AN ASSESSMENT OF THE IMPACTS ON GROUNDWATER QUALITY ASSOCIATED WITH THE BACKFILLING OF DOLOMITIC CAVITIES WITH GOLD MINE TAILINGS

REPORT TO THE WATER RESEARCH COMMISSION

BY

S Dill, RH Boer*, HJJ Boshoff**, AR James** and BI Stobart****

* Ferret Mining & Environmental Services (Pty) Ltd, PO Box 72313, Lynnwood Ridge, 0081, South Africa

WRC Report No 1122/1/07

ISBN 978-1-77005-566-7

MAY 2007

ACKNOWLEDGEMENTS

The research in this report emanated from a project funded by the Water Research Commission (WRC) and the Far West Dolomite Water Association (FWDWA) entitled:

AN ASSESSMENT OF THE IMPACTS ON GROUNDWATER QUALITY ASSOCIATED WITH THE BACKFILLING OF DOLOMITIC CAVITIES WITH GOLD MINE TAILINGS

The Steering Committee for this project consisted of the following persons:

Mr HM du Plessis (Chairman)	Water Research Commission
Mr G Steenveld	Water Research Commission
Dr R Boer	Ferret Mining & Environmental Services
Mr AR McLaren	Water Management & Environmental Consultant
Mr G le Roux	Department of Water Affairs
Mr E van Wyk	Department of Water Affairs
Mr M Fayez	Department of Water Affairs
Prof AB de Villiers	Potchefstroom University
Dr DG Wyler / Dr A Parsons	Chamber of Mines
Mr EJ Amis	AngloGold
Dr AH Leuschner / Dr CJ Swart	Goldfields / Far West Rand Dolomitic Water Association
Mr M Marais	Far West Rand Dolomitic Water Association
Ms M Naidoo / Ms E Swart	Department of Minerals and Energy
Mr D Richter	Department of Minerals and Energy
Dr RJ Kleywegt	Council for Geosciences
Mr U Sibyls	AngloGold
Mr P Woodhouse	Far West Rand Dolomitic Water Association

The funding of the project by the organisations mentioned above and contributions by members of the Steering Committee are gratefully acknowledged.

This project was only possible with the co-operation of many individuals and institutions. The Authors wish to express their sincere thanks to the numerous people that have willing contributed data and information to the project, in particular:

Dr CJ Swart

Dr RJ Kleywegt

Mr AR McLaren

Dr L Stock

Dr D Wymer

EXECUTIVE SUMMARY

INTRODUCTION

The dolomites of the Far West Rand comprise one of South Africa's most important groundwater resources. Partial de-watering of the dolomite aquifers over recent decades to allow safe extraction of gold ore from the Witwatersrand reefs located below the dolomite resulted in the draw down of the water table within the dolomite aquifer to form a cone of depression. The effect of depressing the water level was to bring on the onset of sinkhole formation at an unprecedented rate. Sinkholes continue to form to this day. For the past decades it has been common practice to backfill some of the sinkholes in the interest of public safety and to reduce recharge and hence pumping of groundwater, to maintain the dewatered state of the compartments. Often the backfill material used was gold mine tailings ("gold tailings"), which was readily available at a reasonable cost in close proximity to the sinkholes.

This study addresses the impact that the backfilling of sinkholes with gold tailings may have on the groundwater quality in the dolomite aquifer.

OBJECTIVES

The objectives of the research project were as follows:

- To quantify potential impacts on groundwater quality arising from the future filling of sinkholes using mine waste materials.
- To assess the relative significance of the backfilling of the sinkholes as a source of groundwater contamination compared with other sources of contamination such as tailings dams, waste rocks dumps and return water dams.
- To assess the potential effectiveness of alternative fill materials and methods in reducing negative impacts on groundwater quality.
- To assess the provisions of both current and pending legislation to ensure that proposals arising from the project conform to the requirements of such legislation.

PROJECT APPROACH

To address the objectives of the project, the following was undertaken:

- A review of the situation on the Far West Rand.

- The potential impacts from the sinkhole backfill material on the ground water in the immediate vicinity (directly below) the backfilled sinkhole was investigated. A geochemical model, referred to as the Near Field Model (NFM) was developed to predict the quality of leachate over time, from the point when the tailings is first disposed of into the sinkhole, to 50 years into the future.
- Having characterised the effect of a single backfilled sinkhole on the aquifer in the immediate vicinity of the backfill, the next step was to evaluate the effect that one or a combination of similar backfilled sinkholes would have on the entire compartment. This issue is addressed using a separate solute transport model and is referred to as the Far Field Model (FFM).
- A brief study of the physical stability of backfilled sinkholes to evaluate the sustainability of the current backfill practices and identify those factors that should be considered in the design and method of backfilling to reduce the risk of re-activation of backfilled sinkholes.
- A review of the practice of backfilling sinkholes within the framework of the South African legislation to assess the legal compliance of the practice with respect to the current legal framework.

FINDINGS

The following findings arose from the research project:

Impacts on the Groundwater Quality in the Dolomite Aquifer arising from the Backfilling of Sinkholes using Gold Tailings

- The seepage in the upper (aerobic) part of the backfilled sinkhole may initially be of poor quality (acidic with elevated concentrations of sulphate and aluminium). Iron appears to precipitate as hematite.
- The seepage quality improves with time (depending on the flow rate). After 50 years the seepage in the upper section of the sinkhole is generally of good quality independent of the flow rate.
- The seepage in the lower (anaerobic) part from the backfilled sinkhole will be of good quality (near neutral pH, low sulphate concentrations, low concentrations of other elements).
- Seepage of good quality passing the unsaturated zone does not undergo major chemical changes. Acidic seepage will be neutralised under low flow conditions and partially neutralised under average flow conditions. As the neutralisation of the acidic seepage causes the dissolution of dolomite, the TDS in the seepage is likely to be elevated to high.
- After the seepage has been mixed with the groundwater in the dolomite aquifer, the water quality is generally good (near neutral pH, low sulphate concentrations, low concentrations of other elements) and is likely to be fit for human consumption with the exception for

uranium, which may be present in elevated concentrations in gold tailings from the Far West Rand.

- Uranium is leached from the backfill material under a wide range of pH (acidic to alkaline). The concentration of dissolved uranium in the leachate depends mostly on the total uranium concentration in the backfill. The pH will govern what uranium species will be leached from the backfill. Probable maximum uranium concentrations in the leachate are in the order of 300 mg/ℓ but more likely concentrations, based on leach tests of gold tailings from the Far West Rand are in the order of 0.3 mg/ℓ.

- Backfilling of isolated sinkholes located some distance (e.g. 500 m) away from any other backfilled or potentially backfilled sinkhole does not pose a pollution threat in terms of leachable chemicals from the gold or uranium tailings.

- Backfilling of sinkholes in highly concentrated zones where sinkholes are close to one another could give rise to a pollution plume depending on the leachable uranium concentration of the tailings. Provided that the leachable concentration of uranium is shown to fall below 0.3mg/ℓ, the risk of a pollution plume developing with concentrations exceeding the SA target water quality guideline value of 0.07mg/ℓ will not occur, even with the more conservative estimate of backfilled sinkholes density.

- Leachate concentrations in excess of 0.3 mg/ℓ U from the backfilled sinkholes generally cause groundwater pollution in excess of the WHO WQ guidelines with the exception of backfilled sinkholes measuring no more than one idealised backfilled sinkhole of 0.40 ha in extent.

As a general guideline, backfilling of sinkholes with gold tailings from the Far West Rand has a high risk of causing impacts on the dolomite aquifer in excess of the SA WQ guidelines if the leachate concentration were to exceed 30 mg/ℓ U. However, when the effective zone of backfill exceeds 0.4 ha/km^2, the SA WQ guidelines have a high probability of being exceeded if the leachate concentration exceeds 3.0 mg/ℓ U.

The relative Significance of the backfilled Sinkholes as a Source of Groundwater Contamination compared with other Sources of Contamination

- Although the modelling has shown that the impact from a tailings dam is very pronounced, the mitigating effects from the compacted soil cover beneath the tailings dam have not been considered by the model. Contamination assessments undertaken for soils from footprints of removed tailings dams indicated generally elevated uranium concentrations in the soil with concentrations of less than 1 mg/ℓ U in the groundwater in close proximity to the tailings dams. The model therefore seems to overestimate the impact of contamination from the tailings dam to the aquifer by probably one order of magnitude.

- The modelling indicated that the uranium plumes reached their full aerial extent after 50 to 100 years; thereafter the plume would only increase marginally for the following centuries. Based on a comparison of the total uranium content of the tailings with the leach rate, complete leaching of the uranium from the tailings will take several hundred to thousands of years. The plume will finally reduce and eventually disappear, when all uranium has been leached from the respective sources of pollution. The long-term impact of backfilling may thus be considered practically the same as the impact after 50 to 100 years, when the plume has reached its full extent.

The Stability of backfilled Sinkholes

- Backfilling of sinkholes with purely non-cohesive materials is unlikely to provide a long-term walk-away solution and poses a significant safety risk to humans due to the risk of sudden subsidence, caused by reactivation of the sinkhole or erosion of the backfill from beneath the surface.
- Backfilling of sinkholes with a cohesive material such as clay or cement-modified gold tailings material may significantly reduce the risk of occurrence of subsidence or re-activation, but not the consequence of subsidence.
- Backfilling of sinkholes with natural material from borrow areas in close proximity to sinkholes has the disadvantage of depleting the surrounding area of soil and also increasing the risk of sinkhole formation in the borrow area as a direct result of changed drainage conditions.
- Backfilling of sinkholes with a combination of different materials is likely to provide the optimal solution from a cost, subsidence risk and consequence viewpoint.

The above viewpoint must be weighed against the alternative of not backfilling the sinkholes. By not backfilling the sinkholes, the sinkhole presents a permanent safety risk and a potentially far more serious pollution risk attributable to the potential for illegal disposal of waste materials including hazardous wastes. This alternative policy is thus probably a more significant risk to human health and safety and the aquifer water quality than the tailings backfill option.

Legal Review

The following problems regarding the legality of the backfilling sinkholes with mine waste (or any other waste) were identified:

- The current activity of backfilling sinkholes with mine waste is not in compliance with the law;
- According to a number of Acts the activity has to be licensed. The question arises whether each single sinkhole to be backfilled will require a license in accordance with the law which is likely to be costly and time consuming or if the activity as such can be licensed for a certain

region based on the general understanding of the problem and site specific information provided for each of the sinkholes to be backfilled;

- Liability from the activity arises from statutory law. Statutory law liabilities may be related to failure to obtain permits/licenses, failure to comply with permit/licensing conditions, failure to comply with Section 19 of the National Water Act (which refers to the responsibilities of a party causing pollution – The Polluter pays Principle) and/or Section 28 of the National Environmental Management Act (both acts require a polluter to undertake reasonable measures in managing pollution and preventing pollution from occurring or recurring) and failure to secure the sinkhole;

- Liability from the activity arises from common law. Common law liabilities may be related to a claim from a person(s) suffering harm or loss caused by the activity with an element of wrongfulness (negligent or intent) for an award of damages;

As sinkholes will have to be secured for the safety of the public and any structures in close proximity to sinkholes, and in order to avoid illegal dumping of general or hazardous waste materials, backfilling of sinkholes with an appropriate material is the most suitable long-term solution. At present, the practice of backfilling sinkholes with mine waste, irrespective of how low its pollution risk actually is, is not in compliance with the law and further consideration to resolve the issue is required.

CONCLUSIONS

The following conclusions were drawn from this study:

Long term Status of the Dolomite Compartments

- On cessation of mining, the water in the dolomite compartment is expected to rise to the same level as was present prior to mining. Mining through the dykes is unlikely to have a significant effect on the final water levels achieved. The time to reach the final level is provisionally estimated to be between 11 and 30 years after mining ceases.

Materials for Backfilling

- The limited availability of materials other than gold tailings and mine waste rock within the Far West Rand geographic area make backfilling with alternative materials significantly more expensive. Gold tailings or mine waste rock would therefore comprise the material of first choice, provided that these materials do not pose a pollution risk. It is understood that in many cases the mine waste material for the backfill has been mixed with cement, which would have reduced the materials tendency for acid formation and the general leachability of chemical elements from the backfill material compared to ordinary tailings material. Detailed consideration of materials other than mine waste rock and tailings was not considered to be warranted for this study.

Physical Stability of backfilled Sinkholes

- Tests conducted on a single backfilled sinkhole have indicated the presence of weak layers and cavities at depth despite the fact that the surface of the backfilled sinkhole shows no sign of subsidence. This indicates that the most significant geotechnical problem associated with backfilling using non-cohesive materials is internal erosion and re-activation of the sinkhole. Engineers will need to address this issue in future to identify economic and safe methods and material combinations to prevent internal erosion of the backfill.

Future Rate of Sinkhole Formation

- After cessation of mining, the rate of formation of sinkholes might increase temporarily above the current rate, once the water level reaches a critical level estimated to be between 5 and 10 m below the final water level. The rate is unlikely to exceed the rate experienced in the early days of de-watering when the water level was first dropped by 5 to 10 m. Thus the final long-term concentration of sinkholes may increase but is unlikely to increase by more than twice the current value.

Current and future physical Distribution of Sinkholes

- The decision of whether to allow the sinkhole to be backfilled with the most readily available source of material, namely gold tailings, needs to take cognisance of the physical distribution of the sinkholes. If the sinkholes were evenly distributed over the entire compartment, the, impact of backfilling would be considerably less than if the sinkholes were concentrated into a few small areas. Modelling of the impact of backfilling of sinkholes needs to consider the effect of clustering of sinkholes caused by specific geological or topographical features. Sinkholes are likely to continue to form in specific areas susceptible to sinkhole formation rather than in new areas that have not previously experienced any sinkholes. The intensity of sinkholes (No./km^2) is likely to increase in specific areas more than in other areas.

The Potential for backfilled Sinkholes to pollute the Groundwater

- The geochemical model presented in this report for the assessment of backfill impacts, comprising both the near field and far field components, makes use of internationally accepted models and computer codes that do not need further validation. The approach used to predict the effect of gold tailings used as backfill on the dolomite aquifer quality, can also be used to assess the relative effect of different sources of contamination (e.g. backfilled sinkholes versus tailings dams). The approach makes use of recognised test methods for calibration of the model parameters. Individual aspects of the model have been calibrated based on laboratory tests or literature values.

- The Near Field Model (NFM) results indicate that with the possible exception of uranium, the leachate quality from the gold tailings backfill does not pose a significant health risk to humans that use the aquifer in future. The human health risk from heavy metal poisoning due to groundwater consumption is mitigated by the high pH buffering capacity of the dolomite water which ensures that any dissolved metals entering the aquifer, if not diluted, will be readily precipitated and hence immobilised, keeping heavy metal concentrations below levels that could be unsafe for human consumption.
- The NFM showed that uranium could exist in the aqueous form under both acidic and alkaline conditions, only the speciation varied. A uranium concentration as high as 310mg/ℓ is possible to achieve based on the thermodynamic model for ordinary tailings modelled. Amelioration of the tailings (e.g. through the addition of cement) may reduce the maximum concentration predicted by the thermodynamic model
- The Far Field Modelling (FFM) was undertaken to establish whether uranium was indeed a potential health risk and if so, under what conditions a uranium pollution plume would develop.
- The FFM showed that the backfilling of single isolated sinkholes with gold tailings cannot adversely affect dolomite water quality with respect to uranium, irrespective of the uranium leachate concentration.
- The backfilling of clusters of sinkholes (comprising say 30 or more sinkholes in a 1km^2 area) could result in the development of a uranium pollution plume over time, depending on the uranium leachability. The more extensive the cluster, and the more concentrated the sinkholes in geographic extent, the greater the risk of pollution.
- Uranium leachability is the single most important factor in deciding the sustainability and hence acceptability of using gold tailings to backfill sinkholes from a pollution potential point of view. Provided that the uranium leachability is below 0.8 mg/ℓ, the risk of pollution levels increasing above background by more than the SAWQ guideline level of 0.07mg/ℓ is insignificant. The WHO guideline value of 0.002mg/ℓ U has a higher risk of being exceeded, uranium leachability in excess of 0.002 mg/ℓ will cause the background water quality to increase in excess of the WHO guideline.

Legal Review

- The legal review showed that the practice of backfilling sinkholes with tailings or mine waste rock is not in compliance with the law. The issue is however complex as a result of historic agreements between the Government and the mining industry and past decisions and precedents.

- Sinkholes will have to be secured for the safety of the public and structures in the close proximity to structures. Furthermore since open sinkholes are associated with a significant risk of illegal dumping, backfilling of sinkholes appears a logical and appropriate solution. Further consideration to resolve the legality of the backfilling practice will however be required should mine waste materials be used in future for this purpose.

TABLE OF CONTENTS

LIST OF APPENDICES

(APPENDICES ARE AVAILABLE ON THE ACCOMPANYING CD)

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

1.1 BACKGROUND TO THE INVESTIGATION

The dolomites of the Far West Rand comprise one of South Africa's most important groundwater resources.

Partial de-watering of the dolomite aquifers over recent decades to allow safe extraction of gold ore from the Witwatersrand reefs located below the dolomite resulted in the draw down of the water table within the dolomite aquifer to form a cone of depression. The effect of depressing the water level was to bring on the onset of sinkhole formation at an unprecedented rate. Sinkholes continue to form to this day. The formation of sinkholes resulted in the mining companies purchasing vast tracts of land, which up until the advent of gold mining in this region, had been used for a range of activities, including market gardening. Today, the land is still held by the Far West Dolomite Water Association (FWDWA).

As has occurred on the Central and East Rand, gold mining will not continue indefinitely, and at some time in the future, the mines will cease operations, the pumps which have maintained the cone of depression within the dolomites will be switched off and the mines cavities will fill with water that infiltrates via a series of fissures. Eventually, once the mine voids have re-filled, the water level in the dolomites will start to rise. While the mines contributed significantly to the economic development of the country, the cost of the legacy left by the mines as a result of tailings dams, sinkholes, contaminated underground workings and a potentially permanently altered hydrogeological regime, will need to be borne by the companies' successors and future generations.

This study addresses just one aspect of the future legacy, namely the issue of the sinkholes that have formed to date and will probably continue to form in future.

1. How should the sinkholes be dealt with?
2. Should they be left as they are?
3. Is it acceptable to backfill the sinkholes with gold tailings or mine waste rock?
4. How is the magnitude of the impact of backfilling sinkholes with gold tailings likely to compare with the magnitude of the impact of tailings dams?
5. What are the chances that having re-filled the sinkholes, they will reactivate?

The study has been conducted in a generic rather than a site-specific manner with the objective of providing guidelines to all parties who may be affected by the problem in one way or another. The study focuses primarily on the three currently de-watered compartments, namely the Bank, Venterspost and Oberholzer aimed at finding a set of general principles, which is applicable to all compartments in the Far West Rand.

1.2 SIGNIFICANCE OF THE DOLOMITE COMPARTMENTS AS A WATER RESOURCE

Of all aquifers in South Africa, the dolomites of the Chuniespoort Group represent the most important aquifer. This is due to the high to very high storage capacity and the often highly permeable characteristics of this rock type (Barnard et al., 2000). Due to the importance of this aquifer a number of large scale investigations have been undertaken in the past.

The continuity of the dolomite aquifer is interrupted by vertical and subvertical intrusive dykes. These low permeability or impermeable rocks serve as barriers to the movement of groundwater through the dolomite, resulting in the formation of compartments. The dolomites of the Chuniespoort Group around Johannesburg are found in the following areas (refer to Figure 1 for details):

- A localised circular area north of Heidelberg comprising the Natalspruit Compartment.
- A localised stretched out area around and west of Delmas comprising the Bapsfontein/Delmas Compartment and the Varkfontein/East Rand Basin.
- A vast area starting south of Pretoria extending in westerly direction past Lichtenburg and Zeerust comprising some 14 compartments.
- A large area starting south of Johannesburg, extending in westerly and later in south westerly direction past Potchefstroom and Klerksdorp. This area includes the study area of the Far West Rand. This regional area comprises 7 compartments of which 4 compartments have been dewatered for the purpose of mining. The dewatered compartments are (from east to west):
    - The Gemsbokfontein Compartment
    - The Venterspost Compartment
    - The Bank Compartment and
    - The Oberholzer Compartment

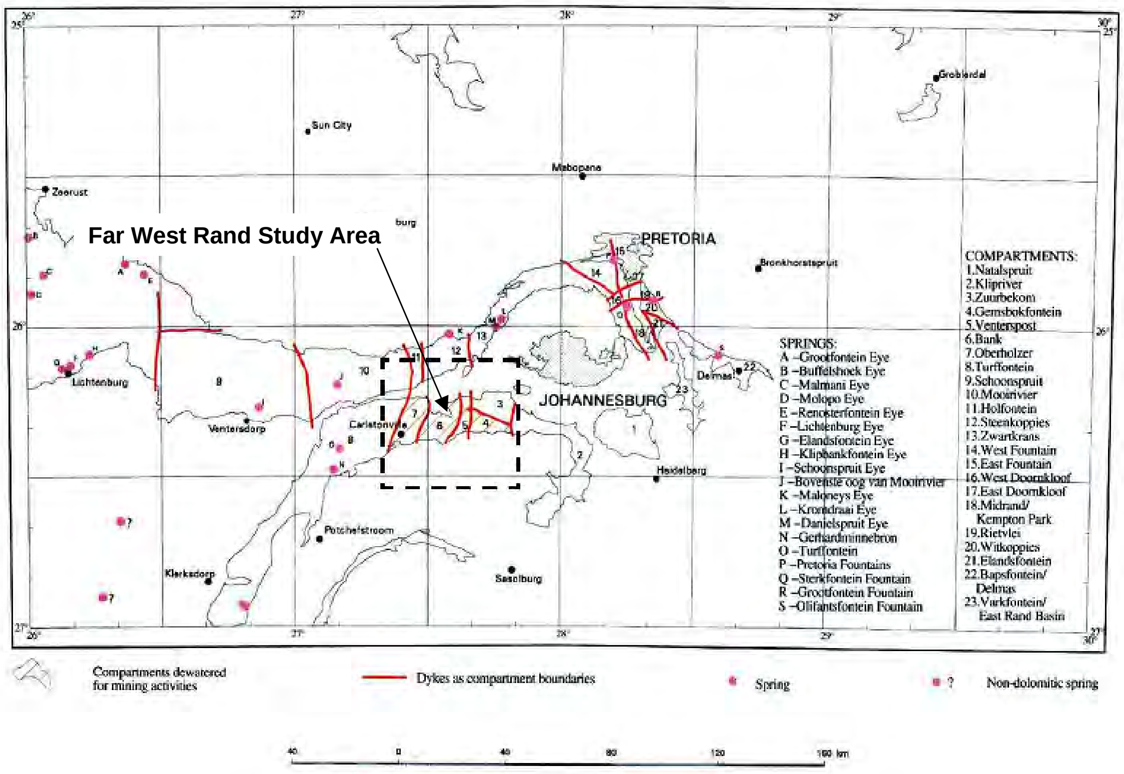


FIGURE 1: CHUNIESPOORT DOLOMITE COMPARTMENTS (MODIFIED AFTER BARNARD, 2000)

1.3. OBJECTIVES OF THE INVESTIGATION

The objectives of the research project were as follows:

- To quantify potential impacts on groundwater quality arising from the future filling of sinkholes using mine waste materials.

- To assess the relative significance of the backfilling sinkholes as a source of groundwater contamination compared with other sources of contamination such as tailings dams, waste rocks dumps and return water dams.

- To assess the potential effectiveness of alternative fill materials and methods in reducing negative impacts on groundwater quality.

- To assess the provisions of both current and pending legislation to ensure that proposals arising from the project conform to the requirements of such legislation.

1.4. LIMITATIONS

The report focuses primarily on the long-term effect of backfilling of sinkholes with mine waste materials and results refer primarily to the period after the cessation of mining activities and once the mine voids have been re-flooded. The effect of the flooded mine voids on the water quality of the aquifer is however not considered. The reason for limiting the study to this period is that at present the dolomite aquifers are largely dewatered to a depth below the cavernous zone and the significance of any impact from the backfilled sinkholes is lost since most of the water enters the mine voids prior to being pumped out of the mine void as part of the mine dewatering operation.

1.5. APPROACH TO THE RESEARCH

To address the objectives of the project the following was done:

- A review of the situation on the Far West Rand was undertaken:

  To understand the geochemical and geohydrological situation in the Far West Rand.

  To determine the dolomite aquifer characteristics, and the effect that mining is likely to have on the final water levels within the dolomite compartments after mining ceases and the mine voids and aquifer water levels are re-established.

  To develop a conceptual model for the leaching and transport of contaminants from backfilled sinkholes.

  To assess the historic rate of sinkhole development and backfilling of sinkholes in order to estimate the likely or potential future rate of sinkhole development during the post mining period.

  To ascertain the geotechnical characteristics of backfill materials.

- The potential impacts from the sinkhole backfill material on the ground water in the immediate vicinity (directly below) the backfilled sinkhole was investigated. Laboratory testing of samples of gold tailings recovered from a backfilled sinkhole and tailings dam were undertaken to characterise the tailings in terms of its elemental composition and leachability. A model, referred to as the Near Field Model (NFM) was developed to predict the quality of leachate over time, from the point when the tailings is first disposed of into the sinkhole, to 50 years into the future. The NFM comprises a thermodynamic model incorporating certain kinetic reactions, which was applied to the backfilled sinkhole problem to predict the quality of water leaving the backfill, after having reacted with:

  The tailings material

  The material of the vadose zone

The dolomite aquifer water

- Having characterised the effect of a single backfilled sinkhole on the aquifer in the immediate vicinity of the backfill, the next step was to evaluate the effect that one or a combination of similar backfilled sinkholes would have on the entire compartment. This issue is addressed using a separate solute transport model and is referred to as the Far Field Model (FFM). The FFM involved:

  The preparation of a groundwater flow model to model flow through a typical dolomitic compartment in the Far West Rand.

  Contaminant transport modelling to evaluate the impact of the leachate from backfilled sinkholes and tailings dams on the dolomite aquifer to ascertain the magnitude and extent of the resulting pollution plumes.

- A brief study of the physical stability of backfilled sinkholes to evaluate the sustainability of the current backfill practices and identify those factors that should be considered in the design and method of backfilling to reduce the risk of re-activation of backfilled sinkholes.
- A review of the practice of backfilling sinkholes within the framework of the South African legislation to assess the legal compliance of the practice with respect to the current legal framework.

1.6. STRUCTURE OF THE REPORT

This report consists of 7 chapters. The first chapter provides an introduction to the research.

Chapter 2 provides background information that needed to be considered before the impact assessment could be undertaken and forms the framework for the impact assessment objectives of the research. Ideally, many of the issues addressed in Chapter 2 should have been dealt with prior to addressing the specific issues of this research. Since key questions (such as will the water levels of the dolomite aquifers recover to their pre-mining levels?) had not been addressed prior to commencement of this research, a significant portion of the research was necessitated to focus on such issues.

Chapter 3 reviews the practice of backfilling sinkholes with mine waste material. Chapter 4 addresses the assessment of the impact that the backfilling of sinkholes has on the dolomite aquifer. Chapter 5 considers the issues related to the stability of backfilled sinkholes. The legal review of the practice to backfill sinkholes with mine waste material is covered in Chapter 6 and the conclusions of the research are presented in Chapter 7 of this report.

2. BACKGROUND INFORMATION

2.1. GEOLOGY OF THE FAR WEST RAND

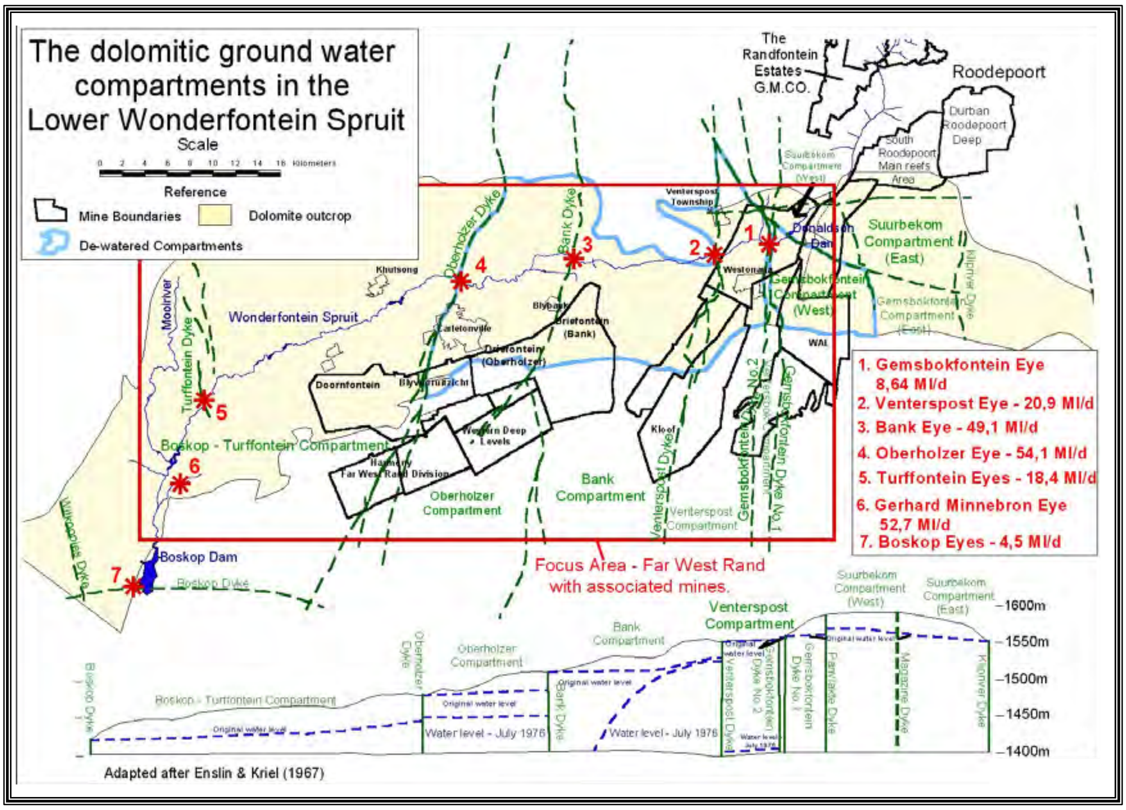
2.1.1. REGIONAL GEOLOGY

The location of the area of concern to the study (shown in Figure 2 below) lies immediately south of the basement anticline, which extends westwards from Randfontein through Klerkskraal to the vicinity of Ventersdorp. In a southerly direction the area extends towards the axis of the Potchefstroom Syncline, which borders the northern boundary of the Vredefort Dome.

The Precambrian geological succession of the area is represented by granites and gneissic rocks of the Archaean basement overlain by the Witwatersrand Supergroup (mainly quartzites, within which the famous gold-bearing reefs occur), thereafter the Ventersdorp Supergroup (mainly lavas) and finally the Transvaal Supergroup. The Transvaal Supergroup comprises a thin basal quartzite succession, the Black Reef Formation, rocks succeeded by the Chuniespoort Group dolomitic limestones and intercalated cherts, about 1,2 km thick and, finally, the mainly alternating shale and quartzite successions of the Pretoria Group which also contains a prominent andesitic lava unit. Deposition of the three supergroups took place between 3000 and 2000 million years ago.

Post-Witwatersrand Supergroup but pre-Chuniespoort Group tectonics was mainly of a broad block-faulting nature. Pre-Chuniespoort erosion has left half-graben wedges of Ventersdorp Supergroup rocks overlying similarly faulted Witwatersrand Supergroup rocks. The resulting pre-Chuniespoort topography was relatively smooth and the successions up to and including the Chuniespoort Group were involved in the folding that produced the Potchefstroom Syncline and, in post-Chuniespoort Group times, affected by relatively minor rejuvenation of the earlier faults.

Fairly widely spaced dykes, mainly of syenitic composition and related to the Pilanesberg Complex, intruded the area. The dykes are oriented approximately north-south but east-southeast and west-southwest conjugate directions are evident in one dyke and sections of other dykes.



Adapted after Enslin & Kriel (1967)

FIGURE 2: LOCALITY AND EAST WEST CROSS SECTION

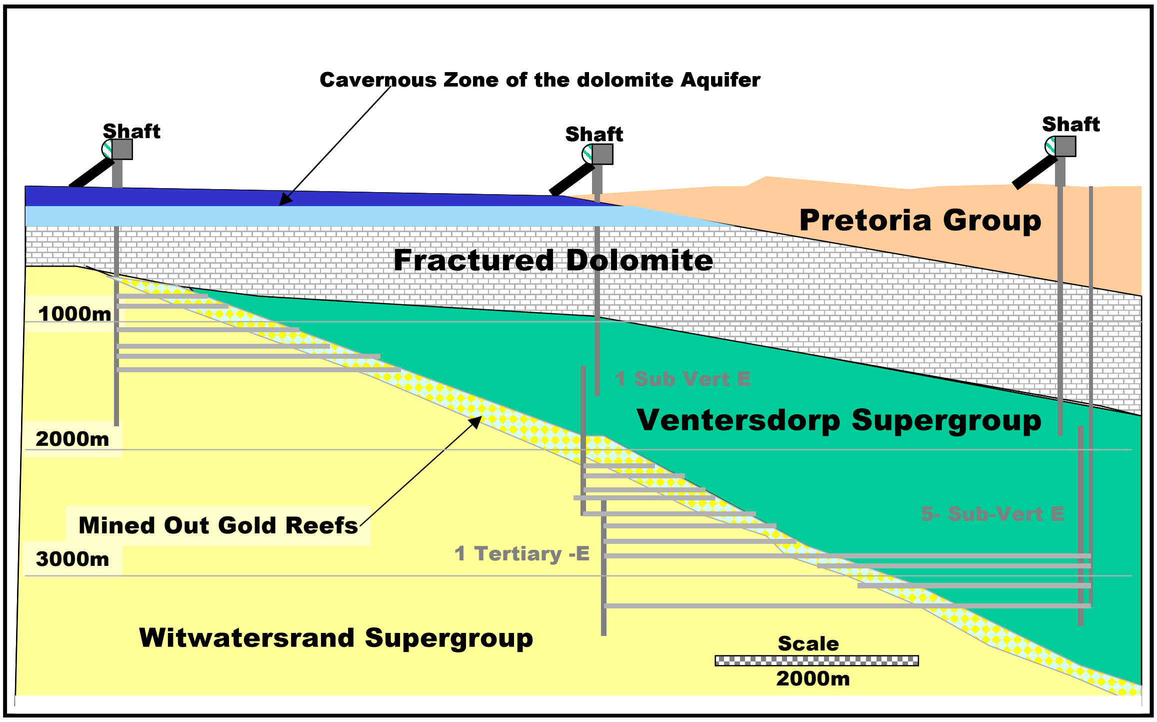


FIGURE 3: TYPICAL NORTH SOUTH GEOLOGICAL CROSS SECTION

After deposition of the dolomites, further folding took place such that the dolomites in the vicinity of the Far West Rand now dip to the south at angles between 6° and 12° and the dip of the underlying Witwatersrand quartzites and Ventersdorp Lavas increased further. Faults associated with this folding event extended through the Witwatersrand and dolomite rocks. A series of faults extend from the Vredefort Dome, to the south of the Far West Rand, in a northerly direction towards the Pilanesberg. These faults were later intruded by syenite and diabase associated with the Pilanesberg Complex. These dykes play a major role in determining the water level in the dolomite aquifers and separate them into a series of dolomite compartments. The dolomite compartments are named after the dyke forming the western boundary of the particular compartment.

Dolomite dissolution in the zone immediately above the water table, caused by weak carbonic acid, resulted in the development of a series of cavities in the dolomite.

Dolomite dissolution has continued to the present day, resulting in the formation of a series of cavities generally concentrated within the upper 150m. Since the ground surface has been eroded, and the water table has moved down accordingly, the depth of active solution cavity formation has also been lowered, resulting in the formation of cavities at different depths. A PhD thesis dealing with sinkhole development in the Far West Rand describes two sets of such sinkhole cavities (Wolmarans, 1984), namely:

a) A zone of cavities located above the pre-mining water table, which corresponds to earlier dissolution and form sinkholes unrelated to mine de-watering, and

b) A zone approximately 60m beneath this, which corresponds to more recent dissolution activity.

These zones occur across each compartment at approximately the same elevation within each compartment. The consistency in the elevation of the cavities is attributed to the relatively flat piezometric surface that occurs within each compartment. The formation of sinkholes in the zone above the pre-mining water table is not related to the dewatering activities of the recent decades.

2.1.2. NEAR SURFACE GEOLOGY

A vertical profile through the dolomites generally reveals a highly irregular, pinnacled dolomite structure and in-filled cavities of chert gravel. The residuum changes progressively from a low bearing capacity, highly porous clayey mass of manganese oxides known as wad and chert through a more compact mixture of chert and manganese oxides to a compact chert breccia cemented by manganese and iron oxides (Brink, 1979). The consistency of the overburden generally deteriorates with depth and competent chert gravel is frequently underlain by wad or even cavities before solid rock is reached. Consequently, the prediction of sinkhole formation and assessment of the competency of underlying rock is extremely difficult. The upper layer generally comprises a layer of transported material. A pebble marker is often detected separating the transported layer from the residual material.

The dolomite is often overlain by inliers of sedimentary Karoo Supergroup rocks (Ecca Group). For a chert-rich dolomite, the residuum generally grades from a coarse, angular chert gravel to the finer insoluble components of dolomites namely wad and clay. An irregular rock head consisting of pinnacles and boulders with solution caverns in the upper layers of the "solid" dolomite follows this. The vertical scale of this gradation is highly variable over the range 0,1 to 20 times the average value (Kleywegt et al., 1986).

It is common to find that the consistency or *in-situ* strength of the material usually reduces with depth from the relatively competent chert gravel to the compressible wad before it increases sharply as hard rock is encountered.

2.2. GROUND WATER IN THE FAR WEST RAND

2.2.1. AQUIFER CHARACTERISTICS

Aquifer Boundaries

The dolomite compartments are bounded to the north by the granite. Granite has a relatively low storativity and transmissivity and hence the flow across this boundary is negligible.

To the south, the compartments are bounded by the Pretoria Group rocks, which, although underlain by the dolomites at depth, are considered an effective hydrogeological barrier. This is explained by the fact that a cavernous zone is not developed in this area. Fracture flow is limited by the extreme depths and pressures resulting in negligible transmissivity in the southerly direction.

To the east and west, the compartments are bounded by the syenite and diabase dykes of Pilanesberg age, which effectively divides the dolomitic rocks into a series of separate groundwater compartments, namely Suurbekom, Gemsbokfontein, Venterspost Sub- and Venterspost, Bank, Oberholzer and Turffontein.

Prior to de-watering, the lowest point of each dyke controlled the water level in the compartment to the east of the dyke. Given the very high transmissivity of the dolomite within the first 200m of the surface as a result of the dissolution process, the water level was relatively uniform throughout the compartment. The spring, which occurs at the lowest point immediately upstream of the dyke bounding each compartment, is often referred to as the eye. Based on evidence from pre-mining water levels, the piezometric difference across the aquifer was typically of the order of 2m measured between the upstream dyke contact and the downstream eye.

Note that the surface water catchment boundaries extend significantly beyond the aquifer boundaries.

For the purpose of the impact assessment, the aquifer boundaries were taken to be as described above.

Aquifer Storativity

Studies in the Carletonville area indicated that the storativity decreases about 7 fold with increasing depth of 85 metres. A decline from an estimated 9.1% at a depth of 61 m below surface to 1.3% at 146 m below surface was reported (Enslin & Kriel, 1967). In later studies, the storativity in the dolomite was reported to generally vary between 1 and 5% (Bredenkamp et al., 1985). The reduction of storativity with depth reflects the change from a cavernous aquifer formed as a result of the dissolution process to a fractured aquifer at depth. The upper portion of the aquifer is therefore the most significant in terms of a water resource.

The assessment of the impact of backfilling on the aquifer has focused on the upper cavernous portion of the aquifer. For the purpose of water quality modelling, the simplifying assumption that the cavernous aquifer depth is 50m and that the storativity and permeability is constant over this depth has been made.

Recharge

There are a wide range of recharge rates have been reported by Fleisher (1981), Wolmarans (1984) Bredenkamp (1993), Enslin and Kriel (1967) and Foster (1989). The range varies from less than 5% to as much as 55% of Mean Annual Precipitation (MAP) (after Hodgson WRC Report No. 699/1/01, page 5-28). The wide range in values is attributable to the different methods used to estimate recharge as well as the natural variability.

In general, the lower the recharge rate, the greater the impact of backfill on the groundwater. For this reason, ***a recharge rate of 5% MAP was adopted for the generic impact assessment, which represents the lower end of the range and a conservative estimate.***

Eye Yields

The yields of the natural springs (“eyes”) in the area prior to de-watering are presented in Table 2 and the location of the eyes is shown in Figure 2.

TABLE 1: WONDERFONTEIN SPRUIT CATCHMENT AND FLOW RATES (REPORT GH 1849)

COMPARTMENT	SURFACE AREA		SPRING NAME AT COMPARTMENT OUTLET	AVERAGE FLOW IN THE PRE-MINING PERIOD (M.G.P.D.)
	SQ. MILES	KM^2		
Suurbekom	38.7	100.2	Klip River Spring	Dry – Flow unknown; reportedly the flowed some 100 years ago
Gemsbokfontein	32.8	85.0	Gemsbokfontein Spring	1,9 (8,64Ml/d)
Venterspost	21.0	54.4	Venterspost Spring	4.6 (20,9 Ml/d)
Bank	60.5	156.7	Wonderfontein Spring	10,8 (49,08Ml/d)
Oberholzer	59.4	153.8	Oberholzer Spring	11.9 (54,08Ml/d)
Boskop-Turffontein	272	704.5	Turffontein Springs Gerhardminebron Springs Boskop Springs	4.05 (18,41Ml/d) 11.6 (52,72Ml/d) 1.0 (4,545Ml/d)

m.g.p.d = million gallons per day

Fleisher (1978) documents the annual discharge from the Bank spring prior to de-watering. The discharge varies between 16.04 million m^3 /annum (44Ml/d) and 22,03 million m^3/annum (60Ml/d) between 1958/9 and 1966/7.

Piezometric Contours prior to Mining

Annexure 10 of the Final Report of the Interdepartmental Committee on Dolomite Mine Water: Far West Rand (November 1960) presents a map showing the piezometric contour elevations. Pre-mining contour elevations were available for the Oberholzer compartment, which give a minimum gradient of approximately 1:1 000 (10 feet over 2 miles **equals** 3 m over 3.2 km). The effect of increasing the losses through the Pilanesberg dykes would be to flatten out the piezometric gradient across the aquifer. This would give rise to reduced advective transport of contaminants and hence higher contaminant concentrations close to the source of contamination.

Aquifer Permeability

The main groundwater flow in the aquifer seems to be correlated to the main streams in the surface drainage network. Observations concerning the groundwater flow in relation to the surface watercourse made in the Far West Rand prior to mining seem to confirm that the zone of main groundwater flow is confined to the immediate vicinity of the main surface watercourse in the area, the Wonderfontein Spruit. A survey of total dissolved solids (TDS) in boreholes in the dolomite compartments undertaken in 1959, showed that the elevated TDS contended to increase in the direction of the Wonderfontein Spruit and that contamination from the Wonderfontein Spruit tends to remain within a narrow band of in the immediate vicinity of the Wonderfontein Spruit. From this observation it can be concluded that the major conduit for groundwater flow must be present in the vicinity of the Wonderfontein Spruit and that the regional groundwater flow directions tend to be towards the Wonderfontein Spruit from both the northern and southern side.

Values quoted in the literature for the transmissivity of the dolomite aquifer range between 25 and 5 000 m^2/day for the Zuurbekom Compartment (Simonic, 1993) and are otherwise quoted to “be variable but […] as large as 7 000 m^2/day” (WRC Report 699/1/01 page 5-28). This indicates that the transmissivities for the dolomite aquifer are highly variable.

For the purpose of the impact assessment, the flow model was calibrated by adjusting the permeability of the dolomite until it gave the correct flow rate (equivalent to the documented flowrate of the compartment’s downstream spring prior to mining). The hydraulic gradient assumed was 1:5 000 (between the piezometric level adjacent to the dyke at the upstream boundary and the piezometric level at the eye) and this calibrated to a conductivity for the dolomite of 0.006 m/s for a flow of 20.9 Ml per day at the Venterspost Spring.

2.2.2. INTER-COMPARTMENTAL FLOW

Prior to mining, the compartments comprised relatively independent hydrogeological structures. Losses through the dykes are believed to have been relatively small and insignificant compared to the flow from the eye of each compartment. The pre-mining situation is shown conceptually in Figure 4.

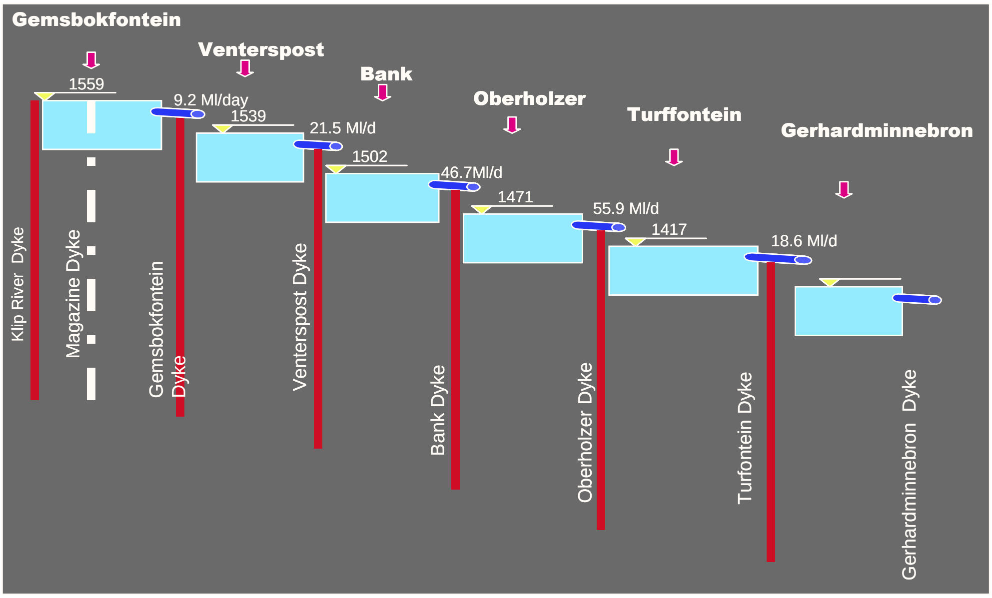


FIGURE 4: CONCEPTUAL MODEL FOR THE PRE- MINING COMPARTMENT CONNECTIVITY

Mining development through the compartment forming Pilanesberg dykes has changed the integrity of the dykes and on decommissioning of the mines, the leakage rate through the dykes is expected to be significantly higher than the leakage rate prior to mining. The situation during mining is illustrated in Figure 5.

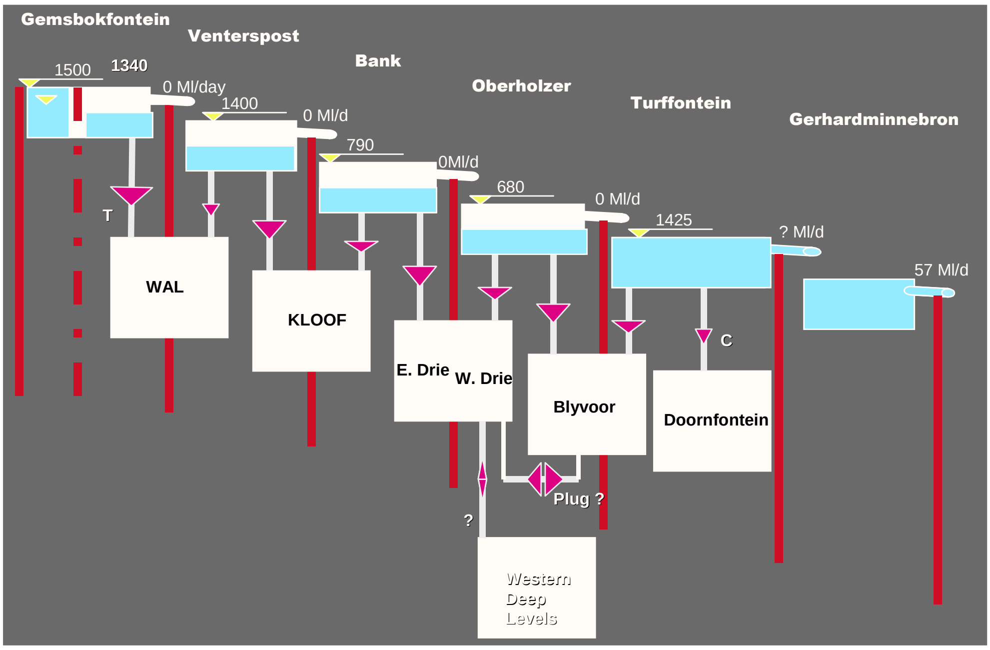


FIGURE 5: CONCEPTUAL MODEL FOR THE MINING PERIOD

Once mining ceases, pumping from the mine voids will cease and the mine voids will be flooded due to infiltration from the overlying aquifer. The issue of whether the water level in the dolomite will only rise to the level of the only undisturbed barrier (namely the Turffontein Dyke), or whether it will rise to the pre-mining water level has not yet been scientifically proven and has yet to be seen. The extent to which the water level rises is not governed by the integrity of the dyke alone, but also by the fractured aquifer.

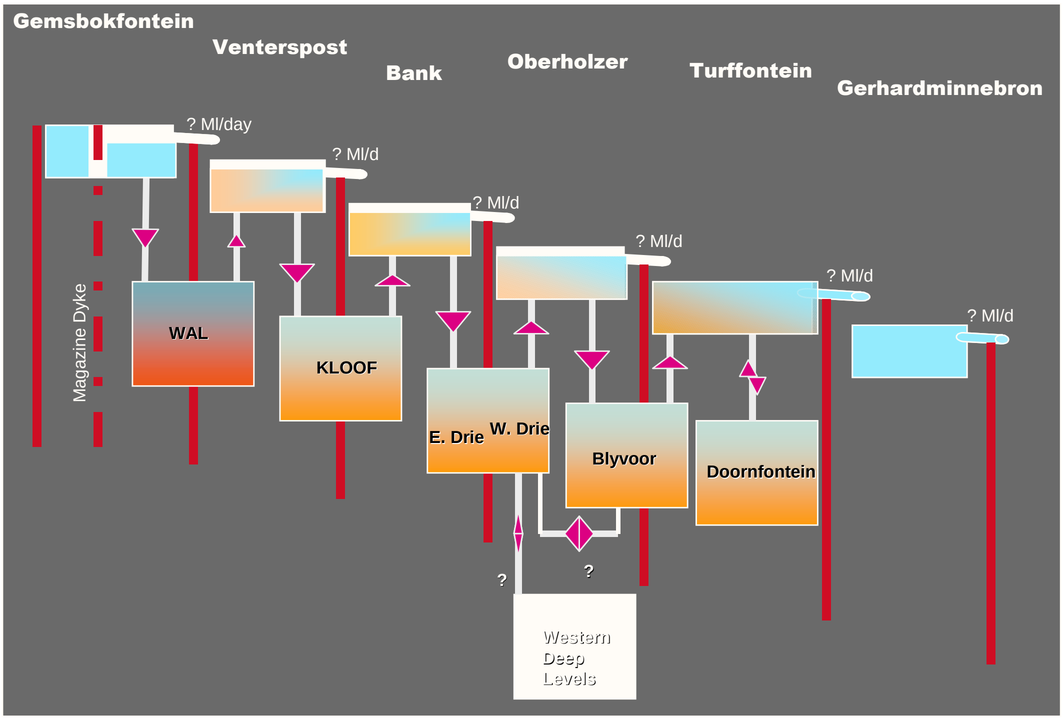


FIGURE 6: **CONCEPTUAL MODEL FOR THE POST-MINING PERIOD**

Applying the Darcy equation of saturated flow to any adjacent two compartments in the conceptual model illustrated in Figure 6, and assuming that a head difference exists between the average piezometric levels in the two compartments, Δh , the inter-compartment flux may be calculated from Equation 1, which is illustrated in Figure 7.

If the total recharge,

EQUATION 1

$$R_1 >> Q = \frac{\Delta h}{\sum_{i=1}^{n} \frac{l_i}{k_i A_i}} = \frac{\Delta h}{\frac{l_1}{k_1.A_1} + \frac{l_2}{k_2.A_2} + \frac{l_3}{k_3.A_3}}$$

Where:

Q = Total flux entering the dolomite aquifer from the mine void (Ml/day)

l_i = Flow path length across the porous media

A_i = Area of flow, (depends on mining area, area of dolomite aquifer affected by the mine void, etc.)

k_i = Permeability (m/s) of the fractured rock aquifer

R_1 = Total Recharge to the upstream compartment

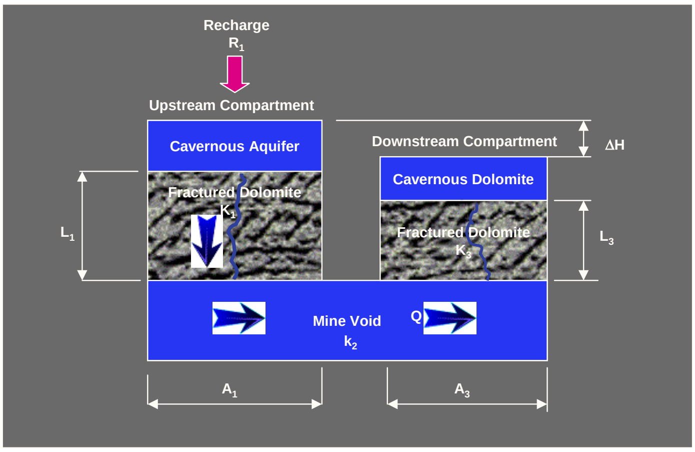


FIGURE 7: CONCEPTUAL INTER-COMPARTMENTAL FLOW MODEL

The 2nd term in the denominator can be ignored since the permeability of the mine void itself is very high compared to that of the fissures. The head loss through the mine void itself will be negligible.

In the post-mining environment there could be a difference Δh of at most 34m, between the Bank and Oberholzer Compartments, and 38m between Venterspost and Bank Compartments. These relatively small head differences (compared to the head difference during the mining period) may not be sufficient to drive the entire recharge volume R_1 through the mine void and then up into the downstream compartment. If this is the case, the upstream compartment water levels will ultimately re-establish to their pre-mining levels. The view that the pre-mining water levels will re-establish after mining ceases, is contrary to that documented by several other Authors. It is the Authors view however that other studies did not take cognisance of the resistance to flow offered by the fractured dolomite aquifer, and hence concluded that the water level would finally equilibrate at the level of the Turffontein Compartment throughout the Oberholzer, Bank and Venterspost compartments.

The implications of a re-established water level after mining ceases are that the dolomite aquifers could once again become a major water resource, provided that they are not polluted.

For the purpose of this study, assumptions have been made (based on the argument outlined above) that:

- ***Pre-mining water levels will re-establish,***
- ***the cavernous zone of the dolomite aquifer will once again fill up and represent the most significant storage zone; and***
- ***that the eyes will once again flow.***

It can be further deduced from the above conceptual model that increasing the inter-compartmental flow rate through the dyke via the mine void will tend to:

- Increase the rate of flushing of stored contaminants from the mine void to the fractured aquifer. The injection of contaminated water from the underlying mine void into the cavernous zone could be the predominant source of pollution for a period of time.
- Reduce the eye flow rate.
- If the recharge rate R_1 periodically drops below the inter-compartmental flow rate Q, it may temporarily cause the piezometric levels to drop. This may in turn result in:
- Periods of increased ground instability and more sinkholes.

2.2.3. WATER USE

An indication of past groundwater abstraction rates and spring flow from the relevant compartments is tabulated in Table 2 below. The yield of the boreholes is classified as excellent as more than 50% of the boreholes on record produce borehole yields in excess of 5 l/s with a recorded maximum of 126 l/s.

TABLE 2: SUMMARY OF AVERAGE ANNUAL GROUNDWATER ABSTRACTION AND SPRING FLOW FROM THE VARIOUS COMPARTMENTS OF THE CHUNIESPOORT GROUP (BARNARD ET AL., 2000, MODIFIED)

COMPARTMENT	NO	SPRING FLOW	IRRIG-ATION	DOME-STIC	MINING	MUNICIPAL INDUSTRY	SOURCE REFERENCE
Zuurbekom	3				7.6	10.0	Fleisher (1981)
Gemsbokfontein	4		1.5		43.2		Leskiewicz (1984a)
Venterspost	5				27.0		Fleisher (1981)
Bank	6				36.0		Fleisher (1981)
Oberholzer	7				19.0		Fleisher (1981)
Turffontein	8	40.8					Fleisher (1981)
Spring flow and groundwater abstraction rates reported as million cubic meter per annum							

The compartments shaded in grey are the compartments in the Far West Rand of interest to the study.

2.2.4. WATER QUALITY IN THE DOLOMITE COMPARTMENTS

The water quality in the dolomite aquifer of the Far West Rand is generally of good quality suitable for all water uses. An assessment of 223 water samples from boreholes in the Far West Rand showed that the average groundwater quality has the following characteristics:

- Neutral pH.

- Low to moderate EC.
- Cation concentrations mainly related to the geological formation from which the water originates (Ca and Mg and to a lesser extent Na and K).
- Anion concentrations mainly related to the geological formation from which the water originates (CO_3 and to a lesser extent primarily influenced by anthropogenic activity, SO_4, NO_3 and Cl).

The evaluation of the data variability showed that:

- A very low coefficient of variation (5%) was observed for the pH, which is to be expected due to the buffer capacity of the $CaMgCO_3$ system, which will kept the pH within a narrow range around 7.6.
- Coefficients of variation of around 100% were observed for the EC, TDS, Ca, Mg and Total Alk. These variations are considered within the range of natural variability of the water quality due to geochemical processes between the water and the host rock.
- Increased coefficients of variation (< 200%) were observed for a number of cations, namely Na, K and F. In the case of these cations the observed maxima were significantly higher (about 10 times) than the average, indicating some localised elevated concentrations of these cations occurring in the aquifer.
- Coefficients of variation in excess of 200% were observed for nitrate, chloride and sulphate. The average concentrations of these anions were 40 to 70 times higher then the observed minima and the maxima were about 20 to 30 times higher then the average. This is a clear indicator that the water quality in the dolomite aquifer is impacted from contamination sources, which release these anions into the groundwater. Typical sources for this kind of contamination are industrial operations, agriculture practices and mining activities.

A summary of the water quality chemistry of the dolomite aquifer is presented in Table 3 below.

TABLE 3: CHEMISTRY OF GROUNDWATER FROM THE CHUNIESPOORT GROUP (BARNARD ET AL., 2000)

ELEMENT / PARAMETER	STATISTICS DRAWN FROM A POPULATION OF 223 SAMPLES				
	Minimum value	**Mean value**	**Maximum value**	**Standard Deviation**	**Coefficient of variation**
PH	5.8	7.6	9.5	0.4	5%
Electric Conductivity (mS/m)	4.4	62.9	397.0	56.0	89%
Total Dissolved Salts (mg/ℓ)	43.1	443.6	3402.0	403.0	91%
Calcium (mg/ℓ Ca)	1.0	52.7	436.0	54.0	102%
Magnesium (mg/ℓ Mg)	1.0	35.4	223.0	31.0	88%
Sodium (mg/ℓ Na)	1.0	24.1	299.0	39.0	162%
Potassium (mg/ℓ K)	0.1	2.3	39.0	4.2	183%
Chloride (mg/ℓ Cl)	1.0	37.7	900.0	83.0	220%
Sulphate (mg/ℓ SO_4)	1.0	70.5	2172.0	233.0	330%
Total Alkalinity (mg/ℓ $CaCO_4$)	8.0	177.3	664.0	94.0	53%
Nitrate (mg/ℓ N)	0.1	5.6	122.0	12.1	216%
Fluoride (mg/ℓ F)	0.1	0.3	2.8	0.4	133%

2.3. SINKHOLES IN THE FAR WEST RAND

2.3.1. SINKHOLE DEVELOPMENT MECHANISMS

The mechanism for the formation of a sinkhole is described in Brink (1979). Although sinkholes occur naturally in dolomite rocks their rate of formation increases dramatically when the water level in the dolomites decreases such that the arches formed across the cavities by wad, soil and chert, change from a submerged to an unsubmerged state. The effect of the lower water level is as follows:

- The effective loading on the arch increases by 1.9 / 0.9 = 2.1 (saturated density ~1.9; buoyant density ~0.9) compared to the loading prior to the reduction in water level. This stresses the arching material but is not usually sufficient to cause collapse.

- Infiltrating water migrates downwards through the chert/ wad /soil arch material causing erosion and the gradual “onion peeling” of the arch material as it collapses into the cavity. The arch is eroded until it collapses into the underlying cavity.

While the impact of de-watering on the dolomite compartments is well documented, less is known about the impact of re-watering and the re-establishment of groundwater levels in the dolomite. An indication of the consequence of re-establishment of the water levels was observed during the period 1975 to 1978, when the Venterspost Compartment was partially recharged as a result of high rainfall in the area and the overflow of groundwater from the adjacent and un-dewatered Gemsbokfontein compartment. Prior to the re-watering event, the piezometric elevations had been drawn down by up to 100m. During this event, the water levels in the vicinity of the inflow point returned to the pre-mining level. During this period ground instability is reported to have occurred. The renewed cycle of ground instability was smaller than that which occurred during the initial de-watering period. Four types of movement were reported to have occurred:

- New sinkholes developed in areas that had not shown any sign of movement during the initial de-watering phase;
- Old sinkholes which had been filled in the early 1960's became active again;
- Old paleo-sinkholes, which had been stable during the de-watering phase, became active again;
- Areas of subsidence showed acceleration in the rate of subsidence. This is associated with the return of the water level to the level of the residuum material.

The relatively stable conditions observed during times of a relatively constant water level, should therefore be regarded as meta-stable. Based on the historic evidence of sinkhole formation both during de-watering and re-watering, it would appear that instability and sinkhole formation is likely to arise whenever the water level is moved through the zone of structural support.

2.3.2. GEOGRAPHIC DISTRIBUTION OF SINKHOLES

A plot of the location of sinkholes that have occurred on the Far West Rand, based on information contained in GIS database (Erasmus, 2000, unpublished), indicates that the occurrence of sinkholes is non-uniform over the compartments and tends to be clustered around particular geological and geographic features. The plot has been used to determine the maximum number of sinkholes occurring in any single square kilometre and the average number of sinkholes occurring in any square kilometre. From the plot it is concluded that the average number of sinkholes per square kilometre is 31 with a minimum of 10 sinkholes and a maximum of 45 sinkholes.

The significance of this is that modelling the contaminant load as a uniform distribution is clearly inappropriate as it can severely underestimate the impact of the "nugget effect" or clusters of backfilled cavities. The current average cluster density of 30 sinkholes per square kilometre was used as the basis for evaluation in the Far Field Model.

2.3.3. FORMS OF SINKHOLES

Sinkholes come in different shapes and sizes. Their aerial extent and depth may be governed to a large extent by the geology. For illustrative purposes, four examples of groups of cavities are described in Table 4 below. While this list is not scientifically derived and many exceptions will arise, the list is useful in demonstrating that relationships can be observed between geology, location, size and aerial distribution or concentration of cavities.

TABLE 4: TYPICAL FORMS OF CAVITIES

	A	B	C	D
Typical Geological Association	Associated with fault zones	Associated with areas where dolomites are covered with Karoo rock, or rocks of the Pretoria Group that have sufficient strength to span the cavity	Chert -rich dolomite. Chert forms arch across cavity throat which then collapses	Associated with dolines, and crack forms around the edge of the doline
Typical depth of sinkhole	Up to 200m	Shallow, typically less than 10m	Typically 7 to 25m	Varies
Typical diameter of opening	Small diameter, typically 0,5m to 5m	Often up to 100 to 150m	1 to 5m	<0,5m across crack
Common areas of occurrence	Along the north-south Rustenburg–Bank Fault	Within a 2km band of the outcrop of the Pretoria Group and where major remnants of Karoo rocks are found	Within a 2km band of the Wonderfontein Spruit. These sinkholes are relative to the depth of the original groundwater table (see Kleywegt & Enslin, 1973)	Primarily associated with chert-poor dolomite

It is the Authors view that the significance of the above with respect to this study is that many of the sinkholes will form in clusters, associated with particular geological or physical features e.g. dykes, drainage channels or leaking pipelines. The environmental impact of a cluster of sinkholes backfilled with mine tailings will be different to the environmental impact of the same number of sinkholes evenly distributed over the compartment.

The impact assessment must therefore consider the impact of a wide variety of potentially backfilled sinkhole combinations ranging from (a) large isolated sinkholes to (b) clusters of closely spaced smaller backfilled sinkholes.

2.4. RATE OF SINKHOLE DEVELOPMENT

2.4.1. HISTORIC RATE

Records of sinkholes that formed within the de-watered compartments have been kept since the 1960's by the FWDWA and it is understood that regular surveys of the sinkholes in the Far West Rand are undertaken. These records include information on the volume of grout or backfill material that was used to backfill the cavities. However, these data appear not to have been verified and evaluated and no data with respect the historic rate of sinkhole formation could be readily obtained during the course of the project.

It is recommended that the existing body of data with respect to the historic sinkhole development is reviewed, verified and evaluated, aimed at establishing the trend of historic sinkhole development in the Far West Rand. In addition, the information should be displayed using a GIS to develop maps of the FWR showing the progressive development of sinkholes for the past four decades.

2.4.2 FUTURE RATE OF SINKHOLE FORMATION

There are three periods of interest that are likely to experience different rates of sinkhole formation (and hence backfilling rates) in future, namely:

- The period up to cessation of mining activities and re-flooding of the mine void.
- The period during re-watering of the dolomite aquifer when the water level moves up through the sensitive zone that provides structural support through the arching mechanism to the overlying material.
- The post re-watering steady state period, once more or less constant water levels are achieved.

These periods, and the anticipated sinkhole development rates are shown conceptually in Figure 8.

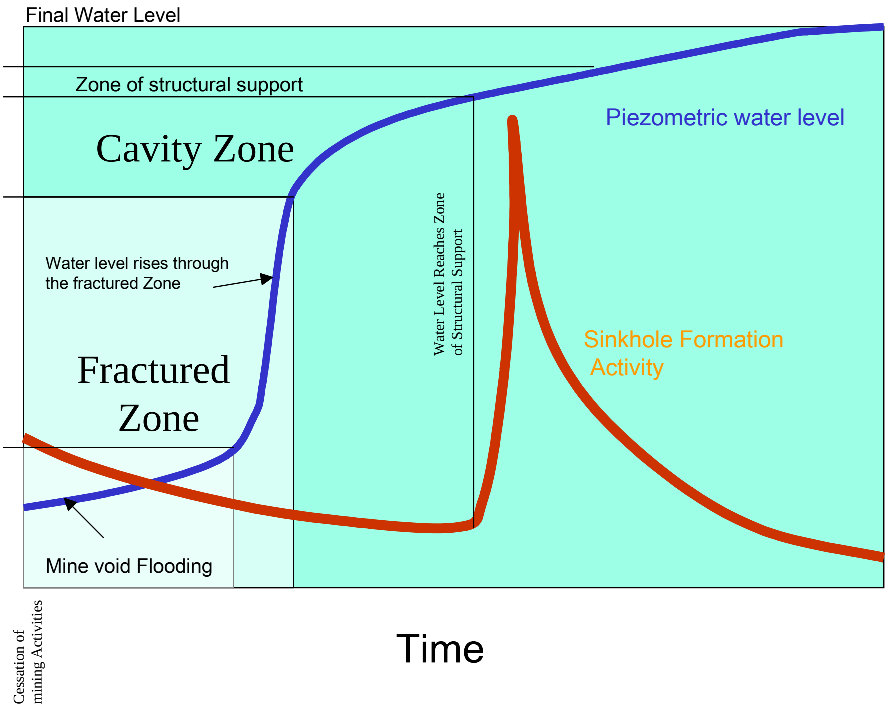


FIGURE 8: CONCEPTUAL RELATIONSHIP BETWEEN RE-FLOODING AND SINKHOLE ACTIVITY

The rate of sinkhole formation is briefly discussed for each of the periods in the proceeding sections.

Period up to Cessation of Mining

Since de-watering of the compartments will continue throughout this period, the expected rate of sinkhole formation is likely to be very similar to the recent historic mean rate of sinkhole formation.

Period of Re-watering

On cessation of mining the mining voids will fill up first, followed by the fracture zone within the dolomite aquifer. The water level is expected to rise rapidly through the fracture zone as a result of the relatively low storativity, and then slowly through the cavity zone of the dolomite aquifers as a result of the high storativity in this zone. Prior to the commencement of the study, no literature could be found documenting the time to re-flood the mine voids or aquifer after cessation of mining. The volume of the mine void is currently estimated to be in the order of 0,7 million Ml. Enslin and Kriel (1967) calculated that the combined storage capacity of the Venterspost and Oberholzer Compartments is about 1,13 million Ml (1,13 km^3) and Schwartz and Midgley (1975) calculated (using a different method) the storage capacity of the Bank Compartment to be 2,2 million Ml. Adding these two figures (1,125 plus 2,2) gives 3,33 million Ml. This compares with the aggregate volume documented by Vegter (1987) of these three compartments of 3,5 million Ml.

Mine dewatering has only partially dewatered the dolomite compartments, resulting in a cone of depression with the lowest points of the cone concentrated at the dewatering points. Assuming that the cone of depression comprises say 25% of the total aquifer volume (a more accurate estimate would require a more detailed study), the dewatered volume in the dolomite aquifer is expected to be in the order of 875 000 000 m^3 or 0.88 million Ml.

On cessation of pumping by the mines, the mine voids together with the aquifer would need to be recharged before steady state conditions are re-established with a relatively constant water level across each compartment as was the case in pre-mining times. Thus, the total volume to be recharged is estimated at 1, 58 million Ml. This volume will recharge as a result of rainfall (estimated at say 9% to possibly 15% of MAP per annum) and as a result of flow events in the Wonderfontein Spruit.

Flow events in the Wonderfontein Spruit are currently controlled by the presence of Donaldson Dam and two pipelines that were constructed to convey water flow past the Venterspost, Bank and Oberholzer compartments to minimise recharge of the de-watered compartments. On cessation of mining the need for these pipelines will have to be re-evaluated. Should the decision be taken to remove the pipelines, the recharge from the Wonderfontein Spruit to the dolomite aquifer will a play a significant role in determining the time span for the final ground water elevations to be reached in the dolomite aquifer. However, in the absence of recharge from the spruit, the time span is estimated to be in the order of 74 years based on the calculation given below.

Volume of water required to re-establish the water level to the pre-mining water levels:

1 580 000 000 m^3 / (0.650 m * 365 000 000 m^2 * 0.09) = 74 years worth of normal recharge, where:

- 1 580 000 000 m^3 is the total void to be filled;
- 0.650 m (or 650 mm) is the Mean Annual Rainfall;
- 365 000 000 m2 (or 365 km^2) is the total surface area of the Venterspost, Bank and Oberholzer compartments; and
- 0.09 (or 9%) is the conservative estimate of recharge.

If the upper recharge limit of 15% is used the estimated time span will reduce to less than 45 years.

Flood events in the Wonderfontein Spruit are however likely to play a major role in reducing this time span even further. The Mean Annual Runoff (MAR) at the Wonderfontein Eye is in the order of 11 700 000 m^3 per annum (based on hydraulic records (1958 – 2000) collected by gauging station C2HO30 situated at the Wonderfontein Eye, Hydrological Information System, DWAF, 2002). Given the anticipated high degree of hydraulic connectivity between the river and the aquifer, recharge from the Wonderfontein Spruit could equal or even exceed the MAR. Based on the assumption that 25% of the MAR in the Spruit will eventually recharge to the dolomite aquifer the length of the conservative estimate of 74 years could be reduced to 65 years, while the less conservative estimate of 45 years could be reduced to 41 years.

The above calculations show that the time period for the recharge of the dolomite aquifer in the three compartments under consideration may vary significantly, even if the pipelines at Donaldson dam will stay in place after mining has ceased. The estimated time span for the recharge of the dolomite aquifer in the three compartments varies between 41 and 74 years.

The calculations concerning the time span of recharge undertaken by Swart et al. (refer to the publication in Appendix D of this report) used a different approach. The total volume dewatered was based on mine dewatering figures calculating the extent of dewatering for the three compartments. The resulting total volume dewatered of 1.806 million m^3 (refer to Table 5 in the publication) is some 0.226 million m^3 higher than the total volume calculated above (0.7 for the mine void + 0.22 for the Venterspost compartment + 0.227 for the Bank compartment + 0.356 for the Oberholzer compartment – all in million m^3).

The resulting time periods for the recharge of the compartments proposed by Swart et al. vary between 16 and 18 years for the respective compartments with a possibility of less than 10 years under high rainfall conditions. However, the calculation presented excluded the time period required to fill up the mining voids. The recharge figures for the compartments were assumed to equal the pre-mining flows of the respective springs (20.9 Ml/d for the Venterspost spring, 49.1 Ml/d for the Bank Spring and 54.1 Ml/d for the Oberholzer Spring). The comparative recharge figures calculated above are some 51 to 58 % lower (when assuming a 9% recharge) and some 15 to 30% lower (when assuming a 15% recharge to the dolomite aquifer). If the time period required to recharge the total mining void is included into the calculation (assuming that the entire recharge in the three compartments reports to the mining void first before recharging the dolomite aquifer) some 15.5 years will have to be added to the time figures stated. The time period to recharge the mining void and the dolomite aquifer according to Swart et al. would therefore range between some 25 years as a best case scenario to some 34 years under normal rainfall conditions, which is not that different from the shortest time span of 41 years calculated above.

As all calculations have been based on a number of assumptions, the final answer will only be obtained once mining has ceased and the recharge of the mining void and the dolomite compartment has been completed. The estimated time period varies between less than 20 years (according to Swart et al.) to about 74 years (according to the authors of this report) depending on a number of factors such as the future fate of the pipelines from Donaldson Dam and the Mean Annual Precipitation during the recharge period. However, the authors of the research report and the publication are in agreement that the springs will flow again some time in the future, once mining has ceased in the Far West Rand.

It is reasonable to deduce from the discussion on the formation of sinkholes that the rate of occurrence of sinkholes will not be constant throughout the re-watering period but will be highest during the period when the water level rises through a critical zone, corresponding to the level at which structural arching is most active. This corresponds to the final 5 to 10m of the cavity zone before the final groundwater elevation in the compartments is reached.

