composting time tends to be preferable to a long composting time to maximize the amount of small chain organics available for metabolic reactions.
- The sulphate reduction rate can be expected to range from 200 to 600 mmoles/m^3/day, but design should be based on an assumed rate of 300 mmoles/m^3/day.

7.3.3.4 Phytoremediation

The idea of using vegetation in the amelioration of impacts of mining on water quality is to take up surface run-off and seepage to preventing movement and leaching. Threes are recognized as being potentially major consumer of water, with the genus *Eucalyptus* targeted as a consequence of both South African and international experience, the hypothesis is that consumptive water use likely to be higher where trees are established on sites which would otherwise be carrying grass or other low biomass vegetation (Versfeld, 1998).

Currently a trial plantation block of 20ha is planned for the area between the WC-TSF and the WE-TSF. From the investigations previously mentioned in this thesis, this area was identified as high impact seepage site, with highly contaminated shallow groundwater and soils. The intention is to research uptake quantities from the trees and to identify the most suitable species for such saline conditions.

Refer to Appendix B for species to be used for the trial sites (*I. Weiersbye, 2002)*

Figure 65: Photo's of plantation trial site

7.3.4 Methods to be used and/or treat contaminated water

Today's typical groundwater remediation and cleanup technologies involve one or another of the "pump and treat" varieties. Such concepts involve pumping the water to ground level to a treatment unit. There are several well-founded ways to purify water. This water could then be re-use as potable water or discharge into streams or rivers.

A second option is to re-use the contaminated water in the metallurgical or cooling operations. This option seems to be viable during operations but not for the de-commissioning phase. Before water could be re-used, a fitness for use study needs to be completed to identify the limits of water quality and physical characteristics of the identified operation.

8 Conclusions, Recommendations & Strategic Groundwater Management Concept

8.1 Overview

The main objective of this thesis was to develop a logical approach towards mine closure regarding groundwater assessments and remediation purposes, Table 47 summarise this approach with a flow diagram. The need for groundwater assessments during the operation and later during the de-commissioning phase was highlighted. This approach was systematically discussed and explained, and consequently applied within a practical site-specific situation in the form of a case study. The main driving force behind this thesis was therefore to explain the steps that need to be followed to achieve the technical (scientific based) geohydrological end-results. The end results, in turn, must then be evaluated to achieve the main objective – the main objective, for that matter, is actually very simple (refer to the matrix represented by Figure 3):

- To explain the "rules of the game": to mine management,
- To identify "key uncertainties" in the field of groundwater and mass transport,
- To identify and develop options, and
- To make management decisions.

The conclusions of this thesis however, will therefore not be focused on the technical data and scientific interpretations of field and lab results (as discussed in Section 3), but will rather concentrate on the approach and methodology that was followed to accomplish the objectives. The following listed the main findings of this thesis.

- It is important to construct objectives of mine closure and long-term groundwater management annually and not let it be a once off pre-compilation of a set of objectives and aims. It is important to keep up with technology and legal requirements,
- It is better for a manager, responsible for groundwater management, to divide the mine lease area or area of responsibility into smaller more manageable geographical areas. This could be done according to surface drainage boundaries, aquifer characteristics and identified plumes. Each major plume could then be named, characterised and manage according to company objectives and legal requirements. It will also be easier to do performance assessments of management options after wards,
- Responsible water managers of mining houses must have the willingness to instruct DWAF and DME into certain directions, rather than waiting for them to give the first step into a certain direction. A proactive attitude is therefore very important. Certain ideas and concepts regarding water quality objectives, groundwater remediation, etc can then be work-shopped and a "win-win" situation could be identified,
- It is important for mine personnel responsible for a certain environmental aspect, like water, to do extensive research on the mine's operational history and "sins of our fathers". This will enable one to have a better feeling for identified regions and identified problems. A critical study of old reports should be part of this research exercise. There must be lessons that needs to be learnt form the past,
- Possible sources of groundwater pollution must be identified and understood. It is therefore important to do some reading on certain unknown or unclear mining operations to obtain scientific background and to understand certain contaminants. Again, this will enable one to have a better overview of identified problems, but will also give more credibility on professional opinions,

- The importance of legal aspects must be emphasised, current policies and opinions from responsible government departments must be known at all times. It is also important to be updated on the newest legislation and acts,
- The personnel responsible for certain environmental aspects, like groundwater or surface water, must be schooled in that field. It is important to develop resources in the right direction and focus on main issues,
- The groundwater and surface water-monitoring program needs to be optimised and updated on an annually basis. The importance of monitoring, the lab analysis and the interpretation of the results on a continues basis, must be understand and explained to operational managers,
- Before the details of the local aquifer are assessed is it important to understand the physical geography of the area of interest. For the purpose of geohydrology, it mainly included geology, topography, surface drainage and climatic data. Other schools like vegetation and soil studies could be included. A further aspect of geography is the demographic field thereof – details of down-stream users, interested and affected parties and regional socio-economic features could be beneficial during the investigation,
- The next step should be to understand the characteristics of the local aquifer system. The geological and geohydrological concepts of the area needs to be reported and graphically illustrated to responsible managers and for the purpose of numerical groundwater modelling,
- It is critical that the environmental risk assessment (ERA) process that is followed when developing a mine closure strategy should follow a consistent and structured process. The basic principle incorporated into the proposed approach is that the level of detail of ERA should be appropriate to the risk that exist, i.e. minor risks need not be subjected to a detailed quantitative risk assessment process, while significant risks should not stop at a simple qualitative assessment.
- In some cases, and also depended on the objectives and level of impact, certain extended fieldwork needs to be included. This could include, or in some case must include; down-the-hole logging of certain parameters, sampling of tailings and waste rock for acid base accounting, geo-chemical modelling of the material, identification of the natural attenuation ability of the aquifer system, soil analysis of seepage areas, etc. It must be remembered that an assessment for the purposes of mine closure needs to include qualitative as well as quantitative analysis, predictions and assumptions – it could therefore be necessary to include more detailed field investigations and analysis to optimise the level of certainty. The inclusion of more detailed studies, is however included in the current draft minimum requirements form DWAF (DWAF, 2003). It is however the responsibility of mine managers to discuss these requirements with DWAF and DME to reach consensus of requirements and objectives.
- In the absence of reliable data, consciously conservative assumptions must be made and applied for model application purposes with respect to the problem to be modelled, without jeopardising the value of the model,
- Possible groundwater remediation options must be identified and a comprehensive research on identified options must be started. The identified option needs to be included in numerical model simulations as part of the feasibility study. After that it is advisable to start with a small-scale trial site to finalise concepts and identify operational behaviour against groundwater characteristics.
- Long term predictions on pollution, migration rates and loads to receiving water bodies must be calibrated according to field monitoring data. This should be started before actual de-commissioning phase.
- The compilation of technical reports with conclusions and recommendations is usually misunderstood or wrongly interpreted and neglected by the receiver or line manager. It must be realised that geohydrology and associated site assessment usually contains scientific based and complicated data; recommendations must therefore be readable, simple and practical to apply.

