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Water Resource Planning Systems Series

Water Quality Planning

Feasibility Study for a Long-Term Solution to address the Acid Mine Drainage associated with the East, Central and West Rand Underground Mining Basins

Assessment of the Water Quantity and Quality of the Witwatersrand Mine Voids

Study Report No. 5.2

P RSA 000/00/16512/2

August 2012

SECOND DRAFT

V2.0

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SC: Study Component

 # - These reports will not be made available until the appropriate implementation process stages have been reached as they may potentially compromise future procurement and legal processes.

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Executive Summary

Active mining and dewatering of the gold mines along the West, Central and East Rand underground mining basins (herein after referred to as the "Western, Central and Eastern Basins" of the Witwatersrand) declined and essentially ceased in 2010. The void left as a result of mining has been steadily filling with water, which interacts with the exposed rocks in the mine void to form Acid Mine Drainage (AMD). In the case of the Western Basin, the AMD has been decanting on surface since 2002. Surface decanting in other basins is predicted to occur in the not too distant future if no action is taken. AMD is known to be of poor quality and poses a threat to the environment and to the water resources of the Vaal River basin.

Currently, Short-Term Interventions (STI) are underway that involve the installation of pumping facilities to stop uncontrolled surface decanting in the Western Basin and to prevent surface decanting from taking place in the other basins. Facilities for the basic treatment of the water are also to be installed. In parallel with these developments, a more permanent solution to the problem is being investigated.

This report provides an assessment of the geology, hydrogeology and hydrochemistry of the Western, Central and Eastern Basins so as to provide the background information necessary for the planning of abstraction and water treatment operations for the longer term solution to the problem. The report also assesses aspects of the STI and how these can be effectively incorporated into the Long Term Solution (LTS).

Although there are some areas where an alternative LTS may be prepared, the STI is considered to be broadly acceptable and the proposed solution is generally considered to be suitably conservative and appropriate for addressing the immediate risks.

There are several recommendations for some alternatives to be addressed in the long term solution resulting from this Feasibility Study. Only in the case of the Central Basin is there insufficient time for the Short-Term solution to consider these longer term recommendations before the critical water level is reached.

Critical Water Levels

A key objective of this study is to define certain critical water levels and estimate the time at which the water in each basin will reach these levels. The critical water levels under consideration are:

(a) Environmental Critical Level (ECL), being the level in the mine void above which the water should not be allowed to rise, to protect specific environmental features, including groundwater resources.;

(b) Socio-Economic Critical Level (SECL), being the level in the mine void above which the water should not be allowed to rise, to protect specific social or economic features, such as Gold Reef City museum and active or planned mining.;

(c) *Target Operating Level (TOL), being the water level in the mine void which should generally be maintained by pumping or gravity flow, and is determined by the freeboard required below the ECL or SECL, to prevent the ECL or SECL being breached at any time.;*

In the Western Basin, to reduce the risks of pollution of springs feeding the Tweelopies Spruit and subsurface flow to the Sterkfontein dolomite aquifer that hosts the Cradle of Humankind, the water level could be lowered to 1600 m amsl and held there for an appropriate duration to establish whether the situation downstream in the Tweelopies Spruit improves. If leakage of direct AMD ceases then this ECL should be maintained (the water could be held at this level), if not it should be lowered further to the Environmentally Critical Level (ECL) of 1550 m amsl level proposed in the TCTA Report (2011a). No SECL is currently anticipated for the Western Basin.

The ECL for the Central Basin is determined to be at an elevation of 1520 m amsl. This is based on a depth of 100 metre below surface at ERPM, and should adequately protect the shallow weathered aquifer. However, a program of drilling across the Central Basin is recommended to improve definition of the depths of the shallow aquifer, which will enable a more accurate elevation to be determined for the ECL.

The Gold Reef City (GRC) museum tourist level (1484 m amsl) in Crown Mines 14 (CM 14) Shaft was taken to be the critical factor in determining the SECL. The SECL is set at an elevation of 1474 m amsl to accommodate the lowering of the double decker conveyance and to ensure that the museum can still be visited as a heritage site.

Consideration could be given to plugging the shaft at GRC at some point below the museum level and then allowing the water level in the void to rise to 100 m below surface at ERPM. The cost of plugging at this level may be economic in the long term, however the rising water levels may pose significant technical and logistical challenges, notwithstanding problems associated with perceived risks for a tourist facility. Currently, GRC are investigating this and the possible relocation of the museum facility from 5 Level to 2 Level (1624 m amsl).

However, an SECL of about 400 m below surface at SWV (1 253 m amsl) is being considered to allow mining to that depth. If this takes place then before mining operations close down an ECL or SECL will have to be set before the water is allowed to rise. Whatever levels are set, monitoring of the near surface aquifers of the basin is important.

In the Eastern Basin, the 1280 m amsl ECL, as proposed by the STI (TCTA Report, 2011a), is considered to be conservative and for the STI it is considered prudent to keep the water at this level below the base of the dolomite. If adequate monitoring of the water quality in the dolomites has been established, and no pollution is observed at the ECL of 1280 m amsl, the water level can be allowed to rise, in say 10m steps, to a higher ECL, possibly as high as 1470 m amsl or 70 m below surface. No SECL is currently set for the Eastern Basin. The ECL is estimated in this study to be reached by middle 2014. The TCTA Report (2011a) predicts that the ECL will be reached between December 2014 and May 2015, and these differences may be due to extrapolation issues with limited data.

In all three basins under consideration there remains potential for new mining operations to become economically feasible, especially under an economic environment of increasing gold prices, in which case SECL's would have to be set.

Surface water ingress

The impact of surface water resources ingressing directly into the underground workings is significant for all three basins. The ingress mainly occurs via reef outcrops, open cast pits and backfilled workings, tailings dams, as well as from rivers and other water bodies. The majority of the ingress cannot easily be controlled as there are many diffuse sources within the basins. Follow up studies should therefore be carried out to establish both the practicality and cost effectiveness of controlling the ingress from the various sources. This could in the long term potentially reduce the required pumping rates and hence lower pumping, treatment and maintenance costs.

It is predicted that climate change will cause an increase in average monthly rainfall and hence must be taken into account in future studies regarding ingress volume predictions. The impact of climate change could be fairly significant within the Western and Eastern basins mainly due to the extensive river systems within these basins. A smaller impact is expected with the Central Basin as the majority of ingress occurs from high base flows within the rivers due to leaking sewer lines and drainage systems.

Pumping rates

In this study pumping rates required to maintain a static water level at a particular TOL and hence SECL or ECL were calculated, using void volume and historic water level data, and are presented in comparison with those of the TCTA Report in Table A.

Table A: Comparison of pumping rates to maintain critical water levels.

Basin	Approx. Average Pumping Rates (TCTA) (Mℓ/day)		Proposed Pump Capacity and Estimated Rate (this study) (Mℓ/day)	
	Average	Range	Pump Capacity	Average Rate
Western	27	23-35	40	23
Central	57	34-84	50	46
Eastern	82	38-110	100	80

In the Central Basin and possibly in the Eastern Basin it is recommended that pumping be undertaken from more than one shaft per basin. Ideally, shafts that are better connected to the mine void at multiple and preferably shallow levels are recommended. Pumping from several shafts will reduce the danger of a shaft becoming ineffective due to collapse of either the shaft itself or of underground haulages. In addition, pumping from shallower levels is likely to result in a more rapid improvement in water quality, at least in the Central Basin where direct surface water ingress is evident.

In the Central Basin, there are numerous incline shafts across the length of the basin that could be investigated for their suitability as pump locations. Access and infrastructural constraints may necessitate the consideration of large diameter boreholes drilled into the mine void for pump installation. Pipelines may have to be installed to convey water to central treatment plants in a similar manner to that employed by the companies that re-treat slimes dams. The use of multiple shaft and borehole pump sites will be further investigated in the options analysis of this Feasibility Study.

In order to pump upstream of, and take advantage of synergies with any of the domestic waste-water treatment works, abstraction sites should be located between DRD and Crown Mines.

In the Eastern Basin, consideration should be given to pumping from shafts in the south-eastern portion of the basin (Marievale), so as to discharge the treated water further downstream in the Blesbokspruit, thereby removing the risk of recycling the treated water.

Passive solutions allowing natural surface decant at preferred ECL's, rather than pumping, will be further investigated in the options analysis. A tunnel designed to intersect the Central Vertical Shaft at ERPM has previously been proposed, allowing Central Basin water to decant naturally to the Elsburgspruit where a treatment plant could be installed.

Water quality

In Table B, the current estimates on the chemistry of the AMD in the three basins are compared with those given in the TCTA Report (2011a). As a general observation, it appears that the data sources consulted in this study report lower salt concentrations than those recorded in the TCTA Report (2011a). At least some of this is due to dilution effects from surface water ingress, as illustrated in Figure A.

In this diagram, the data cluster marked K is regarded as the best estimate of primary AMD. These samples have pH values of between 2 and 4, and TDS values of ca. 3850±1000 mg/ℓ. The salt load shows relatively little variation in composition. The weight ratios of SO4:Ca:Mg:Na:Fe:Al = 65:15:5:5:1:0.5 (ranges: 60-75:10-25:4-7:4-10:0.1-6:0-3), as determined for Central Basin data, on average seem to hold well for the other basins as well.

Most of the Western Basin AMD samples plot in a narrow band at an EC of ca. 350 mS/m, which represents about 3850 mg/ℓ of total dissolved solids (TDS), and recorded pH values of between 2 and 7, depending on the degree of neutralisation (red arrow), probably by interaction with dolomitic water.

The Central Basin data is scattered over a wide field, reflecting the diversity of samples within the database, ranging from extremely contaminated surface samples (EC ~ 1050 mS/m) to water within the potable range. A large number of samples plot at EC ~100 to 200 mS/m and pH between 2 and 6. The latter samples originate largely from the DRD Circular and CM 3 Vent shafts, and represent the dilution effect of surface ingress (blue arrow) on the AMD in the mine void.

The Eastern Basin samples cluster at an EC of about 300 mS/m (TDS ~ 3300) and pH between 5 and 8. These samples follow a trend (black arrow) which summarises the recorded improvement of the water quality during pumping. This improvement is probably the combined result of dilution and neutralisation by dolomite-equilibrated water.

Table B: Summary comparison of chemical data.

		TCTA Report			This Report		
Water Quality Parameter	Units	Basin			Basin		
		Western (95th percentile)	Central (95th percentile)	Eastern (flooded condition)	Western (95th percentile)	Central (95th percentile)	Eastern (95th percentile)
pH*	-	3.4-4.0#	2.3	5#	3	3.2	7.1
TDS	mg/ℓ	7174	7700	5500	5388	3888	4248
Conductivity	mS/m	548	730	450	426	354	367
Calcium (Ca)	mg/ℓ	461	580	550	823	483	421
Magnesium (Mg)	mg/ℓ	345	380	230	-	161	165
Sodium (Na)	mg/ℓ	139	150	325	243	185	264
Sulphate (SO_4)	mg/ℓ	4556	5200	3275	3410	2464	2581
Chloride (Cl)	mg/ℓ	65	260	260	-	69	253
Acidity/Alkalinity	mg/ℓ	2560**	2425**	750**	1255+	125##	541##
Iron (Fe)	mg/ℓ	933	1,000	370	799	177	206
Aluminium (Al)	mg/ℓ	54	50	1	-	44	2
Manganese (Mn)	mg/ℓ	312	60	10	114	20	6
Uranium (U)	mg/ℓ	0.2	-	-	0.1	0.2	0.5

*5th percentile #Assumed 5th percentiles **Acidity - Calculated $CaCO_3$ +Acidity mg/l ##Alkalinity mg/l $CaCO_3$ All units as quoted in source documents

As a reasonable approximation of the likely water qualities during abstraction, Table C presents water chemistry data from underground samples only (or direct decant sites in the case of the Western Basin).

Table C: Summary of 95th percentile underground/decant mine water chemistry.

Parameter	Unit	Basin (95th Percentile)		
		Western	Central	Eastern
pH#	@ 25˚C	3.5	2.4	5.9
TDS^	mg/l	5434	5118	3358
Conductivity	mS/m @ 25˚C	442	465	363
Ca	mg/l	703	563	421
Mg	mg/l	-	258	165
Na	mg/l	227	171	264
SO4	mg/l	3623	3062	2624
Cl	mg/l	-	146	254
Acidity/Alkalinity	mg/l	1520	-	550
Fe	mg/l	954	108	227
Al	mg/l	-	193	2.4
Mn	mg/l	89	50	5.9

^Estimated # 5th percentile

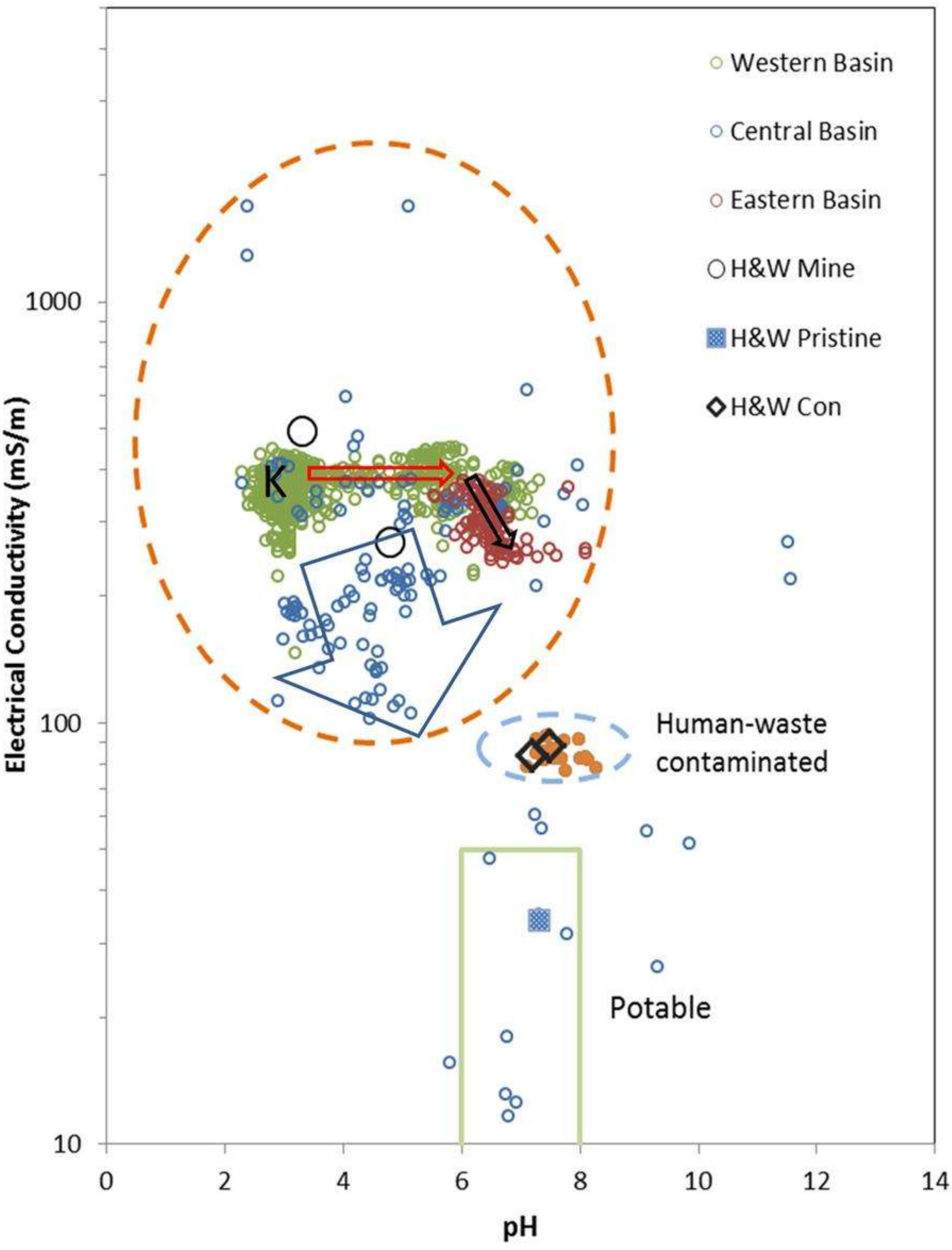

Figure A: Simplified chemical relationships (H&W = Holland and Witthueser, 2009).

The uncertainties inherent in the data, and in particular in the detail of the void characteristics, do not allow for high accuracy predictions to be made. These uncertainties will best be solved by adopting an initially conservative approach and by a well-considered water quality monitoring program once pumping commences as part of the STI. However, some variability in the water quality during the initial stages of pumping should be expected. This situation will stabilise when the systems approach dynamic equilibrium.

Contents

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LIST OF ACRONYMS

AMD	Acid Mine Drainage
BBBEE	Broad Based Black Economic Empowerment
BEE	Black Economic Empowerment
BKS	BKS Group (Pty) Ltd
BRI	Black Reef Incline
CB	Central Basin
CD	City Deep
CM	Crown Mines
CMR	Consolidated Marin Reef
COD	Chemical Oxygen Demand
CRG	Central Rand Gold
CSIR	Council for Scientific and Industrial Research
DG	Director-General
DO	Dissolved Oxygen
DRD	Durban Roodepoort Deep
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry
EB	Eastern Basin
ECL	Environmental Critical Level
EIA	Environmental Impact Assessment
EMP	Environmental Management Plan
ERPM	East Rand Proprietary Mines
FM	Facilities Management
GDARD	Gauteng Department of Agricultural and Rural Development
GIS	Geographic Information System
GRC	Gold Reef City
HDS	High Density Sludge
IGTT	Inter-Governmental Task Team
IMC	Inter-Ministerial Committee
IRP	Integrated Regulatory Process
IWULA	Integrated Water Use License Application
LTS	Long Term Solution
m amsl	metres above mean sea level
MAP	Mean Annual Precipitation
Mn	Manganese
MoU	Memorandum of Understanding
MPCA	Minnesota Pollution Control Agency
NEDLAC	The National Economic Development and Labour Council
NGO	Non-Governmental Organisation
NNR	National Nuclear Regulator
NPV	Net Present Value
NWA	National Water Association
PFMA	Public Finance Management Act, 1998 (Act No. 36 of 1998)
PPP	Public Private Partnership
PSCM	Public Sector Comparator (Model)

PSP	Professional Service Provider
RFP	Request for Proposals
RL	Rand Leases
RO	Reverse Osmosis
RoD	Robinson Deep
RsD	Rose Deep
SAC	Study Administration Committee
SAHRA	South African Heritage Resources Agency
SJ	Simmer and Jack
SMC	Study Management Committee
SMME	Small, Medium, Micro Enterprises
SoW	Scope of Work
SRK	SRK Consulting (Pty) Ltd
SSC	Study Stakeholder Committee
STI	Short-Term Intervention
STS	Short-Term Solution
SWV	South West Vertical
TA 1	Treasury Approval 1
TCTA	Trans Caledon Tunnel Authority
TDS	Total Dissolved Solids
T&T	Turner & Townsend
ToR	Terms of Reference
TSF	Tailings Storage Facility
U	Uranium
WB	Western Basin
WBEC	Western Basin Environmental Corporation
WESSA	Wildlife and Environment Society of South Africa
WRC	Water Resource Commission
WUC	Western Utilities Corporation
VCR	Ventersdorp Contact Reef

GLOSSARY OF TERMS

Adit	An adit is an entrance to an underground mine which is horizontal or nearly horizontal, by which the mine can be entered, drained of water, and ventilated.
AMD	Outflow of acidic water from (usually abandoned) metal mines or coal mines.
Annexure	Documents produced by others attached to the report.
Appendix	Documents produced by the Study Team attached to the report.
Aquifer	Zone below the surface capable of holding groundwater.
Brownfields	Abandoned or underused industrial and commercial facilities available for re-use.
Central Basin	Central Rand underground mining basin.
Conglomerate	A course-grained clastic sedimentary rock, composed of rounded to sub-rounded fragments larger than 2mm in diameter set in a fine-grained sandy matrix and commonly cemented by calcium carbonate, iron oxide, silica, or clay.
Decant (in mining)	Surface discharge of water from an abandoned mine.
Derelict	A derelict is a civil wrong in terms of which a person (legal or juristic) causes harm to another.
Discharge	Seepage of groundwater at the surface.
Dyke	Vertical, planar body of igneous rock formed by the solidification of molten rock in a crack.
Eastern Basin	East Rand Underground mining basin.
Environmental Critical Level	The water level in the mine void above which the water in the mine void should not be allowed to rise, to protect specific environmental features, including groundwater resourced.
Erosion	A process which involves the wearing away of the land surface by the mechanical action of transported debris.
Fault	Crack in the Earth along which differential movement of the rock mass has occurred.
Feasibility Study	An analysis and evaluation of a proposed project to determine if it is technically sound, socially acceptable, and economically sustainable.
Fractured rock aquifer	A water-bearing rock mass (aquifer) in which the open spaces that accommodate the water are the result of cracks in the rock.
Freeboard	The vertical distance below the Environmental Critical Level, below which the water level should generally be maintained, to allow for seasonal peak ingress, pump down time, and the like.
Greenfield	An undeveloped site, especially one being evaluated and considered for commercial development or exploitation
Groundwater	Water occupying openings below ground.

Haulage	A tunnel excavated along which ore and various forms of equipment are transported primarily by rail.
Head Cut Advance	Step-changes in bed surface elevation where intense, localized erosion takes place.
Karst	Karst topography is a geological formation shaped by the dissolution of soluble rocks, typically carbonate rocks such as limestone and dolomite.
Key Stakeholder	Defined as directly affected parties, those who have a high level of negative or positive influence (in government and civil society domains, and on the direction and success of AMD long-term initiatives) and those whose input is critical to the study (for e.g., representatives of various National, Provincial, and Local and District Government, NGOs, organised business, mining, industry, labour, agriculture, affected mines, affected water utilities, community leaders, academics, etc.).
Layout	The arrangement (site layout, pipe route, etc.) of a specific option.
Long-Term Solution	A solution that is sustainable in the long term with regards to the technical, legal, economic, financial and institutional aspects.
Mine plan	Accurate drawing showing the positions of mine excavations.
Option	One of a number of combinations of abstraction works, treatment process, and solutions for the disposal of waste and treated water
Potable water	Water safe enough to be consumed by humans and used with low risk of immediate or long term harm. Defined in South Africa according to South African National Standard (SANS) 241 specification.
Preferred Option	The solution, or combination of solutions, for the three basins that will be selected for further investigation in the feasibility phase, and if found feasible, that would eventually be recommended to the Client.
Ramsar Convention	An international treaty for the conservation and sustainable utilization of wetlands,[1] i.e., to stem the progressive encroachment on and loss of wetlands now and in the future, recognizing the fundamental ecological functions of wetlands and their economic, cultural, scientific, and recreational value. It is named after the town of Ramsar in Iran.
Reef	Term used on the Witwatersrand mines for conglomerate.
Request for Information	A Request for Service Providers to provide information on their product or service, e.g. technologies. It is not part of a Procurement process.
Request for Qualifications	A Request for Qualifications from Service Providers to allow a shortlist to be prepared. It is normally the first step in the Procurement process.
Request for Proposals	A request for technical and financial proposals in compliance with a defined SoW and adjudication criteria from (Pre-Qualified) bidders to allow one of the bidders to be appointed to provide an agreed service.
Scenarios	An alternative projection of the macro environment which affects AMD, such as climate change, electricity load shedding, and changes in quality or quantity of water ingress to the mine void.
Scenarios	Alternative projections of the macro environment which affects AMD, such as climate change, electricity load shedding, and changes in quality or quantity of water ingress to the mine void.
Shallow weathered aquifer	A water-bearing rock mass (aquifer) in which the open spaces that accommodate the water are the result of near-surface weathering of the rock.
Short-Term Interventions (Short-	Measures that are being implemented in the short term while the long term feasibility study is undertaken.

Term Solution as stated in Terms of Reference)	
Socio Economic Critical Level	The water level in the mine void above which the water must not be allowed to rise, to protect specific social or economic features, such as Gold Reef City museum and active or planned mining.
Stakeholder	A person, group, or community who has an interest in or are affected by AMD and the feasibility study to address the problem.
Strata	In geology and related fields, a stratum (plural: strata) is a layer of sedimentary rock or soil with internally consistent characteristics that distinguish it from other layers.
Subsurface Decant	Subsurface flow of water from one mine compartment or geological structure to another.
Surface Decant	Discharge of water from a mine to the surface.
Syncline	A basin shaped fold with younger layers closer to the centre of the structure.
Target Operating Level	The water level in the mine void which should generally be maintained by pumping or gravity flow, and is determined by the freeboard required below the ECL or SECL.
Vadose Zone	The zone in the soil profile between the surface and the water table.
Water table	The level in an aquifer below which all voids are filled with water.
Western Basin	West Rand underground mining basin

1 INTRODUCTION

1.1 Background to the Feasibility Study

Active mining and dewatering of the mines along the West, Central and East Rand goldfields of the Witwatersrand Basin (herein after referred to as the "Western, Central and Eastern Basins") declined and essentially ceased in 2010. The void left as a result of mining has been steadily filling with water, which interacts with the exposed rocks in the mine void to form Acid Mine Drainage (AMD). In the case of the Western Basin, the AMD has been decanting since 2002. Decanting in other basins is expected to occur in the not too distant future. AMD is known to be of poor quality and poses a threat to the environment and to the water resources of the Vaal River basin.

The need for urgent government action to address the AMD challenges associated with the Eastern, Central and Western Basins have been known for some time.

After an internal DWA meeting held on 10 November 2008, attended by key role-players to discuss a way forward for managing AMD, it was resolved that DWA should go out on tender, as a matter of priority, with a Terms of Reference (ToR) aimed at planning the implementation of a self-sustainable long-term solution to address the existing and potential pollution from AMD.

Following increasing media attention in response to the AMD, linked to the need for inter-governmental co-operation, an Inter-Ministerial Committee (IMC) on AMD, comprising the Ministers of Mineral Resources, Water and Environmental Affairs, Science and Technology and the Minister in the Presidency: National Planning Commission, had been established, with the first IMC meeting taking place on 1 September 2010.

A Team of Experts was subsequently instructed by a Task Team, co-chaired by the Directors-General of Mineral Resources and Water Affairs, to advise the IMC in respect of AMD, with the first Team of Experts meeting taking place on 13 September 2010.