In the absence of any better data, the future rate of sinkhole formation applicable to the post mining period will have to be based on the experience documented by Kloof Goldmine on the partial re-watering of the Venterspost Compartment from 1975 to 1978, which shows that another period of instability is likely to arise when the water levels increase and approach the pre-mining water levels.

Based on the Kloof Gold Mine 1975 –1978 re-watering data, it is the Authors view that ***the rate of sinkhole formation towards the end of this period is unlikely to exceed the rate that occurred initially when the water level was dropped by 5 to 10 m in each compartment during the de-watering phase***.

Period after the Attainment of the final Water Level

Once the final water level is reached, the rate of sinkhole formation is expected to decrease with time and ultimately approach the pre-mining formation rate. The time that it would take to reach the pre-mining sinkhole formation rate is difficult to predict and may vary within the range of several years to several decades.

Once the final water level is attained, the rate of sinkhole formation is expected to slow down over time ultimately approaching the pre-mining rate.

It may be concluded (although not proven) that soon after the final water elevation has been attained, ***the density of sinkholes might well be twice that observed at present*** at any part of the catchment. It is the Authors view that the density of sinkholes will most probably be between the current density and twice the current density before the rate of sinkhole formation once again reaches meta-stable conditions and reduces to a rate similar to pre-mining conditions. This assumption has been applied in the Far Field Model to evaluate the long-term (post mining period) effect of backfilling of these sinkholes with mine waste.

3. BACKFILL MATERIALS

3.1. HISTORIC USE OF MATERIALS FOR BACKFILLING

The majority of cavities that open to surface are never backfilled. Grouting of cavities has been restricted to areas where subsidence or sinkhole formation threatens the integrity of structures such as roads, railway lines and buildings. Backfilling of open sinkholes has been limited to the following areas:

- Areas where backfilling of sinkholes has been considered warranted from an aesthetic perspective.
- Areas where there is a physical danger to people, such as in a highly populated areas.
- Beneath tailings dams where a sinkhole has formed in the tailings dam.

A review of the available material in the area has confirmed that the following materials have historically been used for backfilling of cavities:

- Soil – usually from a nearby borrow area.
- Mine waste rock – from development operations. Often the waste rock contains pyrite.
- Tailings from several of the mining operations.
- Tailings and cement mixtures used in grouting operations to stabilise roads, buildings, etc. Cement contents of up to 10% have been used.
- Other objects such as scrap metal to form a plug at the base of the sinkhole.
- Combinations of the above.

Only a relatively small proportion of the open holes have been backfilled with tailings. Holes that have been filled with tailings are restricted to:

- Sinkholes that develop on tailings dams.
- An area in the vicinity of the Wonderfontein Spruit which was “rehabilitated” after the development of a large number of sinkholes using tailings and waste rock from Venterspost Mine.

Based on historic records (Erasmus, 2000, unpublished), the composition of backfill materials in the Oberholzer and Bank compartments is estimated to be as follows:

- Approximately 75% of all backfilled sinkholes were filled with soil and domed;
- Approximately 25 % were filled with waste rock, covered with a red soil capping and domed;

- Within the Bank Compartment, tailings were used extensively on the grouting (slimes with cement) of cavities along the Johannesburg–Potchefstroom and Bank roads.

In the Venterspost Compartment, a sinkhole backfill project was undertaken in 1988 in the Wonderfontein Spruit river valley just to the north of Westonaria. The majority of the sinkholes were filled with mine waste rock (~75% of the volume) and the remaining voids were hydraulically filled with ordinary gold tailings. This method is estimated to account for some 60% of the filled voids in the Venterspost Compartment. The remaining 40% have been filled with soil.

Within the mining properties, the majority of sinkholes were filled with mine waste rock, as this was a cheap source of readily available material.

In future, particularly after the cessation of mining activities, the material that is most abundantly available for the purpose of backfilling of sinkholes is clearly mine tailings and waste rock. Excessive use of the thin layer of available natural soil overlying the dolomites is likely to aggravate sinkhole formation and use of this material as a bulk backfill material is therefore not desirable. Given the abundance of tailings in the area, the study has focused on the impact that backfilling of sinkholes with mine tailings material would have on the aquifer.

3.2. FUTURE USE OF MATERIALS

Inspection of the area reveals that the following materials are typically available within a reasonable distance of the three compartments of concern:

- Gold tailings (various dumps)
- Uranium tailings
- Mine waste rock (various dumps)
- Gold Sand dumps (Randfontein)
- Gypsum (Kynoch fertiliser)
- Natural soils
- Power Station Ash
- Smelter Slag

An evaluation of these materials is presented in Table 5.

TABLE 5: COMPARATIVE EVALUATION OF ALTERNATIVE FILL MATERIALS

MATERIAL	GOLD TAILINGS	URANIUM TAILINGS	MINE WASTE ROCK	MINE SAND DUMPS	GYPSUM	NATURAL CLAY/SOIL	CHROME SLAG
Availability	Abundant	Abundant	Abundant	Abundant	Abundant	Scarce	Abundant
Leachability	Very high Low pH etc.	High but lower w.r.t uranium	Moderate [1]	Very high	Very high, acidic	Low	Inert[2]
Permeability	Low	Low	High	Moderate	Low	Low	High
Dispersivity	Low	Low	Very Low	Low	Very high	Varies	Zero
Method of transport and placement	Mechanical and/or hydraulic	Mechanical and/or hydraulic	Mechanical	Mechanical	Mechanical and/or hydraulic	Mechanical	Mechanical
Shear Strength	25° to 35°	25° to 35°	27° to 40°	25° to 35°	18° to 20°	Varies	25° to 35°
Cohesive Strength	0 Kpa	0 Kpa	0 Kpa	0 Kpa	5 KPa	Varies	0 KPa
Impact of removal from source	Minimal	Minimal	Minimal	Minimal	Minimal	Increased risk of sinkhole formation at source, etc.	Positive
Closest Source	Various tailings dams	Various tailings dams	Various	Randfontein	Potchefstroom	Adjacent to sinkhole	Rustenburg/ Brits area

Note: In some cases amendment of these materials would alter the properties of the material slightly (e.g. the addition of cement to gold tailings would increase the cohesive strength, reduce the dispersivity, permeability and leachability)

From the above analysis, gypsum should not be considered as a potential backfill material. Gold tailings, uranium tailings and mine waste rock comprise the three most convenient sources of material. Of these three, gold tailings has the most significant impact on the groundwater because of its elevated uranium concentrations relative to the mine waste rock and uranium tailings. Use of natural soil from the immediate vicinity of the sinkhole has the limitation that removal of the soil has a negative impact on the area and increases the risk of sinkhole formation. Use of alternative materials such as chrome slag, which can be chemically inert and is produced in relatively large quantities in the Rustenburg area, should be considered.

For the purpose of this study, the impact of backfilling sinkholes with gold tailings has been assessed, as gold tailings will as a general rule have the greatest impact compared to mine waste rock and uranium tailings. If the impact of backfilling with gold tailings is acceptable, backfilling with either or a combination of the other two materials will give rise to a reduced impact.

---

[1] Attributable to low surface area. Leachate quality is however poor

[2] Depends on technology – closed furnace technology can produce virtually an inert slag.

4. IMPACT OF BACKFILLING SINKHOLES ON THE AQUIFER WATER QUALITY

4.1. IMPACT ASSESSMENT APPROACH

The approach used to evaluate the impact of backfilling sinkholes on the dolomite aquifer has been to conduct a generic study rather than a site-specific investigation. The reason for this is that the study is aimed at evaluating the practise of backfilling sinkholes rather than the impact of a particular set of sinkholes or a specific site.

In order to do this, a number of general assumptions needed to be made for the model. These assumptions are listed in Section 4.2. An attempt has been made to make assumptions that are generally applicable and follow a precautionary approach in so far as a more conservative situation, condition or value than that assumed is unlikely to arise.

The modelling phase is described in three sections, namely:

- The field and laboratory testing of gold tailings
- The development and results of the Near Field Model (NFM), and
- The development and results of the Far Field Model (FFM).

The concept of the NFM is described with the aide of Figure 9. A geochemical model capable of modelling thermodynamic and kinetic reactions is used to model the interaction of:

- gases (oxygen and carbon dioxide),
- water which infiltrates through the backfill material at a given rate; and
- solids (tailings minerals, dolomite and wad material) and dissolved species (SO_4, HCO_3, Na, Cl, Mg, Al, Fe, Mn, Si, U, etc.).

The model is used to analyse the sensitivity of the leachate quality to parameters such as the infiltration rate and fugacity. Finally, the leachate is mixed with dolomite water and a set of equilibrium reactions allowed to take place which result in a “mixed” water quality.

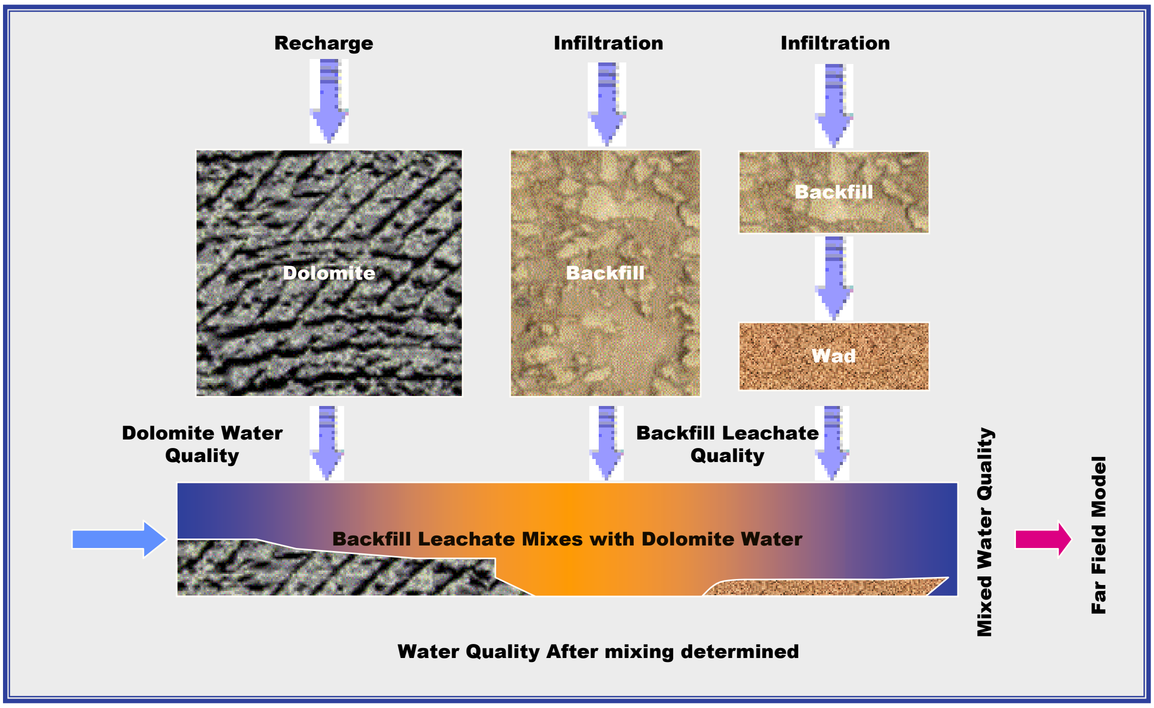


FIGURE 9: **NEAR FIELD MODEL CONCEPT TO DETERMINE CONTAMINANT FLUX FOR FAR FIELD MODEL**

After consideration of the mixed water quality, the contaminant, which is considered to have potentially the most detrimental effect on the aquifer is identified and selected for analysis in the Far Field Model. Up until this stage, the modelling has been restricted in geographical terms to the immediate footprint area of the backfilled sinkholes. The far field model (refer to Figure 10) determines the impact on the aquifer in a broad geographical context and examines the effect of cluster of backfilled sinkholes, advective transport, dispersion, sorption and radioactive decay.

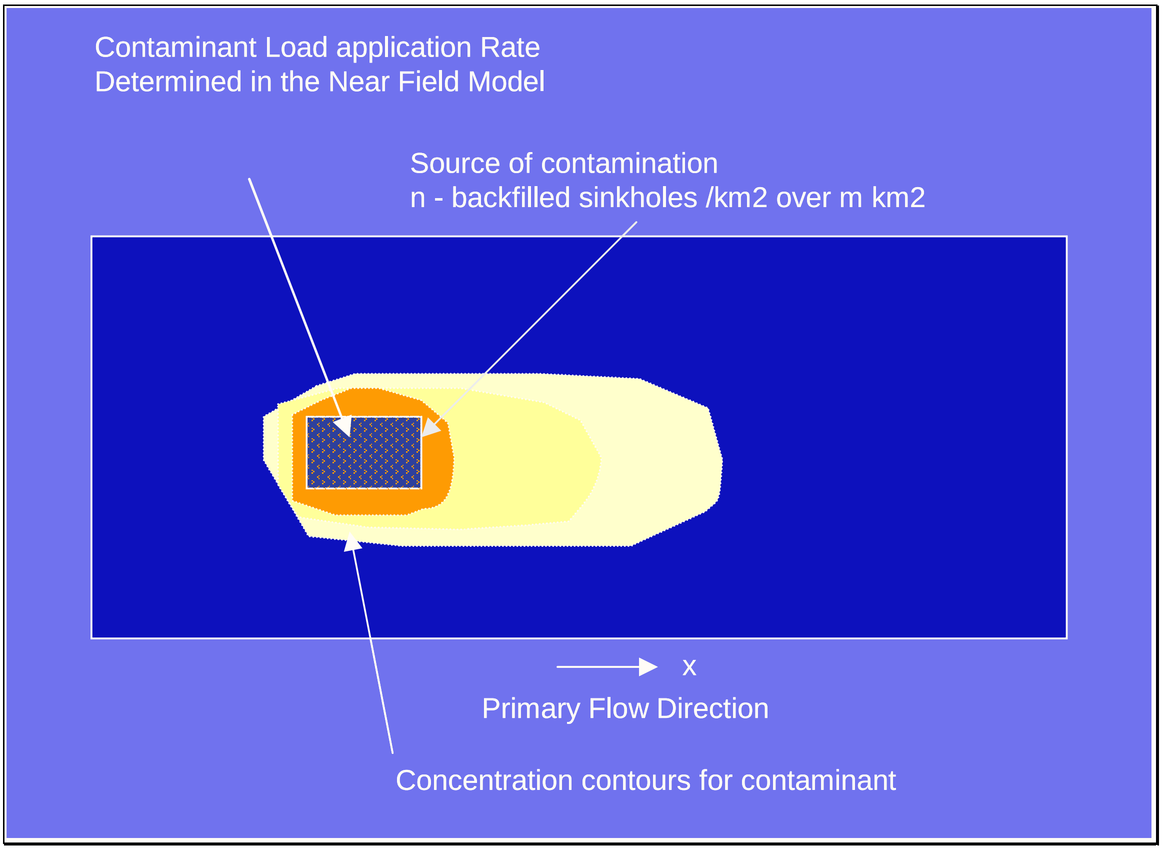


FIGURE 10: **FAR FIELD MODEL CONCEPT**

4.2. GENERAL ASSUMPTIONS

The findings of the previous sections of the project have given rise to a number of assumptions that have been applied in determining the impact of backfilling of sinkholes on the dolomite aquifer. These assumptions may be summarised as follows:

The Dolomite Aquifer

- Pre-mining water levels are likely to re-establish themselves again after mining ceases as a result of the limited permeability of the fractured rock aquifer and relatively small hydraulic gradient between the upstream compartment and the downstream compartment. This implies that the dolomite aquifers will once again become aquifers of major importance and the impact of the backfilling after mining ceases is therefore the most critical period to consider for the de-watered compartments.
- Since little use is made of the water in the dolomite compartments at present, and since water that enters the compartment tends to pass through the mine void as a result of the de-watering process, the focus of modelling should be on the post-mining period when water levels have been re-established.

- While the storativity of the aquifer decreases with depth, the cavernous zone is limited to the top portion of the dolomite only and stored in excess of 50% of the total aquifer volume. An effective aquifer depth of 50m for the cavernous zone has been assumed for the post-mining period.

Sinkhole Characteristics

- Sinkhole activity is likely to increase once the water level re-establishes itself and particularly when the water level passes through the zone of structural support.
- Sinkhole intensity varies across the compartment, sinkholes tend to be concentrated into clusters. The maximum intensity of clusters was found to be about 30 sinkholes per km^2. Thus, based on a factor of 2, the maximum intensity is not likely to increase above 60 per km^2 after re-watering.
- Based on the GIS information made available, the intensity of sinkholes varied from 10/km^2 to 45/km^2 with an average of 30/km^2. For the assessment of the impact resulting from backfilled sinkholes it is recommended that:

  The average current intensity of 30/km^2 be used as the base case

  The current maximum intensity of 45/km^2 as an expected worst case

  The base case sinkhole intensity be doubled to 60/km^2 to simulate excessive sinkhole development on re-establishment of the pre-mining water table.
- Typically, based on the limited data set provided by the FWDWA the aerial extent of sinkholes varies from 365 m^2 to 1170 m^2 with an average of 1050 m^2.

The actual area used in the model was 3906 m^2 based on a finite element size of 62.5 x 62.5 metres.

- The area covered by sinkholes averages 31 500m^2/km^2 (resulting in 3.2% of 1 km^2 being affected by sinkholes).

Backfill Materials

- The most readily available material for backfill, probably the cheapest, and potentially one that has the most significant impact on the aquifer water quality is gold tailings. While other materials including uranium tailings and mine waste rock are also available, they are likely to have a less significant impact on the groundwater if used to backfill sinkholes.

The impact assessment considered gold tailings only. It should be noted that in many cases where sinkholes in the Far West Rand were backfilled with tailings, the tailings backfill was mixed with cement, which stabilises the tailings and reduces the potential environmental

impact of the backfill. The impact assessment considered non-cemented gold tailings as a conservative case.

4.3. CHEMICAL CHARACTERISTICS OF GOLD TAILINGS

4.3.1. ELEMENTAL COMPOSITION OF GOLD TAILINGS

The elemental and mineralogical composition of gold tailings material was taken from literature data. Tables 7 and 8 below show published data on the composition of gold tailings.

TABLE 6: TYPICAL ANALYTICAL VALUES FOR SIGNIFICANT ELEMENTS AND MINERALS IN WITWATERSRAND AURIFEROUS REEF MATERIAL (AFTER FEATHER & KOEN, 1975, MINERALS SCI. ENG. VOL. 7, NO. 3, PP. 189 – 224)

Element	Sample 1	Sample 2	Element	Sample 1	Sample 2
Au [mg/ℓ]	50	44	Quartz [%]	88.3	88.9
Ag [mg/ℓ]	8	5	Titanium [%]	0.1	0.1
U_3O_8 [mg/ℓ]	870	290	Zircon [%]	0.1	0.2
Muscovite [%]	4.4	3.0	Chromite [%]	0.2	0.2
Pyrophyllite [%]	0.1	0.2	Pyrite [%]	6.6	3.2
Chlorite [%]	0.8	4.9			

TABLE 7: APPROXIMATE MINERAL COMPOSITION OF THE TAILINGS FROM A TYPICAL TAILINGS DAM AND ESTIMATED RANGES CONTAINED IN SUCH A SLIMES DAM (FROM AVMIN REPORT: LGM/MINLAB/659 – TARGET MINE, FREE STATE)

MINERAL	MASS [%]	
	SPECIFIC SAMPLE	RANGE
Quartz	75	25-90
Muscovite	10	2-20
Pyrophyllite	10	5-75
Chlorite	5	1-10
Pyrite	Nd	<5
Iron oxide hydroxide hydrates	Nd	<5
Iron sulphate hydrates	Nd	<5
Calcium carbonate	Nd	<0.5
Calcium sulphate hydrates	1	0.5-2
Sodium chloride	0.1	<0.2

The above data was used for the Near Field Model in modelling the leachability of the tailings. For comparative purposes tailings samples from a tailings dam on one of the mines in the Far West Rand

(Westdriefontein No. 4 Tailings dam) were collected and analysed in April 2002. These samples were analysed for their respective elemental composition by XRF and for their leachable elements by SA_AR leach test. The analysis was undertaken by SGS Lakefield (XRF and SA_AR Leach Solution) and the ISCW at the ARC in Pretoria (Analysis of the SA_AR by ICP-MS). The analytical results are given in Table 9 and 10.

TABLE 8: ELEMENTAL COMPOSITION OF TAILINGS SAMPLES FROM TD WEST DRIEFONTEIN NO.4 (ANALYSED BY XRF)

Element	**Sample 1**	**Sample 2**	**Sample 3**	**Element**	**Sample 1**	**Sample 2**	**Sample 3**
SiO_2 [%]	76.8	80.0	79.3	MnO [%]	0.06	0.19	0.05
TiO2 [%]	0.39	0.31	0.39	P2O5 [%]	0.04	0.04	0.06
K2O (%]	1.50	1.13	1.28	Na2O [%]	<0.05	0.06	0.08
MgO [%]	1.68	0.99	1.65	Cr2O3 [%]	0.04	0.03	0.04
Al2O3 [%]	9.11	7.63	8.62	V2O5 [%]	0.01	<0.01	0.01
Fe2O3 [%]	5.66	3.78	4.50	LOI [%]	3.25	3.74	2.44
CaO [%]	0.64	1.21	0.56	Sum [%]	99.0	99.3	99.6
U_3O_8 [mg/kg]	37	53	18				

Sample 1 taken at 1 m depth by hand auger on top of the TD
Sample 2 taken at 2.7 m depth by hand auger at the base of the TD
Sample 3 taken as a grab sample at the incoming pipeline (fresh tailings)
LOI – Light on ignition; Sum parameter for organic content

4.3.2. GOLD TAILINGS LEACHABILITY

The leachability of the gold tailings material was determined from two sets of samples. The first set of samples was taken from Tailings dam No.4 at the Westdriefontein mine by use of a hand auger, while the second set of samples was taken as composite samples by hand auger from a sinkhole that had been hydraulically backfilled in 1970 with gold mine tailings (“gold tailings”). The backfilled sinkhole was hand augered to a final depth of 3.2 m and the composition of the tailings material was analysed by South African Acid Rain Leach test of sub samples collected every 0.5 metres. The results of the analysis from the tailings dam samples are presented in Table 10 and the analytical results from the 30-year-old backfill material are presented in Table 9.

TABLE 9: LEACHABLE ELEMENTS OF TAILINGS SAMPLES FROM TD WESTDRIEFONTEIN NO.4 (ANALYSED BY SA_AR LEACH AND ICP-MS)

		SAMPLE 1	**SAMPLE 2**	**SAMPLE 3**	**COMPARISON OF S3 TO S1&2**
Dilution Factor		2	2	2	
Element	Isotope	[ug/ℓ]	[ug/ℓ]	[ug/ℓ]	
Lithium	Li 7	6.01	4.65	5.10	O
Beryllium	Be 9	0.95	0.99	1.63	O
Boron	B 11	33.3	32.5	111	O
Titanium	Ti 48	600	1047	497	O
Vanadium	V 51	0.67	0.74	0.99	O
Chromium	Cr 52	0.90	0.72	2.70	O
Manganese	Mn 55	1017	Over range	1014	O
Cobalt	Co 59	20.3	46.8	40.8	O
Nickel	Ni 60	101	129	94.0	O
Copper	Cu 65	17.7	14.9	7.69	O
Zinc	Zn 66	338	209	203	O
Arsenic	As 75	1.17	23.0	12.5	O
Bromine	Br 79	36.0	32.8	107	O
Selenium	Se 82	2.54	1.69	1.32	O
Strontium	Sr 88	290	293	453	O
Molybdenum	Mo 95	1.20	1.90	0	-
Cadmium	Cd 114	2.65	1.12	0.94	O
Tin	Sn 120	1.91	1.68	0.87	O
Antimony	Sb 121	0.73	2.61	4.61	O
Tellurium	Te 126	0.51	0.80	0.53	O
Iodine	I 127	5.80	3.47	0	-
Barium	Ba 138	79.3	91.0	116	O
Lanthanum	La 139	1.20	1.41	0.36	O
Tungsten	W 184	0.37	0.46	0.85	O
Platinum	Pt 195	0.64	0.56	0.22	O
Mercury	Hg 202	37.1	34.0	1.88	-
Thallium	Tl 205	0.04	0.07	0.08	O
Lead	Pb 208	4.79	10.1	9.93	O
Bismuth	Bi 209	0.12	0.12	0	-
Uranium	U 238	335	579	9.10	--
* = Semi-Quantitative					

O	no significant change in elemental concentration		
++	increase by 10 - 100 times	--	decrease by 10 - 100 times
+	Increase by <10 times	-	decrease by <10 times

Sample 1 taken at 1 m depth by hand auger on top of the TD

Sample 2 taken at 2.7 m depth by hand auger at the base of the TD

Sample 3 taken as a grab sample at the incoming pipeline (fresh tailings)

The last table column shows a comparison of elemental concentrations between fresh and weathered tailings material in the TD

The comparison of the residual tailings material (S1 & S2) with the fresh tailings material (S3) showed generally very little difference between the samples.

- The final paste pH of the SA_AR for the samples showed a pH of 5.28 (S1) and 5.67 (S2) for the residual samples compared to pH 5.60 (S3) for the fresh sample. This indicated very little difference in the acid formation for the respective three samples.
- The concentrations in the leached elements for the three samples is variable to some extent but generally quite similar (less than 10x times difference in the concentration between the respective samples was observed for most of the elements)
- Some of the elements in the leachate from the fresh tailings material are lower than in the residual samples. These were molybdenum, bismuth, iodine, mercury and uranium.

The leachate quality of the tailings dam samples is generally good with the exception of manganese (not toxic), mercury (potentially toxic) and uranium (potentially toxic). The elevated concentrations of mercury and uranium in the tailings leachate would render the leachate unsuitable for human consumption.

The backfill material from the sinkhole

During the sample collection from the backfilled sinkhole a visual difference was observed between the top sample (0.5 m depth) and the samples from the underlying material (1.0 to 3.2 m depth). All samples except the top sample showed a grey colour, while the top sample showed a yellow to light brown colour typical of oxidised gold tailings. This indicated that the top half metre of the tailings material, which has been in direct contact with the atmosphere for the past 30 years, has weathered to some extent.

The weathering of the tailings material causes the formation of acid seepage due to the oxidation of sulphides in the presence of water and oxygen, which in turn will increase the breakdown of the mineral structure of the tailings material with subsequent leaching of contaminants from the tailings material. To prove the point a comparison of the analytical results for the top sample with the results from the deeper samples has been undertaken (refer to the last column in Table 10).

TABLE 10: COMPOSITION OF LEACHATE FROM TAILINGS BACKFILL (DETERMINED BY SA_AR LEACH TEST AND ICP-MS)

Element [mg/ℓ]	Sample 1	Sample 2	Sample 3	Sample 4	Sample 4	Sample 5	Comparison S1 to S2-5
Depth [m]	0.5	1.0	1.5	2.0	2.75	3.20	
Al	6.4	<0.15	<0.15	<0.15	<0.15	<0.15	++
As	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	O
B	0.19	0.16	0.17	0.18	0.15	0.11	O
Ba	0.19	0.22	0.12	0.13	0.12	0.30	O
Bi	<1.1	<1.1	<1.1	<1.1	<1.1	<1.1	O
Ca	45	45	78	59	53	79	-
Cd	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	O
Co	0.09	0.37	<0.07	0.08	0.08	0.07	O
Cr	<0.07	<0.07	<0.07	<0.07	<0.07	<0.07	O
Cu	0.14	<0.05	<0.05	<0.05	<0.05	<0.05	+
Fe	7.8	0.82	0.12	0.20	0.31	0.10	++
K	<1.4	3.9	2.3	2.7	2.8	1.9	-
Li	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	O
Mg	2.8	18	11	11	5.0	4.4	-
Mn	0.16	9.5	1.8	1.9	1.6	1.5	-
Mo	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	O
Na	2.2	2.0	2.4	5.5	5.6	3.6	O
Ni	0.15	0.17	<0.13	<0.13	<0.13	<0.13	+
P	<1.2	<1.2	<1.2	<1.2	<1.2	<1.2	O
Pb	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	O
S	82	59	50	43	39	22	+
Sb	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	O
Si	1.4	1.2	2.4	1.0	2.5	0.82	O
Sn	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12	O
Sr	0.04	0.14	0.10	0.09	0.10	0.11	-
Ti	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	O
V	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	O
Zn	0.37	0.53	0.40	0.57	0.43	0.48	-
Zr	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	O
Ag	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	O
Hg	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	O
Se	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	O
Ph	3.1	5.6	6.0	5.9	5.6	6.0	--
T Alk	<10	34	88	73	50	137	--
F	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	O
SO_4	278	152	120	104	104	58	+
Cl	1	1	1	<1	2	2	O
CN	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	O
NO_3	12	12	12	12	10	13	O
PASTE pH	2.4	7.4	7.9	7.8	7.8	7.8	--

Element [mg/ℓ]	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 4**	**Sample 5**	**Comparison S1 to S2-5**
Depth [m]	0.5	1.0	1.5	2.0	2.75	3.20	
PASTE Eh	537	289	235	256	275	296	++

O	no significant change in elemental concentration		
++	increase by 10 - 100 times	--	decrease by 10 - 100 times
+	Increase by <10 times	-	decrease by <10 times

The last table column shows a comparison of elemental concentrations between the aerobic top layer and the underlying anaerobic layers of tailings material in the backfilled sinkhole

The comparison of the analytical results from the top sample (S1) with the deeper samples (S2-S5) showed the following:

- The paste pH of the top sample was acidic indicating that acid formation in the top layer of the sinkhole backfill is occurring at present
- Some of the metal concentrations in the top layer are elevated (particularly iron and aluminium) indicating that the residual acid in the top layer caused the dissolution of metal compounds resulting in higher concentrations in the leachate
- While the concentrations of the major cations in the leachate are fairly similar for all deeper samples, the cations in the leachate of the top sample show the lowest concentration. This indicates that leaching of the major cations from the top layer into the underlying material has occurred in the past.

The oxidation of sulphide minerals in the top layer of the tailings material increases the solubility of metal compounds containing elements such as iron and aluminium, which ultimately results in the weathering of a narrow band of the tailings material in direct contact with the atmosphere and consequential loss of material from these layers. However, this weathering process is very slow as only 0.5 metres has been affected by oxidation over a period of 30 years.

It can be assumed that the oxidation of the backfill material will continue and the depth of oxidation will increase with time. However, as the depth of oxidation increases the oxygen flux into the material will decrease, therefore significantly reducing the rate of oxidation in the material. This means that the oxidation and weathering of the next 0.5 m of tailings material will take significantly longer than 30 years. It is likely that at depth of less than 2 metres the oxidation rate will become so low that for all practical purposes the oxidation of the tailings material through oxygen flux from the surface has come to an end.

- The backfill material deeper than 0.5 metres has not been affected by the weathering process. Some of the leachate concentrations of the 1 metre sample are elevated in comparison to the samples below (1.5 – 3.2 m). This would indicate that these contaminants leached from the top layer are retained in the underlying tailings in direct contact with the weathered material.

4.3.3. RADIOLOGICAL CHARACTERISTICS OF TAILINGS

Radionuclides in the gold tailings

Limited radiological analyses of tailings material for uranium and radon were undertaken from 13 mines in the Far West Rand. The results of the uranium analyses conducted on tailings samples are presented in Table 11 below.

TABLE 11: RADIOLOGICAL ANALYSES OF GOLD MINE TAILINGS FROM THE FAR WEST RAND (WYMER, 2000)

MINE	TOTAL TAILINGS PRODUCED [Tons]	URANIUM 238 [Bq/g]
Doornfontein	52 683 000	1.314
Blyvooruitzicht	79 365 000	0.394
West Driefontein	93 540 000	1.558
East Driefontein	52 005 000	1.455
Deelkraal	20 235 000	0.350
Elandsrand	26 316 000	0.420
Western Deep Levels	122 827 000	1.429
Kloof	48 423 000	0.766
Leeudoorn	2 740 000	1.707
Libanon	60 388 000	1.452
Venterspost	69 184 000	1.220
Elsburg	4 881 000	1.707
Western Areas	95 307 000	3.493
TOTAL	727 894 000	
Tons-weighted mean U238 activity		**1.471**

The radiological activity of uranium (U238) in the tailings material from the respective mines varied from 0.394 to 3.493 Bq/g with a mean of 1.471 Bq/g (tons-weighted average). This compared to a mean of 1.707 Bq/g (tons weighted average) for radium (Ra226).

Decay Series of U238

As demonstrated by the data above the gold tailings from the Far West Rand contain sufficiently high concentrations of uranium to result in mine waste material with radiological activity. The specific activity of U238 is 12 455 Bq/g with a half-life of 4.5 $*10^9$ years (Sociamedia, 2000). The radiological activity of the tailings material from the Far West Rand is about 10 000 times lower (0.01%) than that of U238. U238 is the parent nuclide of a decay series, which is given in Table 12 below.

TABLE 12: DECAY SERIES OF U238 (SOCIAMEDIA, 2000)

Nuclide	Half-Life	Radiation *)
U238	$4.468*10^9$ years	Alpha
Th234	24.1 days	Beta
Pa234m	1.17 minutes	Beta
U234	244 500 years	Alpha
Th230	77 000 years	Alpha
Ra226	1 600 years	Alpha
Rn222	3.8235 days	Alpha
Po218	3.05 minutes	Alpha
Pb214	26.8 minutes	Beta
Bi214	19.9 minutes	Beta
Po214	63.7 microseconds	Alpha
Pb210	22.26	Beta
Bi210	5.013 days	Beta
Po210	138.378 days	Alpha
Pb206	Stable	

only major decays shown

*) in addition all decays emit gamma radiation

Health Hazards from Radionuclide Exposure

From the U238 decay series, it is evident that for majority of the time uranium would be in existence as U238 followed by U234. In comparison to uranium all other nuclides with half-lifes in excess of days including thorium, radium, radon and lead have very short half life spans. The principal radiation hazards from uranium containing tailings material is related to:

- Emissions into the atmosphere from radon gas
- Windblown dust
- Contaminated leachate and seepage into surface water and groundwater

The alpha radiation of the 8 alpha emitting nuclides in the U238 series present a radiation hazard by external radiation on ingestion and inhalation. The gamma radiation mainly of Pb214 and Bi214, together with the beta radiation of Th234, Pa234m, Pb214, Bi214 and Bi210 present an external radiation hazard. For ingestion and inhalation, also the chemical toxicity of uranium has to be taken into account (Sociamedia, 2000). Within the scope of this study, the only main exposure pathway to radionuclides is the ingestion of contaminated groundwater and/or surface water due to radionuclide contaminated leachate from tailings backfilled sinkholes entering these water resources.

While toxicity information is available for radium and thorium, a number of studies have been undertaken concerning the radiological and chemical toxicity of uranium taken in by oral ingestion:

- A “minimal risk” level for intermediate ingestion proposed by ATSDR (1997) is an oral uptake of 1 ug of uranium per kg body weight per day, based on a study (Ortega, 1989) with rats at uptake of 1.1 mg per kg per day.
- Jacob (1997) proposed a “tolerable” uptake of 0.7 ug per kg per day based on adverse effects observed in a study (Mc Donald-Taylor, 1992) with kidneys of rabbits at resorption rates of 3.2 ug U per kg per day.
- The World Health Organisation has established a tolerable Daily Intake of 0.6 ug/kg body weight per day based on a study (Gilman 1998) with kidneys of rats at uptakes of 60 ug U per kg per day.

A comparison of the respective studies is given in Table 13 below. Current drinking water quality guidelines for uranium vary from 2 ug/ℓ (WHO 1998, provisional guideline), to 10 ug/ℓ (Health Canada, 1999), to 30 ug/ℓ (USEPA, 2000) to 70 ug/ℓ (South African Water Quality Guidelines, 1998).

TABLE 13: INGESTION OF URANIUM (BASED ON CHEMICAL TOXICITY)

Study	**TDI [ug/(kg*d)]**	**ALI [mg]**	**DDWC [ug/ℓ]**
ATSDR, 1997	1	25.6	51
Jacob, 1997	0.7	17.9	36
WHO, 1998	0.6	15.3	31

TDI = Tolerable Daily Intake

ALI = Annual Limit on Intake based on 70 kg body weight

DDWC = Derived Drinking Water Concentration based on 500 L/a

The radiological hazard regarding the ingestion of uranium for the public has been established for different kinds of uranium ranging from pure natural uranium to depleted recycled uranium (0.2%). The data are presented in Table 14 below.

TABLE 14: INGESTION OF URANIUM (BASED ON RADIOLOGICAL HAZARD)

	Dose Factor [mSv/g]	ALI [mg]	DDWC [ug/ℓ]
Natural uranium with progeny	31.7	31.5	63
Pure natural uranium	1.23	813	1630

ALI = Annual Limit on Intake based on 1 mSv per annum

DDWC = Derived Drinking Water Concentration based on 1 mSv/a, 500 L/a

In comparison the DDWC for the radiological hazard is between 1.8 to 45.8 times higher than the average DDWC (36 mg/ℓ) for the chemical toxicity of uranium. This means that the risk related to chemical toxicity from uranium through the ingestion of drinking water is up to 46 times higher than the comparative radiological risk.

In summary the following applies for the radionuclide health risk assessment:

Uranium is present for the majority of the time in the U238 decay series,

In the decay of natural uranium Th234 and Pa234 grow in within a few months, where after the activity remains stable for more than 10 000 years,

Comparative chemical toxicity and radiological hazard data are available for uranium only,

Therefore uranium was selected as the respective radionuclide for the groundwater quality impact assessment.

Leaching of uranium from uranium containing tailings material

The geochemical modelling of the Near Field Model (refer to Appendix B) indicated that the range of the uranium concentration in the leachate arising from the tailings backfill may vary between 0.3 to 300 mg/ℓ. Experiments with in-situ leaching wells for the production of uranium showed that the uranium concentration in the solution produced from these wells depends on a number of parameters. The initial concentration from an individual well soon peaked within a few days at values of typically 300 to 600 mg/ℓ and then declined rapidly. The decline slowed down as the uranium concentrations reached 30 – 50 mg/ℓ. Wells were usually shut down when the concentrations reached 10 – 30 mg/ℓ after 8 –18 months of operation (IAEA, 1989, p.17).

The rather large range of uncertainty needed to be reduced by at least two orders of magnitude to allow obtaining results, which were not wide open to discussion. Therefore, a number of tailings samples were collected from the Westdriefontein tailings dam No. 4 to determine the uranium leaching concentrations, which can be expected from tailings material being used for the backfilling of the sinkholes. The samples were analysed for total uranium (by XRF) and leachable uranium (by SA_AR Leach test) at SGS Lakefield Laboratories in Johannesburg.

A comparison of the uranium concentration in the tailings material (obtained by XRF analysis) and the resulting leachate quality (obtained by SA_AR leach test) is presented in Table 15.

TABLE 15: URANIUM CONCENTRATION IN THE TAILINGS SAMPLES FROM TAILINGS DAM WESTDRIEFONTEIN NO. 4 – COMPARISON OF TOTAL U (ANALYSED BY XRF ANALYSIS) AND LEACHABLE U (ANALYSED BY SA_AR LEACH TEST AND ICP-MS)

SAMPLE	TOTAL U [mg/kg]	LEACHABLE U [ug/ℓ]	U LEACHED [%]
1	37	335	33.6
2	53	579	43.7
3	18	9.1	2.0

Sample 1 taken at 1 m depth by hand auger on top of the TD
Sample 2 taken at 2.7 m depth by hand auger at the base of the TD
Sample 3 taken as a grab sample at the incoming pipeline (fresh tailings)

Note: the SA-AR Leach Test uses 50 g of dry solids in 2 000 ml in water; this is equivalent to 112 pore volumes of water. To flush all the uranium from sample 1 would take at least 112 / 0.336 = 333 pore volumes. To calculate the time period required to complete flush the material will depend on the water flux through the material

The uranium concentration in the leachate of the respective tailings samples varied between 9 ug/ℓ and 579 ug/ℓ, while the total uranium concentration in the tailings material varied between 18 and 53 mg/kg. It appears that the uranium leachability from the residual samples (S1 & S2) is considerably higher (about 34 to 44% of the total uranium is leached) than the uranium leachability of the fresh tailings sample (about 2.0% of the total uranium is leached).

4.3.4. CONCLUSIONS

The following conclusion are drawn from the field and laboratory testing and analysis of available data:

- An existing tailings dam was sampled and analysed. The analysis of residual and fresh tailings samples showed little different in the elemental composition and the leachable elements of the tailings material. The seepage arsing from the tailings material is not fit for human consumption due to elevated mercury and uranium concentrations.
- An existing backfilled sinkhole was examined and sampled. It was observed that limited oxidation of the top section of the backfill, which is exposed to the atmosphere, did occur over a period of 30 years;
- A distinct zone of oxidation was observed, which is however limited (about 0.5 m thick) compared to residual backfill material (in excess of 3.5 m);
- For the purpose of assessing the impact on the groundwater quality due to radionuclides being leached from the sinkhole backfill, uranium was selected as the radionuclide to be considered;
- Leach tests performed on gold tailings samples taken from an operational tailings dam have indicated that the leachable uranium concentration from the tailings material varies between 0.09 to 0.58 mg/ℓ with an expected average of 0.30 mg/ℓ.

4.4. THE NEAR FIELD MODEL

4.4.1. OBJECTIVE

The Near Field Model (NFM) determines the mass flux of contaminants per unit area of backfilled sinkhole that enters the dolomite aquifer from a backfilled sinkhole.

The resulting concentration of a contaminant of concern will be used in the Far Field Model as the initial point load, by multiplying the concentration C, by the flux, q. The flux q is a function of the sinkhole area.

4.4.2. THEORY

Flow Paths

Figure 11 presents a conceptual cross section through a backfilled sinkhole. Conceptually, water enters through the top surface of the backfill and percolates through the fill. At some point, it leaves the backfill and either enters the dolomite aquifer directly, or passes through a zone of dolomite, wad and chert material before entering the aquifer. There are a wide variety of variations to the idealised paths described above (e.g. Capillary rise) but for the purpose of this impact assessment the above two paths adequately describe the movement of water from surface to the aquifer.

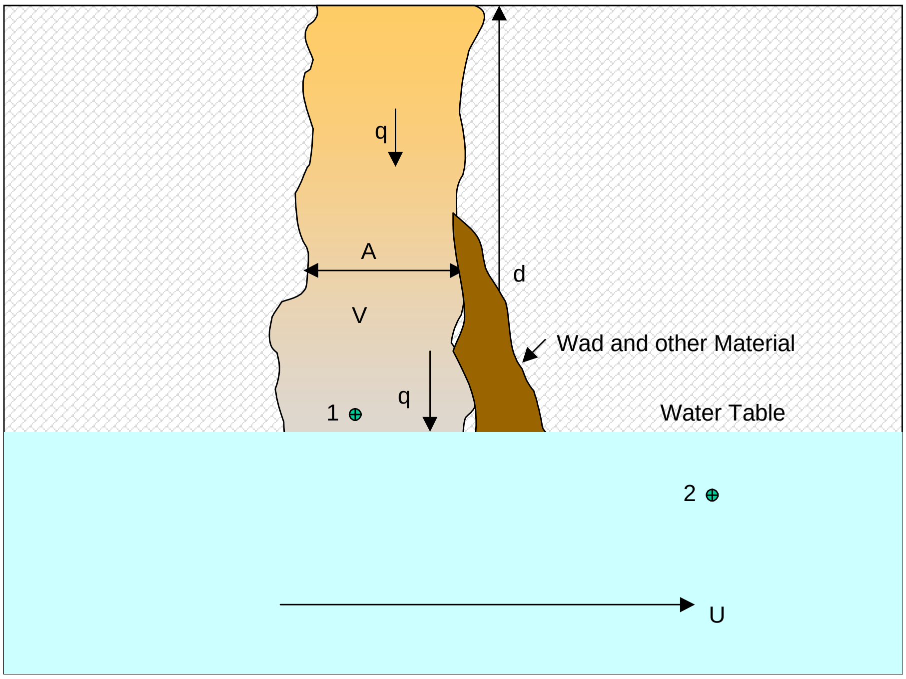


FIGURE 11: DERIVATION OF THE LEACHATE VOLUME FUNCTION

Flow Rates

The rate at which water percolates down through the backfill is practically controlled by:

- The permeability of the backfill, which for gold tailings is generally of the order 0.000009 m/day to 0.009 m/day.
- The availability of water, which might vary from a relatively small percentage of MAP (e.g. 1%) to significantly more than MAP in the event that the backfilled sinkhole forms a depression in a drainage channel for example.

Sulphide Oxidation, Acid Generation and Neutralisation

The concentration of a particular contaminant in the backfill leachate is a complex function of a number of physical and chemical processes. The presence of sulphide-containing minerals in the backfill creates a localised environment with a high potential for acid generation. Oxidising water, percolating through the material oxidises sulphide minerals, creating acidic conditions. The acidity may then be neutralised by the presence of minerals such as carbonates and to a lesser extent, Fe and Al hydroxides, aluminosilicate minerals and also the adsorption of H^+ ions onto mineral surfaces.

Geochemical Zones in the Backfill

Blowes and Jambor[i] evaluated the pore water chemistry of sulphide tailings at a Zn-Cu mine in Quebec and describe three zones within the tailings. Oxidation of the sulphide minerals and subsequent dissolution gave rise to a zone depleted of sulphides within the top layer. In the intermediate layer, oxidation of sulphides continued. The extent of the intermediate zone is dependent on the availability of oxygen, which is in turn dependent on the degree of saturation and particle size distribution. Below the intermediate zone was an unoxidised zone where neutralisation reactions played a significant role but oxidation of the sulphide minerals was negligible. A similar series of zones might be expected for the backfilled sinkholes.

Visual observation of the material brought to surface during the hand auguring exercise conducted on the backfilled sinkhole (backfilled in 1970), revealed similar zones, as indicated by the colour of the tailings. Below a depth of approximately 1m (the lower zone) the tailings was grey (typical of fresh un-oxidised gold tailings) whereas tailings in the intermediate zone was yellow. A top zone was clearly discernable, although it was characterised by salt encrustation as a result of capillary rise rather than a well flushed top zone as might arise in a wetter climate.

For the tailings material studied by Blowes and Jambor, the average sulphide content was 50wt% and the carbonate content 1,5wt%, i.e. the acid generating capacity far exceeded the neutralising capacity. It was calculated that the acid generated in 1m of tailings required a 25m-flow path downstream of the acid generating zone to be neutralised. For this reason the acid plume could easily move out of the zone of active acid generation to the lower zone and the natural material beneath. While the dolomite aquifer has enormous buffering potential to the extent that and acid plume is unlikely to extend far from the backfilled sinkhole, it is possible that significant dissolve metal loads could enter the dolomite aquifer.

Minerals likely to precipitate and therefore play an important role in limiting the concentrations of major cations and anions (including Fe^{2+}, SO_4^{2-}, Ca^{2+}, Na^+ and K^+) in the leachate include: geothite (∀-FeOOH), lepidocrocite (-FeOOH), ferrihydrite ($Fe[OH]_3$), jarosite ($KFe_3[SO_4]_2[OH]_6$), and gypsum ($CaSO_4.2H_2O$) (Deutsch, 1997, pp 191).

Ion exchange, acid neutralisation, precipitation and adsorption/desorption alter the composition of leachate as it leaves the backfill and enters the dolomite zone. Since certain of these processes take place rapidly compared to the travel time, the chemistry of pore water may be expected to change significantly within a relatively short distance from the backfill, or in the case of backfill that is submerged, possibly even before the contaminants leave the backfill. At some point (refer to Point 2 in Figure 11), the leachate will be neutralised. Less soluble species are likely to have precipitated out of the solution.

Oxygen Fugacity

A key aspect of the geochemistry is the role that the tailings and surrounding material plays in limiting the oxygen flux to the sulphide-containing tailings particles. Three oxygen transport mechanisms are relevant namely:

- Transport as dissolved oxygen with percolating water
- Diffusion of oxygen from the surface downwards through the primarily air-filled void spaces, and
- Barometric pumping in which atmospheric pressure within the tailings pore spaces continually attempts to equalise pressure at ground surface by drawing in or expelling air via the many shrinkage cracks present in the tailings.

The oxygen transport mechanisms described above give rise to various profiles of oxygen fugacity versus depth from surface. While the depth of each zone may vary significantly, the backfill may be described as comprising two zones, namely:

- An aerobic zone in which the oxygen fugacity (f $O_2(g)$) may vary between 0.1 and 1 (atmospheric);
- An anaerobic zone in which the oxygen fugacity is likely to be 0.1 and lower.

Significant Geochemical Reactions

A comprehensive geochemical model to predict the release of the contaminants to form leachate and the effect of the dolomite water and associated materials (e.g. wad, dolomite and chert) on the leachate needs to include:

- Gaseous / water reactions
- Water/ rock processes controlling the solution composition.

Significant gaseous /water reactions for the dolomite water chemistry include:

- Speciation of dissolved carbon dioxide. The partial pressure of carbon dioxide will influence the speciation of carbonates. The partial pressure of carbon dioxide is influenced by the organic matter present in the vadose (unsaturated) zone and oxygen. These react to form carbon dioxide and water, thereby raising the partial pressure of carbon dioxide within the pore spaces.

Water/Rock Processes controlling solution composition include:

- pH and redox-dependent reactions. Acidic leachate will be neutralised on entering the dolomitic zone resulting in the precipitation of much of the metal as secondary minerals.

- Adsorption/desorption reactions, including ion exchange and surface complexation which will be prevalent within the materials with a high surface area including in particular the tailings and the clayey wad material that is found in the weathered zones.

- Mineral precipitation and dissolution reactions.

The reactions described above take place along the flow path. Some reactions will occur virtually instantaneously, while others will take place over a prolonged period and hence long distance from the point at which the leachate entered the aquifer.

The use of equilibrium constants and distribution coefficients to calculate solution concentration as a function of mineral solubility, adsorption/desorption, and ion speciation/complexation, assumes that the system reaches equilibrium. This assumption is generally reasonable for reactions that take place in solution, with the exception of redox reactions, which tend to take place very slowly, resulting in a much longer flow path before redox equilibrium is reached.

The assumption that equilibrium is reached may also be considered valid for adsorption of solutes onto solid surfaces within the timeframe of groundwater residence times. De-sorption is generally considered to be much slower than absorption, except in the case of cation exchange reactions, which result in dis-equilibrium of the groundwater. For this reason it is necessary to choose only those minerals and redox pairs that are reactive and can equilibrate with the system.

4.4.3. NFM METHOD

The computer code “The geochemists workbench, Version 3.0 was used to for the NFM.

For this purpose the geochemical modelling package “The Geochemist’s workbench, Version 3.0” was used to model the rapid reactions that took place on contact of the leachate with the dolomite water.

A detailed methodology description is given in the report entitled “Geochemical Modelling of the effect of tailings backfill used in dolomitic cavities on the ground water quality in the Far West Rand – Near Field Model” which is included in Appendix A to this report.

The NFM model is described with the aide of Figure 9 as follows:

- Water enters a unit area of tailings backfill and is allowed to react with the tailings;
- The water percolates through the tailings and enters the unsaturated zone above the dolomite water table where it is allowed to further react with dolomite material in the unsaturated zone;
- The leachate enters the dolomite aquifer and reacts with this water allowing (if necessary) precipitation of any super-saturated salts on contact with the mass of neutral dolomite water.

The resulting aqueous phase concentrations of each element are determined together with the speciation. The change (accumulation or depletion) of solid phase components is also tracked to monitor the depletion of minerals etc.

The sequence of events in the NFM is as follows:

- ➢ Step 1: Water in contact with the gold tailings backfill in the sinkhole comes to equilibrium.
- ➢ Step 2: Reaction of the seepage with host rock in the unsaturated zone (dolomite); Dissolution of dolomite and neutralisation of seepage water may occur, if the seepage is acidic. Neutral seepage passes the unsaturated zone without major chemical reactions.
- ➢ Step 3: Mixing of the sinkhole seepage with the water from the dolomite aquifer.

- Geochemical modelling of the following was undertaken:
    - ➢ Water in contact with backfill material in sinkhole – Aerobic zone
    - ➢ Water in contact with backfill material in sinkhole – Anaerobic zone
    - ➢ Migration of seepage through the unsaturated zone
    - ➢ Interaction between seepage and saturated zone (dolomite aquifer)

The leachate mixing model will initially allow any mineral to form and to precipitate. Should a mineral form or precipitate, which in reality is unlikely to occur or which, based on literature, would take very long to precipitate (in comparison with groundwater residence times), further model runs will be undertaken and the formation and precipitation of these minerals will be suppressed.

The most important considerations for the NFM are given below.

4.4.4. NFM LIMITATIONS

The model assumes constant oxygen and CO_2 fugacity within each zone.

4.4.5. NFM COMPONENTS

Recharge of the Model Sinkhole

- The first component of the model comprises rainwater in contact with the backfill (tailings material) under atmospheric conditions. Wad material is represented as manganese oxide and iron oxide minerals.

Gold Tailings Backfill Model - Aerobic Zone

- The first component of the model comprises rainwater in contact with the backfill (tailings material) under atmospheric conditions.

Gold Tailings Backfill Model- Anaerobic Zone

- The second component of the model comprises the seepage water from the aerobic zone in contact with the backfill (tailings material) under anaerobic conditions.

Wad Material / Unsaturated zone

- Wad material is represented as manganese oxide and iron oxide minerals. The unsaturated zone is represented by dolomite. The seepage arising from the anaerobic backfill will be in contact with the solid phase (wad and dolomite) in the unsaturated zone.

Leachate and Dolomite Water Mixing Model

- The results of the leach tests were used as the basis for the leachate chemistry. 1 part of leachate was mixed with x part dolomite water and the effect of precipitation was determined using the geochemical model.

- The equilibrated solution was then mixed with a set ratio of volumes with the leachate solution.

4.4.6. GEOCHEMICAL MODEL VERIFICATION

Geochemical modelling of a particular system does not result in unique solutions. What complicates the outcome is the degree to which geochemical modelling routines have been calibrated. It is therefore imperative that the role of the sensitive parameters is understood and their influence on the modelling results be quantified. The following exercises were conducted to verify the model.

For the model verification the following modelling exercises were undertaken:

- The effect of pyrite oxidation on the pH in dolomitic groundwater in a closed system vs. an open system

- The effect of rock wall buffering
- The effects of changing activity and fugacity on pyrite dissolution
- The effects of changing activity and fugacity on calcite dissolution
- Mobility of potentially toxic heavy metals
- Mobility of uranium species

The verification step confirmed that:

- The system is controlled by the availability of oxygen. In a closed system, where oxygen is only provided as dissolved oxygen entering the backfill with the water inflow, pyrite oxidation is limited and the pH of the system will only drop marginally. In a system open to the atmosphere pyrite oxidation will occur at a much higher rate until pyrite is depleted;
- During the oxidation of pyrite the sulphate concentration will increase significantly, while the iron concentration will only increase marginally due to the formation of secondary minerals. If the pyrite oxidation is not limited due to oxygen availability the pH will drop from neutral to about pH 2.5;
- Other factors influencing the modelling results are the mineral composition of the tailings material used for backfill and the surface area of such material. The variation in the surface area of tailings material is generally limited and the significance of this factor is considered small. The mineral composition of the tailings material on the other hand could be highly variable (concerning the absence or presence of certain minerals in the tailings material as well as their respective concentrations) and therefore are considered a significant factor.

4.4.7. RESULTS

The geochemical modelling of a backfilled sinkhole showed that:

Aerobic zone of the backfill

- The water quality in the aerobic zone is likely to deteriorate initially due to pyrite oxidation in the backfill material causing the pH to drop to pH 2 to 4 and increase the sulphate concentration to initially to between 100 and 700 mg/ℓ (depending on the flow rate). The concentration of other elements is generally low (<10 mg/ℓ) with the exception of aluminium (up to 38 mg/ℓ under low flow conditions).

- Iron is generally low and appears to be controlled by the formation and precipitation of the secondary mineral hematite, which is generally supersaturated. However, in cases where the secondary mineralisation does not occur readily, dissolved iron concentration will be present in the leachate, these are expected to be in the order of <20 mg/ℓ).

- With time the pH recovers to near neutral conditions and the sulphate reduces to concentrations between 10 to 200 mg/kg (depending on the flow rate) within 5 years. Under low flow conditions aluminium remains elevated to about 40 years.

Anaerobic zone of the backfill

- In the anaerobic zone the water quality is generally good as pyrite oxidation is suppressed due to the lack of oxygen in the backfill. The pH ranges between 6.9 and 7.8 (depending on the flow rate). The sulphate concentration varies between 5 and 25 mg/ℓ (depending on the flow rate), while the concentration of the other elements including aluminium is low (<5 mg/ℓ).

Unsaturated zone

- In the unsaturated zone the water quality is generally good. Although some oxygen may be present in the unsaturated zone (either in gaseous or dissolved form) due to the fractured and weathered nature of the dolomite, pyrite is absent. Therefore no chemical reactions detrimental to the water quality will take place. The pH is neutral to alkaline (depending on the flow rate). The sulphate concentrations are low (5 and 25 mg/ℓ, depending on the flow rate), as are the other elements including aluminium (<5 mg/ℓ).
- In case that acid seepage does enter the unsaturated zone (e.g. in case of a shallow sinkhole with a larger surface area), the pH remains low (<pH 3) under high flow conditions but increases to near neutral under low flow conditions within 5 years (Figure 12). The sulphate concentrations will be elevated to high (ranging between 300 to 1 000 mg/ℓ. Other elements, particularly calcium, will also be elevated (Figure 13).

The dolomite aquifer

- After the seepage has entered the dolomite aquifer and mixed the dolomitic groundwater, the water quality is generally good. The pH is near neutral under all flow conditions (refer to Figure 14). Sulphate is generally low (<20 mg/ℓ) and all other elements are also low (<5 mg/ℓ) (Figure 15).

Leachability of uranium

- The mobility of radioactive element species from the backfill material forms an important part of this investigation. Modelling of the uranium species on a sliding pH path showed that uranium chloride and -sulphate species are moderately soluble under acidic saline conditions, while the uranium hydroxide species are more soluble. However, the most common uranium hydroxide species appear to be highly soluble under acidic and alkaline conditions (Figure 16).
- **Unfortunately, the physico-chemical conditions, which inhibit the mobility of toxic heavy metals and the production of acidic conditions, promote the mobility of uranium**

hydroxides. This has the potential to pose serious problems during planning of rehabilitation strategies for sinkholes.

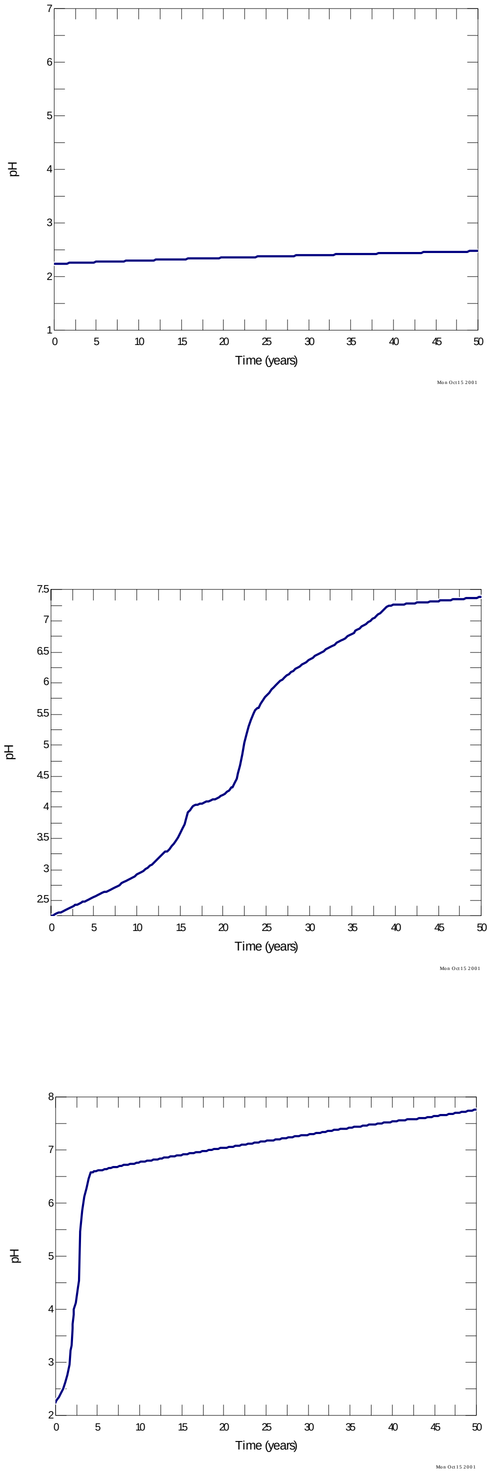
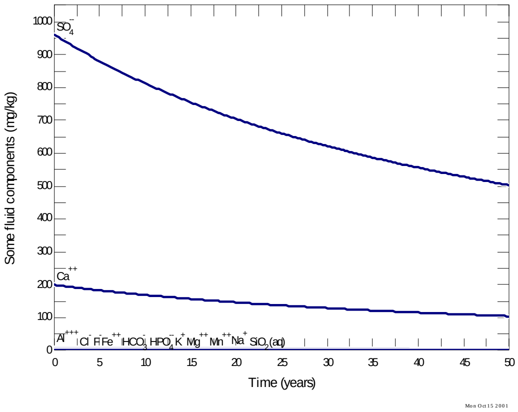
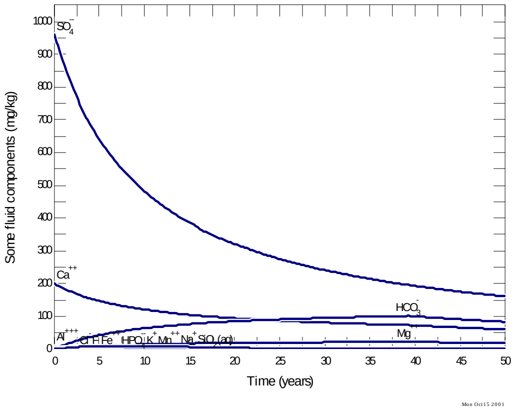


FIGURE 12: VARIATION IN PH OF ACID SEEPAGE OVER TIME SEEPING THROUGH THE UNSATURATED ZONE AT DIFFERENT FLOW RATES: (TOP) 1000 L/YEAR, (MIDDLE) 260 L/YEAR, (BOTTOM) 32 L/YEAR





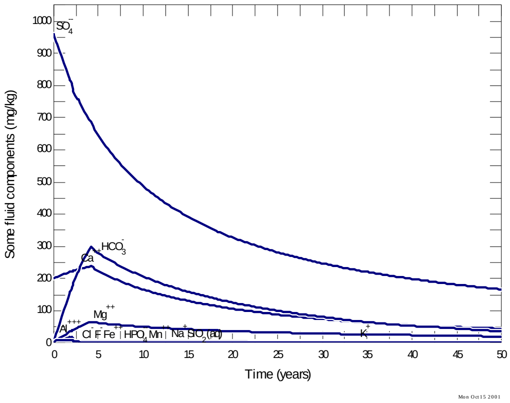


FIGURE 13: COMPOSITION OF ACID SEEPAGE SEEPING THROUGH THE UNSATURATED ZONE AT DIFFERENT FLOW RATES: (TOP) 1000 L/YEAR, (MIDDLE) 260 L/YEAR, (BOTTOM) 32 L/YEAR

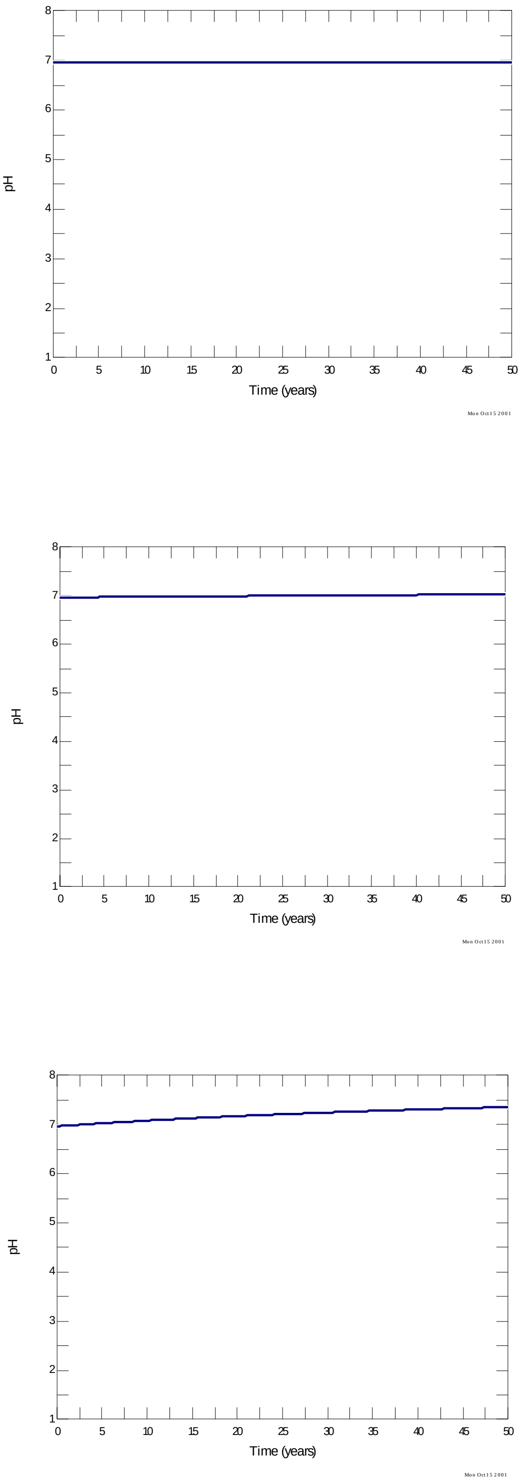


FIGURE 14: VARIATION IN PH OF AQUEOUS SOLUTION OVER TIME FOR LEACHATE INTERACTING WITH GROUNDWATER IN THE SATURATED ZONE AT DIFFERENT FLOW RATES: (TOP) 1000 L/YEAR, (MIDDLE) 260 L/YEAR, (BOTTOM) 32 L/YEAR

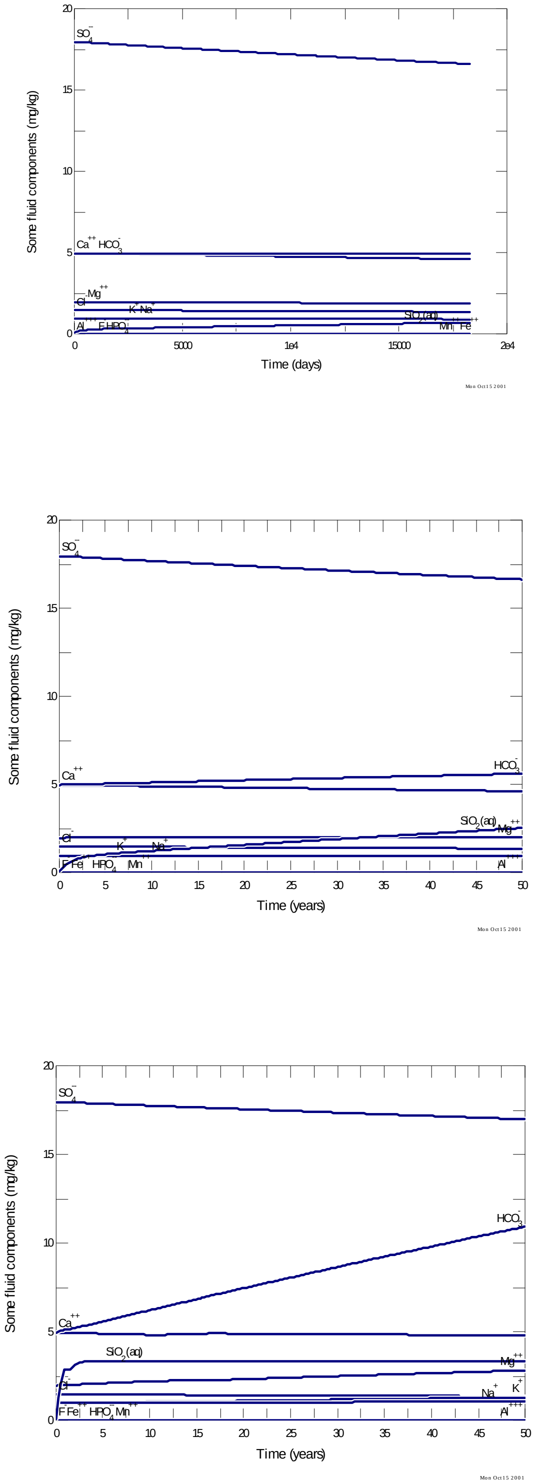


FIGURE 15: **CONCENTRATION OF CHEMICAL COMPONENT IN A FLUID INTERACTING WITH GROUND WATER IN THE SATURATED ZONE AT DIFFERENT FLOW RATES: (TOP) 1000 L/YEAR, (MIDDLE) 260 L/YEAR, (BOTTOM) 32 L/YEAR**

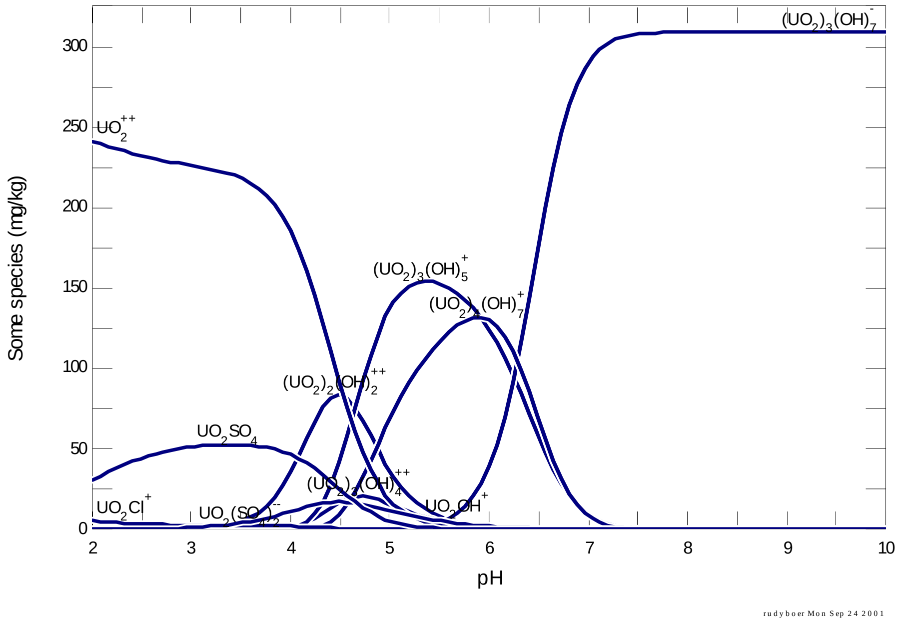


FIGURE 16: CONCENTRATIONS OF URANIUM OXIDE SPECIES AT 25°C IN AQUEOUS SOLUTION, CALCULATED USING A SLIDING PH PATH (DIAGRAM INCLUDES THE URANIUM OXIDE AND URANIUM HYDROXIDE SPECIES)

The modelling of the water quality from the backfill material in the sinkhole showed that:

- The geochemical reactions considered in the backfill are generally slow, the flow rate through the backfill is therefore a critical factor. A high flow rate will wash out reaction products and only allow limited time for geochemical reactions to take place resulting in a better water quality than is the case where the infiltration rate is very low;
- Low flow in the system will not wash out reaction products readily and the time available will allow geochemical reactions to take place.
- This indicates that backfilled sinkholes situated in close proximity to or in a water course, will release a significantly lower concentration of contaminants compared to a similar backfilled sinkhole located away from a drainage channel as a result of . a) limited availability of oxygen and b) a higher water flux through the backfill.
- Although backfilled sinkholes away from drainage channels, which can be considered partially saturated, in principle produce a worse seepage water quality (higher concentration of contaminants) than their fully saturated counterparts, the water quality emerging from such sinkholes is generally good as the sulphide oxidation rate is controlled by the relatively low air permeability of the gold tailings. The larger part of the backfill (ranging between 70 to 95%) is anaerobic due to oxygen consumption and saturation of the material which is not impacting

negatively on the water quality but on the contrary may improve the water quality due to buffering processes;

- The seepage arising from the backfill will finally mix with dolomite water, which, after re-establishment of the water table, will be available in comparatively large quantities.

Mixing of the leachate with dolomite water may result in a rapid increase in the pH and dilution. While the increase in pH may favour the precipitation of metals, the decrease in concentration reduces the extent of supersaturation, hence any contaminants in the aqueous phase in the backfill leachate, are likely to remain largely in the aqueous phase in the dolomite aquifer.

4.4.8. NFM FINDINGS

- Of all the radionuclides that are present in gold tailings, uranium is the most appropriate radionuclide to use for basing decisions regarding future backfilling of sinkholes with gold tailings since uranium is present for most of the time in the radiological decay chain and data for chemical and radiological toxicity are available for uranium only;
- Uranium concentrations of up to 300 mg/ℓ could be released into the environment under acidic, neutral and alkaline conditions in the backfill material. While the pH in the backfill material influences the metal concentrations leached from the tailings material due to precipitation of metals under alkaline conditions, the uranium concentration will not reduce significantly, however the form of the uranium species leached is pH dependent.
- The outer rim of backfill material reacts to produce AMD. However, the large volume encapsulated within this shell of oxidized material is almost unaffected by oxidation reactions and does not contribute towards the load of salts emanating as seepage. The availability of oxygen dictates the extent to which AMD forms within the tailings-filled sinkholes. By implication, there is a correlation between the extent of the oxidized zone and the volume of AMD generated. Furthermore, the implication is that flushing of the system is not a rehabilitation option, since new un-oxidized material would be exposed continuously, resulting in a steady supply of AMD;
- The water flux through the backfill affects the water quality emanating from the backfill.. The tailings material requires time to interact with the passing fluids in order to let water-rock reactions proceed. This is one of the few parameters that can be controlled to an extent, in a practical manner.;
- The adsorption of metals onto the surfaces of secondary minerals is an important scavenging mechanism, which reduces the concentration in effluent. Low pH conditions keep the secondary minerals in solution.

As discussed in Section 4.3 in terms of the radioactive elements, only the uranium-bearing species were tested. Most uranium species are soluble over a wide pH range at elevated to high concentrations, resulting into the release and leaching of uranium from uranium containing backfill material. One of the more common uranium hydroxide species, namely $(UO_2)_3(OH)_7$ is extremely soluble under alkaline conditions. Thus, uranium will migrate under physico-chemical conditions that are otherwise favourable for the inhibition of toxic heavy metals due to precipitation.