8.2 *Strategic Groundwater Management Concept for surface contamination sources*

To summarise and to focus on the end result of the investigation, the following concept for strategic groundwater management, in a simple table format, could be compiled. The main reason for this table format is to collate all the mane technical findings in a simple and readable format. It must be remembered that these tables could not contain to complicated geohydrological data. It must be understandable and readable to operational managers and people with very little environmental background. The more detail report will serve as reference for DWAF, DME and internal geohydrologists and environmental managers. These table should be update annually and numerical modelling calibrated also on an annually basis.

The principle of focus on the more significant groundwater issues will be followed. For that matter, all issues are listed and assess in the document. Only the main contamination plumes, which have and will have a significant impact on receiving water bodies, will be described in the following strategic groundwater management tables. The costs must be estimated with the guidance of engineers and consultant in the different field of expertise required for a certain remediation project.

The tables will therefore allow for the following detail:

Table 46: Explanation of data contained in strategic groundwater management tables

Name	**Description**
Plume Name	This is a short description of the delineation of the plume to describe locality. More than one plume with a high priority could exist in a specific investigation or geographical region.
Area	The total area of the plume in [ha]. This area is calculated by using the outline of the 200 mg/l SO4 plume for the current situation. The 200mg/l is a conservative value when consider background and maximum values.
Volume	The total volume is an approximate calculation of area multiplied by the assumed depth of contamination, multiplied by the average porosity of the area. Therefore 1900 0000m2 x 40m X 0.1. The volume given by [m3] must rather be seen as the total potential capacity within that aquifer that could contain contaminated water. This usually gives a misperception of groundwater dynamics but seems to be a conservative estimate of the current volume of contamination. A more reliable figure could be incorporated which could be obtained from the numerical model.
Plume extend and possible discharge	This gives and overview of the results from the mass transport model (delineation of the plume), current seepage from tailings and current seepage of the plume at the Vaal River or receiving water body
Concluding remarks on aquifer characteristics	This gives and overview of the results from the flow modelling, and typical aquifer characteristics.
Sites	This list all the relevant sources of pollution in a given area
Appr. % of Cont.	Approximate percentage of contribution to the pollution within the area.
Capital Cost Estimate of Best Available and Practicable Technique(s) for specific site	These list the identified techniques to reduce pollution and to rehabilitate the groundwater to reach background water qualities. This is listed to give management an idea of groundwater liabilities and to identify management plans towards closure.
Estimated Operational & Maintenance Costs	To give an idea of what the operational and maintenance costs could be.
Comments	This provides and idea of pro's and con's and possible deliverables.

PLUME NAME:	***VAAL RIVER WEST - West Tailings via Game Park***	***AREA (ha): 1900***	***VOLUME (m3): 76,000,000.00***
Plume extend and possible discharge:	Currently all these sites contributes a certain amount of salt leakage into the aquifer flowing from north (4# area) towards the Vaal River in the south (Game Park area). The estimate seepage rate of the relevant portion of the tailings is in the region of 2000 m3/day. Currently the plume is in steady state and about 250 m3/day seeps into the Vaal River which is situated about 4 km to the south, and about 550 m3/day reach the surface via ET. At this moment an uncertain amount of salts is washed into the river from surface salt accumulation.		
Concluding remarks on aquifer characteristics:	Currently groundwater and dissolved pollutants flow via shallow perched aquifer (0-3m), mainly on top of the chert poor dolomites to the south, where salts is surfacing via ET and washed into Vaal River by abnormal rain-effects, seeps into the Vaal River via baseflow and seeps into deep aquifer systems.		

Site	**Appr. % of cont.**	**Capital Cost Estimate of Best Available and Practicable Technique(s) for specific site**				**Estimated Operational & Maintenance Costs**			**Comments**
		Description	**Cost/Unit**	**Units Req.**	**TOTAL**	**Cost/ Unit/y**	**Time (years)**	**TOTAL for all units**	
West Tailings Dam Complex	64.69	Woodlands (units in ha)	R 15,500.00	1000	R 15,500,000.00	R 325.00	20	R 6,500,000.00	About 34 986 m3/day will be extracted. Trees could only extracted water to a max depth of 10m, the amount of salts to be extracted is currently uncertain. A minimum of R500/m3 of wood could be returned. Will require permits and charges for Eucalypt.
West Extension Tailings Dam	13.80								
Old evaporation area west of Bokkamp - seasonal recharge of tailings effluent	10.57								
Bokkamp dam and path of previously overflows	4.23								
Game park dam - current dam wall build with tailings material and accumulation of salts due to up-gradient contamination	3.17	Interception boreholes (units in bh's)	R 280,000.00	50	R 14,000,000.00	R 20,000.00	40	R 40,000,000.00	About 7 000 m3/d will be extracted. A well field could penetrate polluted aquifers to any depth, but the required natural yields are not always accomplished. Return - 7000 m3/day @ R2.30 = R5 875 000 / year (R 235 000 000 over 40 years) + reduction in waste discharge costs. Will require water permits and charges.
No.3# Waste rockdump & Surroundings	1.00								
No.4 # Waste rock dump	0.68								
Open unlined tailings effluent trenches - at toe of tailings dams and towards Bokkamp Dam	0.34								
Skelm dam - old evaporation dam at toe of No.3# Waste Rock Dump	0.51	Possible Treatment of extracted water (units in ML/d)	R 12,000,000.00	5	R 60,000,000.00	R 365,000.00	40	R 73,000,000.00	
No. 9 Gold Plant effluent dams	0.51								
Redundant West Extension Storm Water Dam	0.51								
No 3# Concrete Stormwater Channel		Impact of the identified sources could be limited by applying clean-up and rehabilitation work. This could especially be applied to old redundant evaporation areas, old trenches, etc. If accumulated salts in the unsaturated top soil surface be decreased by means of vegetation and or physical clean-up work, the load to the environment could be reduced by almost 40%.							
#3 Sewage Plant Area									

PLUME NAME:	***VAAL RIVER WEST - Towards Schoon Spruit***	***AREA (ha):***	***550***	***VOLUME (m3):***	***22,000,000.00***
Plume extend and possible discharge:	Currently all these sites contributes a certain amount of salt leakage into the aquifer flowing from the western part of the West Complex Tailings towards the Schoon Spruit in the west. Currently the plume is in steady state and about 154m3/day seeps into the Spruit, this will increase drastically over the next 20 years. The estimate seepage rate of the relevant portion of the tailings is in the region of 500m3/day.				
Concluding remarks on aquifer characteristics:	Currently groundwater and dissolved pollutants flow via shallow perched aquifer (0-5m), mainly on top of solid Ventersdorp formation and seeps into the Schoon Spruit via baseflow.				