On 9 February 2011, Cabinet approved the IMC report, which *inter alia,* required that a Feasibility Study be undertaken, aimed at implementing a self-sustainable long-term solution to address the management of AMD.

DWA went out on tender, advertising Bid No. WP10569 for an 18-month Feasibility Study for a Long-Term Solution (LTS) to address the Acid Mine Drainage (AMD) associated with the East, Central and Western Rand underground mining basins (This Feasibility Study), on 29 July 2011, once again inviting proposals from prospective PSPs, with tender closure scheduled for 1 September 2011.

Bid adjudication took place on 13, 26 September and 4 October 2011. The choice of Aurecon as the preferred bidder was subsequently approved on 8 December 2011.

A contract between DWA and Aurecon, with a contract start date of 30 January 2012 was concluded in January 2012.

It was emphasised that this study is very urgent, is in the public eye, and that all related decisions must be defendable. The Feasibility Study should investigate a wide range of possible solutions and disqualify those found to be not suitable.

If the salt loading on the Vaal River System associated with discharges of AMD from mines and sewage effluent are not eliminated or suitably reduced, excessive dilution-releases from the Vaal Dam will be required to achieve the Resource Quality Objectives (RQO) in the Vaal Barrage and downstream river. This will result in unusable surpluses developing in the Lower Vaal River, externalising the cost of pollution to the Lower Orange River. Should the AMD issue and specifically the desalination, not be addressed appropriately by 2014/15, the acceptable levels of assurance of water supply will be threatened. This means that there will be an increasing risk of water restrictions in the Vaal River Water Supply area. The Aurecon proposal was for a 15 month study proposal and in the contract negotiation a 13 month contract period was agreed, 5 months shorter than envisaged in the bid documents, although the Scope of Work remained the same.

Although a longer Study period would allow some more information to become available and analyses to be completed, the shorter Study period is in the best interests of managing AMD and protecting the environment and water resource.

The implications of the shorter study period and the urgency to reduce the salt loadings on the Vaal System are that implementation decisions will have to be made on the understanding of the best information and technical analyses that can be completed by the time decisions must be made. These may lead to a conservative approach, but opportunities to refine the projects which are implemented, during their operation as more information becomes available, will have to be considered.

1.2 Background to the Short-Term Intervention

Following Cabinet approval of the IMC report on 9 February 2011, funds were allocated to DWA by National Treasury with the purpose of implementing some of the recommendations of the Team of Experts on AMD, namely:

- To investigate and implement measures to pump the underground mine water in order to prevent the violation of the Environmental Critical Levels (ECLs);
- To investigate and implement measures to neutralize and remove metals from the AMD; and
- To initiate a feasibility study to address the medium- to long-term solution, which should be initiated as soon as possible since the STIs may influence the medium-to long-term solution.

On 6 April 2011, the Minister of Water Affairs issued a Directive to the the Trans-Caledon Tunnel Authority (TCTA) to undertake "Emergency Works Water Management". The Directive specifies a number of conditions, including that the "TCTA shall liaise with the DWA regarding the longer term AMD management objectives and ensure compatibility of the Project with future application of AMD."

Based on this Directive, the TCTA commissioned BKS, in association with Golder Associates, to design and implement the STI. The TCTA due diligence report was submitted as draft in June 2011 and as final in August 2011.

The SoW for this Feasibility Study for the LTS does not include a review of either the status, or the content and extent, of TCTA's mandate from DWA. The SoW of this study, with respect to the STI is to:

- Understand the proposed STI in sufficient detail to:
- Plan the LTS;
- Determine how to integrate the STI and LTS;
- Identify any potential long term risks arising from the proposed STI, and propose prevention or mitigation measures; and
- Assess the implications of the proposed STI on the proposed institutional model for the implementation, operation, maintenance and or management of the preferred solution for the LTS.
- Undertake a Feasibility Study of all options, irrespective of the STIs, in the interest of finding the best LTS.

1.3 Approach to the Study

This Feasibility Study comprises two phases, the Pre-Feasibility and Feasibility Phases.

A key stand-alone component is an assessment of the legal situation which forms the basis for apportioning liabilities. This work will be described in the reports on "Legal Considerations for Apportionment of Liabilities" and "Alternative Approaches for Apportioning Liabilities".

Developing a LTS to address AMD requires the careful assessment and integration of the following key elements. Each of these key elements forms a study component of which the results are included in a report, as shown:

Pre-Feasibility Phase

i. A sound understanding of the hydrogeology, the underground water resources, sources of surface water ingress, spatial distribution and connectivity of mined voids, the current water quality and projections of future volumes, levels and water qualities.

This assessment will be based on the substantial volume of information in previous studies. **This Report**

ii. Understanding the STI and how it can be integrated into the LTS. This study will establish a sound understanding of the short-term measures and assess how the STIs can be incorporated into a LTS and the impact of the short-term interventions on the selection of a LTS. **Described in the "Report on the Current Status of the Management of AMD".**

iii. The possibilities for the use or discharge of raw, neutralised or desalinated AMD which will meet the objective of reducing the salt load on the Vaal River System to acceptable levels and which do not have an unacceptable social or environmental impact. The options for use and requirements for safe disposal of waste products from various treatment technologies must also be assessed. **Described in the "Report on the Options for Use Disposal or Discharge of Water and Waste".**

iv. Suitable technologies for treating either raw AMD or the discharges from the STI, to standards that will not negatively impact on the environment and will be acceptable to a range of users. **Described in the "Report on Treatment Technology Options".**

v. Defining the possible combinations of alternative locations for abstraction, treatment and discharge points for water and waste and the configuration of the infrastructure, including pipelines and pump stations, required to treat the AMD into a range of options. This will require the technical assessment of the number and location of abstraction points, desalination plants, waste disposal sites and alternatives for discharging water. The large range of alternatives will be screened at a high level to give a short list of practical technical options.

   The capital and operating costs of the short listed practical options will be determined to give a present value of life time cost. A social and environmental screening for fatal flaws will be carried out and possible financial benefits from sale of water or waste will be considered. The perceived reaction of the public to the options will also be considered. Identification or selection of the preferred option based on the costs, benefits and impacts. **Described in the "Pre-Feasibility Report".**

Feasibility Phase

The more detailed studies of the preferred option in this phase will include:

i. Concept Development / Feasibility Assessment

   Once the preferred option has been agreed the infrastructure layout for treatment works, pipelines and waste discharge will be prepared and costed, and an environmental scoping will be undertaken of each of the identified sites that form part of the preferred option. **Concept Design and Costing Report and Book of Drawings.**

ii. Assessment of alternative institutional, financial and procurement models for implementation, ranging from a "traditional" government funded and implemented solution through Public-Public Partnerships (P Pub P) to a Public Private Partnership

(PPP), and any combinations. This will include a detailed value assessment of the selected option, i.e. cost-benefit comparisons and assessments and risk analysis. **Described in the "Institutional Procurement and Financing Options Report".**

iii. Throughout the Study, the requirements for implementation will be considered in developing an Implementation Plan. Where necessary, the activities required for implementation, which must commence in parallel with this Study, will be identified. **Described in the "Implementation Action Plan".**

Stakeholder engagement and public communications are very important components of the Study and are on-going. These include Study Stakeholder Committee meetings, focus group meetings, newsletters and a website. **The results will be concluded in the "Report on Key Stakeholder Engagement and Communications".**

The study comprises a number of inter-related components and key steps and the relationships are shown in **Figures 1.1** and **1.2**.

1.4 Aims and Objectives of this component

The principal aim of this component of the study is to assess the present and likely future quantity and quality of the mine void water that is to be treated. In order to achieve this aim, a sound understanding of the following aspects is required:

(1) The geology and hydrogeology of the region;

(2) The spatial distribution and interconnectivity of the mine void that hosts the underground water;

(3) Sources of water ingress into the mine void; and

(4) Water qualities within the mine void and the variation therein.

A substantial number of previous studies have been completed on this subject and this report does not aim to provide a detailed review of each of these studies. However, the assessment is based on the wealth of information available as a result of previous work.

The main objectives of this component of the Feasibility Study are:

(1) To estimate the time at which the water in each basin will reach certain critical water levels and when and where surface decant is expected to occur if the natural rate of rise continues unchecked. The critical water levels under consideration are:

   (a) Environmental Critical Level (ECL), being the level which shall ensure the safety of the environment, including the ground water resources;

   (b) Socio-Economic Critical Level (SECL), being the level which shall preserve cultural-historic infrastructure and current or planned economic activity, e.g. mining;

   (c) Target Operating Level (TOL), being the optimum safe water level, below the ECL and SECL, which shall prevent, allowing for periodic fluctuation and maintenance, the ECL or SECL to be reached. The TOL will be based on engineering considerations and will be determined at a later stage in the study;

(2) To estimate the volumes of water that must be abstracted from various underground mining compartments to achieve and maintain agreed water levels and any changes with time;
(3) To assess the quality of the water delivered and which will need to be treated, as well as the probable changes with time;
(4) To provide confidence levels for all predictions. All the data presented in this report is based on the latest available information and the confidence levels are considered to be the best that the data allows; and
(5) To provide recommendations for further investigation by other components in the Feasibility Study, in particular the options analysis.

The potential water resource available in the mine void is often discussed but rarely quantified. **Table 1.1** provides estimates of the relative capacities of the Vaal Dam and the mining voids of the Western, Central and Eastern Basins. The total combined capacity of the mine void is equivalent to about one third the capacity of the Vaal Dam. The likely possible combined annual water yield from the mine void amounts to 150 Megalitres per day (Mℓ/day) to its consumers. For comparison, Rand Water currently supplies approximately 4000 Mℓ/day. Although the annual volume of void water is very small in the context of the Vaal River system and the supply volume of Rand Water, the salt load introduced into the Vaal from the mine void is disproportionately large, necessitating removal of salts prior to release into the Vaal River System.

Table 1.1: Volume comparison of the Vaal Dam and estimated mine voids, with annual pumping rates indicated by this study.

Water bodies	Million m^3
Vaal Dam	
Capacity (volume)	2536
Average inflow (per annum)	1400
High inflow observed (per annum)	7605
Basins (estimated)	
Western	43
Central	467
Eastern	304
Total	814
Proposed maximum pumping rate from mine voids (per annum)	
Western	22
Central	18
Eastern	37
Total	77
Rand Water Board water supply (per annum)	1460

Whilst it is not the scope of this component of the Feasibility Study to assess the economic and engineering viability of all options, it is important to be cognisant of the potential cost impact of various options for addressing the AMD issues to allow options to be screened for

further study. The central considerations of this component, principally the volume and quality of the mine void water and abstraction aspects (e.g. time to surface decant and critical water levels without intervention, minimum pumping volumes, potential variations in water quality with depth, interconnectivity of the mine void), all inform the viability of various options for further investigation in the options analysis component of the study. Such additional options include pumping from shallower depths at multiple sites and natural or controlled decant, i.e. tunnel or siphon abstraction.

The scope of this report does not include a comprehensive review of shaft selection criteria, but does aim to comment on shaft selection as it pertains to connectivity to the mine void, specifically considering the following aspects:

- Connectivity to the shallow mine void (to maximise the potential of flushing the system with ingress water and reduce the risk of drawing potentially poor quality water from depth);
- Connection to the mine void on multiple levels (to minimise the risk of collapse on a singular level).

A critical consideration of this study is whether the basis for the STI to address the AMD problem is accurate and appropriate. This is defined by the due diligence report and associated appendices, "Witwatersrand Gold Fields: Acid Mine Drainage (Phase 1)", issued in August 2011 by BKS (Pty) Ltd on behalf of the Trans-Caledon Tunnel Authority (TCTA), herein referred to as the "TCTA Report (2011a)".

The status quo assessment of the AMD situation in the Witwatersrand according to the TCTA Report (2011a) is taken as the baseline for the Feasibility Study and any points of departure from the TCTA Report (2011a) assessment are described in detail.

1.5 Methodology

In order to effectively review the basis for the STIs as defined in the TCTA Report (2011a), it was necessary to establish a dataset that is as complete and current as possible. The data was then independently assessed to derive predictions of surface and subsurface decant times, water qualities, ingress and pumping volumes. **Figure 1.1** illustrates the methodology applied in this study.

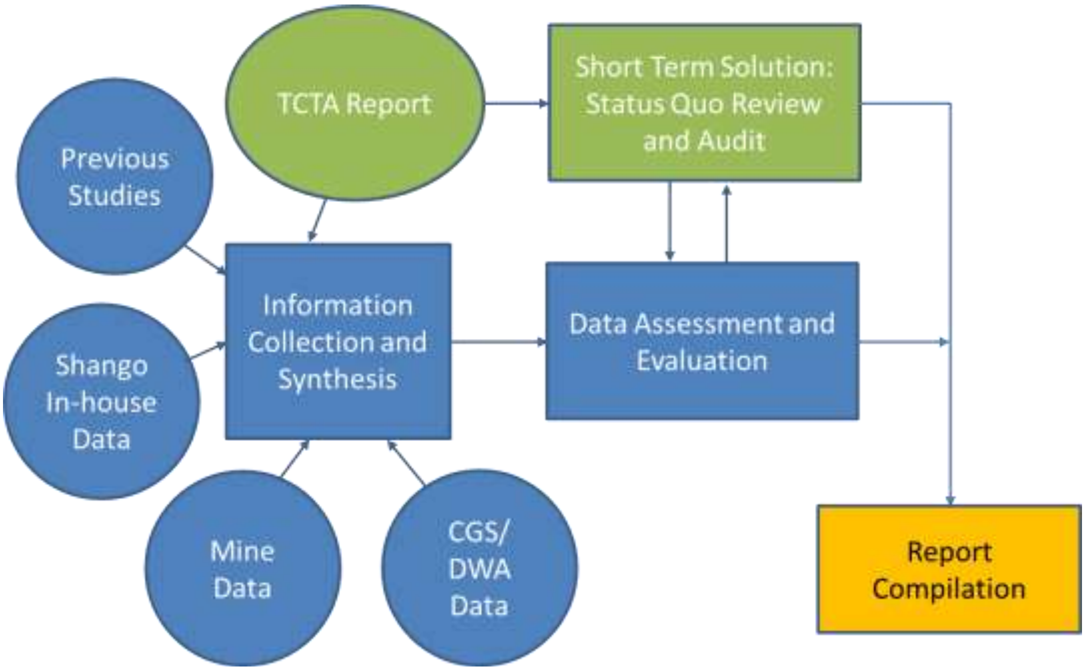


Figure 1.1: Illustration of the methodology used in this project.

1.6 Data Utilised

The data required for this study includes the key components highlighted in **Figure** 1.2. General internet and reference searches were undertaken to add to the extensive public domain information already available. Internet sources such as industry news, academic, company and state websites were investigated. Once an inventory of available data availability was compiled, information considered significant to the study was identified and sourced.

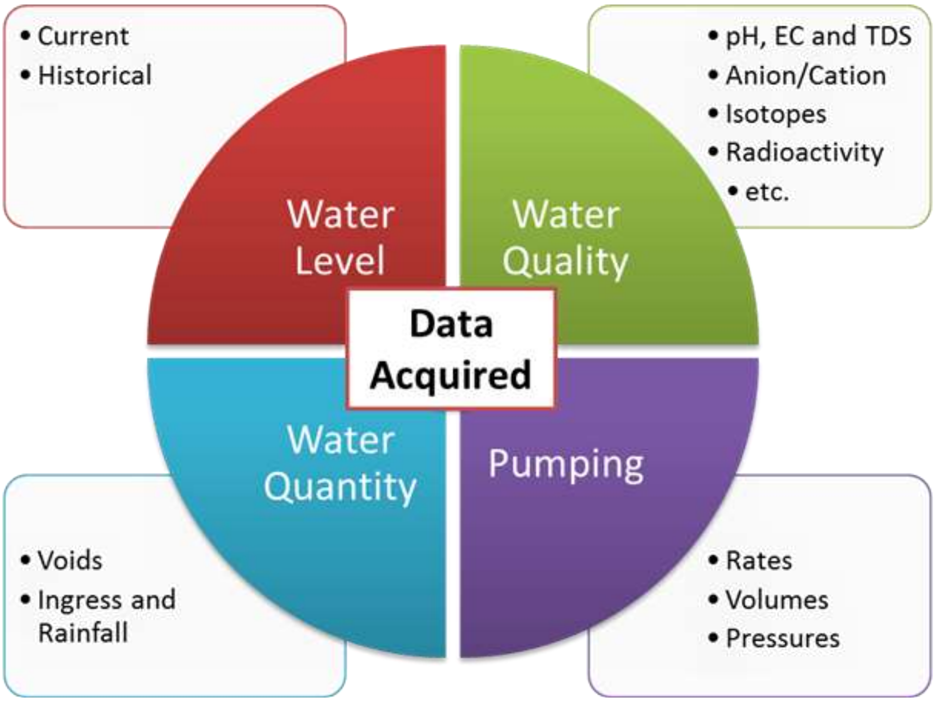


Figure 1.2: Illustration of the data acquired for this study.

The consultants have collected extensive datasets across the basins for other studies over the past 8 years. Gaps in this data were identified and then explored. Where information was not readily available, workshops were held with various stakeholders and experts in an effort to address these gaps, which has enabled a comprehensive database to be established. **Table 1.2** lists the main contributors during the project to date. The data from the Golder/BKS feasibility studies for the Western Utilities Corporation (WUC) was also supplied to the team.

It should be noted that data acquisition is on-going and the database will continue to expand as new information is acquired.

Table 1.2: Sources of data acquired.

Company	Source	Basin	Water Data				General Data		
			Quality	Quantity	Level	Pumping	Spatial	Literature	Rainfall
DWA	Eddy Van Wyk	Central, East and West Rand	☑	☐	☑	☐	☐	☐	☑
CGS	Henk Coetzee	West Rand	☑	☑	☑	☑	☑	☑	☐
Shango Solutions	In-house Database	Central, East and West Rand	☑	☑	☑	☑	☑	☑	☐
Gold One	Richard Sterward	East Rand and West Rand	☐	☐	☑	☐	☑	☐	☐
Rand Uranium	Basie van der Walt	West Rand	☑	☑	☑	☑	☐	☐	☐
Wits University	Prof Terence McCarthy	East Rand	☑	☑	☐	☑	☐	☑	☐
The Weather Service	General personnel	Central, East and West Rand	☐	☐	☐	☐	☐	☐	☑
CSIR	Phil Hobbs	West Rand	☑	☐	☐	☐	☑	☑	☐
ERPM/DRD	Vivian Labuschagne	Central Rand	☑	☑	☑	☑	☐	☐	☐
North West University	Frank Winde	Central Rand	☐	☑	☑	☐	☑	☐	☐
SRK/Aurecon	SRK/Aurecon	Central, East and West Rand	☐	☐	☐	☐	☐	☑	☐
Camden Geoserve	Peter Camdem-Smith	Central Rand	☐	☐	☑	☑	☐	☐	☑
CGS	Magda Roos	Central, East and West Rand	☐	☐	☑	☐	☑	☐	☐

For the assessment of surface water ingress, the most relevant data and information that was reviewed is tabulated in **Table 1.3** below.

Table 1.3: Summary of data reviewed for the assessment of surface water ingress.

Report Title	Authors and Date	Brief Summary
Witwatersrand Gold Fields Acid Mine Drainage : Contract TCTA 08-041 Water Balance and levels	BKS in association with Golder Associates, (2011)	Status quo of expected water levels and summary of water balance for Witwatersrand gold fields
Western Utilities Corporation (WUC) – DFS Resource Estimation in the West Rand Basin	Golder Associates, (2009)	Summary report and water balance based on previous work related to water volumes entering the underground workings in the West Rand Basin
Western Utilities Corporation (WUC) – DFS Resource Estimation in the Central Rand Basin	Golder Associates, (2009)	Summary report and water balance based on previous work related to water volumes entering the underground workings in the West Rand Basin
Western Utilities Corporation (WUC) – DFS Resource Estimation in the East Rand Basin	Golder Associates, (2009)	Summary report and water balance based on previous work related to water volumes entering the underground workings in the West Rand Basin
Ferret Mining & Environmental Services (Pty) Ltd. A strategic Water Management Plan for the Prevention of Water Ingress into Underground Workings of the Witwatersrand Basin-Phase 1.	Boer et al., (2004)	Study to determine the main sources of water ingress and the possible measures to prevent water ingress into the mine workings
Report to the Inter-Ministerial Committee on Acid Mine Drainage – Mine Water Management in the Witwatersrand Gold Fields with special emphasis on Acid Mine Drainage.	Expert Team of the Inter-Ministerial Committee (2010)	Study to determine impacts and possible solutions to the AMD problems for the Western , Central and Eastern basin
Witwatersrand Gold Fields Acid Mine Drainage – Due Diligence Report by BKS (Pty) Ltd, BKS Report no J01599/05	BKS in association with Golder Associates (2011)	Study to determine possible ways of decreasing the AMD problem
Sustainable Development through Mining – West Rand Goldfield: Regional Closure Strategy.	Henk Coetzee (Draft report, 2011)	Study to determine possible remediation measures to decrease the ingress of surface water into the mine workings
Sustainable Development through Mining – Regional Closure Strategy for the Central Rand Goldfield.	Strachan, L. et al. (Draft report, 2011)	Study to look at short and long term measures to reduce the ingress of surface water into the mine workings as part of mine closure planning
Sustainable Development through Mining – Regional Mine Closure Strategies for the East Rand Basin	Mafanya, T., Esterhuyse, S. (Draft report, 2011)	Study to give guidance on future mine closure strategies regarding the control and management of AMD
Desktop assessment of the risk for basement structures of buildings of Standard Bank and Absa in Central Johannesburg to be affected by rising mine water levels in the Central Basin	Winde et al (2011)	Study undertaken by the Mine Water Research Group NWU and includes in depth assessment of possible ingress sources to Central Basin

2 STATUS QUO AS DEFINED BY PREVIOUS WORK

The parameters pertaining to the AMD volumes and qualities, as well as surface decant and ECL levels as quoted in the IMC Report (2010) and the TCTA Report (2011a) are summarised in **Table 2.1** to **Table 2.3**.

Table 2.1: Water yields per basin from the TCTA Report (2011a).

Basin	Approx. Average Pumping Volume	Approx. Pumping Range
	Mℓ/day	Mℓ/day
Western	27	23-35
Central	57	34-84
Eastern	82	38-110

Note: Based on pumping 19hrs/day

Table 2.2: AMD water quality.

Water Quality Parameter	Units	IMC Report (2010)			TCTA Report (2011a)		
		Western	Central	Eastern	Western	Central	Eastern
		(Median, Harmony)	(Inflow, Scott, '95)	Median, CGS	(95th percentile)	(95th percentile)	(flooded condition)
TDS	mg/ℓ	6580	4936 [(a)]	2041	7174	7700	5500
Conductivity	mS/m	510	467 [(b)]	246	548	730	450
Calcium (Ca)	mg/ℓ	-	-	-	461	580	550
Magnesium (Mg)	mg/ℓ	-	-	-	345	380	230
Sodium (Na)	mg/ℓ	-	-	-	139	150	325
Sulphate (SO_4)	mg/ℓ	4010	3700	1037	4556	5200	3275
Chloride (Cl)	mg/ℓ	-	-	-	65	260	260
pH	-	-	-	-	3.4-4.0	2.3 [(c)]	5
Acidity ($CaCO_3$)[(d)]	mg/ℓ	-	-	-	2,560	2,425	750
Iron (Fe)	mg/ℓ	697	112	38	933	1,000	370
Aluminium (Al)	mg/ℓ	-	-	-	54	50	1
Manganese (Mn)	mg/ℓ	-	-	-	312	60	10
Uranium (U)	mg/ℓ	-	-	-	0.2	--	--

[a] Derived from TDS/EC ratio of 10.6, [b] Derived by summation of reported salts
[c] 5th percentile, [d] Calculated.

Table 2.3: Water level summary table of the Western, Central and Eastern Basins.

Source Document	Decant Level (mamsl)	Decant Point	ECL (mamsl)	Depth of Proposed Long-term Static Water Level (m)	Rationale	Level not to be Exceeded (e.g. bottom of aquifer)	Other Considerations	Rate of Rise (avg.)	Date to Reach ECL	Abstraction Point	Abstraction Shaft Collar Level (mamsl)	Abstraction Shaft Depth (m)	Pump level (mamsl)	Maximum Static Head
Western Basin														
IMC Report	1680	Winzes 17 & 18	1530	150 m below decant point	Protection of dolomitic groundwater in the Cradle of Humankind	Not mentioned	N/A	Already decanting		N/A	N/A	N/A	N/A	N/A
TCTA Report	1680	Winzes 17 & 18	1550	130 m below decant point 165 m below 8 Shaft (abstraction point)	Protection of dolomitic groundwater in the Cradle of Humankind	Not mentioned	N/A			8 Shaft	1715	445	1530 to 1500	214.9
Central Basin														
IMC Report	N/A	N/A	1503	150 m below SWV Shaft	Protection of dolomitic aquifer south of Boksburg	Not mentioned	Possible mining by CRG Gold Reef City Tourist Level(200 m below SWV)	0.59 m/d	Jun-12	N/A	1653	N/A	N/A	N/A
TCTA Report	1617	Cinderella East Shaft	1467	150 m below decant point (location uncertain) 186 m below SWV (abstraction point)	Protection of weathered and fractured aquifers within the basin	Not mentioned	Mining by CRG to a level of 1278 amsl	Calc. as approx. 0.59 m/d	June '12 (high rainfall) August '12 (avg. rainfall)	SWV Shaft	1753 (presumably incorrect, should be 1653)	1400 (approx.)	1414 to 1384 / 1243 (depending on CRG)	339
Eastern Basin														
IMC Report	1550	N/A	1150	400 m below probable decant point	Protection of overlying dolomitic aquifer	Not mentioned	N/A	Grootvlei Mine was still pumping at that time		Grootvlei 3 Shaft	N/A	N/A	N/A	N/A
TCTA Report	1549	Nigel 3 Shaft	1280	269 m below decant point 290 m below Grootvlei Shaft 3 (abstraction point)	Protection of dolomitic groundwater	Not mentioned	Possible mining by Gold One down to 1040 m amsl	Calculated as approx. 0.50 m/d	December '14 (high rainfall) April '15 (avg. rainfall)	Grootvlei 3 Shaft	1570	800 (approx.)	1191 to 1134 /1040 (depending on Gold One)	436

Note: In the work of the IMC and TCTA the term ECL was used to define the proposed status water level which is now termed Target Operating Level.