4.4.9. NFM RECOMMENDATIONS

- Of all the potential contaminants identified in the NFM, uranium poses the most significant pollution risk associated with sinkholes that are backfilled with gold tailings. The Far Field Model should therefore focus on the transport of uranium through the dolomite aquifer. In the event that the FFM demonstrates that backfilling of sinkholes with gold tailings poses a significant environmental threat as a direct result of uranium contamination, the practise should be discontinued.
- In the event that the FFM indicates that uranium is not a significant environmental threat, then the NFM has demonstrated that other contaminants including toxic heavy metals, are unlikely to pose a significant pollution risk and cannot reasonably be expected to result in degradation of the aquifer water quality.
- While the uranium speciation is likely to change as the uranium leaves the backfill and enters the dolomite aquifer, the aqueous phase uranium is likely to remain much the same. That, is, uranium is not expected to come out of solution on contact with the dolomite aquifer water.
- The concentration of uranium in the tailings is very high in comparison to the rate of leaching of uranium. For the purpose of the FFM, the uranium mass flux may be assumed to be steady state for the entire period of the FFM, which is in excess of 500 years.
- The concentration of uranium in the backfill leachate has been determined from the NFM to be up to 300mg/ℓ. The total concentration of the uranium leached depends on the initial U concentration in the backfill and the pH of the leachate. The pH also influences the speciation of the U in the leachate.
- The mass flux to be used in the FFM should be between 0.30917e-9 $g/m^2/s$ (at 0.3 mg/ℓ U) and 309.17e-9 $g/m^2/s$ (at 300 mg/ℓ U).

As the analysis of the tailings material from an operational tailings dam has shown, of the two extreme values determined in the NFM, the lower value is the probably the more likely one to occur in the field.

4.5. THE FAR FIELD MODEL

4.5.1. OBJECTIVE

The objective of the far Field Model (FFM) is to quantify the impact of the practise of backfilling sinkholes with gold tailings material, on the cavernous upper portion of the dolomite aquifer. This has been achieved with the use of a mathematical solute transport model which models the movement of water through the cavernous zone and the transport of the contaminant of greatest potential concern, namely uranium. A mass flux of uranium is mathematically injected into the aquifer at different locations and the extent of the resulting plume calculated at different times. The model allows the impact of factors, which influence the development, and extent of the plume to be evaluated in a generic rather than a site-specific manner. This will facilitate the formulation of a policy with respect to backfilling of sinkholes with gold tailings based on reasonable and scientific grounds. The policy must ensure that backfilling of sinkholes is only allowed to the extent that the sustainable use of the aquifer as a potentially significant water resource of the future, is not jeopardised.

Specifically, the FFM has been used to evaluate:

- The effect of increasing the intensity of backfilled sinkholes (backfilled sinkholes per square kilometre). This is to take cognisance of the fact that on re-flooding of the cavernous zone after mining ceases; the intensity of sinkhole formation is likely to once again increase for a limited period of time.
- The effect of the orientation of the sinkholes relative to the primary flow direction. The purpose of this is to demonstrate that the orientation of the sinkholes relative to the groundwater flow direction could significantly influence the plume and should possibly be taken into account in the policy.
- The impact of a tailings dam located on top of the dolomite relative to a zone of backfilled sinkholes. The purpose of this was to enable a comparison between the impact that is likely to arise from a tailings dam versus the impact that is likely to arise from the backfilling of a sinkhole or cluster of sinkholes. The purpose of this was to provide a perspective of the magnitude of the potential impact of backfilled sinkholes.
- The effect of the varying the average mass flux of uranium entering the dolomite aquifer from each of the backfilled sinkholes. The average mass flux of uranium entering the dolomite aquifer per unit area from backfilled sinkholes and a tailings dams is dependent on:
  - ➢ The water flux through the backfill
  - ➢ The concentration of uranium in the leachate as determined from the NFM and the in-situ field-testing.

The FFM simulates the effect of advective and dispersive transport and sorption and decay of uranium, as it occurs along the flow path in the X-Y (horizontal) plane.

4.5.2. SOLUTE TRANSPORT THEORY

The contaminant transport theory applied to the FFM is described in Appendix B to this report.

4.5.3. MODEL LIMITATIONS

The model assumes that the cavernous zone of the dolomite aquifer is a homogenous porous media. Since the scale of inhomogeneities in dolomite is typically relatively large, the model would for example not be capable of accurately predicting the concentration of a contaminant in a particular borehole located close to a source of contamination, since the assumption of homogeneity of the aquifer is not valid on such a small scale. Use of the model to make site-specific predictions over a small scale (of say <50m) should be done with caution. However, since this project is focused on the prediction of the generic impact of the backfill material on the aquifer water quality, rather than the specific impact of a particular backfilled sinkhole or small cluster of backfilled sinkholes, the limitations of the model do not constitute a flaw in the approach.

The compounding effect of uranium discharges from upstream sources has not been considered in this model.

Unlike tailings dams, backfilled sinkholes do not necessarily have a layer of soil between the aquifer and the tailings, which could be capable of sorbing a significant portion of the uranium leached from the tailings material. The effect of sorption of uranium by the soil layer has not been considered in this model and the results may therefore over-estimate the actual concentration of uranium in the aquifer in the case of the tailings dam evaluation.

The modelling has not evaluated the effect of abstraction from the aquifer (via boreholes) on the concentration of uranium in the abstracted water or on the effect that abstraction could have on the dispersion of uranium. If however the stance is adopted that backfilling should not be allowed if a uranium pollution plume develops in which the concentrations exceed the guideline values, this issue is not relevant. Alternatively, it would need to be considered on a site and case specific basis.

4.5.4. GENERIC DOLOMITE COMPARTMENT MODEL

Based on the recommendations arising out of the NFM, the FFM has been applied to uranium only.

A generic dolomite compartment was modelled, the dimensions of which were assumed to be 10km parallel to the major flow direction and 5km perpendicular to major flow direction. These dimensions are similar to the Venterspost compartment, which has the median area of the 3 compartments of concern.

The depth of the aquifer was assumed to be 50m based on the discussion in Chapter 3 of this document.

Rainfall recharge over the entire dolomite compartment was assumed to be 5 % of MAP. Recharge through the backfill was assumed to be the same as that of the surrounding area, i.e. no special measures to limit infiltration were included.

The inflow at the upstream eye was set to 20.9Ml/day, which is similar to that which occurred prior to mining at the Venterspost eye.

The hydraulic head difference between the upstream end of the aquifer adjacent to the dyke nearest the upstream eye, and the eye of the compartment was assumed to be 2m. This was based on the typical pre-mining head difference documented in Report GH1849.

The boundary conditions were set up such that flow was not allowed across any of the boundaries except at the location of the upstream and downstream eyes. Water may only be lost from the compartment via the downstream spring or “eye”.

The central zone of the dolomite compartment (corresponding to the Wonderfontein Spruit) was assumed to be more permeable than the remaining portion of the dolomite compartment. The ratio of permeability of the central zone was assumed to be 7 x that of the remaining portion of the aquifer. The more cavernous zone in the immediate vicinity of the Wonderfontein Spruit was represented as a 125 m wide zone.

The general boundary conditions are illustrated in Figure 17.

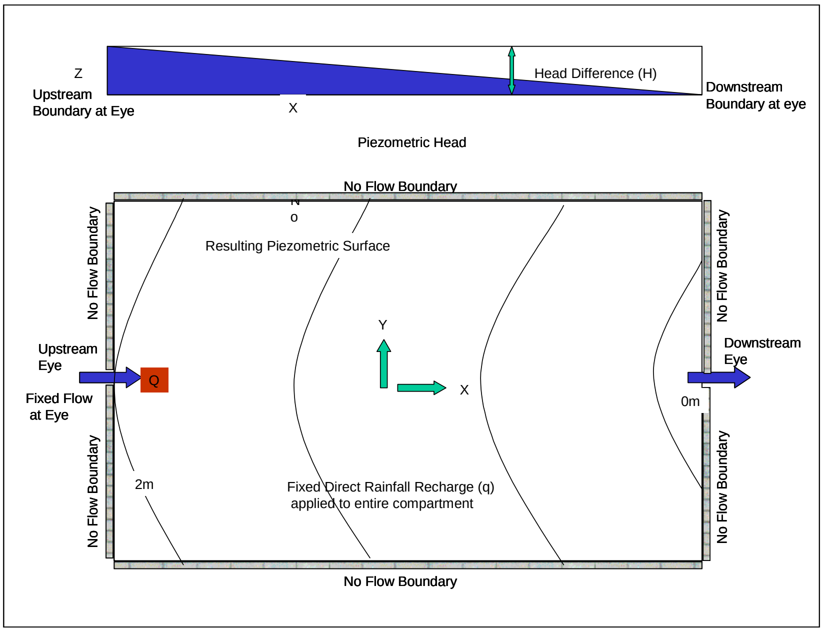


FIGURE 17: FLOW MODEL BOUNDARY CONDITIONS AND RESULTING PIEZOMETRIC SURFACE

4.5.5. MODEL METHOD

Computer code

The modelling was done using the computer programme SEEP/W and CTRAN/W version 4.0. SEEP/W deals with the flow model while CTRAN/W deals with the contaminant transport aspects.

Flow Model

The flow model was set up to model the situation once the groundwater levels have recovered to approximately their pre-mining level.

The permeability of the dolomite in the X direction was adjusted until the model gave a head loss across the dolomite compartment of 2m. The calculated dolomite permeability was compared with values quoted in the literature and found to be of a similar magnitude.

The results of the flow model were used as input to the solute transport model.

Uranium Flux from a gold tailings dam or backfilled sinkholes

The uranium flux from backfilled sinkholes was modelled as a steady state mass flux boundary applied to one ore more nodes in the model. For the purpose of this model, a standardised mass flux boundary condition was applied.

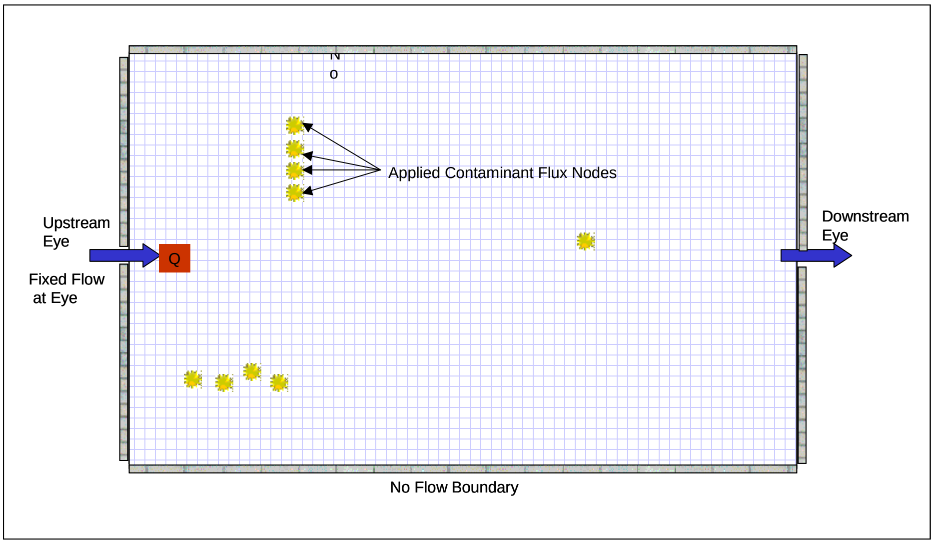


FIGURE 18: DISTRIBUTION OF INDIVIDUAL SINKHOLES IN THE COMPARTMENT

Solute Transport Modelling

The process of solute transport modelling was as follows:

1. Selected nodes on the grid were designated as backfilled sinkholes elements and assigned a mass flux q_u .(g/m^2/s)

2. The CTRAN model was run over a period of up to 800 years, using the results from the steady state flow model (SEEP/W) as input, and the plume concentrations calculated at different time intervals between t=0 and t=800 years.

3. A sensitivity analysis was conducted to ascertain the sensitivity of the model results to the uranium leachate concentration, hydrodynamic dispersion coefficient, sorption function and radioactive decay constant.

4. The process was repeated for different orientations, locations and spatial concentrations of BSE's and uranium leachate concentrations.

5. An acceptable concentration for the contaminants of concern was identified based on national and international water quality guideline values.

6. The aerial extent of the uranium contaminant plume was determined from the results of the CTRAN analysis. The aerial extent was measured as the area of the plume where the concentration of uranium exceeded the selected water quality guideline values.

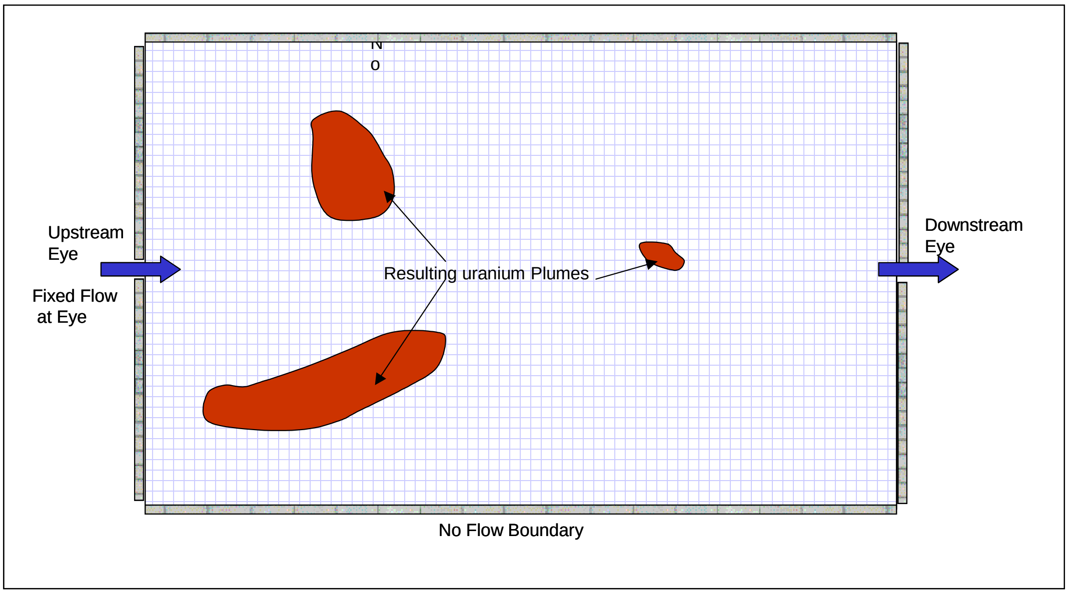


FIGURE 19: GROUNDWATER CONTAMINATION PLUMES IN THE DOLOMITE AQUIFER CAUSED BY INDIVIDUAL SINKHOLES

4.5.6. SENSITIVITY ANALYSIS

The sensitivity of the results to the following variables was assessed:

- The concentration of uranium C_i in the tailings leachate.
- The sorption function, S
- The hydrodynamic dispersion function, D
- The radioactive decay constant, λ_i

The sensitivity analysis indicated that the results were not sensitive to the latter three variables and hence only the results for variations in the uranium leachate concentration are presented. The pollution plumes tended to stabilise with time and generally remained relatively constant in extent within 100 years. Only the 100-year results are presented since they are the worst case and virtually identical to all proceeding years up to the 800 years simulated.

4.5.7. CRITERIA FOR POLLUTION

While there is a wide range of possible future uses of the groundwater, for the purpose of this study, drinking water standards have been used. A review of the standards reveals that there is a significant variation in the standard for uranium in drinking water. For the purpose of this study, the South African Water Quality Guideline value (SA WQ Guidelines, Volume 1, Domestic Use, DWAF, 2nd ed., 1996) and the World Health Organisation's (WHO) drinking water guidelines have been used. The SAWQ gives a target value for domestic use of <0.07ppm (<70 ug/ℓ) while the WHO drinking water standard is <0.002ppm (<2 ug/ℓ).

4.5.8. SCENARIOS EVALUATED

The FFM has been used to evaluate a series of backfilled sinkhole distributions to assess the effect of:

- The concentration of uranium in the leachate entering the dolomite aquifer.
- The location of the backfilled sinkholes relative to the location of the stream.
- The spatial orientation of the backfilled sinkholes relative to the general aquifer flow direction
- The spatial concentration of backfilled sinkholes
- The relative impact of tailings dams compared to a cluster of backfilled sinkholes.

The analyses are described in further detail below:

Uranium Leachate Concentration

Based on the results of the NFM, the uranium concentration in the leachate was varied over the range 0.3mg/ℓ to 300mg/ℓ for each scenario. As this is the most sensitive parameter, the results are presented for each of the proceeding scenarios of 0.3mg/ℓ, 3mg/ℓ, 30mg/ℓ and 300mg/ℓ.

Location of backfilled Sinkholes relative to the Wonderfontein Spruit

Analyses were conducted to compare the pollution plume arising from a single BSE located at different points in the aquifer. The results of the following analyses are presented:

ANALYSIS	DESCRIPTION	EXPLANATION
1	In the stream	
2	Next to the stream	125 m from the stream
3	Away from the stream	1200m from the stream

Spatial Orientation of backfilled Sinkholes

As described in Section 3, sinkholes have a tendency to be associated with topographical or geological features such as stream, faults and dykes, which tend to be orientated in some direction relative to the general flow direction. Two extreme cases are presented as follows:

ANALYSIS	**DESCRIPTION**
1	5 BSE’s orientated perpendicular to the primary flow direction outside the stream zone.
2	5 adjacent BSE’s orientated parallel to the primary flow direction, located out of the stream zone.

Long term Increase in spatial Concentration of backfilled Sinkholes

Although there is significant uncertainty regarding the magnitude, timing and extent, it was identified in Section 4 that on re-establishment of the water level in the dolomite compartments after decommissioning of the gold mines, a period of increased ground instability is likely to re-occur, and that further sinkholes are likely to develop, which might well need to be backfilled. For the purpose of this model, the final intensity of sinkholes has been assumed to increase between one and twofold, and to increase within a very short period after re-watering. Based on the GIS information (Erasmus, 2000, unpublished) the current average sinkhole intensity was found to be 30 sinkholes/km^2. Thus, some time after re-establishment of the water level in the dolomite compartment, the sinkhole intensity over a single square kilometre may be between the current maximum of 30 and 60 sinkholes/km^2. The analyses were therefore conducted for 30, 45 and 60 BSE’s concentrated into a 1km^2 area.

Relative Impact of a Tailings Dam

The impact of a tailings dam with a footprint measuring 1 km x 1.5 km was analysed to compare the resulting plume with that of the other scenarios involving backfilled sinkholes. The uranium mass flux q_u, was adjusted to take account of the fact that the entire element is covered with tailings (for details refer to Appendix B). Two analyses were conducted, one with the tailings dam located just outside the stream zone, as shown in Figure 20 and the other with the tailings dam located some 1.2 km from the stream zone.

Relative Impact of other Mine Waste Facilities

The impact of rock dumps and return water dams has not been modelled but the following general comments pertain to these facilities by way of comparison to a tailings dam:

- Return water dams, if they are unlined, potentially contribute to greater seepage load to the groundwater than the associated tailings dam itself. This is self evident if one compares the flux of the tailings dam with the flux of the return water dam, which may be estimated using D’Arcy’s law

  $$Q = k * i * A$$

  Where Q equals flow

  k equals permeability

  i equals hydraulic gradient

  A equals foot print area

- In the case of the rock dump the contaminant load to the groundwater may be greater or less than that of a tailings dam. Main factors determining the waste load are:

    Foot print area

    Leachability of the rock (as a function of several factors, e.g. particle size distribution, sulphide content, etc.)

    Permeability of the waste rock (which is several orders of magnitude higher than that of tailings)

    Time since deposition of the waste rock material

While one should be aware that generalisations can be misleading, the general order of priority in terms of pollution load to the groundwater is probably:

Return water dams > Tailings dams > Waste rock dumps.

4.5.9. RESULTS

The results are summarised in Table 16, which compares the concentration in the aquifer with the selected international and national water quality guidelines.

TABLE 16: SUMMARY OF THE CONTAMINATION ASSESSMENT FOR THE VARIOUS MODELLED SCENARIOS AFTER 100 YEARS (COMPLIANCE WITH WQ GUIDELINES FOR THE GROUNDWATER IN THE DOLOMITE AQUIFER)

Scenario	**WHO drinking water guideline=0.002 mg/ℓ U** **SAWQ= 0.07 mg/ℓ U**			
Leachate concentration. [mg/ℓ U]	***0.3***	***3.0***	***30***	***300***
Single BSE				
In the stream	WHO	WHO	SAWQ	>198mg/ℓ
Next to the stream	WHO	SAWQ	SAWQ	>32 mg/ℓ
Away from the stream	WHO	SAWQ	>10mg/ℓ	
Row of BSE's				
Perpendicular to the flow direction	WHO	WHO	SAWQ	>30mg/ℓ
Parallel to the flow direction	WHO	SAWQ	SAWQ	>6mg/ℓ
Cluster of BSE's				
30 BSE's over 1 km^2	SAWQ	>10mg/ℓ		
45 BSE's over 1 km^2	SAWQ	>7mg/ℓ		
60 BSE's over 1 km^2	SAWQ	>6mg/ℓ		

Scenario	**WHO drinking water guideline=0.002 mg/ℓ U** **SAWQ= 0.07 mg/ℓ U**			
The Tailings Dam **(1 000 x 1 500 m footprint)**				
Next to the stream zone	SAWQ	>1.4mg/ℓ		
1.2 km away from the stream zone	SAWQ	>0.8mg/ℓ		

The concentration limits given in the red block indicate the maximum leachable concentration that could be tolerated to just not exceed the SAWQ guideline value of 0.07mg/ℓ.

For the purpose of this document, the term pollution is used to describe a situation in which the concentration of uranium in the aquifer exceeds one or more of the standards described above.

4.5.10. DISCUSSION

The model demonstrated that the retention time for any contaminant released into the aquifer was highly dependent on where the contaminant was released. Particle tracking showed that particles placed in the more cavernous zone associated with the stream some 8.5 km from the eye require less than 50 years to reach the eye, while particles in areas of lower flow also 8.5 km distance from the eye required 200 years or longer to reach the eye.

The extent of absorption of uranium onto the dolomite (the predominant rock form in the aquifer) is insignificant. The sensitivity analysis for the effect of adsorption showed that only 1% of the total uranium mass would be retained in the aquifer by adsorption to the dolomite, while the majority of the uranium is present in the aqueous form in the groundwater.

Single idealised backfilled Sinkhole

- A uranium leachate concentration of 0.3 mg/ℓ U from a single idealised sinkhole did not result in pollution of the dolomite aquifer.
- Once the leachate concentration reached or exceeded 1.0 mg/ℓ U, plume concentrations from a single BSE exceeded the WHO’s drinking water standard.
- Once the leachate concentration rose above 30 mg/ℓ U, plume concentrations in excess of the SAWQ guideline value occurred even for a single BSE.
- The maximum U concentration in the aquifer caused by a backfilled sinkhole situated outside the stream zone is expected to be about 6 times higher than for an equivalent backfilled sinkhole situated in the stream zone.
- The average area impacted by a backfilled sinkhole situated outside the stream zone was about 2.5 times larger than for a sinkhole situated in the stream zone.

Row of Sinkholes

- Leachate from the BSE at a concentration of 0.3 mg/ℓ U from a row of sinkholes arranged perpendicular to the stream did not cause pollution of the dolomite aquifer, whereas leachate from a row arranged parallel to the flow direction did cause the WHO WQ standard to be exceeded.
- Only once the U concentration from the backfill exceeded 31 mg/ℓ, did the concentration in the aquifer caused by a row of backfilled sinkholes arranged perpendicular to the flow direction exceed the WHO WQ guideline value.
- For the backfilled sinkholes arranged in parallel to the aquifer flow direction, once the concentration of uranium in the leachate exceeded 7.0mg/ℓ, the concentration in the aquifer exceeded the WHO WQ limit.
- The maximum U concentration in the aquifer caused by a row of five BSE's arranged parallel to the flow direction and situated next to the stream is approximately 5 times higher than for a row of sinkholes perpendicular to the flow direction and situated next to the stream.
- The average area of the aquifer impacted by the backfilled sinkholes varied quite considerably depending on the orientation of the sinkhole cluster relative to the aquifer flow direction. At low uranium leachate concentrations (3.0 mg/ℓ U) the extent of the pollution plume area of impact caused by the BSE's in perpendicular orientation is about 60% higher than the pollution plume cased by the sinkholes in parallel orientation.
- As the contaminant leachate concentration increases, the orientation of the backfilled sinkholes makes less of a difference. With an increase in the leachate concentration of one order of magnitude (30 mg/ℓ U) the difference in the area of the pollution plume was only 7%.

Cluster of Sinkholes

- The maximum U concentration in the aquifer caused by clusters of backfilled sinkholes with higher leachate concentrations (30 and 300 mg/ℓ U) situated next to the stream exceeded the SA WQ guideline by between 3 and 45 times.
- All tested scenarios exceeded the WHO WQ guideline.
- The sinkholes clusters impacted on a relatively large proportion of the aquifer (approx. 20 to 30% of the total model area of 50 km^2 (5 000 ha)
- The average area impacted by the clusters of backfilled sinkholes is less than 1 km^2 at low leachate concentrations of less than or equal to 0.3 mg/ℓ U.
- The pollution plume increases rapidly to about 10 km^2 at a leachate concentration of 3.0 mg/ℓ U and reached a maximum of 15 km^2 at a leachate concentration of 300 mg/ℓ U.

- The increase in the aerial concentration of sinkholes causes an increase in the maximum uranium concentration in the pollution plume rather than an increase in the aerial extent of the pollution plume.

Relative Impact of a Tailings Dam

- Leachate from the idealised tailings dam resulted in the WHO WQ in the dolomite aquifer being exceeded for all uranium leachate concentrations modelled.
- Leachate from the tailings dam also exceeded the SA WQ guideline for all leachate concentrations modelled except for 0.3 mg/ℓ U. Leachate concentrations in excess of 1.5 mg/ℓ U would cause an impact on the water quality in the dolomite aquifer in excess of SA WQ guidelines.
- The maximum U concentration in the aquifer caused by a tailings dam further away from the stream is about 1.5 times higher than for a tailings dam in close proximity to the stream.

The area of the aquifer impacted by the simulated tailings dam (footprint area 1.5 km^2 or 150 ha) varied from 6.3 km^2 at very low leachate concentrations (0.3mg/ℓ U) to 17.8 km^2 at very high leachate concentrations (300mg/ℓ U).

The average area impacted by the tailings dam situated immediately adjacent to the highly cavernous stream zone is approximately twice as high as for a tailings dam situated further away from the highly cavernous zone. At very high leachate concentrations the area of the contaminated plume from a tailings dam next to the stream is only 1.2 times that for a tailings dam situated further away from the stream.

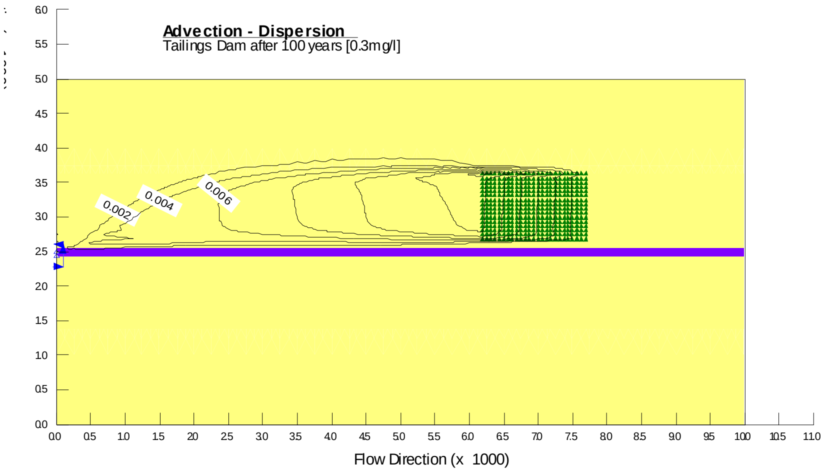


FIGURE 20: ANALYSIS OF A TAILINGS DAM IMPACT FOR A TAILINGS DAM LOCATED ADJACENT TO THE STREAM ZONE (100 YEARS, U = 0.3 MG/ℓ)

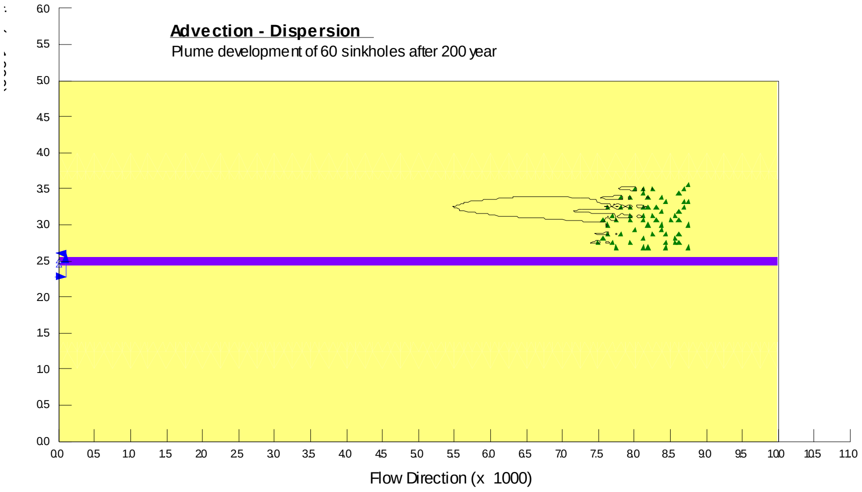


FIGURE 21: ANALYSIS OF BSE'S CLUSTER (60 UNITS) ADJACENT TO THE STREAM ZONE (200 YEARS, U = 0.3 MG/ℓ)

Cumulative Impact of other Uranium Source Terms

Since sorption of uranium and decay have been found to be insignificant, the results of the FFM can be added directly to any background uranium concentrations that already exists in the aquifer.

4.5.11. FINDINGS OF THE FAR FIELD MODEL

The following conclusions may be drawn from the model.

- The most sensitive parameter with respect to the development of a uranium pollution plume is the uranium leachate concentration.
- The second most sensitive parameter is the aerial concentration of backfill. The more distributed the backfilled sinkholes, the lower the risk of pollution. The percentage of uranium leached from gold tailings and sorbed onto the rock surface of the dolomite aquifer is expected to be insignificant.
- The effect of other sources of uranium pollution needs to be added to the results presented in this report.
- Backfilling of isolated sinkholes located some distance (e.g. 500m) away from any other backfilled or potentially backfilled sinkhole does not pose a pollution threat in terms of leachable chemicals from the gold or uranium tailings.
- Backfilling of sinkholes in highly concentrated zones where sinkholes are close to one another could give rise to a pollution plume depending on the leachable uranium concentration of the tailings. Provided that the leachable concentration of uranium is shown to fall below 0.3mg/ℓ,

the risk of a pollution plume developing with concentrations exceeding the SA target water quality guideline value of 0.07mg/ℓ will not occur, even with the more conservative estimate of backfilled sinkholes density.

- Should the leachable concentration of the tailings exceed 6mg/ℓ, extreme caution should be applied to backfilling of all sinkholes. Based on the modelling undertaken it may be concluded that backfilling of sinkholes in the Far West Rand with gold tailings can potentially cause pollution. The risk of pollution of the dolomite aquifer is however highly dependent on:
    - The concentration of uranium in the leachate from the backfill.
    - The spatial orientation of the zone of sinkholes. A zone of sinkholes that form along an East – West plane parallel to the general flow direction has a much higher risk of degrading the aquifer than the equivalent zone which forms along a north south plane.
    - The spatial concentration of sinkholes. Where sinkholes are backfilled with tailings close to one another, the risk of a pollution plume developing is significantly higher.
    - The location of the backfill relative to the more permeable cavernous zone along the Wonderfontein Spruit. Clusters of backfilled sinkholes that form in the Wonderfontein Spruit have a less detrimental effect on the aquifer water quality than an equivalent cluster would have that formed away from the more cavernous zone as a result of the increased water flux through this zone and the enhanced dilution and dispersion effects.
- Leachate concentrations in excess of 0.3 mg/ℓ U from the backfilled sinkholes generally cause groundwater pollution in excess of the WHO WQ guidelines with the exception of backfilled sinkholes measuring no more than one idealised backfilled sinkhole of 0.40 ha in extent.
- As a general guideline, backfilling of sinkholes with gold tailings has a high risk of causing impacts on the dolomite aquifer in excess of the SA WQ guidelines if the leachate concentration were to exceed 30 mg/ℓ U. However, when the effective zone of backfill exceeds 0.4 ha/ km^2, the SA WQ guidelines have a high probability of being exceeded if the leachate concentration exceeds 3.0 mg/ℓ U.
- The relative impact of tailings dams compared to backfilled sinkholes is considerably greater as evidenced by the fact that the model showed that the tailings dam caused pollution with a uranium leachate concentration in excess of 0.3 mg/ℓ U.
- Considering the current SA water quality guidelines, sinkholes, which are situated in the stream or in close proximity to the stream, (these account for the majority of sinkholes in the Far West Rand) may be backfilled with gold tailings provided the leachable U concentration from the tailings material is less than 30 mg/ℓ.

- Although the impact from a tailings dam has been shown to be very pronounced the mitigating effects from the compacted soil cover beneath the tailings dam have not been considered by the model. Contamination assessments undertaken for soils from footprints of removed tailings dams indicated generally elevated uranium concentrations in the soil with concentrations of less than 1 mg/ℓ U in the groundwater in close proximity to the tailings dams. The model therefore seems to overestimate the impact of contamination from the tailings dam to the aquifer by probably one order of magnitude.
- The modelling indicated that the uranium plumes reached their full aerial extent after 50 to 100 years, thereafter the plume would only increase marginally for the following centuries. Based on a comparison of the total uranium content of the tailings with the leach rate, complete leaching of the uranium from the tailings will take several hundred to thousands of years. The plume will finally reduce and eventually disappear, when all uranium has been leached from the respective sources of pollution. The long term impact of backfilling may thus be considered practically the same as the impact after 50 to 100 years, when the plume has reached its full extent.

There is clearly a need to apply a precautionary approach to backfilling of sinkholes of uranium containing gold tailings. Backfilling will not result in pollution where a sinkhole develops in isolation from other sinkholes and needs to be backfilled. Backfilling of sinkholes that form within the more cavernous zone associated with the Wonderfontein Spruit have a higher risk of causing a more extensive but lower concentration pollution plume, since the orientation of the sinkhole clusters is generally parallel to the aquifer flow direction and the water flux through the aquifer is higher at this point.

Clusters of sinkholes that form away from the river are likely to give rise to a less extensive plume but one with a higher peak concentration.

4.6. WATER QUALITY IMPACT ASSESSMENT CONCLUSIONS

Based on the water quality impact assessment undertaken by means of the NFM and the FFM the following conclusions are drawn concerning the impacts on the water quality in the dolomite aquifer caused by the backfilling of sinkholes with gold tailings:

Conclusions from the NFM

- The seepage in the upper (aerobic) part of the backfilled sinkhole may initial be of poor quality (acidic with elevated concentrations of sulphate and aluminium). Iron appears to precipitate as hematite.

- The seepage quality improves with time (depending on the flow rate). After 50 years the seepage in the upper section of the sinkhole is generally of good quality independent of the flow rate.
- The seepage in the lower (anaerobic) part from the backfilled sinkhole will be of good quality (near neutral pH, low sulphate concentrations, low concentrations of other elements).
- Seepage of good quality passing the unsaturated zone does not undergo major chemical changes. Acidic seepage will be neutralised under low flow conditions and partially neutralised under average flow conditions. As the neutralisation of the acidic seepage causes the dissolution of dolomite, the TDS in the seepage is likely to be elevated to high.
- After the seepage has been mixed with the groundwater in the dolomite aquifer, the water quality is generally good (near neutral pH, low sulphate concentrations, low concentrations of other elements) and is likely to be fit for human consumption with the exception for uranium.
- Uranium is leached from the backfill material under a wide range of pH (acidic to alkaline). The concentration of dissolved uranium in the leachate depends mostly on the total uranium concentration in the backfill. The pH will govern what uranium species will be leached from the backfill. Probable maximum uranium concentrations in the leachate are in the order of 300 mg/ℓ but more likely concentrations, based on leach tests of gold tailings from the Far West Rand are in the order of 0.3 mg/ℓ.

Findings from the FFM

- Backfilling of isolated sinkholes located some distance (e.g. 500m) away from any other backfilled or potentially backfilled sinkhole does not pose a pollution threat in terms of leachable chemicals from the gold or uranium tailings.
- Backfilling of sinkholes in highly concentrated zones where sinkholes are close to one another could give rise to a pollution plume depending on the leachable uranium concentration of the tailings. Provided that the leachable concentration of uranium is shown to fall below 0.3mg/ℓ, the risk of a pollution plume developing with concentrations exceeding the SA target water quality guideline value of 0.07mg/ℓ will not occur, even with the more conservative estimate of backfilled sinkholes density.
- Leachate concentrations in excess of 0.3 mg/ℓ U from the backfilled sinkholes generally cause groundwater pollution in excess of the WHO WQ guidelines with the exception of backfilled sinkholes measuring no more than one idealised backfilled sinkhole of 0.40 ha in extent.
- As a general guideline, backfilling of sinkholes with gold tailings has a high risk of causing impacts on the dolomite aquifer in excess of the SA WQ guidelines if the leachate concentration were to exceed 30 mg/ℓ U. However, when the effective zone of backfill exceeds 0.4 ha/km^2, the SA WQ guidelines have a high probability of being exceeded if the leachate concentration exceeds 3.0 mg/ℓ U.

4.7. RECOMMENDATIONS ARISING FROM THE GENERIC IMPACT ASSESSMENT

If backfilling of sinkholes with tailings is based on the findings of the modelling exercise the following is recommended:

- Tailings material intended for the backfill of sinkholes should be tested for total and leachable uranium concentrations prior to its use.
- If tailings material is used to backfill sinkholes the uranium concentration in the tailings material should be less than 0.3 mg/ℓ U, provided the aquifer does not feature any residual U concentration.
- As tailings dams have a much greater potential to pollute the dolomite aquifer, the uranium concentrations in the tailings material, the tailings dam pore water and the groundwater in the vicinity of these tailings dams should be assessed. Tailings dams, which are older than 50 years, in close proximity to boreholes used for domestic purposes should be assessed first.

5. PHYSICAL STABILITY OF MINE WASTE BACKFILL

5.1. OBJECTIVE

The objective of this portion of the project was to identify issues relating to the physical stability of backfilled sinkholes are identified and considered. In order to address this issue, previously backfilled sinkholes have been inspected to identify shortcomings and assess factors that give rise to physical instability. Physical instability could pose a safety risk to humans.

5.2. METHOD

Work on the geotechnical aspects of backfill has been limited to:

- Site inspections of a number of open and backfilled sinkholes; and
- CPT testing of a single backfilled sinkhole.

The results are presented below.

5.3. RESULTS

The CPT results confirmed the presence of cavities developing in the backfill at depth below surface. While there was no evidence of disturbance or subsidence at surface, the CPT resistance indicated frequent zones virtually zero resistance.

The following observations were made from the site inspections and discussions with relevant persons:

- The condition of the backfilled sinkholes in the vicinity of the Wonderfontein Spruit to the north of Westonaria may generally be described as poor with a large number of sinkholes having reactivated subsequent to backfilling.
- It is understood that the frequency of re-activation of cavities that were grouted with tailings with a small percentage of cement is low.

5.4. DISCUSSION

The problems experienced with the backfilling of sinkholes may be summarised as follows:

- From an engineering viewpoint, the sidewalls of a sinkhole, which form the supporting structure for the backfill, are often unstable or become unstable over relatively large areas and therefore collapse themselves.
- During backfilling, the lateral and vertical load applied to the sidewalls of the cavity may either stabilise or destabilise the sidewall depending on the geometry and load applied.
- The sidewalls are also subjected to erosion as a result of percolating water and may become partially eroded along certain drainage paths. This has the effect of transferring loads to other areas over a period of time, which again can result in instability of the sidewall and re-activation of the sinkhole immediately adjacent to the backfilled cavity.

Key to the geotechnical success of the backfill is the resistance to internal erosion.

Factors that influence the risk of reactivation and potential methods to mitigate this risk are briefly described below:

- *The volume of water that passes through the backfill*. Backfilled sinkholes where stormwater is diverted around the backfill area are likely to experience a lower frequency of re-activation. Where sinkholes develop in streams, special precautions will be required as these sinkholes will always be subject to larger volumes of percolating water. Where sinkholes develop away from streams, the sinkhole should be domed and covered to ensure that percolation through and in the immediate vicinity of the sinkhole is avoided.

- *The cohesive strength of the backfill*. On placement of fresh tailings, waste rock or sand into the sinkhole, the tailings material has no cohesive strength. Once the tailings becomes unsaturated, it starts to behave as a cohesive material but loses its apparent cohesive properties on re-saturation. Thus, sinkholes that are backfilled with tailings are most likely to suddenly reactivate during or shortly after wet periods. The cohesive properties of the tailings may be enhanced through the addition of a material that will cause the tailings to develop pozzalanic (cementing) properties. Such materials might include cement, lime, fly ash etc. While the addition of even small percentage of cement may not significantly alter the overall shear strength of the backfill, the resistance to internal erosion may be significantly improved. In assessing the cement and lime options, consideration needs to be taken of the possible effect of pyrite oxidation on the cement. Cement addition will be more effective where cement is added to the deeper portions of the tailings backfill, which are less likely to be exposed to oxygen.

- *The dispersivity of the backfill and surrounding material*. Dispersive soils are soils that contain high concentrations of readily soluble cations and anions. Such soils, when subject to seepage tend to lose a significant portion of their mass and subsequently their shear strength. Gold tailings is relatively low in Na and Cl and is not classified as a dispersive soil. It is however subject to weathering and sulphides and carbonate minerals in particular will dissolve with time. The rate of dissolution is however very slow and not expected to have a significant effect on the backfill strength.

- *Internal erosion of the waste or surrounding material*. The particle size distribution and the relative particle size distributions of different materials that might be used in the backfilling operation. Terzaghi proposed a number of conditions that need to be satisfied to ensure that drainage materials are compatible with one another (finer particles from material A will not migrate into material B) and that finer particles do not migrate out of a material. The criteria are based on the ratio of the particle sizes and were determined experimentally. The conditions are as follows:

- Internal erosion $\frac{D_{15}\ldots Filter}{D_{85}\ldots Soil} <$ 4 to 5

- Material compatibility $\frac{D_{85}\ldots Filter}{D_{15}\ldots Filter} <$ 4 to 5

The internal erosion criteria should always be satisfied. The compatibility criteria can be overcome by the installation of intermediate materials or the application of a geomembrane.

- *Reactivation through the throat of the sinkhole*. Ideally, the throat of the sinkhole should be plugged with a cohesive high strength material. This is however difficult to achieve in practise since access to the throat is often very dangerous and since the material in the immediate vicinity of the throat may be unstable. The detailed design of the backfill needs to ensure that a plug is formed by whatever means practical. The absence of a plug virtually guarantees re-activation at some stage in future.

- The onion peeling effect observed in many of the sinkholes cannot be abated with non-cohesive materials such as tailings or mine waste rock unless measures are taken to prevent gradual erosion in the upward direction as a result of loss of material through the throat. While this does not preclude the use of tailings or mine waste rock as a backfill material from a geotechnical perspective, there is clearly a need to identify cost effective methods to eliminate internal erosion. This can only be achieved if suitable methods can be identified to prevent the loss of fines through the throat and from other areas within the body of backfill material. This may require the inclusion of layers of cemented backfill or the inclusion of layers of geofabric to control the internal erosion problem.

5.5. CONCLUSIONS

The following conclusions may be drawn from this aspect of the study:

- Backfilling of sinkholes with purely non-cohesive materials is unlikely to provide a long-term walk away solution and poses a significant safety risk to humans due to the risk of sudden subsidence, caused by reactivation of the sinkhole or erosion of the backfill from beneath the surface.
- Backfilling of sinkholes with a cohesive material such as clay or cement-modified gold tailings material may significantly reduce the risk of occurrence of subsidence or re-activation, but not the consequence of subsidence.
- Backfilling of sinkholes with natural material from borrow areas in close proximity to sinkholes has the disadvantage of depleting the surrounding area of soil and also increasing the risk of sinkhole formation in the borrow area as a direct result of changed drainage conditions.
- Backfilling of sinkholes with a combination of different materials is likely to provide the optimal solution from a cost, subsidence risk and consequence viewpoint.
- The above viewpoint must be weighed against the alternative of not backfilling the sinkholes. By not backfilling the sinkholes, the sinkhole presents a permanent safety risk and a potentially far more serious pollution risk attributable to the potential for illegal disposal of waste materials including hazardous wastes. This alternative policy is thus probably a more significant risk to human health and safety and the aquifer water quality than the tailings backfill option.

5.6. RECOMMENDATIONS

The following recommendations arise from this part of the study:

- Any material used for backfill should satisfy the Terzaghi internal filter criteria and should ideally be compatible with the material comprising the side-walls of the cavity. The backfill material selected should be non-dispersive.
- The final surface should be domed to minimise the ingress of water, which would give rise to possible erosion.
- Care should be taken prior to backfilling to clean the contact zone between the side-wall and the fill to ensure a sound contact between the surrounding dolomite, soil and the backfill. Use could be made of remotely operated equipment such as high pressure spray guns to achieve a cleaner contact.
- Backfill should have a low permeability final cover to minimise the ingress of water.

- Sinkholes that develop within drainage channels and the Wonderfontein Spruit should be backfilled with a cohesive material such as cemented tailings to significantly reduce the risk of reactivation. A strong capping, such as mass concrete should be placed over the top of the backfilled sinkhole to reduce the consequence of re-activation.

6. FINDINGS OF THE LEGAL REVIEW

The legal review concerning the backfilling of dolomitic cavities highlighted a number of problems arising from the current legal situation.

In considering the practice of backfilling sinkholes with mine waste ("the activity") the law that is relevant to this legal opinion includes the following:

- **The** National **Water Act, 36 of 1998** ("National Water Act");
- **Regulation 704, 4 June 1999** ("R704") promulgated in terms of the National Water Act;
- **Regulation 1191, 8 October 1999** ("R1191") promulgated in terms of the National Water Act
- **The Minerals Act, 50 of 1991**("Minerals Act"),
- **Regulation 992, 26 June 1970 as amended** ("R992") promulgated in terms of the Minerals Act;
- **The Environment Conservation Act, 73 of 1989** ("Environment Conservation Act");
- **Regulation 1183, 5 September 1997** ("R1183") promulgated in terms of the Environment Conservation Act;
- **The National Environmental Management Act, 107 of 1998** ("NEMA")
- **The National Nuclear Regulator Act, 47 of 1999** ("NNRA")**;**
- **Regulation 848, 23 April 1994 ("R848") promulgated in terms of the Nuclear Energy Act, 131 of 1993;** and
- **The common law**.

All law applicable to the activity should be written, interpreted and applied in accordance with the provisions of the **Constitution of the Republic of South Africa, 1996** ("the Constitution"). In particular, **Section 24** of the Constitution provides that everyone has the right to an environment that is not harmful to their health or well-being and to have the environment protected for present and future generations by reasonable legislative measures that prevent pollution and ecological degradation, promote conservation, and secure ecologically sustainable development while promoting justified economic and social development.

The following problems regarding the legality of the backfilling sinkholes with mine waste (or any other waste) were identified:

- The current activity of backfilling sinkholes with mine waste is not in compliance with the law;
- According to a number of acts the activity has to be licensed. The question arises whether each single sinkhole to be backfilled will require a license in accordance with the law which is likely to be costly and time consuming or if the activity as such can be licensed for a certain region based on the general understanding of the problem and site specific information provided for each of the sinkholes to be backfilled;
- Liability from the activity arises from statutory law. Statutory law liabilities may be related to failure to obtain permits/licenses, failure to comply with permit/licensing conditions, failure to comply with Section 19 of the National Water Act (which refers to the responsibilities of a party causing pollution – The Polluter pays Principle) and/or Section 28 of the National Environmental Management Act (both acts require a polluter to undertake reasonable measures in managing pollution and preventing pollution from occurring or recurring) and failure to secure the sinkhole;
- Liability from the activity arises from common law. Common law liabilities may be related to a claim from a person(s) suffering harm or loss caused by the activity with an element of wrongfulness (negligent or intent) for an award of damages;

As sinkholes will have to be secured for the safety of the public and any structures in close proximity to sinkholes, and in order to avoid illegal dumping of general or hazardous waste materials, backfilling of sinkholes with an appropriate material is the most suitable long term solution. At present, the practice of backfilling sinkholes with mine waste, irrespective of how low its pollution risk actually is, is not in compliance with the law and further consideration to resolve the issue would be required.

The full legal review is included in Appendix C of this report.

7. CONCLUSIONS

The following conclusions may be drawn from this study:

Long term Status of the Dolomite Compartments

- On cessation of mining, the water in the dolomite compartment is expected to rise to the same level as was present prior to mining. Mining through the dykes is unlikely to have a significant effect on the final water levels achieved. The time to reach the final level is provisionally estimated to be between 11 and 30 years after mining ceases.

Materials for Backfilling

- The limited availability of materials other than gold tailings and mine waste rock within the Far west Rand Geographic Area make backfilling with alternative materials significantly more expensive. Gold tailings or mine waste rock would therefore comprise the material of first choice, provided that these materials do not pose a pollution risk. Detailed consideration of materials other than mine waste rock and tailings was not considered warranted for this study.

Physical Stability of backfilled Sinkholes

- Tests conducted on a single backfilled sinkhole have indicated the presence of weak layers and cavities at depth despite the fact that the surface of the backfilled sinkhole shows no sign of subsidence. This indicates that the most significant geotechnical problem associated with backfilling using non-cohesive materials is internal erosion and re-activation of the sinkhole. Engineers will need to address this issue in future to identify economic and safe methods and material combinations to prevent internal erosion of the backfill.

Future Rate of Sinkhole Formation

- After cessation of mining, the rate of formation of sinkholes might increase temporarily above the current rate, once the water level reaches a critical level estimated to be between 5 and 10 m below the final water level. The rate is unlikely to exceed the rate experienced in the early days of de-watering when the water level was first dropped by 5 to 10 m. Thus the final long term concentration of sinkholes may increase but is unlikely to increase by more than twice the current value.

Current and future physical Distribution of Sinkholes

- The decision of whether to allow the sinkhole to be backfilled with the most readily available source of material, namely gold tailings, need to take cognisance of the physical distribution of the sinkholes. If the sinkholes were evenly distributed over the entire compartment, the, impact of backfilling would be considerably less than if the sinkholes were concentrated into a few small areas. Modelling of the impact of backfilling of sinkholes needs to consider the effect of clustering of sinkholes caused by specific geological or topographical features. Sinkholes are likely to continue to form in specific areas susceptible to sinkhole formation rather than in new areas that have not previously experienced any sinkholes. The intensity of sinkholes (No./km^2) is likely to increase in specific areas more than in other areas.

The Potential for backfilled Sinkholes to pollute the Groundwater

- The geochemical model presented in this report for the assessment of backfill impacts, comprising both the near field and far field components, makes use of internationally accepted models and computer codes that do not need further validation. The approach used to predict the effect of gold tailings used as backfill on the dolomite aquifer quality, can also be used to assess the relative effect of different sources of contamination (e.g. backfilled sinkholes versus tailings dams). The approach makes use of recognised test methods for calibration of the model parameters. Individual aspects of the model have been calibrated based on laboratory tests or literature values.

- The Near Field Model (NFM) results indicate that with the possible exception of uranium, the leachate quality from the gold tailings backfill does not pose a significant health risk to humans that use the aquifer in future. The human health risk from heavy metal poisoning due to groundwater consumption is mitigated by the high pH buffering capacity of the dolomite water which ensures that any dissolved metals entering the aquifer, if not dilluted, will be readily precipitated and hence immobilised, keeping heavy metal concentrations below levels that could be unsafe for human consumption.

- The Near Field Model showed that uranium could exist in the aqueous form under both acidic and alkaline conditions, only the speciation varied. A uranium concentration as high as 310 mg/ℓ is possible to achieve based on the thermodynamic model for the backfilled sinkhole.

- The Far Field Modelling was undertaken to establish whether uranium was indeed a potential health risk and if so, under what conditions a uranium pollution plume would develop.

- The FFM showed that the backfilling of single isolated sinkholes with gold tailings cannot adversely affect dolomite water quality with respect to uranium, irrespective of the uranium leachate concentration.

- The backfilling of clusters of sinkholes (comprising say 30 or more sinkholes in a 1 km^2 area) could result in the development of a uranium pollution plume over time, depending on the uranium leachability. The more extensive the cluster, and the more concentrated the sinkholes in geographic extent, the greater the risk of pollution.

- Uranium leachability is the single most important factor in deciding the sustainability and hence acceptability of using gold tailings to backfill sinkholes from a pollution potential point of view. Provided that the uranium leachability is below 0.8 mg/ℓ, the risk of pollution levels increasing above background by more than the SAWQ guideline level of 0.07mg/ℓ is insignificant. The WHO guideline value of 0.002 mg/ℓ U has a higher risk of being exceeded, uranium leachability in excess of 0.002 mg/ℓ will cause the background water quality to increase in excess of the WHO guideline.

Legal Review

- The legal review showed that the practice of backfilling sinkholes with tailings or mine waste rock is not in compliance with the law. The issue is however complex as a result of historic agreements between the Government and the mining industry and past decisions and precedents.

- Sinkholes will have to be secured for the safety of the public and structures in the close proximity to structures. Furthermore, since open sinkholes are associated with a significant risk of illegal dumping, backfilling of sinkholes appears a logical and appropriate solution. Further consideration to resolve the legality of the backfilling practice will however be required should mine waste materials be used in future for this purpose.

8. RECOMMENDATIONS

The following recommendations are flowing from the project:

- The current law, policies and processes needs to be reviewed and amended to make backfilling of sinkholes with materials that are not harmful to the environment legal and practicable.

- On re-flooding of the dolomitic aquifer, after mining has ceased, a monitoring programme should be devised and implemented to measure the water quality in the aquifer. This would require the drilling of deeps borehole (well be low the depth of sinkholes) and will allow a distinction to be made between the impact of mining and other sources of pollution (e.g. sewage works, stormwater run-off, inflow from upstream compartments, etc.) and the impact resulting from the backfilled sinkholes.

- Monitoring of domestic boreholes in close proximity of areas where there has been extensive backfilling of sinkholes or where there is a need for the backfilling of sinkholes, should be monitored on an annual basis with the appropriate parameters to ensure that the water is safe for domestic use.

- Prior to backfilling of any sinkholes with either gold- or uranium tailings, the tailings should be subjected to the SA Acid Rain Leach test and the suitability of the tailings should be judged by the numbers given in Table 17 above. Should it be found that the material is likely to cause a problem, either a different material with lower leachable uranium concentrations should be sourced or a site specific Far Field Model should be developed.

- It is recommended that tailings dams associated with plants that produced tailings historically used in the backfill of sinkholes be sampled and analysed for total and leachable uranium. If the leachable uranium concentration is below 0.3 mg/ℓ, it may be concluded that there is a insignificant risk to groundwater quality and domestic water users.

- The table below indicates the concentrations of leachable uranium that will cause pollution of the existing background water quality in the Far West Rand exceeding the South African Water Quality uranium guideline for the respective scenarios assessed in this research project.

	LEACHABLE U CONCENTRATION *)
Tailings dams on the dolomite aquifer	> 0.8 mg/ℓ
Clusters of sinkholes	> 6 mg/ℓ
Isolated sinkholes	> 10 mg/ℓ

*) Determined by SA Acid Rain Leach Test

9. REFERENCES

ATSDR [US Agency for Toxic Substances and Disease Registry] (1997): “Toxicological profile for uranium”, Draft for Public Comment, September 1997

Barnard, HC (2000): “An Explanation of the 1:500 000 General Hydrogeological Map – Johannesburg 2526”, Department of Water Affairs and Forestry, South Africa

Beukes, JHT (1987): “Ground movement and the formation of sinkholes due to the partial re-watering of Venterspost Compartment 1975-1978”, Seminar on the Engineering Geological Evaluation of sites on Dolomite, University of Pretoria

Blowes & Jambor (1990): “The pore water chemistry and mineralogy of the vadose zone of sulphide tailings”, Waite Amulet, Quebec, Canada, Appl. Geochem., 5, 327-346

Brink, ABA (1979): “Engineering geology of Southern Africa’, Building Publications, Pretoria

Chamber of Mines of South Africa (1996): “Guidelines for Environmental Protection – The Engineering Design, Operation and Closure of Metalliferous, Diamond and Coal Residue Deposits”, Vol. 1/1979 (Revised 1983 and 1995)

Day, PW & Wagener, F von M (1984): “Sinkholes: Their Geology, Engineering and Environmental Impact”, Proceedings of the first multidisciplinary conference on sinkholes, Orlando/ Florida/ 15 –17 October 1984

De Freitas, MH & Wolmarans, JF (1978): “Dewatering and Settlement in the Bank Compartment of the Far West Rand, South Africa”. Symposium on Water in Mining, Siamos, Granada, Spain

Deutsch, WJ (1997), “Groundwater Geochemistry – Fundamentals and Applications to Contamination”, Lewis Publishers, New York, ISBN 0-87371-308-7

Director of Water Affairs (1960): “Final report of the Interdepartmental Committee on Dolomitic Mine Water: Far West Rand” (unpublished), In: Klegwegt RJ, Pike DR (1982): Surface subsidence and sinkholes caused by the lowering of the dolomitic water table on the Far West Rand

Enslin, JF & Kriel, JP (1959): “Some results obtained from a hydrological study of a dolomitic catchment in the Transvaal, Union of South Africa”, Specialists Conference on Hydrology Yaounde, Camerouns

Enslin, JF & Kriel, JP (1967): “The assessment and possible future use of the dolomitic groundwater resources of the Far West Rand, Transvaal, Republic of South Africa”, International Conference on Water for Peace, Washington, Vol 2, pp 908-18

Enslin, JF, Klegwegt, RJ, Beukes, JHT & Gordon-Welsh, JF (1976): “Artificial recharge of dolomitic groundwater compartments in the Far West Rand Gold Fields of South Africa, Geological Survey, Department of Mines, Pretoria, Republic of South Africa

Erasmus, E (2000): Personal Communication

Fleisher, JNE (1981): “The Malmani subgroup in the south-western Transvaal, Republic of South Africa”, PhD Thesis, University of the Orange Free State

Gilman, AP, Villeneuve, DC, Secours, VE, et al. (1998): ”Uranyl nitrate: 28-day and 91-day toxicity studies in the Sprague Dawley rat”, Toxicological Sciences, Vol.41 No1 (Jan), 1998, p.117-128

Hodgson, FDI, Usher BH, Scott, R, Zeelie, S, Cruywagen, L-M & de Necker, E (2001): “Prediction techniques and preventive measures relating to the post-operational impact of underground mines on the quality and quantity of groundwater resources”, WRC report 699/1/0, ISBN No. 1 86845 701 X

IAEA (1989): “In situ leaching of uranium: Technical, Environmental and Economic Aspects”, IAEA-TECHDOC-492, IAEA, Vienna

Jacob, P, Prohl, G, Schneider K, Vol, J-U (1997): “Machbarkeitsstudie zur Verknuepfung der Bewertung radiologischer und chemisch-toxischer Wirkungen von Altlasten”, Umweltbundesamt der Bundesrepublik Deutschland

Kleywegt RJ & Pike DR (1982): “Surface subsidence and sinkholes caused by the lowering of the dolomitic water table on the Far West Rand Gold Fields of South Africa”, Ann Geol Surv S Afr (16): 77-105

Kleywegt RJ, Roux P & Beukes JHT (1986): “Dolomitic ground water problems on the Far West Rand”, Geocongress 1986

Knight, K (1964): “An estimate of the total quantity of water abstracted from the Oberholzer Dolomitic Compartment up to the end of 1964, and possible rate of replacing the water”, In: Brink, ABA & Partridge, TC (1965):”Transvaal Karst: Some considerations of development and morphology, with special reference to sinkholes and subsidences on the Far West Rand”, South African geography J., 47, p.11-34

McDonald-Taylor, CK, Bhatnagar MK, Gilman A, et al. (1992): “Uranyl nitrate induced glomerular basement membrane alterations in rabbits: A quantitative analysis”, Bull. of Environ. Contamination and Toxicology, Vol.48, No.3, p. 367-373

Ortega, A, Domingo JL, Llobet, JM et al. (1989): “Evaluation of the oral toxicity of uranium in 4 week drinking water studies in rats”, Bull. of Environ. Contamination and Toxicology, Vol.42, No.6, p. 935-941

Schwartz, HI & Midgley, DC (1975): “Evaluation of geohydrological constants for the Far West Rand dolomitic formations”, Civil Eng. in South Africa, Feb. 1975

Sociamedia (2001):”Uranium radiation properties”, www.sociamedia.nl/~wise/uranium/u-tox.html

Sociamedia (2001):”Uranium toxicity”, www.sociamedia.nl/~wise/uranium/rup.html

Taute, AH & Tress, PW (1971): “De-watering of the flooded undergroud workings in the Bank Compartment”, South African Mining and Engineering Journal, Vol. 8.3, Number 4061, pp 23–45

Till, JE & Meyer HR (1983): “Radiological Assessment – A textbook on Environmental Dose Analysis”, United States Nuclear Regulatory Commission, Washington DC, NUREG/CR-3332

Vegter (1987): “Constraints of utilization of groundwater resources in dolomitic strata in South Africa”, 2nd Multidisciplinary Conference on Sinkholes and the Environmental Impacts of Karst, Orlando, Florida, USA

WHO [World Health Organisation] (1998): “Guidelines for Drinking Water Quality”, Second edition, Addendum to Volume 2: Health Criteria and Other Supporting Information, WHO/EOS/98.1, Geneva1998

Wolmarans, JF (1984): “Dewatering of the dolomitic area on the Far West Rand: Events in perspective (in Afrikaans), DSc Thesis, University of Pretoria, South Africa

---

APPENDIX A

AN ASSESSMENT OF THE IMPACTS ON GROUNDWATER QUALITY ASSOCIATED WITH THE BACKFILLING OF DOLOMITIC CAVITIES WITH GOLD MINE TAILINGS

- NEAR FIELD MODEL -

FINAL REPORT TO THE WATER RESEARCH COMMISSION

BY

RH Boer*, S Dill and AR James****

* Ferret Mining & Environmental Services (Pty) Ltd, PO Box 72313, Lynnwood Ridge, 0081, South Africa

** Metago Environmental Engineers (Pty) Ltd, PO Box 1596, Cramerview, 2060, South Africa

APPENDIX TO WRC REPORT NO 1122/1/07

EXECUTIVE SUMMARY

The theoretical predictive modelling of the behaviour of the geochemical system yielded a number of important points to consider when developing a strategic rehabilitation scenario for the backfilling of sinkholes in dolomitic terrain, using gold mine tailings material. The main findings could be explained in a logical manner, based on first principles:

- The outer rim of backfill material reacts to produce AMD. However, the large volume encapsulated within this shell of oxidized material is almost unaffected by oxidation reactions and does not contribute towards the load of salts emanating as seepage. The availability of oxygen dictates the extent to which AMD from within the tailings-filled sinkholes. By implication, there is a correlation between the extent of the oxidized zone and the volume of AMD generated. Furthermore, the implication is that flushing of the system is not a rehabilitation option, since new un-oxidized material would be exposed continuously, resulting in a steady supply of AMD;

- The flow rate is a critical factor in determining the water quality emanating from a specific environment / geochemical node. The tailings material requires time to interact with the passing fluids in order to let water-rock reactions proceed. The different flow rates studied clearly show that the rate of flow is a critical parameter during any rehabilitation scenario planning, since this is one of the few parameters that could be controlled in a practical manner. When considering these scenarios, a clear distinction must be made between concentration of chemical species in solution and the cumulative load of species in solution;

- The adsorption of metals onto the surfaces of secondary minerals is an important scavenging mechanism, which reduces the concentration in effluent. Low pH conditions keep the secondary minerals in solution; and

- In terms of the radioactive elements, only the uranium-bearing species were tested. The majority of uranium-bearing species are insoluble at pH values above 7. However, one of the more common uranium hydroxide species is extremely soluble under alkaline conditions. Thus, uranium would migrate under the same physico-chemical conditions that would be favourable for the inhibition of toxic heavy metal migration.

The geochemical modelling results indicate that, in general, the water, which would eventually mix with the groundwater, would be of relative good quality. There is, thus, little concern for maintaining the water quality standards at acceptable levels. However, from a water quality perspective the major

concern emanating from this investigation would be the mobility of uranium species under the given near-neutral conditions.

It is recommended that future investigations into the conditions relating to the sinkholes in dolomitic terrain should focus on the rate at which dolomitic host-rock would be consumed in the chemical reactions, i.e. the rate of sinkhole formation, instead of the water quality emanating from the sinkholes. Thus, the structural aspects that dictate the rate of sinkhole formation and the subsequent collapse of the sinkholes deserve more attention.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

1.1. BACKGROUND INFORMATION

The Water Research Commission project K 5/1122 is concerned with the assessment of impacts on groundwater quality associated with the backfilling of dolomitic cavities (“sinkholes”). Tailings material from the gold and uranium mines was identified in the early stage of the project as the most likely source of backfill material to be used in the Far West Rand (FWR).

The scope of work for the project included an assessment of both, the potential pollution impact on the groundwater quality in close proximity of a backfilled sinkhole (“the Near Field Model”) and the regional effect of backfilled sinkholes on the groundwater quality in the dolomite aquifer of the Far West Rand (“the Far Field Model”). This report presents the potential pollution impact arising from a single backfilled sinkhole. The assessment was undertaken by means of geochemical modelling.

This document forms Appendix A of the main report (Metago report 115-002, “The Assessment of Impacts on Groundwater Quality Associated with the Backfilling of Dolomitic Cavities with Gold Mine Tailings”, Report No. 3, January 2003”.

1.2. OBJECTIVE OF THIS DOCUMENT

To assess the potential impact on the dolomite aquifer associated with the backfilling of sinkholes with gold mine tailings, the use of geochemical modelling was proposed. Aim of the geochemical model was to determine a “most likely leachate quality” arsing from a sinkhole backfilled with gold mine tailings. The geochemical model of such a backfilled sinkhole considered the path of flow of water that enters the backfill near the top surface, passes through the body of the backfill and then exits the backfill to either:

- Enter the vadose zone, from where it percolates downwards and eventually enters the dolomite aquifer; or
- Enter the dolomite aquifer directly.

As the model describes the contamination impact caused by the leachate arising from a single backfilled sinkhole within close proximity of that sinkhole, the model was termed “Near Field Model” (“NFM”).

To consider the regional effect that numerous backfilled sinkholes may have on the water quality in the dolomite aquifer, the NFM was followed by the “Far Field Model” (“FFM”). The FFM builds on the findings of the NFM and is described in detail in Appendix B of the main report.

2. METHODOLOGY

2.1. OBJECTIVE

The primary objective of this project was to establish whether the practice of backfilling dolomitic cavities (sinkholes) with tailings material is likely to have an impact on the water quality of the dolomite aquifer in the Far West Rand.

2.2. METHODOLOGY

The modelling was performed according to the principles stipulated in the conceptual model. The various types of water – rock interactions mentioned in the conceptual model were addressed. These include the following:

- Interaction between inflowing water and fill material within the sinkhole;
- Upper aerobic zone of the backfill
- Lower anaerobic zone of the backfill
- Migration of leachate through the unsaturated zone, upon exiting the backfill;
- Mixing of leachate with water in the dolomitic aquifer, and assessment of the impact of backfill leachate on ground water quality.

Key components of the modelling that were undertaken are:

- Determination of the generation of acidity, sulphates and heavy metals from the source term, i.e. filled sinkholes;
- Transport of this acidity away from the source term into the dolomitic compartments through groundwater flow paths;
- Neutralisation of the acidity with concomitant dissolution of the dolomites and precipitation of secondary minerals (including removal of sulphates and metals within these secondary mineral precipitates);
- Resultant quantification of the deterioration of the ground water quality.

The above situation applies to both, the de-watered and re-watered scenarios. Knowledge of the geochemical processes involved, clearly indicates that the first modelling step (generation of acidity) is kinetically driven, while the remaining steps could be equilibrium driven. However, for the purpose of the level of modelling proposed for this assessment, it is considered necessary to undertake the more sophisticated kinetic geochemical modelling to establish the rate of sulphide mineral oxidation. It will be conservatively assumed that all the acid potential is released within the modelling assessment period of 50 years.

For the acid generation, neutralisation studies and precipitation of secondary minerals, the geochemical modelling package “The Geochemist’s Workbench Version 3.0” was used. Available mineralogical and other data was assessed in order to refine the geochemical modelling exercise predictions. Data was sourced from published literature, reports and thermodynamic databases.

2.3. GENERAL REMARKS

One of the objectives of the research project was to establish how the practice of backfilling sinkholes with gold mine tailings impacts the water quality of the dolomite aquifer in the Far West Rand.

For this purpose a three-step conceptual model was developed:

- (1). The first step considered the geochemical interactions of the backfill material with the pore water of the fill material. The pore water will seep through the fill material and exit the backfilled sinkhole as leachate. The leachate will migrate through the unsaturated zone into the dolomite aquifer.
- (2.) The second step of the conceptual model considered the geochemical interactions of the solid phase in the unsaturated zone with the leachate water. After passing the unsaturated zone, the leachate will enter the dolomite aquifer.
- (3.) The third step of the conceptual model considered the effect of the leachate water entering the dolomite aquifer.

The following aspects around the conceptual model were covered for each of the steps in the model:

- Assumptions for the model;
- Elements of the model; and
- Geochemical processes in the model.

3. CONCEPTUAL GEOCHEMICAL MODEL FOR A BACKFILLED SINKHOLE

A conceptual geochemical model was developed for a sinkhole backfilled with gold mine tailings (Figure 1). The gold tailings in the Far West Rand generally contain pyrite and are therefore prone to the generation of Acid Mine Drainage (AMD) when in contact with the atmosphere. Radionucludes, particularly uranium, also form part of the ore body. Uranium is therefore present in the tailings material in varying concentrations.

Both, the AMD generation potential and the presence of uranium in the gold tailings material used to backfill the sinkholes could pose a pollution problem to the groundwater in the dolomite aquifer. The aim of the geochemical model is to predict the expected water quality in the dolomite aquifer in close proximity of a backfilled sinkhole.

For the purpose of this exercise the conceptual geochemical model covered the following aspects:

- Water in contact with the backfill in the aerobic (upper) zone of the backfill
- Water in contact with the backfill in the anaerobic (lower remaining) zone of the backfill
- Water in contact with the dolomite rock in the unsaturated zone
- Water in contact with the groundwater in the dolomite aquifer

The conceptual model is presented in Figure 1.

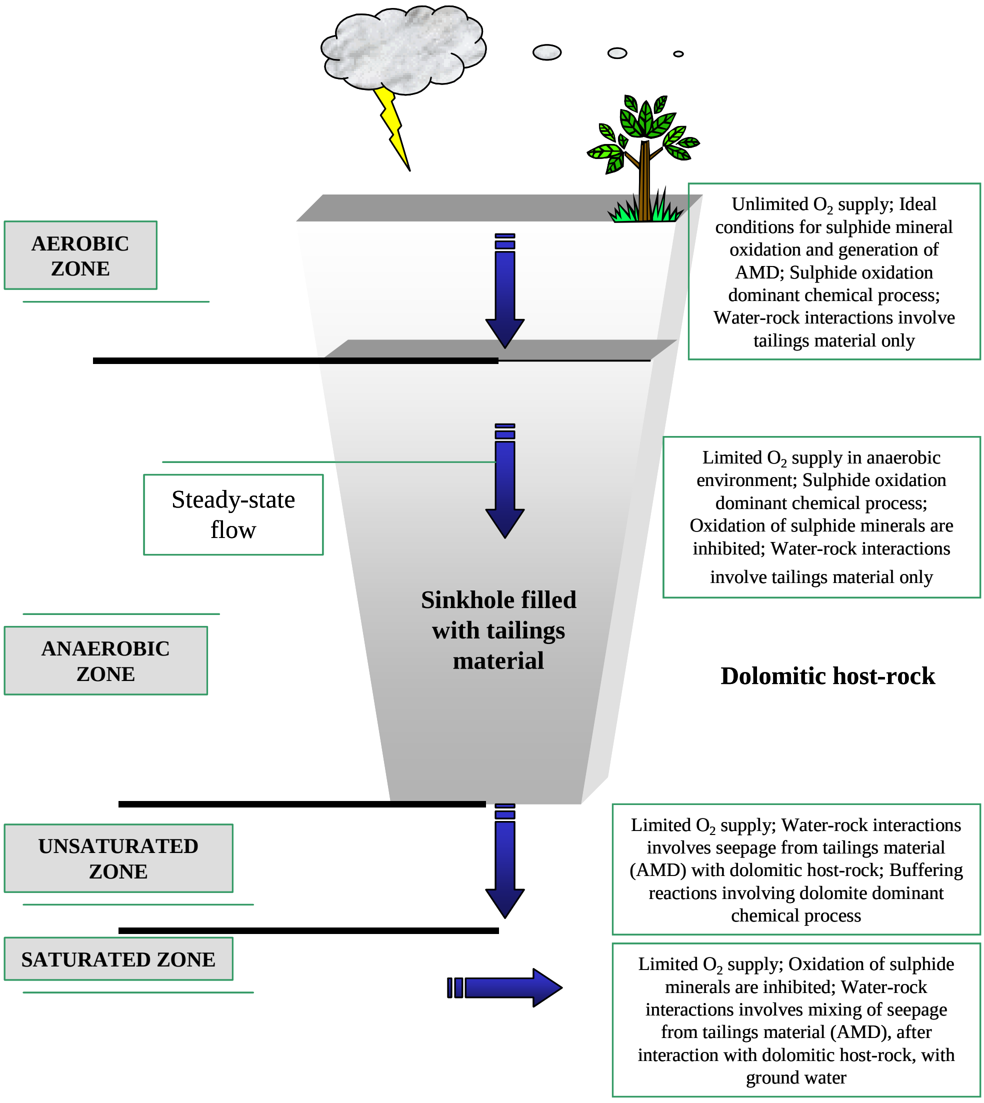


FIGURE 1: SUMMARY DIAGRAM OF THE CONCEPTUAL MODEL FOR THE DOLOMITE-HOSTED SINKHOLES FILLED WITH REACTIVE SULPHIDE-BEARING GOLD MINE TAILINGS MATERIAL

3.1. MODEL STEP I: WATER IN CONTACT WITH THE BACKFILL IN THE SINKHOLE

The model sinkhole under consideration is backfilled with gold mine tailings material. Water will enter the sinkhole and move downwards through the backfill by gravity. The model sinkhole with a depth of 15 metres is situated in the unsaturated zone. The material surrounding the sinkhole is soil in the upper zone followed by unsaturated dolomite rock.