Site	Appr. % of cont.	Capital Cost Estimate of Best Available and Practicable				Estimated Operational & Maintenance Costs			Comments
		Description	Cost/Unit	Units Req.	TOTAL	Cost/ Unit/y	Time (years)	TOTAL for all units	
West Tailings Dam Complex	81.19	Woodlands (units in ha)	R 15,500.00	300	R 4,650,000.00	R 325.00	20	R 1,950,000.00	
Open unlined tailings effluent trenches - at toe of tailings dams and towards Monitoring Pump Station	10.15								
Queen Mary Dams	3.04								
Old Black Reef Treatment Plant	2.01								
Ellaton Mine - Black Reef Area	1.20	Interception boreholes (units in bh's)	R 280,000.00	25	R 7,000,000.00	R 20,000.00	40	R 20,000,000.00	About 3 250 m3/d will be extracted. A well field could penetrate polluted aquifers to any depth, but the required natural yields are not always accomplished.
10# Ore loading Area - current ore stockpile area south of No.1 Gold Plant	0.64								
Old Calcine Dams - north of West Float & Acid Plant	0.64								
6# and 7# Waste rock footprints	0.48								
West Float Acid and Uranium Plant - Stockpile areas and containment facilities	0.32	Infiltration trench (units in m)	R 4,000.00	1100	R 4,400,000.00	R 100.00	20	R 2,200,000.00	A Trench will only cut the plume of - the source must be illuminated
No.1 Gold Plant effluent dams	0.32								
		Possible Treatment of extracted water (units	R 12,000,000.00	3	R 36,000,000.00	R 365,000.00	41	R 44,895,000.00	

8.3 Strategic Groundwater Management Concept for deep underground water

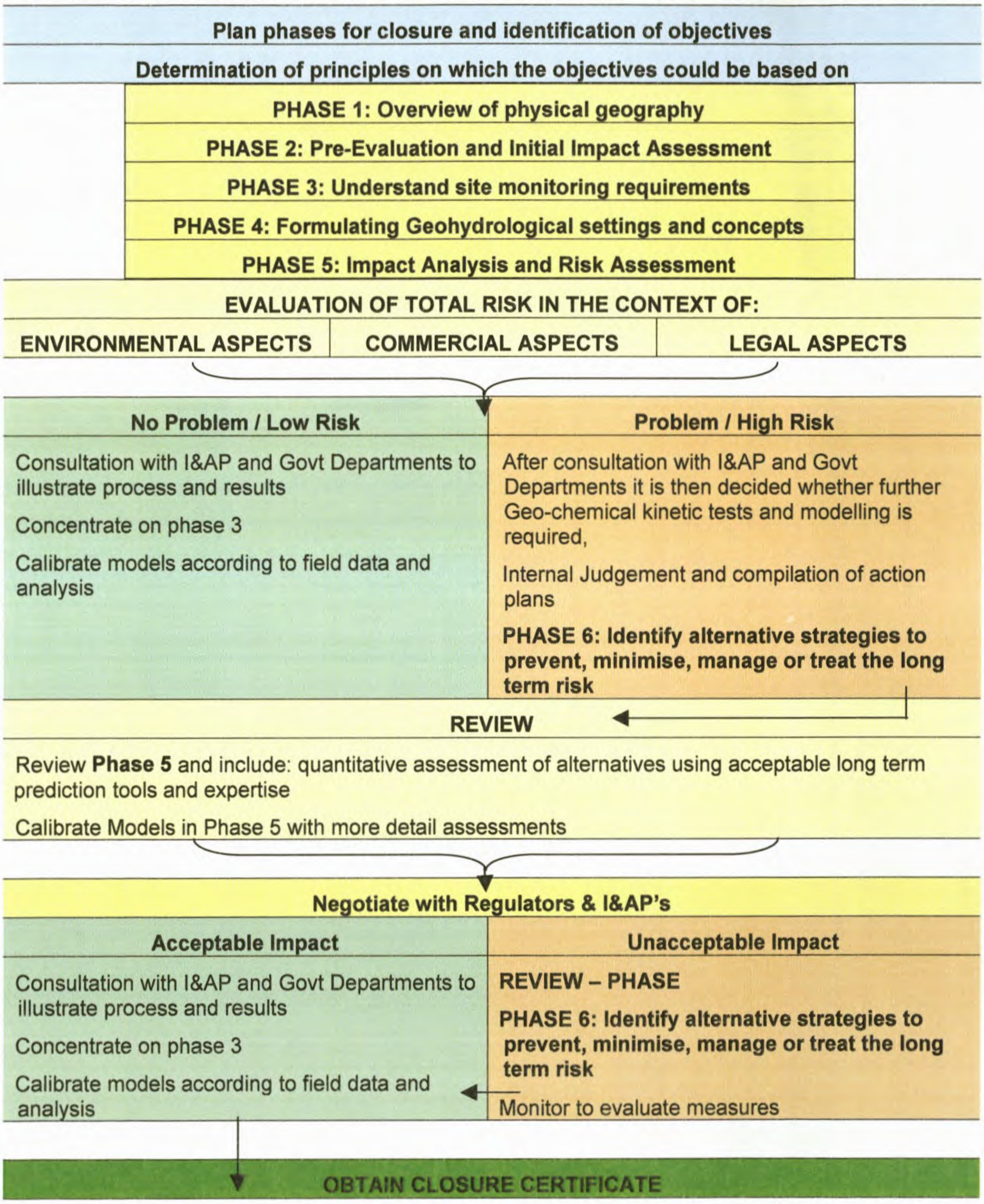
The following aspects, according to Pulles, *et al*, 2003, needs to be consider when applying for mine closure and also to ensure a regional holistic approach on underground water management:

- Construct a 3-dimensional model of all the underground workings for all the mines in the region,
- Define all confirmed and potential hydraulic interconnections between mines,
- Define anticipated remaining life for each mine and shaft,
- Develop a regional-scale groundwater model capable of quantifying major water ingress points, rates of flooding and inter-mine flow rates,
- Undertake a regional-scale geochemical assessment to define regional inter-mine pollution loads,
- Establish the probability of decant of contaminated underground water into the aquifer or surface water systems and the location, volumes and contaminant loads associated with such decants,
- With reference to the applicable water management plan, establish the acceptable volumes and contaminant loads and negotiate and agree with Authorities,
- Apportion acceptable load to each mine within region and reach agreement between mines and Authorities,
- Develop and implement regional monitoring programmes to provide data to validate the basis of the regional mine closure strategy,
- Where some of the mines are expected to impact on adjacent regions, ensure that appropriate communications are maintained with such regions.

8.4 *Concluding remarks*

The following flow diagram summarise the end result of this thesis, which illustrate the process of groundwater assessment towards closure of a gold mine.