The TCTA Report (2011a) selected shafts for pumping for the STI (**Table 2.3**), based on an assessment of the following criteria:

- Infrastructure already available:
- Pumping infrastructure
- Treatment plants and proximity to sludge disposal sites
- Bulk services including electricity
- Land available for plant infrastructure and stability of the ground;
- Shaft barrel stability;
- Connectivity to mine void.

In addition to the above, inclined shafts were not considered. The reason for this was not explicitly described, although it is believed that pump equipment selection was the main factor.

3 GEOLOGICAL AND HYDROGEOLOGICAL SETTING OF THE WITWATERSRAND BASIN

3.1 Geology and Mining

The Western, Central and Eastern Basins are the oldest mining districts of the greater Witwatersrand Basin, a more or less oval-shaped depression about 300 km long and 200 km wide (**Figure 3.1**). The depression hosts the Witwatersrand Supergroup, an approximately 7 km thick sequence of sedimentary rocks, amongst which are layers of gold-bearing conglomerate. These conglomerates, or reefs, have been mined for gold since their discovery in 1886. The ca. 2900 million year old Witwatersrand Supergroup is divided into the lower West Rand Group (about 5 km thick), which consists of equal proportions of quartzite (formerly sandstone) and shale (formerly mudstone), and the upper Central Rand Group (about 2 km thick) which consists primarily of quartzite with numerous conglomerate layers, several of which contain gold in economically extractable quantities (**Figure 3.2**).

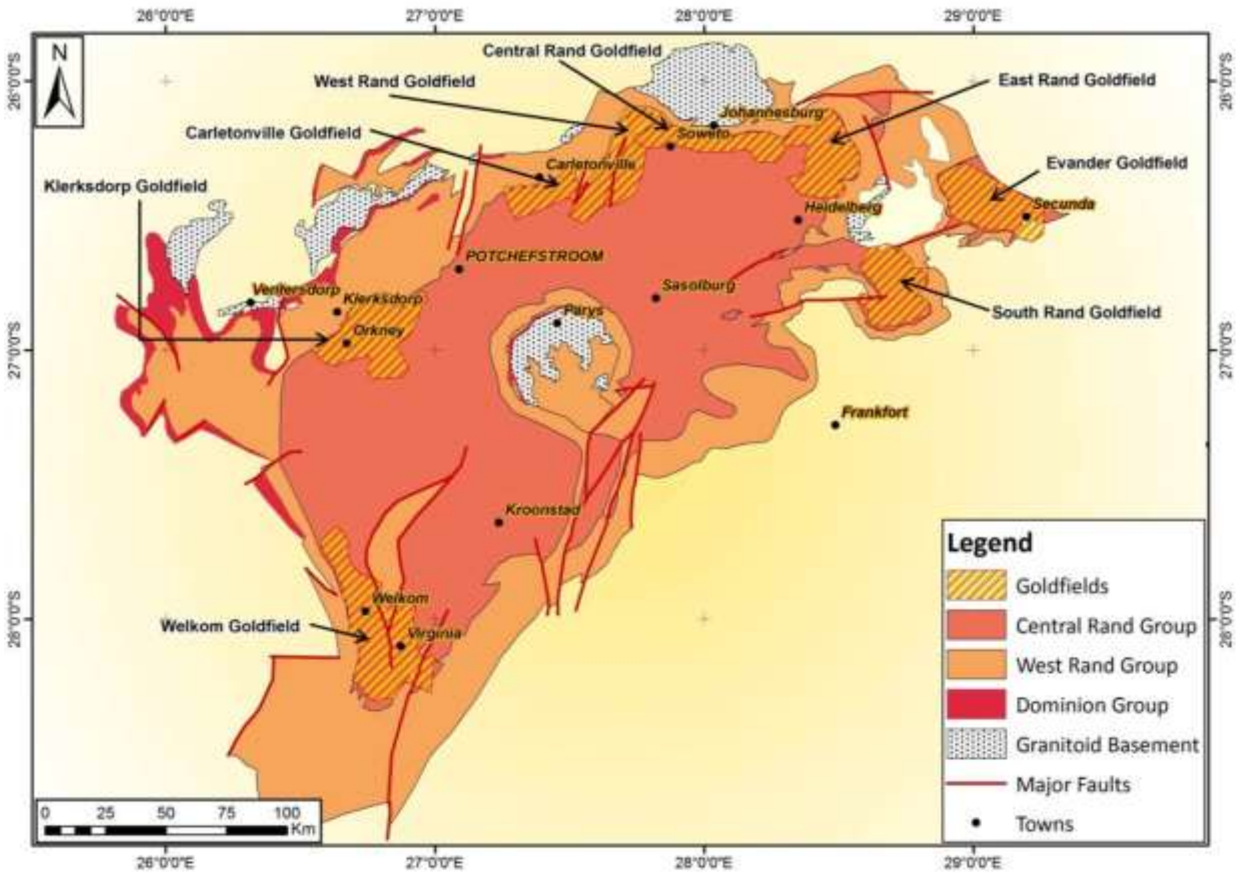


Figure 3.1: Simplified geological map of the Witwatersrand Basin showing the location of the main goldfields.

Rocks of the Witwatersrand Basin are overlain by several generations of younger rock formations. The oldest of these is the Ventersdorp Supergroup (2700 million years old), consisting of a variety of rock types of which the volcanic rock, basalt, is the most important (Klipriviersberg Group). Locally the basalt is separated from the underlying Witwatersrand Supergroup by a gold-bearing conglomerate (the Ventersdorp Contact Reef or VCR). The Witwatersrand and Ventersdorp Supergroups are overlain by sedimentary rocks belonging to the Transvaal Supergroup (about 2600 million years old). A variety of different sedimentary rock types form this Supergroup, the most important of which are quartzite and conglomerate, which is locally gold-bearing (Black Reef), followed by a thick layer of dolomite (Chuniespoort Group). Finally, all of these older rock sequences are overlain by sandstones and mudstones of the Karoo Supergroup (about 300 million years old). The Karoo sequence also contains layers of coal (Ecca Group), some of which are economically exploited within the area of the Witwatersrand Basin, including the Eastern Basin. These post-Witwatersrand rock sequences all contribute to the complex geology of the northern portion of the Witwatersrand Basin in one way or another.

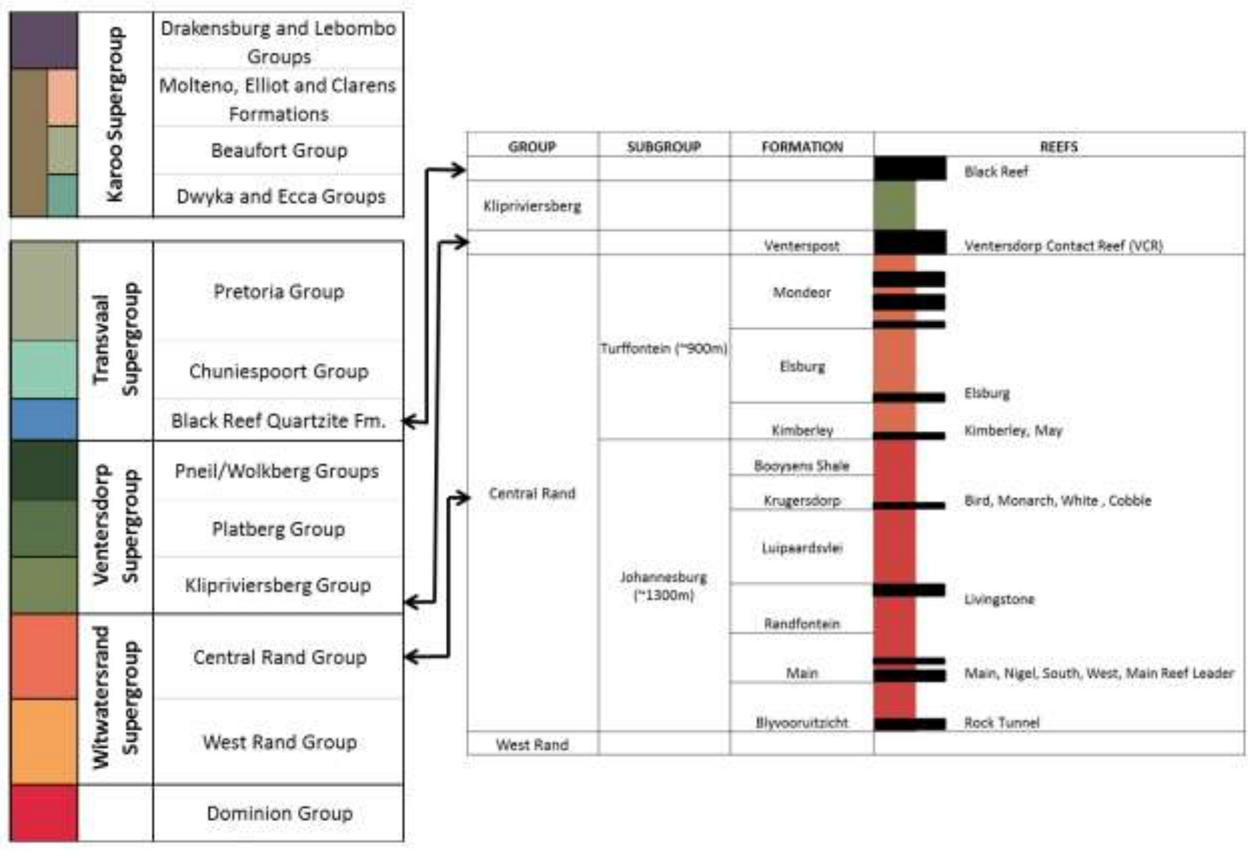


Figure 3.2: Simplified stratigraphic column for the northern goldfields, highlighting the principal reefs mined in the Western, Central and Eastern Basins.

As mentioned above, gold-bearing conglomerates are confined to the Central Rand Group (**Figure 3.2**). Along the northern portion of the Witwatersrand Basin, where the Western, Central and Eastern Basins are situated, most of the gold was contained in conglomerate

layers located near the base of the Central Rand Group (the so-called Main Reef group of conglomerates, which included the Main Reef Leader, Main Reef, South Reef and equivalents. About a third of the way up through the sequence, the Bird Reef conglomerate contained sporadic gold, and about two thirds from the base the Kimberley Reef conglomerate was also sporadically mined (**Figure 3.2**). Finally, mining of the overlying VCR and Black Reef conglomerate was also locally carried out. All of these conglomerate beds contained about 3% of the mineral pyrite (iron sulphide). Gold extraction procedures used on the mines does not extract the pyrite and it reports to the dumps. It is this pyrite which is the source of AMD along the Witwatersrand and elsewhere.

In addition to gold, uranium is also a potentially economic commodity in the Witwatersrand Basin. The Western Basin is the only one of the three basins under consideration to contain significant economically exploitable uranium, notably the Monarch Reef. From 1952 to 1995, approximately 28000 tonnes uranium were produced from mines in this basin. Although uranium is present in the Central Basin, grades were too low to warrant economic extraction. The Eastern Basin only produced about 4200 tonnes of uranium, mainly from the Kimberley reef horizons (Cole, 1998).

The conglomerate layers of the Central Rand Group were laid down sequentially over a period of tens of millions of years. Each conglomerate was originally deposited as a gravel-covered plain hundreds of square kilometres in extent that formed as the rivers, draining the hinterland to the north, coalesced in the slowly subsiding Witwatersrand Basin. For example, the Main Reef was once a continuous gravel-covered plain extending from what is now Randfontein in the west to beyond Springs in the east and south to Heidelberg, an area in excess of 3000 km^2. The Witwatersrand strata were subjected to various tectonic forces as the basin gradually filled and the once continuous strata became warped, tilted and fragmented by faults. Great fissures formed across the sedimentary layers at various times and molten rock flowed upwards through these fissures, erupting on surface to form extensive layers of volcanic rock, such as found in the Ventersdorp Supergroup. The fissures are now represented by dykes, some of which are tens of metres wide. Long periods of erosion also took their toll. Two periods of erosion were particularly destructive, the first preceding the deposition of the Black Reef conglomerate (Transvaal Supergroup), and the second preceding the deposition of the coal-bearing sandstones of the Karoo Supergroup.

The Witwatersrand rocks that we observe today are thus remnants of a much more extensive cover of gold-bearing sedimentary layers. Although originally horizontal, they are now inclined, sometimes even dipping vertically. Large areas of Witwatersrand strata are buried beneath younger rocks, especially in the Western and Eastern Basins (**Figure 3.3**).

The fragmentation of the Witwatersrand rocks is far more evident if the younger Transvaal and Karoo Supergroup strata are removed (**Figure 3.1**) as most of the disruption occurred prior to the deposition of the cover rocks.

The conglomerate layers of the Central Rand Group along the northern portion of the Witwatersrand Basin are broken into three discrete domains: the Western Basin, which is separated from the Central Basin by a fault-bounded block of conglomerate-free West Rand Group (the Witpoortjie Horst), and the Eastern Basin, which is separated from the Central Basin by an arch-like structure over which conglomerate was very poorly developed (the Van Dyk Anticline and Springs Monocline, generally referred to as the Boksburg Gap). There is therefore no interconnectivity of the mine void between these basins. In each of these domains, the layers of conglomerate, typically no more than a metre thick, were mined and the rock brought to surface where the gold was extracted.

The number of conglomerate layers mined varied from domain to domain: in the Western Basin, some twenty separate conglomerate layers were mined, some extensively, others only sporadically; in the Central Basin, four were mined in the west, reducing to only one in the east; and in the Eastern Basin, one was very extensively mined (Main or Nigel Reef) and a second (Kimberley Reef) more sporadically exploited. Locally, mining of the Transvaal-age Black Reef also occurred. Mining of the conglomerate layers extended to a vertical depth of more than 3 km below surface on certain mines in the Central Basin.

The extraction of the conglomerate layers left a huge void, which was continuous where the layers were well mineralised, broken only by dykes and smaller fault off-sets that could not be mined. However, much of the void has probably collapsed or in the deeper levels has closed by slow creep (plastic flow), substantially reducing the void volume (Winde, 2011). Brittle collapse of the shallower workings does not reduce the void volume but rather distributes it amongst smaller voids. The filling of this mining void with water has become the focus of intense scrutiny.

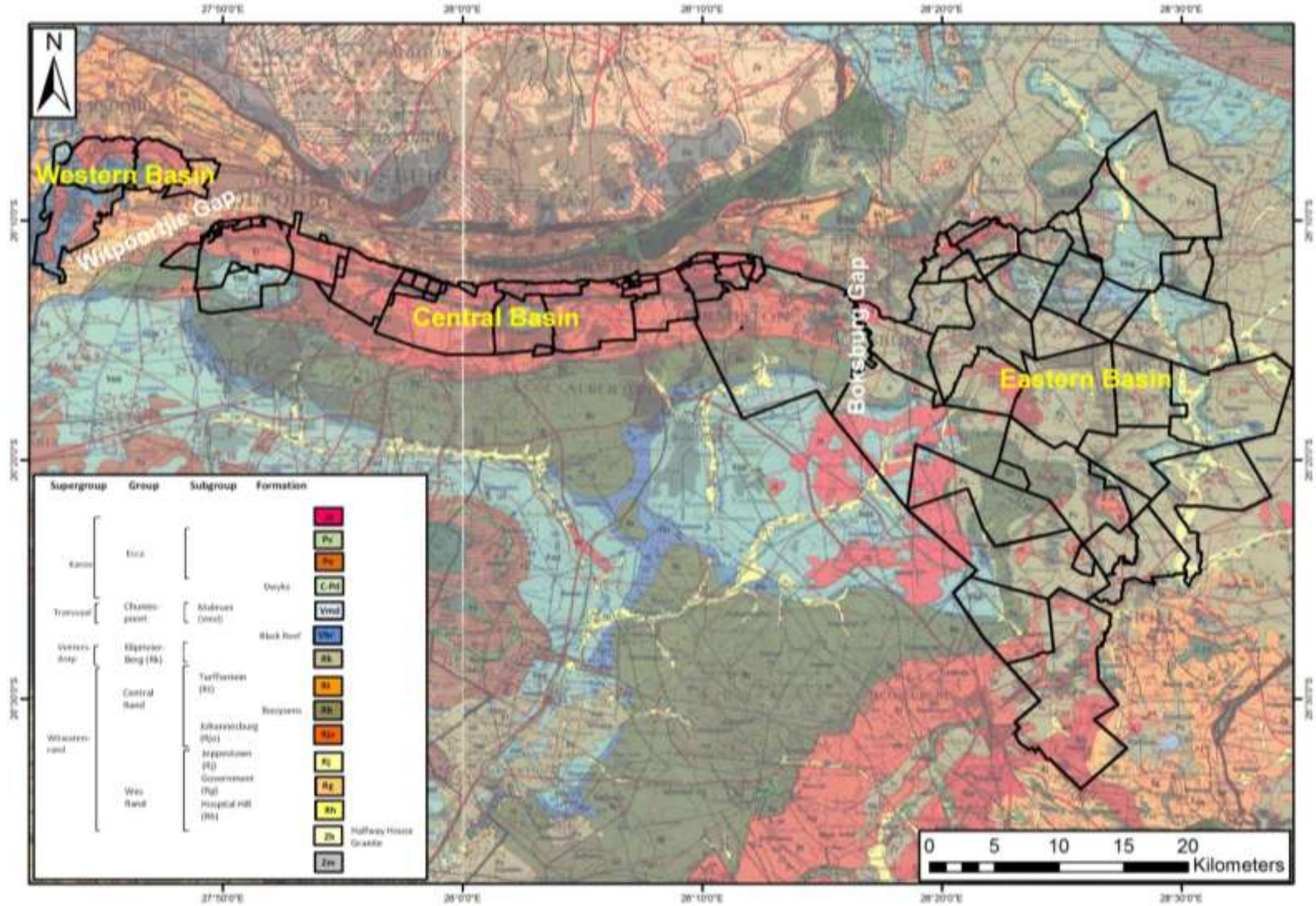


Figure 3.3: The northern extent of the Witwatersrand Basin in the Randfontein-Johannesburg-Nigel area, showing mine boundaries of the West, Central and Eastern Basins.

3.2 Hydrogeology

The regional hydrology and hydrogeology is controlled by the outcropping quartzitic rocks of the Witwatersrand Supergroup that form a continental divide separating rivers flowing northwards towards the Limpopo River (and discharging to the Indian Ocean), from the rivers draining southwards to the Orange River (discharging to the Atlantic Ocean). All the mining occurred on the southern side of the continental divide, with the result that most of the impacted rivers and groundwater occurs within the Orange River catchment.

With the exception of the Transvaal Supergroup dolomite, none of the other rock types described above (Section 3.1) are considered as significant primary aquifers. Most groundwater occurrences are restricted to the shallow weathered zones across all formations and structural features (dyke contacts, fractures and faults) which can be preferential groundwater flow paths (WUC Report, 2009). Nevertheless, water from these shallow, weathered, minor aquifers is also extracted for domestic and agricultural use via boreholes at depths up to 100 m below ground level. Groundwater flow in the shallow weathered aquifer mimics the topography and daylights as springs above less permeable layers and decants as base flow to the streams and rivers. Infiltration of precipitation recharges the shallow weathered aquifer (usually estimated at around 5-7% of the mean annual precipitation).

When mining ceases, the mine voids re-water, resulting in the formation of an artificial "aquifer" in the tunnels, drives and shafts. The vertical hydraulic connectivity of the mine voids with the overlying shallow weathered aquifer and structures is limited, as indicated by field observations, where the depth to the water table is still in the order of 3 to 17 m below surface on average, indicating that the weathered aquifer is not completely dewatered (WUC Report 2009). However, the mine void acts like a sump and depressurisation of the groundwater bearing zones/structures, when intersected by mining results in a flow gradient towards the void. Fissures bearing significant water were often sealed by grouting to restrict ingress.

Figure 3.4 shows the mechanisms of ingress to the mine voids based on a conceptual hydrogeological model down dip through the mined reef.

The dolomitic rocks of the Transvaal Supergroup are karstic due to the erosion and dissolution of the carbonate rocks along joints and fractures. This process has resulted in great water-storage potential and the dolomite aquifer is considered a significant water resource, exploited extensively for domestic and agricultural usage. Where the dolomites are outcropping in the Western and Eastern Basins and in hydraulic connection with the mined out voids, the dolomitic aquifers can contribute a significant component of the total ingress.

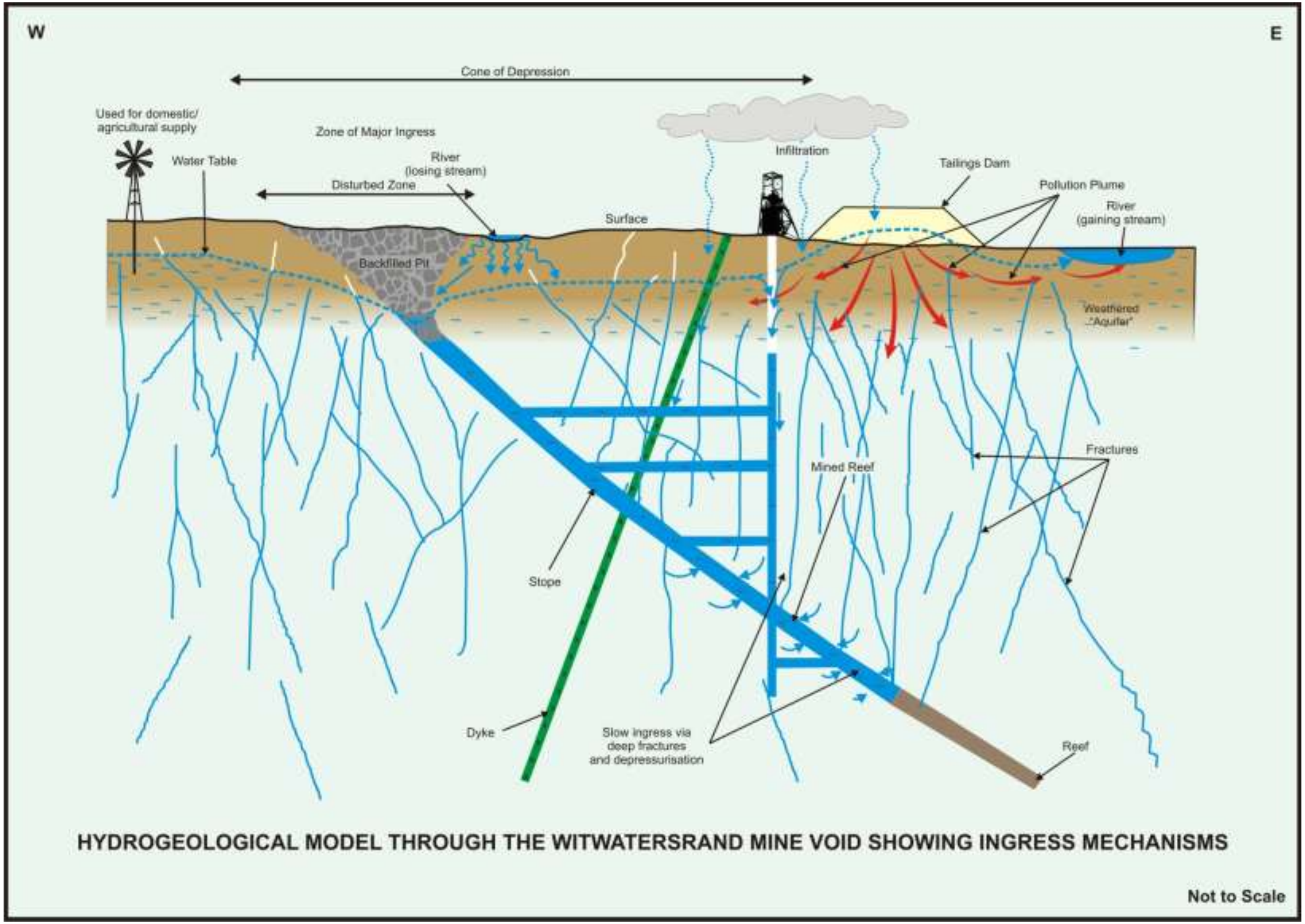


Figure 3.4: Schematic illustration of a conceptual hydrogeological model for the Witwatersrand goldfields.

4 METEOROLOGY AND INGRESS

4.1 Rainfall data

Rainfall data was analysed based on the available record from 1921 October to 2010 October. The main aim of this analysis was to review the historical rainfall pattern over time (90 year record). The figures below cover all three basins in the study area and show the distribution of rainfall over the 90 year period. It is noted in **Figure 4.1** that no significant change occurred over time except in 1975 when severe flooding occurred in most parts of Johannesburg. From **Figure 4.2** below it is noted that the mean annual precipitation has been 694mm for the Johannesburg area.

Period					Month												
					Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Per Decade
Oct	1921	to	Sept	1931	58.5	99.9	98.1	127.7	95.8	92.5	33.5	18.4	6.9	13.7	7.6	26.5	679.3
Oct	1931	to	Sept	1941	43.2	112.3	124.7	112.2	95.8	82.0	38.0	28.2	6.8	7.5	9.0	21.1	680.8
Oct	1941	to	Sept	1951	72.9	96.9	117.8	112.2	101.1	91.5	42.5	24.5	10.5	11.7	5.3	14.7	701.5
Oct	1951	to	Sept	1961	59.9	122.3	113.2	114.6	108.4	74.5	58.7	23.6	6.3	8.8	4.4	29.6	724.4
Oct	1961	to	Sept	1971	74.6	103.3	105.4	128.1	75.8	76.5	66.1	17.1	8.3	4.0	5.5	17.7	682.3
Oct	1971	to	Sept	1981	67.5	110.0	104.1	172.5	94.9	75.2	39.3	13.2	4.2	4.9	9.1	28.3	723.3
Oct	1981	to	Sept	1991	81.2	101.3	116.3	101.4	83.4	92.4	35.5	4.3	11.7	2.8	8.8	25.3	664.3
Oct	1991	to	Sept	2001	82.7	113.2	126.2	113.9	115.3	99.2	36.4	24.9	4.4	0.8	5.2	20.9	743.0
Oct	2001	to	Oct	2010	54.4	78.5	116.0	161.4	85.4	79.2	36.8	12.1	9.4	1.4	6.4	8.2	649.3
MAP																	**694.2**

Figure 4.1: Rainfall per decade over time.