The contact zone of the sinkhole with the surrounding material constitutes a potential preferential flow path for water percolating through the sinkholes causing erosion and wash-out of material leading to instability of the sinkholes at the edges. The erosion may cause the growth of the sinkhole in lateral direction. Although a large volume of water ingressing into the sinkhole may be lost to preferential flow, the model will consider water migration through the entire column of backfill only, as this water will contain the highest contamination concentration. The water recharging the sinkhole is assumed to be rain water. The water quality of the rainwater used for the modelling exercise is presented in Table 1. The composition of the backfill material in the model was based on published data (Table 2 & 3).

TABLE 1: COMPOSITION OF THE RAINWATER RECHARGING THE MODEL SINKHOLE

pH	6.25	log fCO2(g)	-4.0
		fO2(g)	0.3
	[mg/kg]		**[mg/kg]**
Ca	2.0	SiO_2 (aq)	0.2
Mg	2.0	HCO3	1.0
Na	6.0	Cl	1.0
K	1.0	SO4	5.0
Al	0.001	HPO4	0.0001
Fe	0.025	F	0.0001
Mn	0.025		

The water ingresses into the pore space of the backfill in the sinkhole. Here the water will interact with the gas phase and the surface of the fill material particles. After passing through the fill material to the bottom of the sinkhole, the pore water will exit the sinkhole as leachate.

TABLE 2: **TYPICAL ANALYTICAL VALUES FOR SIGNIFICANT ELEMENTS AND MINERALS IN WITWATERSRAND AURIFEROUS REEF MATERIAL (AFTER FEATHER & KOEN, 1975. MINERALS SCI. ENG. VOL. 7, NO. 3, PP. 189 – 224)**

	Sample 1	**Sample 2**
Au (ppm)	50	44
Ag (ppm)	8	5
U_3O_8 (ppm)	870	290
Muscovite [%]	4.4	3.0
Pyrophyllite [%]	0.1	0.2
Chlorite {%]	0.8	4.9
Quartz [%]	88.3	88.9
Titanium [%]	0.1	0.1
Zircon [%]	0.1	0.2
Chromite [%]	0.2	0.2
Pyrite [%]	6.6	3.2

TABLE 3: **APPROXIMATE MINERAL COMPOSITION OF THE SLIMES FROM A TYPICAL SLIMES DAM AND ESTIMATED RANGES CONTAINED IN SUCH A SLIMES DAM (FROM AVMIN REPORT: LGM/MINLAB/659)**

Mineral	**Mass [%]**	
	Specific sample	**Range**
Quartz	75	25-90
Muscovite	10	2-20
Pyrophyllite	10	5-75
Chlorite	5	1-10
Pyrite	Nd	<5
Iron oxide hydroxide hydrates	Nd	<5
Iron sulphate hydrates	Nd	<5
Calcium carbonate	Nd	<0.5
Calcium sulphate hydrates	1	0.5-2
Sodium chloride	0.1	<0.2

Model elements:

- The water entering the sinkhole
- The solid phase of the tailing material used as backfill in the sinkhole
- The gas phase in the tailings material

Model assumptions:

- The water entering the sinkhole is clean water (no significant concentration of any chemical compound) of slightly acidic to neutral pH;
- The sinkhole is covered with a cap made from gravel or compacted soil to avoid washout of the tailings material by surface run-off;
- The impact on the water quality related to the chemical reactions of the capping material with the water entering the sinkhole are considered insignificant and are therefore excluded from this model;
- A number of different materials and mixtures of the respective materials have been used for the backfilling of sinkholes. The backfill material considered in the conceptual model is limited to gold mine tailings material as the sole material used, which constitutes a conservative case;
- The solid phase in the sinkhole is tailings material only. The tailings material has a high specific surface area due to the fine grade of the material;
- The tailings material in the sinkhole consists of two zones, a) the upper (aerobic/anoxic) zone and b) the lower (anaerobic) zone;
- The pore space in the backfill of the sinkhole is low due to compaction and/or consolidation of the material during backfill;
- The upper zone of the tailings material loses water to the atmosphere due to evapotranspiration and is considered unsaturated;
- The lower zone of the borehole has a higher moisture content and is considered partially saturated;
- The gas phase in the pore space in the upper zone is similar to the atmosphere providing oxidising conditions (Eh above 0 mV);
- The gas phase in the pore space of the lower zone has a low oxygen concentration due to depletion by oxidation processes and a high carbon dioxide concentration providing reducing conditions (Eh below 0 mV);
- If the tailings material in the sinkhole contains pyrite, pyrite oxidation will occur in the upper zone of the sinkhole. Depending on the neutralisation potential of the tailings material the upper zone may turn acid with time;
- In the case of the upper zone of the backfill turning acidic, tailings material may weather faster due to the aggressive nature of the pore water and material loss due to dissolution and wash–out will occur;
- From a chemical point of view this is likely to increase the pore volume and accelerate the rate of acid formation, as a larger surface area of acid forming tailings material will be exposed to

the atmosphere. From a physical point the material will lose strength, potentially causing instability of the backfill;

- In the case of the fill material in the upper zone staying alkaline over time the pore space in the upper zone will decrease due to the formation of the metal hydroxides. The reduction of pore space may also decrease the ingress of water into the sinkhole backfill with time; and
- The water will migrate through the backfill material and exit the sinkhole as leachate at the bottom, entering the unsaturated zone underneath the sinkhole.

Geochemical processes in the model:

- Interaction of the pore water with the gas phase in the backfill
- Interaction of the pore water with the tailings material
- Pore water – dolomite interaction

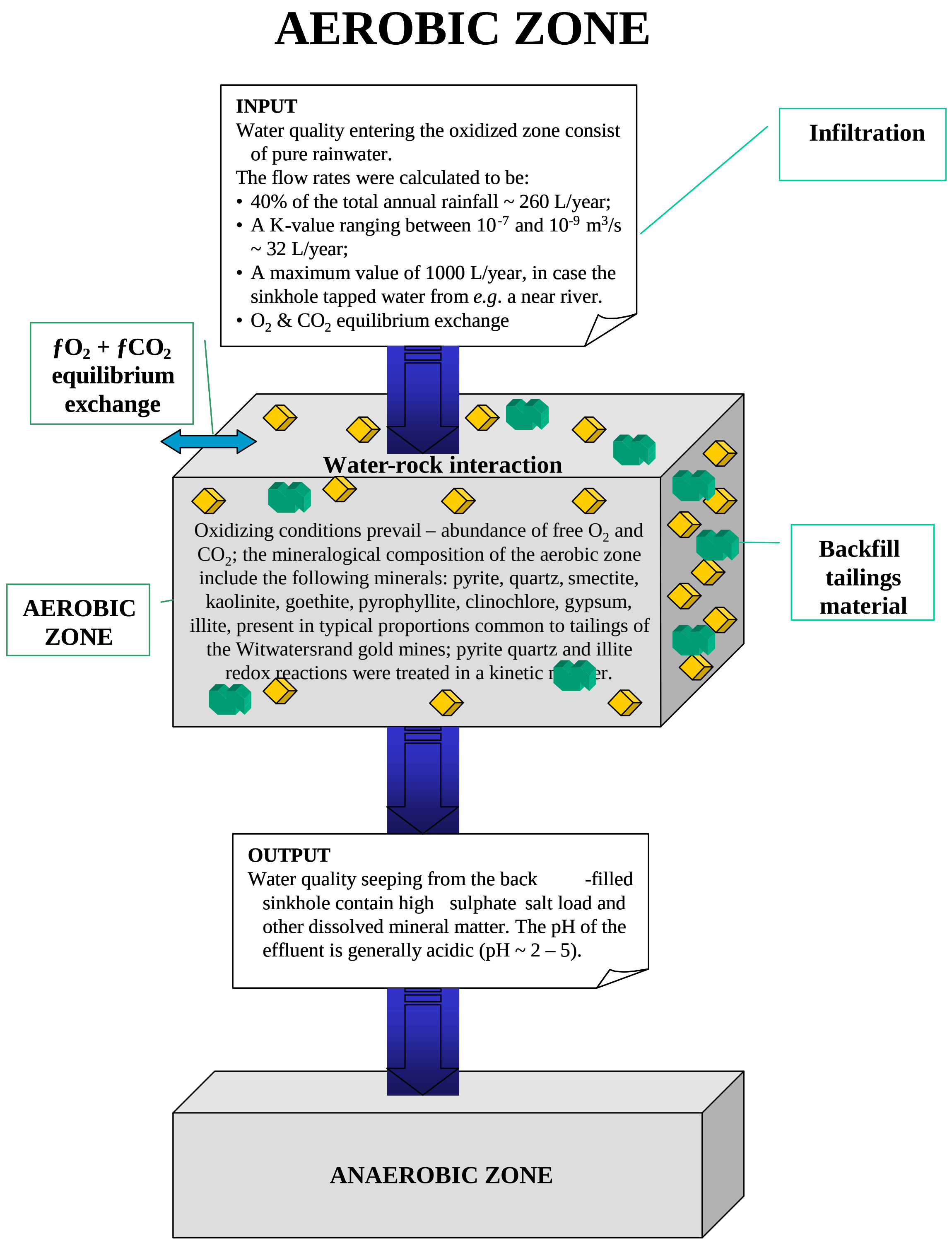
Sources of clean water entering the sinkhole are rainfall, surface run-off or shallow groundwater, e.g. seepage from surface water bodies such as the Wonderfontein Spruit.

3.1.1. UPPER AEROBIC ZONE OF THE BACKFILL

The expected characteristics of the conditions that prevailed in the upper zone of the dolomitic cavities include the following:

- The presence of oxygen in the pore volume of the tailings will lead to oxidation of chemical compounds - redox reactions;
- The oxidation of chemical compounds will lead to the formation of metal oxyhydroxides, particularly iron, aluminium and manganese hydroxides - dissolution / precipitation reactions;
- Pyrite present in the tailings material, will oxidise causing the release of sulphate and acid - ion exchange reactions;
- If the neutralising potential of the tailings material is lower than the acid generating potential, the pore water will turn acidic;
- The production of sulphuric acid will result in the pore water being a considerably more aggressive weathering solution;
- If the neutralising potential of the tailings material is higher than the acid generating potential, the pore water will remain alkaline;
- The reaction of calcium and magnesium carbonates with the sulphate in the acidic pore water will result in the formation of magnesium and calcium sulphate with an excess of anionic carbonates;
- The increase of anionic carbon species (carbonate and bicarbonate) will enhance ionic complexation, resulting in precipitation of complexed compounds;
- The chemical complexation by carbonate and bicarbonate will reduce the major cation and metal concentrations in the pore water.

The conceptual geochemical model for the aerobic zone is depicted in Figure 2.



INPUT

Water quality entering the oxidized zone consist of pure rainwater.

The flow rates were calculated to be:

- 40% of the total annual rainfall ~ 260 L/year;
- A K-value ranging between 10^{-7} and 10^{-9} m^3/s ~ 32 L/year;
- A maximum value of 1000 L/year, in case the sinkhole tapped water from *e.g.* a near river.
- O_2 & CO_2 equilibrium exchange

Oxidizing conditions prevail – abundance of free O_2 and CO_2; the mineralogical composition of the aerobic zone include the following minerals: pyrite, quartz, smectite, kaolinite, goethite, pyrophyllite, clinochlore, gypsum, illite, present in typical proportions common to tailings of the Witwatersrand gold mines; pyrite quartz and illite redox reactions were treated in a kinetic r er.

OUTPUT

Water quality seeping from the back-filled sinkhole contain high sulphate salt load and other dissolved mineral matter. The pH of the effluent is generally acidic (pH ~ 2 – 5).

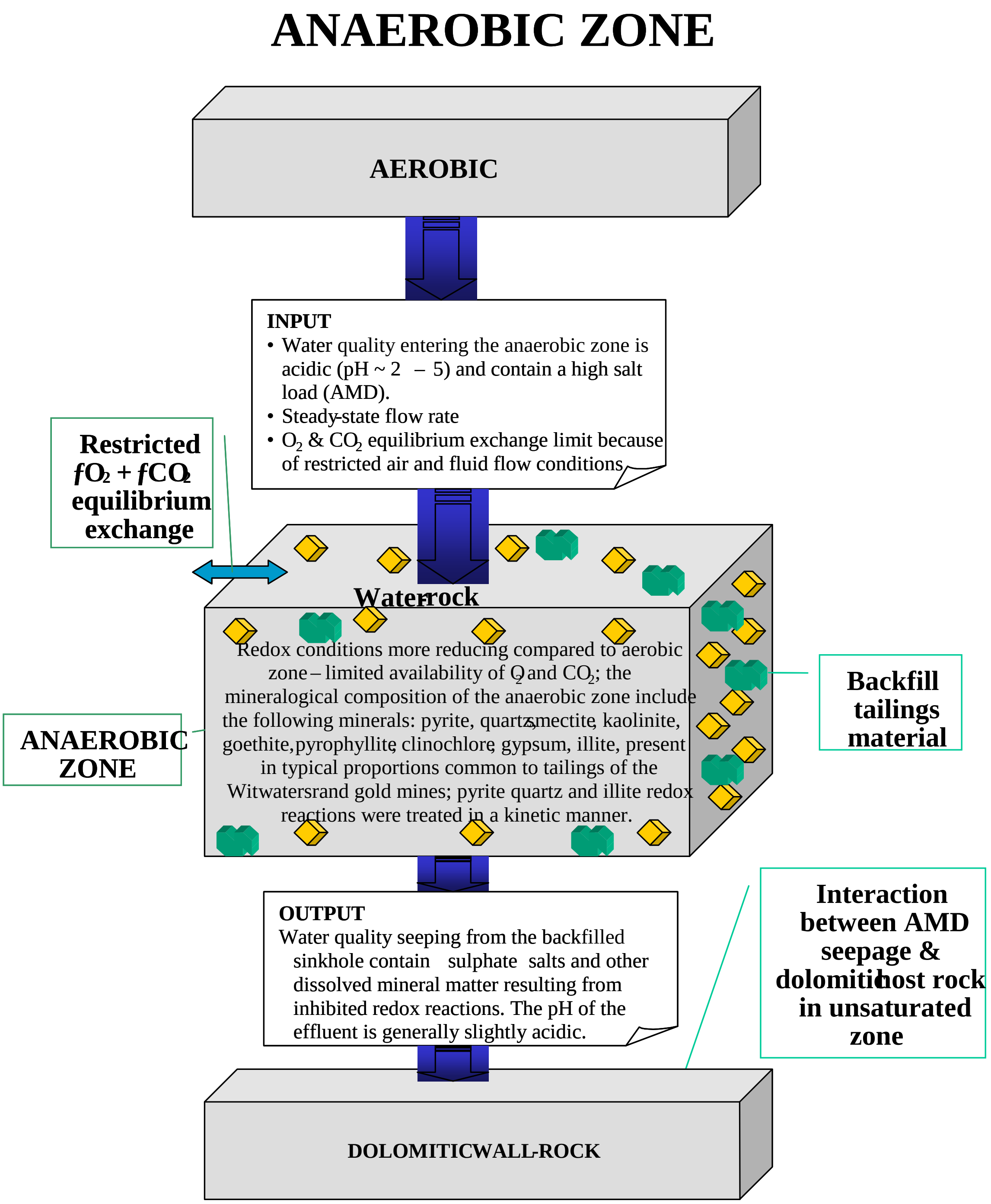
FIGURE 2: CONCEPTUAL GEOCHEMICAL MODEL FOR THE AEROBIC ZONE OF A BACKFILLED SINKHOLE

3.1.2. LOWER ANAEROBIC ZONE OF THE BACKFILL

The expected characteristics of the conditions that prevailed in the lower, oxygen deficient zone of the backfill include the following:

- The presence of oxygen in the pore volume of the tailings material will reduce rapidly and the effects of oxidation reactions will become insignificant; depending on the partial oxygen and carbon dioxide pressures specified;
- Leaching of chemical compounds in the lower zone of the backfill will largely depend on the pH of the pore water resulting from the passage of the water through the upper zone of the sinkhole;
- If the pore water from the upper zone of the sinkhole is acidic and the neutralising potential in the tailings material in the lower zone of the sinkhole is lower than the acid content of the pore water, the pore water will remain acidic;
- The acidic pore water will leach chemical compounds from the tailings material, causing an increase of chemical compounds in the pore water, potentially rendering the pore water contaminated;
- If the pore water from the upper zone of the sinkhole is neutral, the pore water will remain alkaline as no (or very little) acid generation will occur in the lower zone of the sinkhole due to the limitation of oxygen;
- In the case of neutral pore water the concentrations of major cations and metals leached from the tailings material are expected to be minor to negligible;
- The reaction of calcium and magnesium carbonates with the sulphate in the pore water (in case of acidic pore water) will result in an excess of anionic carbonates;
- The increase of anionic carbon species (carbonate and bicarbonate) will enhance ionic complexation, resulting in precipitation of complexed compounds;
- The chemical complexation by carbonate and bicarbonate will reduce the major cation and metal concentrations in the pore water.

Based on the geochemical understanding of the tailings material used for backfill, the potential for contamination of the leachate resulting from the backfilled sinkhole is very low as the concentrations of chemical compounds released into the leachate water under anaerobic conditions are minor to negligible. The geochemical concepts that were considered are shown in Figure 3.



- Water quality entering the anaerobic zone is acidic (pH ~ 2 – 5) and contain a high salt load (AMD).
- Steady-state flow rate
- O_2 & CO_2 equilibrium exchange limit because of restricted air and fluid flow conditions

Redox conditions more reducing compared to aerobic zone – limited availability of O_2 and CO_2; the mineralogical composition of the anaerobic zone include the following minerals: pyrite, quartz, smectite, kaolinite, goethite, pyrophyllite, clinochlore, gypsum, illite, present in typical proportions common to tailings of the Witwatersrand gold mines; pyrite quartz and illite redox reactions were treated in a kinetic manner.

Water quality seeping from the backfilled sinkhole contain sulphate salts and other dissolved mineral matter resulting from inhibited redox reactions. The pH of the effluent is generally slightly acidic.

FIGURE 3: CONCEPTUAL GEOCHEMICAL MODEL FOR THE ANAEROBIC ZONE OF A BACKFILLED SINKHOLE

3.2. MODEL STEP II: MIGRATION OF THE LEACHATE THROUGH THE UNSATURATED ZONE

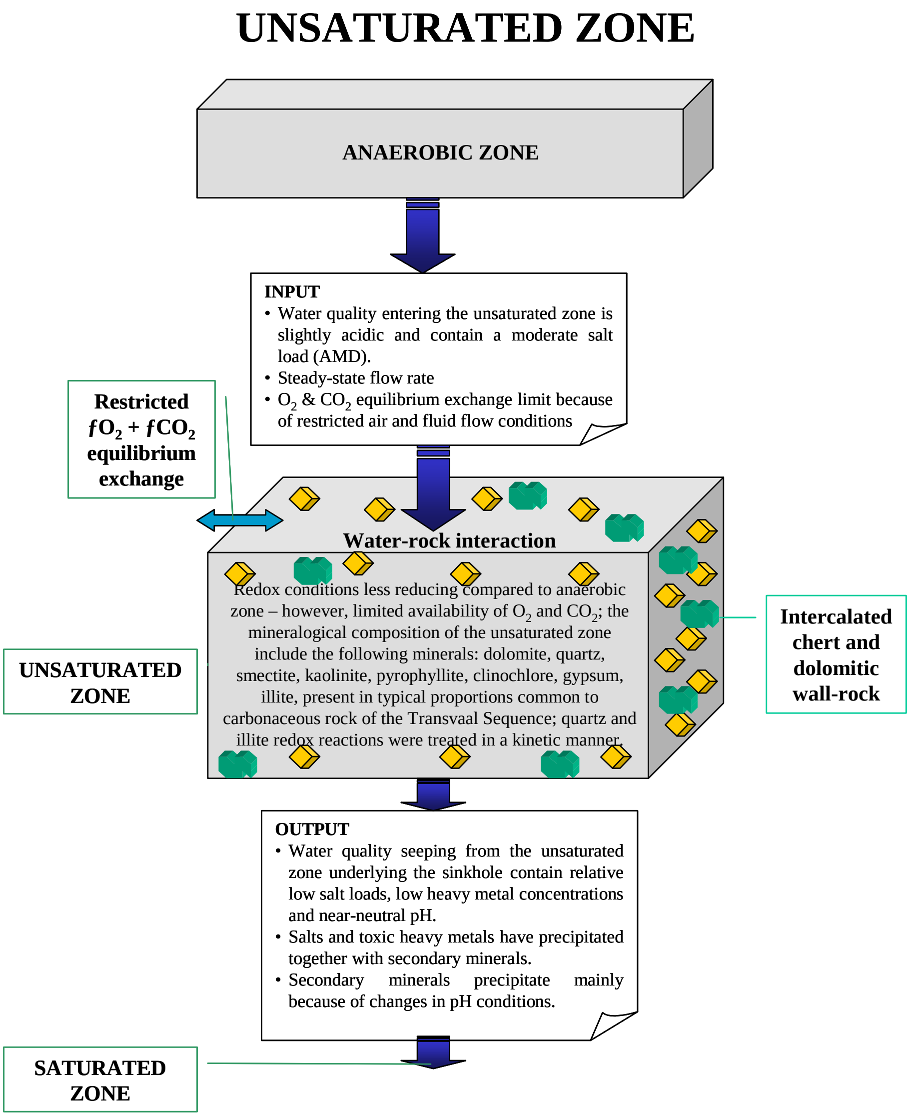
On exiting the sinkhole at the base, the leachate from the sinkhole will enter the unsaturated zone beneath the sinkhole and percolate downwards through the pore space (Figure 4). The leachate will come in contact with the gas phase and the rock surface. Interactions of the water phase with the solid and the gas phase may influence the water chemistry. On passage through the unsaturated zone, the leachate will enter the dolomite aquifer, which is situated beneath the unsaturated zone.

Model elements:

- The leachate from the sinkhole
- The solid phase (dolomite rock) of the unsaturated zone
- The gas phase in the pore space of the unsaturated zone
- Interstitial fluid phase (“connate water”) in dolomite

Model assumptions:

- The leachate entering the unsaturated zone is of neutral to alkaline pH
- The solid phase (the rock) of the unsaturated zone consists of dolomite and associated minerals
- The pore space in the unsaturated zone is higher than the pore space in the backfill of the sinkhole
- Although situated beneath the sinkhole the pore space in the unsaturated zone is mainly filled with air (high oxygen and low carbon dioxide concentration in the gas phase)



INPUT

- Water quality entering the unsaturated zone is slightly acidic and contain a moderate salt load (AMD).
- Steady-state flow rate
- O_2 & CO_2 equilibrium exchange limit because of restricted air and fluid flow conditions

Redox conditions less reducing compared to anaerobic zone – however, limited availability of O_2 and CO_2; the mineralogical composition of the unsaturated zone include the following minerals: dolomite, quartz, smectite, kaolinite, pyrophyllite, clinochlore, gypsum, illite, present in typical proportions common to carbonaceous rock of the Transvaal Sequence; quartz and illite redox reactions were treated in a kinetic manner.

OUTPUT

- Water quality seeping from the unsaturated zone underlying the sinkhole contain relative low salt loads, low heavy metal concentrations and near-neutral pH.
- Salts and toxic heavy metals have precipitated together with secondary minerals.
- Secondary minerals precipitate mainly because of changes in pH conditions.

FIGURE 4: **CONCEPTUAL GEOCHEMICAL MODEL FOR THE UNSATURATED ZONE**

Geochemical processes in the model:

- Interaction of the leachate with the gas phase
- Interaction of the leachate with the dolomite
- Interaction with interstitial fluid phase in undersaturated dolomitic rocks

The most common chemical reactions expected in the leachate water percolating through the unsaturated zone are:

- Presence of oxygen in the pore volume of the unsaturated zone will lead to oxidation of chemical compounds;

- The oxidation of chemical compounds will lead to the formation of metal oxyhydroxides, particularly iron, aluminium and manganese hydroxides;
- If sulphate is present in the leachate the reaction of calcium and magnesium carbonates with the sulphate will result in the formation of magnesium and calcium sulphate with an excess of anionic carbonates;
- The increase of anionic carbon species (carbonate and bicarbonate) will enhance ionic complexation, resulting in precipitation of complexed compounds;
- Fluid mixing and associated processes between the leachate and the interstitial pore water in the dolomite;
- The chemical complexation by carbonate and bicarbonate will reduce potential concentrations of cations and metals n the pore water;
- The chemical complexation by carbonate and bicarbonate will reduce the metal concentrations in the pore water.

3.3. MODEL STEP III: MIXING OF LEACHATE WITH THE WATER IN THE DOLOMITE AQUIFER

Once the leachate has passed through the unsaturated zone, it will enter the dolomite aquifer and mix with the water in the aquifer (Figure 5). It can be safely assumed that the volumes of leachate entering the aquifer are minor compared to the volume of water in the aquifer. This will a) result into a significant factor of dilution for all chemical compounds present in the leachate which are not present in the dolomite water and b) the physico-chemical conditions of the dolomite water will prevail over the physico-chemical conditions of the leachate.

Model elements:

- The dolomite aquifer
- The leachate exiting the unsaturated zone
- Fluid mixing, i.e. leachate and interstitial pore water hosted in dolomitic rocks

Model assumptions:

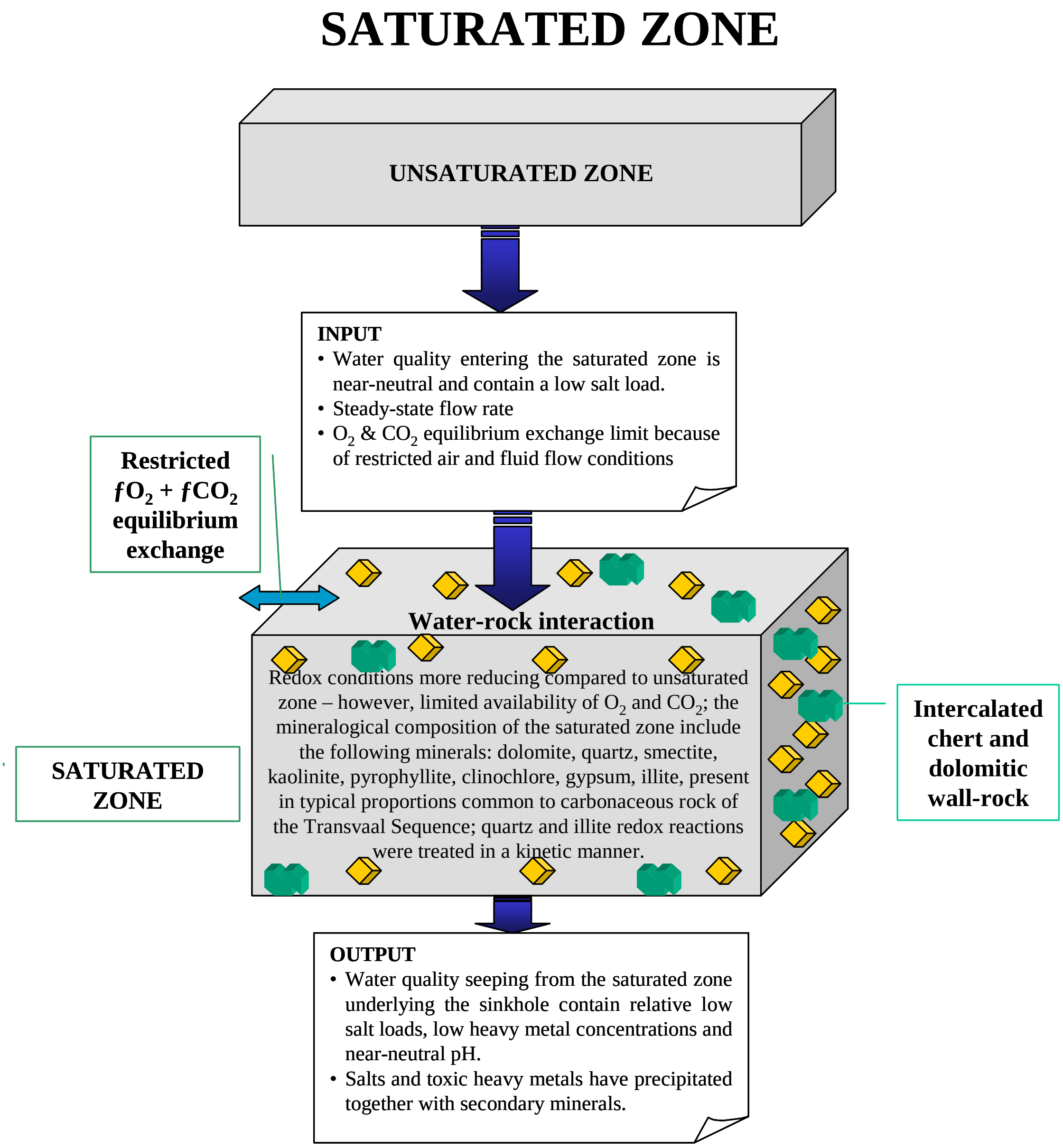
- The solid phase (the rock) of the aquifer consists largely of dolomite
- The dolomite water is of neutral to slightly acidic pH
- Due to saturation the gas phase in the aquifer is negligible
- The quality of the water in the dolomite aquifer is controlled by the dolomite rock
- Interaction between leachate and pore water contained in dolomitic rocks
- The water in the aquifer is in excess compared to the volume of leachate, which recharges from the unsaturated zone.

Geochemical processes in the model:

- Interaction of the leachate with the water in the aquifer

The chemical compounds modelled will be:

- All major anions (sulphate, chloride, etc.)
- All major cations (magnesium, calcium, sodium, potassium and manganese)
- Selected metals (aluminium, iron, cadmium, chrome, copper, lead and zinc)
- Uranium



INPUT

- Water quality entering the saturated zone is near-neutral and contain a low salt load.
- Steady-state flow rate
- O_2 & CO_2 equilibrium exchange limit because of restricted air and fluid flow conditions

Redox conditions more reducing compared to unsaturated zone – however, limited availability of O_2 and CO_2; the mineralogical composition of the saturated zone include the following minerals: dolomite, quartz, smectite, kaolinite, pyrophyllite, clinochlore, gypsum, illite, present in typical proportions common to carbonaceous rock of the Transvaal Sequence; quartz and illite redox reactions were treated in a kinetic manner.

OUTPUT

- Water quality seeping from the saturated zone underlying the sinkhole contain relative low salt loads, low heavy metal concentrations and near-neutral pH.
- Salts and toxic heavy metals have precipitated together with secondary minerals.

FIGURE 5: SUMMARY OF THE IMPORTANT PARAMETERS USED FOR GEOCHEMICAL MODELLING OF THE SATURATED ZONE

4. GEOCHEMICAL MODEL VERIFICATION

Geochemical modelling of a particular system does not result in unique solutions. What complicates the outcome is the degree to which geochemical modelling routines have been calibrated. It is therefore imperative that the role of the sensitive parameters is understood and their influence on the modelling results be quantified. The following exercises were conducted to verify the model.

For the model verification the following modelling exercises were undertaken:

- The effect of pyrite oxidation on the pH in dolomitic groundwater in a closed system vs. an open system
- The effect of rock wall buffering
- The effects of changing activity and fugacity on pyrite dissolution
- The effects of changing activity and fugacity on calcite dissolution
- Mobility of potentially toxic heavy metals
- Mobility of uranium species

4.1. OXIDATION IN BACKFILL MATERIAL

The upper portion of sinkholes in dolomitic terrain is an ideal environment for the oxidation of backfill material, with an abundant supply of oxygen and water. In the absence of atmospheric oxygen, dissolution reactions cause little change in the pH or composition of water. As a separate effect, atmospheric oxygen promotes acid drainage because of its role in the metabolism of bacteria that catalyse both the dissolution of sulphide minerals and the oxidation of dissolved iron. Thus, there is a clear connection between the chemistry of mine drainage and the availability of oxygen (Langmuir D. 1997; *Aqueous Environmental Chemistry*, Prentice Hall, New Jersey, pp. 600). The role of bacterial activity during oxidation has not been considered as part of this exercise. The manner in which provision should be made for bacterial activity allows for prohibitive difficulties and would rather reduce the precision and accuracy of the modelling results. For the purpose of this exercise it was considered more important to be able to compare results emanating from the various modelling routines.

4.1.1. PYRITE OXIDATION IN A CLOSED SYSTEM

In order to investigate the effect of atmospheric oxygen on the oxidation reactions involving pyrite, the following modelling exercise has been constructed. Firstly, a hypothetical groundwater composition was considered, by initially placing the water into contact with the atmosphere dolomite (at 25°C), but which was then instantaneously isolated from the atmosphere. The groundwater was than allowed to react with the tailings material. The formation of the minerals hematite, which does not form directly at low temperature, and goethite was suppressed. Each of these phases is more stable thermodynamically than the ferric precipitate observed to form in acid drainage.

Under this scenario, the initial reaction proceeds as an isolated system until the $O_{2(aq)}$ has been consumed, dissolving a small amount of pyrite according to:

EQUATION 1 $FeS_2 + 7/2O_{2(AQ)} + HCO_3^- \leftrightharpoons Fe^{++} + 2SO_4^{--} + 2CO_{2(AQ)} + H_2O$

The fluids pH in the model changes slightly, decreasing from 6.8 to 6.6, for this particular scenario (Figure 6).

4.1.2. PYRITE OXIDATION IN AN OPEN SYSTEM

Secondly a scenario where the system is open to the atmosphere was considered. In this case, the reaction proceeds without exhausting the oxygen supply, which in the calculation is limitless, driving the pH to a value of approximately 1.7 (Figure 7). In the latter scenario, pyrite oxidation initially proceeds according to the reaction:

EQUATION 2 $FeS_2 + 15/4O_{2(G)} + ½H_2O \leftrightharpoons FeSO_4^+ + SO_4^{--} + H^+$

(Figure 8), producing H^+ and thus causing the water to turn acidic. According to the model, the pyrite dissolution produces ferric iron in an ion pair with sulphate. As the pH decreases, HSO_4^- comes to dominate $SO_4^{--}$and a second reaction becomes important::

EQUATION 3 $FeS_2 + 15/4O_{2(G)} + ½H_2O \leftrightharpoons FeSO_4^+ + HSO_4^-$

The latter reaction produces no free hydrogen ions and hence does not contribute to the fluids acidity.

In nature, at least two aqueous species, $O_{2(aq)}$ and Fe^{+++}, could serve as electron acceptors during the pyrite oxidation. In case of Fe^{+++}, the oxidation reaction proceeds as:

EQUATION 4 $FeS_2 + 14Fe^{+++} + 8H_2O \leftrightharpoons 15Fe^{++} + 2SO_4^{--} + 16H^+$

This reaction, while still not an elementary reaction, more closely describes how the oxidation proceeds on a molecular level (Bethke, C.M. 1996: *Geochemical Reaction Modeling*, Oxford University Press, Oxford, pp.397).

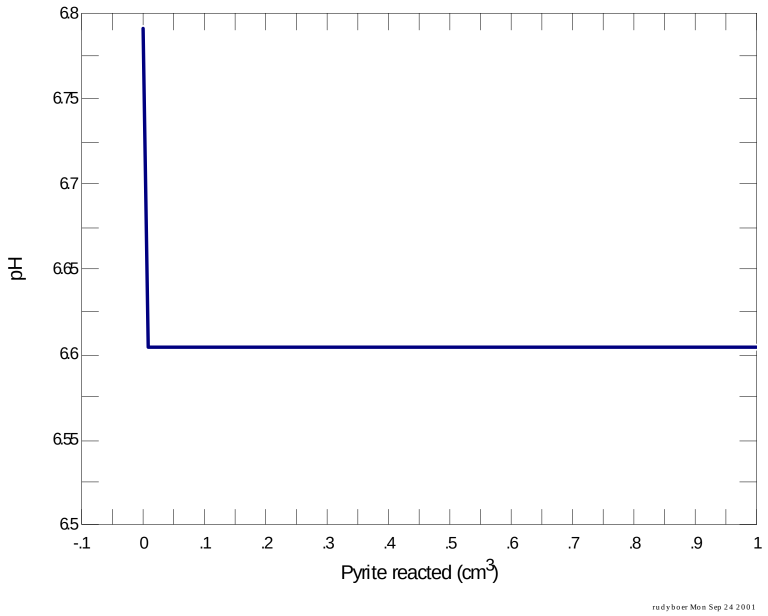


FIGURE 6: CALCULATED VARIATION IN PH DURING REACTION OF PYRITE WITH GROUNDWATER IN CONTACT WITH DOLOMITE AT 25°C ASSUMING THAT THE FLUID WAS NOT IN CONTACT WITH ATMOSPHERIC OXYGEN, I.E. CLOSED SYSTEM

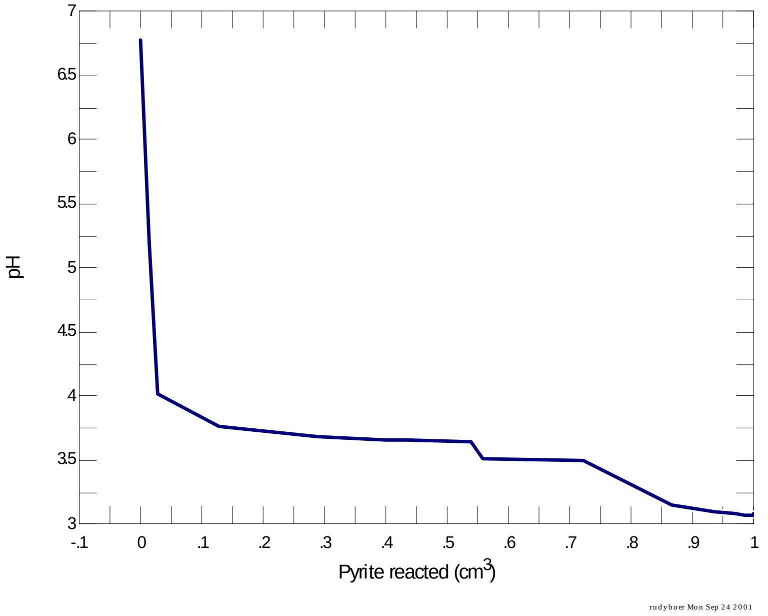


FIGURE 7: CALCULATED VARIATION IN PH DURING REACTION OF PYRITE WITH GROUNDWATER IN CONTACT WITH DOLOMITE AT 25°C ASSUMING THAT THE FLUID WAS IN CONTACT WITH ATMOSPHERIC OXYGEN, I.E. OPEN SYSTEM

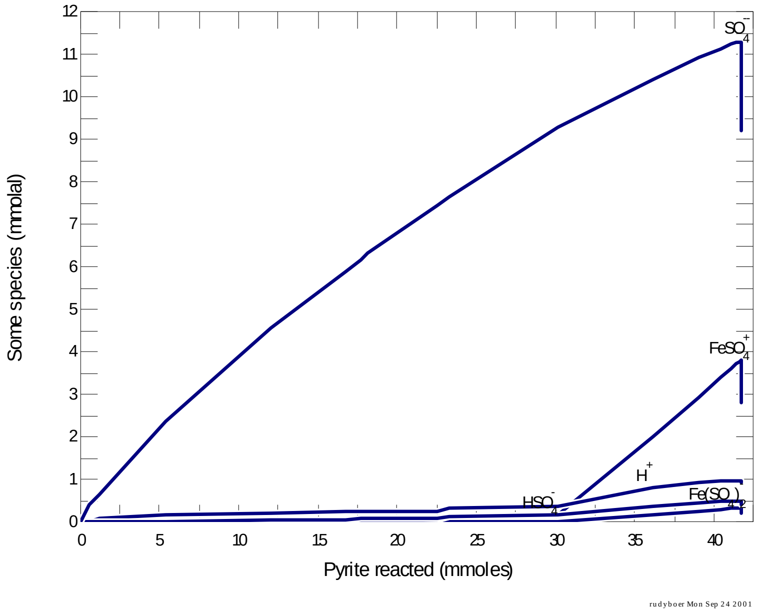


FIGURE 8: **MASSES OF SPECIES PRODUCED BY REACTING PYRITE WITH GROUNDWATER IN CONTACT WITH DOLOMITE IN EQUILIBRIUM WITH ATMOSPHERIC OXYGEN, ACCORDING TO THE REACTION PATH CALCULATED IN FIGURE 7**

Thus, pyrite oxidation and the associated formation of AMD continue to proceed under conditions where oxygen is freely available, such as the top layer in a sinkhole filled with tailings material. However, the outer layer where oxidising conditions prevail reaches approximately 1 – 2 meters into the tailings material. The material inside this encapsulating layer is deprived of oxygen and anaerobic conditions develop. The above section highlights the fact that oxidising reactions would be limited in the anaerobic zone, with less secondary minerals forming and fewer H^+ ions being released.

From the initial exercise it becomes evident that the control (limitation) of oxygen ingress into the backfill is paramount to maintain a good water quality. The open system, where oxygen is not limited, produces a poor water quality of low pH and elevated TDS mainly due to sulphate and iron species.

4.2. THE EFFECT OF WALL ROCK BUFFERING

One of the most important considerations in the predictive geochemical modelling of sinkholes in a dolomitic terrain being filled with tailings material, would be the buffering effect that the carbonate wall rock has on the oxidizing backfill material. Based purely on volumetric considerations it would be expected that the buffering effect of the wall rock material would outweigh the reactive effect of the tailings material. This was checked using the geochemical model.

The main findings are that the reactive tailings material produces an acidic solution that interacts with the dolomitic wall rock material. Instead of an ever-decreasing pH, the acidity of the solution is buffered by the wall rock. This is apparent in Figure 9, which shows that the pH of the solution is only lowered by one unit. Furthermore, it is apparent that none of the reactions result in solutions reaching saturation levels. The solution becomes concentrated in terms of minerals such as jarosite and mirabilite, but these minerals would not precipitate (Figure 10). The components in the fluids increase continuously, in particular the sulphate and carbonate load (Figure 11). In an open system the dilution of the reaction products would assist in ameliorating the problem.

From the second exercise it is evident that the contact of the water with the rock walls will have a strong buffering effect, resulting in a near neutral pH of the water. However, the buffering effect results from a secondary chemical reaction, the dissolution of dolomite in contact with the acid water. Although of neutral pH the resulting water quality is poor due to high TDS caused by sulphate, bicarbonate, calcium and magnesium in the water. Iron is also present in the water although in lower concentrations.

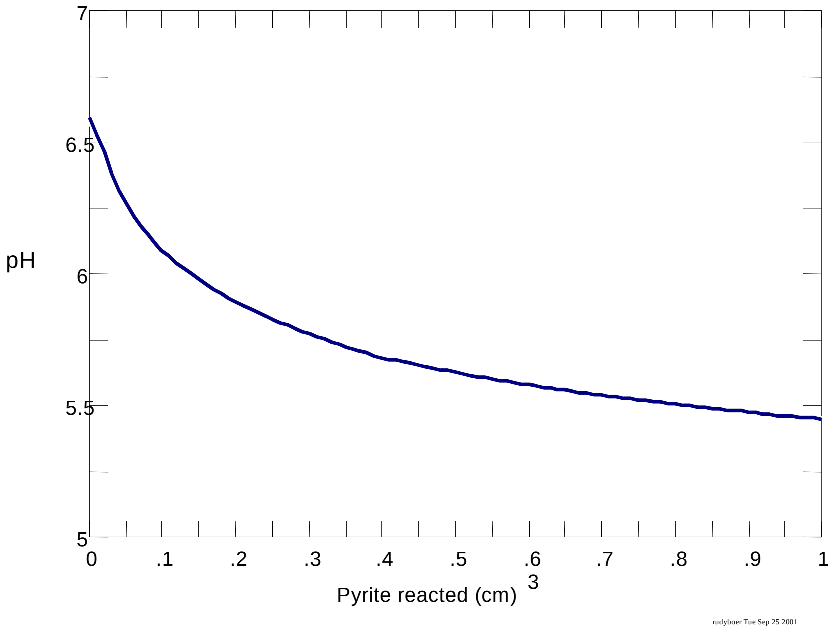


FIGURE 9: VARIATION IN PH DURING THE WATER – ROCK INTERACTIONS INVOLVING WALL ROCKS

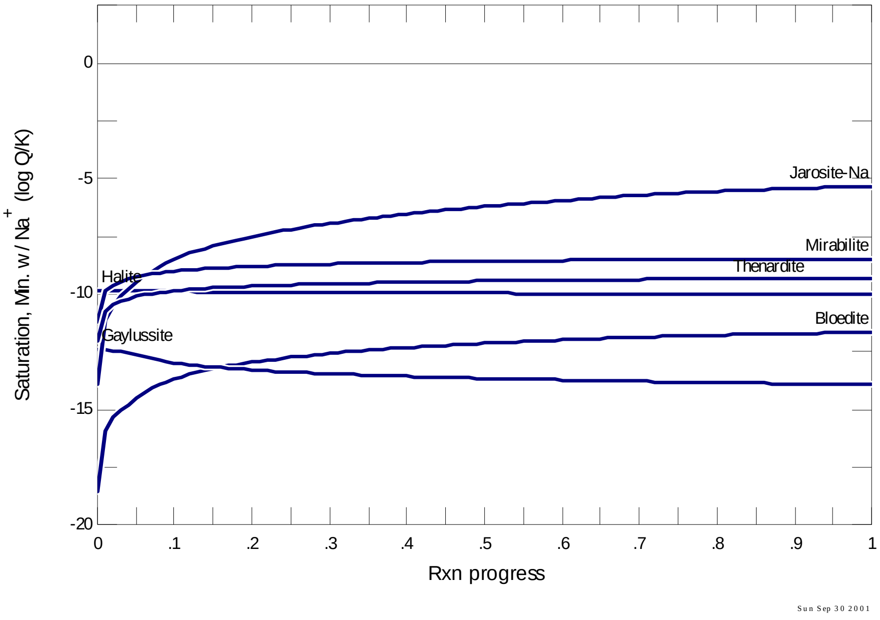


FIGURE 10: MINERAL SATURATION LEVELS IN THE AQUEOUS SOLUTION IN CONTACT WITH THE WALL ROCK

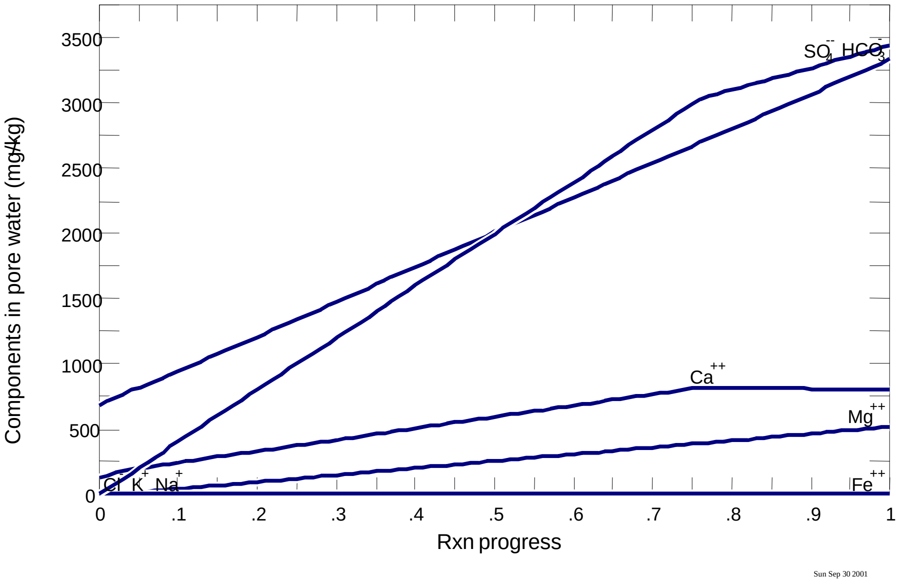


FIGURE 11: CONCENTRATION OF COMPONENTS IN THE FLUID ASSOCIATED WITH WALL-ROCK REACTIONS

4.3. EFFECTS OF CHANGING ACTIVITY AND FUGACITY ON PYRITE DISSOLUTION

In a fixed activity path, the activity of an aqueous species maintains a constant value over the course of the reaction path. A fixed fugacity path is similar, except that the model holds constant a gas fugacity instead of a species activity. However, the latter parameters are seldom fixed in nature (Stumm W. and Morgan J.J. 1970; *Aquatic Chemistry*, Wiley-Interscience, New York, pp.583). The route of a fluid through a backfilled sinkhole migrates through an array of different activity and fugacity environments, as depicted in the conceptual model. Fixing these parameters has advantages in terms of the better understanding of the behaviour of the modelled system. The upper portion of the fluid flow path is dominated by atmospheric conditions. It would thus be appropriate to fix the fugacity conditions in order to trace the reaction path.

The dissolution of pyrite, the main source of AMD in the backfill material, would proceed according to the variation in pH and “mineral mass” as shown in Figure 12, when the oxygen fugacity is *not* fixed. In this particular scenario, 80% of the pyrite dissolves into the water producing hematite. The reaction drives the pH from an initial value of 6.5 to approximately 4 before the water becomes reducing. At this point, the hematite re-dissolves and the fluid reaches equilibrium with pyrite, ending the reaction.

The initial reaction by which hematite forms could be written as follows, as could also be seen from Figure 3:

EQUATION 5 $$4\,FeS_2 + 15O_{2(aq)} + 16\,HCO_3^- \leftrightarrows 2\,Fe_2O_3 + 8SO_4^{--} + 16CO_{2(aq)} + 8H_2O$$

As the water becomes more acidic and the supply of HCO_3^- is depleted, a second reaction becomes dominant:

EQUATION 6 $$4\,FeS_2 + 15O_{2(aq)} + 8H_2O \leftrightarrows 2\,Fe_2O_3 + 8SO_4^{--} + 16H^+.$$

Pyrite continues to dissolve until the available O_2(aq) has been consumed.

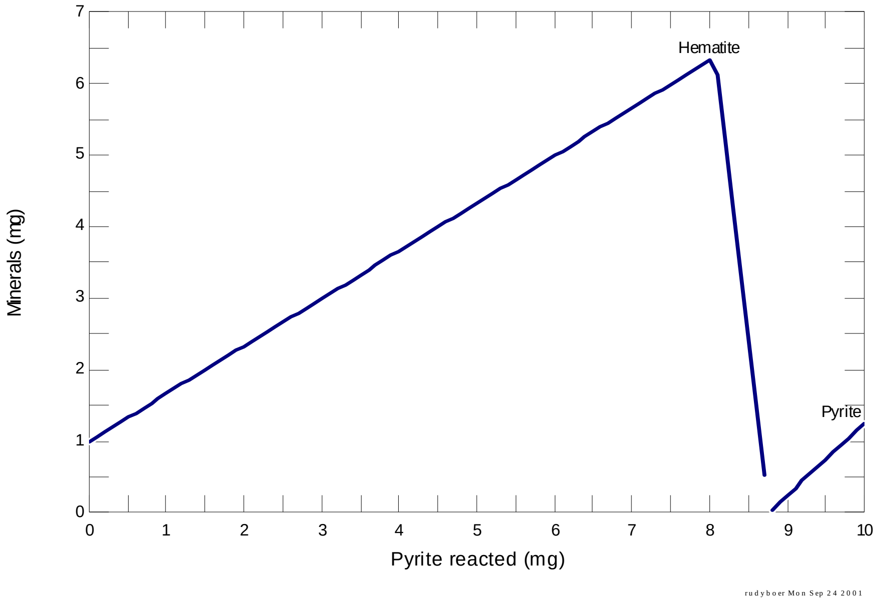


FIGURE 12: **VARIATION IN MINERALOGICAL COMPOSITION; PYRITE REACTS AT 25°C INTO DILUTE WATER IN A CLOSED SYSTEM**

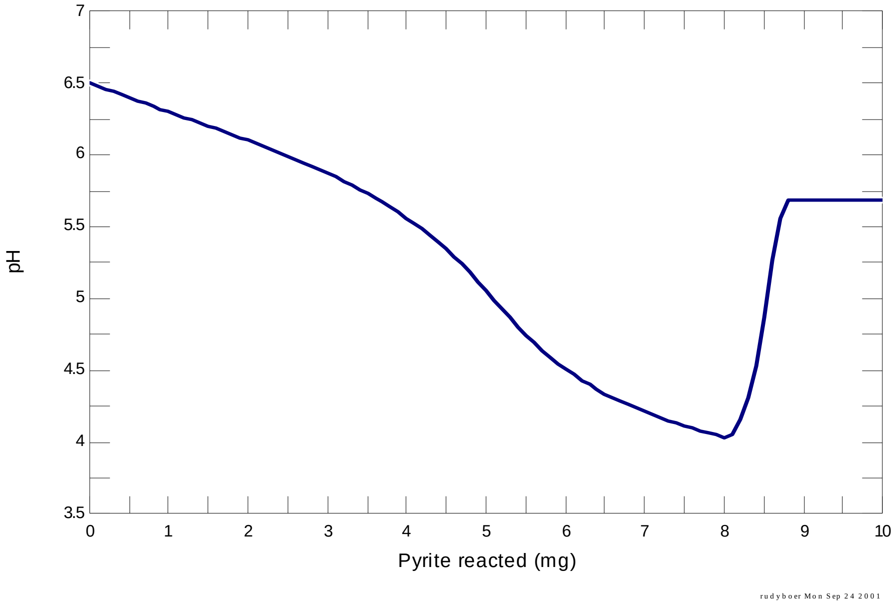


FIGURE 13: **VARIATION IN PH OVER THE REACTION PATH DEPICTED IN FIGURE 12**

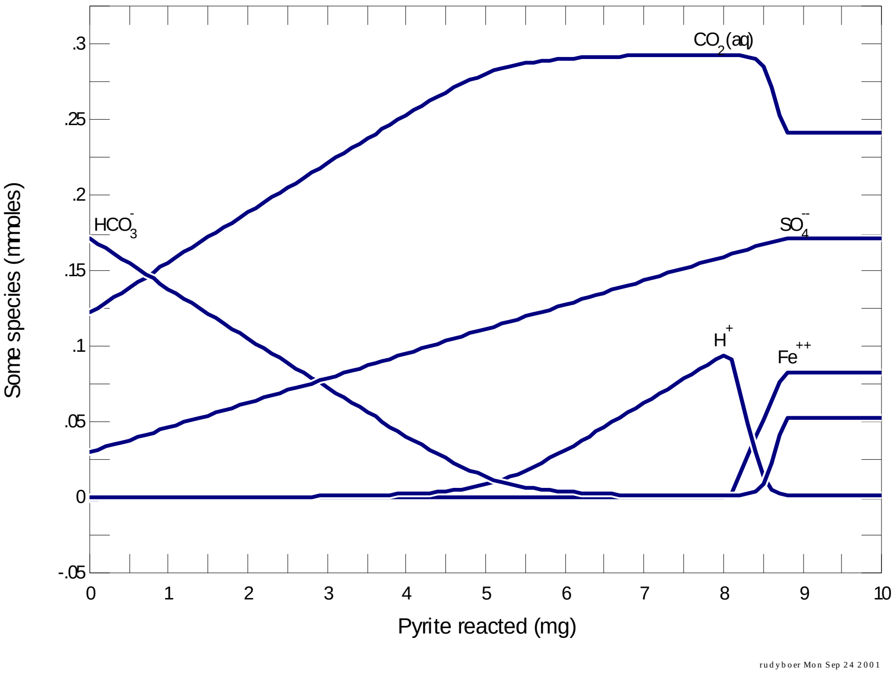


FIGURE 14: VARIATION IN THE CONCENTRATIONS OF AQUEOUS SPECIES INVOLVED IN THE DISSOLUTION REACTION OF PYRITE, FOR THE REACTION PATH SHOWN IN FIGURE 13

In comparison to the above-mentioned scenario where oxygen was allowed to vary, the predictive modelling scenario is very different when oxygen fugacity is fixed. In order to show the difference an almost unlimited supply of pyrite was made available for the theoretical experiment. The fixed fugacity path differs from the previous calculation (in which the fluid was closed to the addition of oxygen) in that pyrite dissolution continues indefinitely, since there is an unlimited supply of oxygen gas. Initially the reaction proceeds as:

EQUATION 7 $4\ FeS_2 + 15O_2(G) + 8H_2O \leftrightarrows 2\ Fe_2O_3 + 8SO_4^{--} + 16H^+$

As could be seen from Figure 6. Later, a second reaction that produces HSO_4^{--}, instead of SO_4^{--}, becomes dominant:

EQUATION 8 $4\ FeS_2 + 15O_{2(AQ)} + 8H_2O \leftrightarrows 2\ Fe_2O_3 + 8HSO_4^- + 8H^+$.

The H^+ produced by these reactions drives pH to values far more acidic than those in the closed system case (Bethke, C.M. 1996: *Geochemical Reaction Modeling*, Oxford University Press, Oxford, pp.397).

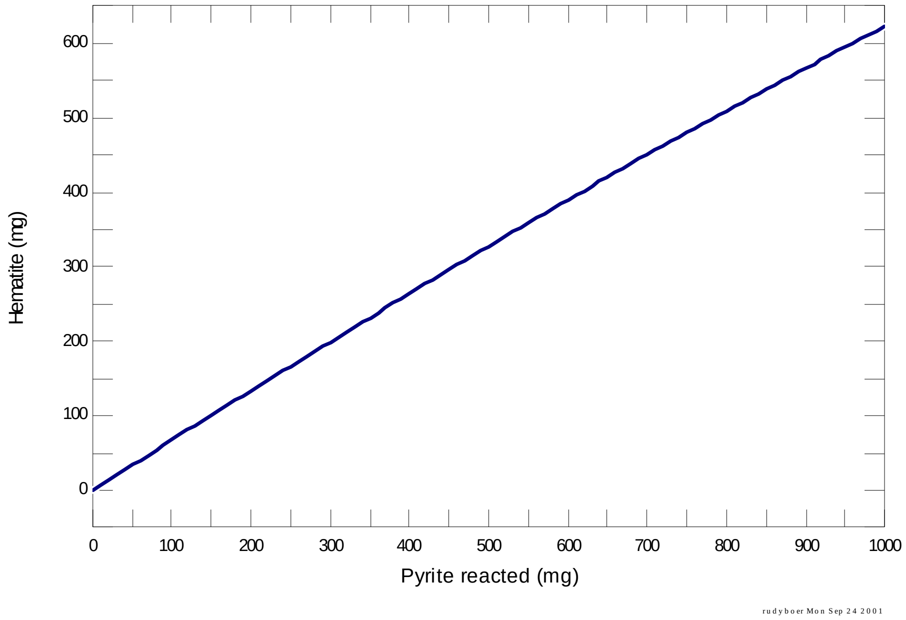


FIGURE 15: MINERALOGICAL RESULTS OF A FIXED FUGACITY PATH WHEN PYRITE DISSOLVES AT 25°C INTO WATER IN AN OPEN SYSTEM

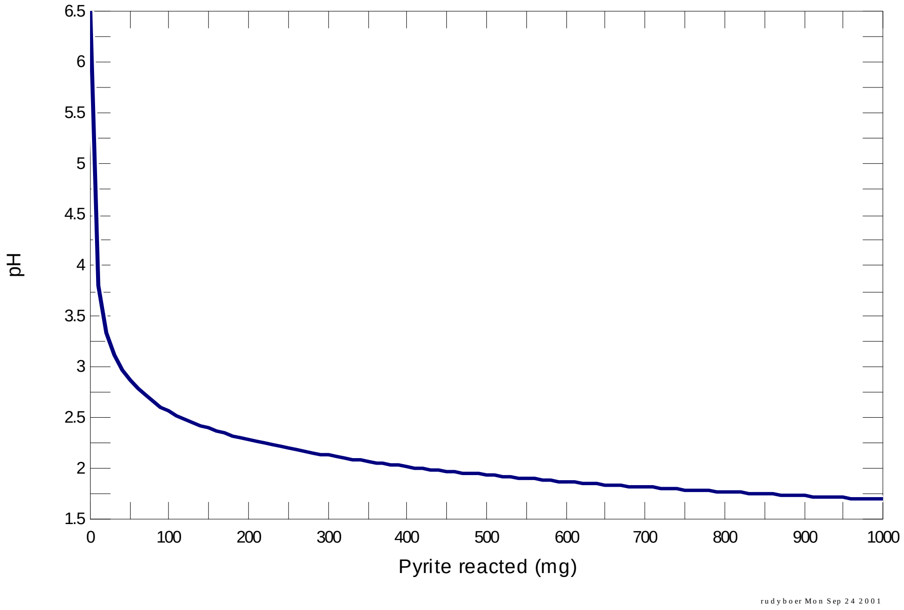


FIGURE 16: VARIATION OF THE PH OVER THE PATH DESCRIBED IN FIGURE 15 ABOVE

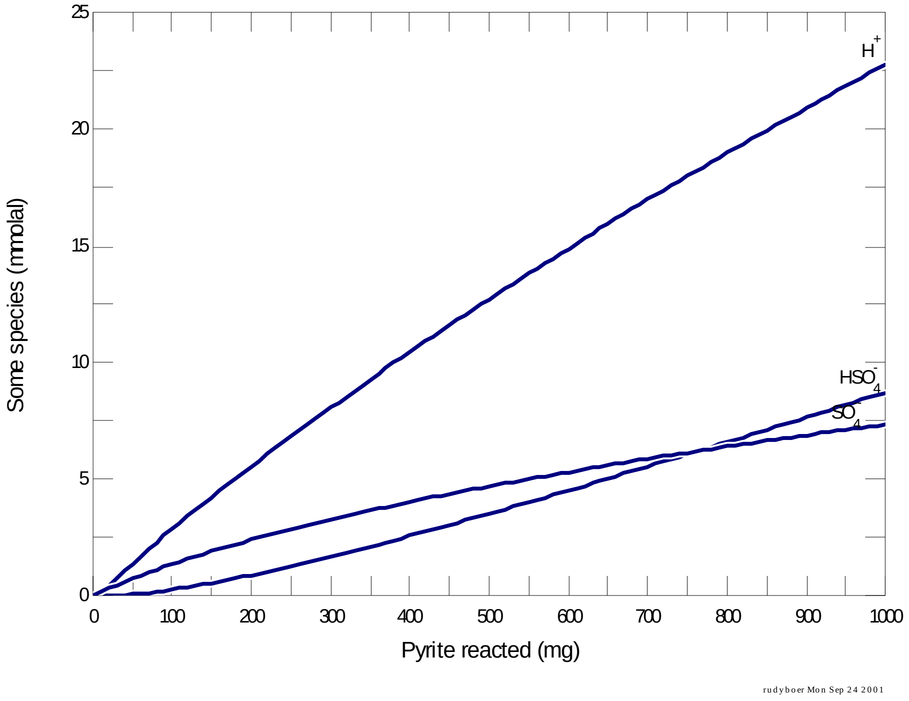


FIGURE 17: CONCENTRATIONS OF SPECIES INVOLVED IN THE DISSOLUTION OF PYRITE FOR THE FIXED FUGACITY PATH SHOWN IN FIGURES 15 & 16 ABOVE

4.4. EFFECTS OF CHANGING ACTIVITY AND FUGACITY ON CALCITE DISSOLUTION

Changing the carbon dioxide fugacity has a significant effect on the solubility of calcite and dolomite. The system that would be applicable for the modelling of tailings backfill material in dolomitic sinkholes start with the CO_2 fugacity being similar to that of the ambient atmospheric conditions, i.e. log fCO_2 of –3.5, to value of log $fCO_2 = 1$ (Bethke, C.M. 1996: *Geochemical Reaction Modeling*, Oxford University Press, Oxford, pp.397). The calculated results show that increasing the CO_2 fugacity decreases the pH to about 6 and lower (Figure 18), causing calcite to dissolve into the fluid. The fugacity increase drives CO_2 from the buffer into the fluid, and most of the CO_2 becomes $CO_{2(aq)}$. The nearly linear relationship between the concentration of $CO_{2(aq)}$ and the fugacity of $CO_{2(g)}$ results from the reaction:

EQUATION 9 $$CO_{2(G)} \leftrightarrows CO_{2(AQ)}$$

which holds aCO_2 proportional to fCO_2 (Figure 19). Some of the gas, however, dissociates to produce HCO_3^- and H^+ and the resulting acid is largely consumed by dissolving calcite. The overall reaction is approximately:

EQUATION 10 $$5CO_{2(G)} + CaCO_3 + H_2O \leftrightarrows 4CO_{2(AQ)} + Ca^{++} + 2HCO_3^-.$$

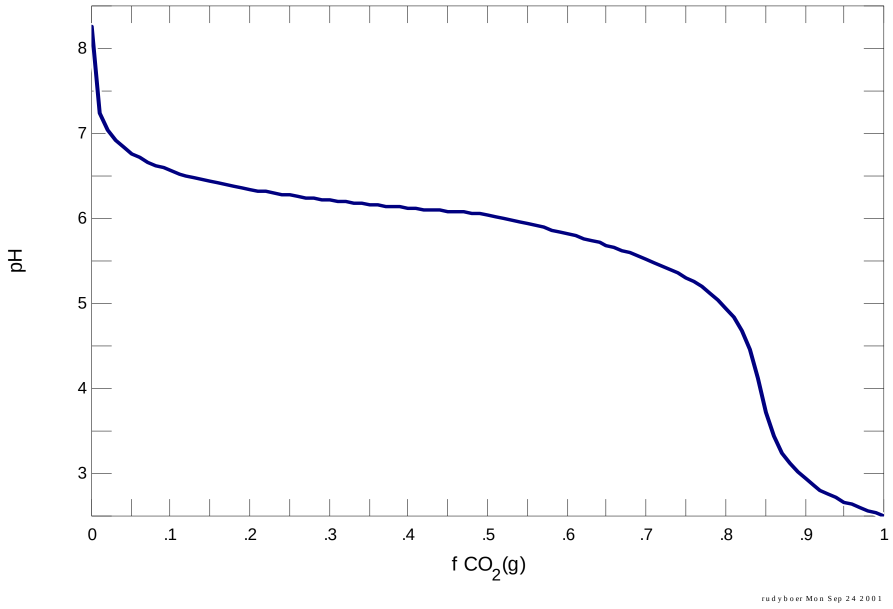


FIGURE 18: EFFECT OF CO_2 FUGACITY ON THE PH WHEN CALCITE IS DISSOLVED AT 25°C USING A SLIDING FUGACITY PATH

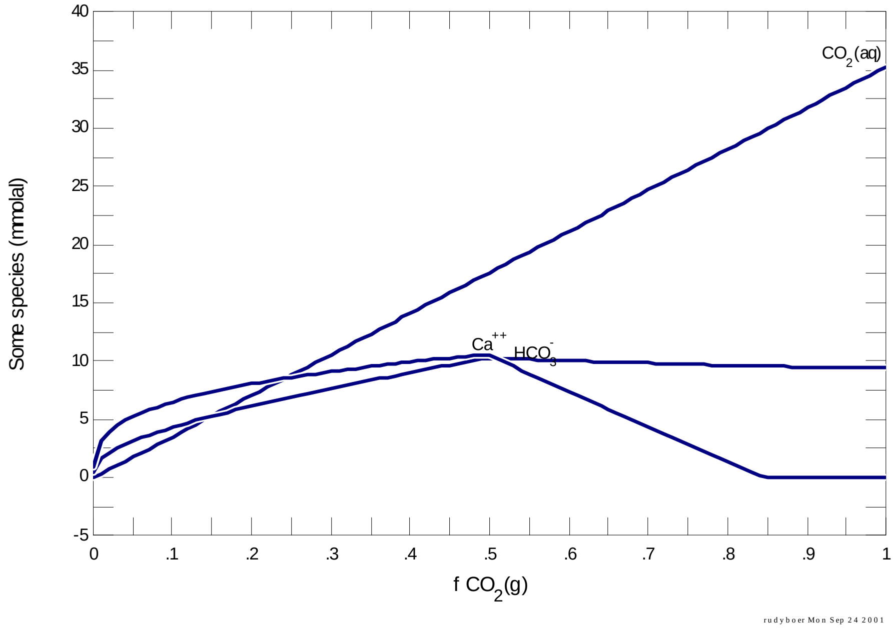


FIGURE 19: CORRELATION BETWEEN ƒ$CO_{2(G)}$ AND SOME SELECTED SPECIES

4.5. MOBILITY OF POTENTIALLY TOXIC HEAVY METALS

The understanding of the mobility of potentially toxic heavy metals (“heavy metals”) is of prime importance in the context of this study. Heavy metals are liberated from the sulphide minerals during dissolution reactions in an oxidizing environment. Following the liberation, these heavy metals are captured by processes of surface complexation onto hydrous ferric oxide surfaces (Langmuir D. 1997; *Aqueous Environmental Chemistry*, Prentice Hall, New Jersey, pp. 600). In order to simulate such processes the surface complexation model of Dzombak and Morel (1990) have been used (Bethke, C.M. 1996: *Geochemical Reaction Modeling*, Oxford University Press, Oxford, pp.397). By suppressing the formation of the ferric minerals hematite (Fe_2O_3) and goethite (FeOOH), as well as specifying the amount of ferric oxide [represented in the calculation by $Fe(OH)_3$ precipitate] in the system, it is possible to study the surface complexation behaviour of Fe-species (Bethke, C.M. 1996: *Geochemical Reaction Modeling*, Oxford University Press, Oxford, pp.397). The variation in concentration of the surface species with pH is depicted in Figure 20 (salinity of the system is approximated by a 0.1 molal NaCl solution). In order to evaluate the surface behaviour of more complex solutions, a solution containing $CaSO_4$, as well as Hg^{++}, Cr^{+++}, $As(OH)_4^-$ and Zn^{++} was introduced (Figure 21). A more complicated distribution of species is observed. At low pH, the H^+ activity and positive surface potential drive SO_4^{--} to sorb. Alkaline conditions promote the sorption of bivalent cations, such as Hg^{++}, Zn^{++} and Cu^{++}.

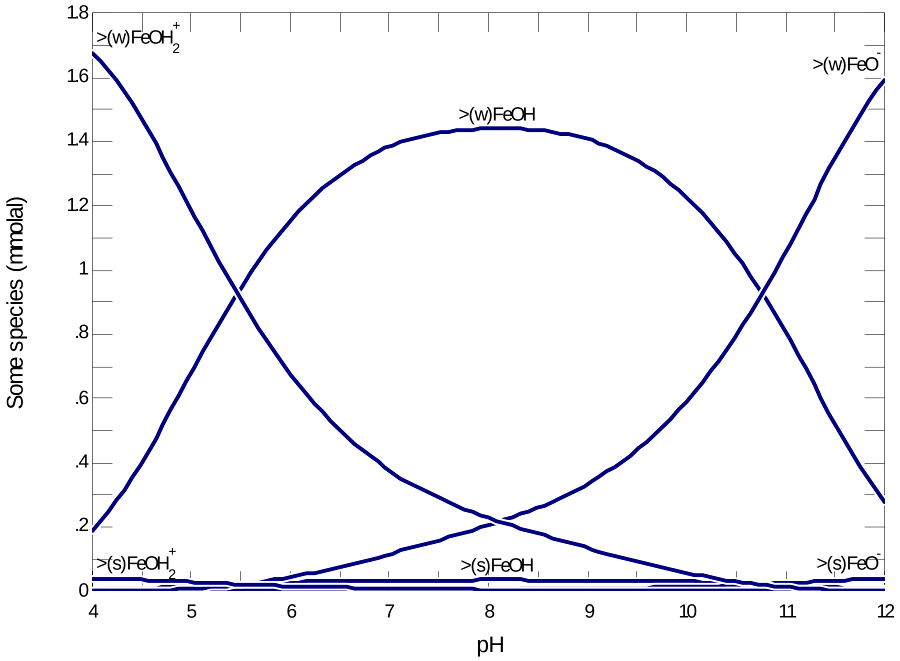
The Cr^{+++} component, as an example, follows a pattern distinct from the other metals, sorbing at only near-neutral pH. The component, present as Cr^{+++} at low pH, reacts successively to form $CrOH^{++}$, $Cr(OH)_2^+$, $Cr(OH)_3$ and $Cr(OH)_4^-$ as pH increases. Significantly, the reactions for the species predominant at low pH favour the desorption of chromium when the H^+ activity is high, and those for the species predominant under the alkaline conditions favour desorption when the H^+ activity is low. Hence Cr(III) sorbs strongly only when the pH is near neutral.

4.6. MOBILITY OF URANIUM SPECIES

The mobility of radioactive element species forms an important part of this investigation. The minerals deposits of the Witwatersrand are part of a world-class uranium-gold deposit and not only a goldfield, as is commonly perceived. The mobility of the radioactive species is poorly understood in the context of weathering conditions within the dolomitic sinkholes. The calculations for the uranium oxide species, as well as a number of selected species (Langmuir D. 1997; *Aqueous Environmental Chemistry*, Prentice Hall, New Jersey, pp. 600; Bethke, C.M. 1996: *Geochemical Reaction Modeling*, Oxford University Press, Oxford, pp.397) have been summarized in Figures 22 and 23. It is apparent that the uranium chloride and sulphate species are moderately soluble under acidic saline conditions, while the uranium hydroxide species are more soluble (Figure 22). However, the most common uranium hydroxide species appear to be highly soluble under acidic and alkaline conditions (Figure 23).

The uranium containing minerals that would precipitate from such a system would be of the hydrous uranium oxide type minerals, which precipitate over a range of pH conditions (Figure 24).