Table 47: Summary of Approach – Flow diagram of Groundwater Assessment towards mine closure



Plan phases for closure and identification of objectives

Determination of principles on which the objectives could be based on

PHASE 1: Overview of physical geography

PHASE 2: Pre-Evaluation and Initial Impact Assessment

PHASE 3: Understand site monitoring requirements

PHASE 4: Formulating Geohydrological settings and concepts

PHASE 5: Impact Analysis and Risk Assessment

EVALUATION OF TOTAL RISK IN THE CONTEXT OF:

ENVIRONMENTAL ASPECTS	**COMMERCIAL ASPECTS**	**LEGAL ASPECTS**

No Problem / Low Risk	**Problem / High Risk**
Consultation with I&AP and Govt Departments to illustrate process and results Concentrate on phase 3 Calibrate models according to field data and analysis	After consultation with I&AP and Govt Departments it is then decided whether further Geo-chemical kinetic tests and modelling is required, Internal Judgement and compilation of action plans **PHASE 6: Identify alternative strategies to prevent, minimise, manage or treat the long term risk**

REVIEW

Review **Phase 5** and include: quantitative assessment of alternatives using acceptable long term prediction tools and expertise

Calibrate Models in Phase 5 with more detail assessments

Negotiate with Regulators & I&AP's

Acceptable Impact	**Unacceptable Impact**
Consultation with I&AP and Govt Departments to illustrate process and results Concentrate on phase 3 Calibrate models according to field data and analysis	**REVIEW – PHASE** **PHASE 6: Identify alternative strategies to prevent, minimise, manage or treat the long term risk** Monitor to evaluate measures

OBTAIN CLOSURE CERTIFICATE

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Appendix A:

Description of the Metallurgical processes currently in operation as part of the investigation area.

West Float Plant

Pre-leach: Currently slime is received from the hydraulic reclaimed areas, West Pay Dam and West Emergency Dam, at a relative density of approximately 1.5. This stream of slurry is received into the Pre-leach pachucas. Slaked Lime, at approximately 1.8 kilograms per ton, for pH correction and Sodium Cyanide at approximately 220 grams per ton, is added to dissolve the gold. Calcine residue from the uranium recovery section is also added to the pre leach slurry. The slurry is pumped to No. 2 Gold Plant for gold extraction.

Flotation: Slurry to Flotation is received from two sources namely No. 9 and No. 1 Gold Plant. Both sources can be fed directly to the residue pachucas or to the stock tanks. The stock tanks feed the dilution pachuca where the relative density is brought down to 1,250. The slurry is then pumped to the cluster cyclones for dewatering and upgrading of both sulphur and gold grades. The cyclone overflow is clarified in the 60m dewatering thickener and the thickener underflow is pumped to the residue. The underflow of the cyclones is fed to the conditioning pachucas where the slurry is conditioned with calcine water at a pH of 7.0 for ten hours. The conditioned slurry is then fed to the Flotation Plant. Activator, currently Copper Sulphate, is added at the float steady head, at approximately 60 grams per ton. Depressant, at approximately 30 grams per ton, frother, at approximately 20 grams per ton, and Collector, at approximately 30 grams per ton, are all added to the rougher cells. The Pyrite floated off the cleaner cells is thickened in a thickener before being pumped to the Acid Plant. The float residue is pumped to the residue pachucas. The thickener overflow is returned to the Flotation Plant. Slurry in the residue pachuca is pH adjusted to a pH of 8.5 with slaked lime before disposal on the slimes dam.

Carbon Columns: Process water from thickener overflow is pumped through the Carbon Columns where dissolved gold is absorbed onto the Carbon. The loaded Carbon is dispatched in batches to No. 8 Gold Plant for elution.

Reagent Preparation: *Lime:* Unslaked lump lime is received by rail and stored under cover. A single mill is used to grind and slake the lime, to be used on the plant and at No. 1 Gold Plant. Steel balls are used in the mill as grinding media.

Manganese: Manganese is received by road and stockpiled at the feed end of the milling section. The Manganese is milled using steel balls in the mill as a grinding media. The milled product is cycloned and the overflow is stored in the Manganese pachuca to be used as a reagent in the uranium leach process. The underflow of the cyclone is returned back to the mill and re-milled.