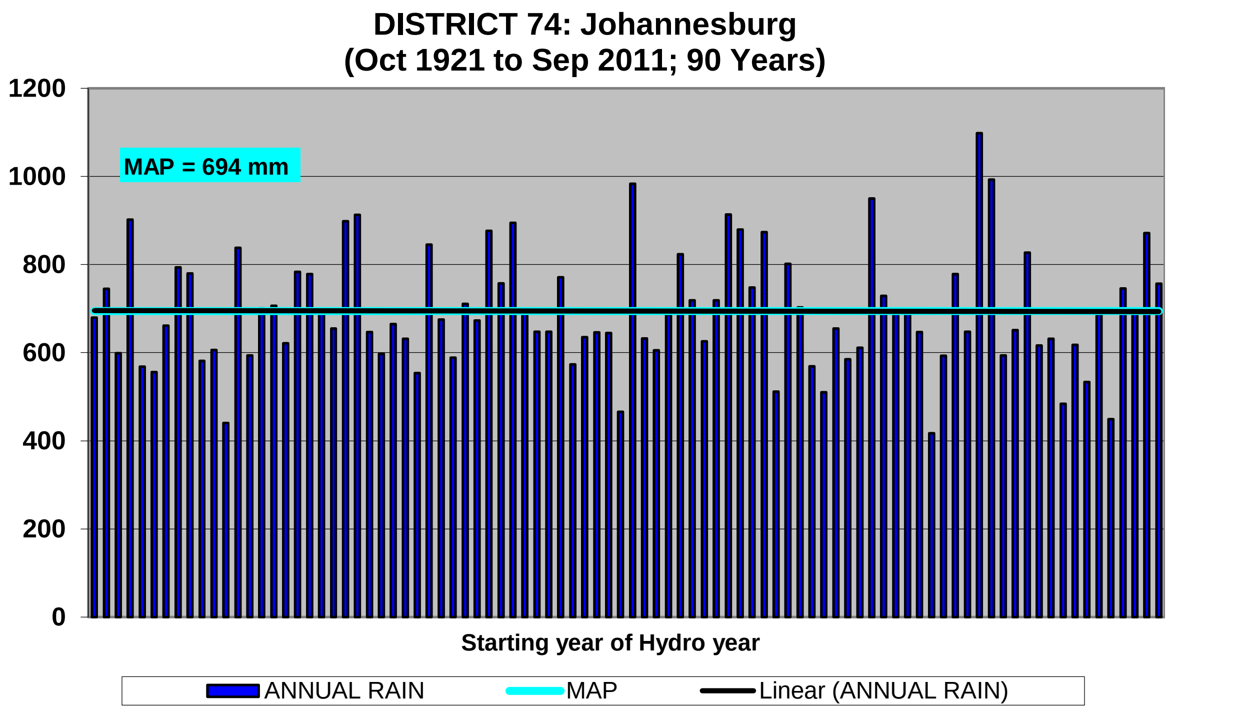


Figure 4.2: Rainfall per year over time.

As an independent validation of the rainfall data presented in the WUC Report (2009), selected weather station data was used for each basin (**Figure 4.3**). These stations are referred to in the individual basin sections of this report (sections 6.5.1, 7.5.1, and 8.5.1).

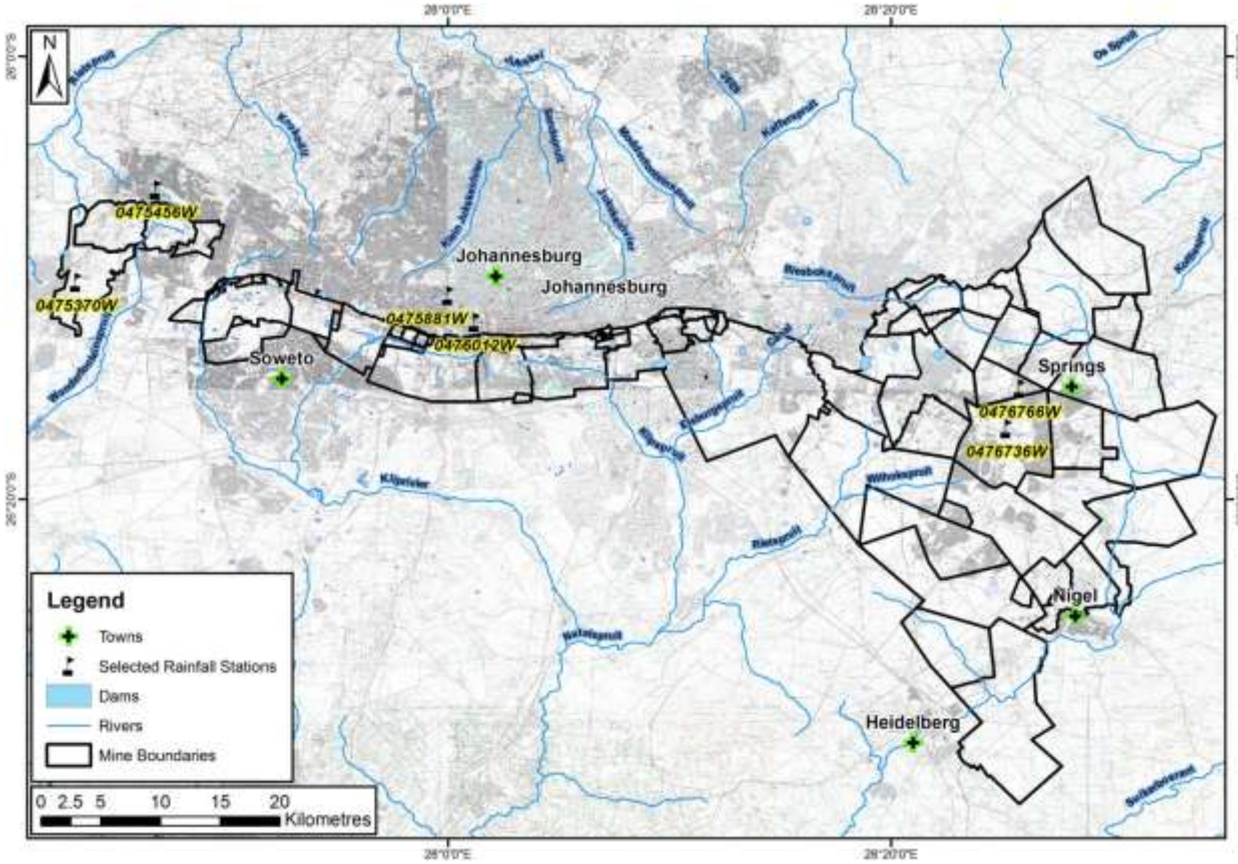


Figure 4.3: Selected weather stations across the basins used for verification of rainfall data.

4.2 Climate Change

An important factor to consider is potential climate change that may affect weather patterns, as well as deviations in rainfall. The University of KwaZulu-Natal (Schulze, 2010) has recently conducted a study to determine the potential deviations in rainfall within the Southern African region. The study was based on the Global Climate Model (GCM), which was then downscaled to cover the Southern African region. The results are shown in **Figure 4.4**.

The following observations are made:

- Most of the provinces in South Africa are predicted to experience an increase in the average annual precipitation as well as monthly average rainfall;
- In Gauteng Province, an average ratio of increase between 1.2 and 1.4 is expected; i.e, the average annual rainfall is expected to be between 20% and 40 % more than the rainfall in 2010;
- In view of the above, the volume of ingress may increase with the increase in annual rainfall in basins that are sensitive to rainfall- runoff patterns such as the Western and

Eastern Basins. This is mainly due to the seasonality of the river systems in these basins rather than the constant flowing rivers within the Central Basin attributed to leaking pipes and sewerage discharges.

- The recommended water level monitoring should be used to determine abstraction rates.
- Since the achieved volumes of ingress, effectiveness of measures to reduce ingress and average volumes to be pursued are all uncertain, no specific provisions have been made.

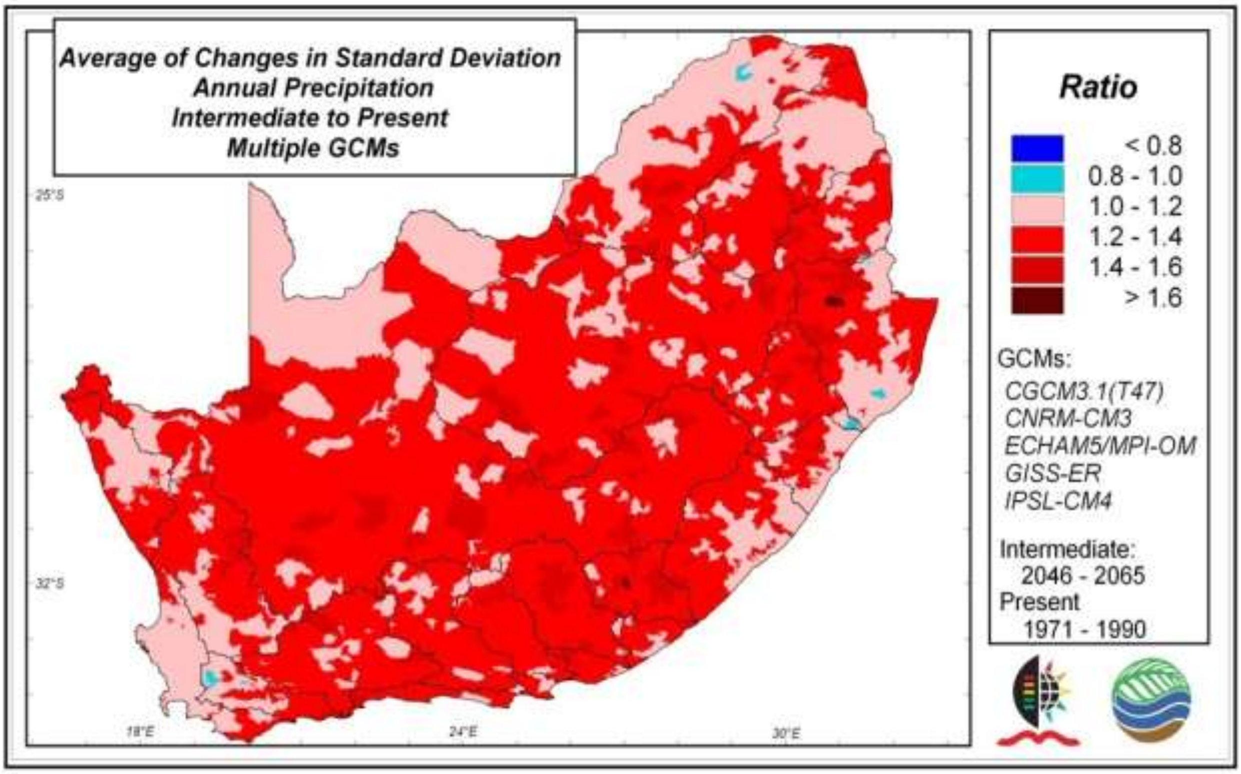


Figure 4.4: Average change in annual precipitation (Schulze, 2010). "Ratio" is defined as the expected change in annual rainfall in relation to actual annual rainfall during 2010 which was used as a bench mark for the study.

4.3 Ingress Mechanisms

In order to try to minimise the amount of water entering the mine voids, it is important to identify the possible ingress mechanisms. This would aid in keeping the ingress as low as possible, as well as reducing long term pumping treatment and maintenance costs.

The main objectives of the ingress review are summarised as follows:

- Identify and source existing information on the ingress of surface water into the mine void;
- Review existing available information and extract main findings on the mechanism of ingress and possible mechanisms to reduce the surface water ingress
- Determine the potential impact of the surface water ingress and source thereof on the decant volumes and water quality;
- Identify potential gaps in information and findings of the studies done to date;

- Give recommendations on possible additional studies/monitoring programmes required to improve the confidence of the predicted ingress volumes; and
- Give recommendations on priorities for and potential benefits of reducing ingress.

The following potential ingress sources and associated mechanisms were identified:

- Recharge through undisturbed geology;
- Ingress through shafts, inclines, adits and rehabilitated/backfilled open cast pits;
- Surface water resources (rivers, dams) seeping directly into mine openings and shallow groundwater systems above zones of historical surface operations and shallow undermining;
- Tailings dams and mine dumps are seen as areas of enhanced and concentrated seepage where the volume of water entering the mine workings is usually found to be high;
- Leaking sewerage lines and water mains, poor stormwater management and waste treatment.

4.4 Minimising Ingress

Natural recharge through the weathered aquifer is a diffuse process, and in general the management of this ingress will not be practicable. Care should however be taken to avoid the enhancement of the recharge of this aquifer through proper stormwater management in urban areas and other measures to avoid ponding of water on the surface. However, ingress could be reduced for the following ingress sources detailed below:

Mine residue deposits

In particular sand dumps and slimes dams have been identified as sources of ingress, particularly where these overly areas of shallow undermining or backfilled surface operations. These impacts can be addressed either by removal of dumps and reworking to extract residual gold and uranium and final disposal on a properly engineered site, or by capping dumps to prevent the infiltration of water and shaping the dumps to allow water to run off, rather than infiltrate. Ideally capping should be done with impermeable material, but even soil cover has been shown to significantly reduce infiltration (WUC Report, 2009).

Rehabilitated/backfilled pits

The pits that have already been rehabilitated usually act as a “sink” to surface water ingress due to increased permeability of the backfill materials that in the pit. It is therefore suggested that for these areas additional layers of backfill are placed over the pit area, compacted and shaped such that stormwater runoff is diverted and drained away from the pit. In addition to this an impermeable clay layer should be placed over the backfill to reduce the infiltration potential

Existing open pits

Where mined out reef outcrops are close to, or crossed by, watercourses and runoff areas, they should also be covered with an impermeable layer where practically possible. Shaping of this area should also be done so as to minimise the surface runoff from entering the reef area.

Existing open pits should be backfilled with suitable materials such as tailings from reprocessing plants, such that the pit no longer accumulates surface water. The final layer of the backfill should again be a clay layer such that the infiltration potential is minimised.

Mine Tailings and Dumps

Investigation of potential ingress from existing residue deposits - Removal of residues and capping or shaping of the remaining deposits. It is noted that the current method for re-working of the tailings dumps by hydraulic monitoring could also increase ingress into the mine void, due to the large water volumes utilised, but in the longer term, removal of these facilities will result in an overall improvement of the surface water and hence mine void water quality.

Rivers, water bodies and stormwater drainage systems

Where a river crosses a shallow mined out area or a potential water bearing structure such as a major fault or dyke with suspected or proven hydraulic connection to the mine voids , possible canalisation and/or diversion should be considered. At water bodies such as dams and vlei areas, it will not be easy to implement control measures as this is primarily a diffuse source. This is sometimes not practical and hence more detailed and site specific studies are required. Further investigations that could be considered are:

- Identification and upgrade of stormwater where diverted into abandoned surface workings.
- Identification and prevention of the flow of stormwater into open pits.
- Audit of possible ingress via leakage from stormwater and main water supply systems.
- Upgrading of stormwater management to prevent ponding, encourage run-off and ensure that stormwater is discharged to streams away from possible mine void ingress areas.

It should be noted that before any of the above control measures are implemented, further detailed and site specific cost-benefit studies would needs to be undertaken. This would aid the client in determining the net benefit of implementing the control measures in relation to initial capital expenses and a reduction in long term operating and maintenance cost of the decanting pumps, as well as the water treatment works and waste material handling facilities.

The IMC provides an action plan for short and medium- to long-term interventions for the management of AMD and is attached as Appendix A4. Although it does not provide any detail with regards to ingress prevention it does state that for the short-term prevention of ingress should be commenced immediately (or be continued in areas where it's already

taking place). These short-term measures are discussed in more detail for each basin as they also form part of the long-term solution.

Specific Proposals

A summary of specific proposals which are captured in various reports is given in Appendix A.

The Council for Geosciences (CGS) are currently conducting a study which has ingress control as a component.

5 WATER QUALITY

5.1 AMD

It is generally accepted that the ultimate source of the AMD in the Witwatersrand gold mines is the pyrite (ca. 3%) contained in the auriferous conglomerates that are being mined. On exposure during the mining process, and with the addition of water and oxygen, the pyrite oxidises to sulphuric acid and iron. This is a complex process, but is generally simplified to the following reactions (Stumm and Morgan, 1981):

(1) Oxidation of pyrite and solubilisation of ferrous Fe

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

(2) Oxidation of ferrous to ferric Fe

$$4Fe^{2+}(aq) + O_2(g) + 4H^+(aq) \rightarrow 4Fe^{3+}(aq) + 2H_2O(l)$$

(3) Direct oxidation of pyrite by ferric Fe (pH<3)

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

(4) Precipitation of ferric hydroxide (“yellow boy”) (pH>3)

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

Although reactions 1 and 2 can take place spontaneously, they are typically slow and rate-determining. In nature, microbial catalysation of these two reactions by archaea and bacteria (e.g. acidophyllic *Thiobacillus ferrooxidans*) is well documented (Rawlings and Kusano, 1994, Trudinger, 1996). However, the end-product of these oxidation reactions is invariably a corrosive and potentially toxic AMD of variable quality (acidity and dissolved solids), depending on the quantity ratio of pyrite to water that was involved.

Dissolved sulphate forms the main salt component present in AMD of the Witwatersrand, making as much as 60 to 80 per cent of the total dissolved solids (TDS), and presents the main challenge in treatment of the acid mine water. In addition, the Witwatersrand AMD may be enriched in heavy metals, including variable trace quantities of uranium, that derive from the metal sulphides, metal oxides and silicate minerals present in the auriferous conglomerate reef.

It is conceivable that poor quality AMD can be either prevented, or ameliorated (i.e. returned to potable water quality) by dilution or chemical treatment (**Figure 5.1**). Since the prevention option is unlikely to be practically achievable, the other two options almost invariably need to be considered. Dilution is an attractive choice but may require large quantities of fresh water to mix in with the AMD (blue arrows, **Figure 5.1**). For typical Witwatersrand AMD (TDS ~ 4000 mg/l), the dilution ratio needed is one part AMD with at least 10 parts fresh water. Among the chemical treatments, liming (green arrow, **Figure 5.1**) is one of the least costly

options, causing a reduction of pH but only incomplete reduction in the salt load (Bowell, 2000). For more effective desalinations, more aggressive (and expensive) sulphate removal treatments (black arrow, **Figure 5.1**) are clearly advisable. For the metal-rich Witwatersrand AMD, a biological sulphate reduction process, which also removes heavy metals (Bowell, 2000), is considered optimal (**Figure 5.2**).

Mixing (blue arrows, **Figure 5.1**) is a two-way process. Either the AMD can be diluted to potable water, as suggested above, or potable water can be contaminated by AMD. The latter situation appears to occur in the vicinity of old mine dumps where surface runoff may enter open derelict mine shafts and workings and contaminate the mine void water. As a preventative measure, these dumps can either be moved or chemically isolated. Moving the dumps will reduce their negative impact at the site of removal, but will transfer the problem to the site of deposition. The costs involved in such massive earth moving operations are considered prohibitive given that they present an incomplete solution. Chemical isolation would probably also be costly due to the complexity of the task.

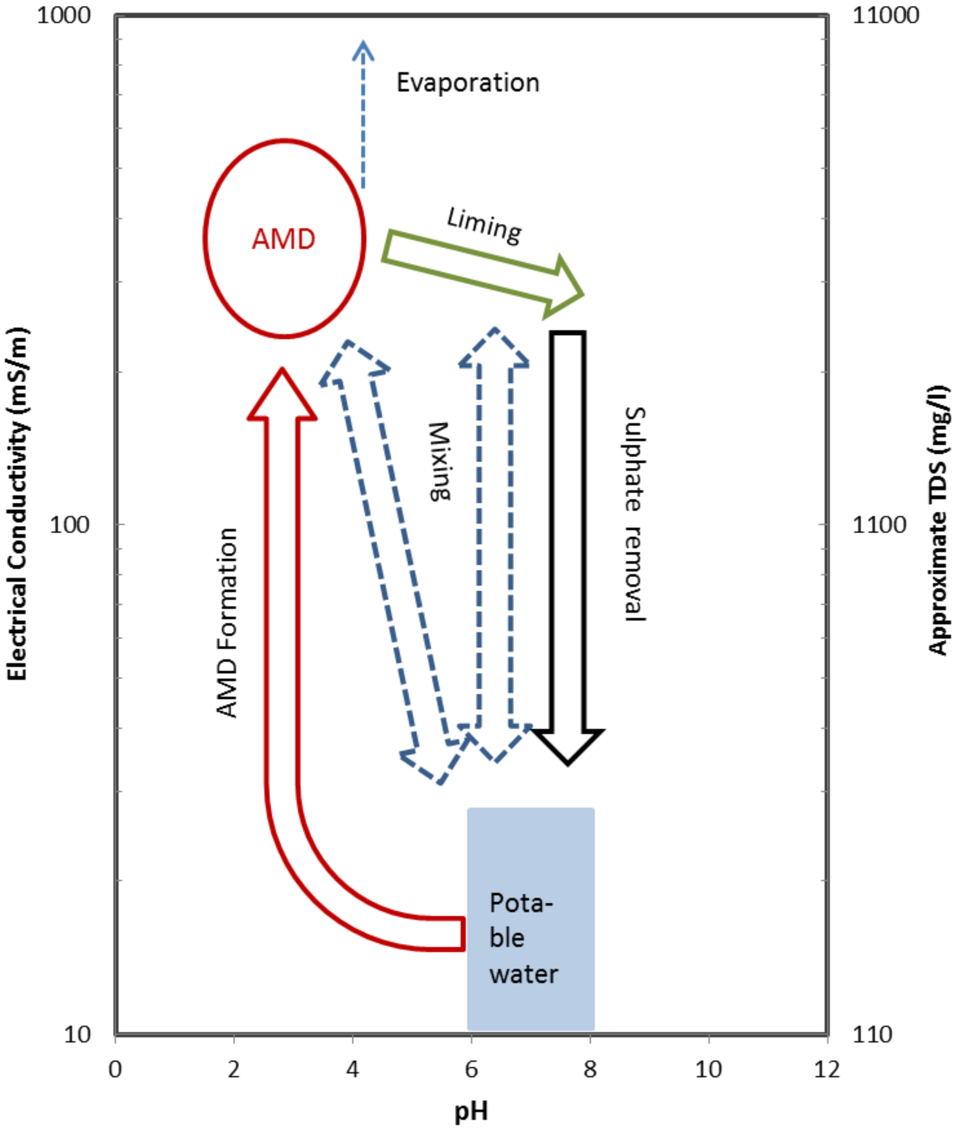


Figure 5.1: Schematic presentation of AMD formation and treatment.

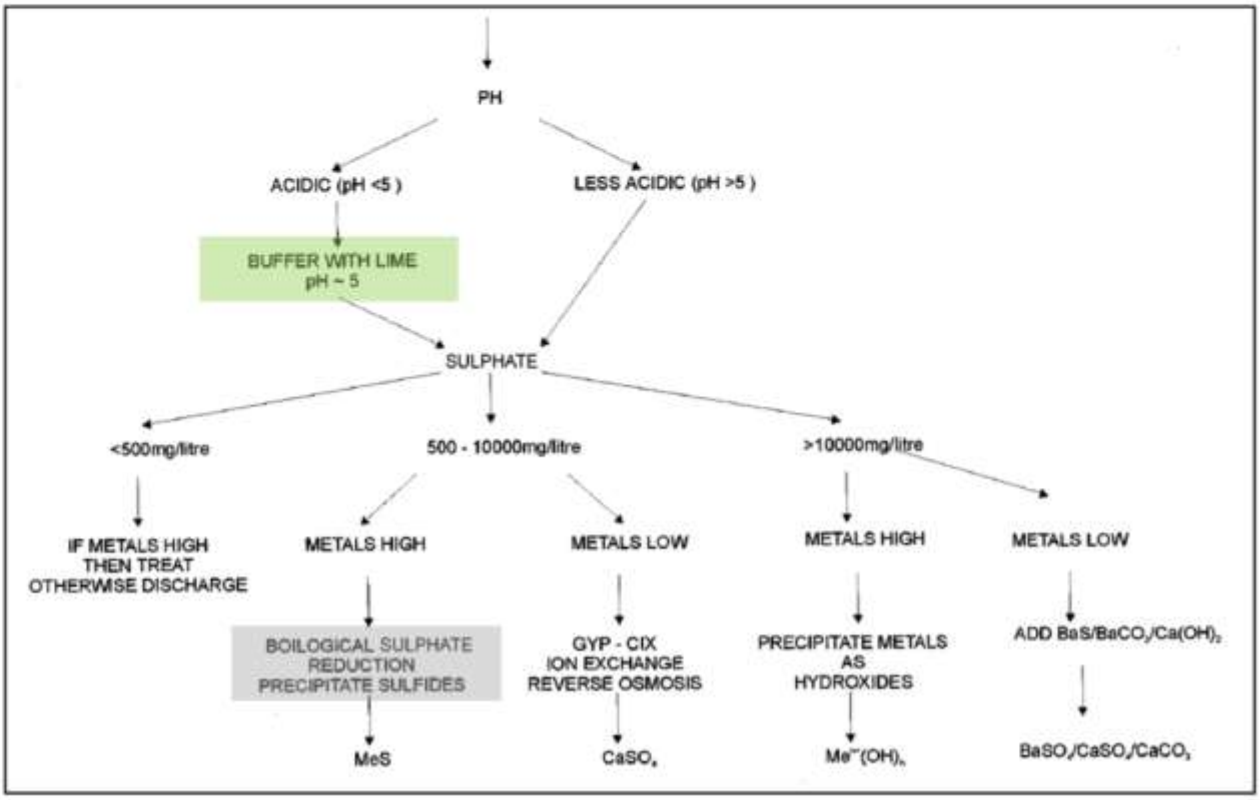


Figure 5.2: Treatment options of AMD after Bowell (2000).

The total salt in solution, expressed as Total Dissolved Solid (TDS), is an important parameter in AMD in that it determines the quantity of sludge that will be generated on treatment. It is evident from the data sources consulted that TDS was seldom directly determined. In this report, the following estimates were used as appropriate where TDS was not directly determined:

(1) summation of anion and cation concentrations for reasonably complete analyses;

(2) for incomplete analyses and SO4 is available, TDS(mg/l) ~ 1.5*SO4(mg/l); and

(3) where SO4 is not available but EC was measured, TDS(mg/l) ~ 11*EC(mS/m).

These equations are empirically determined and have been found to hold reasonably well for all three basins. It should also be noted that the TDS estimation using EC corresponds closely with the 10.6*EC (mS/m) equation used in the IMC Report (2010).