Unfortunately, the same conditions which inhibit the mobility of most toxic heavy metals, as well as inhibiting the production of acidic conditions, also promotes the mobility of uranium in its hydrous oxidized state. The contradiction has the potential to pose serious problems during planning of rehabilitation strategies.



rudyboer Mon Sep 24 2001

Figure 20: Concentrations of sites on a hydrous ferric oxide surface exposed at 25°C to a 0.1 molal NaCl solution, calculated using a sliding pH path

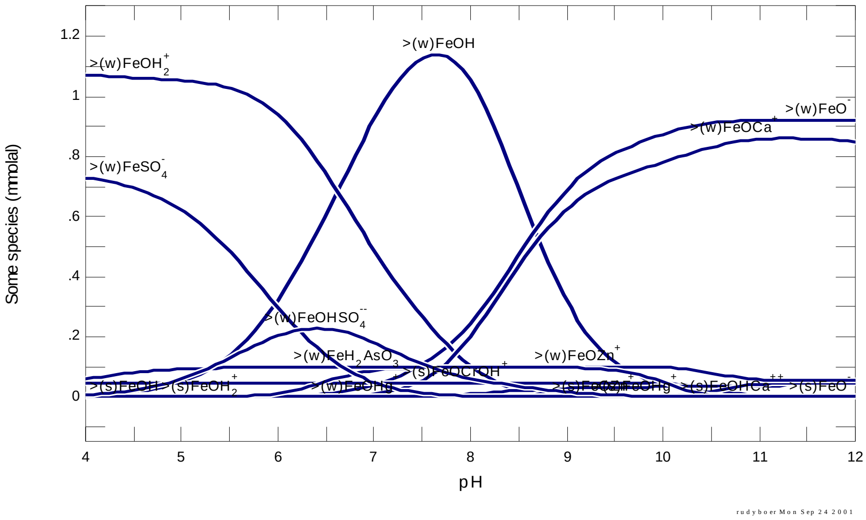


FIGURE 21: CONCENTRATIONS OF SURFACE SPECIES ON HYDROUS FERRIC OXIDE EXPOSED AT 25°C TO A SOLUTION CONTAINING CA, SO_4, HG, CR, AS AND ZN, CALCULATED USING A SLIDING PH PATH

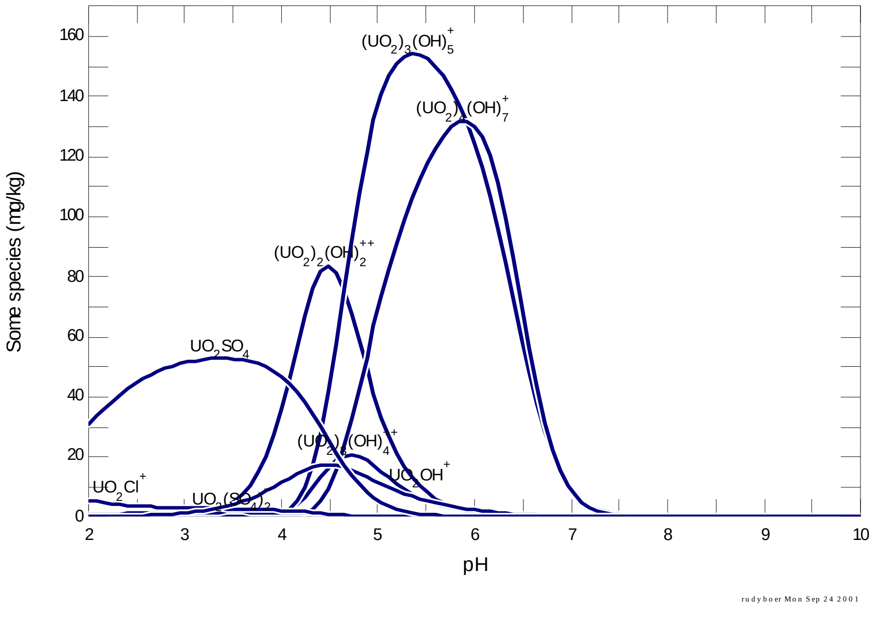
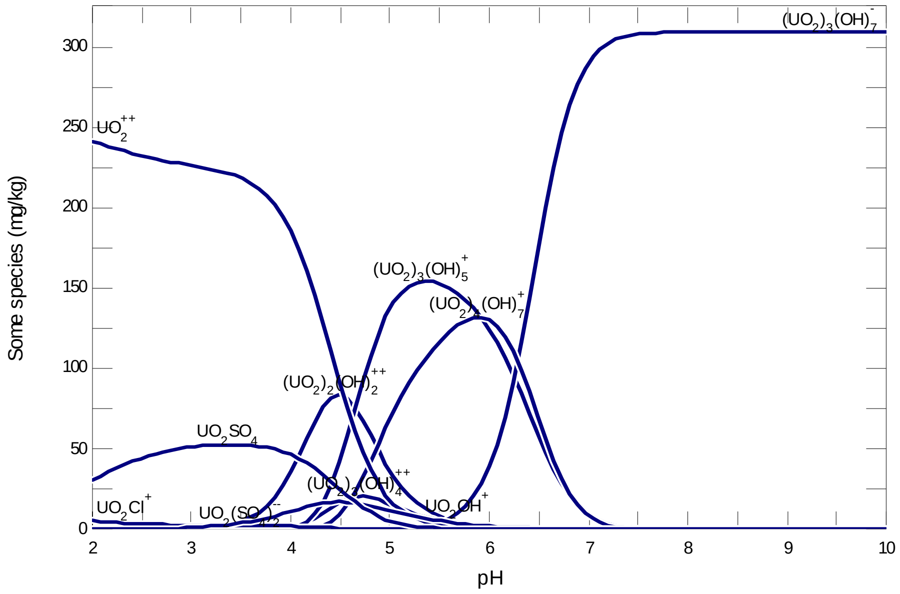
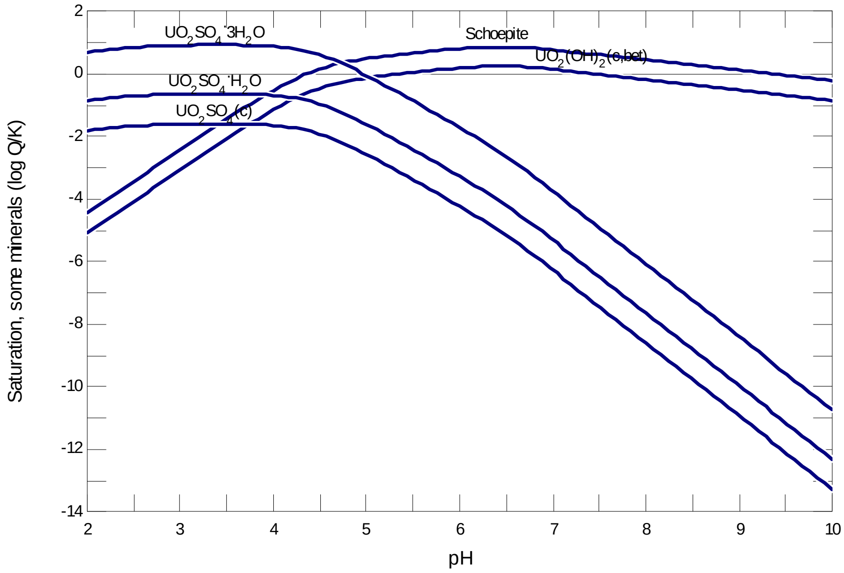


FIGURE 22: CONCENTRATIONS OF URANIUM OXIDE SPECIES AT 25°C IN AQUEOUS SOLUTION, CALCULATED USING A SLIDING PH PATH



rudyboer Mon Sep 24 2001

FIGURE 23: CONCENTRATIONS OF URANIUM OXIDE SPECIES AT 25°C IN AQUEOUS SOLUTION, CALCULATED USING A SLIDING PH PATH (DIAGRAM INCLUDES THE URANIUM OXIDE AND URANIUM HYDROXIDE SPECIES)



rudyboer Mon Sep 24 2001

FIGURE 24: SATURATION LEVELS OF HYDROUS URANIUM-RICH MINERALS PREVAILING IN THE MODELLED SYSTEM AT 25°C, CALCULATED USING A SLIDING PH PATH

5. GEOCHEMICAL MODELLING

The relevance of predictive geochemical modelling results is directly related to the quality of the input data. Input data need to be representative of the scenario under investigation and should provide the required basis to build a geochemical model. The data accumulated for this exercise have been sourced from case studies, which formed part of the larger project, as well as selected published databases (see Tables 1 to 3). A database containing leach test data for Witwatersrand tailings material from a backfilled sinkhole (refer to Section 4.3 in the Main Report) has been used to calibrate the predictive geochemical models.

Different scenarios have been modelled using a range of flow rates. The flow rates used in the modelling exercise were:

- A low value of 32 L/year (which correspond to a K value of 10^{-7} m^3/s). This value is for tailings materials with a low transmissivity;
- An average value of 260 L/year (based on the recharge of 40% of the Mean Annual Precipitation of 650 mm for the area); and
- A high value of 1000 L/year for sinkholes in close proximity or within a rive bed, which are often submerged by water.

5.1. WATER IN CONTACT WITH BACKFILL MATERIAL IN SINKHOLES – AEROBIC ZONE

The assumption was made that the reactions proceed to equilibrium with regard to the supply of oxygen and carbon dioxide. No limitations were placed on the availability of these components in the aerobic zone, thus, optimising the conditions for pyrite oxidation to proceed. The mineralogy that was used is typical of Witwatersrand type tailings material. Rainwater was used as the incipient water quality.

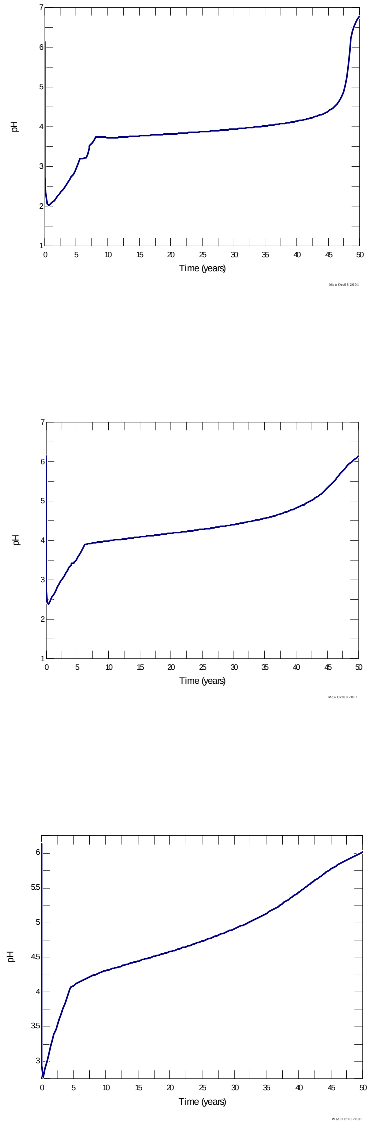


FIGURE 25: VARIATION IN PH OF AQUEOUS SOLUTION OVER TIME FOR A FLUID INTERACTING WITH THE TAILINGS MATERIAL IN THE AEROBIC ZONE AT DIFFERENT FLOW RATES: (TOP) 1000 L/YEAR, (MIDDLE) 260 L/YEAR, (BOTTOM) 32 L/YEAR

The geochemical modelling results indicate that in general the pH initially reduces to pH 2-3 and over time a steady recovery to near-neutral conditions is observed. Recovery of the pH to value above 4 take about five years in the low flow scenario, 5 to 10 years in the medium flow scenario and close to 10 years in the case of the high flow scenario. The best recovery of the final pH (pH 6.8) after 50 years is observed for the high flow scenario (Figure 25).

Minerals are more likely to become supersaturated in the low flow rate scenario (Figure 26). Kaolinite and hematite seems to be supersaturated throughout the 50-year modelling period. However, under the lower flow rates, hematite becomes under-saturated and stops precipitating as a secondary mineral phase. It is important to note that the participation of hematite and goethite should actually be suppressed. Hematite does not form directly at low temperatures. Each of the latter two minerals is more stable thermodynamically than the ferric precipitate observed to form in AMD. Quartz precipitates initially, but becomes under-saturated after approximately 5 years. Alunite [$KAl_3(SO_4)_2(OH)_6$] only precipitates under the low flow rate conditions. Mineral phases such as gypsum, dolomite and calcite do not reach super-saturation levels and therefore do not precipitate. The acidic conditions that prevail in the aerobic zone, together with the relative high flow rate, prevent secondary minerals from precipitating.

The pore water composition corroborate the mineral stability calculations in the sense that the TDS for the high flow rate environment is almost an order of magnitude lower compared to the lower flow rate scenario (Figure 27). Although the concentration of the various chemical species are lower in the high flow case, the load emanating from such a scenario would ultimately be significantly higher because of the fast rate of accumulation of the chemical species. Therefore, a clear distinction must be made between concentration and chemical load when these modelling results are interpreted in terms of designing a rehabilitation strategy. A more detailed scrutiny of the concentration profiles (Figure 28) indicates a dramatic increase in aluminium during the low flow conditions. The increase in aluminium concentration corresponds with the stability peak for alunite, which contains a significant amount of aluminium in its crystal structure. The excess aluminium in the system is probably a result of the decomposition of primary Al-bearing silicate phases. Kaolinite, an Al-bearing clay mineral, would also be introduced to the system during the period of Al abundance in the fluid (Figure 29).

Thus, the leachate initially emanating from the aerobic zone would be acidic, containing high proportions of sulphate salts and relatively high concentrations of toxic heavy metals.

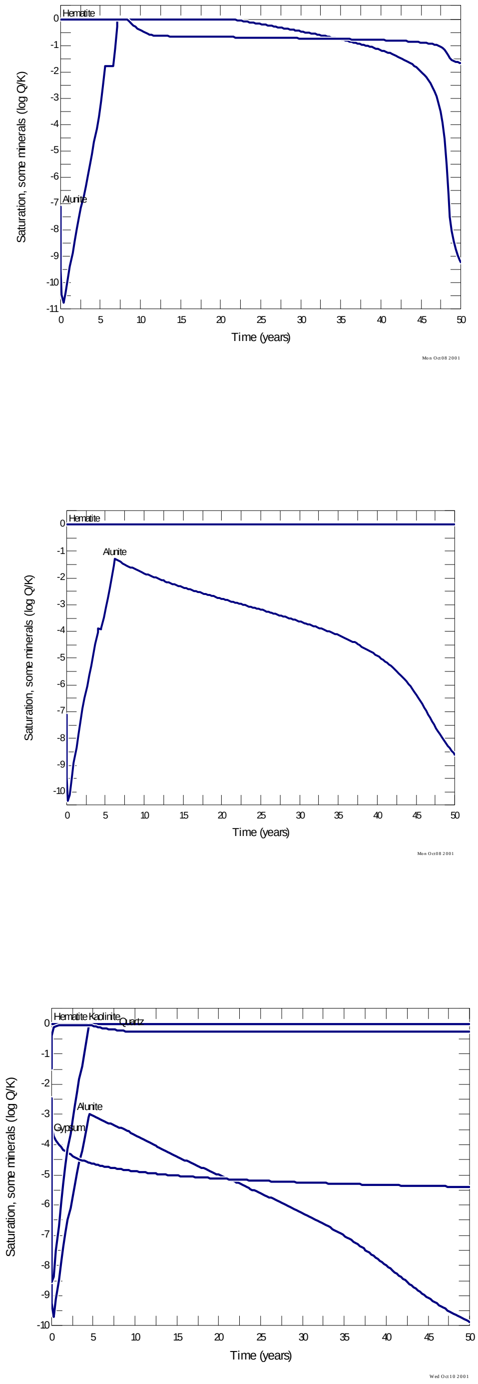


FIGURE 26: MINERAL SATURATION IN A FLUID INTERACTING WITH THE TAILINGS MATERIAL IN THE OXIDISED ZONE AT DIFFERENT FLOW RATES: (TOP) 1000 L/YEAR, (MIDDLE) 260 L/YEAR, (BOTTOM) 32 L/YEAR

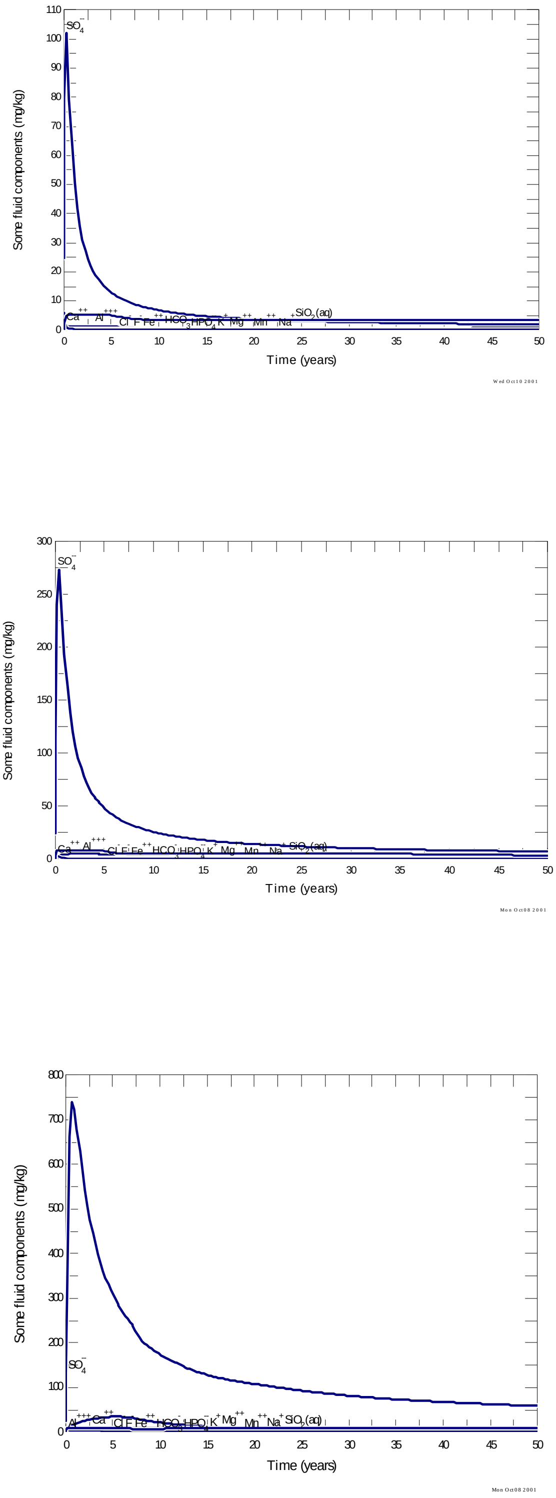


FIGURE 27: CONCENTRATION OF CHEMICAL COMPONENTS IN AQUEOUS FLUID INTERACTING WITH TAILINGS MATERIAL UNDER OXIDIZING CONDITIONS AT DIFFERENT FLOW RATES: (TOP) 1000 L/YEAR, (MIDDLE) 260 L/YEAR, (BOTTOM) 32 L/YEAR

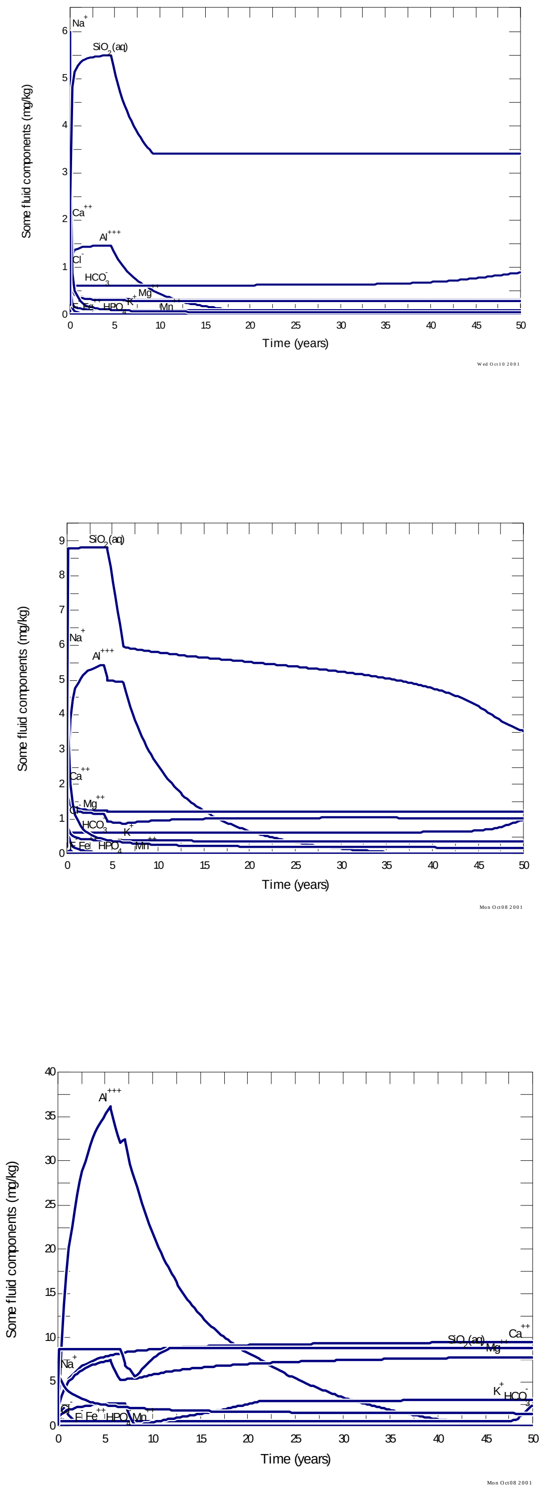


FIGURE 28: CONCENTRATION OF CHEMICAL COMPONENTS IN AQUEOUS FLUID INTERACTING WITH TAILINGS MATERIAL UNDER OXIDISING CONDITIONS, EXCLUDING SO_4 PROFILE AT DIFFERENT FLOW RATES: (TOP) 1000 L/YEAR, (MIDDLE) 260 L/YEAR, (BOTTOM) 32 L/YEAR

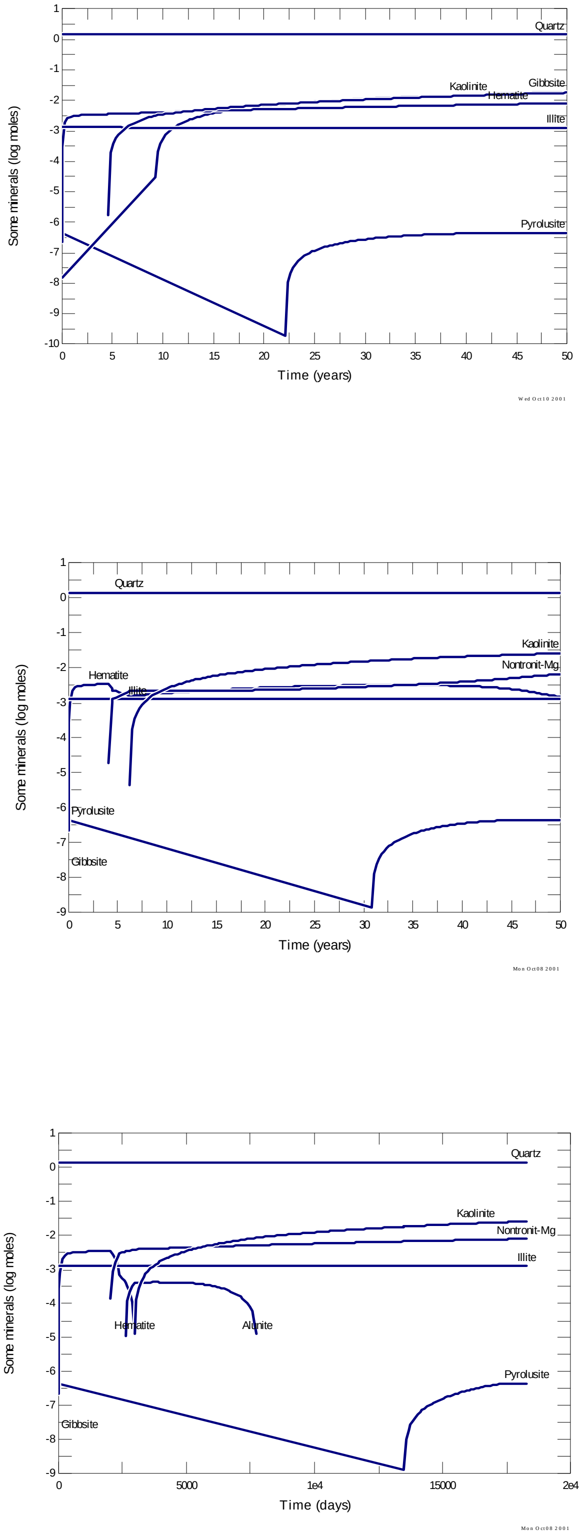


FIGURE 29: RELATIVE SEQUENCE IN WHICH MINERALS ARE STABLE AT DIFFERENT FLOW RATES: (TOP) 1000 L/YEAR, (MIDDLE) 260 L/YEAR, (BOTTOM) 32 L/YEAR

5.2. WATER IN CONTACT WITH FILL MATERIAL IN SINKHOLES – ANAEROBIC ZONE

The anaerobic zone contains similar material to the type that was modelled in the aerobic zone. However, the availability of oxygen has been restricted, whereas the carbon dioxide partial pressure has been increased. Thus, the effect is an inhibition of oxidizing reactions. The thermodynamic parameters have been kept similar for the two modelling scenarios, apart from the modal mineralogical composition, which did not show the same degree of weathering. The reason for such an oversimplification is mainly to be able to compare modelling results for the different scenarios. However, from a purely scientific perspective, it would probably have been better to introduce a sliding scale for a number of internal and external thermodynamic parameters. The anaerobic zone was modelled as a stand-alone option, similar to the approach followed during the modelling of the aerobic zone. To obtain a proper understanding of the entire system, the different geochemical nodes would eventually have to be linked.

In the anaerobic system no acidification of the water is observed, as the pH for all flow scenarios is neutral to slightly alkaline. The observed pH ranged from 6.9 to 7.8 with the low flow scenario having the highest pH (7.6 to 7.8). Because of the inhibition of pyrite oxidation under anaerobic conditions due to a lack of oxygen, the pH remains at relatively elevated levels compared to the aerobic scenario (Figure 30).

With regard to the precipitation of secondary minerals, kaolinite remains stable under high flow rates, but falter after a while in low flow rate conditions (Figure 31). Quartz is precipitating or is about to precipitate for the entire 50-year modelling period. Dolomite shows a dramatic increase in concentration, but still does not reach super-saturation in order to precipitate. The TDS values of the interstitial fluid (pore water) are low for the high flow scenario and increases with the decreasing flow rate (Figure 32 & 33). Thus, at the low flow scenario there is a high salt load present in the water. On a more detailed scale, the aluminium show the same behavioural pattern compared to the aerobic zone.

The inhibition of oxygen availability clearly affects the release of chemical species into the aqueous and gaseous environments resulting in generally low concentrations of dissolved species (< 5 mg/L) under high and average flow conditions. Slightly higher concentrations are observed under low conditions where sulphate concentrations are around 25 mg/L. The water quality arising from the anaerobic zone of the backfill material is expected to show a good water quality likely to be suitable for domestic use.

Furthermore, the order in which minerals would precipitate remains the same for the different modelling scenarios (Figure 34).

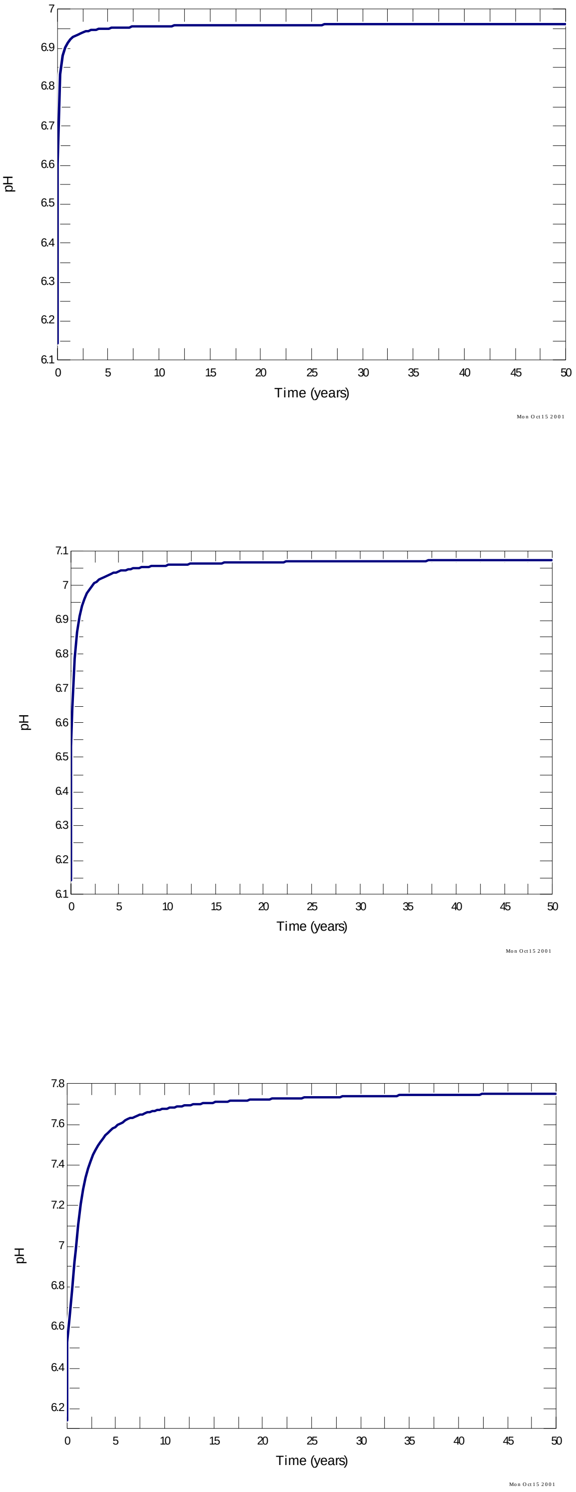


FIGURE 30: VARIATION IN PH OF AQUEOUS SOLUTION OVER TIME FOR A FLUID INTERACTING WITH THE TAILINGS MATERIAL IN THE ANAEROBIC ZONE AT DIFFERENT FLOW RATES: (TOP) 1000 L/YEAR, (MIDDLE) 260 L/YEAR, (BOTTOM) 32 L/YEAR

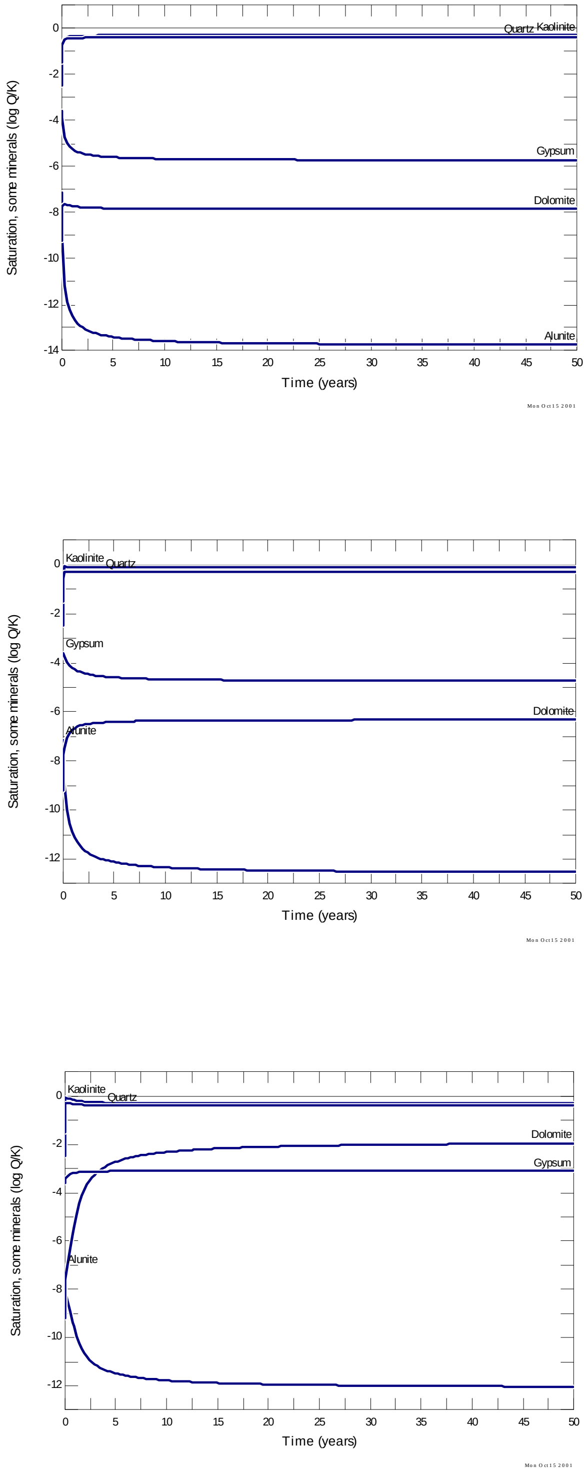


FIGURE 31: MINERAL SATURATION IN A FLUID INTERACTING WITH THE TAILINGS MATERIAL IN THE ANAEROBIC ZONE AT DIFFERENT FLOW RATES: (TOP) 1000 L/YEAR, (MIDDLE) 260 L/YEAR, (BOTTOM) 32 L/YEAR

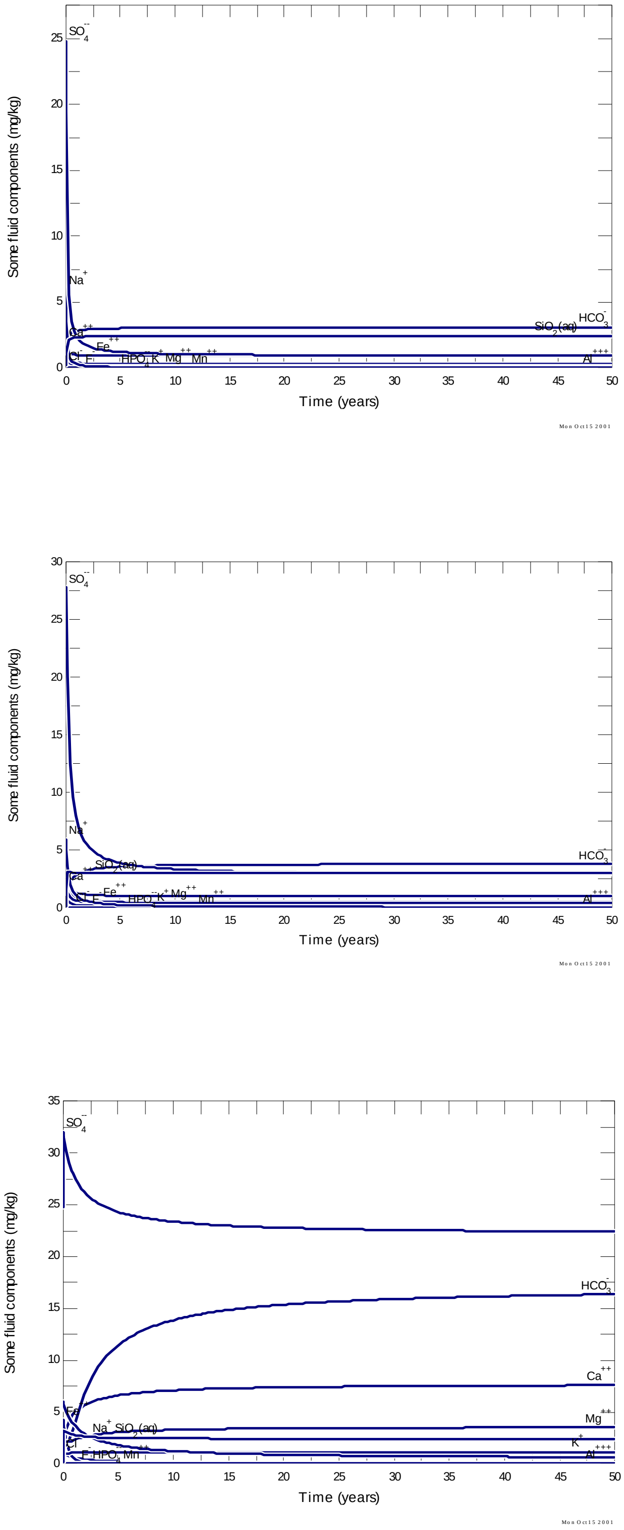


FIGURE 32: CONCENTRATION OF CHEMICAL COMPONENTS IN AQUEOUS FLUID INTERACTING WITH TAILINGS MATERIAL UNDER ANAEROBIC CONDITIONS AT DIFFERENT FLOW RATES: (TOP) 1000 L/YEAR, (MIDDLE) 260 L/YEAR, AND (BOTTOM) 32 L/YEAR

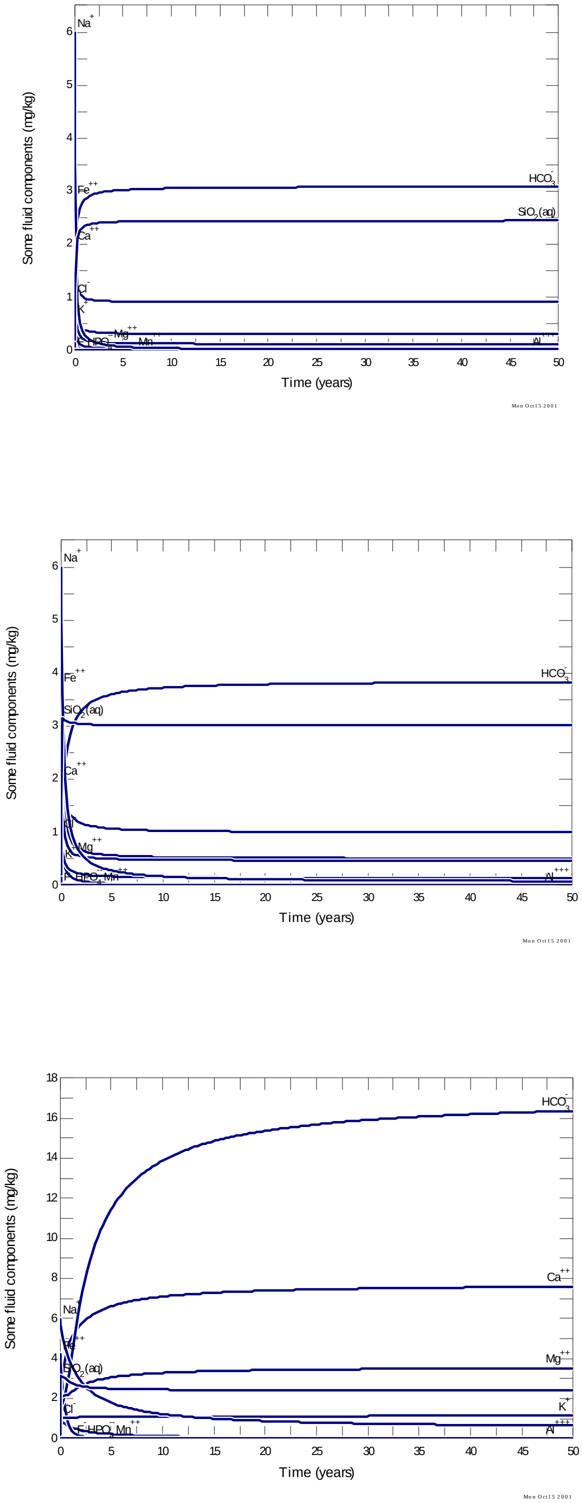


FIGURE 33: CONCENTRATION OF CHEMICAL COMPONENTS IN AQUEOUS FLUID INTERACTING WITH TAILINGS MATERIAL UNDER ANAEROBIC CONDITIONS, EXCLUDING SO_4^{2-} PROFILE AT DIFFERENT FLOW RATES: (TOP) 1000 L/YEAR, (MIDDLE) 260 L/YEAR, (BOTTOM) 32 L/YEAR

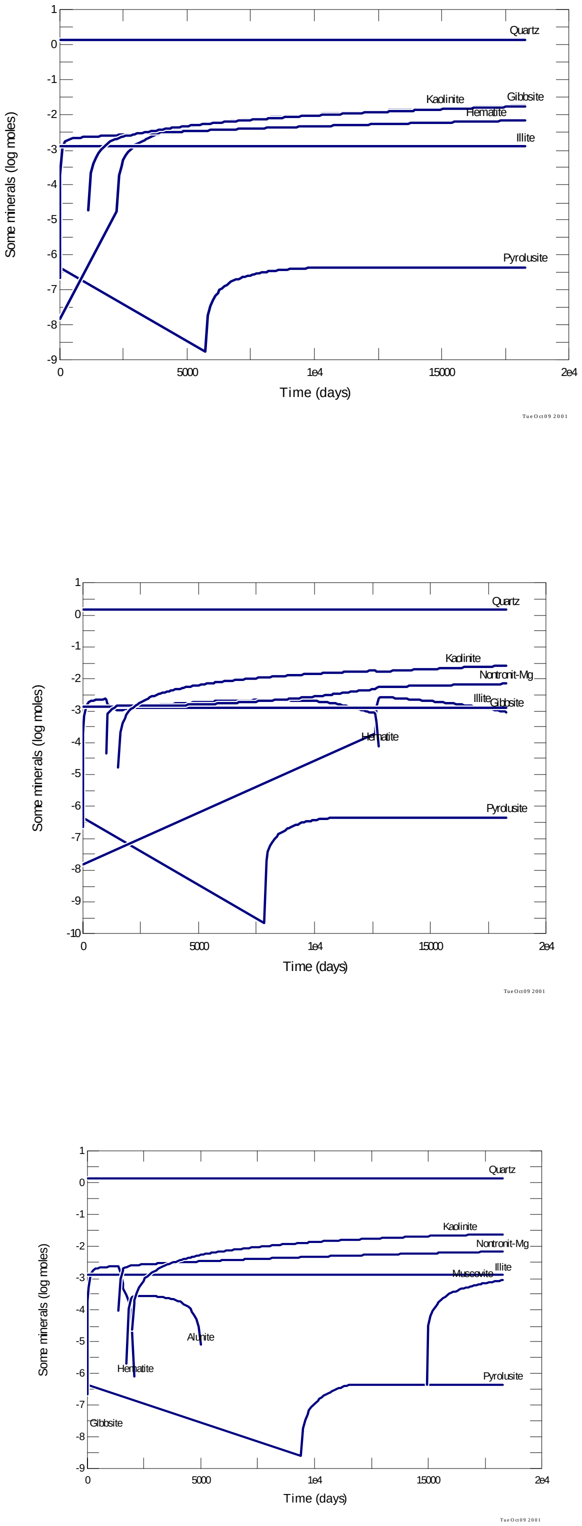


FIGURE 34: **DIAGRAM DEPICTING THE SEQUENCE IN WHICH MINERALS PREVAIL FROM THE SYSTEM UNDER ANAEROBIC CONDITIONS AT DIFFERENT FLOW RATES: (TOP) 1000 L/YEAR, (MIDDLE) 260 L/YEAR, (BOTTOM) 32 L/YEAR**

5.3. MIGRATION OF LEACHATE THROUGH UNSATURATED ZONE

Once the seepage has exited the backfill of the sinkhole, a new set of water – rock interactions will take place. The sinkholes that are being dealt with in this study all occur in dolomitic host-rocks, which consist mainly of intercalated layers of dolomite, chert and shale horizons. The carbonaceous nature of the dolomitic host rock would have a buffering effect on any acidic leachate entering the unsaturated zone. In this modelling scenario, the three top (overlying) nodes have been connected in terms of leachate emanating and entering the unsaturated zone (underlying node).

5.3.1. CONSIDERATIONS FOR ACID SEEPAGE ARISING FROM THE SINKHOLE

In the case where acid seepage arises from the sinkhole, the buffering effect of the dolomite does not affect the water quality when high flow rates prevail (Figure 35). This may partially be a function of the slow chemical reaction rate for dolomite. Under average flow conditions, the shape of the pH profile mimics the dolomite dissolution curve. The geometric similarity between these two curves strongly suggests the dominant role of dolomite in determining and controlling the pH of the entire system. Under low flow conditions, the pH recovers rapidly, within three years, to near-neutral conditions. These exercises reiterate the critical importance of flow rate in any strategic rehabilitation scenario.

Under acidic conditions and high flow rates the secondary minerals would remain in solution (Figure 36). Hematite would start to precipitate after approximately 20 years. However, in the reduced flow rate scenarios the minerals precipitate more readily. Hematite and quartz remained super-saturated for the duration of the modelling period, considering the average flow rate. The aluminium-bearing minerals, such as gibbsite, alunite and kaolinite, precipitate together during a relative short period of five years (Figure 36). Other mineral phases, such as the carbonate group of minerals, would start to precipitate towards the end of the modelling period. Under the conservative flow rate conditions, the secondary minerals become super-saturated as the pH reaches near-neutral values. Gypsum precipitates initially, but soon follows the trend set by magnesite and remains slightly under-saturated.

The pore water composition shows generally a decrease in the sulphate concentration for the various flow rate scenarios (Figure 37). The initial sulphate concentration reduces from about 1 000 mg/L to 550 mg/L under high flow conditions and to about 150 mg/L under average and low flow conditions within 50 years. From the above it is evident that a high flow scenario will contribute to a much larger extent to the contamination of the dolomite aquifer than average or low flow. Dissolution of dolomite is the predominant chemical reaction, as is evident in the increased bi-carbonate, calcium and magnesium concentrations in the pore water. The sequence, in which the minerals form in the system are depicted in Figure 38.

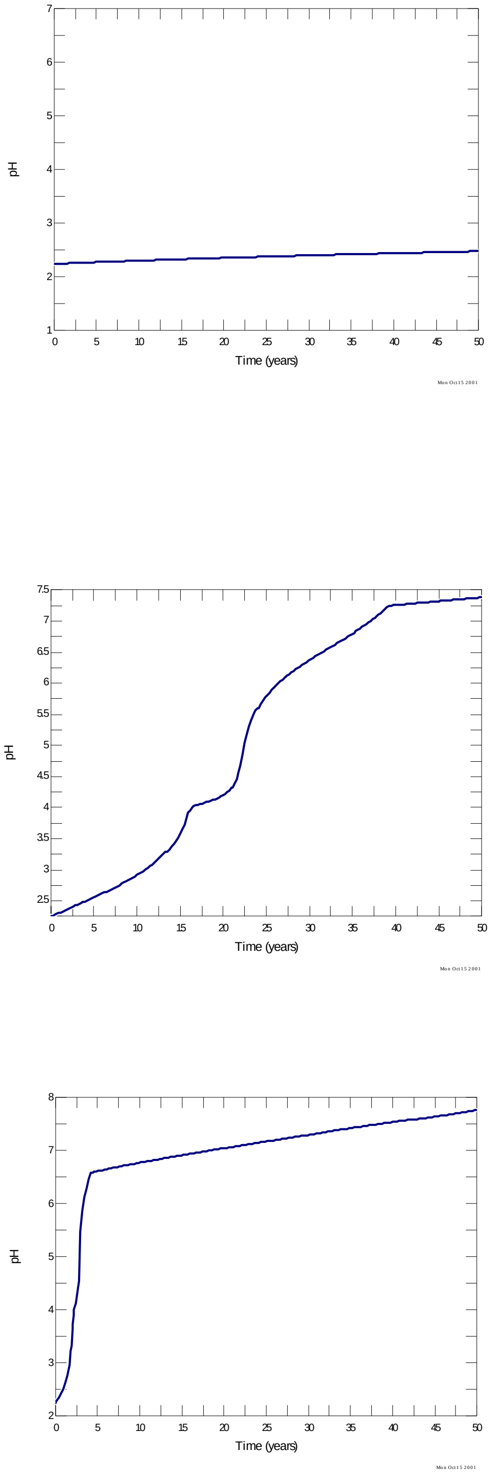


Figure 35: Variation in pH of aqueous solution over time for a fluid seeping through the unsaturated zone at different flow rates: (top) 1000 L/year, (middle) 260 L/year, (bottom) 32 L/year

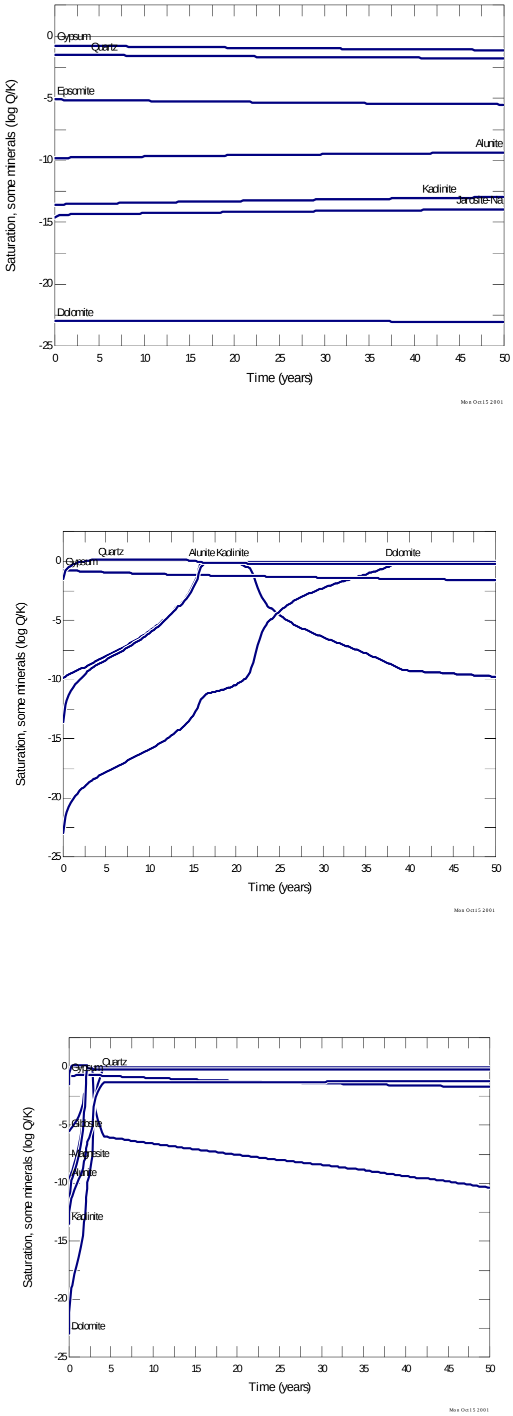


FIGURE 36: MINERAL SATURATION IN A FLUID SEEPING THROUGH THE UNSATURATED ZONE AT DIFFERENT FLOW RATES: (TOP) 1000 L/YEAR, (MIDDLE) 260 L/YEAR, (BOTTOM) 32 L/YEAR

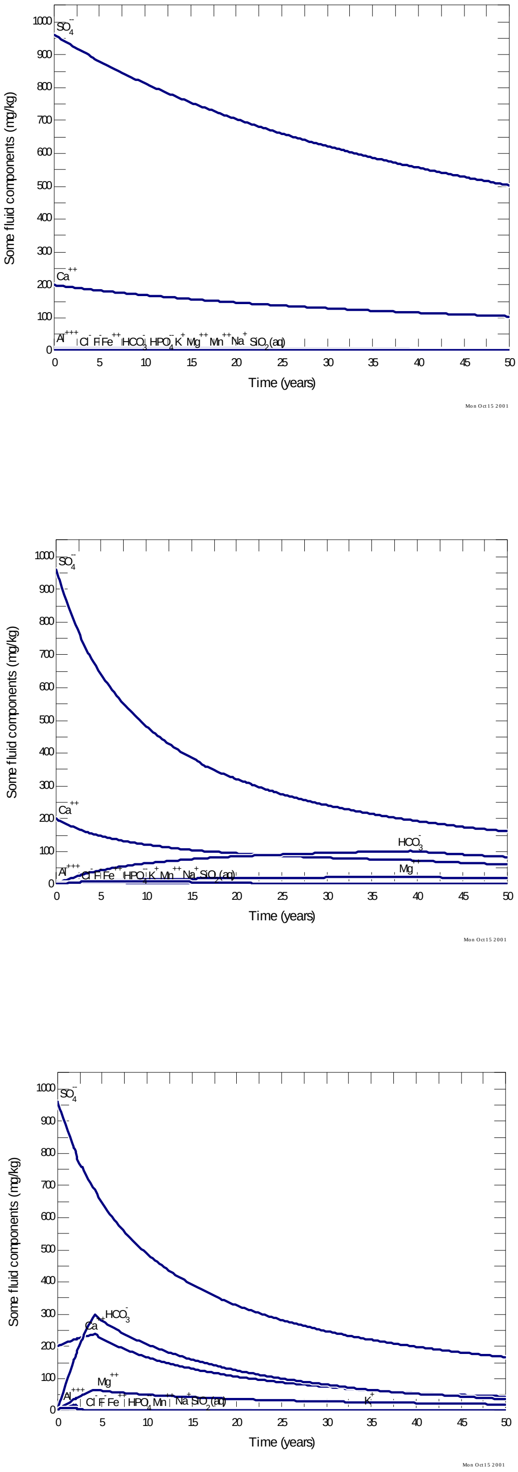


FIGURE 37: **FLUID COMPOSITION IN A FLUID SEEPING THROUGH THE UNSATURATED ZONE AT DIFFERENT FLOW RATES: (TOP) 1000 L/YEAR, (MIDDLE) 260 L/YEAR, (BOTTOM) 32 L/YEAR**

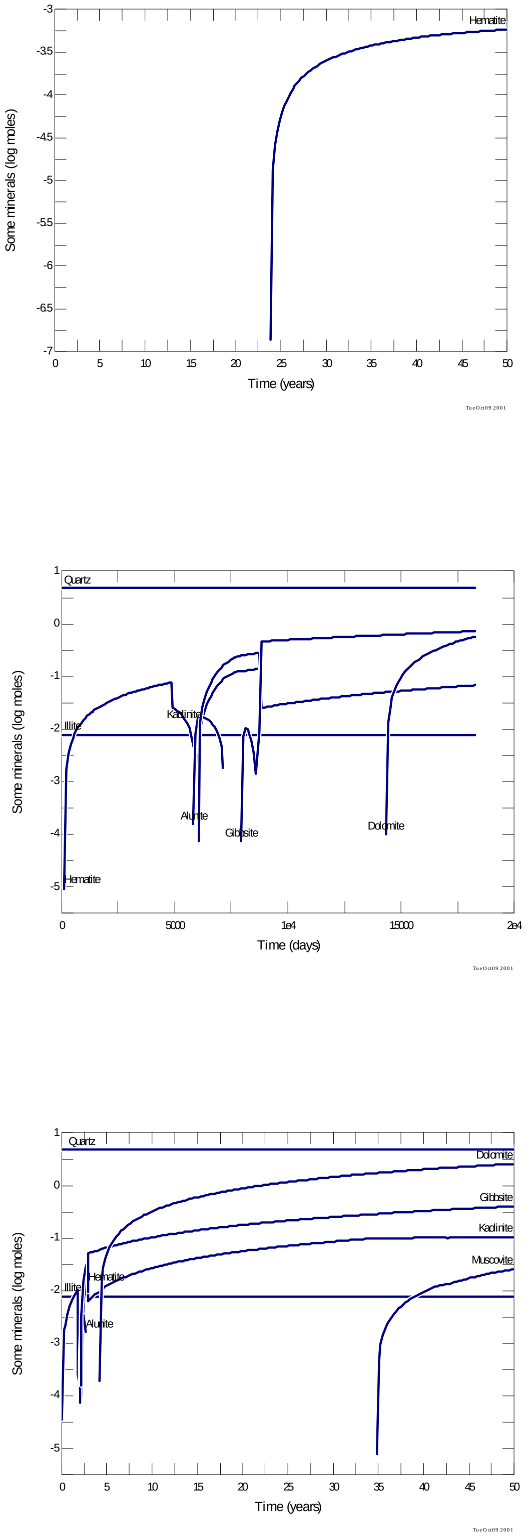


FIGURE 38: SEQUENCE IN WHICH MINERALS WOULD FORM IN THE UNSATURATED ZONE AT DIFFERENT FLOW RATES: (TOP) 1000 L/YEAR, (MIDDLE) 260 L/YEAR, (BOTTOM) 32 L/YEAR

5.3.2. CONSIDERATIONS FOR NEUTRAL SEEPAGE ARISING FROM THE SINKHOLE

In the case where neutral seepage arises from the sinkhole, the expected water quality is near drinking water quality and the passage through the unsaturated zone is not likely to affect the water quality in any way.

5.4. INTERACTION BETWEEN LEACHATE AND SATURATED ZONE

The water emanating from the overlying unsaturated zone, which enters the saturated zone, is generally of good quality. Mixing the water from the unsaturated zone with the dolomite-hosted ground water causes a further improvement in the water quality mainly due to dilution.

The pH of the final water in the dolomite aquifer remains near-neutral for all flow scenarios (Figure 39). The formation of minerals shows that under high and average flow conditions all minerals are undersaturated. Under low flow conditions kaolinite and quartz may form, while hematite and gibbsite are still undersaturated (Figure 40).

The dissolved species in the water are generally low with most of the compounds < 5 mg/L and sulphate <20 mg/L. The TDS composition of the pore water remains low, which was to be expected since there is no pyrite in the system to react (Figure 41). The sequence, in which the minerals would precipitate, should they reach super-saturation, is depicted in Figure 42.

With the exception of uranium, the final water quality in the dolomite aquifer for all flow scenarios is good and is likely to be suitable for domestic use.

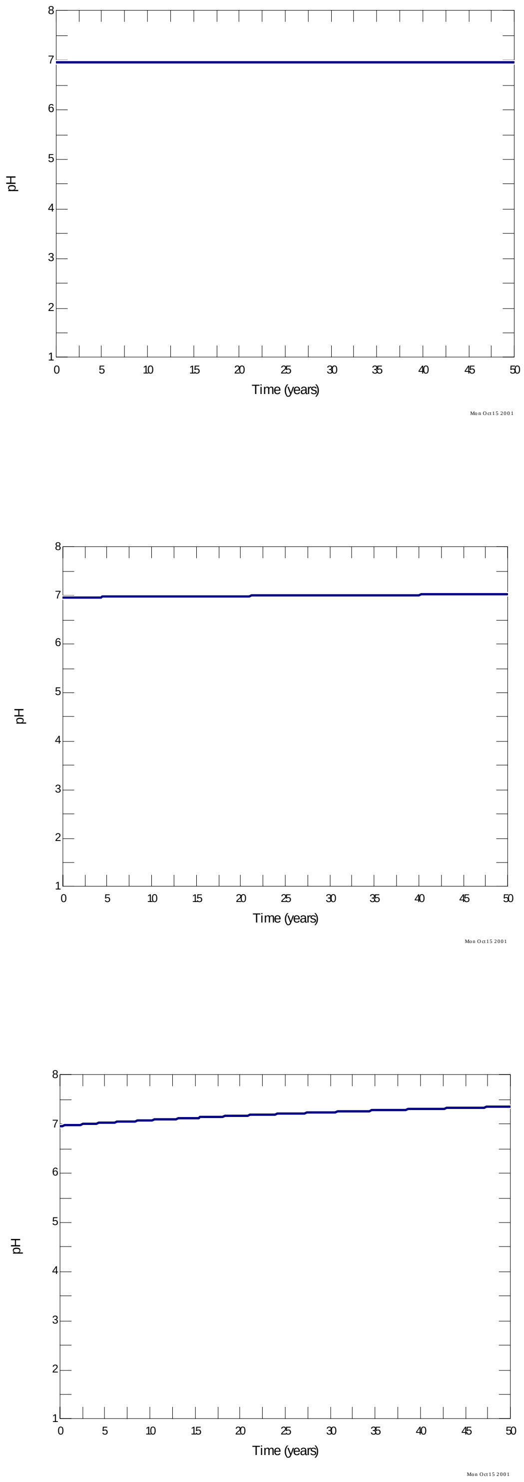
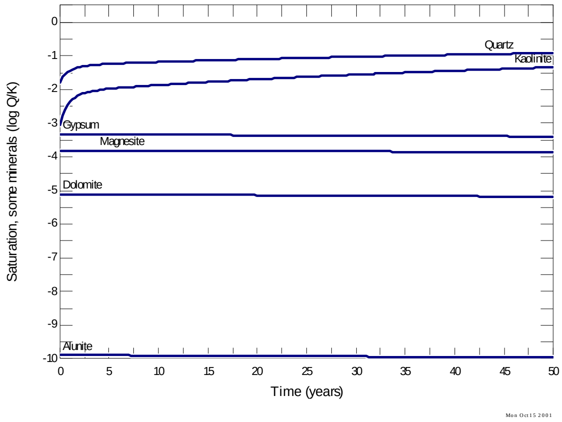
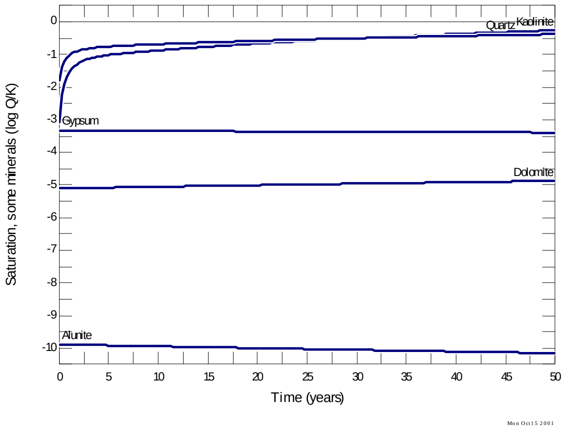


Figure 39: **Variation in pH of aqueous solution over time for leachate interacting with ground water in the saturated zone at different flow rates: (top) 1000 L/year, (middle) 260 L/year, (bottom) 32 L/year**





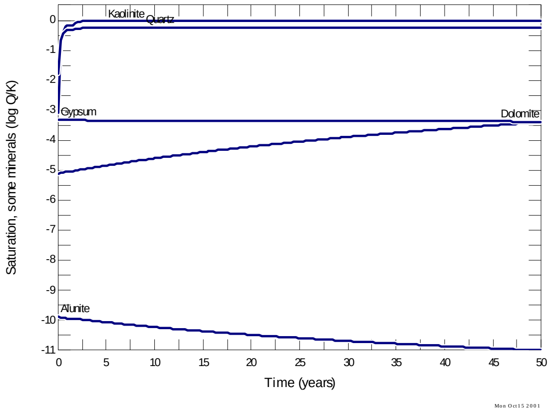


FIGURE 40: MINERAL SATURATION IN LEACHATE INTERACTING WITH GROUND WATER IN THE SATURATED ZONE AT DIFFERENT FLOW RATES: (TOP) 1000 L/YEAR, (MIDDLE) 260 L/YEAR, (BOTTOM) 32 L/YEAR

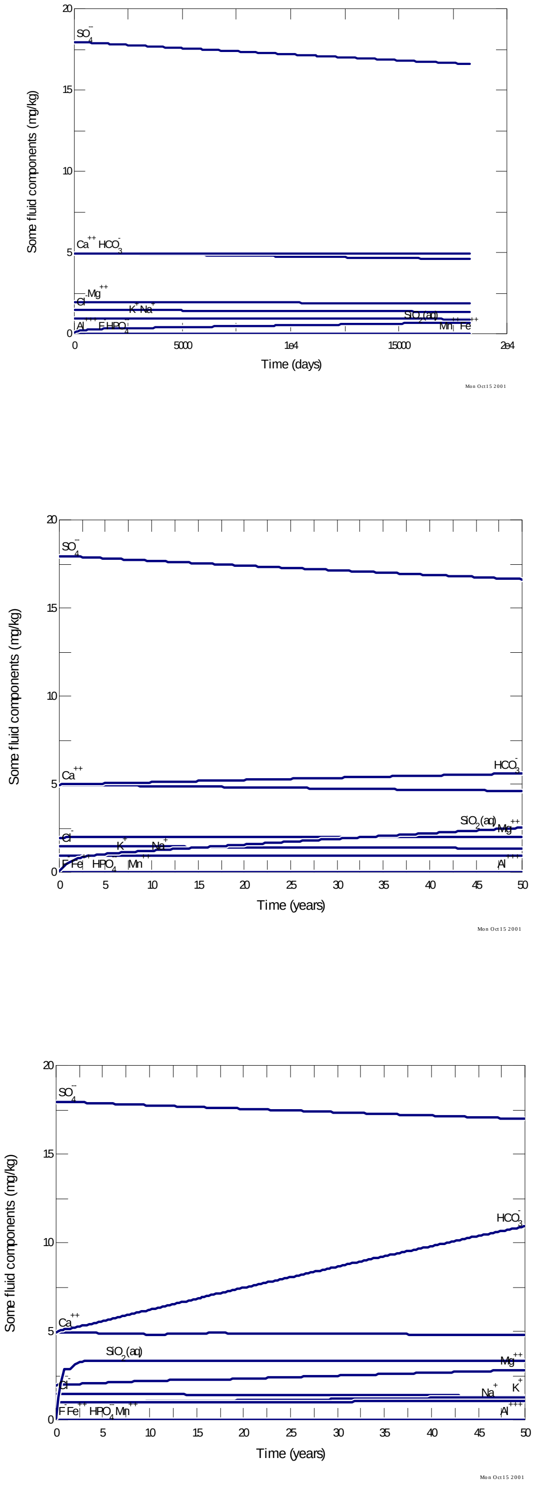


FIGURE 41: CONCENTRATION OF CHEMICAL COMPONENT IN A FLUID INTERACTING WITH GROUND WATER IN THE SATURATED ZONE AT DIFFERENT FLOW RATES: (TOP) 1000 L/YEAR, (MIDDLE) 260 L/YEAR, (BOTTOM) 32 L/YEAR

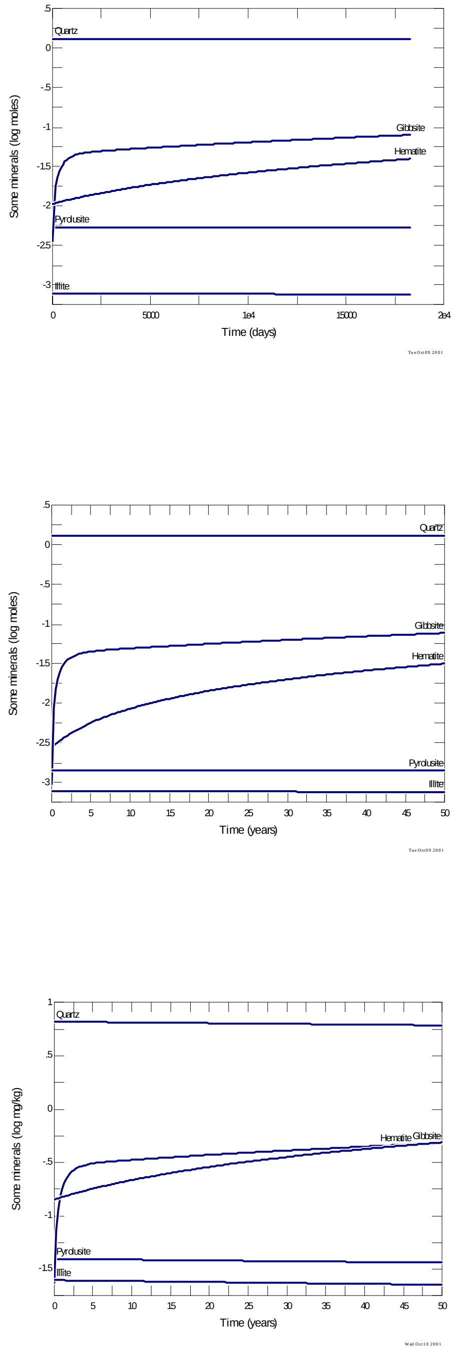


FIGURE 42: SEQUENCE IN WHICH MINERALS PREVAIL DURING THE REACTION PROGRESS BETWEEN LEACHATE AND GROUND WATER IN THE SATURATED ZONE AT DIFFERENT FLOW RATES: (TOP) 1000 L/YEAR, (MIDDLE) 260 L/YEAR, (BOTTOM) 32 L/YEAR

5.5. LEACHATE WATER QUALITY FROM THE MODEL SINKHOLE

The leachate water quality from the sinkhole initially varies significantly depending on the flow passing through the sinkhole. The lesser the flow is that passes through the sinkhole, the worse the water quality becomes that exits the sinkhole. A low flow (32 L/a, equals rainfall recharge of 5% MAP) resulted in a much poorer water quality indicated by elevated cations and anion concentrations compared to the cation and anion concentrations at average flow (260 L/a, equals rainfall recharge of 40%) or high flow (1000 L/a, equals rainfall recharge of 150% MAP for sinkholes situated within the Wonderfontein Spruit or in close proximity thereof).

Over the modelling period of 50 years however, the final water qualities for the respective flow scenarios show generally a good water quality arising from the sinkholes. With the exception of uranium, the final water quality expected in the in the dolomite aquifer is of a good quality suitable for domestic use.

A comparison of the resulting leachate water quality in the sinkhole is given in Table 4 to 7 below. The table gives the leachate water quality after a modelling period of 50 years for the following:

- The leachate water leaving the aerobic zone (where pyrite oxidation is at a maximum)
- The leachate water leaving the anaerobic zone (the outflow from the sinkhole)
- The leachate water leaving the vadose zone
- The water quality in the dolomite aquifer after mixing of the leachate and the dolomite groundwater has occurred

Only the components in elevated concentrations are shown (concentrations >0.009 mg/kg). The saturated minerals forming in each of the zones are also indicated.

TABLE 4: **LEACHATE WATER QUALITY IN THE AEROBIC ZONE OF THE SINKHOLE BACKFILL AFTER 50 YEARS AT DIFFERENT FLOW RATES (OBTAINED FROM THE GEOCHEMICAL MODEL, CONCENTRATIONS IN MG/KG)**

SPECIES	**FLOW**		
	32 L/a	**260 L/a**	**1000 L/a**
PH	6.0	6.1	6.6
Al^{+++}	-	-	-
Ca^{++}	9.52	1.20	0.31
Cl^{-}	0.03	-	-
Fe^{++}	-	-	-
HCO_3^{-}	2.38	0.99	0.89
K^{+}	2.95	0.37	0.09
Mg^{++}	7.85	1.01	0.29
Na^{+}	1.46	0.18	0.04
SO_4^{--}	59.12	7.47	1.94
$SiO_{2(aq)}$	8.81	3.53	3.41
Saturated minerals:			
	Quartz	Hematite	Pyrolusite
	Mg-montmorillonite	Mg-montmorillonite	Hematite
	Pyrolusite	Kaolinite	Gibbsite
	Kaolinite	Pyrolusite	Kaolinite

TABLE 5: **LEACHATE WATER QUALITY IN THE ANEROBIC ZONE OF THE SINKHOLE BACKFILL AFTER 50 YEARS AT DIFFERENT FLOW RATES (OBTAINED FROM THE GEOCHEMICAL MODEL, CONCENTRATIONS IN MG/KG)**

SPECIES	**FLOW**		
	32 L/a	**260 L/a**	**1000 L/a**
PH	7.8	7.1	7.0
Al^{+++}	-	-	-
Ca^{++}	9.52	1.2	0.31
Cl^{-}	0.03	-	-
Fe^{++}	-	-	-
HCO_3^{-}	16.62	2.86	1.36
K^{+}	1.92	0.37	0.09
Mg^{++}	7.98	1.01	0.29
Na^{+}	1.46	0.18	0.04
SO_4^{--}	46.99	5.94	1.54
$SiO_{2(aq)}$	8.89	3.41	3.41
Saturated minerals:			
	Quartz	Gibbsite	Pyrolusite
	Ca-montmorillonite	Ca-montmorillonite	Hematite
	Muscovite	Kaolinite	Gibbsite
	Kaolinite	Pyrolusite	Kaolinite
	Muscovite		
	Pyrolusite		

TABLE 6: **LEACHATE WATER QUALITY IN THE UNSATURATED ZONE AFTER 50 YEARS AT DIFFERENT FLOW RATES (OBTAINED FROM THE GEOCHEMICAL MODEL, CONCENTRATIONS IN MG/KG)**

SPECIES	**FLOW**		
	32L/a	**260L/a**	**1000L/a**
PH	7.8	7.4	7.0
Al^{+++}	0.01	-	-
Ca^{++}	44.65	60.44	28.02
Cl^{-}	0.16	0.16	0.09
Fe^{++}	0.01	-	-
HCO_3^{-}	36.17	83.60	30.16
K^{+}	1.92	0.71	0.24
Mg^{++}	20.08	18.68	6.66
Na^{+}	2.89	1.24	0.61
SO_4^{--}	166.8	161.1	87.68
$SiO_{2(aq)}$	3.44	3.41	3.28
Saturated minerals:			
	Pyrite	Dolomite	Pyrolusite
	Mg-montmorillonite	Ca-montmorillonite	Hematite
	Dolomite	Kaolinite	Gibbsite
	Kaolinite	Gibbsite	Ca-montmorillonite
	Muscovite	Pyrolusite	
	Ca-montmorillonite	Fluorapatite	
	Gibbsite		
	Fluorapatite		
	Smectite		

TABLE 7: WATER QUALITY IN THE DOLOMITE AQUIFER AFTER MIXING WITH THE LEACHATE AFTER 50 YEARS AT DIFFERENT FLOW RATES (OBTAINED FROM THE GEOCHEMICAL MODEL, CONCENTRATIONS IN MG/KG)

SPECIES	**FLOW**		
	32L/a	**260L/a**	**1000L/a**
pH	7.3	7.0	6.9
Al^{+++}	-	-	-
Ca^{++}	4.82	4.64	4.62
Cl^{-}	1.38	1.38	1.38
Fe^{++}	-	-	-
HCO_3^{-}	10.97	5.63	4.93
K^{+}	1.33	0.97	0.93
Mg^{++}	2.85	2.00	1.88
Na^{+}	1.10	0.94	0.92
SO_4^{--}	17.02	16.66	16.63
$SiO_{2(aq)}$	3.36	2.55	0.73
Saturated minerals:			
	Mg-montmorillonite	Pyrolusite	Pyrolusite
	Pyrolusite	Hematite	Hematite
	Gibbsite	Gibbsite	Gibbsite

The calculation of the stability of uranium species in the leachate arising from the model sinkhole, were determined in a sliding pH scale from pH 2.0 to pH 10.0 with a concentration of 1 mmol UO_2 in an acidic solution (1 mmol H_2SO_4).

The assessment of the leachate quality arising from the model sinkhole showed that the pH was generally neutral to alkaline (pH 6.8 to pH 8.0). The results for the uranium species presented in Table 8 below have therefore been limited to the range of pH 6.0 to pH 10.0.

TABLE 8: **URANIUM OXIDE SPECIES [MG/KG] IN AQUEOUS SOLUTION BETWEEN PH 6 AND PH 10 AT A U CONCENTRATION OF 1 MMOL (237.8 MG/KG)**

UO SPECIES	**PH**					
	6.0	**6.8**	**7.6**	**8.4**	**9.2**	**10.0**
$UO_2(SO_4)_2$	0.005	- - -	- - -	- - -	- - -	- - -
UO_2Cl	0.004	- - -	- - -	- - -	- - -	- - -
UO_2SO_4	0.120	- - -	- - -	- - -	- - -	- - -
UO_2	0.386	0.0099	- - -	- - -	- - -	- - -
$(UO_2)_3(OH)_4$	1.457	0.039	- - -	- - -	- - -	- - -
$(UO_2)_2(OH)_2$	1.608	0.042	- - -	- - -	- - -	- - -
UO_2OH	2.428	0.393	0.036	0.003	- - -	- - -
$(UO_2)_3(OH)_5$	124.5	21.08	0.619	0.016	- - -	- - -
$(UO_2)_4(OH)_7$	130.3	22.55	0.378	- - -	- - -	- - -
$(UO_2)_3(OH)_7$	39.14	263.7	308.4	309.4	309.4	309.4
TOTAL	299.948	307.764	309.433	309.419	309.400	309.400

The results demonstrate that uranium under slightly acidic and near neutral conditions (pH 6.0 and 6.8) is present in a number of different species such as -sulphates, -chloride, -oxide and -oxyhydroxides, although the concentrations of all uranium species other than the uranium oxyhydroxides are very low (<1.0 mg/kg). Under alkaline conditions the dominating uranium species is $(UO_2)_3(OH)_7$ reaching its maximum concentration in the liquid phase (309.4 mg/kg) at pH 8.4.