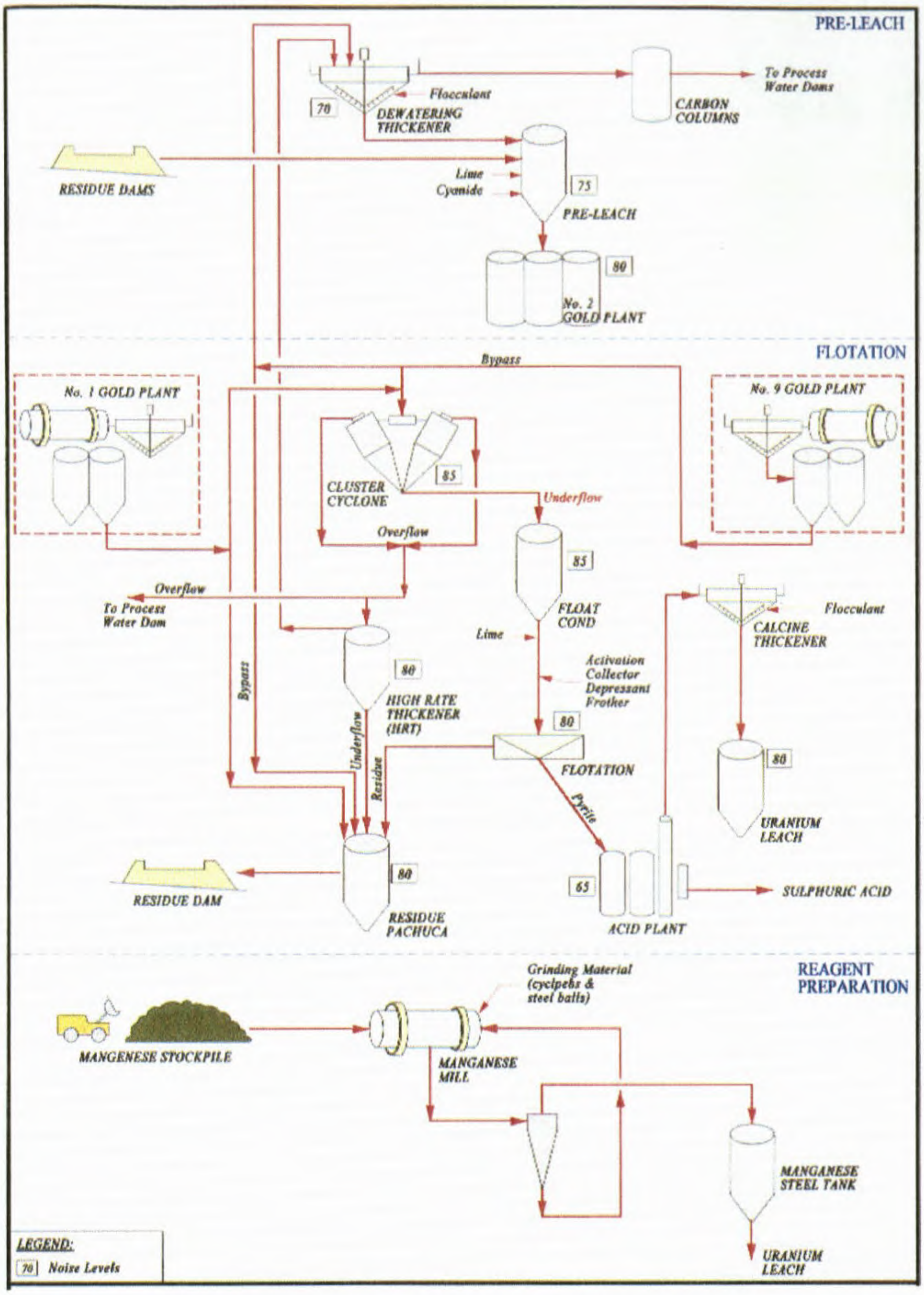

Figure 66: Process flow diagram – West Float Plant (AngloGold EMPR, 2001)

West Acid Plant

The West Acid Plant was commissioned in the 1950's and has operated continuously since. In 1971 it was refurbished and an additional calcine gold recovery section was commissioned. Sulphuric Acid is produced by the contact process using pyrite as the sulphur source.

A maximum of 6 600 tons of 100% Sulphuric Acid per month is manufactured using approximately 7300 tons of Pyrite at 32% Sulphur content.

Roasters: The Pyrite is repulped to a relative density of approximately 2.0 before being fed to the roaster feed guns of three parallel-fluidised bed roasters. Operation of the roasters is carried out at 750° to 800° C. This temperature is continuously maintained by the exothermic reaction resulting from the burning of fresh Pyrite.

Gas Cleaning, Drying and Absorption: Following the roasting stage the two products, gas and Calcine, are treated separately. The gas is purified and cooled in the:

- Cyclones
- Swemco Tower
- Electrostatic Mist Precipitators and
- Stripping Tower

The purified and cooled gas, at approximately 8.5% SO_2, is dried in the Drying Tower, using 93% Sulphuric Acid. With the aid of a blower, the gas is delivered via heat exchangers to a four-stage converter. In the converter use is made of oxygen from air and a Vanadium Pentoxide catalyst to convert the Sulphur Dioxide to Sulphur Trioxide. The Sulphur Trioxide gas is absorbed using 98% Sulphuric Acid, and the resultant acid is diluted with the acid from the Drying Tower to produce a net increase in 98% Sulphuric Acid stock. The waste gases are dispersed into atmosphere via the 45-metre high stack.

Calcine: The Calcine or Iron Oxide produced in the roasting stage is quenched, cooled and pumped as slurry to a thickener. The calcine is then leached for Uranium and subsequently gold.

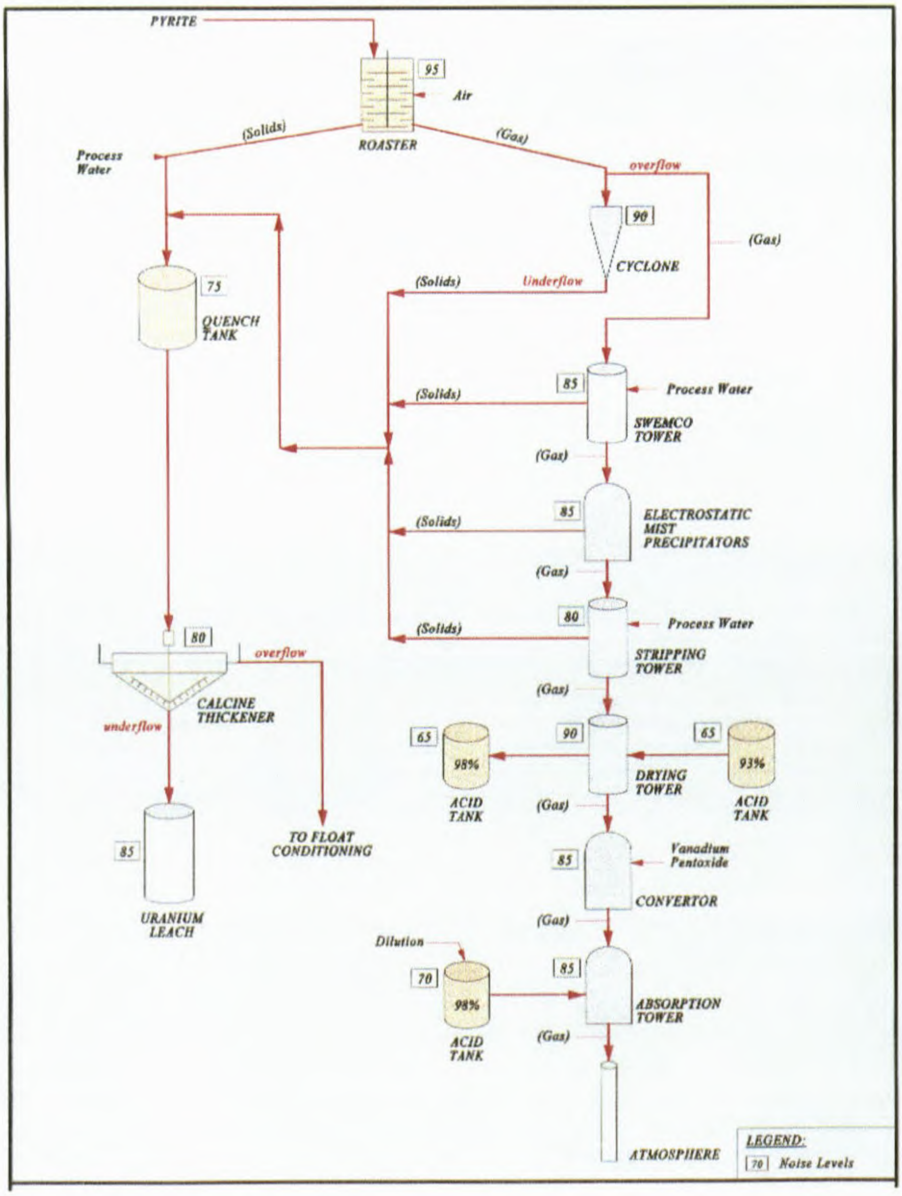

Figure 67: Process Flow Diagram – West Acid Plant

West Uranium Plant

The West Uranium Plant extracts uranium, in the form of Ammonia Di-uranate, as a by-product from Calcine. Below is a brief description of the various metallurgical processes involved.