5.2 HDS Composition

Whilst the treatment aspects of High Density Sludge (HDS) are addressed by other components in this Feasibility Study, the possibility of disposing of the sludge into the underground environment of the mine void has been ventured and is therefore discussed briefly in this report. The estimated bulk composition of HDS on the Witwatersrand is provided in **Table 5.1**.

Table 5.1: Estimated HDS sludge composition (Study Report no 5.4 on Treatment Technology Options).

Precipitate [dry basis]	Units	Sludge Composition		
		Western Basin	Central Basin	Eastern Basin
$Fe(OH)_3$	%	32.5%	31.6%	38%
$Fe(OH)_2$	%	1.4%	3.7%	2%
$Al(OH)_3$	%	3.0%	0.1%	0%
$Mn(OH)_2$	%	9.2%	1.6%	1%
CaF_2	%	0.0%	0.0%	0%
$Ca_3(PO_4)_2$	%	0.0%	0.0%	0%
$Mg(OH)_2$	%	0.0%	0.0%	4%
$CaCO_3$	%	4.9%	4.4%	1%
$CaSO_4$	%	49.1%	58.6%	55%
Total Sludge [dry]	*Tons/day*	*148.4*	*345.7*	*152.5*
Total [if filter cake @ 65% solids]	*Tons/day*	*228.3*	*531.8*	*234.6*
Total [if filter cake @ 65% solids]	*m3/day*	*142.7*	*332.4*	*146.6*
Total [if sludge @ 10% solids]	*Tons/day*	*1484.2*	*3457.0*	*1525.0*
Total [if sludge @ 10% solids]	*m3/day*	*1349.2*	*3142.7*	*1386.3*

The sludge consists primarily of gypsum and hydrated oxides of iron and manganese. It has a relatively low carbonate content. Witwatersrand AMD also contains significant amounts of other metals which have not been listed in **Table 5.1**. Some indication of their abundance relative to iron is provided by the AMD seepage analyses shown in **Table 5.2**.

The majority of the metals listed in **Table 5.2** will precipitate along with iron and manganese in the liming process of the HDS plant and hence the sludge is likely to contain significant quantities of cobalt, copper, nickel and chromium. It will probably also contain some uranium due to co-precipitation.

Table 5.2: Chemical composition of acid mine seeps in Germiston, Central Basin (Naiker et al., 2003).

Analytical results for ground and surface waters collected over 10 km reach of the Natalspruit[a]

Sample	pH	Eh mV	Cond mS/cm	SO_4^{2-} mg/l	Cl^- mg/l	Cr mg/l	Zn mg/l	Pb mg/l	Cu mg/l	Fe mg/l	Mn mg/l	Co mg/l	Ni mg/l	Na mg/l	Ca mg/l
1S	7.01	277	0.37	250	21.00	1.65	0.1	0.00	0.10	2.38	0.30	0.00	0.13	10.24	84.60
1G	7.04	157	0.81	300	12.00	2.01	5.0	0.10	0.20	9.78	0.40	0.00	0.10	19.07	125.20
2S	6.17	269	1.5	500	12.00	2.01	1.5	0.10	0.10	26.61	6.20	0.69	1.02	49.26	125.80
3S	7.90	277	0.5	360	17.40	2.01	0.0	0.10	0.10	0.62	0.00	0.00	0.10	18.06	69.40
4E	3.08	600	5.71	2080	80.00	5.90	8.0	0.40	6.00	384.30	86.60	14.30	17.88	25.64	133.10
4S-A	5.78	316	1.31	680	17.50	2.19	1.0	0.10	0.10	19.19	8.30	0.37	1.06	38.99	121.00
4S-B	5.49	375	1.37	570	17.40	2.19	1.1	0.10	0.10	23.82	8.00	3.10	1.26	24.36	141.60
4S-C	5.25	400	1.38	530	18.06	1.65	1.2	0.10	0.20	24.84	8.50	0.62	1.38	46.81	145.20
4G-A	3.76	432	5.45	1750	36.40	9.97	8.0	0.70	6.00	453.40	68.00	11.40	15.28	22.60	125.70
4G-B	3.78	431	4.77	1400	26.70	5.82	7.0	0.30	5.00	379.00	72.00	10.30	15.38	23.28	116.40
5S	7.14	158	0.94	430	17.40	2.01	0.1	0.10	0.10	12.09	1.40	0.00	0.35	36.05	127.30
5G	4.56	408	1.33	570	23.50	2.01	1.4	0.20	0.40	3.69	2.40	0.00	0.57	29.09	204.10
6S	6.73	201	0.85	370	18.20	2.01	0.3	0.20	0.20	10.09	0.60	0.00	0.43	44.95	117.30
6G	3.96	394	5.7												
7S	4.49	442	1.14	530	16.00	2.01	1.5	0.20	0.30	77.60	2.00	0.00	1.27	29.31	100.90
8S	6.36	236	1.2	500	12.00	2.01	0.5	0.20	0.20	17.38	2.80	0.00	0.64	44.55	122.90
9S	6.14	291	1.04	430	10.80	2.01	0.4	0.10	0.10	14.70	2.50	0.00	0.59	35.40	127.10
10S	6.53	234	1.01	490	12.00	2.01	0.4	0.10	0.20	13.06	2.10	0.00	0.55	40.55	115.30

S, surface water, G, ground water; E, seepage water.

[a] Samples were collected in October 1999.

Under elevated pH conditions (the HDS pH is estimated to range from 8 to 10), most of these metals will remain in the solid form as hydrated oxides. However, should the sludge be transferred into the subsurface environment, which is inherently acid due to sulphide oxidation, the carbonate will dissolve and once that is gone, the metal oxides will also dissolve into the void water. Unless the voids where the sludge is deposited can be isolated, this will probably result in continual recycling of the more serious pollutants particularly if the sludge is not disposed of at considerable depth. The anticipated improvement in the quality of water being pumped from underground could be seriously delayed.

The current volume of the mine void at depth (say > 1000m) is unknown but it is postulated (Winde 2010) that the stopes will have closed. The remaining void will be haulages and cross cuts, etc., which generally slope towards the shafts. It is therefore not considered prudent to consider disposing of the HDS into the mine void without a specialist feasibility study into all the implications. This investigation would also have to investigate the status and accessibility of shafts into potential compartments, particularly lime shafts to depth are all multi stage shafts. An alternative of very deep boreholes should be considered, but will have a high capital cost.

Ideally, the sludge should be converted into a saleable form. If the iron could be separated from the gypsum, it could possibly be used as a pigment in paint or even sold to scrap metal recyclers. Every effort should be made to achieve this goal. In the interim, co-disposal with tailings is the preferred option.

6 WESTERN BASIN

6.1 Geological Setting

The Witwatersrand Supergroup strata in the Western Basin have been folded into an open, basin-like syncline which plunges towards the southeast (**Figure 6.1**). The dips of the Central Rand Group strata vary from about 20° to as much as 70° to the south, southeast and east in this syncline. The syncline terminates against an up-faulted block known as the Witpoortjie Gap or Horst, which is bounded by the Witpoortjie Fault in the north and Roodepoort Fault in the south.

The Witwatersrand strata in the Western Basin are partially buried beneath younger Transvaal Supergroup strata, specifically the Black Reef and overlying dolomite (**Figure 6.1**). Unlike the Witwatersrand strata which are strongly folded, the rocks of the Transvaal Supergroup have experienced only very gentle warping and are tilted only a few degrees from the horizontal to form shallow troughs and swells. Some of these rises and depressions may even reflect the original topography of the surface on which the Black Reef was deposited.

The dolomite that overlies the Black Reef in the syncline (**Figure 6.1**) is generally thin and largely decomposed to form a very porous, iron-manganese oxide mixture known as wad. Only isolated remnants of the original dolomite remain. Further to the northwest the dolomite is more extensively developed and hosts the famous Cradle of Humankind Heritage Site.

The lower West Rand Group strata contained little gold, but in the upper Central Rand Group, many of the conglomerate beds contained economic gold and as many as 22 reefs were mined to varying extents. The up-faulted Witpoortjie Horst consists of West Rand Group strata and was thus not mined. The reefs in the West Rand syncline were followed down from surface to a maximum depth of around 1.5 km where they terminate against the Witpoortjie Fault (**Figure 6.1**). The conglomerate layer in the Black Reef is sporadically mineralised and was mined using both open-cast and underground mining methods.

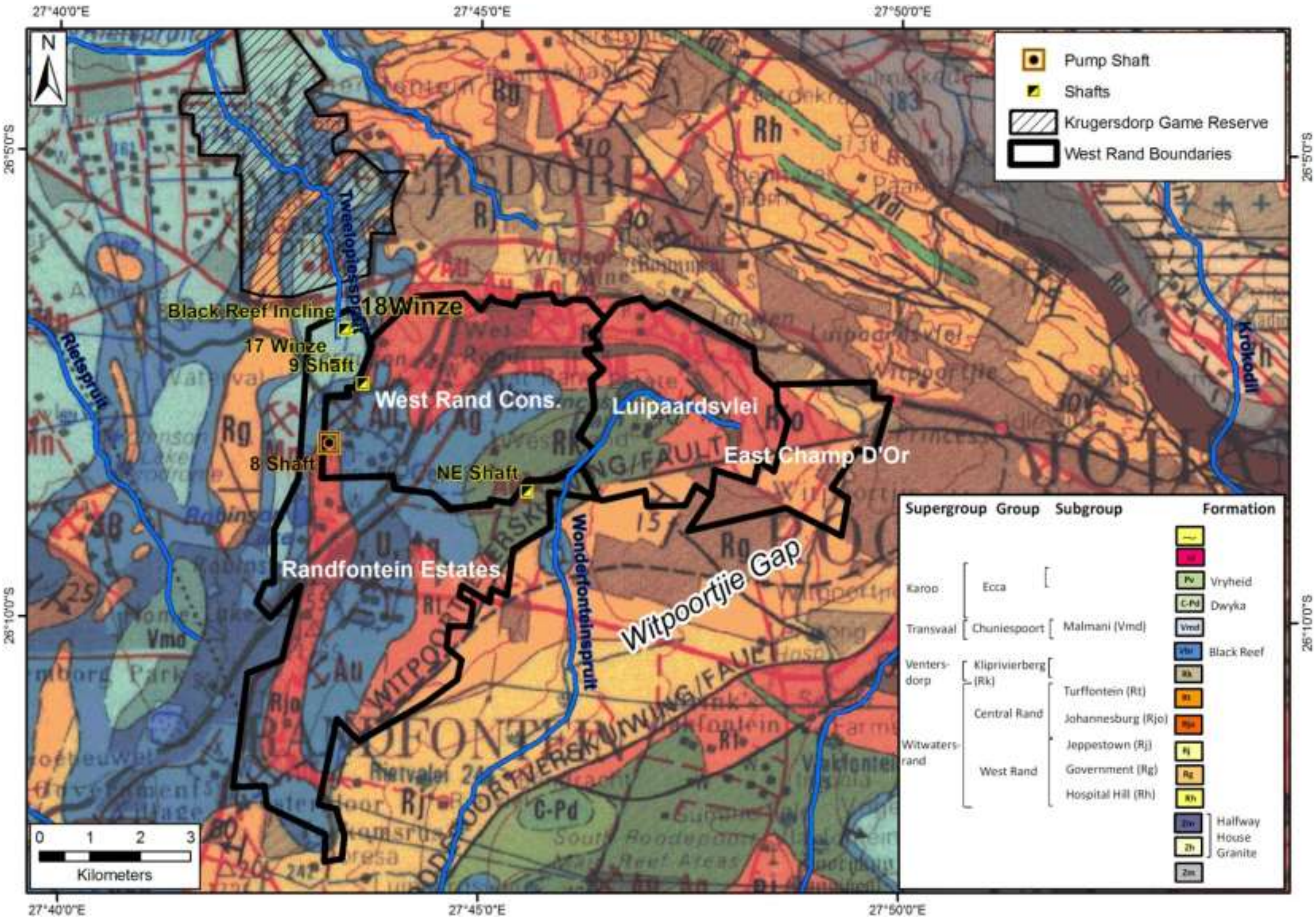


Figure 6.1: Geological map of the Western Basin, showing mine boundaries and selected shaft positions.

6.2 Hydrogeological Setting

Figure 6.2 shows the conceptual hydrogeological model for the Western Basin in a cross-section from northwest to southeast. Groundwater occurs in the weathered and fractured sedimentary rocks of the Witwatersrand rocks. These shallow water-bearing horizons are not considered to contain economic and sustainable aquifers but localised high yielding boreholes exist where significant fractures, seldom deeper than 60 m below surface, are intersected. The hydraulic conductivity and storativity of the weathered aquifer is generally low and groundwater movement through this aquifer is therefore slow.

The dolomite outlier within the syncline (**Figure 6.1**) represents the most prominent aquifer in close proximity to the Millsite tailings facility and the Western Basin mine voids, and is consequently the most vulnerable to groundwater contamination. The dolomite aquifer in the Western Basin is separated by Witwatersrand quartzite from the Sterkfontein dolomite aquifer, which lies to the northwest of the syncline and hosts the Cradle of Humankind World Heritage Site. There is some speculation that groundwater flow across the fractured Witwatersrand rocks could allow for some interaction between the compartments but this is unproven. The Sterkfontein compartment is more likely to be impacted by surface water contamination from the Tweelopies Spruit, into which surface decant from the mine void is currently occurring (Hobbs and Cobbing, 2007 and Hobbs, 2011).

The Zuurbekom dolomite aquifer is located to the south of the Witpoortjie Horst and is unlikely to have a direct interaction with the West Rand Basin. However, this dolomite aquifer, which extends along the entire length of the Western and Central Basins has been severely polluted by discharge from the tailings dumps (Kafri and Foster, 1989).

Since the Western Basin mine void was completely flooded in 2002, the water table is close to surface and the hydraulic gradient has been reversed such that groundwater flow is from the mine void and decanting across the hydraulic divide into the Tweelopies Spruit and ultimately into the Limpopo Catchment from shafts and boreholes, and the Black Reef incline.

By lowering the water table in the mine void, the hydraulic gradient will be towards the mine void and uncontrolled decant will be stopped.

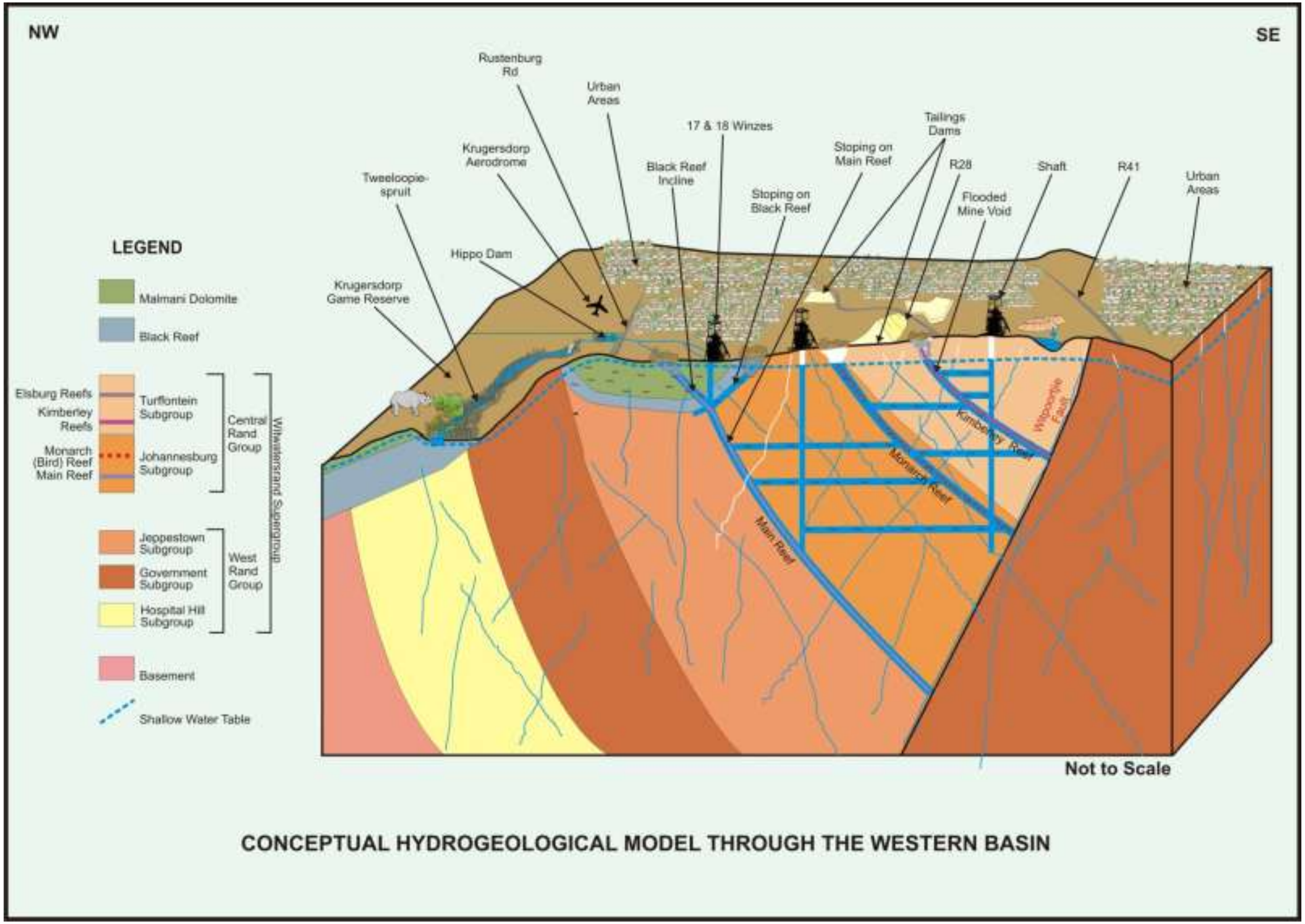


Figure 6.2: Schematic illustration of a conceptual hydrogeological model for the Western Basin.

6.3 Mine Voids

6.3.1 History, distribution and connectivity

The Western Basin consists of four mines: Randfontein Estates, West Rand Consolidated, East Champ d'Or, and Luipaardsvlei (**Figure 6.3**). As such, it is distinct from the West Rand goldfield that, in addition to the aforementioned mines, also includes the Doornkop, Cooke Section, Ezulwini and South Deep mines to the south of the Western Basin.

The major mined out area is shown in **Figure 6.3**, which illustrates the huge extent of the mine void. In the last few decades, the shallower, lower grade reefs have been mined by open-cast methods. The mine void of the Western Basin is separated from the Central Basin by the Witpoortjie Gap, a horst block bounded by the Witpoortjie Fault in the north and Roodepoort Fault in the south. No Central Rand Group strata are preserved in the Witpoortjie Gap and consequently no mining took place. The southern mines of the West Rand goldfield are also not connected to the Western Basin mine void due to the Witpoortjie Gap.

A thorough evaluation of the interconnectivity of the Western Basin mine void is prohibited by the long mining history, from the late 19^{th} Century onwards, and the large number of reefs exploited. However, the available evidence supports a high degree of interconnectivity and reasonably free flow within the void.

Water is considered to enter the mine void in a variety of ways.

- Rainfall and local runoff enters the void directly along the disturbed zone that follows the outcrops of the numerous mined reefs. For example, extensive open-cast mining of the flat-lying Black Reef conglomerate has taken place in the area (notably by Lindum Reefs). These workings were often backfilled with overburden. Also, the Black Reef workings occasionally intersected the underlying mining void of the Witwatersrand reefs. The combined effect of these mining practices has probably hugely increased the area of disturbed zone above the mine void, thus increasing recharge into the deeper void.
- Groundwater from the shallow weathered aquifer, where it is undisturbed by mining, flows laterally into the disturbed zone and enters the void.
- At depth, depressurisation caused by the mine void will lead to groundwater flow into the void via permeable structures.

6.3.2 Water Levels

Following cessation of mining in the area in 1998, the mine void in the Western Basin filled with water and finally began to decant on surface in 2002. Surface decanting takes place through three old shafts, the Black Reef Incline (BRI) (1669 m amsl) and No's 17 (1679 m amsl) and 18 Winzes (1677 m amsl).

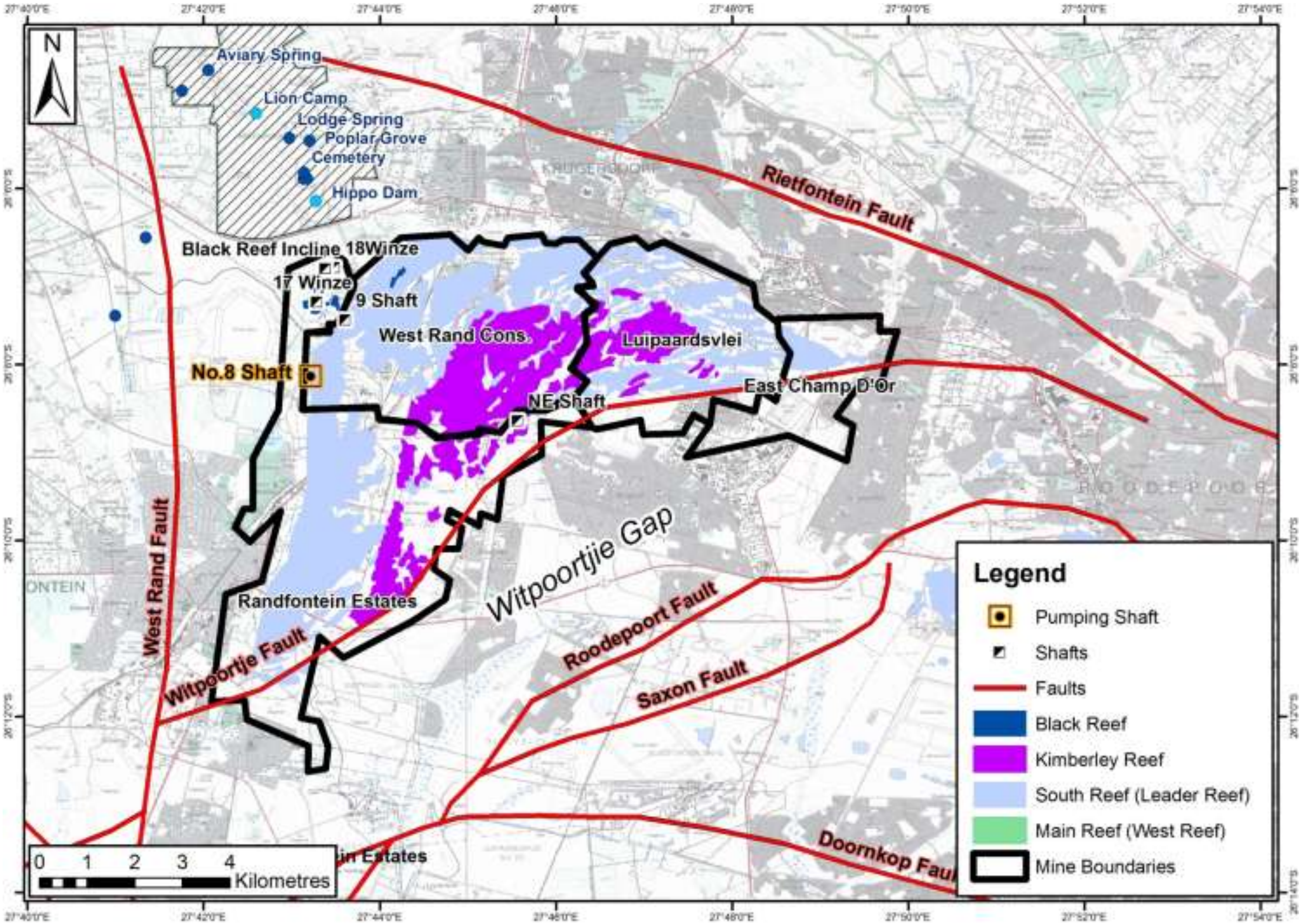


Figure 6.3: Mine voids of the Western Basin. Decanting shafts (17,18 Winze and Black Reef Incline) are annotated, as are significant springs and dams on the Tweelopies Spruit. Note that the reef voids are projected to surface, therefore upper reef voids will obscure lower reef voids in some areas.

The 17 and 18 Winzes (a winze is a shaft sunk at an angle so as to lie on the reef plane) seem to have accessed the West (Main) Reef conglomerate beneath the Transvaal Supergroup strata (**Figure 6.1** and **Figure 6.4**). Once the West Reef void had filled, mine water probably decanted underground into the Black Reef workings (**Figure 6.4**) and from there seeped into the shallow dolomite trough lying west of the Main Reef sub-crop. Other Witwatersrand reefs may also be connected to the Black Reef workings, however the West Reef is the most significant from an underground decant perspective. The very first surface decant took place from a water borehole situated alongside the Tweelopies Spruit, just below the position of the BRI portal. This was followed by decant from the BRI and finally the two winzes as the water level in the void continued to rise. This finally resulted in a rise in the water table and the Hippo Dam downstream in the Krugersdorp Game Reserve filled with water (H Coetzee, pers. com.).

The water discharging from the mine workings is acidic and contains elevated concentrations of iron, manganese and other metals. Upon exposure to air, the dissolved iron undergoes oxidation, further lowering the pH. The iron, manganese and other metals then precipitates as unsightly yellow to orange or black oxide sludge along the bed of the Tweelopies Spruit. Where the river cascades over falls or rapids, thick crusts of iron and manganese oxides have formed. Over the years since surface decant commenced, the extent of this iron precipitate has extended progressively further downstream. The water is toxic and has a profound impact on aquatic biodiversity.

The geological relationships along the course of the Tweelopies Spruit and in the vicinity of the surface decant points are of some interest and are illustrated in **Figure 6.5**. The elevation of the water level in the void is shown by water level measurements in the Central Vent Shaft and CPS borehole to be at 1671 m amsl. The cross-section illustrates the direct connection between the Black Reef and overlying dolomite and the sub-cropping West (Main) Reef void (see also **Figure 6.4**, which suggests that the stoping on the West Reef intersected that on the Black Reef). This connection only exists at elevations close to the sub-crop of the West Reef against the Black Reef. At lower elevations, the West Reef void diverges from the Black Reef as the former dips to the southeast and the latter to the west (**Figure 6.5**). The section moreover shows that the dolomite-bearing trough in the vicinity of the surface decant points is isolated from the main dolomite area in the Cradle of Humankind by West Rand Group strata of the Witwatersrand Supergroup (also noted by Hobbs and Cobbing, 2007).