This indicates clearly that uranium leached from the tailings material under alkaline conditions will not precipitate but will be present in its dissolved form in the leachate. The final concentration of the uranium in the leachate would however depend on:

- The initial uranium concentration in the tailings material
- The chemical composition of the tailings material
- The prevailing pH
- The flow velocity of the seepage through the tailings backfill

The modelled uranium concentration of 1 mmol U (237.8 mg U) is considered to be conservative but is likely to be representative for some of the tailings material produced historically. The uranium concentrations in the tailings material produced in the Far West Rand at present are expected to be considerably lower and subsequently the uranium concentrations in the leachate from sinkholes backfilled with this material are therefore also expected to be lower.

6. DISCUSSION & CONCLUSIONS

The theoretical predictive modelling of the behaviour of the geochemical system yielded a number of important points to consider when developing a strategic rehabilitation scenario for the backfilling of sinkholes in dolomitic terrain, using tailings material. The main findings could be explained in a logical manner, based on first principles:

- The outer rim of backfill material reacts to produce AMD. However, the large volume encapsulated within this shell of oxidized material is almost unaffected by oxidation reactions and does not contribute towards the load of salts emanating as seepage. The availability of oxygen dictates the extent to which AMD will form within the tailings-filled sinkholes. By implication there is a correlation between the extent of the oxidized zone and the volume of AMD generated. Furthermore, the implication is that flushing of the system is not a rehabilitation option, since new un-oxidized material would be exposed continuously, resulting in a steady supply of AMD;
- The flow rate is a critical factor in determining the water quality emanating from a specific environment / geochemical node. The tailings material requires time to interact with the passing fluids in order to let water-rock reactions proceed. The different flow rates studied clearly show that the rate of flow is a critical parameter during any rehabilitation scenario planning, since this is one of the few parameters that could be controlled in a practical manner. When considering these scenarios, a clear distinction must be made between concentration of chemical species in solution and the cumulative load of species in solution;
- The adsorption of metals onto the surfaces of secondary minerals is an important scavenging mechanism, which reduces the concentration in effluent. Low pH conditions keep the secondary minerals in solution, and;
- In terms of the radioactive elements, only the uranium-bearing species were tested. The majority of uranium-bearing species are insoluble at pH values above 7. However, one of the more common uranium hydroxide species is extremely soluble under alkaline conditions. Thus, uranium would migrate under the same physico-chemical conditions that would be favourable for the inhibition of toxic heavy metal migration.

The geochemical modelling results indicate that, in general, the water, which would eventually mix with the groundwater, would be of relatively good quality. There is, thus, little concern for maintaining the water quality standards at acceptable levels. However, from a water quality perspective the major concern emanating from this investigation would be the mobility of uranium species under the given near-neutral conditions.

It is recommended that future investigations into the conditions relating to the sinkholes in dolomitic terrain should focus on the rate at which dolomitic host-rock would be consumed in the chemical reactions, i.e. the rate of sinkhole formation, instead of the water quality emanating from the sinkholes. Thus, the structural aspects that dictate the rate of sinkhole formation and the subsequent collapse of the sinkholes deserve more attention.

7. REFERENCES

Bethke, C.M. (1996): *Geochemical Reaction Modeling*, Oxford University Press, Oxford

Feather & Koen (1975): Minerals Sci. Eng. Vol. 7, no. 3, pp. 189 – 224

Langmuir D. (1997): *Aqueous Environmental Chemistry*, Prentice Hall, New Jersey

Stumm W. and Morgan J.J. (1970): *Aquatic Chemistry*, Wiley-Interscience, New York

R Boer

S Dill **Alistair James** Pr Eng

Metago Environmental Engineers (Pty) Ltd

APPENDIX B

AN ASSESSMENT OF THE IMPACTS ON GROUNDWATER QUALITY ASSOCIATED WITH THE BACKFILLING OF DOLOMITIC CAVITIES WITH GOLD MINE TAILINGS

- FAR FIELD MODEL -

FINAL REPORT TO THE WATER RESEARCH COMMISSION

BY

S Dill, HJJ Boshoff and AR James

Metago Environmental Engineers (Pty) Ltd, PO Box 1596, Cramerview, 2060, South Africa

APPENDIX TO WRC REPORT NO 1122/1/07

EXECUTIVE SUMMARY

To assess the potential impact on the dolomite aquifer associated with pollutants arising from sinkholes backfilled with gold mine tailings, a flow and contamination transport model, referred to as the Far Field Model (FFM) was developed. The model simulates the movement of pollutants in the horizontal direction away from the source term(s) and the development of a plume surrounding the source term(s).

The objective of the FFM was to develop a generic flow model and contamination transport model to simulate the upper section of a typical dolomite aquifer, which may be impacted on by pollution caused by sinkholes filled with gold and uranium tailings material. The simulation of a number of scenarios to evaluate the significance of different factors that might influence the magnitude and extent of the uranium plume was undertaken.

The following was concluded from the FFM:

- Based on the modelling undertaken it may be concluded that backfilling of sinkholes in the Far West Rand with gold mine tailings can potentially cause pollution. The risk of pollution is however highly dependent on:
    - The concentration of uranium in the leachate from the backfill.
    - The spatial orientation of the zone of sinkholes. A zone of sinkholes that form along an East – West plane parallel to the general flow direction have a much higher risk of degrading the aquifer than the equivalent zone which forms along a north south plane.
    - The spatial concentration of sinkholes. Where sinkholes are backfilled with tailings close to one another, the risk of a pollution plume being detected is significantly higher.
    - The location of the backfill relative to the more permeable or cavernous zone. Clusters of backfilled sinkholes that form in the Wonderfontein Spruit have a less detrimental effect than an equivalent cluster would have that formed away from the more cavernous zone as a result of the increased water flux through this zone and the enhanced dilution and dispersion effect.

- Leachate concentrations in excess of 0.3 ppm U from the backfilled sinkholes generally cause groundwater pollution in excess of the WHO WQ guidelines with the exception of backfilled sinkholes measuring no more than one idealised backfilled sinkhole of 0.40 ha in extent.

- As a general guideline, backfilling of sinkholes with gold mine tailings has a high risk of causing impacts on the dolomite aquifer in excess of the SA WQ guidelines when the leachate concentration exceeds 30 ppm U. However, when the effective zone of backfill exceeds 0.4 ha, the SA WQ guidelines have a high probability of being exceeded if the leachate concentration exceeds 3.0 ppm U.

- The relative impact of tailings dams compared to backfilled sinkholes is considerably greater as evidenced by the fact that the tailings dams simulated caused pollution with a uranium leachate concentration of in excess of 0.3 ppm U.

- Considering the current SA water quality guidelines, sinkholes, which are situated in the stream or in close proximity to the stream, (these account for the majority of sinkholes in the Far West Rand) may be backfilled with gold mine tailings provided the leachable U concentration from the tailings material is less than 30 ppm.

- Although the impact from a tailings dam has been shown to be very pronounced the mitigating effects from the compacted soil cover beneath the tailings dam have not been considered by the model. Contamination assessments undertaken for soils from footprints of removed tailings dams indicated generally elevated uranium concentrations in the soil with concentrations of less than 1 ppm U in the groundwater in close proximity to the tailings dams. The model therefore seems to overestimate the impact of contamination from the tailings dam to the aquifer by probably one order of magnitude.

- The modelling indicated that the uranium plumes reached their full aerial extent after 50 to 100 years, thereafter the plume would only increase marginally for the following centuries. Based on a comparison of the total uranium content of the tailings with the leach rate, complete leaching of the uranium from the tailings will take several hundred to thousands of years. The plume will finally reduce and eventually disappear, when all uranium has been leached from the respective sources of pollution. The long term impact of backfilling may thus be considered practically the same as the impact after 50 to 100 years, when the plume has reached its full extent.

There is clearly a need to apply a precautionary approach to backfilling of sinkholes of uranium containing gold tailings. Backfilling will not result pollution where a sinkhole develops in isolation from other sinkholes and needs to be backfilled. Backfilling of sinkholes that form within the more cavernous zone associated with the Wonderfontein Spruit have a higher risk of causing a more extensive but lower concentration pollution plume, since the orientation of the sinkhole clusters is generally parallel to the aquifer flow direction and the water flux through the aquifer is higher at this point. Clusters of sinkholes that form away from the river are likely to give rise to a less extensive plume but one with a higher peak concentration.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

1.1. BACKGROUND

The Water Research Commission project K 5/1122 is concerned with the assessment of the impacts on groundwater quality associated with the backfilling of dolomitic cavities (sinkholes). Tailings from the gold mines were identified in the early stage of the project as the most likely source of backfill material to be used in the Far West Rand (FWR).

Geochemical modelling was undertaken to assess the quality of seepage water arising from a sinkhole. The seepage from the backfill is referred to as leachate and the geochemical model used to assess the leachate quality, the Near Field Model (NFM). The NFM considers the path of flow of water that enters the backfill near the top surface, passes through the backfill end then exits the backfill either entering the:

- vadose zone, from whence it percolates down to the dolomite aquifer or
- the dolomite aquifer directly.

The NFM showed that metals are generally of minor concern as the geochemical conditions in the deeper part of the sinkhole favour metal removal from the aqueous phase due to the formation and precipitation of metal hydroxides and oxyhydroxides.

However, the results obtained from the NFM indicated that uranium would move through the backfill material of the sinkhole unabatedly. Depending on the initial uranium concentration in the tailings material used to backfill the sinkhole, the uranium concentration in the leachate would most likely fall in the range 3.0 to 30 ppm U with potential maximum of about 300 ppm U. Concentrations above 310 ppm U in the leachate are not likely as the uranium mineral schoepite is formed above this concentration. As uranium is therefore considered the most critical potential pollutant, the modelling of the effects of backfilling of the sinkholes on the aquifer is limited to the consideration of the impact of backfilling on the uranium concentration in the aquifer.

To assess the potential impact on the dolomite aquifer associated with uranium, a flow and contamination transport model, referred to as the Far Field Model (FFM) was developed. The model simulates the movement of uranium in the horizontal direction away from the source term(s) and the development of a plume surrounding the source term(s). Unlike the NFM, which describes the chemical changes that occur over a short vertical distance through the backfill and into the aquifer, the FFM determines the concentration of the contaminants over time at any point surrounding the source term (the backfilled sinkhole).

This document forms Appendix B of the main report (Metago report 115-002, "An Assessment of the Impacts on Groundwater Quality associated with the Backfilling of Dolomitic Cavities with Gold Mine Tailings", Report No. 3, December 2004".

1.2. OBJECTIVE OF THE DOCUMENT

To consider the regional effect that backfilled sinkholes may have on the water quality in the dolomite aquifer, the "Far Field Model" ("FFM") was developed. The FFM is a two-dimensional flow model that examined the following scenarios:

- The effect of the location of the backfilled sinkholes in the dolomite compartment. This comprised the analysis of a single backfilled sinkhole element ("BSE") placed in the following manner:
  - in the highly cavernous zone associated with the streambed
  - in close proximity to the streambed, but out of the highly cavernous zone
  - 1,2 km away from the stream.
- The effect of the orientation of the backfilled sinkholes relative to the direction of groundwater movement by placing a row of five BSE's all in close proximity to the stream, either
  - in a line parallel to the stream, or
  - in a line perpendicular to the stream
- The effect of spatial concentration of backfilled sinkholes by analysing a cluster of BSE's (for 30, 45 and 60 BSE's).
- The relative effect of a tailings dam constructed on the dolomite aquifer compared to the effect of backfilled sinkholes. Two cases were considered, namely:
  - A tailings dam placed in close proximity to the stream, and
  - A tailings dam placed 1,2 km away from the stream.

The FFM was used to assess the severity of the pollution impact on the dolomite aquifer by evaluating the pollutant concentration and the spatial extent of the pollution plumes arsing from the respective modelled scenarios.

2. TERMS OF REFERENCE

The terms of reference for the Far Field Model (FFM) were as follows:

- Development of a generic flow model to simulate the upper section of a typical dolomite aquifer, which may be impacted on by pollution caused by sinkholes filled with gold and uranium tailings material.

- Development of the contaminant transport model for uranium to predict the generic impact of backfilling of sinkholes with tailings on the dolomitic aquifer water quality.

- The simulation of a number of scenarios to evaluate the significance of different factors that might influence the magnitude and extent of the uranium plume.

3. BACKGROUND INFORMATION

3.1. GENERAL MODELLING INFORMATION

The mass of uranium in the aqueous phase in a portion of aquifer is equal to the net mass flux transported due to advection and dispersion, less the net mass flux sorbed, less the net mass flux decayed to a daughter product, plus the net mass flux decayed from a parent radioactive material.

The general equation for the transport of a contaminant through a one-dimensional homogenous porous medium is given in Equation 1:

EQUATION 1 (CTRAN USER MANUAL & TILL ET AL: RADIOLOGICAL ASSESSMENT 1983,PP 4-14)

$$\theta \frac{\partial C_i}{\partial t} + \rho_d \frac{\partial S_i}{\partial t} \frac{\partial C_i}{\partial t} = \theta D_i \frac{\partial^2 C_i}{\partial x^2} - U \frac{\partial \ C_i}{\partial x} - \lambda_i \theta C_i - \lambda_i S_i \rho_d + \lambda_{i-1} \theta C_{i-1} + \lambda_{i-1} S_{i-1} \rho_d$$

The equation describes the material balance of the member of a decay chain and the preceding chain members.

The symbols have the following meanings:

θ = Volumetric water content (M_{water}/M_{solid})

C_i = Concentration of contaminant i, in the element

∂t = Time step

∂x = Element length

ρ_d = Density of the homogenous porous medium

S = Slope of the sorption function (distribution coefficient)

D = Hydrodynamic dispersion coefficient

U = Specific discharge or Darcian velocity

λ_i = Decay coefficient of species i

λ_{i-1} = Decay coefficient of parent radionuclide

The terms in the equation represent the various mechanisms by which the mass of a contaminant in an element changes with time. The terms are summarised below:

$\theta \frac{\partial C_i}{\partial t}$ = Change in mass of contaminant in the aqueous phase

$\rho_d \frac{\partial S_i}{\partial t} \frac{\partial C_i}{\partial t}$ = Change in mass of contaminant in the solid/sorbed phase

$\theta D_i \frac{\partial^2 C_i}{\partial x^2}$ = Change in mass due to dispersion of the contaminant

$U \frac{\partial\ C_i}{\partial x}$ = Change in mass due to advection

$\lambda_i \theta C_i$ = Reduction in mass due to radioactive decay of the contaminant in the aqueous phase to the daughter product

$\lambda_i S_i \rho_d$ = Reduction in mass due to radioactive decay of the contaminant in the sorbed or solid phase to the daughter product

$\lambda_{i-1}\theta C_{i-1}$ = Increase in mass due to radioactive decay of the parent species to the aqueous phase

$\lambda_{i-1}S_{i-1}\rho_d$ = Increase in mass due to radioactive decay of the parent species to the solid phase.

The FFM, takes the aqueous phase concentration of a contaminant of concern predicted in the NFM, using the results of leach tests and equilibrium modelling after equilibrating the leachate with the dolomite water and models the effect of the other transformations (sorption and decay) that take place along the flow path. In this way the FFM models the effect of removal and dispersion of trace elements of concern, at different distances away from a source term.

The sorption function for uranium in dolomite was obtained from the literature (AECL, 1996, Shott et al., 1998).

3.2. ANALYSIS OF TAILINGS MATERIAL FOR URANIUM

The Near Field Model (NFM) showed that the main chemical of concern in the leachate from sinkholes is uranium (for details refer to the report in Appendix A of this report) which may range from low concentrations (0.03 ppm U) to as much as 310 ppm U. The uranium concentration in the leachate is dependant on:

- The initial concentration of the uranium in the tailings material.
- The contact time of the pore water with the tailings material.
- The redox potential in the tailings, which influences to some extent which uranium oxides and -oxyhydroxides are formed.
- The pH, which at average to high uranium concentrations (238 mg/kg) in the tailings material influences the kind of uranium species precipitated, but below 310 ppm U has virtually no influence on the total concentration leached from the tailings material.

To ascertain the actual uranium concentrations likely to be encountered in the gold tailings material and the actual leachable uranium concentration, tailings samples were collected and analysed to determine the total and leachable uranium concentration.

3.2.1. SAMPLING OF TAILINGS MATERIAL

Tailings material samples were obtained from tailings dam No. 4 at West Driefontein Mine using a hand auger to obtain those samples, which were taken at depth in the dam. The samples analysed were as follows:

- Fresh tailings material directly from the metallurgical plant.
- Tailings material from the well oxidised zone of the dam (sample was obtained by hand auger from the side slope of the tailings dam at a depth of 1.0 m).
- Tailings material from below the phreatic surface (sample was obtained by hand auger from the toe of the tailings dam at 2.7 metre depth). The significance of this sample is that the leachate quality from this zone is the most representative of the leachate that enters the natural soils beneath the tailings dam. Because this sample was taken from below the phreatic surface, it represents a zone that is continually flushed by seepage water.

3.2.2. ANALYSIS OF TAILINGS MATERIAL

The samples were analysed for elemental composition by XRF (for the analytical results refer to Table 1 below) and for leachable elements by South African Acid Rain Test and ICP MS (SA_AR; for the analytical results refer to Table 2 below).

TABLE 1: ELEMENTAL COMPOSITION OF TAILINGS MATERIAL FROM WEST DRIEFONTEIN MINE (ANALYSED BY XRF)

	Fresh Tailings	**Fresh Tailings - Duplicate -**	**Weathered Tailings – 1 metre -**	**Weathered Tailings – 2.7 metres -**
SiO_2 [%]	79.7	79.7	76.8	80.0
TiO_2 [%]	0.39	0.39	0.39	0.31
K_2O [%]	1.26	1.28	1.50	1.13
MgO [%]	1.65	1.68	1.68	0.98
Al_2O_3 [%]	8.62	8.84	9.11	7.63
Fe_2O_3 [%]	4.49	4.50	5.66	3.78
CaO [%]	0.56	0.56	0.64	1.21
MnO [%]	0.05	0.06	0.06	0.19
P_2O_5 [%]	0.06	0.05	0.04	0.04

	Fresh Tailings	**Fresh Tailings** **- Duplicate -**	**Weathered Tailings – 1 metre -**	**Weathered Tailings – 2.7 metres -**
Na_2O [%]	0.08	0.08	<0.05	0.06
Cr_2O_3 [%]	0.03	0.04	0.04	0.03
V_2O_5 [%]	0.01	0.01	0.01	<0.01
LOI [%]	2.39	2.44	3.25	3.74
SUM [%]	99.3	99.6	99.0	99.3
U_3O_8 [ppm]	18	18	37	53

Cells shaded in green indicate relative gain in the respective element in comparison to the fresh tailings material

Cells shaded in orange indicate relative loss in the respective element in comparison to the fresh tailings material

The accuracy of the analytical method for the main elements in the tailings material is in the order of 10%. While the coefficient of variation of the respective element proportions in the fresh tailings is not known, certain elements show a difference in excess of 50% to the concentration in the fresh tailings. This difference is more likely caused by elemental transport (depletion from one zone and accumulation in another) rather than a natural variation in the elemental composition of the tailings over time. Of significance are the following:

- A loss of magnesium was observed in the zone of seepage (below the phreatic surface)
- Calcium, manganese and uranium oxide increased in the deeper tailings layer

This would indicate that a number of elements are transported from the top to the bottom of the tailings dam with the water flow. Once the elements have entered the saturated zone within the phreatic surface of the tailings dam, they can be readily transported from the tailings dam into the receiving environment with the arising leachate. Based on the analyses above, the most likely elements to arise with the tailings dam leachate are magnesium, which already has been depleted in the base layer, calcium, manganese and uranium. These observations coincide with the findings of the geochemical modelling undertaken in the NFM. Of the elements present in the leachate, the element of concern is uranium due its chemical and radiological toxicity to humans. The other elements are considered non-toxic to humans in the concentrations that they arise from the tailings dam (for details refer to Table 5 in Appendix A).

The fresh tailings material had the lowest uranium concentration (18 ppm), followed by the shallow toe layer (37 ppm) with the highest concentration present in the sample taken from below the phreatic surface (53 ppm). This may indicate that uranium is leached from the top and precipitated towards the bottom of the tailings dam.

Alternatively, the varying uranium concentrations in the tailings may be related to the variation of the uranium content in the ore.

The uranium analysis confirms that the uranium concentration in the tailings material from West Driefontein's No. 4 tailings dam is considerably lower than the uranium concentration of 290 to 870 ppm U_3O_8 found in the Witwatersrand auriferous material in the past (for details refer to Table 1 in Appendix A, after Feather & Koen, Minerals Sci. Eng. Vol. 7, no.3, pp 189-224).

The leachability of the elements from the tailings samples was determined by SA_AR leach test.

TABLE 2: LEACHABLE ELEMENTS FROM THE TAILINGS MATERIAL OF WEST DRIEFONTEIN MINE (LEACHED BY SA_AR, DETERMINED BY ICP-MS)

Element (all units in ppb)		Fresh Tailings	Fresh Tailings - Duplicate -	Weathered Tailings – 1 metre -	Weathered Tailings – 2.7 metres -
Lithium	Li 7	5.1012	5.2328	6.01	4.65
Beryllium	Be 9	1.6283	1.7237	0.94793	0.98853
Boron	B 11	110.96	109.13	33.305	32.469
Titanium	Ti 48	497.38	509.73	600.61	1047.2
Vanadium	V 51	0.71652	0.98767	0.67348	0.73567
Chromium	Cr 52	2.7002	2.605	0.90322	0.71983
Manganese	Mn 55	1041.1	1005.5	1016.9	Over range
Cobalt	Co 59	40.801	41.795	20.294	46.753
Nickel	Ni 60	94.003	96.409	100.69	128.79
Copper	Cu 65	7.6904	3.6941	17.662	14.876
Zinc	Zn 66	202.98	99.705	337.8	209.42
Arsenic	As 75	12.502	9.3745	1.172	22.982
Bromine	Br 79	107.44	136.09	36.021	32.816
Selenium	Se 82	1.3215	2.2244	2.5361	1.6885
Strontium	Sr 88	453.22	461.91	290.49	292.74
Molybdenum	Mo 95	0	0	1.1998	1.9008
Cadmium	Cd 114	0.93557	0.8737	2.6465	1.12
Tin	Sn 120	0.87305	0.45494	1.9017	1.6801
Antimony	Sb 121	4.6066	2.4061	0.73161	2.6055
Tellurium	Te 126	0.525	0.259	0.50976	0.79685
Iodine	I 127	0	0	5.7993	3.4666
Barium	Ba 138	116.27	116.64	79.267	91.001

Element (all units in ppb)		**Fresh Tailings**	**Fresh Tailings - Duplicate -**	**Weathered Tailings – 1 metre -**	**Weathered Tailings – 2.7 metres -**
Lanthanum	La 139	0.36382	0.39438	1.1986	1.4125
Tungsten	W 184	0.85265	0.85608	0.36882	0.45761
Platinum	Pt 195	0.22055	0.20175	0.64096	0.5599
Mercury	Hg 202	1.8758	1.6672	37.099	34.039
Thallium	Tl 205	0.08395	0.0829	0.03755	0.07126
Lead	Pb 208	9.9255	11.143	4.786	10.105
Bismuth	Bi 209	0	0	0.12057	0.11717
Uranium	U 238	9.090	10.65	334.6	578.9

The leachability of uranium increases with increasing total uranium concentration. In case of the higher uranium concentrations (34 and 57 ppm U_3O_8 in the tailings material respectively), the leachability of the uranium is in the order of 100 times less than the total concentration (0.334 ppm compared to 37 ppm for the shallow toe layer and 0.578 ppm compared to 53 ppm for the deeper layer). In case of the lower uranium concentration in the fresh tailings material, the leachability of the uranium is in the order of 2 000 times less than the total concentration (0.001 ppm U compared to 18 ppm U_3O_8 in the fresh tailings material).

The uranium concentration in the pore water of a sinkhole backfilled with tailings material is therefore likely to be in the range 0.001 to 0.5 ppm depending on the total uranium concentration in the tailings material used for backfilling of the sinkhole. This concentration range for uranium is at the lower end of that predicted by the NFM (0.03 ppm to 310 ppm U) for the leachate from a backfilled sinkhole.

3.3. URANIUM POLLUTION POTENTIAL

Prior to mining and subsequent dewatering of several of the compartments, the water quality in these dolomite aquifers was generally of good quality and suitable for most water uses. Mining activities, which have been ongoing for decades, have impacted detrimentally on the groundwater and surface water quality of the Wonderfontein Spruit in particular. Notwithstanding the above, and given that the project seeks to quantify the potential impact of the general possible practise of backfilling sinkholes with gold tailings, it was assumed that:

- The background water quality is generally good and meets potable standards.
- The human health risk is related to the uptake of contaminants (in this case uranium) by consumption of groundwater as drinking water.

- Humans in the area may be exposed to groundwater for in excess of 30 years with a regular daily consumption of groundwater of 2 litres.

The underlying principle for the contamination assessment of the dolomite aquifer associated with the backfilling of sinkholes using mine tailings is undertaken in accordance with the principles of the National Water Act (Act 36 of 1998) which states that while contamination may occur, pollution of the aquifer as the water resource is generally not acceptable. This would require that the groundwater in the dolomite aquifer, which at present in general is of such a quality that it can be used for potable purposes, should remain so in future and should not be allowed to degrade to the extent that it is no longer suitable for use a potable water.

The contamination assessment was undertaken in relative terms, which assumed that the groundwater in the aquifer does not contain significant concentrations of uranium. The impact of leachate from the backfilled sinkholes and the tailings dam was conducted for a range of leachable uranium concentrations varying from 0.3 to 300 ppm U using a stepped increase of one order of magnitude.

The national and selected international water quality guidelines with regard to uranium contamination of drinking water used as reference values for the water quality assessment are given in Table 3 below.

TABLE 3: DRINKING WATER GUIDELINES CONCERNING URANIUM

	URANIUM [mg/l]	ALPHA PARTICLES
SA WQ Guideline for Domestic Use	0 - 0.070 ***0.070 - 0.284***	0 - 0.5 Bq / L
World Health Organisation	0.002 (P)	0.1 Bq / L
USEPA National Primary Drinking Water Standards	NA	15 piecocuries / L
USEPA Risk Based Concentrations – Region III	0.0073	NA

SA target water quality range of low risk

NA – Not Available

(P) – Provisional Guideline Value. This term is used for constituents for which there is some evidence of a potential hazard but where available information on health effects is limited; or where an uncertainty factor grater than 1 000 has been used in the derivation of the tolerable daily intake (TDI)

The range for the target water quality in the SA WQ guideline for domestic use is based on the observation of no significant effect on water consumers with an annual cancer risk of < 1 in four million due to radiation. The next higher range of guideline values of low risk (0.070 to 0.284) “may potentially pose a slight risk of renal toxicity in sensitive individuals, where renal function is impaired, but unlikely to have demonstrable renal toxicity in healthy individuals” with an annual cancer risk of less than one in one million.

The assessment of the modelling results was based on the WHO guideline as the lower limit (0.002 ppm U) and the SA guideline value for uranium in drinking water (0.07 ppm U) as the higher limit. For the purpose of this study, any section of the dolomite aquifer above 0.07ppm U is considered polluted. The extent of pollution plumes depicted in the respective figures and the areas of impact calculated were based on the lower limit of 0.002 ppm U.

4. URANIUM TRANSPORT IN THE DOLOMITE AQUIFER

4.1. DEVELOPMENT OF THE FAR FIELD MODEL

Use was made of the two-dimensional finite element programme SEEP/W, which is capable of solving the Darcian equations for flow through a saturated and unsaturated porous medium. The programme was used to model flow in the horizontal (X,Y) plane under steady state flow conditions.

Once the SEEP/W model was calibrated, the results of the SEEP/W analysis are imported into the finite difference programme CTRAN/W and used to model contaminant transport. CTRAN/W is capable of solving equation 1 above, except that it is not able to handle the formation of uranium due to radioactive decay of parent radionuclides. This was not considered a significant constraint to the model as the half-life of uranium species varies between 10^5 to 10^9 years compared to a maximum time period of 800 years used for the modelling exercise.

A uranium flux is applied to selected nodes to simulate a steady state “injection” of leachate from the backfilled sinkhole(s) into the aquifer. The CTRAN model is then run over a series of time steps to calculate the concentration of the contaminant at each node for each time step.

4.2. THE SEEP/W MODEL (FLOW MODEL)

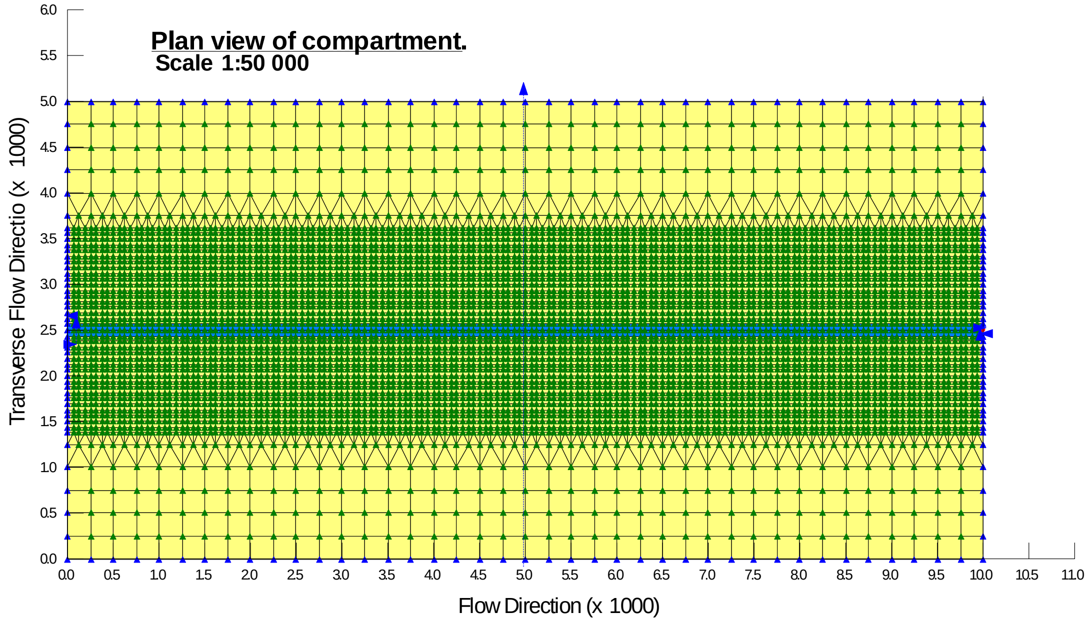
The SEEP/W model was used to model a typical generic dolomite aquifer of the Far West Rand. While the model results are not intended to be specific to a particular compartment, the Venterspost compartment was used as a basis for modelling to ensure that appropriate parameter values (including aquifer dimensions, flow rates, head losses etc.) were used and that the conclusions drawn are generally applicable to any of the compartments.

The parameters and values used in the model are given in Table 4 below.

TABLE 4: SEEP/W MODEL PARAMETERS

PARAMETER	VALUE	COMMENT
Area	50 km^2 (10 km x 5 km)	The area was analysed in a 250m x 250m (general area) and 62.5m x 62.5m grid (for the stream bed)
Thickness of the Aquifer	60 metres	Average value for the compartment
GW Inflow	0.19368 m^3/s	At the spring discharging into the aquifer with a hydraulic head of 2m height
GW Outflow	0.24190 m^3/s	GW flow + recharge
Recharge	0.05153 m^3/s 0.0720 m^3/s	Over the area of 50 km^2 for the assessment of impact from sinkholes Over the area of 1.5 km^2 for the assessment of impact from a tailings dam
No. of Grids	40 x 10 @ 250 x 250 m	General model area
No. of fine grids	160 x 40 @ 62.5m x 62.5m	Stream bed & adjacent area
Material Properties	Stream bed with fast GW flow (high conductivity) and the surrounding material with lower conductivity	Conductivity was derived by adjusting the conductivity until the head difference between the upstream boundary and downstream boundary equalled 2m

PARAMETER	VALUE	COMMENT
Recharge	5% of MAP	MAP = 0.65 m/a 5% of MAP = 32.5 mm/a or 1.03057e-9 m/s
Boundary Conditions	Compartment boundary with a no-flow boundary. Inflow at one node with a 2m hydraulic head Outflow at two nodes at 0.1209 m^3/s (total: 0.2419 m^3/s)	inflow = outflow – recharge. The value for the inflow was obtained from Tab 5 in Main Report, the recharge as given above and the outflow was calculated by the model
Conductivity	Stream bed = 0.041m/s Surrounding area = 0.0058 m/s.	Obtained from calibrating the flow model



Outer grid spacing 250m x 250m Inner grid spacing 62.5m x 62.5m

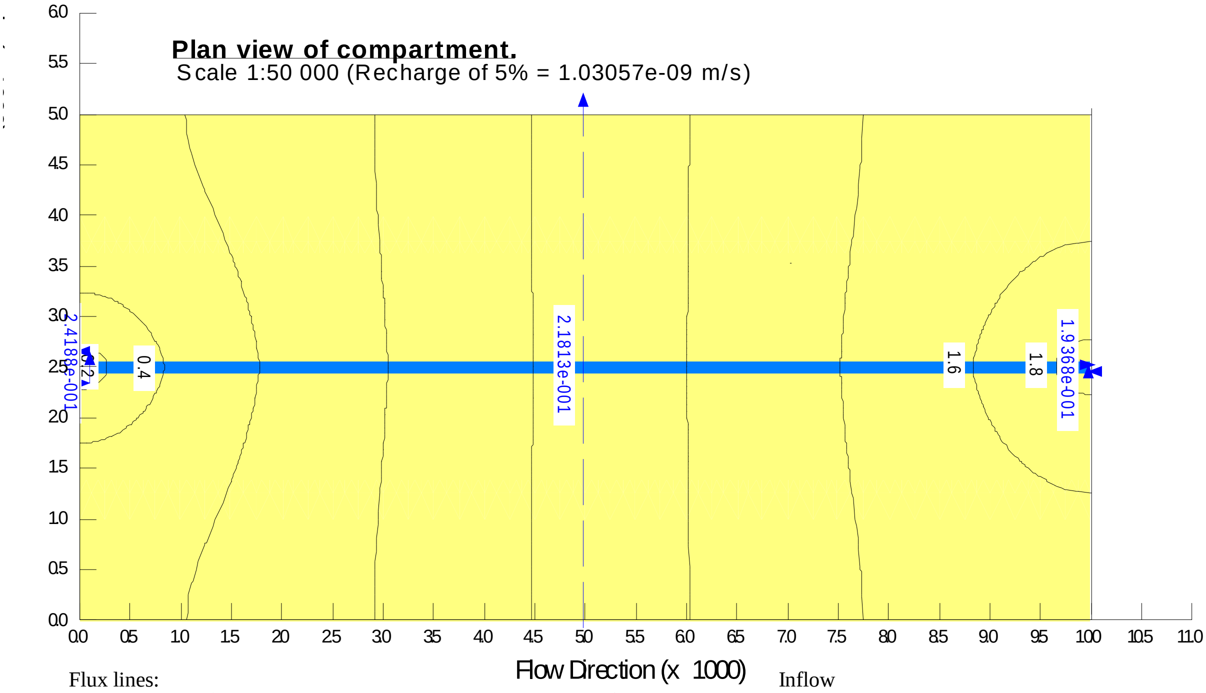
FIGURE 1: FINITE ELEMENT MESH USED FOR THE GENERIC FLOW MODEL (COMPILED WITH SEEP/W)

- A range of values is documented in the literature for the recharge of the dolomitic aquifers of the Far West Rand. Published values typical fall within the range 2.5 and 20% of MAP. For the purpose of this study, a recharge value of 5% MAP, which is towards the lower end of the documented range was chosen. This is in line with the precautionary approach.

- A steady state influx to the aquifer from the upstream boundary, representing the recharge from the upstream "eye" was taken to be 20.9 ML/d. This is based on values documented in the literature.

- The conductivity of the highly cavernous zone in the vicinity of the Wonderfontein Spruit was assumed to be seven times higher than that of the surrounding dolomite aquifer. This assumption was based on anecdotal evidence, which indicated that the cavernous zone in the immediate vicinity of the Wonderfontein Spruit is significantly more developed than to either side of this zone.

- Typical values for conductivities of dolomite material were obtained from literature (Domenico & Schwartz, 1990, Physical and Chemical Hydrogeology and “Introduction to Groundwater, Short Course, November 2000) and entered into the model. Based on these initial conductivity values, an iterative process of changing the conductivity of the respective materials in the model was undertaken until a hydraulic head difference between in influx point and the eye was 2 metres, representing the pre-mining and assumed post mining elevation head difference between the eastern and western side of the compartment.



Flux lines:
= (1.03057 x 10^{-9} x 10000 x 5000) + 1.9368 x 10^{-1} = 0.24521 m^3/s
Outflow = 0.2419 m^3/s Contours: Total hydraulic head in 0.2 m intervals.

FIGURE 2: HYDROSTATIC HEAD CONTOURS OF THE DOLOMITE AQUIFER MODEL

4.3. THE CTRAN MODEL (CONTAMINATION TRANSPORT MODEL)

The CTRAN model was used to simulate the transport of uranium in the horizontal direction through the upper part of the dolomite aquifer. The aqueous phase uranium concentration determined by the

NFM was used to determine boundary conditions for selected nodes in the FFM to evaluate a range of sinkhole and tailings dam arrangements and situations.

The steady state SEEP/W model result file forms the basis for the CTRAN model, thus all the parameters shown in Table 4 are relevant to the CTRAN model. In addition, the parameters shown in Table 5 are specific to the CTRAN model.

In order to represent the backfilling of a sinkhole with gold tailings material in the finite element model, the concept of a backfilled sinkhole element ("BSE") was introduced to enable modelling. A BSE is a single element in the finite element model into which the contaminant (in this case uranium) is introduced at a given rate per time unit given by the boundary function. The smallest element in the model measures 62.5m by 62.5m. Thus, a single BSE in the model would either represent a single sinkhole of the same dimensions or a group of very closely spaced sinkholes of smaller individual dimensions which add up to the same total surface area of 3906.25m^2 (62.5 x 62.5 m) Cleary, sinkholes in the field vary considerably in size but for the purpose of modelling, this standard size was adopted. A single BSE is equivalent to a large number of combinations of different sized sinkholes. For example, a BSE could represent 10x22m diameter sinkholes arrange in a small group or cluster within very close proximity to one another.

The contaminant mass flux boundary condition applied to the BSE in the model is calculated as the product of the leachate concentration and the water flux per unit area of element. Thus we use a leachate concentration of say 0.3mg/l based on the results of the NFM, and a water flux of 5% of MAP, the mass flux boundary condition applied to the BSE would be 0.30917e-9 g/m^2/s. Cleary, if measures were to be implemented which reduce the infiltration to 1% of MAP, the boundary condition would be 1/5th of that value. Similarly, if the leachate concentration or area of the sinkhole group was reduced, the mass flux boundary condition can be reduced. For example, if the impact of backfilling a single isolated sinkhole measuring 50m^2 were to be analysed, and the leachable uranium concentration was found to be 0.3mg/l, the mass flux boundary condition applied to the BSE would be 50/(62.5 x 62.5) x 0.309x10^{-9}g/m^2/s.

TABLE 5: CTRAN MODEL PARAMETERS

PARAMETER	VALUE	COMMENT
Boundary Conditions	Steady state mass flux boundaries used for different concentrations	Different uranium concentrations with a constant recharge rate were used
Mass Flux Functions for uranium in the leachate water from the BSE	0.30917e-9 g/m^2/s [0.3 ppm U] 3.0917e-9 g/m^2/s [3.0 ppm U] 30.917e-9 g/m^2/s [30 ppm U] 309.17e-9 g/m^2/s [300 ppm U]	
Dispersivity	Low = 1.97m and 5.21m and high = 18.7m and 49.6m	First value for transverse and second for longitudinal dispersion.
Diffusion	1 x 10^{-009} m^2/s	Personnel communication with Dr J v Blerk[1]
Adsorption Function	1mg/l = 1.685 x 10^{-009} (g uranium / g dolomite)	From Till et al. "Radiological Assessments", 1983
Radioactive Decay	Has not been considered	The contribution of radiation from radioactive decay has been considered negligible due to the long half life of uranium (244 500 to 4.7*10^9 years) compared to the assessment period with a maximum of 800 years

4.4. CTRAN SIMULATIONS

The following factors were investigated:

- Particle Retention Time -Particle tracking analyses were done to determine the retention time of conservative particles within the aquifer.
- The sensitivity of the uranium plume to the adsorption function.
- The effect of the location of the backfilled sinkholes in the compartment. This comprised the analysis of a single BSE placed:

  in the highly cavernous zone associated with the streambed

  in close proximity to the streambed, but out of the highly cavernous zone

  1,2 km away from the stream.

---

[1] Aquisim Consulting - Dr. J. v Blerk – Shott et al., 1998 & AECL, 1996

- The effect of the orientation of the backfilled sinkholes relative to the direction of groundwater movement by placing a row of five BSE's all in close proximity to the stream, either

  in a line parallel to the stream, or

  in a line perpendicular to the stream

- The effect of spatial concentration of backfilled sinkholes by analysing a cluster of BSE's (for 30, 45 and 60 BSE's)
- The relative effect of a tailings dam constructed on the dolomite aquifer compared to the effect of backfilled sinkholes. Two cases were considered, namely, a tailings dam

  placed in close proximity to the stream, and a tailings dam

  placed 1,2 km away from the stream.

.

5. CTRAN SIMULATION RESULTS

5.1. INTRODUCTION

To assess the sensitivity of the model to certain parameters a number of simulations were undertaken to test the effect of those parameters. These included:

- The effect of particle migration tested via particle tracking;
- The effect of adsorpotion on uranium mobility;
- The effect of sinkhole locations in the aquifer; and
- The effect of the orientation of backfilled sinkholes relative to the predominant groundwater flow direction.

5.2. PARTICLE TRACKING

Particles in the aquifer are likely to travel at different speeds due to the different conductivities in the aquifer. To assess the travelling speed and likely vectors of the particle migration, a particle tracking exercise was undertaken. For this purpose, particles were placed at different nodes namely:

- In the highly cavernous zone in the vicinity of the Wonderfontein Spruit

- Outside the highly cavernous zone but in close proximity to the Wonderfontein Spruit
- Outside the highly cavernous zone further away from the Wonderfontein Spruit

The results were recorded at different time steps, namely 50, 100, 200 and 400 years. The particle tracking analysis results are shown in Figure 3

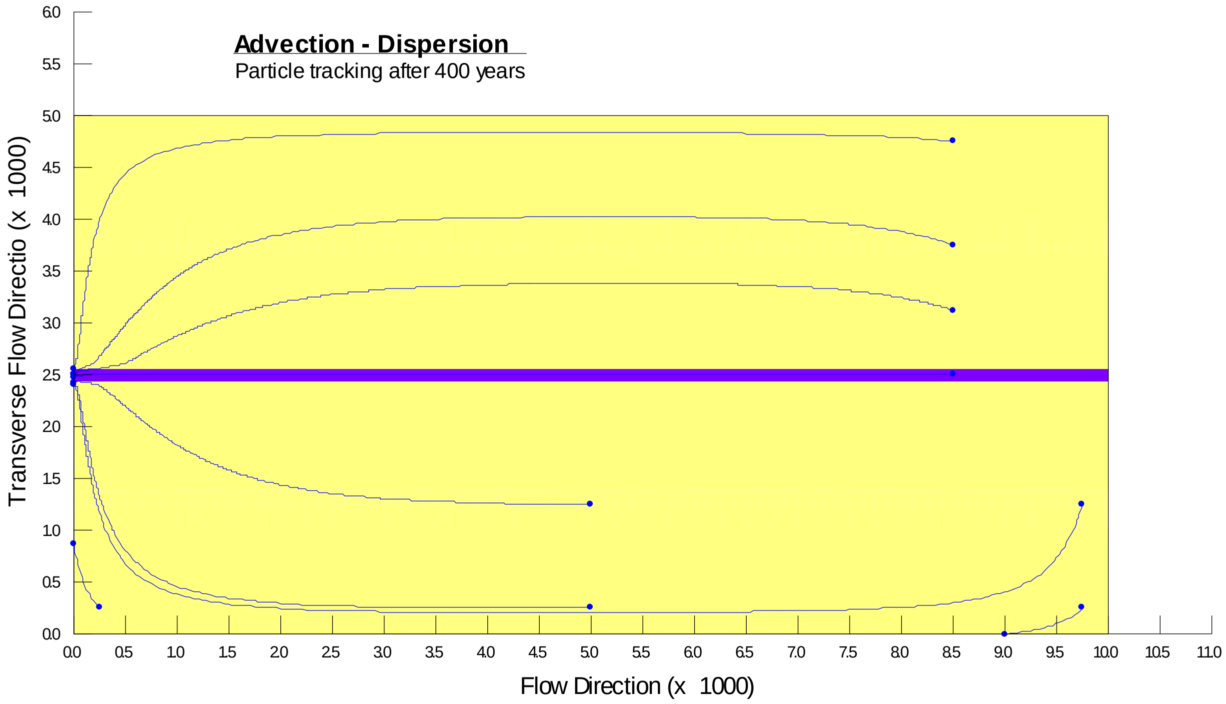


Figure 3: Particle Tracking in the Aquifer Model after 400 Years

The particle tracking analysis revealed that a non-reactive particle placed anywhere within the highly cavernous stream zone will exit the compartment within approximately 50 years. The time taken for a particle placed anywhere else to reach the exit eye varies but is typically of the order of 100 to 400 years. The slowest areas were those adjacent to the upstream boundary and towards the southern or northern extremities of the aquifer.

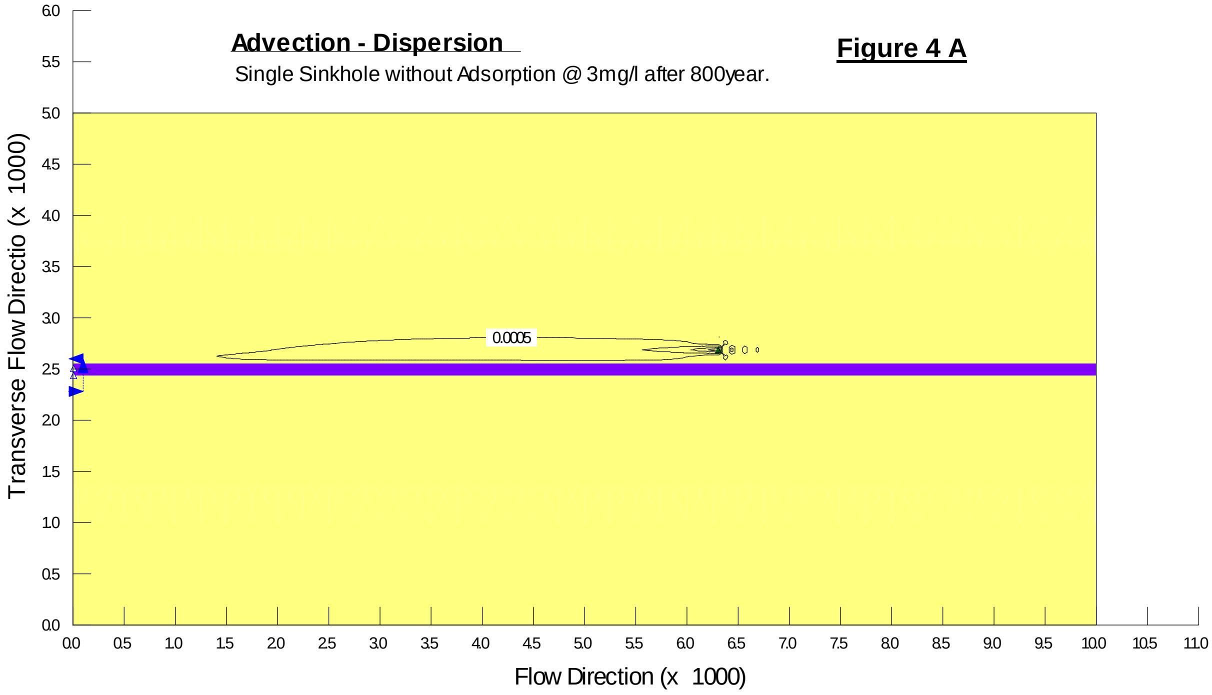
5.3. Sensitivity of Uranium Mobility to the Adsorption Constant

The sensitivity of uranium concentrations in the aquifer to the value of the uranium adsorption constant was determined by comparing the results of the 800 year analysis conducted for a single BSE placed next to the highly cavernous zone with a leachate concentration of 3.0ppm firstly without adsorption and then with the adsorption function set to 1.685×10^{-9} g U per g dolomite).

- The above value was derived from the literature (Till et al, 1983).

- After 800 years, the analysis showed that in both cases a plume with a boundary contour of 0.0005 ppm U developed. In the case of the model without the adsorption function, the total mass accumulation equalled 2.7267e+004 g U (all uranium present in the aqueous phase). The analysis with the adsorption function gave a total mass accumulation of 2.7548e+004 g U with 99% of the uranium being present in the aqueous phase (2.7267e+004 g U) and only 1% adsorbed onto the surface of the dolomite (2.815e+002 g U).

- From this analysis it was concluded that adsorption of uranium (at least for the relevant range, namely below 3.0ppm U) does not play a significant role. To simplify further analyses, adsorption was ignored. This simplification tends to result in a slight over-estimate of the aqueous phase uranium concentration at any point in the aquifer and an underestimate of the time that it will take for the uranium to migrate out of the system. Since the time modelled for depletion of the uranium source is extremely long (in excess of 800 years) the implications of the simplification are not considered significant.



Single sinkhole 125m from main stream:

Contamination at boundary condition qm vs. Time

No detectable concentration near the point after 800 years.

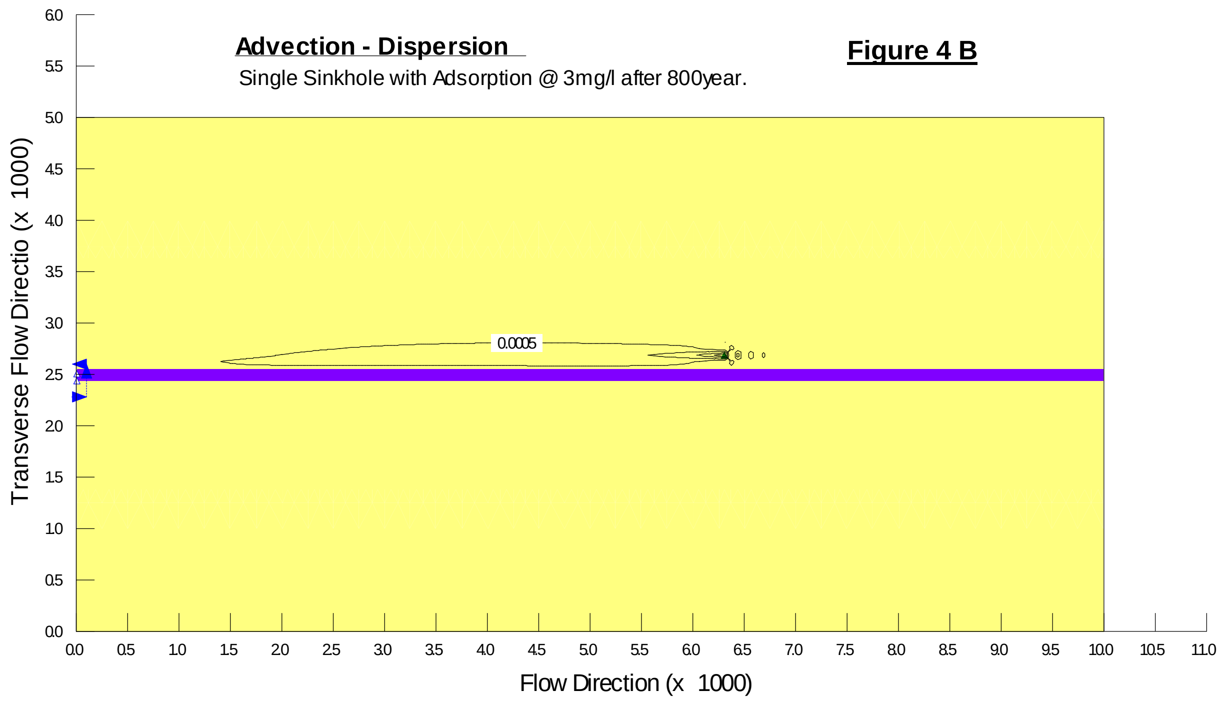
Boundary function 3 [3mg/l] without adsorption.

Mass Accumulation:

Total: 2.7267e+004

In Fluids: 2.7267e+004

On Solids: 0.000e+000



<u>Single sinkhole 125m from main stream:</u>

Contamination at boundary condition qm vs. Time
No detectable concentration near the point after 800 years. Boundary function 3 [3mg/l] with adsorption.

<u>Mass Accumulation:</u>

Total: 2.7548e+004
In Fluids: 2.7267e+004
On Solids: 2.815e+002

FIGURE 4: COMPARISON OF A CONTAMINATION PLUME DEVELOPING FROM A SINGLE SINKHOLE WITH ADSORPTION AND WITHOUT ADSORPTION

5.4. LOCATION OF BACKFILLED SINKHOLES

The results of the analyses for a single BSE placed at different locations within the dolomite compartment are summarised in Table 6 below.

TABLE 6: SUMMARY OF THE CONTAMINATION ASSESSMENT FOR A SINGLE SINKHOLE

BSE CONCENTRATION [ppm U]	SINKHOLE IN THE STREAM	SINKHOLE NEXT TO THE STREAM	SINKHOLE FAR AWAY FROM THE STREAM
0.3	0.0001 ppm U after 800 years	0.0003 ppm U after 800 years	0.0004 ppm U after 1 year 0.002 ppm U after 100 years 0.002 ppm U after 800 years
3.0	0.0011 ppm U after 800 years	0.003 ppm U after 1 year 0.0064 ppm U after 10 years 0.0065 ppm U after 800 years	0.0039 ppm U after 1 year 0.015 ppm U after 10 years 0.021 ppm U after 100 years 0.021 ppm U after 800 years
30	0.009 ppm U after 1 year 0.011 ppm U after 10 years 0.0106 ppm U after 800 years	0.03 ppm U after 1 year 0.064 ppm U after 10 years 0.065 ppm U after 800 years	0.039 ppm U after 1 year 0.155 ppm U after 10 years 0.207 ppm U after 100 years 0.207 ppm U after 800 years
300	0.09 ppm U after 1 year 0.106 ppm U after 10 years 0.106 ppm U after 800 years	0.3 ppm U after 1 year 0.64 ppm U after 10 years 0.65 ppm U after 50 years 0.65 ppm U after 800 years	0.398 ppm U after 1 year 1.55 ppm U after 10 years 2.069 ppm U after 100 years 2.069 ppm U after 800 years

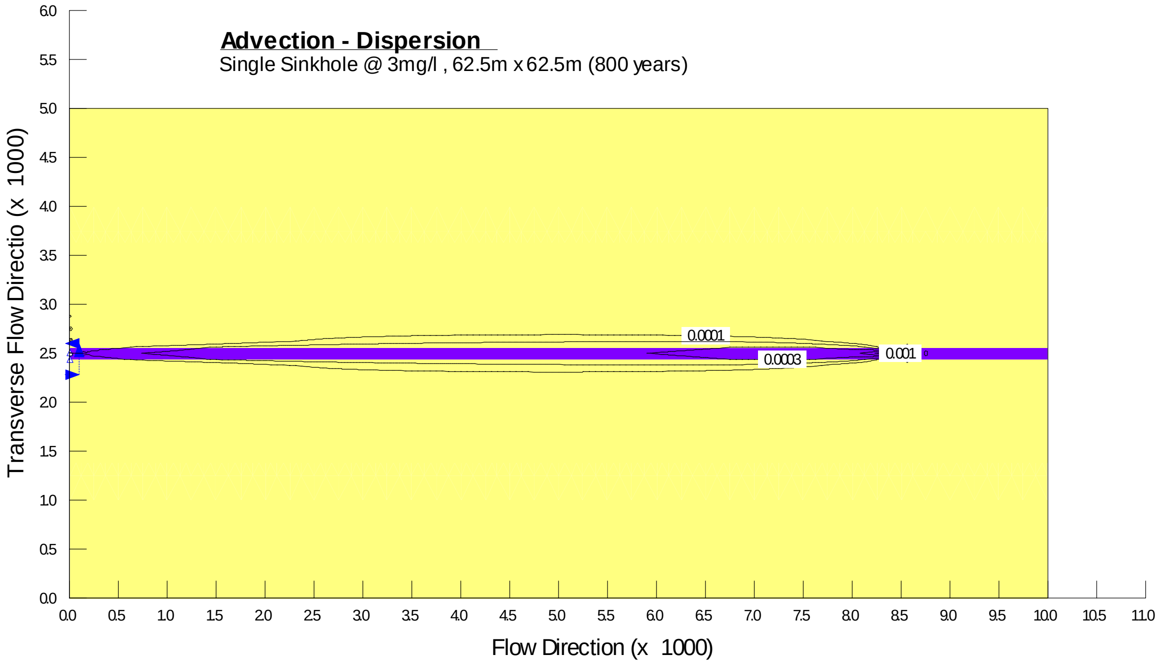
dark green – complies with WHO WQ guideline

light green - does not comply with WHO WQ guideline
but complies with SA WQ guideline for domestic use

red - does not comply with either standard (considered polluted)

The results indicated that provided the leachable uranium concentration remained below 0.3ppm U, the equivalent of a single BSE in isolation does not give rise to a pollution plume. Once the leachable uranium concentration increased to 3.0ppm, the WHO WQ guideline value was exceeded. It was found that the BSE uranium leachate concentration had to exceed 30 ppm to cause the plume concentration to exceed the SA WQ guideline value.

Backfilled sinkholes located within the highly cavernous stream zone are less likely to cause pollution than backfilled sinkholes situated outside of this zone. This is attributable to the higher water flux through the more cavernous zone, which gives rise to greater dilution and dispersion, and hence lower concentrations in the aquifer.



Sinkhole in main stream:

Maximum concentration after 800 years = 0.001mg/l Mass boundary function 3 [3mg/l].

FIGURE 5: **CONTAMINATION PLUME FROM A SINGLE BSE IN THE CAVERNOUS ZONE AT A BSE LEACHATE CONCENTRATION OF 3.0 PPM U**

The extent of the pollution plume is smaller for a single BSE situated in the stream compared to one outside the highly cavernous zone as a result of the difference in dilution. The aerial extent of the groundwater contamination plume at different stages after placement of the backfill is summarised in Table 7 below.

TABLE 7: COMPARISON OF THE AERIAL EXTENT AND MAXIUMUM URANIUM CONCENTRATION PLUME CAUSED BY A SINGLE BSE (LEACHATE CONCENTRATION 300 PPM U)

Years Since Backfilling [Years]	Width [m]	Length [m]	Area [km^2]	Max. U [ppm]	Width [m]	Length [m]	Area [km^2]	Max. U [ppm]
	In the highly cavernous zone				*Next to the highly cavernous zone*			
1	125	350	0.044	0.09	250	300	0.075	0.3
10	240	2750	0.660	0.106	350	2000	0.700	0.64
50	250	7750	1.94	0.106	760	7750	5.89	0.65
100	320	8250	2.64	0.106	800	8000	6.40	0.65
200	350	8260	2.89	0.106	850	8150	6.93	0.65
400	360	8370	3.01	0.106	880	8200	7.22	0.65
800	370	8380	3.10	0.106	890	8250	7.34	0.65

From the assessment of a single BSE with a leachate concentration ranging from 0.3 to 300 ppm U it was shown that:

- Leachate of low concentration (0.3 ppm U) from a single BSE did not cause pollution of the dolomite aquifer.

- Leachate from a single BSE of 1.0 ppm U or higher caused a pollution plume in which the concentration exceeded the WHO WQ guideline.

- Leachate from a single BSE above 30 ppm U caused a pollution plume in which the concentration exceeded the SA WQ guideline.

- The maximum U concentration in the aquifer caused by a single BSE situated next to the highly cavernous stream zone was approximately 6 times higher than for a BSE situated in the highly cavernous stream zone.

- The average area impacted by a BSE situated next to the highly cavernous stream zone was about 2.5 times higher than for a sinkhole situated in the stream.

5.5. ORIENTATION OF BACKFILLED SINKHOLES

The assessment of a row of five BSE's placed either in parallel to or perpendicular to the stream showed that the BSE's orientated parallel to the stream were more likely to cause pollution. A summary of the analysis results is given in Table 8 below.

TABLE 8: SUMMARY OF THE CONTAMINATION ASSESSMENT FOR A ROW OF FIVE BSE'S

BSE concentration [ppm U]	BSE's parallel to the Stream	BSE's perpendicular to the stream
0.3	0.0005 ppm U after 1 year 0.003 ppm U after 10 years 0.003 ppm U after 800 years	0.0006 ppm U after 800 years
3.0	0.0046 ppm U after 1 year 0.023 ppm U after 50 years 0.030 ppm U after 800 years	0.003 ppm U after 1 year 0.0068 ppm U after 10 years 0.0069 ppm U after 800 years
30	0.046 ppm U after 1 year 0.31 ppm U after 50 years 0.31 ppm U after 800 years	0.033 ppm U after 1 year 0.068 after 10 years 0.069 after 800 years
300	0.46 ppm U after 1 year 2.36 ppm U after 10 years 3.18 ppm after 100 years 3.18 ppm U after 800 years	0.33 ppm U after 1 year 0.68 ppm U after 10 years 0.69 ppm U after 800 years

dark green – complies with WHO WQ guideline

light green - does not comply with WHO WQ guideline
but complies with SA WQ guideline for domestic use

red - does not comply with either standard (considered polluted)

The results indicate that alignment of backfilled sinkholes with the general flow direction results in a significantly higher risk of any borehole downstream of the backfilled sinkholes intercepting a pollution plume. The analysis showed that a pollution plume developed within 1 to 10 years giving a U concentration in the plume of between 1.5 times (0.003 ppm U) and 2 300 times higher (0.46 ppm U) than the WHO WQ guideline value. The leachable uranium concentration in the backfill material from a row of sinkholes in parallel to the stream has to exceed approximately 7 ppm U to cause a pollution plume at concentrations in excess of the SA WQ guideline value.

A row of BSE's orientated perpendicular to the stream causes about 4.5 times lower maximum U concentrations yet the total area impacted by the sinkholes is similar. The aerial extent of the U plume is summarised in Table 9 below.

TABLE 9: AERIAL EXTENT OF GROUNDWATER CONTAMINATION PLUME CAUSED BY A ROW OF FIVE BSE SITUATED NEXT TO THE STREAM

Time since backfilling [Years]	Width [m]	Length [m]	Area [km^2]	Max. U [ppm]	Width [m]	Length [m]	Area [km^2]	Max. U [ppm]
	In parallel to the stream, 300 ppm U				*Perpendicular to the stream, 300 ppm, U*			
1	100	510	0.051	0.46	280	290	0.080	0.33
10	410	3070	1.26	2.36	295	2555	0.754	0.68
50	550	6850	3.77	3.12	480	6850	3.29	0.69
100	580	6850	3.97	3.18	535	6850	3.66	0.69
200-800	612	6850	4.19	3.18	595	6850	4.08	0.69
	In parallel to the stream, 30 ppm U				*Perpendicular to the stream,30 ppm U*			
100 – 800	515	6850	3.53	0.318	550	6850	3.77	0.069
	In parallel to the stream, 3 ppm U				*Perpendicular to the stream, 3.0 ppm U*			
100 –800	210	4270	0.89	0.031	270	5894	1.59	0.0069

The extent of the pollution plume associated with a linear zone of five backfilled sinkholes resulting from backfill concentrations ranging between 30 to 300 ppm U is quite considerable (ranging between 3.5 to 4.2 km^2 or about 6 to 8% of the total compartment surface area). The expected maximum uranium concentrations in the plume are reached after 50 – 100 years and remain high for the following 700 years, which presents the remainder of the assessment period

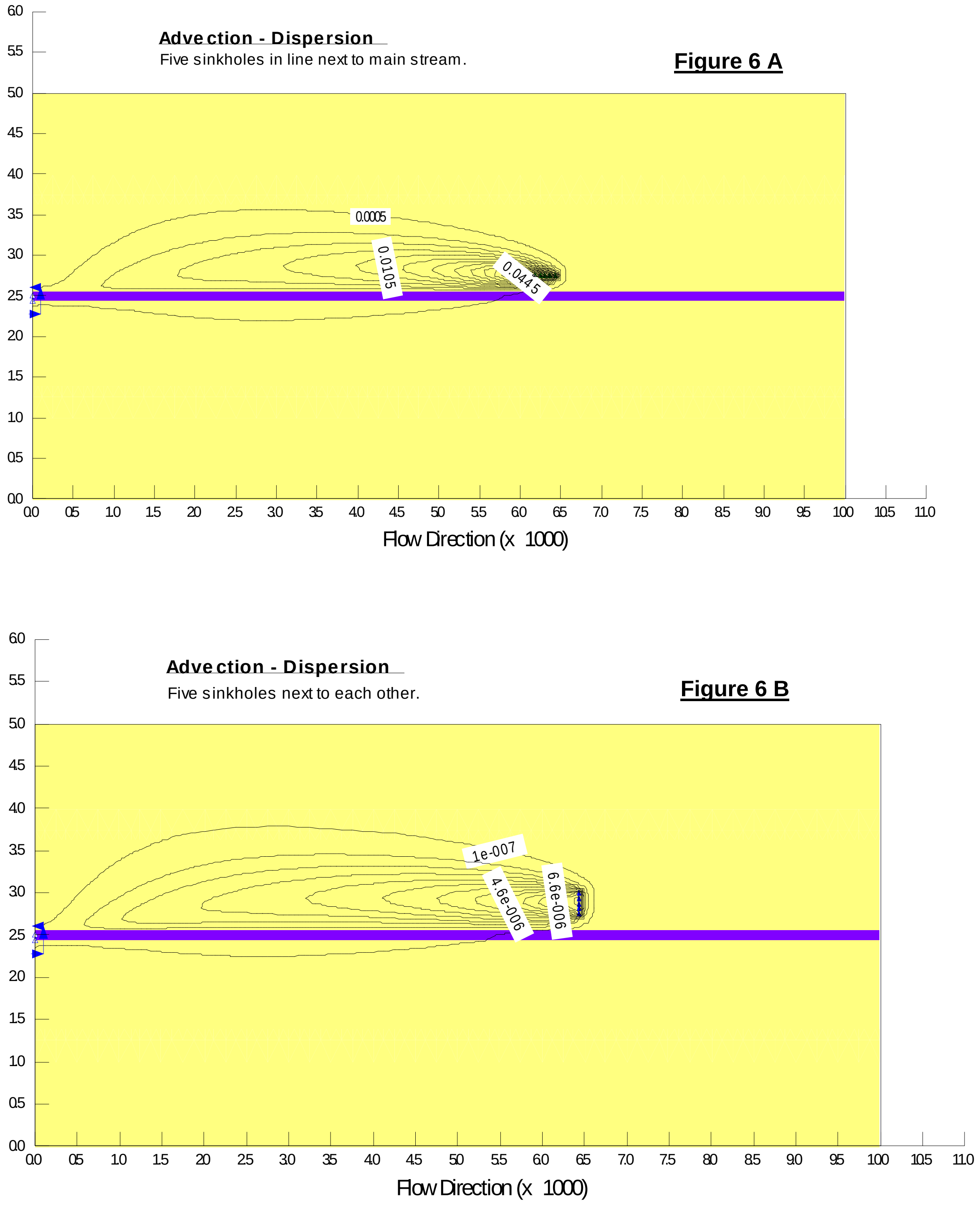


FIGURE 6: **COMPARISON OF THE CONTAMINATION PLUMES ARISING FROM A ROW OF BACKFILLED SINKHOLES IN CLOSE PROXIMITY TO THE STREAM**

At lower leachate concentrations the total area of the aquifer impacted reduced by about 16% (from 4.19 km^2 to 3.53 km^2 at 30 ppm U in the case of the parallel row of sinkholes or about 7% of the total area) and by about 77% (from 4.19 km^2 to 0.98 km^2 at 3.0 ppm U in the case of the parallel row of sinkholes or about 2% of the total area).

The orientation of the row of sinkholes had a significant effect on the total area of the impacted aquifer. At very high leachate concentrations (300 ppm U) the impacted area is similar. While the impacted area of the aquifer is still quite similar with a leachate concentration of 30 ppm U, at the lower leachate concentration (3.0 ppm U) the area of the aquifer impacted by the sinkholes with perpendicular orientation is about 80% larger. However, no contamination plume developed for the sinkholes in perpendicular orientation at very low leachate concentrations (0.3 ppm U). The area of the contamination plume arising from the parallel sinkholes was small (in the order of 0.005 km^2).

From the assessment of a row of backfilled sinkhole it was shown that:

- Leachate of low contamination (0.3 ppm U) from a row of sinkholes perpendicular to the stream did not cause contamination in the dolomite aquifer;

- Leachate of low contamination (0.3 ppm U) from a row of sinkholes in parallel stream did cause contamination in the dolomite aquifer in excess of the WHO WQ guideline but the water quality remained within the SA WQ guideline;

- Leachate from a row of sinkholes perpendicular to the stream of about 31 ppm U or higher caused contamination in the dolomite aquifer in excess of the WHO WQ guideline;

- Leachate from a row of sinkholes in parallel to the stream about 7.0 ppm U or higher caused contamination in the dolomite aquifer in excess of the WHO WQ guideline;

- The maximum U concentration in the aquifer caused by a parallel row of five backfilled sinkhole situated next to the stream is about 5 times higher than for a perpendicular row of sinkholes situated next to the stream;

- The average area of the aquifer impacted by the backfilled sinkholes varied quite considerably. At low leachate concentrations (3.0 ppm U) the area of impact caused by the sinkholes in perpendicular orientation is about 60% higher;

- With an increase in the leachate concentration by one order of magnitude (30 ppm U) the difference in the extent of the contamination plume between the two scenarios assessed reduced to about 7%;

- At high leachate concentrations (300 ppm U) the contamination plume arising from the sinkholes in parallel orientation is only marginally larger; and

- With lower leachate concentrations (3 to 30 ppm U) the footprint of the pollution plume resulting from the sinkholes perpendicular to the stream is larger (between 8 and 70%).

5.6. CLUSTER OF BSE’S

Typically in the FWR sinkholes often occur in groups or clusters. To characterise these clusters, the size and number of sinkholes was determined from a map provided by Mr E Erasmus, which derived from a GIS database. For the purpose of the sinkhole cluster characterisation, a 1 x 1 km grid overlay the map of the FWR and the number of sinkholes per grid were counted. It was found that the average number of sinkholes in a cluster is about 30.

With time however, further sinkholes may form within the cluster and so in order to judge the effect of an increase in the sinkhole density over time, modelling analyses were also performed for clusters containing 45 and 60 sinkholes. A summary of the results is given in Table 10 below. For the purpose of this analysis, one sinkhole was taken to be equivalent to 1 BSE. Effectively each sinkhole was assumed to measure 62.5 x 62.5m corresponding to the size of one element. This is a conservative assumption.

TABLE 10: SUMMARY OF THE CONTAMINATION ASSESSMENT FOR CLUSTERS OF BSE’S

BSE conc. [ppm U]	Cluster of 30 BSE/km^2	Cluster of 45 BSE’s/km^2	Cluster of 60 BSE’s/km^2
0.3	0.0004 ppm U after 1 year 0.0010 ppm U after 10 years 0.0021 ppm U from 100 to 800 years	0.0004 ppm U after 1 year 0.0019 ppm U after 10 years 0.0027 ppm U after 100 years 0.0027 ppm U after 800 years	0.0004 ppm U after 1 year 0.0019 ppm U after 10 years 0.0032 ppm U after 100 years 0.0032 ppm U after 800 years
3.0	0.004 ppm U after 1 year 0.016 ppm U after 10 years 0.021 ppm U after 50 years 0.021 ppm U after 800 years	0.0043 ppm U after 1 year 0.019 ppm U after 10 years 0.027 ppm U after 100 years 0.027 ppm U after 800 years	0.0043 ppm U after 1 year 0.019 ppm U after 10 years 0.032 ppm U after 100 years 0.032 ppm U after 800 years
30	0.043 ppm U after 1 year 0.163 ppm U after 10 years 0.210 ppm U after 50 years 0.210 ppm U after 800 years	0.043 ppm U after 1 year 0.190 ppm U after 10 years 0.277 ppm U after 100 years 0.277 ppm U after 800 years	0.043 ppm U after 1 year 0.190 ppm U after 10 years 0.320 ppm U after 100 years 0.320 ppm U after 800 years
300	0.430 ppm U after 1 year 1.630 ppm U after 10 years 2.13 ppm U after 50 years 2.17 ppm U after 800 years	0.430 ppm U after 1 year 1.93 ppm U after 10 years 2.77 ppm U after 100 years 2.77 ppm U after 800 years	0.43 ppm U after 1 year 1.91 ppm U after 10 years 3.20 ppm U after 100 years 3.20 ppm U after 800 years

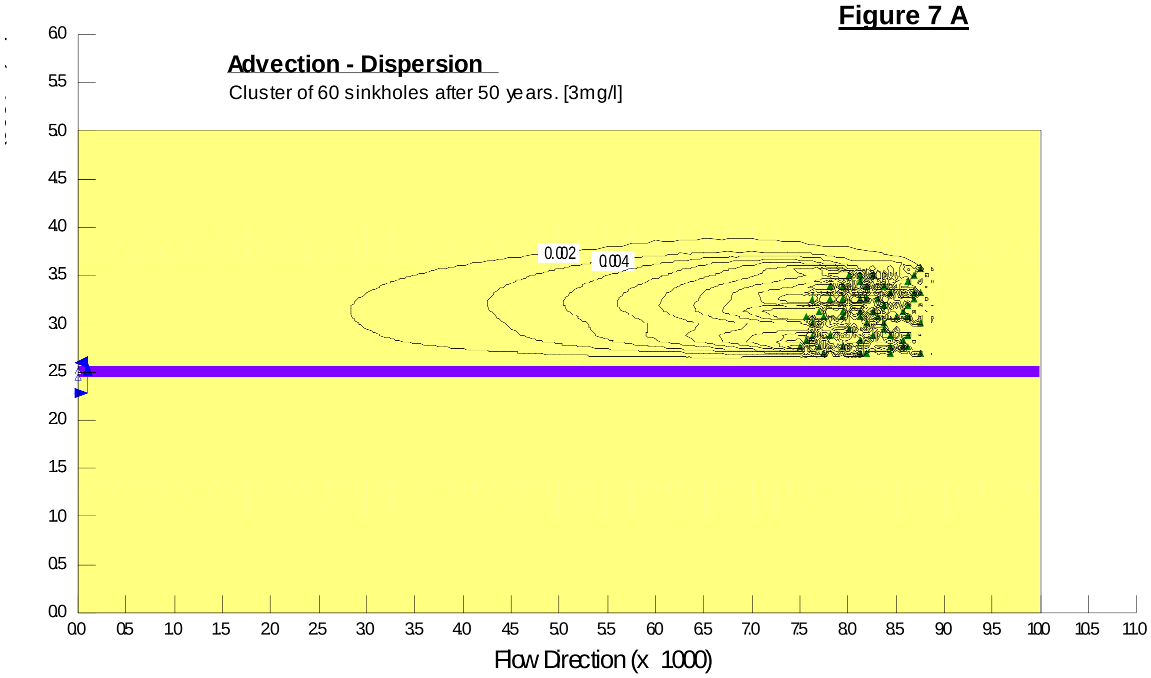
dark green – complies with WHO WQ guideline

light green - does not comply with WHO WQ guideline
but complies with SA WQ guideline for domestic use

red - does not comply with either standard (considered polluted)

The uranium concentration in the leachate from a cluster of 30 BSE's has to exceed approximately 10 ppm U to cause a plume with a U concentration in excess of the SA WQ guideline value.