Leaching: Calcine from the Acid Plant roasters is thickened and pumped at a RD of approximately 1.450 to the leach pachucas. The dissolution of the uranium from the Calcine is achieved by means of a batch leach process. This process involves the contact of Calcine with 35kg/t Sulphuric Acid and 3kg/t Manganese Dioxide at 55 degrees Celsius for eighteen hours.

Filtration: Liquid/solid separation is done by means of rotary drum filters. The uranium bearing filtrate is then passed on to the clarification stage whereas the washed solids are repulped to a density of 1.500 and pumped to the pre leach section for gold extraction. In the pre leach section the calcine is mixed with the West Pay Dam slime, the pH is adjusted to pH 10.5 with slaked lime on the Carbon in the Pumpcells at No. 2 Gold Plant.

Clarification: The pregnated solution is pumped to a pre-settler to remove the excess solids from the solution. Solution from the pre-settler is then pumped to an intermediate storage before clarification. Single stage clarification is done by precoat rotary drum filters as the

final preparation stage prior to the solvent extraction process. Base flow flocculant is used as a pre-coat. The clarified uranium bearing solution is then pumped to the pregnant solution tank.

Solvent Extraction: Concentration and purification of the uranium in solution is achieved by the solvent extraction process. This process involves extraction, scrubbing and stripping. Reagents involved are Pegasol, Alamine and Isodecanol, with Ammonium Hydroxide used in the stripping stage for pH control. The product from the solvent extraction process is termed O.K.-liquor and is pumped to the O.K.-liquor tank.

Recovery / ADU: Ammonium Di-Uranate (ADU) is precipitated from the O.K.-liquor by raising the pH to 7.5 with ammonia gas, at a temperature of 38 degrees Celsius, in the mixers / precipitators. The precipitated ADU gravitates to a thickener. The overflow from the thickener (ammonium sulphate) is returned to the stripping section. The thickener underflow is then repulped with potable water prior to subjecting it to centrifuging. During centrifuging the filtrate, containing the impurities, is separated from the ADU. The final product (Ammonium Di-uranate) is stored in a storage vessel from where batches are dispatched by road to Nufcor.