There has been a suggestion that contaminated water may be seeping from the dolomite outlier through fractures in the West Rand Group quartzites to emerge in springs blow the lodge in the Krugersdorp Game Reserve. This possibility cannot be verified on the basis of currently available information, but is considered to be unlikely. The contaminated springs in the reserve are more likely to arise from infiltration of contaminated surface water into the dolomite immediately upstream of the lodge (e.g. Hobbs, 2011).

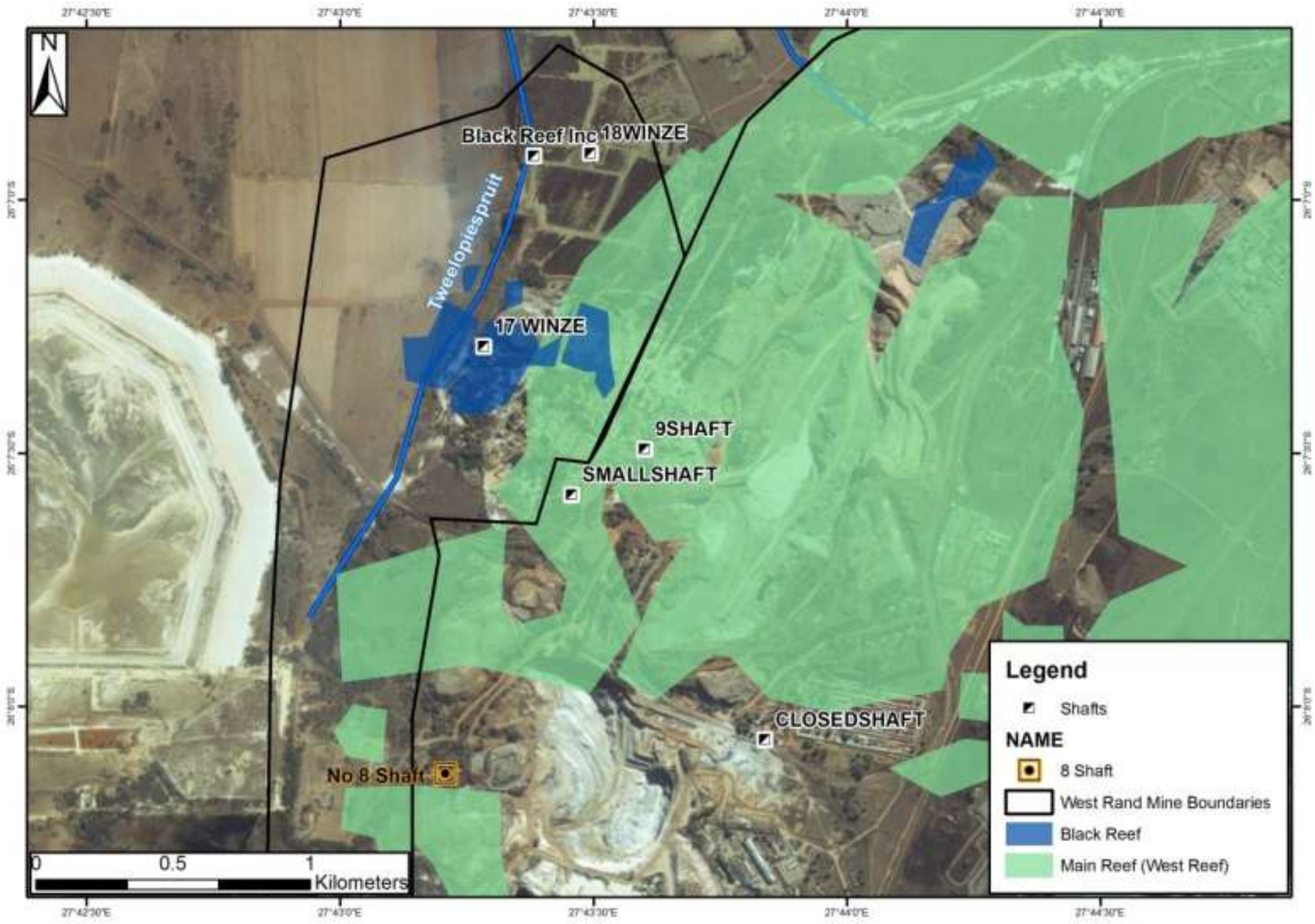


Figure 6.4: Map of stoped areas on the Black and West Reef, showing overlap in the vicinity of 17 Winze.

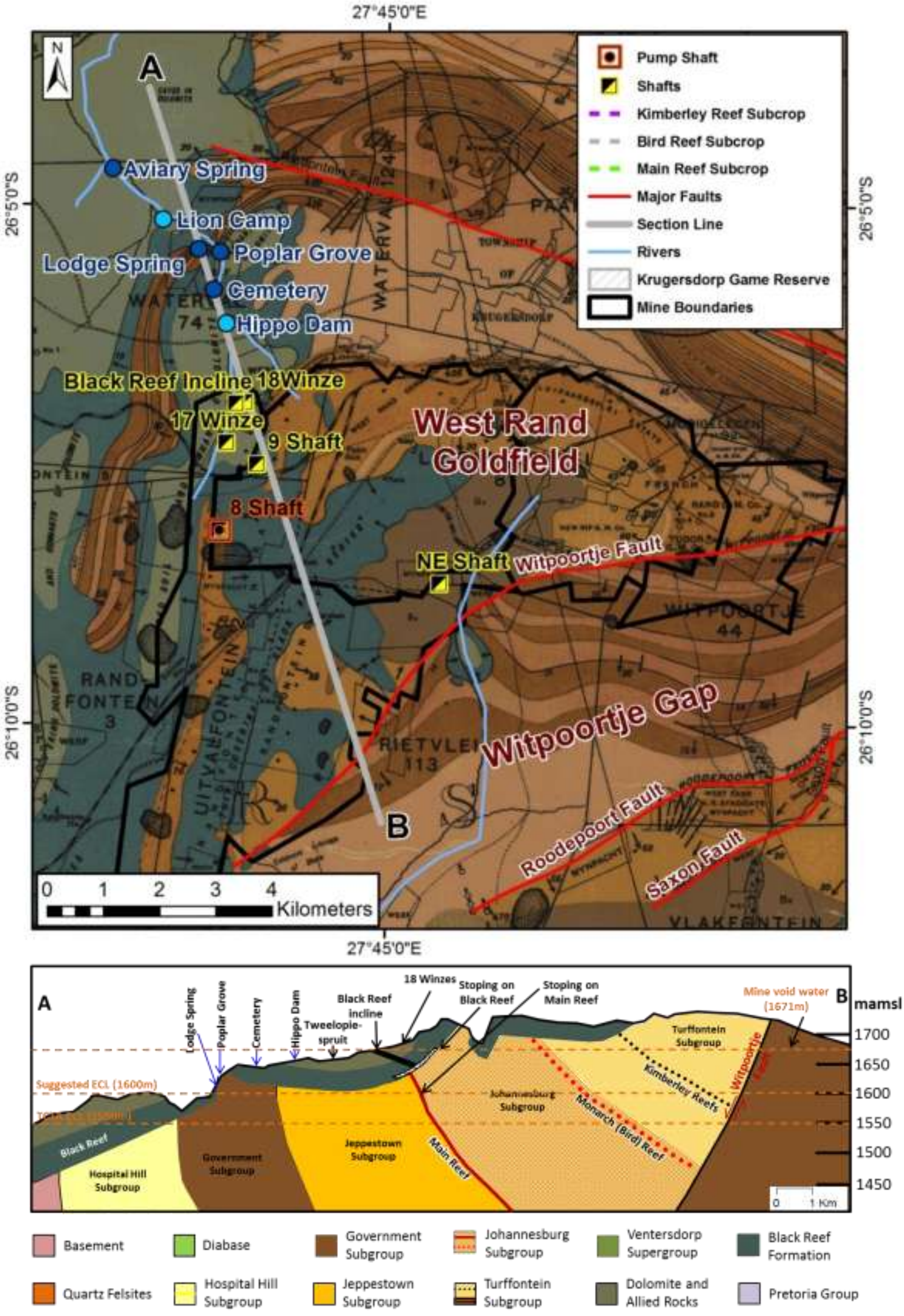


Figure 6.5: Geological map of the West Rand Syncline, with a cross section along the fold axis. Cross section shows the current surface decant water level, ECL as defined in the TCTA Report (2011a), and the ECL as proposed in this report. Hatched area in cross section, from the Main Reef to the Witpoortjie Fault, denotes area of historic mining activities.

Available data on historic water levels and connectivity between mines is limited. However, the large number of reefs mined in the Western Basin, combined with the large number of shafts (**Figure 6.3**), suggests that the mine voids in the entire Western Basin are well connected. **Figure 6.6** gives an indication of the rising water levels leading up to surface decant. The BRI decant level (1669 m amsl) is within 2 m of the decant level measured in the mine at Central Vent Shaft.

Two slope changes, marked as B and C, in the filling curve in **Figure 6.6** suggest major events pertaining to the filling of the Western Basin (Section 4.2.3). The prominent apparent off-set on the filling curve, between March and October 2000, remains unexplained, and could possibly be an artefact.

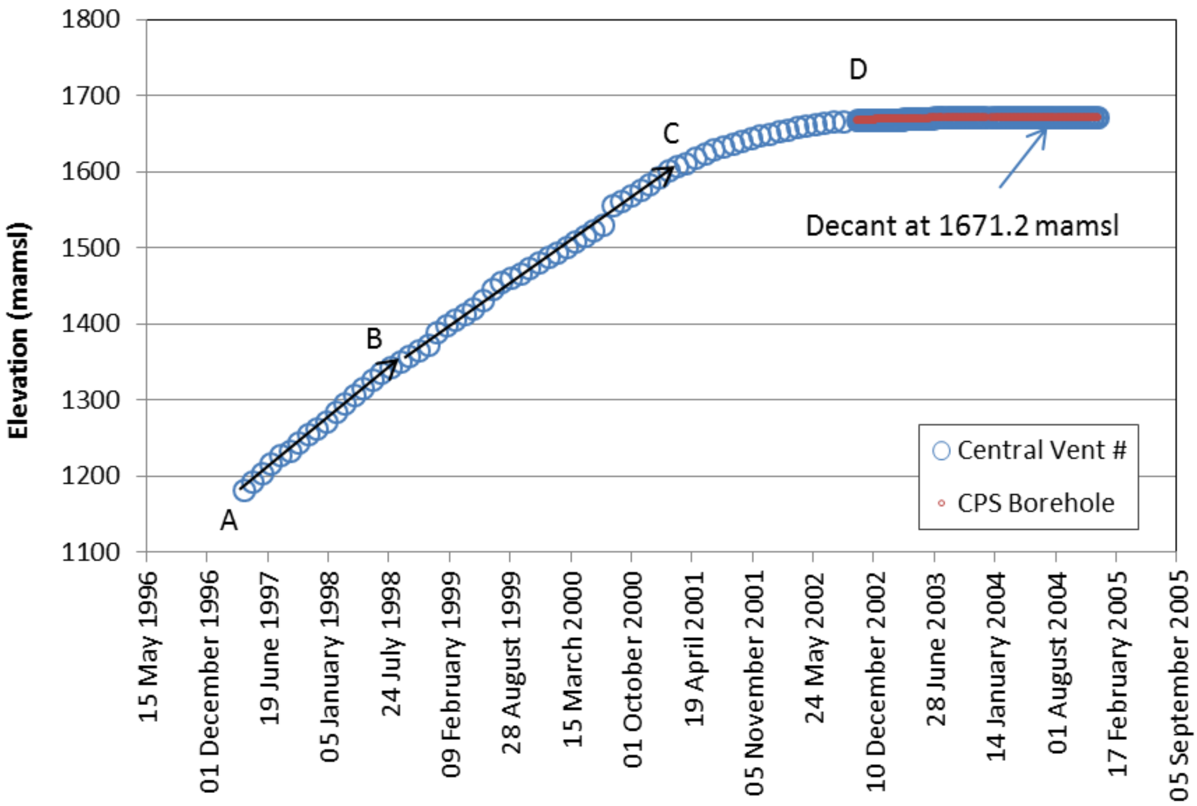


Figure 6.6: Water level rise in the Western basin prior to surface decant in 2002. A, B, C and D marks events in the void filling process (see Section 0 for detail).

6.4 Critical Water Levels

The ECL for the Western Basin (**Figure 6.5** and **Figure 6.7**) has been proposed at an elevation of 1550 m amsl by the TCTA Report (2011a) (**Table 2.1**). It should be noted that this is proposed as a Target Operating Level and allows for some fluctuation and higher water levels to occur from time to time. This elevation was chosen to protect the dolomite in the Cradle of Humankind from possible ingress of untreated water directly from the void or via seepage through fractures connected to the void (Hobbs and Cobbing, 2007).

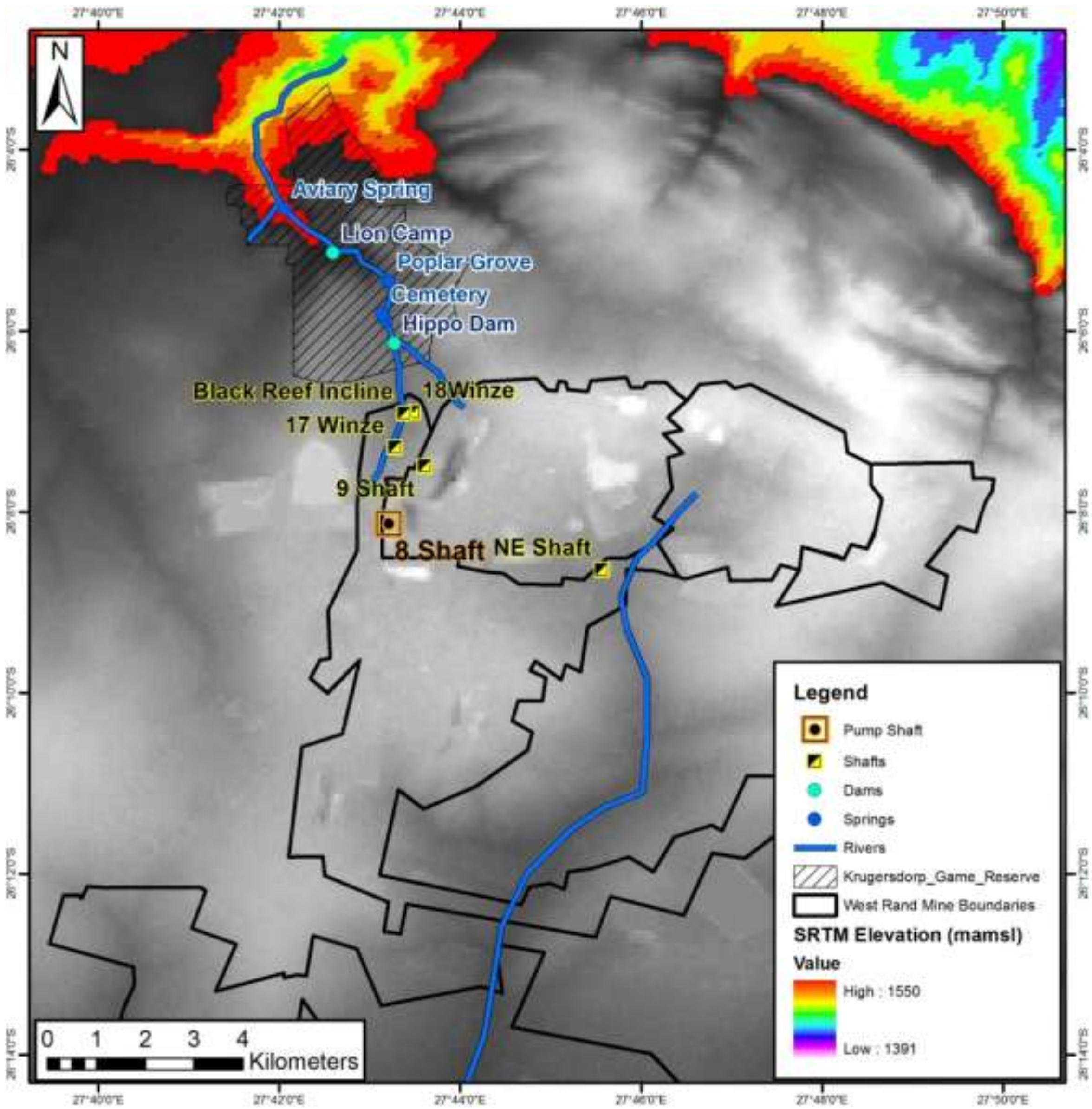


Figure 6.7: Elevations in the Eastern Rand below 1550 m amsl defined by Shuttle Radar Topography Mission (SRTM) data.

6.4.1 Proposed Environmental Critical Level

A key consideration for the definition of an ECL for the Western Basin is the preference to contain the mine void water within the quartzitic rocks of the Witwatersrand Supergroup and away from the dolomite aquifer.

It is evident from **Figure 6.5** that ingress into the Black Reef and its thin overlying veneer of dolomite probably occurs via the sub-crop of West Reef against Black Reef. Supporting information sets this intersection at approximately 1610 m amsl, as indicated in **Figure 6.6** (point C). If the water level in the void were to be lowered substantially, this connection would be broken and the void would then be separated from the dolomite by a thick sequence of shale and quartzite of the West Rand Group (mainly Jeppestown Subgroup). Accordingly, it

is suggested that an ECL at 1550 m amsl may be unnecessarily conservative and an ECL just below the 1610 m amsl level at which mine water appears to have entered the dolomite aquifer via the Black Reef workings, should be commissioned and the appropriate TOL will be determined in the Options Assessment Section of the Pre-Feasibility Report.

An ECL of 1600 m amsl is thus proposed, as it is considered that this will sever the Witwatersrand/Black Reef mine void connection and provide sufficient protection of the dolomitic rocks in the Cradle from direct inflow of void water (**Figure 6.8**). This report forms a component of the Feasibility Study and provides an assessment of the geology, hydrogeology and hydrochemistry of the three focus areas, to provide the background information necessary for the planning of pumping and water treatment operations for the longer term solution to the problem. The report also assesses aspects of the STI and how these can potentially be effectively incorporated into the LTS.

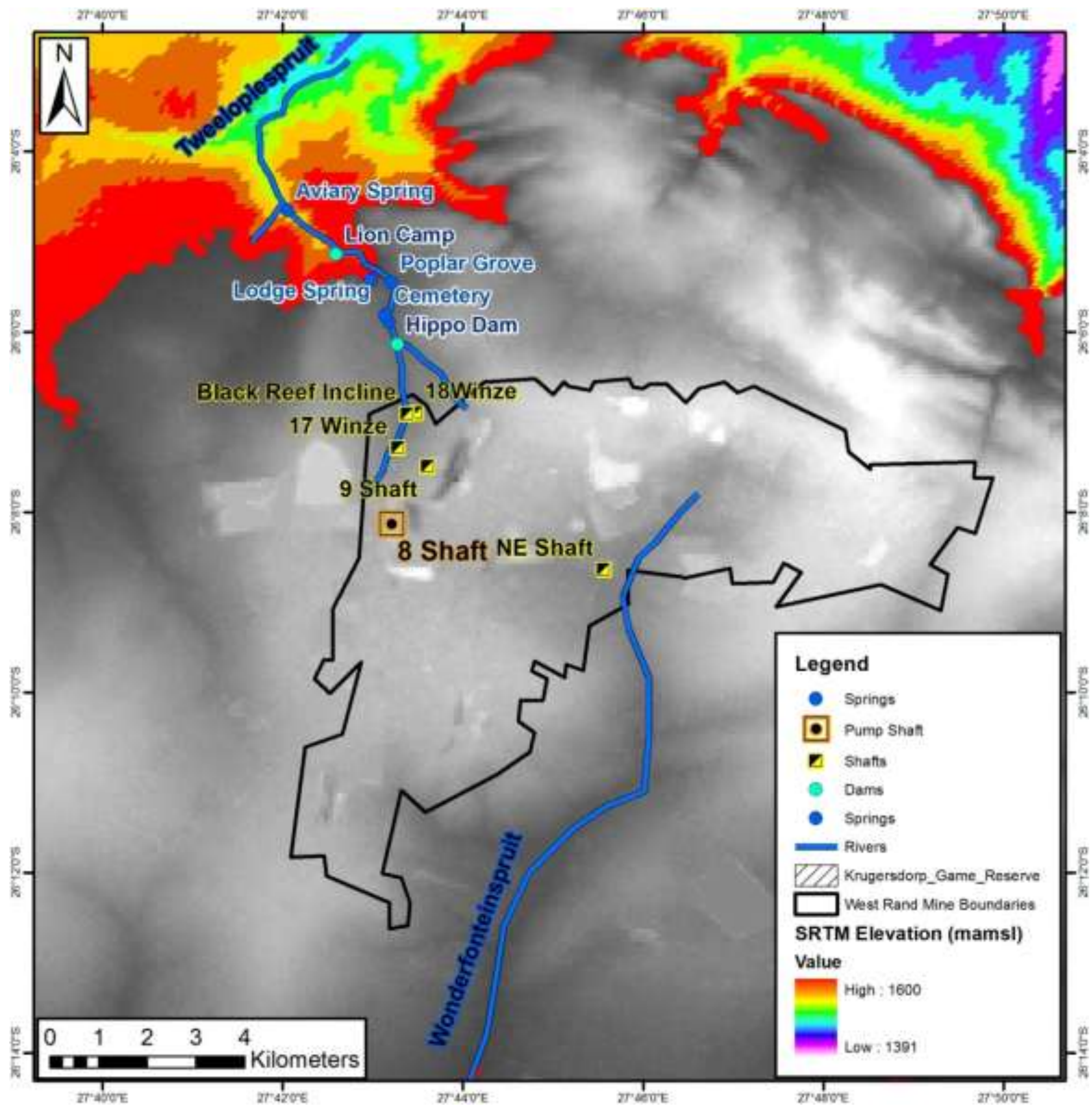


Figure 6.8: Elevations in the Western Basin below 1600 m amsl defined by Shuttle Radar Topography Mission (SRTM) data.

To assess the results of dewatering and reduce the associated risks, the water should be lowered to the TOL associated with the ECL of 1600 m amsl level and held there for an appropriate duration to establish whether the situation downstream improves. Careful monitoring of springs rising at and above 1600 m amsl would therefore be required in order to assess the flow of water from the void into the groundwater. If leakage of direct AMD ceases then the water could be held at this level; if not it should be lowered further, i.e. towards the TCTA proposed level of 1550 m amsl. However, it is important that sufficient freeboard is allowed to cater for pumping strategies, pump failure, maintenance etc.

The void is not the only source of noxious water and this needs to be considered when monitoring the impact of lowering the mine water level on groundwater water qualities. An additional contributor to groundwater pollution outside of the confines of the void comes from the large tailings dump located to the northwest of Randfontein Estates Gold Mine (REGM) (**Figure 6.9**). This source of AMD can only be addressed by removing the dump and remediating the area.

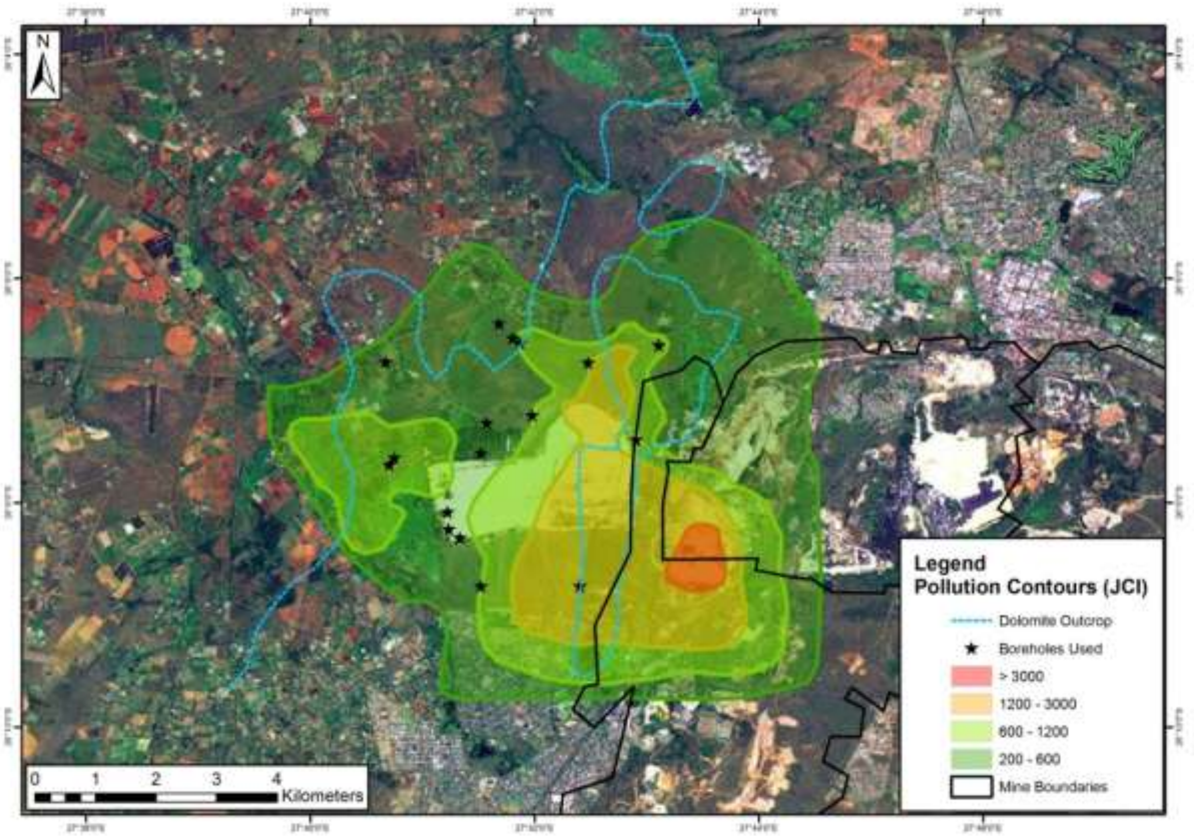


Figure 6.9: Pollution contours (mg/ℓ sulphate) over mine dumps in the Randfontein Estates area during the mid-1990's.