Figure 7 A



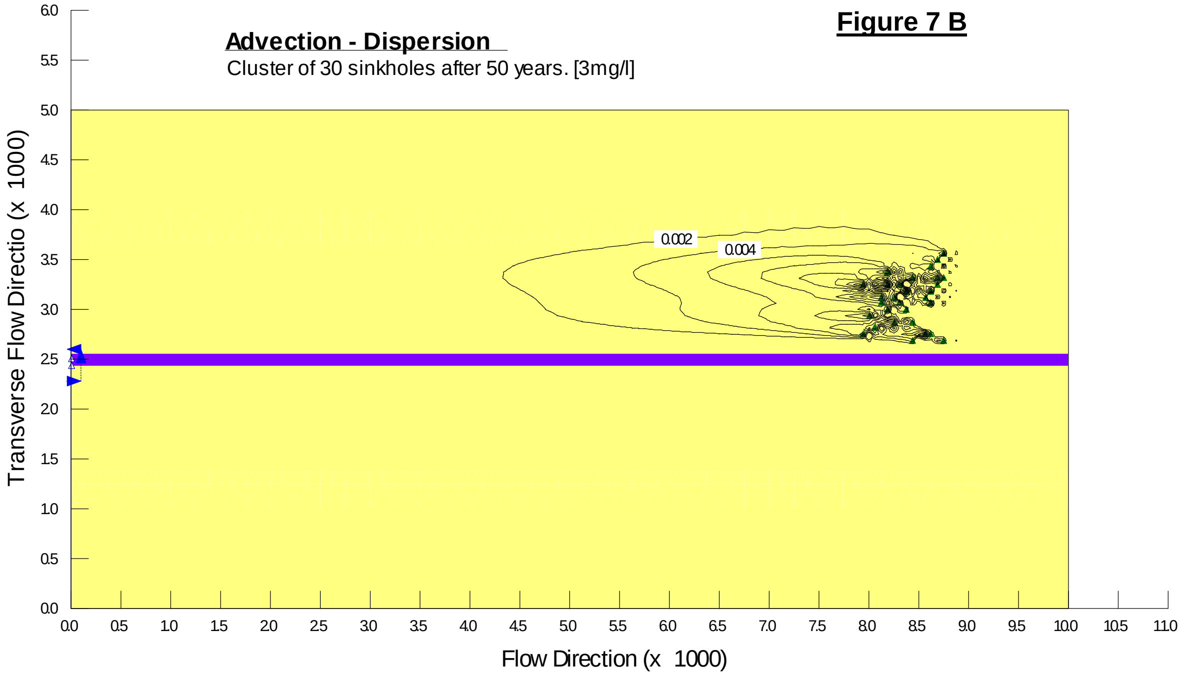


FIGURE 7: COMPARISON OF THE CONTAMINATION PLUME ARSING FROM A CLUSTER OF SINKHOLES SITUATED IN CLOSE PROXIMITY TO THE STREAM

The aerial extent of the groundwater contamination plume caused by the clusters of sinkholes is shown in Table 11 below. The ultimate pollution plume area caused by a cluster of 30 BSE's/ km^2 was 10.2 km^2 for 3.0 ppm U, 13.3 km^2 for30 ppm U and to 15.3 km^2 for 300 ppm U. Thus, the density of sinkholes has a much greater impact on the uranium concentration in the plume than the extent of the plume as such.

TABLE 11: AERIAL EXTENT OF PLUME CAUSED BY CLUSTERS OF SINKHOLES OF VARIOUS DENSITY AND LEACHABLE URANIUM CONCENTRATIONS

Duration [Years]	Width [m]	Length [m]	Area [km^2]	Max. U [ppm]	Width [m]	Length [m]	Area [km^2]	Max. U [ppm]
	0.3 ppm U, 30 BSE's/km^2				*3.0 ppm U, 30 BSE's/km^2*			
1	0	0	0.0	0.0004	30	30	0.0009	0.004
10	0	0	0.0	0.0010	750	562	0.4251	0.016
50	0	0	0.0	0.0021	1136	3566	4.051	0.021
100	0	0	0.0	0.0021	1192	7206	8.588	0.021
200	0	0	0.0	0.0021	1254	7936	9.952	0.021
400-800	0	0	0.0	0.0021	1281	7936	10.166	0.021
	0.3 ppm U, 45 BSE's/km^2				*3.0 ppm U, 45 BSE's/km^2*			
100 – 800	62.5	260	0.016	0.0027	1300	7550	9.81	0.027
	0.3 ppm U, 60 BSE's/km^2				*3.0 ppm U, 60 BSE's/km^2*			
100 – 800	420	1600	0.672	0.0032	1350	7550	10.19	0.032
	30 ppm U,30 BSE's/km^2				*300 ppm U,30 BSE's/km^2*			
1	62.5	62.5	0.0039	0.043	1100	310	0.341	0.43
10	1166	1601	1.867	0.163	1604	2663	4.27	1.63
50	1558	7754	12.081	0.21	1981	7936	15.72	2.13
100	1662	7936	13.189	0.21	2069	7936	16.419	2.17
200	1669	7936	13.245	0.21	2010	7936	15.951	2.17
400	1670	7936	13.253	0.21	1950	7936	15.475	2.17
800	1671	7936	13.261	0.21	1928	7936	15.301	2.17
	30 ppm U, 45 BSE's/km^2				*300 ppm U, 45 BSE's/km^2*			
100 – 800	1500	7550	11.32	0.277	1800	7550	13.59	2.77
	30 ppm U, 60 BSE's/km^2				*300 ppm U, 60 BSE's/km^2*			
100 – 800	1680	7550	12.68	0.320	1820	7550	13.74	3.20

dark green – complies with WHO WQ guideline

light green - does not comply with WHO WQ guideline
but complies with SA WQ guideline for domestic use

red - does not comply with either standard (considered polluted)

The following conclusions may be drawn from the analysis of the clusters of sinkholes.

- At a leachable uranium concentration of below 3 ppm U, a uranium pollution plume in excess of the SAWQ guideline value will not be detected even if the density of backfilled sinkholes were to increase to the equivalent of 60BSE's /km^2. The WHO WQ guideline value will probably be exceeded unless the leachable uranium concentration is below approximately 0.3ppm.

- Once the leachable uranium concentration rises to anything in excess of 3.0ppm U, a significant pollution plume is likely to result even at 30 BSE's/km^2.

- The extent of the pollution plume does not increase significantly with increasing BSE density or increasing uranium leachability. The uranium leachability increased 100 fold resulting in an increased aerial extent of the pollution plume of 1.5 fold. An increase in the BSE density of 2 fold resulted in no significant increase in the extent of the plume.

The long term extent of the plume is significant with the polluted area ultimately approaching 20 to 30% of the "compartment" area in the case of the higher leachable uranium concentrations. At lower leachable concentrations of <0.3ppm U the extent of the plume is less than 1km^2, i.e. it is confined to the backfilled sinkhole cluster area.

5.7. THE TAILINGS DAM

The tailings dam analysis was conducted to demonstrate the relative magnitude and extent that a tailings dam is likely to have in comparison to backfilling of sinkholes with gold tailings. Two hypothetical scenarios were analysed, namely

- A tailings dam situated in close proximity to but outside the highly cavernous stream zone, and

- A tailings dam situated about 1.5 km away from the highly cavernous stream zone.

In both cases the tailings dam footprint was assumed to be 1500 by 1000 metres. Unlike the backfilled sinkholes, leachate from the tailings dam would first pass through the surface soil into the vadose zone, before entering the dolomite aquifer. Adsorption of uranium in the surface soils (in particular clays) is likely to result in a significant reduction in the concentration of uranium in the leachate prior to entering the aquifer. The model does not take cognisance of these adsorption processes that take place in the soil beneath the tailings dam but works on the principle that leachate from the tailings dam enters the aquifer directly. The adsorption capacity of the soils beneath the tailings is finite and as uranium is leached from the tailings dam into the soils, the adsorption sites with tend towards saturation. Thus the assumptions made above may not be very conservative for tailings dams underlain by this soil layers or soils with a poor adsorption capacity. The assumption made in the model could be very conservative for tailings dams underlain by a thick layer of clayey soil.

The water flux assumed in the model was 5% of MAP, the same as that assumed for the backfilled sinkholes and the remainder of the catchment. This is a reasonable estimate of the water flux long after closure of the tailings dam once the phreatic surface within the tailings dam has largely dissipated. Previous seepage modelling undertaken by the Authors has indicated that the time for dissipation to occur is of the order of 50 to 200 years, depending on founding conditions, drainage and tailings permeability. During the operational phase of the tailings dam, the seepage flux can be significantly higher and well in excess of the MAP. Thus, with respect to seepage flux, the analysis presents a best case scenario.

A summary of the contamination assessment results is given in Table 12 below.

TABLE 12: SUMMARY OF THE CONTAMINATION ASSESSMENT FOR A TAILINGS DAM

Leachable concentration [ppm U]	Tailings dam next to the stream	Tailings dam 1.2 km away from the stream
0.3	0.0004 ppm U after 1 year 0.004 ppm U after 10 years 0.014 ppm U after 100 years 0.014 ppm U after 800 years	0.0004 ppm U after 1 year 0.004 ppm U after 10 years 0.016 ppm U after 100 years 0.016 ppm U after 800 years
3.0	0.0049 ppm U after 1 year 0.0435 ppm U after 10 years 0.149 ppm U after 100 years 0.149 ppm U after 800 years	0.0046 ppm U after 1 year 0.048 ppm U after 10 years 0.249 ppm U after 100 years 0.249 ppm U after 800 years
30	0.0495 ppm U after 1 year 0.435 ppm U after 10 years 1.499 ppm U after 100 years 1.499 ppm U after 800 years	0.0465 ppm U after 1 year 0.480 ppm U after 10 years 2.496 ppm U after 100 years 2.496 ppm U after 800 years
300	0.495 ppm U after 1 year 4.35 ppm U after 10 years 15.46 ppm U after 200 years 15.46 ppm U after 800 years	0.465 ppm U after 1 year 4.818 ppm U after 10 years 24.96 ppm U after 200 years 24.96 ppm U after 800 years

dark green – complies with WHO WQ guideline

light green - does not comply with WHO WQ guideline
but complies with SA WQ guideline for domestic use

red - does not comply with either standard (considered polluted)

The analysis shows that SAWQ guidelines are not exceeded, provided that the leachable concentration of the tailings is less than 0.3 ppm U. Once the leachable concentration exceeds 3.0ppm, a pollution plume will develop within 10 years or less, depending on the concentration.

The resulting maximum U concentration in the aquifer exceeded the WHO WQ guideline value by a factor 2 after 10 years with the maximum concentration in the aquifer exceeding the guideline value by factor 7. With the higher leachate concentrations (0.3 to 300 ppm U) the WHO WQ guideline value is exceeded by about factor 7 and 7700. The uranium concentration in the leachate from a tailings dam has to exceed approximately 1.5 ppm U to cause an impact on the aquifer in excess of the SA WQ guideline value.

A tailings dam next to the stream causes higher contamination regarding the maximum concentrations observed in the aquifer than a tailings dam some 1.2 km away from the stream. The contamination concentrations in the aquifer caused by the tailings dam away from the stream were similar at low leachate concentrations (0.3 ppm U), but generally increased with the higher leachate concentrations (3.0 to 300 ppm U) by about 67%.

The aerial extent of the pollution plume from the simulated tailings dam is shown in Table 13 below.

TABLE 13: AERIAL EXTENT OF URANIUM PLUME FROM A TAILINGS DAM

Years since Deposition	Width [m]	Length [m]	Area [km^2]	Max. U [ppm]	Width [m]	Length [m]	Area [km^2]	Max. U [ppm]
	0.3 ppm U, next to Stream Zone				*3.0 ppm U, next to Stream Zone*			
1	0	0	0	0.0004	0	0	0	0.0049
10	1023	355	0.36	0.004	1400	1475	2.07	0.0435
50	1023	3670	3.70	0.012	1800	6180	11.12	0.120
100	1023	6180	6.32	0.014	1950	6180	12.05	0.149
200-800	1023	6180	6.32	0.014	2500	6180	15.45	0.149
	0.3 ppm U, 1.2 km away				*3.0 ppm U, 1.2 km away*			
100 – 800	1000	6245	6.25	0.016	1180	6180	7.29	0.249
	30 ppm U, next to Stream zone				*300 ppm U, Next to Stream zone*			
1	0	0	0	.0495	1250	375	0.468	0.495
10	1450	1490	2.16	0.435	1833	3874	11.625	4.35
50	1880	6180	11.62	1.20	1870	6190	11.58	12.05
100	2000	6180	12.36	1.499	2878	6190	17.78	14.993
200-800	2600	6180	16.07	1.499	2878	6190	17.78	15.46
	30 ppm U, 1.2 km away				*300 ppm U, 1.2 km*			
100 – 800	1250	6180	7.73	2.496	2400	6180	14.83	24.96

dark green – complies with WHO WQ guideline; **light green** - does not comply with WHO WQ guideline but complies with SA WQ guideline for domestic use; **red** - does not comply with either standard (considered polluted)

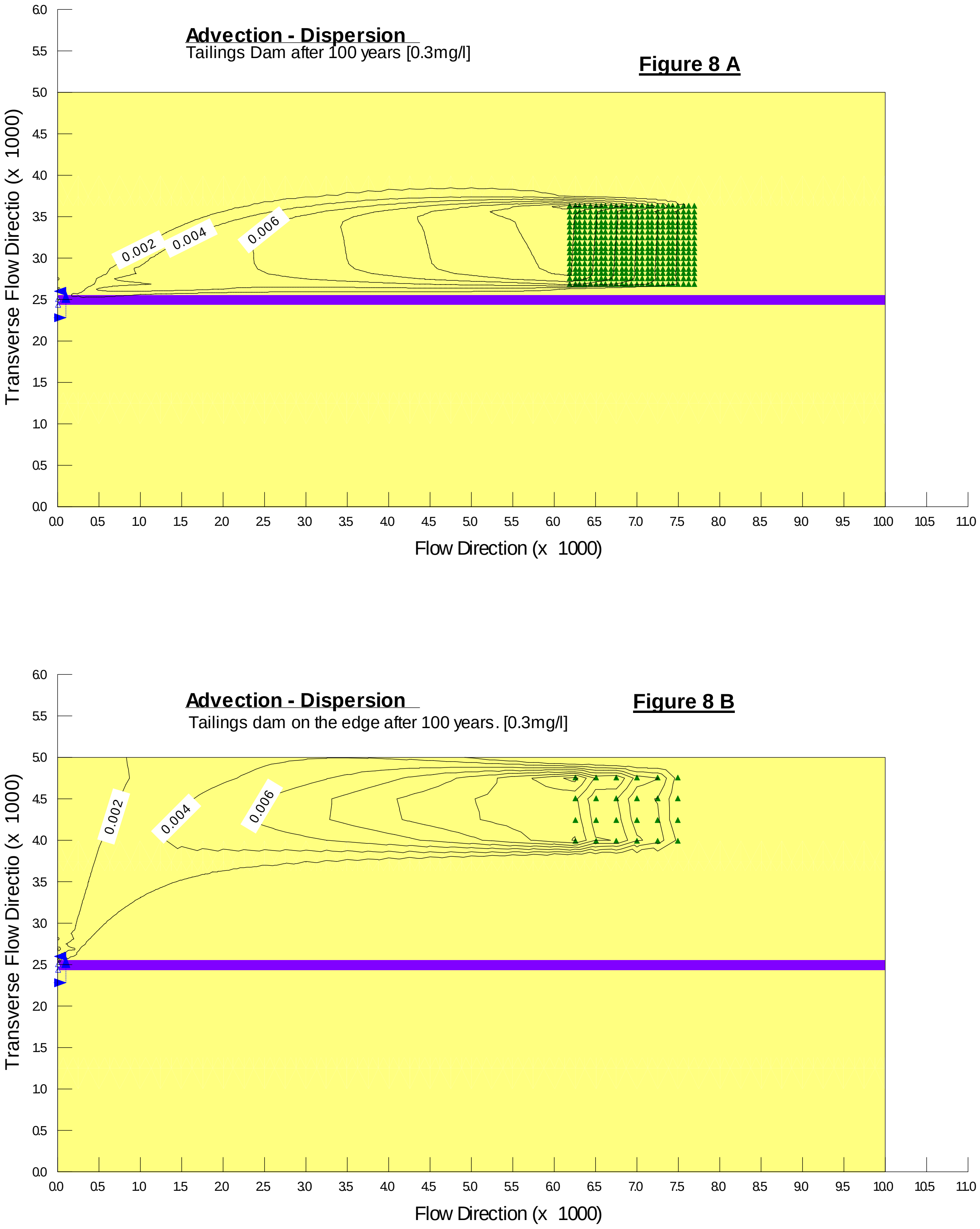


FIGURE 8: **COMPARISON OF THE CONTAMINATION PLUME FROM A TAILINGS DAM NEXT TO THE STREAM AND 1.2 KM AWAY FROM THE STREAM**

As would be expected, the same trends with respect to the magnitude and extent of the pollution plume are found for the tailings dam as for a cluster of BSE's.

The difference is that the tailings dam has a much greater potential impact in terms of the concentration of uranium within the pollution plume. A comparison of Table 10 and Table 12 reveals that:

- To not cause pollution of the dolomite aquifer, the leachable uranium concentration of a tailings dam (assumed foot print 1500 x 1000m) has to be less than 0.84ppm U compared to 10ppm U (about 12 times lower) for a cluster of 30 BSE's (distributed in an area of 1000 x 1000 m).

- The extent of the pollution plume from a cluster of backfilled sinkholes is likely to be similar to the extent of the plume from a similar sized tailings dam. The positioning of the source term over the aquifer has a much more significant influence on the extent of the pollution plume than the type of source term. For example, a cluster of 30 BSE's arranged over 1km^2 resulted in a 10.16km^2 plume footprint compared to the tailings dam (with a footprint 1.5 times larger) in the same area, which resulted in a 15.45 km^2 footprint. The tailings dam located 1.2km from the stream had a plume footprint area of only 7.29km^2.

6. CONCLUSIONS

The Far Field Model has focused on the impact of U on the aquifer water quality since this was found to be the contaminant of greatest concern in terms of the near field model. The Far Field model has been used to evaluate a series of hypothetical backfilled sinkhole distributions to assess the effect of :

- Varying the initial concentration of uranium leached from the base of the backfilled sinkhole.
- Varying the spatial orientation of the backfilled sinkholes relative to the general aquifer flow direction
- Varying the spatial concentration of backfilled sinkholes
- Varying the location of the backfilled sinkholes relative to the location of the stream.
- The relative impact of tailings dams compared to a cluster of backfilled sinkholes was also evaluated.

The results are summarised in Table 14 below, which compares the concentration in the aquifer with an internationally and nationally recognised water quality standard.

TABLE 14: SUMMARY OF THE CONTAMINATION ASSESSMENT FOR THE VARIOUS MODELLED SCENARIOS AFTER 100 YEARS (COMPLIANCE WITH WQ GUIDELINES FOR THE GROUNDWATER IN THE DOLOMITE AQUIFER)

Scenario	**WHO drinking water guideline=0.002 ppm U** **SAWQ= 0.07 ppm U**			
Leachate concentration. [ppm U]	***0.3***	***3.0***	***30***	***300***
Single BSE				
In the stream	WHO	WHO	SAWQ	>198ppm
Next to the stream	WHO	SAWQ	SAWQ	>32 ppm
Away from the stream	WHO	SAWQ	>10ppm	
Row of BSE's				
Perpendicular to the flow direction	WHO	WHO	SAWQ	>30ppm
Parallel to the flow direction	WHO	SAWQ	SAWQ	>6ppm
Cluster of BSE's				
30 BSE's over 1 km^2	SAWQ	>10ppm		
45 BSE's over 1 km^2	SAWQ	>7ppm		
60 BSE's over 1 km^2	SAWQ	>6ppm		
The Tailings Dam **(1000 x 1500 m footprint)**				
Next to the stream zone	SAWQ	>1.4ppm		
1.2 km away from the stream zone	SAWQ	>0.8ppm		

The concentration limits given in the red block indicate the maximum leachable concentration that could be tolerated to just not exceed the SAWQ guideline value of 0.07ppm.

For the purpose of this document, the term pollution is used to describe a situation in which the concentration of uranium in the aquifer exceeds one or more of the standards described above.

The following general conclusions are drawn:

The Model

- The flow model represents an idealised dolomite aquifer compartment. The model represents a compartment, which is recharged from the stream at the upstream boundary and by rainfall over the entire extent of the compartment. Water may only be lost from the compartment via the downstream spring or "eye". The more cavernous zone in the immediate vicinity of the Wonderfontein Spruit was modelled as a 125 m wide zone with a higher permeability than that of the surrounding aquifer.

- Backfilled sinkholes were modelled as a single element in the finite model. Each element has an area of 0.40 ha. A single backfilled sinkhole therefore refers to an area of backfill of 0.40 ha, which in reality might correspond to a cluster of backfilled sinkholes and not just a single backfilled sinkhole. Recharge through the backfill was assumed to be the same as that of the surrounding area, i.e. no special measures to limit infiltration were included.

- Flow modelling was done under steady state conditions. Calibration of the idealised compartment to make it as representative as practically possible of the real compartments, was achieved by adjusting the permeability of the dolomite aquifer until head loss across the aquifer between the upstream boundary and “eye” was equal to that which is typical of the actual compartments. Recharge was set to the estimated recharge.

- The model demonstrated that the retention time for any contaminant released into the aquifer was highly dependent on where the contaminant was released. Particle tracking showed that particles placed in the more cavernous zone associated with the stream some 8.5 km from the eye require less than 50 years to reach the eye, while particles in areas of lower flow also 8.5 km distance from the eye required 200 years or longer to reach the eye.

- The extent of absorption of uranium onto the dolomite (the predominant rock form in the aquifer) is insignificant. The sensitivity analysis for the effect of adsorption showed that only 1% of the total uranium mass would be retained in the aquifer by adsorption to the dolomite, while the majority of the uranium is present in the aqueous form in the groundwater.

Single idealised backfilled Sinkhole

- Leachate from the backfill at a concentration of 0.3 ppm U from a single idealised sinkhole did not cause pollution in the dolomite aquifer.

- Leachate from a single sinkhole of about 1.0 ppm U or higher caused contamination in the dolomite aquifer in excess of the WHO WQ guideline

- Leachate from a single sinkhole above 30 ppm U caused contamination in excess of the SA WQ guideline

- The maximum U concentration in the aquifer caused by a backfilled sinkhole situated outside the stream zone is expected to be about 6 times higher than for an equivalent backfilled sinkhole situated in the stream zone.

- The average area impacted by a backfilled sinkhole situated outside the stream zone was about 2.5 times larger than for a sinkhole situated in the stream zone.

Row of Sinkholes

- Leachate from the backfill at 0.3 ppm U from a row of sinkholes arranged perpendicular to the stream did not cause pollution of the dolomite aquifer, whereas leachate from a row arranged parallel to the flow direction did cause the WHO WQ standard to be exceeded.

- Only once the U concentration from the backfill exceeded 31 ppm, did the concentration in the aquifer caused by a row of backfilled sinkholes arranged perpendicular to the flow direction exceed the WHO WQ guideline

- For the backfilled sinkholes arranged in parallel to the aquifer flow direction, once the concentration of uranium in the leachate exceeded 7.0ppm, the concentration in the aquifer exceeded the WHO WQ limit.

- The maximum U concentration in the aquifer caused by a row of five backfilled sinkholes arranged parallel to the flow direction and situated next to the stream is about 5 times higher than for a row of sinkholes perpendicular to the flow direction and situated next to the stream.

- The average area of the aquifer impacted by the backfilled sinkholes varied quite considerably depending on the orientation of the sinkhole cluster relative to the aquifer flow direction. At low BSE leachate concentrations (3.0 ppm U) the extent of the pollution plume area of impact caused by the sinkholes in perpendicular orientation is about 60% higher than the pollution plume cased by the sinkholes in parallel orientation.

- As the contaminant leachate concentration increases, the orientation of the backfilled sinkholes makes less of a difference. With an increase in the leachate concentration by one order of magnitude (30 ppm U) the difference in the area of the pollution plume was 7%.

Cluster of Sinkholes

- The maximum U concentration in the aquifer caused by clusters of backfilled sinkholes with higher leachate concentrations (30 and 300 ppm U) situated next to the stream exceeded the SA WQ guideline by about 3 to 45 times.

- The WHO WQ guideline was exceeded by all tested scenarios

- The sinkholes clusters impacted on a fairly large area of the aquifer (about 20 to 30% of the total model area of 50 km^2 (5000 ha)

- The average area impacted by the clusters of backfilled sinkholes is less than 1 km^2 at low leachate concentrations (0.3 ppm U)

- The pollution plume increases rapidly to about 10 km^2 at a leachate concentration of 3.0 ppm U and reached a maximum of 15 km^2 at a leachate concentration of 300 ppm U.

- The increase in the number of sinkholes causes an increase in the maximum uranium concentration in the pollution plume rather than an increase in the aerial extent of the pollution plume.

Relative Impact of a Tailings Dam

- Leachate from the idealised tailings resulted in the WHO WQ in the dolomite aquifer being exceeded for all uranium leachate concentrations modelled.

- Leachate from the tailings dam exceeded the SA WQ guideline for all leachate concentration modelled except for 0.3 ppm U. Leachate concentrations in excess of 1.5 ppm U would cause an impact on the water quality in the dolomite aquifer in excess of SA WQ guidelines.

- The maximum U concentration in the aquifer caused by a tailings dam further away from the stream is about 1.5 times higher than for a tailings dam in close proximity to the stream.

- The area of the aquifer impacted by the simulated tailings dam (footprint area 1.5 km^2 or 150 ha) varied from 6.3 km^2 at very low leachate concentrations (0.3ppm U) to 17.8 km^2 at very high leachate concentrations (300ppm U).

- The average area impacted by the tailings dam situated immediately adjacent to the highly cavernous stream zone is approximately twice as high as for a tailings dam situated further away from the highly cavernous zone. At very high leachate concentrations the area of the contaminated plume from a tailings dam next to the stream is only 1.2 times that for a tailings dam situated further away from the stream.

Final Conclusion

- Based on the modelling undertaken it may be concluded that backfilling of sinkholes in the Far West Rand with gold mine tailings can potentially cause pollution. The risk of pollution is however highly dependent on:
    - The concentration of uranium in the leachate from the backfill.

  - ➢ The spatial orientation of the zone of sinkholes. A zone of sinkholes that form along an East – West plane parallel to the general flow direction have a much higher risk of degrading the aquifer than the equivalent zone which forms along a north south plane.
  - ➢ The spatial concentration of sinkholes. Where sinkholes are backfilled with tailings close to one another, the risk of a pollution plume being detected is significantly higher.
  - ➢ The location of the backfill relative to the more permeable or cavernous zone. Clusters of backfilled sinkholes that form in the Wonderfontein Spruit have a less detrimental effect than an equivalent cluster would have that formed away from the more cavernous zone as a result of the increased water flux through this zone and the enhanced dilution and dispersion effect.

- Leachate concentrations in excess of 0.3 ppm U from the backfilled sinkholes generally cause groundwater pollution in excess of the WHO WQ guidelines with the exception of backfilled sinkholes measuring no more than one idealised backfilled sinkhole of 0.40 ha in extent.

- As a general guideline, backfilling of sinkholes with gold mine tailings has a high risk of causing impacts on the dolomite aquifer in excess of the SA WQ guidelines when the leachate concentration exceeds 30 ppm U. However, when the effective zone of backfill exceeds 0.4 ha, the SA WQ guidelines have a high probability of being exceeded if the leachate concentration exceeds 3.0 ppm U.

- The relative impact of tailings dams compared to backfilled sinkholes is considerably greater as evidenced by the fact that the tailings dams simulated caused pollution with a uranium leachate concentration of in excess of 0.3 ppm U.

- Considering the current SA water quality guidelines, sinkholes, which are situated in the stream or in close proximity to the stream, (these account for the majority of sinkholes in the Far West Rand) may be backfilled with gold mine tailings provided the leachable U concentration from the tailings material is less than 30 ppm.

- Although the impact from a tailings dam has been shown to be very pronounced the mitigating effects from the compacted soil cover beneath the tailings dam have not been considered by the model. Contamination assessments undertaken for soils from footprints of removed tailings dams indicated generally elevated uranium concentrations in the soil with concentrations of less than 1 ppm U in the groundwater in close proximity to the tailings dams. The model therefore seems to overestimate the impact of contamination from the tailings dam to the aquifer by probably one order of magnitude.

- The modelling indicated that the uranium plumes reached their full aerial extent after 50 to 100 years, thereafter the plume would only increase marginally for the following centuries.

Based on a comparison of the total uranium content of the tailings with the leach rate, complete leaching of the uranium from the tailings will take several hundred to thousands of years. The plume will finally reduce and eventually disappear, when all uranium has been leached from the respective sources of pollution. The long term impact of backfilling may thus be considered practically the same as the impact after 50 to 100 years, when the plume has reached its full extent.

- There is clearly a need to apply a precautionary approach to backfilling of sinkholes of uranium containing gold tailings. Backfilling will not result pollution where a sinkhole develops in isolation from other sinkholes and needs to be backfilled. Backfilling of sinkholes that form within the more cavernous zone associated with the Wonderfontein Spruit have a higher risk of causing a more extensive but lower concentration pollution plume, since the orientation of the sinkhole clusters is generally parallel to the aquifer flow direction and the water flux through the aquifer is higher at this point. Clusters of sinkholes that form away from the river are likely to give rise to a less extensive plume but one with a higher peak concentration.

7. RECOMMENDATIONS

Based on the findings of the modelling exercise the following is recommended:

- Prior to the backfilling of sinkholes, the concentration of uranium and other radionuclides should be measured in the aquifer.

- Tailings material intended for the backfill of sinkholes should be tested for total and leachable uranium and other radionuclide concentrations prior to its use.

- If tailings material is used to backfill sinkholes the uranium concentration in the tailings material should be as low as possible, with the leachable U concentration preferably be less than 0.3 ppm U, provided the aquifer does not feature any residual U concentration.

- As tailings dams have a much greater potential to pollute the dolomite aquifer, the uranium concentrations in the tailings material, the tailings dam pore water and the groundwater in the vicinity of these tailings dams should be assessed. Tailings dams, which are older than 50 years, in close proximity to boreholes used for domestic purposes should be assessed first.

8. REFERENCES

Atomic Energy of Canada Limited (AECL) (1996), *Preliminary Safety Analysis Report (PSAR) for the Intrusion Resistant Underground Structure (IRUS)*, AECL-MISC-295, Chalk River, Ontario, Canada

Domenico & Schwartz, (1990), *Physical and Chemical Hydrology*, p. 26, John Wiley and Sons, New York, ISBN 0-471-50744-X

Shott, G.J., Barker, L.E., Rawlinson, S.E., Sully, M.J. and Mooe, B.A. (1998), *Performance Assessment for the Area 5 Radioactive Waste Management Site at the Nevada Test, Nye County, Nevada* (Rev. 2.1), DOE/NV/11718-176 UC0721, U.S. Department of Energy, Nevada Operations Office, Nevada, USA

HJJ Boshoff **S Dill**

Metago Environmental Engineers (Pty) Ltd

APPENDIX C

LEGAL OPINION ON THE ACTIVITY OF BACKFILLING DOLOMITIC CAVITIES WITH MINE WASTE MATERIAL

FINAL REPORT TO THE WATER RESEARCH COMMISSION

BY

S Dill, AR James and BI Stobart

Metago Environmental Engineers (Pty) Ltd, PO Box 1596, Cramerview, 2060, South Africa

APPENDIX TO WRC REPORT NO 1122/1/07

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND INFORMATION

Metago Environmental Engineers (Pty) Ltd, (“Metago”) was approached to conduct a research project (“the project”) on the impact that the backfilling of dolomitic cavities (“sinkholes”) with mine waste materials may have on the groundwater quality of the dolomite aquifer in the Far West Rand (“the activity”). The assessment was commissioned by the Water Research Commission of South Africa (“WRC”), which is in the process of evaluating the implications of the activity in the Far West Rand, on behalf of the Far West Rand Dolomitic Water Association (“FWRDWA”).

The scope of work for the project included an assessment of both, the current and pending legislation to ensure that proposals arising from the project conform to the requirements of such legislation. This report presents the legal opinion on the backfilling of sinkholes with mine waste material and forms Appendix C of the main report (Metago report 115-002, “The Assessment of Impacts on Groundwater Quality Associated with the Backfilling of Dolomitic Cavities with Gold Mine Tailings”, Report No. 3, January 2003”.

In the event that agreements regulating the activity exist between DWAF and the Far West Rand Dolomite Water Association and/or individual mines, this legal opinion must be read in conjunction with the said agreements.

1.2. OBJECTIVE OF THIS DOCUMENT

As part of the research project Metago has been requested to prepare a legal opinion on the environmental legal issues associated with the activity. This document sets out the findings of the legal opinion.

2. METHOD

- Review and interpret existing environmental national legislation that is applicable to the activity;
- Consider the potential liabilities associated with the activity for both the members of the Far West Rand Dolomite Water Association and the Authorities;
- Provide a practical interpretation of the legal assessment based on the professional experience and opinion of Metago; and
- Consider alternatives to the activity.

3. SITE DESCRIPTION

3.1. PROPERTY LOCATION AND REGIONAL SETTING

The area concerned is the Far West Rand in the Gauteng Province of South Africa.

3.2. GEOHYDROLOGY

The area concerned, in which the sinkholes exist, is underlain by dolomite. It has been assumed that the aquifer associated with the dolomite is a **major aquifer** as defined by the aquifer classification system used by the Department of Water Affairs and Forestry (“DWAF”). This system, **“A South African Aquifer System Management Classification” by Roger Parsons**, was published by the Water Research Commission in report number KV77/95, December 1995.

In addition the aquifer is assumed to be a water resource as defined in **Section 1(xxvii) of the National Water Act, 36 of 1998**.

The sinkholes are generally situated in the vadose zone above the dolomite aquifer but in some instances may extend through the vadose zone into the aquifer itself.

3.3. INFRASTRUCTURE AND LAND USE

While the sinkholes have been caused by subsidence of land as a result of gold mining activities, the sinkholes occur on both mining and non-mining property.

3.4. BACK-FILL MATERIAL

In conducting the activity either tailings from gold mines (“tailings”) or a combination of tailings and other material will be used. Relevant to this opinion is the physical and chemical make-up of the tailings material and the connection between these aspects and the leachability of potential contaminants from the tailings material.

For the purpose of this opinion it is assumed that:

- The tailings material is waste as defined by **Section 1(xxiii) of the National Water Act**; and
- When the tailings is exposed to the natural elements, including wind and rain, it could leach metals, salts and radioactive nuclides in a manner that could potentially be harmful to the receiving environment and in particular to the water resource quality (ie. the water quality in the aquifer).

4. LEGAL FRAMEWORK

All law applicable to the activity should be written, interpreted and applied in accordance with the provisions of the **Constitution of the Republic of South Africa, 1996** (“the Constitution”). In particular, **Section 24** of the Constitution provides that everyone has the right to an environment that is not harmful to their health or wellbeing and to have the environment protected for present and future generations by reasonable legislative measures that prevent pollution and ecological degradation, promote conservation, and secure ecologically sustainable development while promoting justified economic and social development.

Underneath the umbrella of the Constitution the law that is relevant to this legal opinion includes the following:

- The National Water Act, 36 of 1998 (“National Water Act”);
- **Regulation 704, 4 June 1999** (“R704”) promulgated in terms of the National Water Act;
- **Regulation 1191, 8 October 1999** (“R1191”) promulgated in terms of the National Water Act;

- **The Minerals Act, 50 of 1991**(“Minerals Act”);
- **Regulation 992, 26 June 1970 as amended** (“R992”) promulgated in terms of the Minerals Act;
- **The Environment Conservation Act, 73 of 1989** (“Environment Conservation Act”);
- **Regulation 1183, 5 September 1997** (“R1183”) promulgated in terms of the Environment Conservation Act;
- **The National Environmental Management Act, 107 of 1998** (“NEMA”);
- **The National Nuclear Regulator Act, 47 of 1999 (“NNRA”);**
- **Regulation 848, 23 April 1994 (“R848”) promulgated in terms of the Nuclear Energy Act, 131 of 1993;** and
- **The common law**.

4.1. LICENSING

In order for the activity to be conducted lawfully certain licenses, registrations, exemptions and authorisations may have to be obtained in terms of the **National Water Act**, **R704,** the **Minerals Act,** and the **Environment Conservation Act** as read with **NEMA** and the **NNRA**. The legalities associated with these are discussed in more detail below.

An important issue to note is that in obtaining the licenses, registrations, exemptions and authorisations there may be opportunity to use different approaches. On the one hand, it may be possible to save both time and money and approach the issue in a generic way for a number of sinkholes. On the other hand, it may be necessary to approach the issue on a case by case basis for each individual sinkhole. The potential saving associated with the generic approach is significant and therefore it would be prudent to consult with the relevant authorities and establish a mutually agreed approach at the outset.

4.1.1. NATIONAL WATER ACT

4.1.1.1 Section 5 of the National Water Act requires the Minister to establish a national water resource strategy. As part of this strategy DWAF has published a document referred to as “**Policy and strategy for groundwater quality management in South Africa**” (“Policy document”), dated 2000. In this Policy document the precautionary approach is adopted, in terms of which all groundwater will be assumed to be vulnerable unless it is shown otherwise.

As a balance to the precautionary approach, the Policy document is sensitive to the fact that in the South African context where social and economic growth is important, it will be physically and economically impossible to protect all groundwater resources to the same degree. As a result groundwater resources will be grouped into aquifers and classified according to their importance. This classification will be based on potential yield and the level to which communities depend on the aquifer. The existing classification system used by DWAF is referred to in paragraph 3.2.

As part of the Policy document source directed strategies have been developed. In paragraph 4.1.4 of the source directed strategies it is stated that DWAF will place a general ban on waste disposal and other polluting activities within 200 metres of the recharge zone for major aquifers and sole-source aquifers. Given the assumptions made in paragraph 3.2 above and the fact that tailings material is defined as waste (see paragraph 3.4), the general ban placed by paragraph 4.1.4 of the Policy document could be a fatal flaw to the activity.

4.1.1.2 **Section 19 of the National Water Act** ("Section 19") incorporates the Polluter Pays Principle (PPP). In terms of this principle the owner of land, person (including a juristic person) in control of land or a person who occupies or uses land on which an activity takes place (in the past, present and future) that has caused, is causing or is likely to cause pollution of a water resource must take all reasonable measures to prevent the pollution from occurring, continuing or reoccurring. In light of Section 19, the National Water Act and the associated considerations in this opinion apply to the activity whether it was conducted in the past, is being conducted at present or will be conducted in the future.

Critical to meaning of Section 19 is the definition of pollution as contained in **Section 1(xv)** of the National Water Act. In terms of this definition pollution means the alteration of a water resource so as 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 human beings, aquatic and non-aquatic organisms, the resource quality and property.

In terms of paragraphs 3.2 and 3.4 above, it has been assumed that the tailings material will be deposited in sinkholes that are above or in a major aquifer and that the tailings material could leach metals, salts and radio-active nuclides in such a manner as to at least be potentially harmful to the water quality in the major aquifer. In terms of these assumptions the activity will therefore result in pollution as defined by the National Water Act and therefore the provisions of Section 19 will apply.

The implications of Section 19 are that reasonable measures must be taken to prevent the pollution occurring. In interpreting the concept of 'reasonable measures' the provisions of Section 19(2) must be considered. Section 19(2) provides that these measures may include all of the following:

- Cease, modify or control the activity causing pollution;
- Compliance with any prescribed waste standard or management practice;
- Containment or prevention of the movement of pollutants;
- Elimination of the source of the pollution;
- Remedying the effects of the pollution; and
- Remedying the affects of any disturbance to the bed or banks of a watercourse.

The determination of which of these measures apply is left to the discretion of DWAF in the form of the relevant catchment management agency.

It is the opinion of Metago that DWAF would probably use this discretion to incorporate the principles and provisions of both the **Policy Document** in conjunction with the **Minimum Requirements for the Handling, Classification and Disposal of Hazardous Waste, 2nd edition, 1998** ("Minimum Requirements") as the appropriate waste standard or management practice to be applied to the activity. Notwithstanding the limitations presented by the Policy Document (see paragraph 4.1.1.1) it may be possible to negotiate a solution with DWAF in terms of the Minimum Requirements provided that it is possible to prove that the activity will in fact not have a detrimental impact on a water resource (the major aquifer). Any solution achieved through this negotiation process would probably require significant investment in both time and money. Moreover, there is no guarantee that a solution will be achieved particularly if it is proved that the activity will in fact result in a detrimental impact on a water resource (the major aquifer).

4.1.1.3 **Section 22 of the National Water Act** ("Section 22") requires that a person (including a juristic person) may only use water as defined in **Section 21 of the National Water Act** ("Section 21") as a 'permissible use' or as a 'licensed use'.

For the purpose of this opinion the activity would be seen as a **Section 21(g)** water use that is defined as "disposing of waste in a manner which may detrimentally impact on the environment". The activity is not a 'permissible use' as defined by **Section 22(1)** and **Regulation 1191,** both because the tailings is residue from gold mines and because the sinkholes sit in or above a major aquifer, and therefore it would have to be licensed. In obtaining a license Section **22(2)(c)** states that the water use (in this case the activity) must comply with any applicable waste standards or management practices as prescribed in regulations promulgated in terms of **Section 26(1)(h) of the National Water Act** ("Section 26"), unless the conditions of the relevant license provides otherwise.

Although the **Policy document** and the **Minimum Requirements** have not been incorporated by any regulations promulgated in terms of **Section 26**, DWAF has the discretion to incorporate them as a condition to the license(s) and would in the opinion of Metago probably do so. As stated in paragraph 4.1.1.2 above, negotiations aimed at providing a solution could be justified provided that it is possible to prove that the activity will in fact not have a detrimental impact on a water resource (the major aquifer). Any solution achieved through this negotiation process would probably require significant investment in both time and money. Moreover, there is no guarantee that a solution will be achieved particularly if it is proved that the activity will in fact result in a detrimental impact on a water resource (the major aquifer). The option of saving time and costs by conducting a single generic license application applicable to all mine waste material and all possible sinkholes should be investigated up front.

4.1.2. REGULATION 704

The following regulations prohibit the activity.

4.1.2.1 **Regulation 4(a) of R704** ("Regulation 4(a)") provides that no person (including a juristic person) in control of disposing mine residue (which includes the tailings in question) may place the residue within the 1:100 year flood line or within 100m of a watercourse, or on any ground that is likely to become unstable or cracked. Given that in certain circumstances the sinkholes are both in close proximity to and/or within the Wonderfontein Spruit and that most of the sinkholes are on ground that is likely to become unstable, the activity is likely to be prohibited by Regulation 4(a).

4.1.2.2 **Regulation 4(c) of R704** ("Regulation 4(c)") provides that no person (including a juristic person) in control of disposing mine residue (which includes the tailings in question) may place residue which is likely to cause pollution of a water resource in the workings of any pit or excavation. Given that the leaching of the tailings is likely to cause pollution of a water resource (see paragraph 4.1.1.2 above) and that a sinkhole could be deemed to be a pit or excavation the activity could be prohibited by Regulation 4(c).

4.1.2.3 **Regulation 5 of R704** ("Regulation 5") provides that no person (including a juristic person) in control of disposing mine residue (which includes the tailings in question) may use any residue for any purpose, which is likely to cause pollution of a water resource. Given that the leaching of the tailings is likely to cause pollution of a water resource (see paragraph 4.1.1.2 above) the activity is prohibited by Regulation 5

4.1.2.4 **Regulation 7(a) of R704** ("Regulation 7(a)") provides that every person (including a juristic person) in control of disposing mine residue (which includes the tailings in question) must take reasonable measures to prevent any substance which is likely to cause pollution of a water resource from entering any water resource, and must retain or collect the substance for use, re-use, evaporation or purification and disposal in accordance with the National Water Act. In accordance with the conclusions of paragraph 4.1.1.2 above it is the opinion of Metago that DWAF would probably use this discretion to incorporate the principles and provisions of the **Minimum Requirements** as the appropriate waste standard or management practice to be applied to the activity. The implications of this could be that a significant investment in time and money would have to be made to satisfy the provisions of Regulation 7(a). In addition, there is no guarantee that DWAF will accept the proposed solution.

4.1.2.5 **Regulation 7(b) of R704** (“Regulation 7(b)”) provides that every person (including a juristic person) in control of disposing mine residue (which includes the tailings in question) must design, modify, locate and construct all residue deposits (including sinkholes filled with tailings) so as to prevent the pollution of any water resource and to restrict the possibility of amongst other things the alteration of the flow characteristics of the water resource. As the activity will cause pollution to a water resource (see paragraph 4.1.1.2) it is prohibited by Regulation 7(b).

4.1.2.6 **Regulation 7(e) of R704** (“Regulation 7(e)”) provides that every person (including a juristic person) in control of disposing mine residue (which includes the tailings in question) must prevent the erosion or leaching of materials from any residue deposit (including sinkholes filled with tailings) so as to prevent the material or substance from entering and polluting a water resource. As the activity will cause pollution to a water resource (see paragraph 4.1.1.2) it is prohibited by Regulation 7(e).

There is a possibility that application for exemption from all of the above **R704** regulations can be made in accordance with **Regulation 3 of R704**, however, this possibility is left entirely to the discretion of the Minister of Water Affairs and Forestry and it is Metago’s opinion that before any exemption is granted, consideration would have to be given to the **Policy document** and the **National Water Act**. The content of section **4.1.1** applies accordingly. In addition, it must be noted that if a water license is issued in terms of the National Water Act there is no need to apply separately for exemption from the regulations in R704. These exemptions, if required, will be incorporated into the water license because a water license issued in terms of the National Water Act holds greater authority than the requirements of the regulations.

4.1.3. NATIONAL NUCLEAR REGULATOR ACT

Section 20 of the NNRA read with **Section 2 of the NNRA** provides that any action capable of causing nuclear damage must be registered or exempted. As no applicable regulations have yet been promulgated in terms of the NNRA the applicable test is in this regard is set out in **Regulation 2 of R848.** In terms of Regulation 2 of R848, the provisions of the NNRA do not apply to any material with a level of specific activity of each radioactive nuclide in radioactive material below 0,2 bq per gram.

Once the abovementioned determination has been made for the tailings in question and if the provisions of the NNRA are deemed to apply to the activity the registration/exemption application process will have to be conducted in accordance with the guidelines issued by The **National Nuclear Regulator ("NNR")**. A public health risk assessment with further time and cost implications forms a significant part of this process. The option of saving time and costs by conducting a single generic assessment applicable to all mine waste material and all possible sinkholes should be investigated up front.

Furthermore, If the activity is governed by the provisions of the NNRA and thereby falls within the authority of the NNR, the standards contained in **"Safety Series 115 of 1996: International basic safety standards for the protection against ionising radiation and for the safety of radiation sources"** may wholly or in part be prescribed by the NNR as the standards to comply with when conducting the activity.

4.1.4. MINERALS ACT AND ENVIRONMENT CONSERVATION ACT

Section 39 of the Minerals Act ("Section 39") provides that for mines to conduct operations lawfully they must hold a mining authorisation and they must submit an Environmental Management Programme Report ("EMPR") for existing activities and an EMPR amendment whenever their activities extend beyond the scope of the existing EMPR. The provisions of Section 39 are relevant from the perspective that if the activity is deemed to be an extension to the mine's operations then an amendment will have to be made to the EMPR to include the activity in the EMPR before the activity can be conducted lawfully.

The compilation of the EMPR amendment and the approval thereof by the Department of Minerals and Energy ("DME") will, amongst the input from various government departments and bodies, involve input from DWAF and the NNR as interested and affected parties and therefore the amendment will have to take into account the legal provisions as set out in **4.1.1, 4.1.2 and 4.1.3** above. In addition to the investment in time and costs mentioned in **4.1.1, 4.1.2 and 4.1.3** above, the EMPR (and/or EMPR amendment) will attract its own significant time and money costs.

Similarly, where the activity is not covered by the EMPR process **Section 22 of the Environment Conservation Act** provides that no person (including a juristic person) shall undertake an identified activity that could detrimentally impact on the environment unless the Minister of Environmental Affairs and Tourism has issued written authorisation. This authorisation shall only be issued after consideration of reports concerning the impacts of the proposed identified activity. Alternatively, if one argues that the provisions of Environment Conservation Act do not apply to mine waste then **Section 24 of NEMA** provides that any activity that may significantly affect the environment must be considered, investigated and assessed.

In practice, regardless of whether one applies the Environment Conservation Act or NEMA, an Environmental Impact Assessment (“EIA”) will have to be conducted in accordance with **R1183** because at present these are the only EIA Regulations that have been promulgated.

The compilation of the EIA and the approval thereof by the Department of Environment Affairs and Tourism will involve, amongst various government departments and bodies, input from DWAF and the NNR as an interested and affected parties and therefore the amendment will have to take into account the principles and procedures associated with the legal provisions as set out in **4.1.1, 4.1.2 and 4.1.3** above. In addition to the investment in time and costs mentioned in **4.1.1, 4.1.2 and 4.1.3** above the EIA will attract its own significant time and money costs.

As with the water licenses and the NNRA certificates it may be possible to save time and money by conducting a single EIA or EMPR for all sinkholes rather than on a case-by-case scenario. This aspect should be investigated and agreed with the relevant authorities at the earliest possible stage.

Irrespective of whether the EMPR or EIA process is followed the following issues have been identified as potential significant negative issues that will have to be investigated:

- Impact on water resources (see 4.1.1 and 4.1.2);
- Impact of radio activity (see 4.1.3);
- Impact on Soil;
- Dust pollution;
- Noise pollution;
- Impact on fauna and flora;
- Road degradation and other transport related issues;
- Visual pollution; and
- Health and safety issues not covered by the above points.

Only those issues considered as onerous and/or potentially fatal to the conducting of the activity have been discussed in detail in this opinion from a legal perspective. In regard to the other issues it is considered sufficient merely to mention them in the context of the EIA and/or EMPR processes.

For the sake of completeness, **Section 20 of the Environment Conservation Act** (“Section 20”) provides that no person (including a juristic person) shall establish, provide or operate any disposal site without a permit. A disposal site is “a site used for the accumulation of waste with the purpose of disposing or treatment of such waste. In terms of Government Notice 1986 of 24 August 1990: tailings, waste rock and slimes form mining activities are exempt from the definition of "waste" in this context. Therefore the provisions of Section 20 do not apply to the activity.

4.2. LIABILITY DURING ALL PHASES OF THE ACTIVITY

Liability can arise in one or both of the following ways:

- Statutory liability; and
- Common law liability.

4.2.1. STATUTORY LIABILITY

The activity could attract statutory liability (in the form of imprisonment, fines and/or damages) in any case where there is non-compliance with any legislation. The more likely situations are listed below:

- Failure to obtain the necessary authorisations/permits/licenses/certificates as outlined in **4.1** above;
- Failure to comply with the conditions of the authorisations/permits/licenses/certificates;
- Failure to comply with **Section 19 of the National Water Act** and/or **Section 28 of the NEMA.** Where the latter provides that every person (including a juristic person) who causes, has caused or may cause significant pollution or degradation to the environment (read in a wide sense) must take reasonable measures to prevent such pollution from occurring, continuing or recurring, or, so far as such harm to the environment is authorised by law or cannot reasonably be avoided or stopped, to minimise and rectify such pollution or degradation. Like the National Water Act, although Section 28(3) of NEMA gives an idea of the measures that may be deemed reasonable, the ultimate determination of reasonable measures is left to the discretion of the relevant authority, in this case being the Director-General or provincial head of department of the Department of Environmental Affairs and Tourism; and
- Failure to secure the sinkhole areas by means of fences and warning notices in accordance with both **Regulation 5.2 of R992** and **Regulation 8 of R704**.

4.2.2. COMMON LAW LIABILITY

The activity could attract common law liability (in the form of damages) if a claim for damages against those responsible for the activity can be proven using the principles of delict. In basic terms these principles are:

- A claim by a person(s);
- Suffering harm and/or loss;
- Caused by the activity;
- With an element of wrongfulness (negligence or intent); and
- For an award of damages.

5. ALTERNATIVES

Regulation 5.2 of R992 requires that where mining operations have caused subsidences or cavities on the surface these places must be securely fenced in and conspicuous notice boards must be put up to warn persons off. Failure to do so could render the responsible person(s) at the responsible mines liable for both common law damages caused by the failure to secure the subsidences/cavities and statutory fines and or imprisonment.

Whether a security fence and notice boards will be deemed to be sufficient in the longer term is left to the discretion of the Director: Mineral Development (DME). He/she may, in consultation with the Director-General of DWAF issue a closure certificate to the effect that the surface affected by the sinkholes has been adequately rehabilitated (**Regulation 5.12.5 of R992**).

It is Metago's opinion that the security fence and notice board approach is a short-term solution while the responsible mines are operating and ongoing maintenance is practical. Once the responsible mines are decommissioned they will apply for closure certificate for the activity in terms of **Section 12 of the Minerals Act**. On receipt of the certificate the mines will absolve themselves from complying with the provisions of the Minerals Act in so far as the Minerals Act has application to the sinkholes. In addition, it could be argued that from the date that the closure certificate is issued the mines will pass liability associated with the sinkholes to the state. Given this scenario, it is unlikely that the DME will issue a closure certificate(s) unless the sinkholes have been rehabilitated in a permanent manner that requires less or no ongoing maintenance. Alternatively, a closure certificate may be issued in the unlikely event that the mines' EMPRs (as approved) provide that fencing and notices is an adequate long-term solution.

Given the above argument, the obvious solution is to back-fill the sinkholes and vegetate the scars. In this situation the alternative is one of back-fill material and it may be prudent to invest capital up front and determine which materials are the best alternatives given the constraints of costs and the law as considered in this opinion.

In certain instances the sinkholes are being used as informal landfills. This is clearly illegal both in terms of the **Environment Conservation Act** and **the National Water Act** (refer to 4.1 above). In addition, until the responsible people at the responsible mines receive closure certificates for the sinkholes they are exposed to significant potential liabilities if any harm should come to persons or property because of insufficient fencing and warning notices or because of pollution. It is therefore important that informal waste disposal is prevented from continuing and/or occurring until an acceptable rehabilitation solution is determined and agreed with the relevant authorities.

6. CONCLUSION

As the **National Water Act,** associated law and guidelines (in particular the **Policy document**) currently stand, because the activity involves the disposal of waste on a major aquifer, it is unlikely that the activity could ever be conducted lawfully. Moreover, the current definitions of pollution and waste in the National Water Act are so broad that there may not be any alternative material that will not result in pollution as defined and therefore be classified as waste as defined. Therefore there may be no alternative material that can be used as back-fill material, which would exclude backfilling the sinkholes as a rehabilitation option. These issues raise serious concerns both, about the appropriateness of the law in its current form and about its application.

Notwithstanding the above, if it is possible to prove that there will be no unacceptable negative environmental impacts associated with the activity, it may be possible both to convince DWAF that the measures proposed are reasonable, and based on that, to obtain the necessary license(s) and exemption(s) as described in **4.1.1 and 4.1.2** above. A major obstacle in this regard will be complying with the provisions of the **Policy document** and **the Minimum Requirements** and the associated time and money costs could be so significant as to constitute a fatal flaw for the activity. Moreover, even if the activities are conducted in accordance with the required license(s) and exemption(s) there is no guarantee that the activity will not attract statutory and/or common law liability.

Aside from the provisions of the National Water Act, associated law and guidelines significant time and money will have to be invested to comply with the **NNRA,** the **Minerals Act** and the **Environment Conservation Act** read with **NEMA** (refer to paragraph 4.1.4) to produce the necessary **hazard assessments**, **EMPR (amendment) and EIA reports**.

With regard to the issue of legal compliance the opportunities for rationalisation of work should be investigated and agreed with the authorities at the earliest possible stage. In this regard there may be opportunities to investigate the activity and its impacts at all sinkhole sites in one **hazard assessment, EIA or EMPR (amendment)**. The less cost effective alternative is for each sinkhole to be investigated separately.

Likewise, it may be possible to cover the activity in a generic fashion in one registration/exemption certificate issued in terms of the **NNRA** and if the activity can be licensed at all in terms of the **National Water Act**, there may be opportunity to license the activity by means of a generic **Section 22(2)(c) – Section 40** water license or **Section 22(1)(a)(iii) – Section 39** general authorisation, instead of a separate **Section 22(2)(c) – Section 40** water license application for each sinkhole. Time and money should be invested up front to determine the most cost effective method of complying with the law.

B Stobart **Alistair James** Pr Eng

Metago Environmental Engineers (Pty) Ltd

1 2 Springer

Dear Author:

Please find attached the final pdf file of your contribution, which can be viewed using the Acrobat Reader, version 3.0 or higher. We would kindly like to draw your attention to the fact that copyright law is also valid for electronic products. This means especially that:

- You may not alter the pdf file, as changes to the published contribution are prohibited by copyright law.

- You may print the file and distribute it amongst your colleagues in the scientific community for scientific and/or personal use.

- You may make your article published by Springer-Verlag available on your personal home page provided the source of the published article is cited and Springer-Verlag is mentioned as copyright holder. You are requested to create a link to the published article in Springer's internet service. The link must be accompanied by the following text: The original publication is available at http://link.springer.de or at http://link.springer-ny.com . Please use the appropriate URL and/or DOI for the article. Articles disseminated via SpringerLink are indexed, abstracted and referenced by many abstracting and information services, bibliographic networks, subscription agencies, library networks and consortia.

- Without having asked Springer-Verlag for a separate permission your institute/your company is not allowed to place this file on its homepage.

- Please address any queries to the production editor of the journal in question, giving your name, the journal title, volume and first page number.

Yours sincerely,

Springer-Verlag

The future of the dolomitic springs after mine closure on the Far West Rand, Gauteng, RSA

C. J. U. Swart · A. R. James · R. J. Kleywegt · E. J. Stoch

Abstract Approximately 1.2 km of dolomitic limestone overlies the Far West Rand gold reefs southwest of Johannesburg, South Africa. This karst aquifer is partitioned into several groundwater compartments by predominantly north–south trending syenite dykes. Prior to mining, the primary water flow was westwards, decanting over dyke boundaries as a succession of springs along the Lower Wonderfontein Spruit. Dewatering of the overlying dolomitic aquifer for safety and economic reasons by deep gold mining operations, caused the water levels of four compartments to drop and their respective springs to dry up. By perforating dykes, formerly separated aquifers were hydraulically interconnected by mining. Using historical and recent data of water flow—surface and groundwater—and pumping rates, a geohydrological model is presented. The results suggest that the water tables will rise to their pre-mining levels within 30 years after mining ceases and that the dry springs will flow again, despite the compartments being connected by the extensive mining operations.

Keywords Dewatering · Dolomite · Mining · Rewatering · Republic of South Africa

Received: 6 January 2003 / Accepted: 1 April 2003

C. J. U. Swart (✉)
GFL Mining Services Limited Ground Stability Group,
P.O. Box 6171, Oberholzer 2501, South Africa
E-mail: gsg@worldonline.co.za
Tel.: +27-18-7874435
Fax: +27-18-7875972

A. R. James
Metago Environmental Engineers (Pty) Ltd.,
P.O. Box 1596, Cramerview 2060, South Africa

R. J. Kleywegt
Council for Geoscience, Private Bag X112,
Pretoria 0001, South Africa

E. J. Stoch
P.O. Box 9, Welverdiend 2495, South Africa

Introduction

Background

The northern catchment boundary of the Lower Wonderfontein Spruit, the target area of this review, is the Atlantic Ocean/Indian Ocean watershed (Fig. 1). The bed of the Wonderfontein Spruit passes in a southwesterly direction from its source, south of Krugersdorp, to the Mooi River for approximately 80 km (Figs. 1 and 2). The dolomite of the Far West Rand, which is drained by the Lower Wonderfontein Spruit, is approximately 50 km southwest of Johannesburg in the Gauteng Province of the Republic of South Africa (Fig. 1). The Donaldson Dam is the upstream boundary of the Lower Wonderfontein Spruit and the downstream boundary is its confluence with the Mooi River (Fig. 2).

Until the turn of the 19th century, the Far West Rand was a rural area producing a wide range of agricultural products. Farming was initially associated with the abundant supply of dolomitic water that issued from the numerous springs. Mining followed, almost 100 years later, attracted by the quality of the gold ores. In the early years of gold production, which started in the 1930s, these two major activities co-existed. As mining intensified, large capacity pumps had to be deployed to drain the mines, a practice that allowed mining to continue safely and economically. The associated drop of the water tables caused the related springs to dry up. Surface subsidence in the form of sinkholes and 100-m-plus diameter depressions started to pockmark the countryside.

The interest excited by the discovery of gold waned when, in 1912, the first attempt to access the rich gold-bearing reefs beneath the dolomite was frustrated by an inrush of dolomitic groundwater, pouring from intercepted caverns in the karstic aquifer.

The study area is partitioned by several syenite dykes into large contiguous compartments (Fig. 2). As the 12- to 16-m-wide dykes were for all practical purposes impermeable, springs formed in the valley at their upstream edges.

This paper focuses on the four compartments that were dewatered as a consequence of mining. They were named after settlements in their areas and are known, from east to west, as the Western Gemsbokfontein, Venterspost, Bank and Oberholzer Compartments. These, on average 10-km-wide compartments, which cover approximately 500 km^2, are traversed by an east–west running streambed, known as the Lower Wonderfontein Spruit. This Spruit was

DOI 10.1007/s00254-003-0820-3

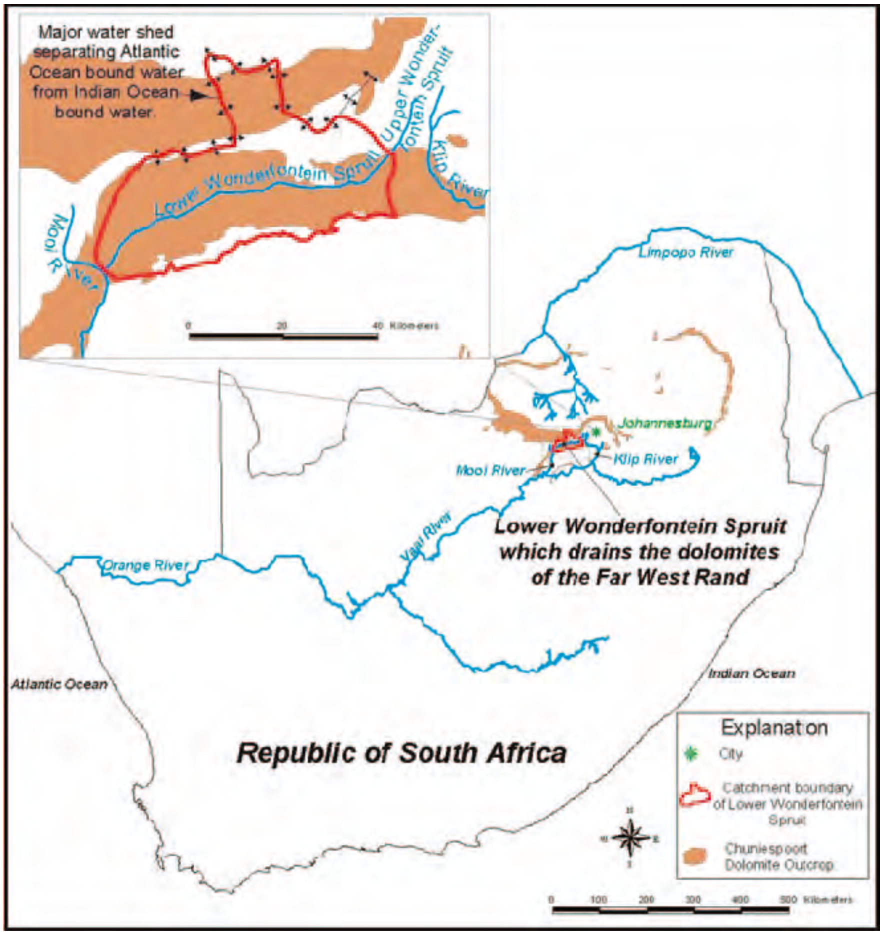


Fig. 1
Locality plan

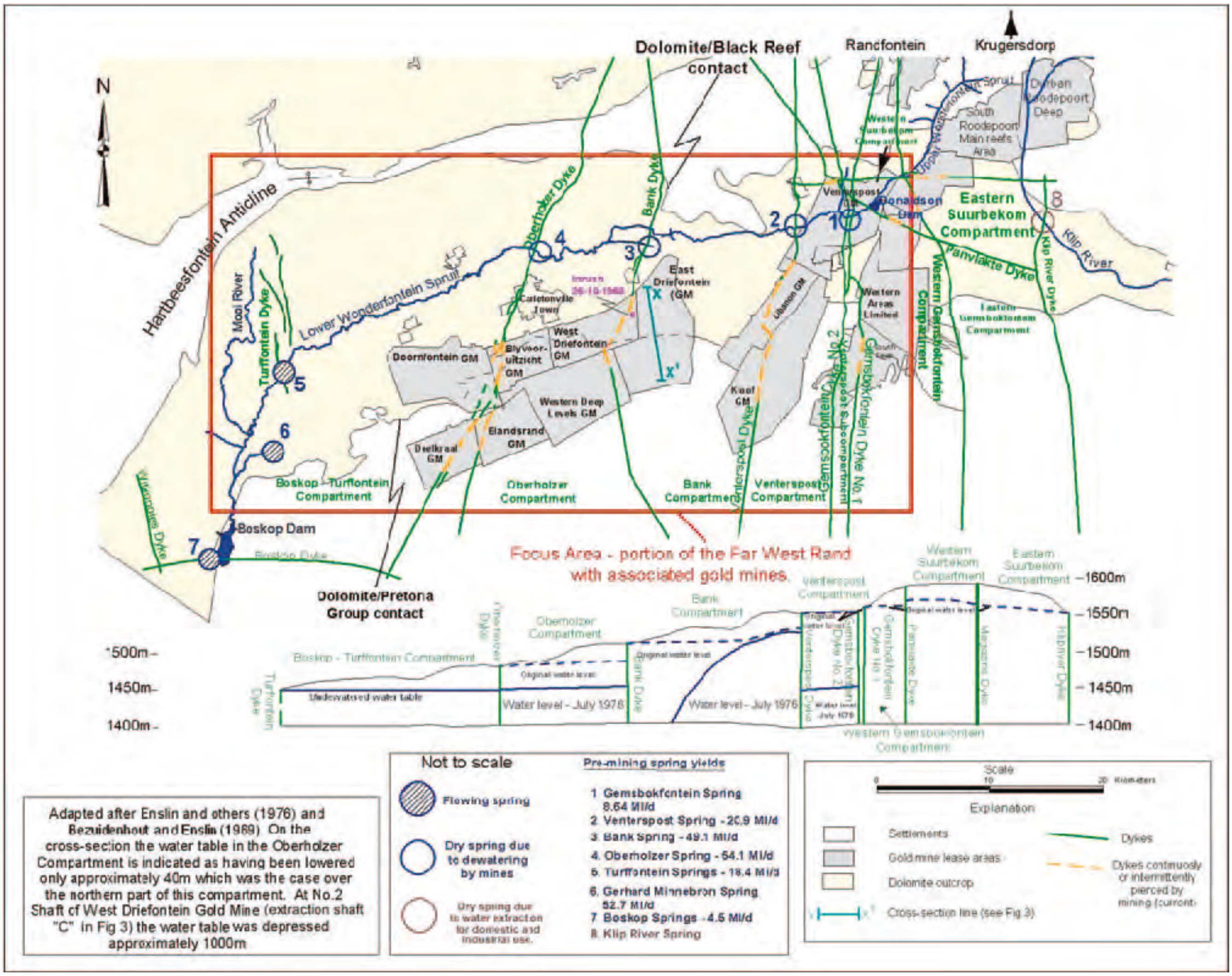
initially drained by irrigation canals built by the settlers (Fig. 2). This streambed intersects each dyke not more than 1.5 km from its associated spring. The Klip River Spring, shown near the right-hand edge of Fig. 2, falls outside the focus area. This spring ran dry in the early 1900s and finally stopped flowing in the 1930s due to sustained extraction from the Eastern Suurbekom Compartment of water for domestic and industrial purposes.

In the early 1960s the State accepted a proposal by some gold mines operating in the region stating that the dolomitic compartments impacted by mining should be dewatered. The water tables in the four dewatered compartments were eventually lowered by about 100 m on average.

Initially, water pumped from the mines and discharged into the Lower Wonderfontein Spruit during the dewatering phase, substituted for the natural flow of the springs. At present, with the exception of the Western Gemsbokfontein Compartment—which as yet is not fully dewatered (Van Biljon, unpublished data 2001) as it is the most recent compartment to be affected—a dynamic equilibrium has been attained in the Venterspost, Bank and Oberholzer Compartments. Water that flows into the mines is removed by pumps and discharged well beyond the catchments of the four compartments being drained (Fig. 3). A 1-m-diameter pipeline was laid parallel to the Lower Wonderfontein Spruit from the Donaldson Dam in the east to the Boskop-Turffontein Compartment in the west to prevent Upper Wonderfontein catchment water from recharging the dewatered compartments (Fig. 3).

Mining pierced several dykes (aquicludes) below, and often well below, the dolomite (Fig. 2). The potential consequence was commented on by the Director of Water Affairs, who chaired an Interdepartmental Committee from 1956 to 1960 (Director of Water Affairs 1960), through De Freitas (1974) and Wolmarans (1986) to Hodgson and others (2001). These authors predict that interlinked mining operations will cause the water tables of connected compartments to equilibrate at an elevation that would result in the formation of a single, mega-compartment issuing from the lowest unaffected spring, namely the Turffontein Springs (Fig. 2). This, in their opinion, will occur after all mining, and consequently pumping, has ceased. Hodgson and others (2001) suggest that in the "mega-compartment" scenario, the elevation of the post-mining water table would be flat and that the depth of the water table would increase progressively from 0 m in the Turffontein portion of the Boskop-Turffontein Compartment, to approximately 150 m in the Western Gemsbokfontein Compartment to the east (Fig. 2).

This paper suggests an alternative. A thesis that the water tables will return to the pre-mining elevations and, as a result, the four springs will flow again, is promoted.



Adapted after Enslin and others (1976) and Bezuidenhout and Enslin (1969). On the cross-section the water table in the Oberholzer Compartment is indicated as having been lowered only approximately 40m which was the case over the northern part of this compartment. At No.2 Shaft of West Driefontein Gold Mine (extraction shaft "C" in Fig 3) the water table was depressed approximately 1000m

Fig. 2
The dolomitic groundwater compartments on the Far West Rand

According to Stirling (personal communication 2003), all the mine shafts have concrete lined barrels. Thus, water in the dolomite aquifer should not be able to flow down the shafts into the mine void below. It is also standard practice to seal exploration boreholes at the base of the dolomite after drilling. The view advanced in this paper thus assumes that no dolomitic water could access the mine void via boreholes or shafts. If not, these potential conduits need to be sealed at the base of the dolomite during mine closure.

From the evidence at hand, it appears that after pumping has ceased, water from the highly weathered and cavernous portions in the upper dolomite aquifer—hereafter referred to as the "cavernous aquifer"—will continue to drain along fissures to the mine voids several hundred to a few thousand meters below. Once the mine and fissures have filled, the transmissivity of the fissures between the cavernous aquifer and the mine would be sufficiently low to redirect some, in certain cases most, infiltrating rain water to flow laterally and thereby gradually fill the cavernous aquifer which, upon replenishment, will cause the springs to flow again. In contradistinction to the assumption that all the rain water would percolate vertically through the water-filled fissures into the flooded mine below and, purportedly decant at the Turffontein Springs as a mega-compartment, it is postulated that the resistance to vertical flow will be sufficient to restore the pre-mining water levels and that the original springs will flow again, albeit intermittently and at changed volumes. Jennings (unpublished data 1965), referring to near-surface voids in "dolomitic residuum"[1], expressed the view that a "recharge (rewatering) of the compartments might weaken the skin of some voids, which may then collapse (to form a sinkhole)." This prediction was confirmed by Beukes (1987) who observed that where the water table returns to pre-mining levels, sinkholes that occurred

---

[1] Wagener (1984) defined dolomitic residuum as that portion of the dolomite which remains behind when part of the rock has been removed by chemical weathering processes and leaching. It comprises chert gravel, wad and small quantities of clay. The residuum is usually mixed with transported material which filters from above.