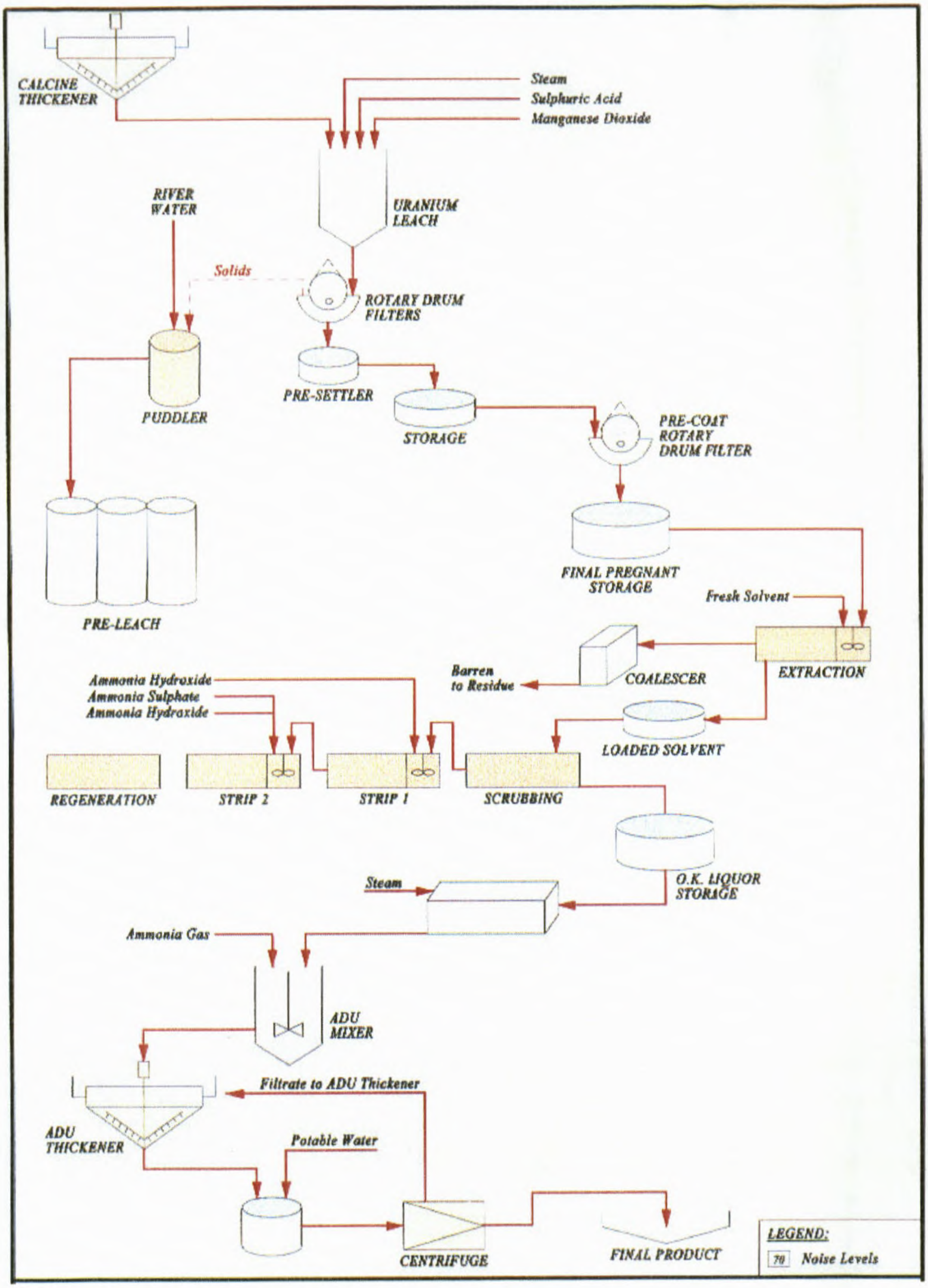

Figure 68: Process flow diagram – West Uranium Plant

No 1 Gold Plant

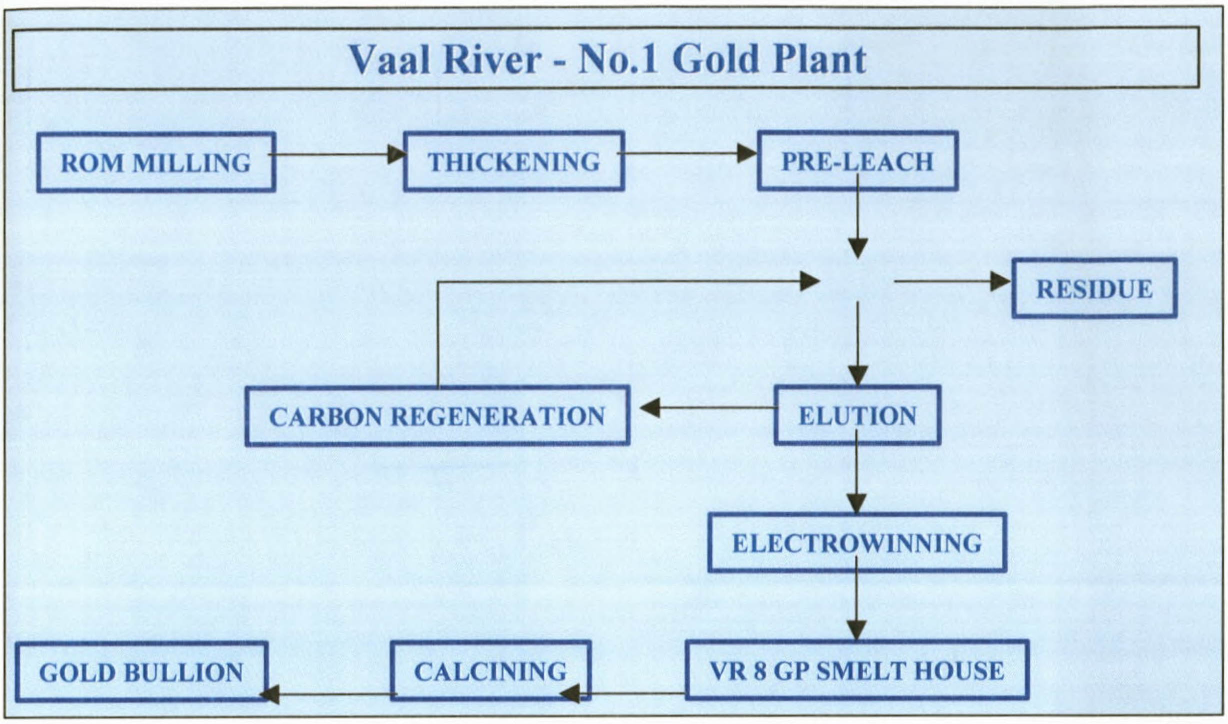

Figure 69: Process flow diagram – No.1 Gold Plant

APPENDIX B. LIST OF TREES & SHRUBS TO BE USED IN THE MINE WOODLANDS PROJECT.

(i) Additional indigenous species will be added if tested and found suitable.
(ii) No CARA-listed Category 1 or 3 trees are included in the list, although they may exhibit good survival and growth on slimes, AMD-seepage and/or salinized substrata in the goldfields.
(iii) CARA category 2-listed trees with bird-dispersed seeds should probably not be planted.
(iv) CARA category 2-listed trees with water-dispersed seeds should be restricted to plantings on the tops of slimes dams only.

Abbreviations per column:

Seed Source: WR: Wits-Anglogold Slimes or Acid Mine Drainage Landraces; **NWR**: non-slimes land-race from local bioclimatic region; **F:** foreign non-slimes race from similar environment in different region; U: reliable seed source not established yet.
Biocontrol = Biocontrol agent available (CARA-listed exotics only)
Herbicide = Herbicide registered (CARA-listed exotics only)

Seed Source	Survival in acid slimes, or AMD	Survival in saline seeps or plumes	Species (exotics are in bold type)	CARA LIST	For slimes dam tops	For slimes dam slopes	For polluted veld & perched aquifers	Biocontrol	Herbicide
WR	yes	yes	*Acacia caffra*		yes	yes	yes		
NWR	yes	yes	*Acacia erioloba*		yes	yes	yes		
NWR	unknown	yes	*Acacia haematoxylon*		yes	yes	yes		
WR	yes	yes	*Acacia hebeclada sbsp. hebeclada*		yes	yes	no		
WR	yes	yes	*Acacia hereroensis*		yes	yes	yes		
WR	yes	yes	*Acacia karroo*		yes	yes	yes		
NWR	unknown	yes	*Acacia mellifera sbsp. detinens*		yes	yes	yes		
WR	yes	yes	*Acacia robusta*		yes	yes	yes		
NWR	yes	yes	*Acacia tortilis sbsp. heteracantha*		yes	yes	yes		
WR	yes	yes	***Acacia cultriformis***	?	yes	yes	yes	?	?
WR	yes	yes	***Acacia dealbata***	2	yes	no	no	?	yes
WR	yes	yes	***Acacia decurrens***	2	yes	no	no	?	yes
WR	yes	yes	***Acacia mearnsii***	2	yes	no	no	yes	yes
WR	yes	yes	***Acacia melanoxylon***	2	yes	no	no	yes	yes
WR	yes	yes	*Asclepias fruticosa*		yes	yes	no		
WR	yes	yes	*Asparagus laricinus*		yes	yes	no		
WR	yes	unknown	*Brachylaena rotundata*		yes	no	yes		

NWR	unknown	yes	*Buddleja glomerata*		yes	yes	yes		
NWR	yes	unknown	*Buddleja saligna*		yes	yes	yes		
NWR	yes	unknown	*Buddleja salviifolia*		yes	yes	yes		
u	yes	yes	***Callistemon spp.***	?	yes	no	no		
u	yes	yes	***Casuarina cunninghamiana***	2	yes	yes	yes		yes
u	yes	yes	***Casuarina equisetifolia***	2	yes	yes	yes		
u	unknown	unknown	***Casuarina glauca***	?	yes	yes	yes		
u	unknown	yes	***Cedrus deodara***		yes	no	yes		
u	unknown	yes	***Cedrus libani***		yes	no	yes		
WR	yes	yes	*Celtis africana*		yes	no	yes		
WR	yes	yes	*Clutia pulchella*		yes	yes	no		
WR	yes	yes	*Cussonia paniculata*		yes	no	no		
f	yes	yes	*Combretum erythrophyllum*		yes	no	yes		
f	yes	unknown	*Dais cotinifolia*		yes	no	yes		
f	yes	yes	*Dichrostachys cinerea*		yes	yes	no		
WR	yes	yes	*Diospryos austro-africana var microphylla*		yes	yes	yes		
WR	yes	yes	*Diospryos lycioides sbsp. guerkei*		yes	yes	yes		
WR	yes	yes	*Diospryos lycioides sbsp. lycioides*		yes	yes	yes		
NWR	yes	yes	*Dodonaea angustifolia*		yes	yes	yes		
NWR	unknown	yes	*Dombeya rotundifolia*		yes	no	yes		
NWR	yes	yes	*Dovyalis caffra*		yes	yes	yes		
NWR	unknown	yes	*Dovyalis zeyheri*		yes	yes	yes		
WR	yes	yes	*Ehretia rigida*		yes	yes	yes		
NWR	unknown	unknown	*Englerophytum magaliesmontanum*		yes	no	no		
NWR	yes	unknown	*Erica caffra*		yes	yes	no		
NWR	yes	unknown	*Erica woodii*		yes	yes	no		
NWR	yes	unknown	*Erythrina zeyheri*		yes	no	no		
			Eucalyptus badjensis						
			Eucalyptus benthamii						
WR	yes	yes	***Eucalyptus camaldulensis***	2	yes	no	yes		
u	yes	unknown	***Eucalyptus cinerea***		yes	no	yes		
uu	yes	unknown	***Eucalyptus citriodora***		yes	no	yes		
f	unknown	unknown	***Eucalyptus dunnii***		yes	no	yes		yes
			Eucalyptus elata						yes
f	unknown	unknown	***Eucalyptus grandis X camaldulensis***	2 ?	yes	no	yes		