6.5 Surface Water Ingress

The Western Basin is situated on a major water divide with the Wonderfonteinspruit (a tributary of the Mooi River) draining to the Vaal River in a southerly direction. The Tweelopies Spruit drains the remainder of the basin in a northerly direction and falls within the Upper Crocodile West Catchment, which flows into the Hartebeespoort Dam and ultimately the Limpopo River.

This area is characterised by undulating topography in the south but more hilly terrain along the northern boundary of the mining area.

For each of the ingress sources described in Section 4.3, a percentage of recharge (ingress) of the rainfall and surface water run-off was estimated taking into account the existing geological formations as well as potential ingress sources to predict the expected ingress volumes into the mine workings. In addition to this, relevant and applicable rainfall records were established before being able to determine the ingress volumes.

6.5.1 Meteorology

The major source of inflow to the basin is direct rainfall onto open surface mine areas or surface runoff generated from rainfall falling onto a catchment area. A 60 year record (1949 to 2009) was used (WUC Report, 2009) as this was at the time of the study the most up to date record available. The extracted monthly average rainfall data is presented in **Table 6.1** and the annual minimum and maximum rainfall is presented in **Table 6.2**.

Table 6.1: Average monthly rainfall data, Western Basin (WUC Report, 2009).

Month	Average Rainfall (mm)	Minimum Rainfall (mm)	Year Recorded	Maximum Rainfall (mm)	Year Recorded
October	68.85	9.9	1958	168.77	1993
November	101.89	25	2002	197.4	1949
December	107.25	47.5	1957	252.5	1949
January	132.03	60.4	1956	292.25	1977
February	98.78	34.4	1976	268.9	1955
March	91.19	9.75	1965	201	1997
April	50.7	0	1956 & 2002	109.35	1975
May	15.03	0	Often	68.55	1975
June	7.61	0	Often	49	1957
July	3.24	0	Often	65.2	1952
August	6.33	0	Often	38.37	1986
September	22.87	0	Often	123.97	1987
Total	**705.75**				

Table 6.2: Annual minimum and maximum rainfall, Western Basin (WUC Report, 2009).

Month	Driest Year- 2002 (mm)	Wettest Year -1955 (mm)
October	67.35	54.65
November	25	137.45
December	114.45	154.35
January	94.25	268.3
February	58.5	268.9
March	38.15	54.25
April	0	60.55
May	4.5	45.25
June	9.25	3.6
July	0	0.25
August	5.5	3.4
September	0	1.3
Total	**416.95**	**1052.25**

In addition to the above extracted data, an independent validation of the rainfall records was completed for the Western Basin. The results are summarised in **Table 6.3** for the most representative weather stations. Two stations were compared: station 0475370W with 86 years of records and station 047456W with 86 years of records (**Figure 4.3**).

Table 6.3: Average monthly rainfall data (independent rainfall stations).

Month	Average Rainfall (mm)	Minimum Rainfall (mm)	Year Recorded	Maximum Rainfall (mm)	Year Recorded
October	67	7.2	1917	215.2	1993
November	108.4	15.8	1935	314.4	1917
December	121	15.4	1944	293.4	1942
January	132.5	30.1	1989	440.2	1977
February	106.3	11	1976	395.8	1943
March	93.2	10.6	1964	238.9	1924
April	50.5	0	Often	176.5	1970
May	20	0	Often	162.1	1935
June	7.2	0	Often	105.7	1943
July	7.7	0	Often	98.2	1951
August	9.1	0	Often	96.6	1917
September	21.5	0	Often	123.6	1986
Total	**744.5**				

The following observations are made when comparing the above rainfall tables :

- Comparison of the reviewed MAP with that of the WUC report shows the reviewed rainfall to be very similar, with the reviewed MAP being about 5.4% higher than the WUC MAP;

- The maximum monthly rainfall based on the review is higher at 440 mm (50%) when compared to the WUC value of 292 mm. This could possibly be due to a more accurate and patched rainfall record used for the this study, which is based on the rainfall database used by DWA for all resource modelling (Middleton and Bailey, 2005);

6.5.2 Review and verification of ingress volumes

The expected ingress of surface water into the mine workings has a marked influence on the abstraction requirements and hence pumping and maintenance costs. Two approaches have been adopted in trying to assess the predicted ingress volumes and the source:

- Determination of the total ingress into the mine void based on surface flow rates as well as assumptions on the percentage infiltration of surface water into the mine void from various geological formations, mine infrastructure and natural drainage systems (WUC Report, 2009), as summarised in this section;
- Determination of the total ingress into the mine void based on mine void volume, water level and pumping data, as described in Section **Error! Reference source not found.**.

6.5.2.1 Sources of ingress and estimated volumes

Relevant data and assumptions made have been taken principally from the WUC Report (2009) on the Western Basin. In addition to this the changes in rainfall have also been reviewed, in order to consider the impact of the rainfall variation on the ingress volumes.

Given in **Table 6.4** are the major ingress areas with relevant comments on the mechanism of ingress into the mine voids and shown in **Figure 6.10**.

Table 6.4: Summary of ingress areas.

No.	Source Type	Detailed Ingress Areas
1	Undisturbed geology /Shallow aquifers	Recharge of a shallow weathered aquifer located above areas of shallow underground mining. The dolomite outlier in the KGR is partially weathered to permeable wad and provides a pathway for direct recharge from precipitation into the hydraulically connected mine voids via the Black Reef workings. The Cradle of Humankind dolomite is not hydraulically connected to the mine void.
2	Surface water (dams, rivers, wetlands)	Upper portions of the Wonderfonteinspruit and the storage of water pumped from the void in Robinson Lake and the wetlands below it. Once the hydraulic gradient has been reversed towards the mine void, decant into the Tweelopies Spruit will cease but ingress from the upper reaches of the Tweelopies Spruit may be induced.
3	Municipal infrastructure (leaking mains and sewerage, stormwater run-off)	Leakage of municipal services (sewers and water reticulation) in urbanised areas overlying the mine voids. Ingress of stormwater directed into abandoned surface mining operations observed in the Mogale City Municipality.
4	Surface mine workings (open pits, shafts, inclines)	West Wits (being used for sludge disposal) and Millsite Pits are holed directly into the mine void. Ingress into the mine void via open pits along the Witpoortjie Fault in south-western area of the

		basin.
5	Tailings dams and mine dumps	Very poor quality seepage and stormwater from Dump 20 into adjacent Millsite Pit. Dumps 38-41 and Valley seep into mine void via dolomite wad aquifer.

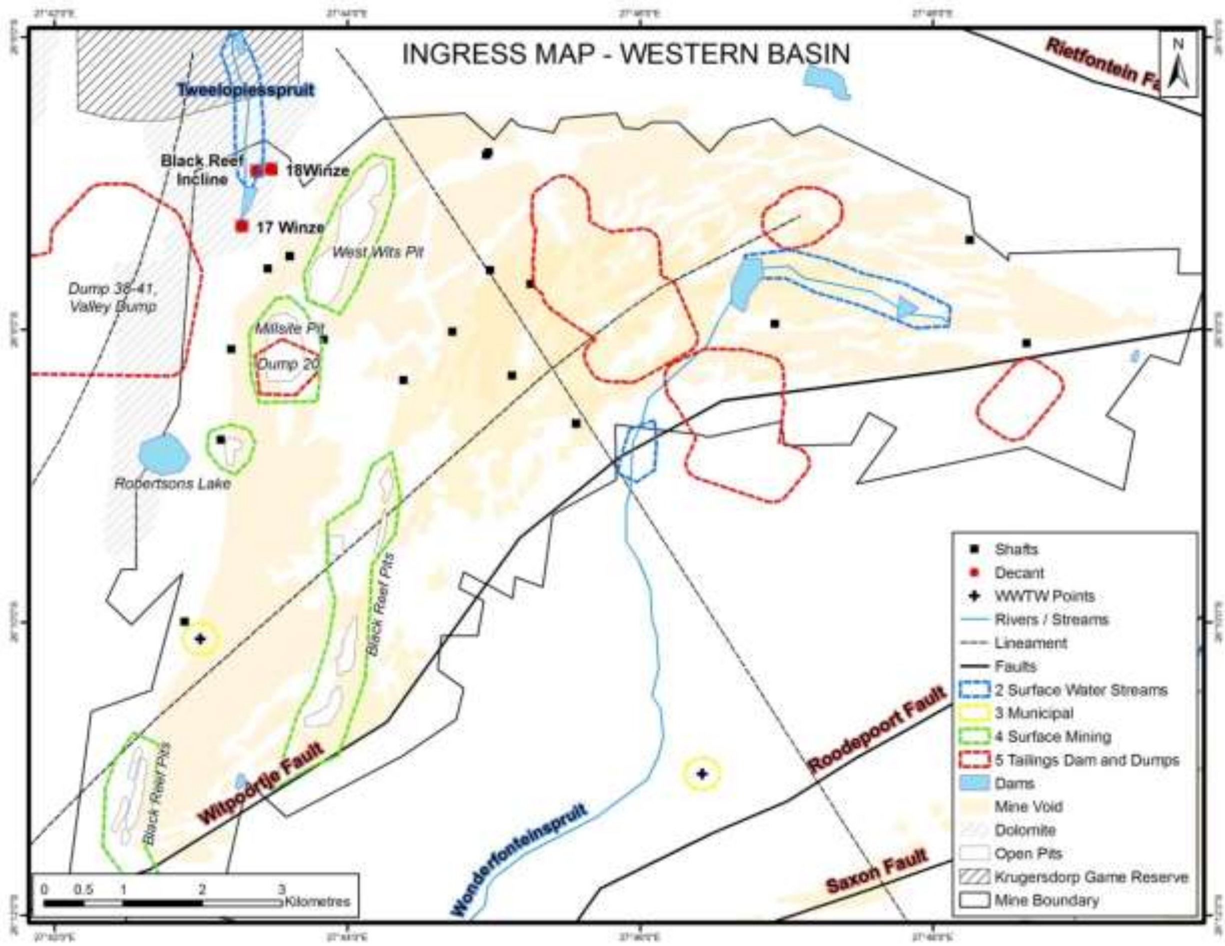


Figure 6.10: Major ingress areas in the Western Basin. Numbers in legend refer to source type in the preceding table.

Based on the average rainfall data as given in **Table 6.1**, as well as flow monitoring, the expected total ingress volume for the Western Basin, as defined in the WUC Report (2009), is about 16 Mℓ/day. An approximate percentage distribution of the total ingress for each of the sources defined in that study is tabulated in **Table 6.5**.

Table 6.5: Predicted ingress sources (average rainfall) (WUC Report, 2009).

Source	Percentage of Total Ingress Volume	Ingress Volume (Mℓ/day)
Groundwater recharge via natural & undisturbed geology	48	7.70
Ingress through reef outcrops	6	0.96
Ingress through rehabilitated & open cast pits	22	3.50

Tailings dams and mine dumps base seepage zones	21	3.36
Ingress from rivers & water bodies	3	0.48
TOTAL	**100**	**16.00**

Taking into account that this study is concerned with a long term solution, it is important to also assess how potential climate change can affect the ingress volume. For this purpose, extreme rainfall variations as well as a potential climate change component have been used to predict the sensitivity of climate change on the expected ingress volumes (**Table 6.2**). The prediction has been based on the Goldsim Model utilised by Golder & Associates (WUC Report, 2009).

A summary of the expected ingress volume variation is given in **Table 6.6** and also shown on **Figure 6.12**.

Table 6.6: Rainfall variation impact on ingress volume, Western Basin.

Rainfall	MAP (mm)	Change in MAP (%)	Predicted Ingress Mℓ/day	Change in Ingress (%)
Average	705	0.00	15.7	0.00
Dry Season	417	-40.85	12.3	-22
Wet Season	1052	49.22	16.1	-3
Extremely Wet	1835	160.28	19.5	24
Climate Change	990.00	40.00	16.00	2

Figure 6.11 is an example of ponding water at the base of the a sand dump in the Western Basin that drains directly into the mine void via the open Millsite Pit."

Figure 6.11: Ponding of water at the base of a large sand dump in the Western Basin area

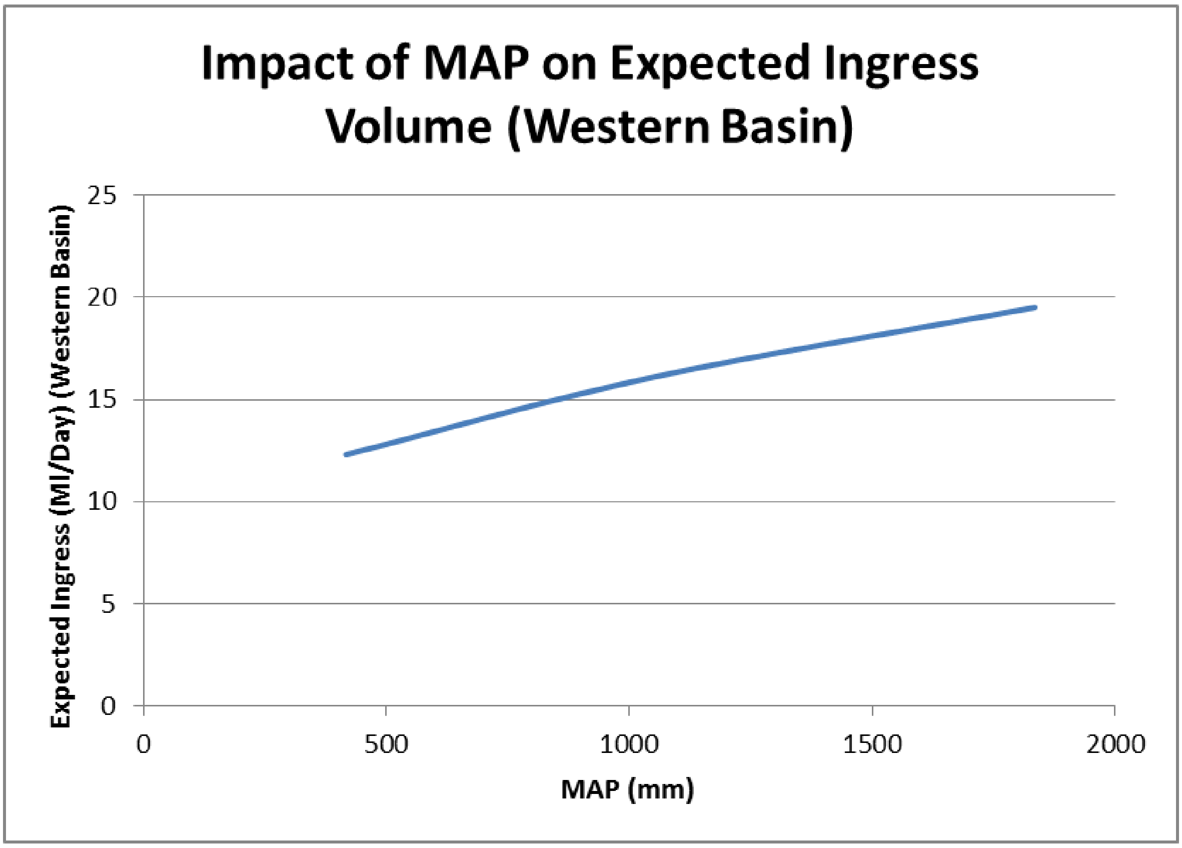


Figure 6.12: Rainfall and ingress variations.

The following observations are made:

- The change in MAP has a fairly low effect on the predicted ingress volume;
- The potential variation in MAP of about 20-40% due to climate change could change the ingress volume by about 2% and hence has a minor impact on the ingress volume.

6.5.3 Ingress estimations based on void volume

The total ingress (m^3/day) into the mine void is a function of the mine void filling rate (VF; m/day) and the mine void surface area (VS; m^2) at a given filling level (m amsl), i.e.

$$\text{Ingress } (m^3/\text{day}) = VF*VS\ (m/\text{day}*m^2 = m^3/\text{day}).$$

Records of the VF at different elevations are available from April 1997 to December 2004, covering the decant episode from the BRI and the 17 and 18 Winzes (Central Vent Shaft, CPS borehole - data provided by B.van der Walt, Rand Uranium, 2012 and H.Coetzee, CGS, 2011). Since VS can be obtained from the void data of Rison Consulting as presented in the TCTA Report (2011a), it is possible to calculate the apparent total ingress into the Western Basin in the years just prior to the surface decant event in 2002. It is noted that the void volume estimates of Rison Consulting, quoted in the TCTA Report (2011a), is based on 10 m intervals. This is at variance with the work of Krantz (1996) who quoted 5 m intervals for the

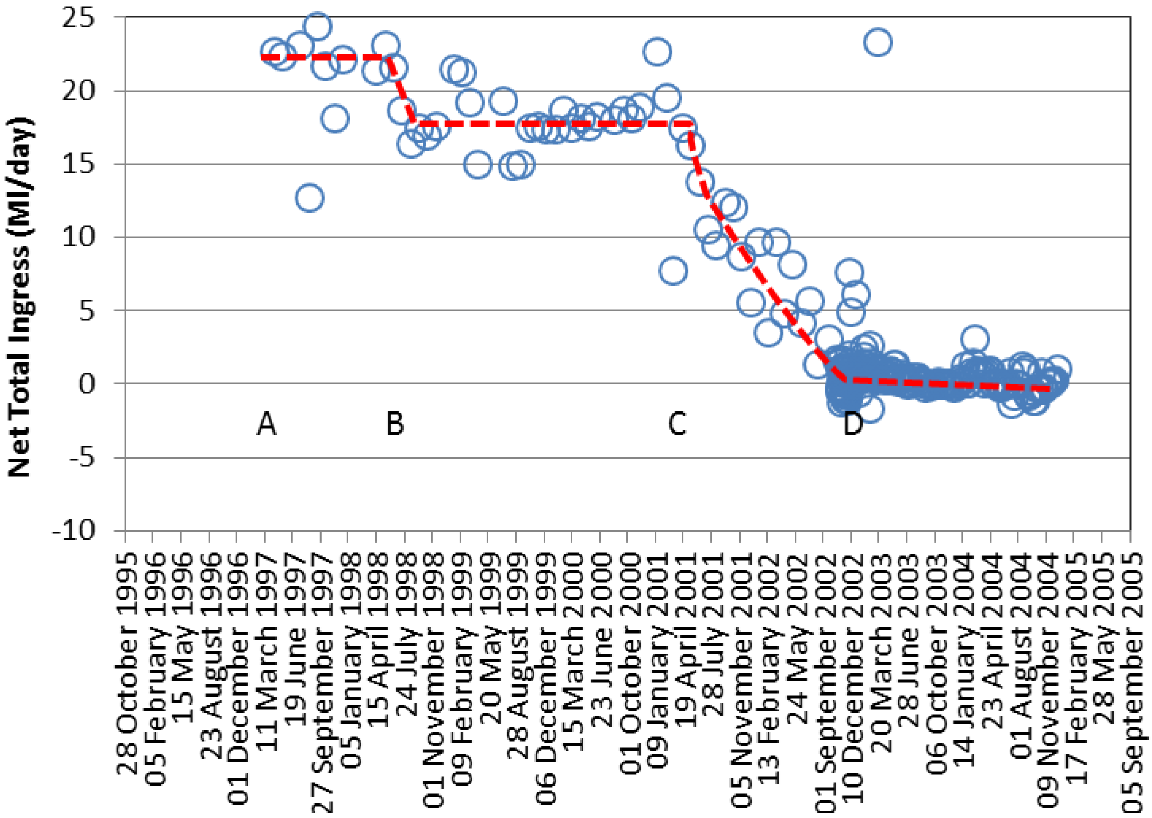
same volumes at the same elevations. In this investigation, the original 5 m interval listed by Krantz (1996) is accepted as the correct number.

The results of the calculations are illustrated in **Figure 6.13**. The following observations are relevant:

(1) The estimated total ingress seems to follow a stepwise reduction as surface decant is approached. This decrease is interpreted to be a reflection of a stepwise increasing void surface area or volume closer to surface, rather than to a true decrease in ingress volumes. A decrease in the hydraulic gradient would be gradual across the depth range and is therefore a less acceptable explanation.

(2) The interpretation presented in (1) is in part a function of the scatter of the void data. The line of best fit used (**Figure 6.14**) does not satisfy the small scale variation in the void data. An alternative interpretation is to assume a gradual decrease in ingress between A and C, which would then possibly give an indication of the decreasing hydraulic gradient. However, although the latter interpretation might have contributed to the process, it is not favoured here due to the distinct flexure of the filling curve at point B in **Figure 6.6**.

(3) Ignoring the excessive scattering in places, the calculated ingress volumes show no clearly discernible seasonal fluctuation, suggesting that enhanced ingress due to seasonal rainfall is not a major factor. More detailed diagrams (not shown here) enforced this notion. This observation is somewhat counter-intuitive but is supported by the fact that the Western Basin forms a well-drained high plateau and that direct natural ingress into the mine void is probably limited as a result. More research work is clearly indicated.



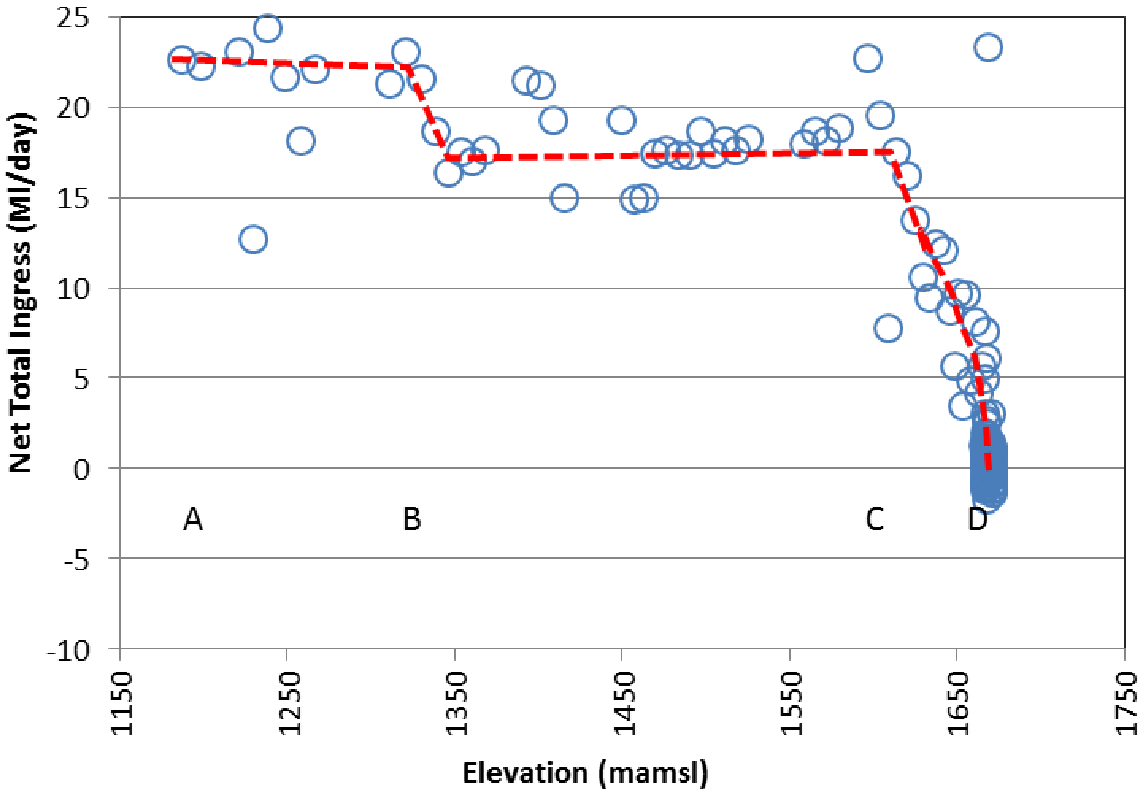


Figure 6.13: Estimated apparent net ingress in the Western Basin. The estimated net total ingress appears to decrease in a stepwise manner, probably related to changes in the volume of the mine void (see text for detail).

(4) The difference in estimated ingress volumes between steps AB (~22.7 Mℓ/day) and BC (~19.3 Mℓ/day) is interpreted as the merging of two sub-basins – one rising and one perched (similar to the Crown Mines and DRD compartments in the Central Basin). Assuming a roughly constant ingress over time, the data suggests that at point B (**Figure *6.13***) the surface area of the void expanded by about 18 percent between 1321 and 1346 m amsl. This compares favourably with a void volume enlargement of ca. 12 percent between 1351 and 1391 m amsl described by Krantz (1996).

(5) At Point C, at a level of ca. 1610 m amsl, the void water may have entered the Black Reef workings and began to spread into the shallow weathered aquifer in the dolomite outlier. This ultimately probably led to the filling of the Hippo Dam and the reactivation of certain springs in the area (**Figure 6.5**).

(6) The rate of flow through the shallow aquifer either did not keep up with the volume of water ingress from the void, or the shallow dolomite aquifer may have filled up, and the final decant on surface (point D, **Figure 6.13**) occurred in 2002 in a borehole close to the Black Reef Incline (BRI). Small negative elevation levels recorded at point D probably derives from measuring errors (±2 m) in the shafts.

(7) The absolute estimated ingress volumes of ca. 19 to 23 Mℓ/day (steps AB and BC) are marginally lower than the measured average surface decant (over the period 2010 to 2011, **Figure 6.15**) which amounts to an average of approximately 27 Mℓ/day (Coetzee, 2011). It has been noted that despite efforts to prevent surface run-off reaching the measuring weir some surface run-off is measured. However it is significantly larger than the ingress volumes at between 7 and 12 Mℓ/day estimated by Harmony Gold Mines (WUC Report, 2009).

(8) It should be stressed that the numbers for estimated ingress presented here are based on averaged void volume data. This averaging of a less well-behaved line, together with the possible error in the void volume definition, evidently introduced considerable variance to the estimated numbers. The difference between 19 and 23 Mℓ/day is preferably seen as an estimate of the possible error, rather than a difference in true ingress.

(9) Finally, the filling pattern observed for the Western Basin might well repeat itself, depending on local geological constraints, in the Central and Eastern Basins. Most important is the influx of the AMD into the shallow weathered aquifers. Similar subsurface decant into the shallow aquifer, with currently unknown side effects, could be expected in the Central and Eastern Basins if the water level is allowed to rise.