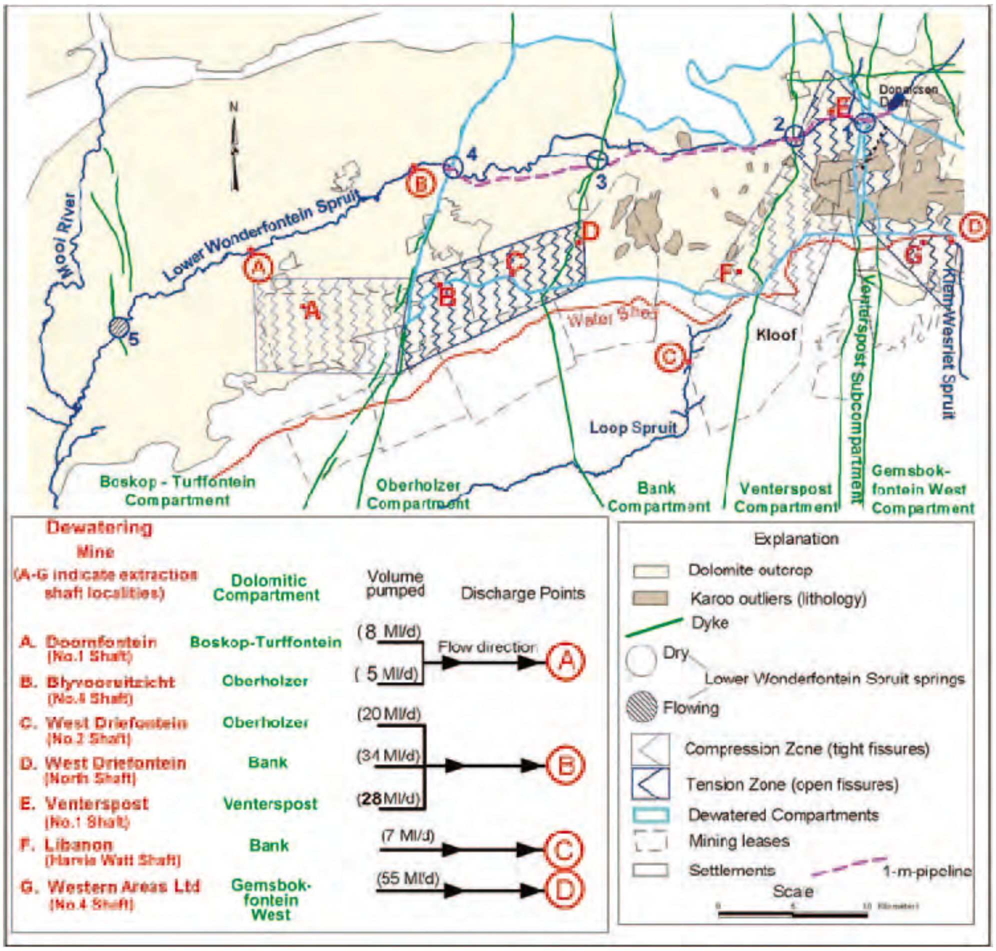


Fig. 3
The Far West Rand showing *1* Compression and tension zones in mines; *2* dolomitic water (groundwater) extraction points; *3* transfer of pumped water

during the dewatering phase could reactivate and that new sinkholes formed. It is, therefore, projected that rewatering will have major implications on the dewatered compartments for the rail and road infrastructure as well as the reticulation of municipal services. The latter is a source of concern given the experience that water pipes affected by relatively minor subsidence, which may occur during rewatering, can rupture. The resultant leaks may, even if located in previously sinkhole-free dolomitic areas, initiate sinkholes.

This investigation was motivated by the strong likelihood of ground movement and the associated socio-economic implications should the water tables be restored to their original elevations in the four dewatered compartments. For a first-order estimate of the post-mine closure, hydrological sequence and consequences was obtained from a model developed to simulate the impact of mining on the dolomite aquifer. Water quality aspects of the rewatering process, however, falls outside the scope of this paper. Some post-mining issues that need to be resolved include:

- Estimating the time it will take to flood the mines;
- Determining the time it will take for post-mining groundwater levels to be established;
- Predicting the maximum levels to which the groundwater will rise and whether this will reach the pre-mining levels, in which event the affected springs will flow again.

Some of these issues were comprehensively investigated by an Interdepartmental Committee from 1956 to 1960 (Director of Water Affairs, (1960). With the information at their disposal it was estimated that all the mines would be closed by 1980 and it was projected that, if the springs should flow again, this would occur some 60 years later, in 2040. The fact that active mining may still be taking place in the year 2040 is an example of how difficult venturing predictions is in an anthropomorphic environment.

Geology and geohydrology of the study area

General sequence of strata

The gold reefs mined in the Far West Rand area occur within the Witwatersrand Supergroup and the contact between the Witwatersrand Supergroup and the overlying Ventersdorp Supergroup (where present). Part of the Black Reef Formation is directly underlain by the Ventersdorp Supergroup, the remainder by the Witwatersrand Supergroup (Fig. 4). The Black Reef Formation in turn is overlain by the

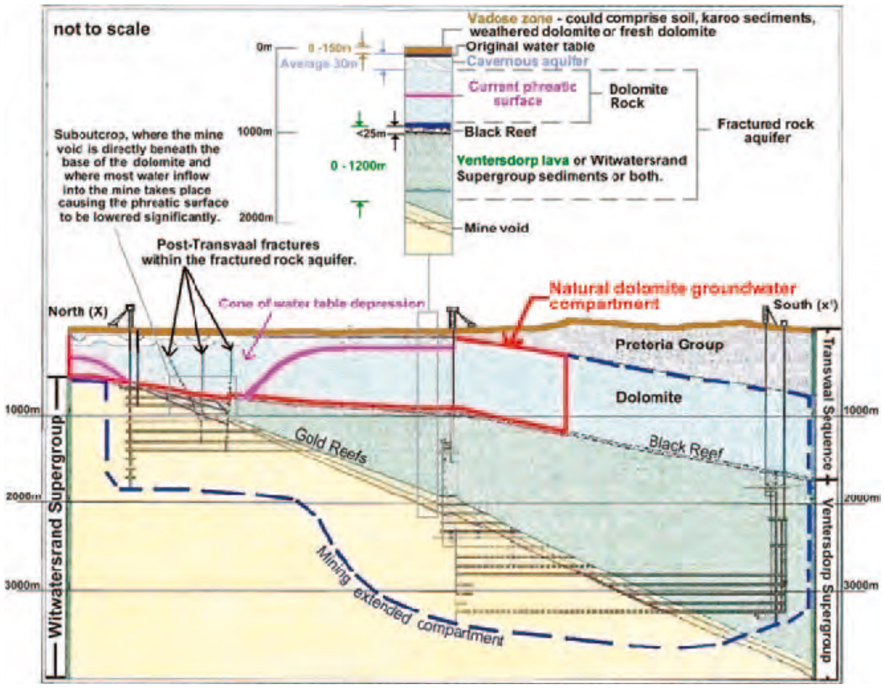


Fig. 4
Simplified cross section through X–X′ in Fig. 2

Chuniespoort Group (Proterozoic) dolomite, which on the Far West Rand is approximately 1,200 m thick and consists of alternating layers of dolomite and chert.

Pretoria Group sediments overlie the dolomite south of the southern dolomite outcrop boundary as shown in Figs. 2 and 4. The Pilanesberg syenite dykes which intruded the succession, including the Pretoria Supergroup, effectively subdivide the dolomite into compartments (Fig. 2). Karoo (Palaeozoic) sediments are infrequently found as outliers filling deeply weathered areas in the dolomite. The Lower Wonderfontein Spruit incised the Karoo deposits (where present along its course) into dolomite (Fig. 2).

The succession occurs on the southern limb of the Hartbeesfontein Anticline (Fig. 2). The Witwatersrand and Ventersdorp Supergroups dip approximately 25° south while the Black Reef Formation, through to the Pretoria Group, dips between 5° to 10° in the same direction (Fig. 4; Table 1).

Dolomite weathering and aquifer development

The thickness of the dolomite residuum is variable over short distances, ranging from 0 m where the dolomitic bedrock outcrops to about 200 m below ground surface. In spite of the variable thickness of the residuum and the presence of highly irregular subsurface bedrock topography, the dolomitic terrain is characterized by a relatively flat topography and sparse outcrops.

Where the surface of the dolomite is not covered by Pretoria Group sediments—termed “Pretoria unshielded dolomite”— and exposed to the elements, it has, in places, developed a highly weathered horizon close to the pre-mining phreatic surface. These highly weathered horizons are prevalent near deeply weathered vertical fractures which provided relatively easy passage for carbonic acid-charged rainwater to infiltrate and dissolve the dolomite on its way to, at, and especially immediately below, the phreatic surface. This was described by Brink (1979) as follows: “Most solution, however, takes place below the water table, in the phreatic zone. Phreatic solution manifests itself in two ways:

– Immediately below the level of the water table, where the water is more acidic than deeper down, large horizontal caverns are corroded into the rock, and
– At depth within the phreatic zone, where widening of fissures by corrosion continues to take place”.

The loosely compacted residuum, and cavities so generated, constitute the cavernous aquifer as it provides a large storage capacity for groundwater.

The horizontal discontinuity of the cavernous aquifer is explained by Kleywegt and Pike (1982) as— dolomitic residuum in the phreatic zone, forming a substantial part of the aquifer in the easternmost dolomitic compartments where the cavernous aquifer is thus horizontal and fairly continuous. Westwards, however, due to lower decant levels over the successive dykes, the contribution of the residuum, along solution widened fissures, to the aquifer decreases until its average depth lies well above the phreatic surface. As a result of post-Transvaal pre-Karoo tectonic fracturing (some of which manifested as widely spaced deep reaching faults) vertical planes (zones) of more intense leaching have developed. The dolomitic residuum in these zones extends as much as 40–50 m (and occasionally much more) below the water table due to the intensity of leaching in certain areas. This results in these zones, together with the dissolution of horizontal caverns leading from the deep reaching faults into dolomitic rock immediately below the pre-mining water table, contributing to the aquifer almost exclusively in the western compartments.

Table 1
Lithostratigraphic column of the Far West Rand (Brink 1979 and Wolmarans 1984)

			Formation	Thickness (m)	Description
Karoo Supergroup (~200 Ma)		Dwyka/Ecca	Vryheid	0–200	Carbon-rich, interlayered gritstone, sandstone, arkoses and carbon-rich mudstone
		Pilanesberg			Syenitic and diabase intrusions
Transvaal Supergroup	Pretoria Group		Rooihoogte	10–150	Chert breccia, conglomerate, gritstone, quartzite and shale
	Chunniespoort Group	Malmani Sub-group	Eccles	~380	Chert-rich, dark-coloured dolomite with stromatolites and oolitic bands. Chert content increases to top
			Lyttelton	~150	Chert-free, dark-coloured dolomite with large stromatolitic mounds
			Upper Monte Cristo	~258	Chert-rich dolomite
			Middle Monte Christo	~162	Chert-poor dolomite
			Lower Monte Christo	~275	Chert-rich dolomite
			Oaktree	~200	Chert-poor dolomite with interlayered carbon rich shale towards the base
			Black Reef	~30	Basal conglomerate and quartzite with interlayered carbon-rich shale
Ventersdorp Supergroup	Klipriviersberg Group			0 – 2,400	Basic to acidic lavas with associated agglomerates and tuffs. Occasional sedimentary deposits
Witwatersrand Supergroup	Central Rand Group			Not known	Mainly sedimentary rocks (all grain sizes) with gold in conglomerates
	West Rand Group			Not known	Slates and lavas
Basement Granite-gneiss				Not known	

Table 2
The time related importance of the recharge mechanisms (quantity only)

Recharge Mechanism	Pre-mining	Mining	Post Mining
Natural recharge from rainfall infiltration	Very Important	Very Important	Very Important
Recharge from the Wonderfontein Spruit and dolomite springs under normal rainfall events	Very important	Except for storm events, relatively unimportant	Depends on future of pipeline[a]
Recharge from the Wonderfontein Spruit and other drainage channels under extreme rainfall events	Unimportant	Very significant but rare	Important
Leakage through dykes from adjacent compartments	Unimportant	Unimportant	Important
Recharge from mine dewatering operations	Nil	Boskop-Turffontein and Eastern Gemsbokfontein	Nil

[a] The pipeline mentioned in column 3 refers to a 1-m-diameter pipeline which connects Donaldson Dam and the Boskop-Turffontein Compartment to convey the water in the Wonderfontein Spruit across the dewatered dolomite compartments, thereby reducing recharge to the mines and related pumping costs

In addition to the cavernous aquifer, dominant fractures associated with the post-Transvaal tensional tectonics extend through the entire dolomite succession and the Ventersdorp lavas (where present) into the underlying Witwatersrand Supergroup. Although the dolomitic bedrock along these fractures has undergone considerably less leaching than higher up—such as in the vicinity of the water table and shallower— the voids created along them, especially in the brittle chert-rich zones, are also part of the system and should therefore be considered when studying the total geohydrological picture. This portion of the geohydrological system is referred to as the "fractured rock aquifer" (Fig. 4). Although displaying a significantly lower storativity and hydraulic transmissivity than the cavernous part of the dolomitic aquifer, it effectively connects the latter with the mine some several hundred to a few thousand meters below. Under the subsection headed "The effect of crustal stresses and thick Pretoria Group strata covering the dolomite on the hydrology" it will be explained that the transmissivity of the fractured rock aquifer is more effective in some instances, less in others.

Compartmental boundaries

Prior to mining, the compartments were discrete aquifers, recharged by surface runoff, spring flow decant over its eastern boundary-dyke, and stream flow. The compartments had differential water tables stepped across the dykes (Enslin and Kriel 1959). The groundwater compartments under broader consideration are from east to west: the Western Gemsbokfontein, Venterspost Sub-, Venterspost, Bank, Oberholzer and Boskop-Turffontein Compartments. These dolomite compartments are bounded as follows (Fig. 2):

North:	The Venterspost Sub-, Venterspost , Bank, Oberholzer and the Boskop-Turffontein, Compartments are effectively confined by the outcrop of the southward dipping, underlying Black Reef Formation. The Western Gemsbokfontein Compartment's northern boundary is the Panvlakte Dyke.
South:	All the compartments are limited by the southward dipping Pretoria Group quartzites and shales, which restrict the development of a cavernous horizon within the dolomite further south. In the case of the Western Gemsbokfontein Compartment a reverse fault "duplicated" some Pretoria Group sediments and the southern boundary is considered by Parsons (unpublished data 1987) to be Pretoria Group sediments south of two large dolomitic inliers.
East and west:	North–south trending syenite dykes create effective hydraulic barriers between the compartments.

A gravimetric survey conducted from 1963 to 1974 by Kleywegt (unpublished data 1975), identified a north–south oriented broad dolomite bedrock crest which practically divides the southern Bank Compartment into a western and an eastern groundwater subunit. The two subunits are, however, connected in the northern part of this compartment (Swart 1986). When dewatering by West Driefontein Gold Mine in the southwestern corner of the Bank Compartment started in 1969, the water table in the western subunit dropped far more dramatically than in the eastern subunit (see cross-section at the bottom of Fig. 2).

The nature of the pre-mining water tables

The pre-mining water level of each compartment was controlled by the elevation of the unweathered dyke where the springs emerged at each compartment's western boundary. Slight downward nett westward gradients, less than 1:250 according to Enslin and Kriel (1967), were maintained towards the spring by the converging flows within a compartment. The average slope of the ground surface of the southern flank of the Lower Wonderfontein Valley is 1:50 and that of the northern flank, 1:100 (De Kock 1967). Below the streambed with a surface gradient of 1:300 (De Kock 1967), the gradient of the water table could be as flat as 1:1,250 (Council for Geoscience unpublished borehole data 1970).

Prior to human settlement, the Lower Wonderfontein Spruit was a westerly draining perennial stream (Director of Water Affairs 1960) augmented by the springs. The natural phreatic surface changed dramatically from a gradual slope towards the springs to inverted cones with a sink (or lowest point) forming above each dewatering mine as the large-scale pumping of groundwater seeping into the underground mine workings progressed. As most of the water enters the mine workings close to the suboutcrop of the gold reefs against the Black Reef Formation at the base of the dolomite (Fig. 4), the sink is generally established between the dewatering shaft and the closest mined-out suboutcrop.

Intercompartmental flow

It was stated earlier that prior to mining, intercompartmental groundwater flow through the dykes was accepted as insignificant. Historically, most of the groundwater flowed over the dykes from one compartment to the next occurring via the Lower Wonderfontein Spruit and the succession of springs.

Recharge

Where mining impacts, recharge of the dolomitic aquifers occurs both naturally and by artificial means. The relative contribution of the different recharge mechanisms changed from the pre-mining to the mining period and it is expected to change once more during the post-mining period as indicated in Table 2. While some recharge processes remain significant throughout, others are only significant during one or two of the periods. The average yields of the springs feeding into the Lower Wonderfontein Spruit prior to mining, as calculated by the Interdepartmental Committee (Director of Water Affairs 1960), are listed in Fig. 2.

Storativity

The Director of Water Affairs, using geological sections through mine shafts and water balance studies, concluded that on the Far West Rand the storativity of dolomite decreases from approximately 15% within the first 30 m of the pre-mining water level to an estimated 1.5% below the cavernous aquifer and much less in deeper areas (Director of Water Affairs 1960). This estimate is compared to those of later researchers in Table 3.

Enslin and Kriel (1967) estimated the combined storage capacity of the Venterspost (0.45 million Ml) and Oberholzer (0.675 million Ml) Compartments to be about 1.125 million Ml (1.125 km^3). Schwartz and Midgley (1975), using a different method, calculated the storage capacity of the Bank Compartment to be 2 million Ml. The total amounts to 3.125 million Ml, which approximates the aggregate of 3.5 million Ml reported by Vegter (1987) for the three compartments.

In the section headed "Geology and geohydrology" it was stated that the degree of development of dolomitic residuum and thus the cavernous aquifer, in deeply leached zones is more prominent in the eastern compartments than further west. Swart and others (2003) evaluated the bedrock depths encountered in 3,579 boreholes scattered

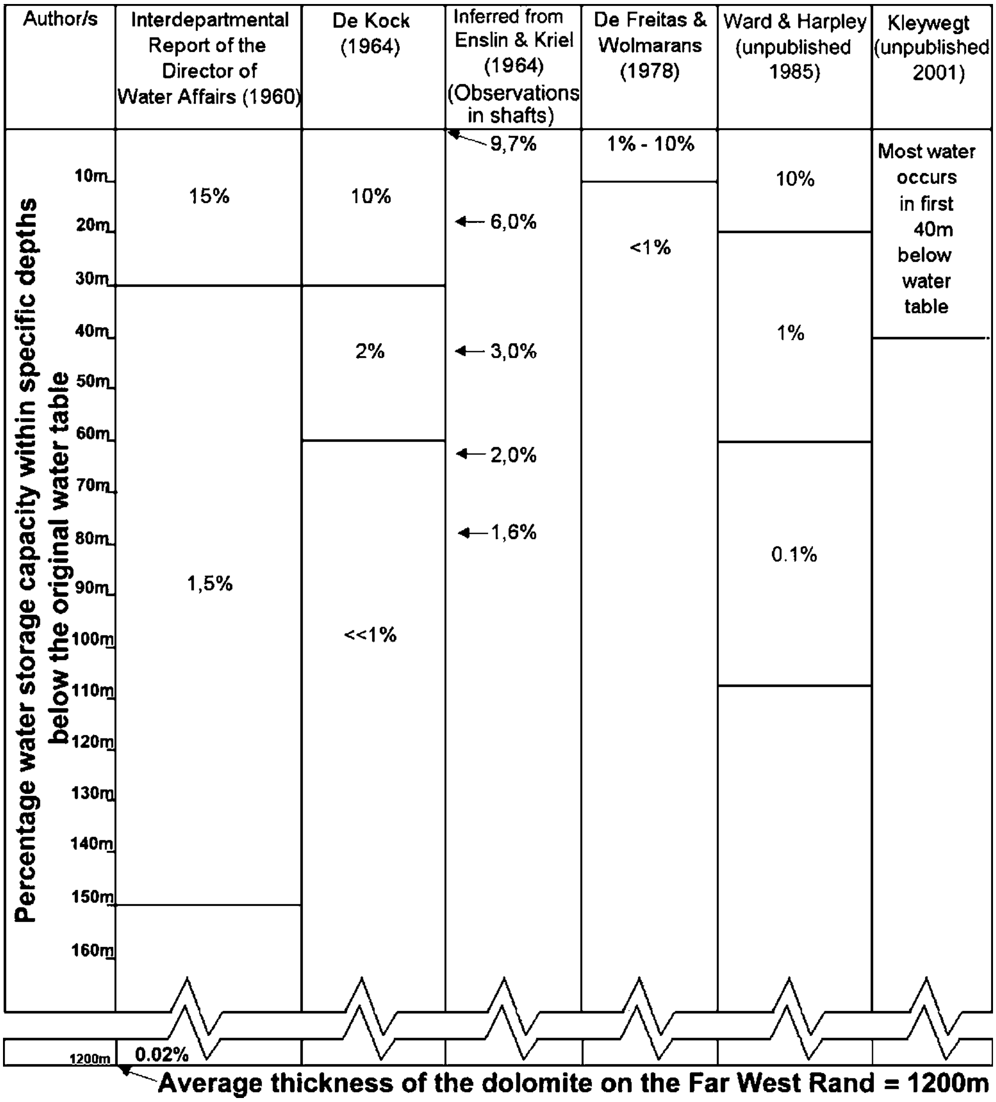


Table 3
Comparison of water storage capacities of the dolomite according to various authors between 1960 and 2001

over the dolomite outcrop area of the Venterspost, Bank and Oberholzer Compartments. It was found that, on average, the bedrock in the Venterspost Compartment is 14 m below the original water table, that of the Bank Compartment 0.5 m below the original water table, whereas in the Oberholzer Compartment the average bedrock is 30 m above the original water table. In the latter compartment, the dolomite bedrock on the southern edge of the compartment rises to approximately 175 m above the original water table as compared to 140 m in the case of the adjacent Bank Compartment. The dolomite surface area of the Venterspost Compartment (54.38 km^2) is approximately a third of that of the Bank and Oberholzer Compartments (approximately 155 km^2 each). The following explains the storage capacity differential of the compartments listed above. The Venterspost Compartment, though its surface area is only a third of that of the Oberholzer Compartment, is weathered deeper relative to the pre-mining water table and therefore its storage capacity is two-thirds that of the Oberholzer Compartment. Brink (1975) expressed reservations whether the Bank Compartment's storage capacity could be as high as 2 million Ml, as calculated by Schwartz and Midgley (1975).

The effect of crustal stresses and thick Pretoria Group strata covering the dolomite on the geohydrology

Inflow into the mines from the overlying dolomitic aquifer is a function of the hydrostatic head and the transmissivity of the post-Transvaal faults within the fractured rock aquifer (Director of Water Affairs 1960; Fig. 4).
Transmissivity on the Far West Rand in turn, is influenced by differential tectonic crustal stresses that manifest as approximately 8-km-wide alternating compression (several post-Transvaal faults tightly cemented with mylonite) and tension zones (mostly post-Transvaal faults filled with clay and loose brecciated material; Wolmarans and Guise-Brown 1978). These geological features govern the rate of flow into the mine and determine whether a mine remained relatively "dry" or became "wet." There is thus a resistance to flow through the fractured rock aquifer which is eased when in a tension zone. In that case, a steady copious flow of water percolates through the fractured rock aquifer, which necessitates dewatering to allow safe and economic mining.

Table 4
The range of recharge values for some compartments drawn from the literature and pumping figures supplied by some of the mines

Compartment	Pre-mining spring flow ascribed to the recharge of the compartment Enslin and Kriel 1959	Calculated recharge if contribution of upstream spring is removed Director of Water Affairs (unpublished 1960)	Recharge based on the mean annual precipitation Enslin and Kriel 1967	Current mine pumping[1] (with 1 m pipeline installed to reduce recharge) Mahlangu and Ransuchit (unpublished data 2001)
Venterspost	20.9 Ml/day		15 Ml/day	28 Ml/day
Bank	49.1 Ml/day	39 Ml/day		41 Ml/day
Oberholzer	54.1 Ml/day	31 Ml/day		25 Ml/day

[1] excludes consumptive use and evaporation losses

The location of alternating tension and compression zones, which were observed only within specific mine boundaries, is illustrated in Fig. 3. From east to west they occur as follows:

- In the Western Gemsbokfontein Compartment, the Western Areas Limited Gold Mine being in a tension zone is a wet mine and had to implement dewatering.
- In the Venterspost Compartment, Venterspost Gold Mine is in a tension zone which necessitated dewatering of that compartment. The northeastern half of Libanon Gold Mine is in a compression zone.
- In the Bank Compartment, the southwestern half of the Libanon Gold Mine is in a compression zone and the eastern extremity of the West Driefontein Gold Mine is in a tension zone. The Bank Compartment had to be dewatered after a major inrush of water in 1968. The Harvie Watt Shaft of Libanon Gold Mine (Fig. 3) is pumping 7 Ml/day rendering the area surrounding the shaft moderately dewatered. Wolmarans and Guise-Brown (1978) did not classify East Driefontein Gold Mine to be located within a tension/compression zone as it was still a relatively new mine at the time.
- In the Oberholzer Compartment, West Driefontein and the Blyvooruitzicht Gold Mines fall within a tension zone and, as a result, are wet mines which required the dewatering of the Oberholzer Compartment. However, comparing the numerical values of the pumping per unit-area-mined of these two mines in 1960, indicates that the transmissivity of the rock strata above the West Driefontein Gold Mine is about six times higher than that of the geological succession above Blyvooruitzicht's mine. At that stage virtually all mining in West Driefontein Gold Mine took place within the central parts of a tension zone traversing the Oberholzer Compartment. Blyvooruitzicht Gold Mine is off the center of the tension zone. It was concluded that permeability appears to attain a maximum over the central portion of a tension zone.
- Within the Boskop-Turffontein Compartment, the Doornfontein Gold Mine is in a compression zone, and is consequently a dry mine. The Boskop-Turffontein Compartment is thus not dewatered.

Where a thick (>150-m) succession of Pretoria Group sediments covers the dolomites above the point where the Witwatersrand gold reefs suboutcrop against the Black Reef at the base of the dolomite, the resultant deep dolomite is protected from weathering and is therefore logically not a Pretoria unshielded dolomite. The reduced water storage capacity of such an under-developed dolomite aquifer renders the underlying mine relatively dry even if the mine is in a tension zone.

The effect of wedges of Ventersdorp Supergroup lava on the geohydrology

The lava wedges tend to restrict the inflow of water into the mines as a consequence of fractures that are tighter than those within the dolomite, or in the Witwatersrand Supergroup. In Fig. 4, the wedge of Ventersdorp Supergroup lava separating the dolomite from the Witwatersrand Supergroup is shown in green. The wedge which within the gold mines attains the greatest thickness in the Bank Compartment, increases vertically from 0 m at the suboutcrop of the Ventersdorp Contact (gold) Reef to approximately 2,000 m at the southeastern corner of East Driefontein and Kloof Gold Mines (Figs. 2 and 4; Engelbrecht and others 1986). On the mines where the lava wedge underlies Pretoria unshielded dolomite, the maximum thickness is only 1,200 m.

In the gold mines of the three eastern compartments under discussion, i.e. Western Gemsbokfontein, Venterspost and Bank, Pretoria unshielded dolomite is in most parts underlain by Ventersdorp Supergroup lava. This implies that Pretoria unshielded dolomite, within which the cavernous aquifer could be well-developed, is separated from the deeper lying mine by Ventersdorp Supergroup lava in gold mines such as Western Areas Limited, Venterspost, Libanon, the northern parts of East Driefontein and the southeastern extremity of that part of West Driefontein in the Bank Compartment (Fig. 2).

In the Oberholzer and Boskop-Turffontein Compartments, the lava wedge is almost absent within gold mines such as West Driefontein (that part of the mine which is in the Oberholzer Compartment), Blyvooruitzicht and Doornfontein Gold Mines (Fig. 2). In these mines the Witwatersrand Supergroup directly underlies the base of the Pretoria unshielded dolomite.

South Deep, Kloof, the southern part of East Driefontein, Western Deep Levels, Elandsrand and Deelkraal Gold Mines (Fig. 2), due to Pretoria shielding are dry mines as they are overlain by much less weathered dolomite. Amis (unpublished data 2003) estimates that Western Deep Levels Gold Mine will in future discard only approximately 0.5 Ml/day. Although a lava wedge is present in these mines, the dryness is mainly due to the thick Pretoria Group sediment cover, which restricted the development of the cavernous aquifer.

The following examples illustrate that the impact of the lava wedge is subordinate to the influence of the crustal stresses discussed in the section headed "Crustal stresses and the effect of thick Pretoria Group strata covering the dolomite":

- In 1943, the Venterspost Gold Mine, which is in a tension zone and where the lava wedge is present, experienced an inflow of approximately 7 Ml/day, whereas in 1956, when the West Driefontein Gold Mine (which was also mining in a tension zone but where the lava wedge is absent) had mined a similar area, the inflow was nearly seven times more, i.e., 45 Ml/day. According to Wolmarans (1984, personal communication 2001), this confirms that lava wedges retard the inflow of water. The geologic differences despite both mines being in tension zones, had to dewater.
- Doornfontein Gold Mine is in a compression zone (Fig. 3), and notwithstanding the lava wedge being absent it was never necessary to dewater the compartment (Boskop-Turffontein Compartment) of this mine.

Data gathered and observations made during mining which are considered relevant with respect to the rewatering scenario

The geohydrology of the cavernous aquifer

- Natural recharge: Accepting that intercompartmental flow through the dykes was negligible prior to mining, the long-term average spring flow is a reasonable estimate of the recharge rate of the compartments (Fig. 2). This view was expressed by the Inter-colonial Commission (1905). Subsequent efforts to estimate the nett recharge are documented[2]. Table 4 lists the current pumping rates in column 4. The difference in estimates between column 1 and columns 2, 3 and 4 in the table may be accounted for by the fact that the latter do not account for water entering the respective compartments via upstream sources (the upstream spring is dry and stream flow is diverted into the 1-m-diameter pipeline). Column 2 presents the pre-mining recharge, excluding water originating upstream of the Oberholzer and Bank Compartments.

The current volumes pumped from the individual mines as shown in Table 4, should also reflect the rate of recharge. When comparing columns 1 and 4 of Table 4, the pumping volume of the Venterspost Compartment (28 Ml/day) is approximately 33% higher than its pre-mining spring yield (21 Ml/day), while for the Oberholzer Compartment pumping (25 Ml/day) is about 116% lower than the compartment's original spring flow (54 Ml/day).

A larger disparity (744% higher) exists in the Western Gemsbokfontein Compartment, where the original spring yield of 9 Ml/day, is much lower than the current pumping volume, 67 Ml/day. According to Van Biljon (unpublished data 2001) the compartment appears to be in an intermediate stage of dewatering and he projects that the pumping will decline to 48 Ml/day at which time dynamic equilibrium will set in when the aquifer is considered dewatered. In an attempt to explain why the pumping rate of this compartment is so much higher than the yield of the pre-mining spring, Van Biljon sited, among others, the following two factors:

- Steep phreatic gradients, caused by dewatering allowing groundwater from surrounding non-dewatered compartments such as the Western Suurbekom and Eastern Gemsbokfontein Compartments, to leak into this compartment through the compartment's boundary dykes; and
- Re-circulation from surface streams into which pumped water was discharged. He further expects that after rewatering of the Western Gemsbokfontein Compartment has taken place, the yield at the Gemsbokfontein Spring will be a maximum of 17 Ml/day.

What contributes to the imbalance in all the dewatered compartments, by not being accounted for, is the loss of water via the mine ventilation system, as well as evaporation and seepage via the extensive tailings dams. Not all the water enters the mine from the dolomite aquifer nor does all the water leave via dewatering pumps[3]. Currently, the volume of water bought from the water authorities (Rand Water) by East Driefontein and West Driefontein Gold Mines, amounts to 9 Ml/day. This artificial water gain by the two mines is coincidentally nearly offset by 8 Ml/day of water loss through ventilation shafts plus 3 Ml/day evaporation from tailings dams (Ransuchit, personal communication 2003).

Although further investigation is required to solve the problems raised in this subsection, Table 4 demonstrates that the aggregate of column 1 (124 Ml/day) compares favourably with the sum of the average flow entering the

---

[2] Inter-colonial Commission (1905), Enslin (1967) and Hodgson and others (2001) assumed the pre-mining yield of the spring of a compartment to be equivalent to the recharge of that compartment. This convention was also adopted in this paper.

[3] Some pumped water re-enters the underground as mine service water, water also leaves the mine through evaporation via the ventilation shafts and tailings dams. Neither volume has been measured on a continuous and regional basis, consequently aquifer draw-down was, estimated from volume pumped minus natural recharge, assumed to be equivalent to the pre-mining spring flow.

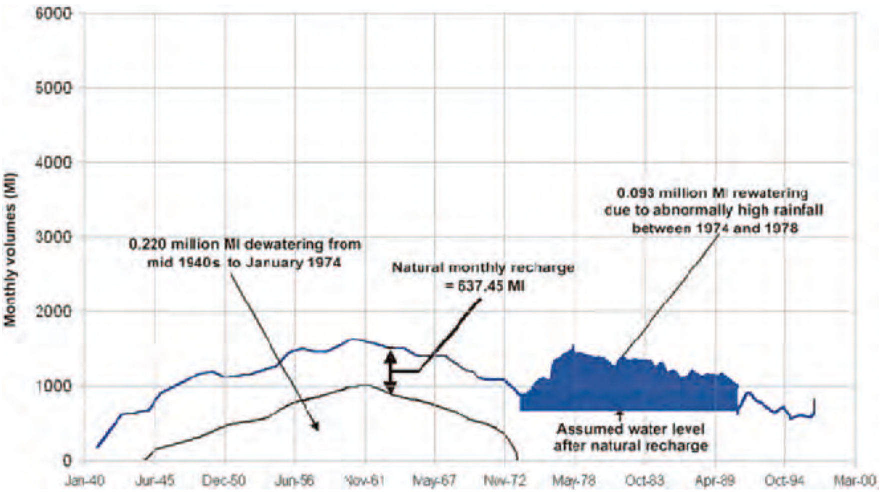


Fig. 5
Venterspost Compartment—Water balance (pumping vs. natural recharge)

1-m-pipeline (Fig. 3) from Donaldson Dam (approximately 30 Ml/day) and the aggregate of column 4 (94 Ml/day). This would suggest that the pumping volumes and the spring yields uphold one another on a regional scale. This allows the use, with a greater measure of confidence, of the pre-mining spring flows as the recharge volumes of the respective compartments.

- The estimated nett dewatered volumes (differences between the pre-mining aquifer storage volume and the current volume stored) of the compartments: This, in the example of the Venterspost Compartment, was calculated by subtracting the historic recharge, being the average long-term pre-mining spring flow, from the volume pumped, for the period of the mid-1940s to January 1974 (Fig. 5). Table 5 lists the dolomite dewatering volumes of the Western Gemsbokfontein, Venterspost, Bank and Oberholzer Compartments. The locations of the dewatering mine shafts (Table 5, column 5) are indicated in Fig. 3.
- Compartments are only partially dewatered: The seventh column of Table 5 shows the combined aquifer draw-down of the Venterspost, Bank and Oberholzer Compartments to be approximately 0.90 million Ml. The 0.90 million Ml represents approximately a quarter of the 3.5 million Ml as referred to in the section headed "Storativity." The practical implication is, therefore, that only partial dewatering of a portion of the dolomitic aquifers in question has taken place.
- An example of temporary, partial rewatering: Earlier in this section it was pointed out that for the Venterspost, Bank and Oberholzer Compartments, the present fairly consistent pumping rates appear to tend to a volume equivalent to their combined pre-mining spring yield which in turn is assumed to reflect the recharge rate, as "what flows in must be pumped out, or the mine would progressively flood." This thesis is supported by the lowered water tables. This trend is reversed during high rainfall periods where the water table rises in concert with increased pumping by the mine. Between 1974 and 1978 abnormally high rainfall in the Venterspost Compartment resulted in a significant rise of the water table (Fig. 5), which rose rapidly by more than 62 m, from 118 m below pre-mining elevation in February 1974, to 55.7 m below pre-mining elevation in July 1977. According to Beukes (1987), the water level below the Lower Wonderfontein Spruit in the Venterspost Compartment peaked at 10 m below the pre-mining water table in early 1978. Beukes (1987) estimated the recharge (rewatering) of the Venterspost Compartment during the exceptionally wet seasons in the 1970s at 0.05 million Ml, which is approximately 50% of the 0.093 million Ml reported in Table 5. From this observation it should be noted that any prediction as to how long it would take to rewater after mining ceased may be considerably "shortened" by extreme and unexpected flood events.
- The anticipated post-mining recharge rate of the compartments: Due to the multitude of sinkholes capable of accepting surface storm flow, particularly in the streambed of the Lower Wonderfontein Spruit (Swart and others 2003), the post-mining rate of recharge is expected to exceed that of the pre-mining period (Table 6).

Groundwater flow down the fractured rock aquifer

- Where mining takes place in tension zones and underlying Pretoria unshielded dolomite water inflow generally increases as mining progresses: In the early stages of mining, the inflow of water into the mine via the fractured rock aquifer generally increased in relation to the stope area developed, as progressively more water- bearing fractures were intersected. A direct relationship between "area mined" and "water inflow" was noted and documented by several observers namely:

  - Louw (unpublished data 1960) on the West Driefontein Gold Mine in the eastern Oberholzer Compartment
  - Irving (unpublished data 1960) on the Blyvooruitzicht Gold Mine in the western Oberholzer Compartment

Table 5
Data used for establishing crude dewatering and re-watering volumes in the Western Gemsbokfontein, Venterspost, Bank and Oberholzer Dolomitic Compartments

Dolomitic Compartment	Surface area (km^2)	Total dolomite aquifer capacity (10^6 MI)[a]	Estimated volume of mine void	Yield of original spring[b]	Date dewatering commenced	Shafts from which dewatering is effected	Dolomite dewatered volume (10^6 MI)	Percentage dewatered	Expected recharge time after mine void had been flooded assuming recharge = figures in column 4	Volume recharged by the 1970s higher than normal rainfall (10^6 MI)
Gemsbokfontein	115.37	–	0.7×10^6 MI	8.64	Mid-1986	No. 4 ShaftWAL	0.087[c] 0.240[d]	–	6.5 years[c]	Not known
Venterspost	54.38[b]	0.46		20,90	1947	No. 1 Shaft Venterspost	0.220	48%	16 years if normal rain 10 >years if higher than normal rain	0.093
Bank	156.69[b]	2.0		49,10	Mid-1969	North Shaft West Driefontein	0.227	16%	18 years	0.092
					1985	Harvie Watt Shaft Libanon	0.046 BankTotal = 0.323			
Oberholzer	153.85[b]	1.05		54,1	1957	No. 2 Shaft West Driefontein	0.303	34%	18 years	Not known
					1964	No. 1 Shaft Blyvooruitzicht	0.053 Oberholzer Total = 0.356			

[a] Vegter (1987)
[b] Enslin and Kriel (1967)
[c] Van Biljon (unpublished data 2001)
[d] Swart (unpublished data 2001)

Table 6
Inflow to mine in the different compartments

Mine	Compartment	Influx from Dolomite Aquifer (Ml/day)
Venterspost	Venterspost	28
Libanon and	Bank	7
West Driefontein		34
West Driefontein	Oberholzer	20
and Blyvooruitzicht		5
Doornfontein	Boskop-Turffontein	8

  - Enslin and others (1976) on the Western Areas Limited Gold Mine in the Western Gemsbokfontein Compartment
  - Wolmarans (1984) on the Venterspost Gold Mine in the Venterspost Compartment and that part of the West Driefontein Gold Mine in the Oberholzer Compartment.

- A major inrush of water into the mine in a non-dewatered compartment: West Driefontein Gold Mine tunneled through the Bank Dyke from the Oberholzer Compartment into the virgin rock of the Bank Compartment during the early 1960s. Stoping (excavating reef) within the southwestern part of the Bank Compartment commenced during 1964. An unprecedented inrush of 360 Ml/day into the mine occurred on 26 October 1968, when water broke through the thin wedge of Ventersdorp Supergroup lava along what is termed a "décollement zone" connecting the Bank Compartment dolomite with the mine (Wolmarans 1986; Fig. 2). The inrush occurred near West Driefontein No. 4 Shaft and continued for the 24 days that it took to construct two watertight concrete plugs to isolate No. 4 Shaft from the inrush area (Taute and Tress 1971; Fig. 2). The Bank Spring gurgled to a stop within a few days after the inrush. As a result of the dramatic inrush, it was decided to dewater the Bank Compartment as well.
- The permeability (transmissivity) of the fractured rock aquifer: This factor will initially determine the rate at which water will report at the mine, which will, in turn, ultimately influence the degree of intercompartmental flux through the mined-through dyke. In this paper, estimates of permeability are derived for a part of the central portion of the Oberholzer Compartment, as this is an area for which appropriate data exist. Regional geological considerations, coupled with patterns of water inflow into the mines, indicate that, with the exception of the uncharacteristic groundwater inrush that took place in the Bank Compartment in 1968, the estimated permeability of this central portion of the Oberholzer Compartment is higher than the average of the other dewatered compartments. It thus follows that if the higher rate of inflow derived from this estimate is applied to the full extent of the dewatered Oberholzer Compartment, the estimate will fall within the upper bound (conservative) limit (Kleywegt and Swart, unpublished data 2002).

  When determining the permeability of the Bank Compartment, the higher permeability (transmissivity) derived for the Oberholzer Compartment was added to the yield of the fracture through which the inrush into the Bank Compartment in 1968 occurred. This approach is considered conservative as it over-compensates for possible future unexpected higher permeabilities.

  Whereas the infiltration into the Oberholzer Compartment is diffused throughout the mined-out area, the inrush experienced in the Bank Compartment in 1968 was down a single large fracture, which still produces approximately 30 Ml/day. No similar fractures that produced as great an inrush have been encountered.
- A conservative estimate of what the pumping rate of the Oberholzer Compartment would have been today if no dewatering had taken place and recharge was sufficient, is derived as follows: By April 1960, when the West Driefontein Gold Mine mined[4] only 194 ha and the water table had dropped relatively little, the pumping rate had reached 92 Ml/day. The respective figures for the Blyvooruitzicht Gold Mine were 715 ha mined, with approximately 60 Ml/day re-circulated. The water table at the re-circulating Blyvooruitzicht shaft remained close to its pre-mining elevation, as the hydraulic head at the suboutcrop had only dropped by 4%. The Blyvooruitzicht and West Driefontein Gold Mines have now almost mined out their entire lease areas: approximately 3,500 ha in the Oberholzer Compartment, which is 18 times larger than the area mined out by West Driefontein by 1960. To arrive at a conservative estimate of what the pumping rate of a non-dewatered Oberholzer Compartment would have been today, the rate of inflow (92 Ml/day) into West Driefontein Gold Mine in 1960 is multiplied by 18 which gives approximately 1,650 Ml/day.

The size of the total mine void and the intercompartmental dykes punctured by it

The mine void will become an artificial aquifer with a significant water storage capacity below the dolomite aquifer: The volume of the mined out areas can be estimated from the mass of rock hoisted by them. This additional artificial volume, which currently stands at 0.6 million Ml (600 million m^3 for the Far West Rand), needs to be taken into consideration when calculating the time that it will take to restore the water tables of the affected compartments (Hodgson and others 2001). Mining has therefore amplified the capacity of the compartments by excavating extensive, deeper-lying connections—haulages and stopes—in the rock beneath the dolomite. Some dykes (aquicludes between compartments) were transected by haulage tunnels, and to a lesser extent by stoping operations, thereby connecting previously unconnected compartments. Figure 2 illustrates the current position with respect to the dykes having been

---

[4] In 1960, Blyvooruitzicht Mine, also in the Oberholzer Compartment, was merely re-circulating pumped water.

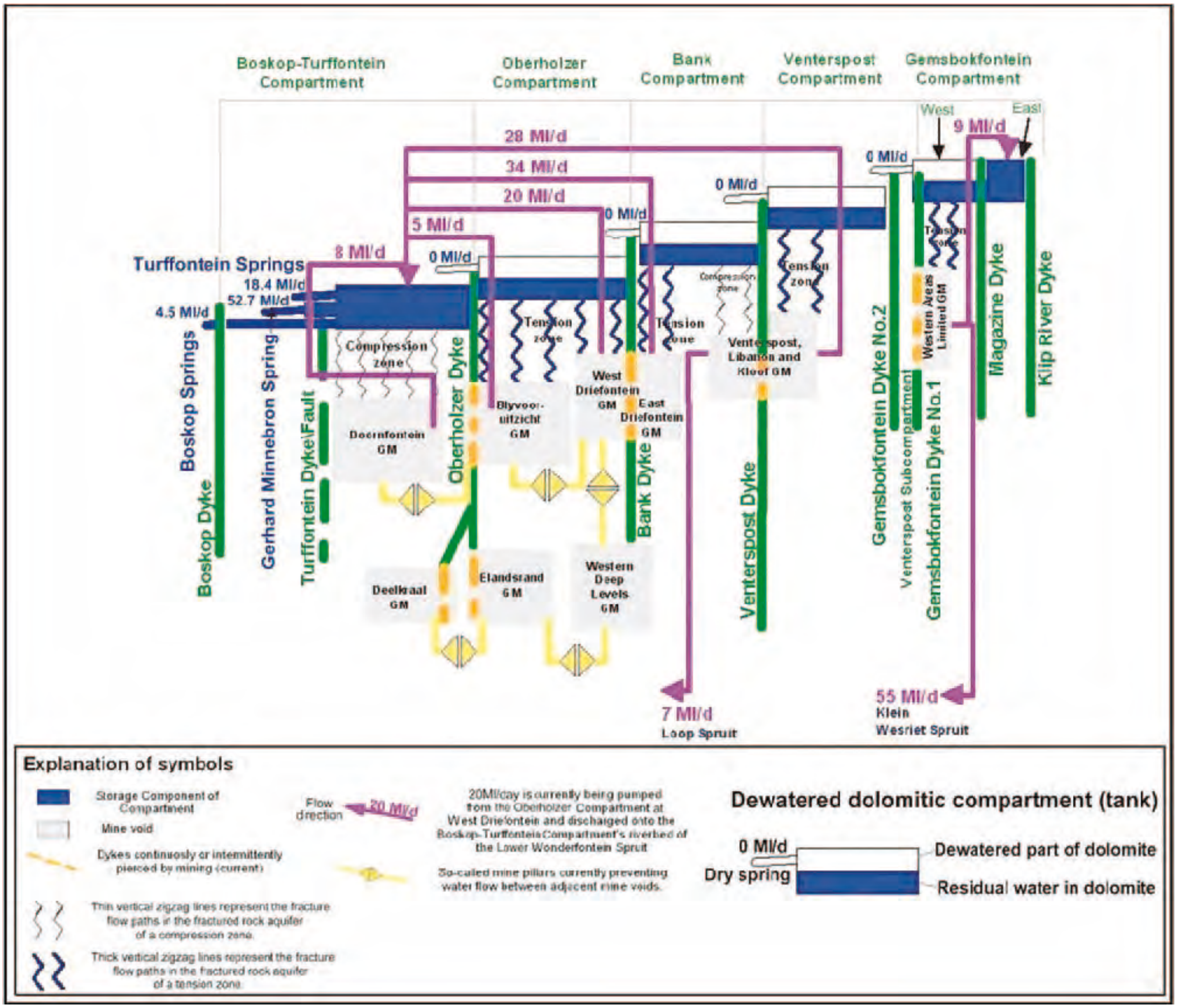


Fig. 6
Cross section of mines and dolomitic compartments showing current water volumes (during mining) being pumped and spring yields

pierced by intermittent thoroughfares (unpublished data, shareholders documents, or mining progress reports, of the various mines 1997).

A schematic representation of the current geohydrology

Based on the information presented in the previous sections, a model was constructed to predict the inter-compartmental flow of the post-mining era. Figure 6, as a diagram of the current Far West Rand dolomitic and mine water flow, provides the basis for the model. Figure 7 amplifies Fig. 6. The storage capacity of the dolomite compartments is represented by a series of tanks. The blue/white tanks represent compartments that have been dewatered, with full blue, indicating the compartments not being dewatered. As the fractured rock aquifer below a compartment presents resistance to flow, it is represented by vertical zigzag blue lines connecting the tank to the mine(s) indicated by gray squares at the base of Fig. 6. Fracture flow resistance varies according to the nature of the conduits with the result that the collective resistance to flow within the fractured rock aquifer will be restricted within a compressive zone. Fractures in compression zones (high resistance) are therefore indicated by thin zigzag blue lines, whereas those in tensional zones (lower resistance) are indicated by thicker zigzag lines (Fig. 6).

Relatively large volumes of water have and are still being removed from the four dewatered compartments, with rainfall being the primary recharge source. Recharge from streamflow in the Lower Wonderfontein Spruit is reduced by a 1-m-pipe which acts as a stream diversion (Fig. 3). On rewatering, water will initially fill the mines, decanting into adjacent compartments where the mine workings transect the dykes (Fig. 6, broken brown lines). Presently not all the dykes have been punctured by mining (Fig. 2). However, this situation is subject to change.

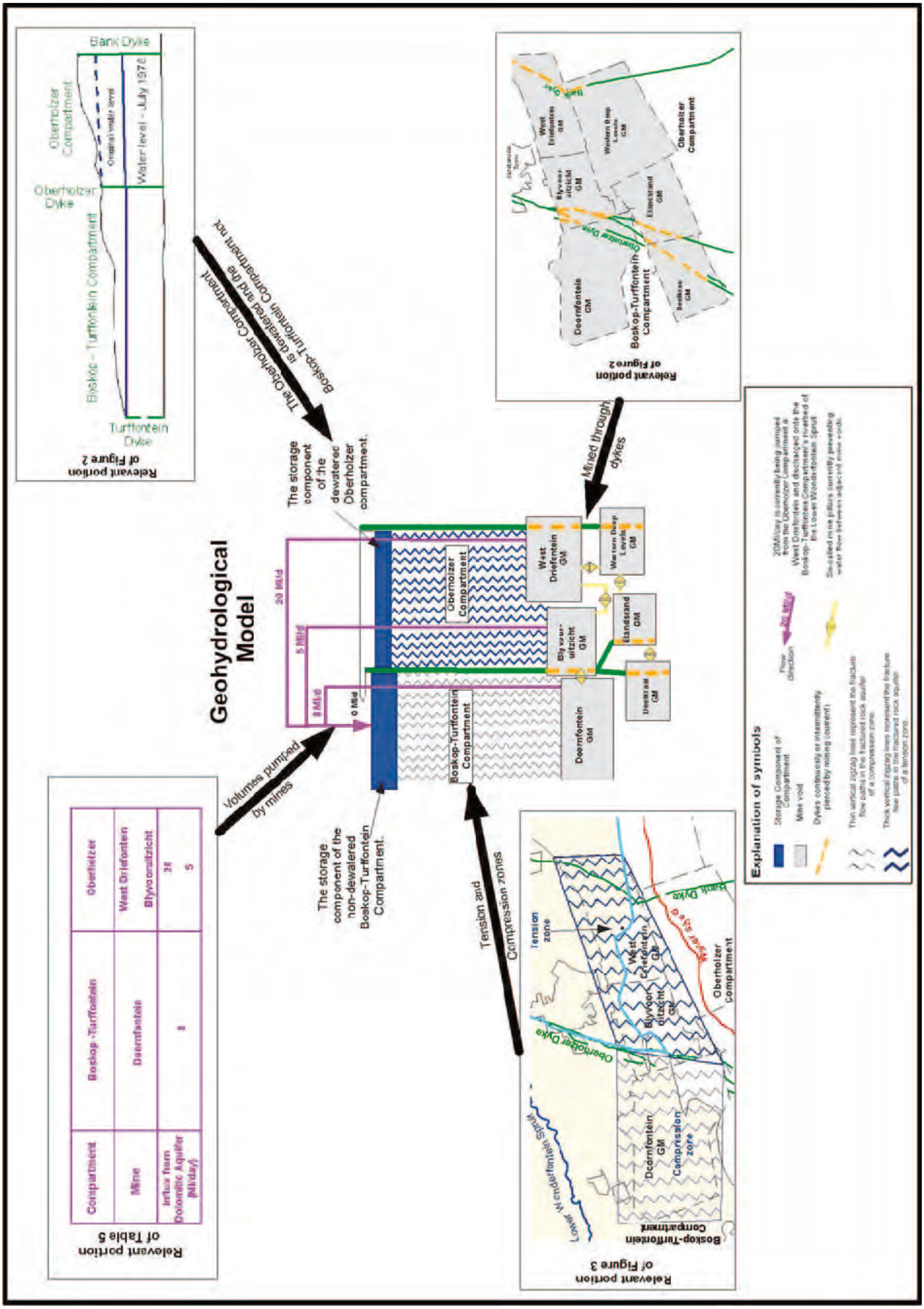


Fig. 7
An illustration using the Boskop-Turffontein and Oberholzer Compartment area as an example to show how information in Table 5, Figs. 2 and 3 was converted into symbols used in the Fig. 6 diagram

A first approximation geohydrological model to estimate post-mining intercompartmental flux, e.g. predicted flux through the mined-through Bank Dyke

To arrive at an estimate of the intercompartmental flow that will prevail in the post-mining period, loosely referred to as the model, some parameters derived from information presented in Fig. 6 as well as from the accumulated historical data were integrated. For reasons of simplicity, the model projects a situation that could prevail should all pumping cease simultaneously. It is anticipated that the following sequence of events will apply (some of the support thereto will be provided in the next section). Initially, the mines will flood, followed by a rapid rise of the water table through the fractured rock aquifer before the dewatered cavernous aquifer is recharged. The rise of water through the dewatered cavernous aquifer will be much slower than through the fractured rock aquifer. Some adjacent mines are separated by "mine pillars" (yellow lines with arrowheads in Fig. 6). These pillars could in the long-term collapse due to the superincumbent surcharge and periodic seismic events. The increase in hydrostatic head, as rewatering progresses, may also result in them becoming permeable. The view that is advanced in this paper suggests that a dynamic equilibrium will ultimately be reached in each compartment at water levels consistent with the historic levels. The head across adjoining compartments should, despite the dykes pierced at mine level, be maintained at the historic elevation differentials of about 35 m. The restoration of the historic heads would result in the rejuvenation of the natural springs of the Lower Wonderfontein Spruit.

Figure 6 is the forerunner of the model which will be employed to estimate the volume of intercompartmental flux in the post-mining area. If the post-mining intercompartmental flux is less than the recharge of that compartment, the relevant spring will flow again. The model is based on calculations which assume that Darcy's law for saturated flow through a porous medium will apply to a fractured rock aquifer, shown as vertical zigzag lines (conduits) in Fig. 6. The smaller the calculated flux, the greater the possibility that the springs will flow again. Assuming that the water level of an upper (eastern) compartment will be higher than the adjacent lower (western) compartment, the hydraulic head will drive water down the upper compartment (downward leg) through the "horizontal" mine void and pierced dyke and then up the lower compartment (upward leg). The upward leg is thus the downslope (lower) compartment where water will flow from the mine upwards to recharge the cavernous aquifer of that compartment. According to James (unpublished, 2003), it is appropriate to assume an effective permeability k for the fractured rock aquifer as a single layer. This postulation allows the flux through a mined-through dyke to be approximated by Eq. (1).

$$Q = \frac{\Delta h}{\sum_{i=1}^{n} \frac{l_i}{k_i A_i}} = \frac{\Delta h}{\frac{l_1}{k_1.A_1} + \frac{l_2}{k_2.A_2} + \frac{l_3}{k_3.A_3}} \tag{1}$$

where:

Q = Total flux passing through the mined-through dyke (Ml/day or m^3/s)
l_i = Flow path length across the ith porous media (m)
A_i = Area of cross-section of flow path (m^2)
k_i = Effective permeability of the fractured media (m/s)
k_1 = Downward leg
k_2 = Flow through mine connecting compartments
k_3 = Upward leg
Δh = The elevation difference between the water tables of the adjacent compartments (m).

The second term in the denominator can be ignored as the permeability of the mine excavations (k_2) will be high relative to the fractured rock aquifers (k_1 and k_3).

Before Eq. (1) can be used to calculate the intercompartmental flux through the mined-through Bank Dyke in the post-mining era, it is necessary to determine values for the terms $\frac{l_1}{k_1.A_1}$ (the downward leg in the Bank Compartment) and $\frac{l_3}{k_3.A_3}$(the upward leg in the Oberholzer Compartment). These terms give a reasonable indication of the hydraulic resistance of the fractured rock aquifer represented by zigzag lines in Fig. 6.

The hydraulic resistance of the Oberholzer Compartment (upward leg in this example) was determined first. Use was made of some of the data/conclusions discussed in the section headed "Data gathered and observations made during mining which are considered relevant in respect of the rewatering scenario", where it was, for instance, explained that:

- Data from the central portion of a tension zone over the Oberholzer Compartment were extrapolated to areas where the relatively lower values of a compression zone may apply, in support of predictions which are conservative. A "flow" of 1,650 Ml/day was calculated.
- The vertical distance between the pre-mining water table and the sink of the dewatering cone at West Driefontein Gold Mine's No. 2 Shaft (a dewatering shaft) (Fig. 3; Table 5 column 6) is approximately 1,000 m, where Q' is the volume of water per unit time that would flow into the "fully mined-out" void of the Oberholzer Compartment when the water table is back at its pre-mining elevation and $\Delta h'$is the vertical distance between the pre-mining water table and the suboutcrop (or lowest point (sink) of the dewatering cone) in the Oberholzer Compartment, in the following equation:

$$\frac{\Delta h'}{Q'} = \frac{l_3}{k_3.A_3} \tag{2}$$

The same hydraulic resistance was applied to the downward leg (in the Bank Compartment) as the mined-out area of the Bank Compartment is comparable to that of the Oberholzer Compartment (3,300 vs. 3,500 ha). Owing to a thick Pretoria Group cover, future mining in the Bank Compartment would not cause additional inflow. The conservative approach is to allow for the largest possible flow across the mined-through Bank Dyke; the 360 Ml/day inrush that occurred in the Bank Compartment in 1968, is added to the *Q'*-value obtained for the Oberholzer Compartment, when calculating the potential flux through the mined-through Bank Dyke.

This will represent a first order estimate of the maximum post-mining flux. Additional reasons why the potential flow through the upward and downward legs used represent conservative values (probable over estimates) are:

- Initial mining took place near the suboutcrop in these compartments. Due to the proximity of the mining operations to the base of the dolomite, inflow into a mine was generally higher than further down-dip along the reef horizon.

  In calculating the *k*-value of the Oberholzer Compartment in West Driefontein Gold Mine, the permeability further down-dip, although generally lower, was assumed to be the same as at the suboutcrop.
- In the area of the suboutcrop of important gold reefs in the Blyvooruitzicht Gold Mine and the West Driefontein Gold Mine in the Oberholzer Compartment, the Ventersdorp Supergroup lavas, which vertically separate the base of the dolomitic succession from the gold-bearing reefs below, are absent. This is not the case in the Bank Compartment where fractures within the lava are relatively tight and tend to hamper the penetration of water into the mine workings. Nevertheless, the *k*-value of the "lava wedge devoid" geological succession at West Driefontein Gold Mine in the Oberholzer Compartment, was applied to the Bank Compartment as well.
- In the Oberholzer Compartment the higher transmissivity of West Driefontein Gold Mine in 1960, when operations of this mine were confined to the central portion of a tension zone, was also applied over the Blyvooruitzicht Gold Mine despite it being situated off the center of the tension zone.

The head ($\Delta h'$) is the height of the pre-mining water table above the suboutcrop which is approximately 1,000 m.[5]

As $\Delta h''$and Q' are effectively known, $\frac{l_3}{k_3.A_3}$for the upward leg (Oberholzer Compartment) can be solved.

$$\frac{l_3}{k_3.A_3}=\frac{\Delta h'}{Q'}=\frac{1000m}{1650Ml/d}=\frac{1000m}{19m^3/s}=52s/m^2\left(\text{which is}\,\frac{1}{transmissivity}\right)$$

Having calibrated the model, it is now possible to apply the model to provide first order estimates of the flux arriving in the cavernous aquifer at the top end of the upward leg in the Oberholzer Compartment.

It follows that: $\frac{l_1}{k_1.A_1}$ for the downward leg (Bank Compartment), where the pre-mining water table is 800 m above the sink, is

$$\frac{\Delta h'(Bank)}{Q'(Oberholzer)+360(volume\ of\ the\ inrush\ in\ 1968)}=\frac{800m}{1650+360}=\frac{800m}{2010Ml/d}=\frac{800m}{23m^{3/s}}=35s/m^3$$

The calculated values for $\frac{l_1}{k_1.A_1}$ and $\frac{l_3}{k_3.A_3}$ can now be used in Eq. (1) to calculate the potential flux through the Bank Dyke:

$$\text{Flux}=Q=\frac{\Delta h}{\frac{l_1}{k_1.A_1}+\frac{l_2}{k_2.A_2}+\frac{l_3}{k_3.A_3}}=\frac{35\ \text{m}}{52\text{s/m}^2+0+35\text{s/m}^2}=\frac{35\ \text{m}}{87\text{s/m}^2}=0.4\text{m}^2/\text{s}=35\text{M1/day}$$

where: Q is the potential intercompartmental flux through the mined-through Bank Dyke and Δh is the difference in elevation of the pre-mining water tables either side of the Bank Dyke.

The value of 35 Ml/day calculated above should be compared with the pre-mining discharge (Table 4, column 1) from the spring of that compartment (Bank Compartment in this case). The potential intercompartmental flux (35 Ml/day) being less than the average recharge rate of the Bank Compartment (49 Ml/day) suggests that after the mine in the Bank and Oberholzer Compartments had been flooded, the water table in the Bank Compartment will rise until eventually the Bank Spring will flow again; although owing to the very conservative calculations by Kleywegt and Swart (unpublished data 2002), its average discharge will be only 30% of the pre-mining volume.

However, recharge from the Wonderfontein Spruit will probably be higher if the flow in the 1-m-pipe conveying water over the compartments is removed and this water is allowed to enter the compartments as potential recharge—mainly through sinkholes, subsidence-related ground cracks, etc. Accelerated recharge, compared to the pre-mining period, will take place if storm water is allowed to enter the sinkholes. It may therefore be concluded, based on this first approximation, that the pre-mining water levels will once again be re-established. Table 4, columns 2 and 4, also provides lower bound values when no water flows in from higher up the Lower Wonderfontein Spruit for recharge of the Bank Compartment, i.e. 39 and 41 Ml/day. The latter values are very close to the flux (Q) calculated above (35 Ml/day). This scenario suggests that the Bank Spring could be near-stagnant during long dry spells.

The following explains how the post-mining period compares to the pre-mining period. Recharge of the dolomite from the Lower Wonderfontein Spruit will initially be

---

[5] The vertical distance between the pre-mining water table and the sink of the dewatering cone at West Driefontein Gold Mine's No. 2 Shaft (a dewatering shaft) (Fig. 3, Table 5 column 6) is approximately 1,000 m.

higher than during the pre-mining period, due to sinkholes and ground surface cracks which allow a significant increase in the rate of recharge. New sinkholes forming during rewatering will aid this process temporarily. The recharge may later decrease as the sinkholes become choked with silt and other erodible detritus. Increased urbanization will significantly increase runoff, causing over-saturation of waterlogged areas. This higher infiltration will increase recharge.

In pre-mining times, water flowed down the Lower Wonderfontein Spruit and did not trigger any problematic sinkholes. It is thus suspected that, well after the rewatering phase, stability to the riverbed would ultimately return. However this needs to be investigated in follow-up studies.

Factors hitherto not fully evaluated and that may increase the transmissivity of the fractured rock aquifer thereby causing the intercompartmental flux to be higher than that estimated above, include the following:

- The hydraulic conductivity in the zone immediately above the mine may increase with time as a result of subsidence and an increase in the number of fractures.
- In areas where the top of the dolomitic bedrock is lower than the pre-mining water table, exploration boreholes, which were not sealed at their intersection with the Black Reef Formation, may serve as conduits between the newly replenished cavernous aquifer and the mine void. Areas where the cement lining of that part of the shaft barrel that runs through the dolomite are deficient or damaged, may also increase flow towards the mine void.

Time to reach final elevation

Assuming a recharge rate to be that of the pre-mining spring flow, a conservative (longer) estimate, subsequent to the flooding of the mine, is that the cavernous aquifer will fill in less than 20 years (Table 5, column 9). Thus given a normal rainfall distribution, the pre-mining water levels will re-establish within 30 years from cessation of pumping (Table 5).

The time required to completely rewater will, however, depend to a large extent on periods of high rainfall and the associated flood events. This qualification is supported by mine pumping data that show dramatic increased pumping rates corresponding with wet cycles (Fig. 5).

The major rewatering impact will, initially, be in the Venterspost Compartment, which is the highest of the succession of dewatered compartments that has large, unfilled sinkholes along the riverbed. The catchment area of the Venterspost Compartment is effectively four times larger than the surface area of the compartment as it covers the entire Upper Wonderfontein Spruit's catchment. Many sinkholes occur in the riverbed of the Venterspost Compartment, which is not the case with the Western Gemsbokfontein Compartment which is immediately upstream of the former. The corresponding ratios (catchment area: compartment area) for the Bank and Oberholzer Compartments are approximately 1:1. Thus, initially, the Upper Wonderfontein Spruit flow will be attenuated by losses into the Venterspost Compartment. Recharge of the Bank Compartment, will accelerate after the Venterspost Compartment has filled. After the Bank Compartment has filled, the recharge rate of the Oberholzer Compartment from the surface fed by spring water will improve.

Expected post-mining intercompartmental flux from east to west in the study area starting at the Gemsbokfontein Dyke

Through the Gemsbokfontein No. 2 Dyke

Owing to the fact that the Gemsbokfontein No. 2 Dyke is not mined through and provided it remains intact in the future, no intercompartmental flux from the Western Gemsbokfontein Compartment via the Venterspost Subcompartment (the Gemsbokfontein No. 1 Dyke is mined through) towards the Venterspost Compartment would be possible (Fig. 2).

Through the Venterspost Dyke

The Libanon and Kloof Gold Mines mined through the Venterspost Dyke (Fig. 2); however, further north the dyke is intact in the Venterspost Gold Mine. Intercompartmental flux between the Venterspost and Bank Compartments through the Venterspost Dyke where it is pierced by the Libanon and Kloof Gold Mines, will be small due to the upward leg represented by the eastern Bank Compartment being relatively impermeable for the following reasons:

- A compression zone is situated over that part of the Libanon Gold Mine in the Bank Compartment (Wolmarans and Guise-Brown 1978; Figs. 2 and 6)
- The dolomite above the point where Kloof Gold Mine pierced the Venterspost Dyke is being protected from weathering by the overlying Pretoria Group sediments.

Here, and in a later subsection headed "Through the Oberholzer Dyke" a more realistic approach with respect to determining the degree of potential intercompartmental flux was adopted. This is in contrast to the conservative approach where flux through the Bank Dyke was calculated earlier in this paper. The reason is that a critical portion of the mined-through Bank Dyke is flanked on either side by tension zones which renders the potential intercompartmental flux through the Bank Dyke more probable than through any other mined-through dyke in the study area. Should, therefore, the very conservative calculations involving the future of the Bank Spring indicate that this spring will resume flow, i.e., intercompartmental flux will not exceed natural recharge, then the other three dried springs will, as a corollary, also flow again.

It is therefore expected that water rising in the upward leg above those parts of Libanon and Kloof Gold Mines on the eastern end of the Bank Compartment will, due to the partial hydrological barrier discussed in the section headed “Compartment boundaries,” have practically no (or little) access to the tension zone over the western Bank Compartment.

Through the Bank Dyke

This was discussed in detail in the section headed “Calibration of the model based on historic dewatering data, e.g. predicted flux through the mined-through Bank Dyke”, where it was suggested that the Bank Spring will flow again although much intercompartmental flux will also take place.

Through the Oberholzer Dyke

The same explanations offered when discussing flux through the Venterspost Dyke above, apply to the potential flux expected between the Oberholzer and Boskop-Turffontein Compartments (through the mined-through Oberholzer Dyke). Doornfontein Gold Mine is in a compression zone and the dolomite of Deelkraal and Elandsrand Gold Mines are covered by thick Pretoria Group sediments. The upward leg is thus very impermeable, indicating a small potential intercompartmental flux. Due to the anticipated flux through the Bank Dyke the post-mining yield of the Oberholzer Spring is expected to be higher than in pre-mining times.

The above subsections strongly suggest that in the post-mining era, the Gemsbokfontein, Venterspost and Oberholzer Springs will certainly resume flow due to the expected low intercompartmental flux predictions. The Bank Spring may not flow during dry spells. It is suggested that should pumping cease today, discounting the contribution of flood events, it may take less than 10 years to fill the mine void and an additional approximately 20 years to recharge the dewatered dolomitic compartments of the Far West Rand, which should be regarded as an upper (long) limit estimate.

To sum up

The data provided by some of the mines in the study area was extrapolated to the other situations on the Far West Rand. The combined pre-mining natural recharge of the four dewatered compartments on the Far West Rand is about 133 Ml/day. It was calculated that the present mine void has a capacity of 0.6 million Ml and that the dolomite aquifer is approximately 1.14 million Ml below its pre-mining water storage capacity. Under the present conditions, “wet period recharge” will increase disproportionately due to the presence of sinkholes, especially along the Lower Wonderfontein Spruit. In the event of flooding, these sinkholes will provide major conduits for rapid recharge of the dolomite aquifer as was experienced in the Venterspost Compartment in the 1974–1978 wet period.

In the absence of a major flood and assuming simultaneous decommissioning of all the mines, it will take approximately 10 years, for the mines to flood. Once the mines have been flooded, the water level will rise rapidly through the fractured rock aquifer. Thereafter, the rate of rise will decrease significantly through the cavernous dolomite aquifer particularly when it enters the final 50 m before reaching the pre-mining water level. This is due to the fact that, 40 to 50 m below the pre-mining water table, the dolomite is cavernous and responsible for up to 15% storage capacity of the aquifer.

Except for the occurrence of unusual flood events, it is estimated that the water level will reach its pre-mining elevation approximately 30 years after the cessation of pumping by the mines.

Conclusion

The hydraulic resistance of the fractured rock aquifer in the lower dolomites is sufficiently high to sustain a head differential of approximately 35 m between compartments which will enable the water tables of the four compartments to return to pre-mining levels. In consequence the now dry springs will flow again.

Acknowledgements The contribution of Dr AH Leuschner of Gold Fields Ltd. is gratefully acknowledged for sanctioning this paper. The design of drawings and other editorial support by Mr. S. Dill, Ms. C. van der Merwe, Mr. C.J. Oosthuizen, Dr. F. Winde and Mr. M.S. Molefe is deeply appreciated. Last, but not least, the Far West Rand Dolomitic Water Association is graciously thanked for making data and other resources available for this study.

References

Beukes JHT (1987) Ground movement and the formation of sinkholes due to the partial rewatering of Venterspost Compartment 1975–1978. In: Proceedings of the Seminar on the Engineering Geological Evaluation of Sites on Dolomite. Geological Survey, Pretoria, pp 86–95

Bezuidenhout CA, Enslin JF (1969) Surface subsidence and sinkholes in the dolomitic area of the Far West Rand, Transvaal, Republic of South Africa. In: Proceedings of the International Symposium on Land Subsidence, Tokyo, Government Printer, Pretoria, 8 pp

Brink ABA (1975) Discussion on evaluation of geohydrological constants for the Far West Rand dolomitic formations. Civil Eng S Afr July 1975, 178 pp

Brink ABA (1979) Engineering geology of South Africa, vol 1. Building Publications, Pretoria, 319 pp

De Freitas MH (1974) The effect of non-dolomitic rocks upon the flow of water in the Bank Compartment. Geology Department, Imperial College London, 33 pp

De Kock WP (1964) The geology and economic significance of the West Wits Line. The geology of some ore deposits in Southern Africa, vol 1. Geological Society of South Africa, Johannesburg, pp 375–381

De Kock WP (1967) The dolomite eyes or fountains of the Wonderfontein Valley in western Transvaal, Fauna Flora, Pretoria, 18:56–66

Director of Water Affairs (1960) Final report. Interdepartmental Committee on Dolomitic Mine Water : Far West Rand. Department of Water Affairs, Pretoria

Engelbrecht CJ, Baumbach GWS, Matthysen JL, Fletcher P (1986) The West Wits Line. Miner Dep of S Afr 1:599–658

Enslin JF (1967) Dolomitic water supplies in the Transvaal, Republic of South Africa. Int Assoc Hydrogeologists, Mem Istanbul, 8, pp 433–476

Enslin JF, Kriel JP (1959) Some results obtained from a hydrological study of a dolomitic catchment area in the Transvaal, Union of South Africa. In: Proceedings of the Specialists' Conference on Hydrology, Yaounde, Camerouns, CCTA, London, 14 pp

Enslin JF, Kriel JP (1967) The assessment and possible future uses of the dolomitic groundwater resources of the Far West Rand, Transvaal, South Africa. In: Proceedings of the International Conference on Water for Peace, Washington. Publ 2, pp 908–18

Enslin JF, Kleywegt RJ, Beukes JHT, Gordon-Welsh JF (1976) Artificial recharge of dolomitic groundwater compartments in the Far West Rand gold fields of South Africa. Proceedings of the International Symposium on Land Subsidence, Anaheim, California, 1976, 7 pp

Hodgson FDI, Usher BH, Scott R, Zeelie S, Cruywagen LM, De Necker E (2001) Prediction techniques and preventative measures relating to the post-operational impact of underground mines on the quality and quantity of groundwater resources. Institute for Groundwater Studies, University of the Orange Free State. WRC Rep 699/1/01, Pretoria

Inter-colonial Commission (1905) Government Printing and Stationary Office, Pretoria

Kleywegt RJ, Pike DR (1982) Surface subsidence and sinkholes caused by the lowering of the dolomitic water table on the Far West Rand Gold Fields of South Africa. Annu Geol Surv S Afr 16:77–105

Schwartz HI, Midgley DC (1975) Evaluation of geohydrological constants for the Far West Rand dolomitic formations. Civil Eng in S Afr, Feb 1975

Swart CJU (1986) The geological evaluation during repair of two provincial roads in the Bank dolomitic water compartment. MSc Thesis, University of Pretoria, 103 pp

Swart CJU, Stoch EJ, Van Jaarsveld CF, Brink ABA (2003) The Lower Wonderfontein Spruit: an exposé. Environ Geol 43(6):635–653

Taute AH, Tress PW (1971) Dewatering of the flooded underground workings in the Bank Compartment. S Afr Min Eng J 8.3(4061):23–45

Vegter (1987) Constraints of utilization of groundwater resources in dolomitic strata in South Africa. In: Beck B (ed) 2nd Multidisciplinary Conference on Sinkholes and the Environmental Impacts of Karst, Orlando, Florida; AA Balkema, Rotterdam

Wagener F von M (1984) Engineering construction on dolomite, Dissertation, Department of Civil Engineering, University of Natal, Durban, 325 pp

Wolmarans JF, Guise-Brown FH (1978) The water hazard in deep gold mining of the Far West Rand—South Africa. In: Symposium on Water in Mining, Siamos, Granada, Spain, pp 329–346

Wolmarans JF (1984) Dewatering of the dolomitic area on the Far West Rand: Events in perspective (in Afrikaans). Dissertation, University of Pretoria, 205 pp

Wolmarans JF (1986) Some engineering–geological and hydrological aspects of mining on the West Wits Line. Miner Dep S Afr, Geol Soc, Johannesburg, pp 791–796