f	unknown	unknown	***Eucalyptus grandis X nitens***	2 ?	yes	no	yes		
f	unknown	unknown	***Eucalyptus macarthurii***		yes	no	yes		
WR	yes	yes	***Eucalyptus melliodora***		yes	no	yes		
f	unknown	unknown	***Eucalyptus nitens***		yes	no	yes		
WR	yes	yes	***Eucalyptus sideroxylon***	2	yes	no	yes		
			Eucalyptus smithii						
u	yes	yes	***Eucalyptus tereticornis***		yes	no	yes		
u	yes	unknown	***Eucalyptus viminalis***		yes	no	yes		
WR	yes	yes	*Euclea crispa var. cispa*		yes	yes	yes		
WR	yes	yes	*Euclea crispa var. ovata*		yes	yes	yes		
WR	yes	yes	*Euclea undulata var. myrtina*		yes	yes	yes		
u	unknown	yes	***Fagus sylvatica***		no	no	yes		
u	yes	yes	***Gleditsia triacanthos sterile hybrids***		yes	no	yes		
WR	yes	yes	*Grewia flava*		yes	yes	no		
NWR	unknown	unknown	*Grewia hispida*		yes	yes	no		
NWR	unknown	yes	*Grewia occidentalis*		yes	yes	yes		
WR	yes	yes	*Gymnosporia buxifolia*		yes	yes	yes		
WR	yes	yes	*Gymnosporia polyacantha*		yes	yes	yes		
NWR	unknown	unknown	*Gymnosporia tenuispina*		yes	yes	yes		
u	unknown	yes	*Indigofera spinescens*		yes	yes	no		
WR	yes	yes	*Leonotis dysophylla*		yes	yes	no		
NWR	unknown	unknown	*Leucosidea sericea*		yes	yes	yes		
WR	yes	yes	*Lophalaena coriifolia*		yes	yes	no		
WR	yes	unknown	*Lotononis divartica*		yes	yes	no		
WR	yes	yes	*Lycium cinereum*		yes	yes	no		
u	yes	unknown	*Lycium echinatum*		yes	yes	no		
u	yes	unknown	*Lycium ferocissimum*		yes	yes	no		
NWR	unknown	unknown	*Lycium hirsutum*		yes	yes	no		
cuttings	yes	yes	***Morus spp. sterile hybrids***		yes	no	yes		
WR	yes	yes	*Mundulea sericea*		yes	yes	yes		
NWR	yes	yes	*Olea europea ssp. africana*		yes	yes	yes		
WR	yes	yes	*Osyris lanceolata*		yes	yes	no		
WR	yes	yes	*Pappea capensis*		yes	yes	yes		
NWR	yes	unknown	*Passerina montana*		yes	yes	no		
			Pinus elliotii	2					

			Pinus greggii						
u	yes	yes	***Pinus halepensis***	2	yes	no	yes		
u	yes	unknown	***Pinus pinaster***	2	yes	no	yes		
u	unknown	unknown	***Pinus pinea***	2	yes	no	yes		
u	unknown	unknown	***Pinus roxburghii***	2	yes	no	yes		
f	unknown	unknown	*Podocarpus elongatus*		yes	no	yes		
f	unknown	unknown	*Podocarpus falcatus*		yes	no	yes		
f	yes	unknown	*Podocarpus henkelii*		yes	no	yes		
f	yes	unknown	*Podocarpus latifolius*		yes	no	yes		
u	yes	yes	***Populus X canescens***	2	yes	no	yes		
u	yes	yes	***Populus deltoides & hybrids***	2	yes	no	yes		
u	yes	yes	***Populus nigra***	2	yes	no	yes		
u	yes	yes	***Populus wislizenii***		yes	no	yes		
WR	yes	yes	*Protea caffra*		yes	yes	yes		
u	yes	unknown	*Protea roupelliae sbsp. roupelliae*		yes	yes	yes		
NWR	unknown	unknown	*Protea subvestita*		yes	yes	yes		
u	yes	yes	***Quercus robur***		yes	yes	yes		
f	yes	yes	*Rhamnus prinoides*		yes	no	yes		
u	yes	yes	*Rhigozum obovatum*		yes	yes	no		
u	yes	unknown	*Rhigozum trichotomum*		yes	yes	no		
NWR	unknown	unknown	*Rhus bolusii*		yes	yes	no		
NWR	unknown	unknown	*Rhus burchellii*		yes	yes	no		
NWR	unknown	unknown	*Rhus ciliata*		yes	yes	no		
WR	yes	yes	*Rhus dentata*		yes	yes	yes		
WR	yes	yes	*Rhus discolor*		yes	yes	no		
NWR	unknown	unknown	*Rhus dregeana*		yes	yes	no		
NWR	unknown	yes	*Rhus erosa*		yes	yes	no		
WR	yes	yes	*Rhus lancea*		yes	no	yes		
WR	yes	yes	*Rhus leptodictya*		yes	no	yes		
WR	yes	yes	*Rhus magaliesmontana*		yes	yes	no		
WR	yes	yes	*Rhus pendulina*		yes	no	yes		
WR	yes	yes	*Rhus pyroides var. pyroides*		yes	yes	yes		
WR	yes	yes	*Rhus rigida*		yes	yes	no		
NWR	unknown	unknown	*Rhus tenuinervis*		yes	yes	no		
NWR	unknown	unknown	*Rhus undulata*		yes	yes	no		

NWR	unknown	yes	*Rhus zeyheri*		yes	yes	no		
WR	yes	yes	*Rhynchosia nitens*		yes	yes	no		
f	yes	unknown	*Salix hirsuta*		no	no	yes		
NWR	yes	no	*Salix mucronata*		no	no	yes		
NWR	unknown	unknown	*Salix subserrata*		yes	no	yes		
WR	yes	yes	***Schinus molle***	Prop. 3	yes	yes	yes		
WR	yes	yes	*Sutherlandia frutescens*		yes	yes	no		
WR	yes	yes	*Sutherlandia microphylla*		yes	yes	no		
u	unknown	unknown	*Tamarix usneoides*		yes	yes	no		
WR	yes	yes	*Tarchonanthus camphoratus*		yes	no	yes		
WR	yes	yes	*Ziziphus mucronata*		yes	yes	yes		
WR	yes	yes	*Ziziphus zeyheriana*		yes	yes	yes		