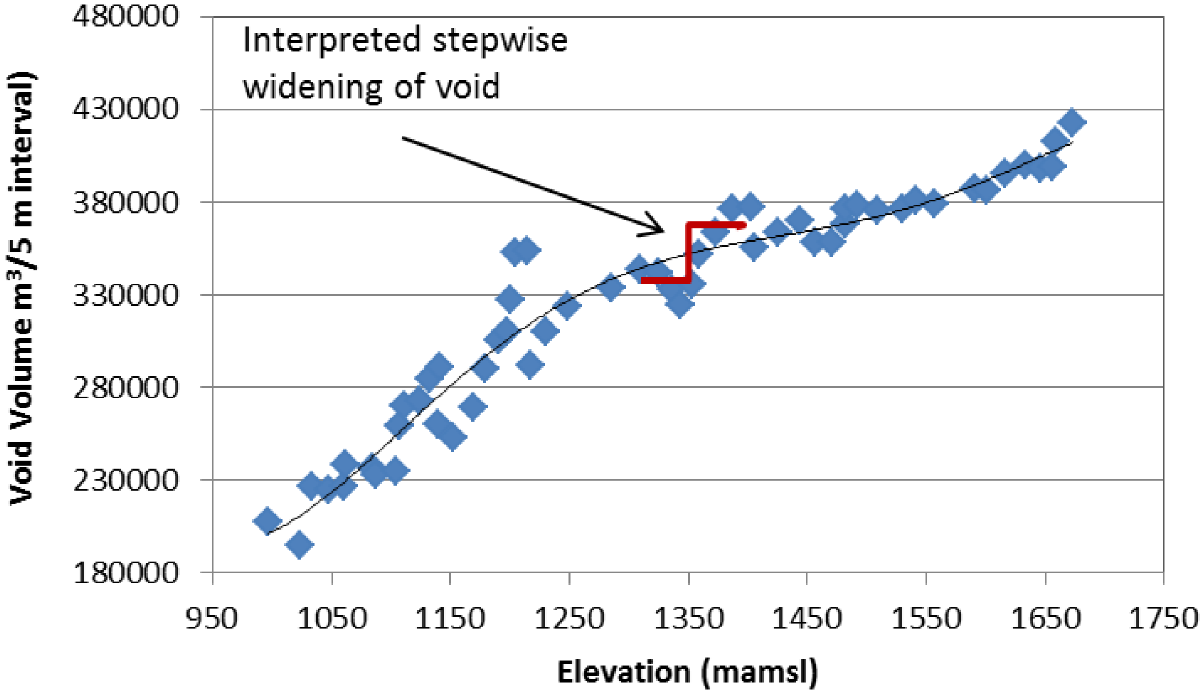


Figure 6.14: Modelled void volume curve used in the calculations.

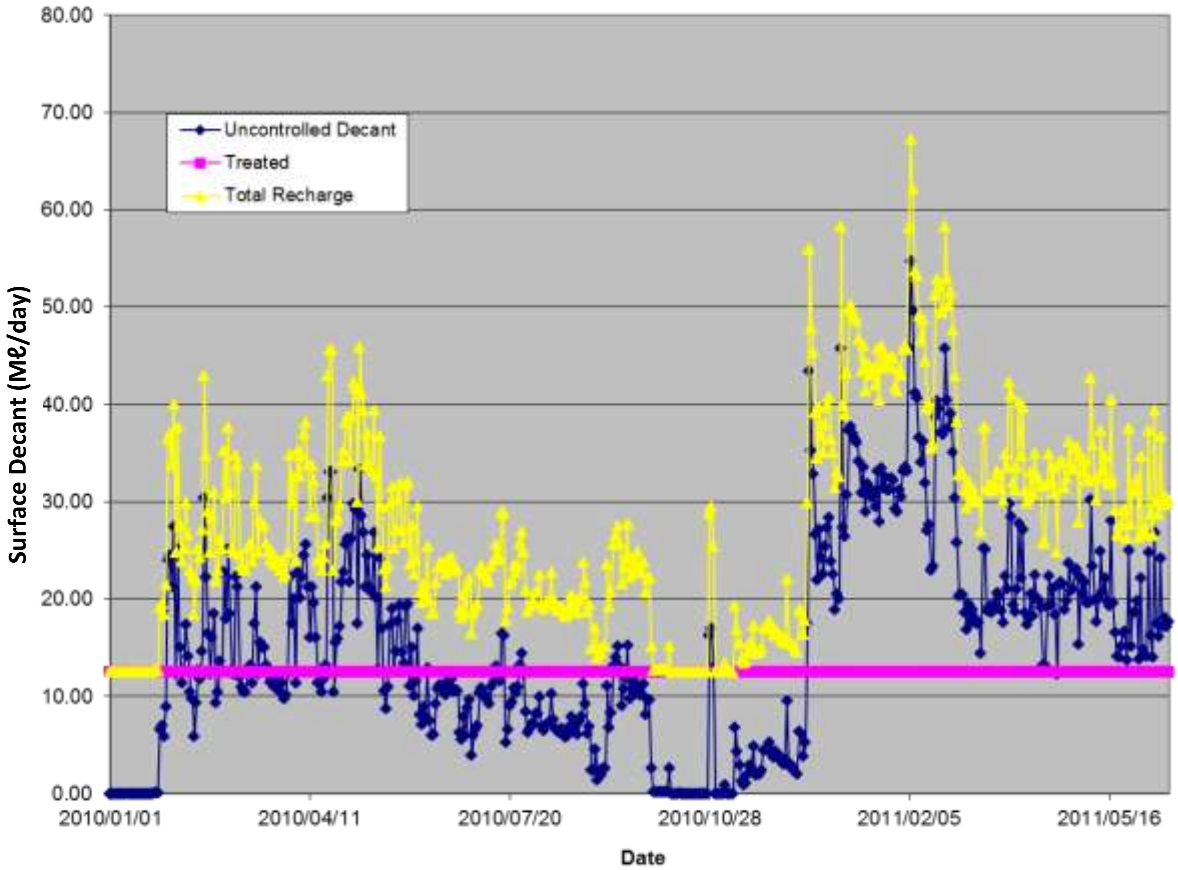


Figure 6.15: Measured surface decant of the Western Basin measured by Rand Uranium (from Coetzee, 2011).

6.5.4 Minimising surface water ingress

It is considered that the ingress as estimated from the void volume study of approximately 19 to 23 Mℓ/day is more accurate than that indicated in the WUC study. In order to reduce surface water ingress as far as possible an initial prioritisation of the main categories of sources, as defined in **Table 6.4** has been made for the Western Basin, as shown in **Table** 6.7.

Table 6.7: Prioritisation of ingress control measures.

Source	Percentage of Total Ingress volume	Expected Ingress Volume (Mℓ/day)	Priority of improved ingress control[1]
Undisturbed geology /Shallow aquifers	48	11	5
Surface water (dams, rivers, wetlands)	3	1	3
Municipal infrastructure (leaking mains and sewerage, stormwater run-off)	0	Low	4
Surface mine workings (open pits, shafts, inclines)	28	6	1
Tailings dams and mine dumps	21	5	2
Total	100	23	

1: A priority "5" has been given to the "Groundwater recharge via natural & undisturbed geology" as no practical and feasible improvements to ingress control can be used for this source.

As can be observed from **Table 6.7**, undisturbed flow through geology amounts to nearly 48 percent of the total ingress volume. No practical reduction in this ingress into the undisturbed geology is possible. The following control measures for the Western Basin, as described in Section 4.4 and Appendix A should be considered for reducing mine void ingress:

- Rehabilitation of existing open pits and sealing shafts and initiates;
- Removal of mine dumps, currently underway;
- Rivers and other water bodies including possible canalisation of the upper reaches of the Wonderfonteinspruit over areas of surface and shallow underground mining is possible but should be as a low priority due to the high capital costs
- Municipal sources, including upgrade of stormwater drainage systems to reduce ingress into abandoned surface workings in the Mogale City area but this is a high cost item for minimal benefit.

Theoretically by implementing control of ingress by managing sources prioritised as 1 and 2, (including rehabilitation of shallow workings, closing shafts, removing tailings and other dumps), the total ingress into the mine void could be reduced by up to 11 Mℓ/day. However,

given that this will be practically impossible to completely achieve, even if one halves this to a total reduction of only 5 Mℓ/day, it at least gives an indication that efforts to manage historical mine ingress sources should be implemented where possible. The economic benefits of ingress control are discussed in the Feasibility Report.

6.6 Pumping Volumes and Abstraction Points

6.6.1 Pumping volumes required

Estimates based on void volume and water level rise (Section 6.5.3) in the mine void of the Western Basin, over the period 1997 to 2002, suggest an ingress of water in the void of about 19 to 23 Mℓ/day. This exceeds the estimates of 7 to 12 Mℓ/day by Harmony Gold Mines (WUC Report, 2009), the number on which their recent pumping rate of 12.5 Mℓ/day was based. The WUC Report (op.cit.) estimates the ingress in the Western Basin at 16 Mℓ/day average (between 11 and 20 Mℓ/day, representing dry and wet seasons, respectively). These numbers are smaller than those from the flume measurements after surface decant (2010-2011; Coetzee, 2011), the latter which suggests a strongly seasonal flow pattern with maxima as high as 50 to 60 Mℓ/day and an average of 27 Mℓ/day (see **Figure 6.14**). This difference might imply the addition of seasonal rainwater collected by the shallow dolomite aquifer, as well as surface runoff, which is likely to occur in uncovered gauging stations. Whatever the true reason, the numbers estimated by different methods are converging.

It is also of interest to note that after surface decant occurred in 2002, a pumping exercise over a period of 13 months (March 2008 to March 2009), abstracting on average 26.57 Mℓ/day, managed to lower the water table by approximately three metres (WUC Report, 2009). This finding broadly supports an ingress rate of about 26 Mℓ/day over the relevant period, which is of the same order of magnitude as that estimated in this report from the void volume.

In evaluating a safe pumping rate, one has to consider the urgency of lowering the water level to EC2 and the effect of the storage in the shallow dolomite aquifer that became flooded when the water in the Western Basin reached a level of 1610 m amsl (**Figure 6.6** and **Figure *6.13***). Considering that in terms of water volumes:

Total mine void ingress + Meteoric recharge = Mine void volume + Dolomite aquifer volume,

and using the data of Krantz (1996), the volume of water that flooded the shallow dolomite aquifer can be estimated (**Table 6.8**), as well as the time needed to empty both the mine void and the storage in the shallow aquifer down to 1610 m amsl.

Table 6.8: Pump rates for Western Basin.

Estimates		
Rate of ingress in mine void	25	Ml/day
Time to fill shallow dolomite aquifer plus mine void	548	Days
Total ingress over period	13700	Ml
Meteoric recharge (10% of 818 mm/a over 5 sq. km)	40	Ml
Total void ingress plus meteoric recharge	13740	Ml
Volume of water stored in mine void	4290	Ml
Volume of water in shallow dolomite aquifer	9450	Ml
Days to empty dolomite aquifer plus mine void	Pump rate Ml/day	Years
	40	2.5
	50	1.5
	60	1.1
	80	0.7
	100	0.5

Coetzee (2011) used the flume-measured surface decant data to calculate a safe pumping rate of 40Mℓ/day, which would be adequate to drawn down the water level in the Western Basin to the required ECL over time. This estimate appears to deal only with annual ingress in the mine void. When the capacity of the shallow dolomite aquifer is also considered (**Table** 6.8) a total pumping capacity of 60 Mℓ/day is indicated to draw down the AMD level to 1610 m amsl over one year. Once this required ECL is reached, the pumping rate could be lowered to attain steady state conditions.

Currently-available data suggests that this longer-term required pumping rate would probably level off at about 20 to 27 Mℓ/day and an average of 23 Mℓ/d is proposed . Monitoring of the volumes abstracted and water level drawdown during implementation of the STI, will provide critical information that should be used for optimising the pumping rates and water levels for the long term solution.

The current immediate scheme with a capacity of 30 Mℓ/d and the proposed STI with a capacity of 27 Mℓ/day (Average) will be adequate.

6.6.2 Suitability of shafts for pumping

Rand Uranium Shaft No. 8 has been chosen by the TCTA for the abstraction of AMD for the Western Basin. The TCTA Report (2011a), and Appendix J of the same, highlights that very little information is available for this shaft and more data is required to conduct a meaningful stability analysis of the shaft barrel. However, Rand Uranium Shaft No. 8 is currently used to pump AMD water by two submersible pumps with a capacity of 8 Mℓ/day each. Initially, the TCTA will be using this capacity, as well as pumping from two other locations (9 Shaft and BRI Dam, **Figure 6.5**). However, the TCTA anticipates that, during implementation of the

STI, capacity will be increased to three submersible pumps in Rand Uranium Shaft No 8, designed to pump 27 Mℓ/day average over 19 hours, and a maximum of 35 Mℓ/day.

The connectivity of the Rand Uranium Shaft No. 8 with the mine void has been proven. A simplified section of the shaft shows that it connects to the mine void on multiple levels and at shallow depths (**Figure 6.16**). The shaft collar elevation is at 1726 m amsl (or 1723 m amsl, according to Google Earth) and the shaft is 445 m deep.

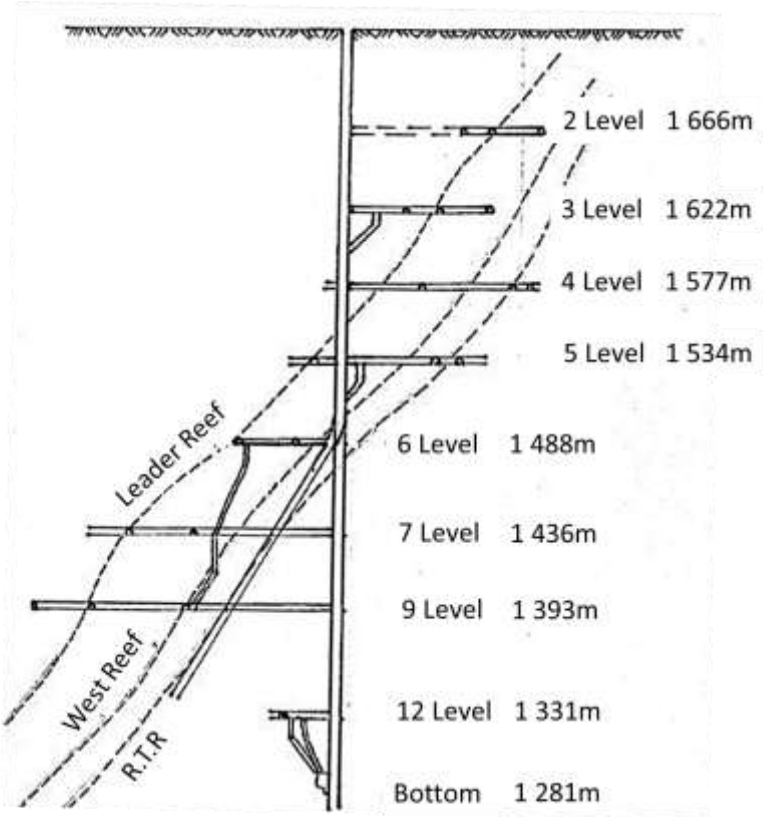


Figure 6.16: Simplified section of Rand Uranium Shaft No. 8 (TCTA Report (2011a), Appendix J).

It is considered to be preferable to pump from shafts that are well connected with the mine void at shallow levels to maximise the recycling of shallow ingress, leaving the deep, highly contaminated water undisturbed. Turnover of the shallow ingress water will lead to more rapid flushing of the shallow system.

Pumping from a shaft that is connected to the mine void close to surface on multiple levels also ensures connectivity even if there is a collapse on one level. The success of the pump station hinges on its ability to dewater the entire basin and ensuring multiple surface decant does not occur due to a lack of connectivity.

Rand Uranium Shaft No. 8 meets all the above criteria. The only potential concern is the shaft stability, as noted in the TCTA Report (2011a).

6.6.3 Alternative options to pumping

Passive solutions allowing natural surface decant at preferred ECLs, rather than pumping were identified. For the higher ECL, a tunnel could connect the stopes on the West (Main) Reef to a point on surface at the waterfall above the lodge in the game reserve. This option will be considered in the options analysis.

6.7 Water Qualities

6.7.1 Data Utilised

Water quality data was synthesised from two principal sources:

(1) Shaft/adit sampling:

These samples were taken at the water surface in the shaft barrel at 17 and 18 Winze or at the outlet of the Black Reef Incline.

(2) Surface sampling:

These samples are taken from various monitoring sites within and adjacent to the Krugersdorp Game Reserve, and include dams and canals/pipes channelling mine water discharge.

Two datasets were collected: dataset A generally considered older data ranging from 2004 to 2009; Dataset B consisted of more recent data from 2011 to 2012 supplied by Rand Uranium. For summary water quality tables, dataset B, summarised in **Table 6.9** was used as this represented the most current data and some potential bias was observed in dataset A, possibly from anthropogenic sources.

Table 6.9: Summary of Data Set B

Location	Sample Type	Source	n
17 Winze	Shaft/adit Decant Point	Rand Uranium/CGS	36
18 Winze	Shaft/adit Decant Point	Rand Uranium/CGS	57
Black Reef Incline (BRI)	Shaft/adit Decant Point	Rand Uranium/CGS	55
Charles Fourie Dam	Surface Monitoring Point	Rand Uranium/CGS	57
Downstream Brick Dam Game Reserve	Surface Monitoring Point	Rand Uranium/CGS	58
Entrance to Lion Camp	Surface Monitoring Point	Rand Uranium/CGS	58
Hippo Pool	Surface Monitoring Point	Rand Uranium/CGS	58
Inlet to Game Reserve A Seepage	Surface Monitoring Point	Rand Uranium/CGS	58
Inlet to Game Reserve B Canal at Flume	Surface Monitoring Point	Rand Uranium/CGS	58
Inlet to Game Reserve Combination of A + B Total Inlet to Game Reserve	Surface Monitoring Point	Rand Uranium/CGS	42
Lion Camp Dam (Aviary)	Surface Monitoring Point	Rand Uranium/CGS	58
Pipe 7, Porra Dam	Surface Monitoring Point	Rand Uranium/CGS	57
		Total	652

n = Number of samples

6.7.2 Water chemistry

A summary of the water quality for several sites in the Western Basin are listed in **Table** 6.10. Of special interest are 17 and 18 Winzes and the Black Reef Incline (BRI), the three known surface decant sites in the Western Basin (Section 6.3.2). Except for slight pH differences, the water quality in the three surface decant sites is almost identical. The BRI, and to some extent Winze 18, water is slightly more neutral than the Winze 17 water and is probably partially buffered by dolomite, as suggested by higher Mn contents.

Table 6.10: Water quality (95 %tiles, period 2011-2012) of selected sites in the Western Basin.

Parameter	pH*	EC	SO4	Na	Fe	Ca	Mn	U	TDS^	Acidity
Unit	@ 25ºC	mS/m @ 25ºC	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l U	mg/l	mg/l
17 Winze	3.45	417	3253	209	895	658	85	-	4879	1373
18 Winze	4.18	446	3658	66	968	713	76	-	5487	1525
BRI	4.62	435	3577	199	923	724	94	-	5366	1540
Hippo Pool	2.79	414	3144	225	369	874	92	0.12	4715	978
Lion Camp Entrance	2.60	373	2702	254	238	743	85	0.07	4052	885
Lion Camp Aviary	2.60	358	2574	230	207	698	69	0.08	3860	849
Brick dam GR	2.60	357	2690	206	193	857	76	0.07	4035	840
Total Inlet GR	2.80	412	3210	242	459	701	123	0.10	4815	1028
Inlet GR Seepage	2.59	427	3463	244	480	874	209	0.10	5194	1151
Inlet GR Flume Canal	5.69	400	2909	249	7	885	32	0.02	4364	95
Porra Dam Pipe7	2.88	422	3280	235	720	739	91	-	4920	1141
C. Fourie Dam	2.68	374	2762	201	298	635	75	0.14	4143	922
* 5th Percentile GR = Krugersdorp Game Reserve ^ TDS estimated										

Data source: B. van der Walt, Rand Uranium, March 2012.

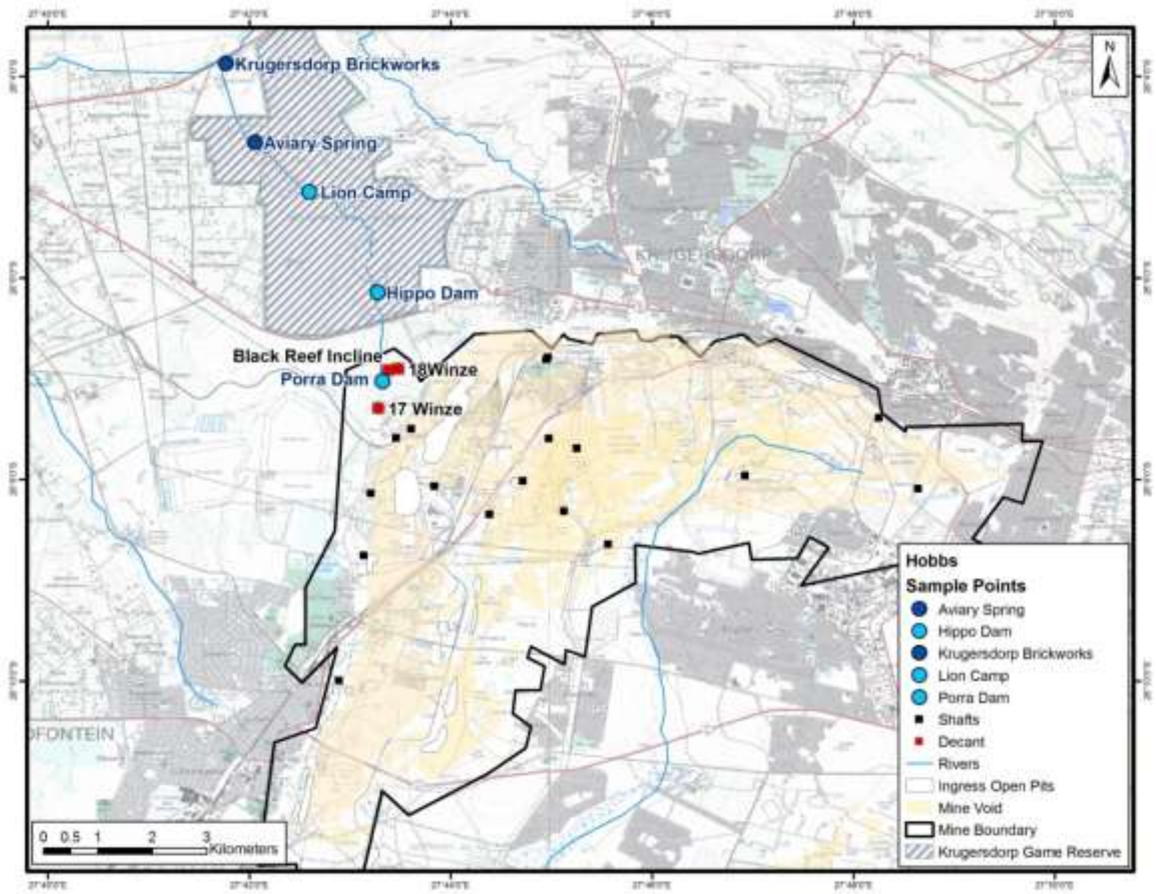


Figure 6.17: Locations of key water chemistry sample sites.

It is noticeable that the pH values for the three surface decant sites are on average higher than for the sites lower down the Tweelopies Spruit. This discrepancy may suggest diverse sources and/or channelling pathways for the AMD escaping from the mine void (see Section 0) and could result in variability of the quality of the water, especially during the initial phases of pumping. Alternatively, however, the slow oxidation of ferrous iron to insoluble ferric hydroxide may also account for the persistence of low pH's downstream of the surface decant, as demonstrated in the Natalspruit by Naicker et al.(2003).

The total observed range for the AMD from the Western Basin is given in **Table 6.11**. Using the current data, the most suitable approximation for the expected water quality for abstraction is based on the principal decant sites only (17 and 18 Winzes, BRI) and is given in **Table 6.12**.

Table 6.11: Compositional ranges for water from 17, 18 Winzes and BRI, Western Basin.

Parameter	Unit	Percentile						
		5th	10th	50th	60th	75th	90th	95th
pH	@ 25˚C	3.5	3.9	5.4	5.5	5.6	5.9	6.0
Conductivity	mS/m @ 25˚C	320	334	385	392	415	434	442
TDS^	mg/l	3549	4031	4628	4743	4890	5208	5434
Iron	mg/l	358	439	662	703	772	890	954
Sulphate	mg/l	2366	2687	3085	3162	3260	3472	3623
Sodium	mg/l	65	86	110	118	132	175	227
Calcium	mg/l	424	470	549	558	584	633	703
Manganese	mg/l	31	38	56	63	70	81	89
Acidity	mg/l	794	864	1039	1062	1174	1406	1520
^Estimated n = 148 for all parameters Data accumulated between January 2011 and March 2012								

Table 6.12: Compositional ranges for water from 17,18 Winzes and BRI, Western Basin.

Parameter	Unit	Percentile				
		95th	90th	50th	10th	5th
pH#	@ 25ºC	3.5	3.9	5.4	5.9	6.0
EC	mS/m@ 25ºC	442	434	385	334	320
TDS^	mg/l	5434	5208	4628	4031	3549
Acidity	mg/l	1520	1406	1039	864	794
Ca	mg/l	703	633	549	470	424
Na	mg/l	227	175	110	86	65
Fe	mg/l	954	890	662	439	358
Mn	mg/l	89	81	56	38	31
SO4	mg/l	3623	3472	3085	2687	2366
^Estimated n = 148 for all parameters Data accumulated between January 2011 and March 2012 # pH values in reverse percentile order, e.g. 95th percentile is 5th percentile						

6.7.3 Change of water quality with time

Documentation supporting the notion of improvement of water quality with time has been provided by Hobbs (2011) and Goga (2011). **Figure 6.18** illustrates the observed improvement with time of water from the Western Basin. Likewise, it has been observed that the uranium content, over the past 9 years of water decanting on surface from the Western Basin, has reduced from over 6000 µg/l U, initially, to 100-200 µg/l U. This decrease is probably due to less U being mobilised from the mine void (Winde, 2011).

For Winze 17, the data is highly variable (**Figure 6.19**). Until 2007, the water from Winze 17 was relatively uncontaminated, but deteriorated abruptly in early 2008. This sudden change in chemistry is interpreted to derive from chemical layering in the winze water column, with a column of fresh water from surface ingress probably sitting on deeper noxious AMD.

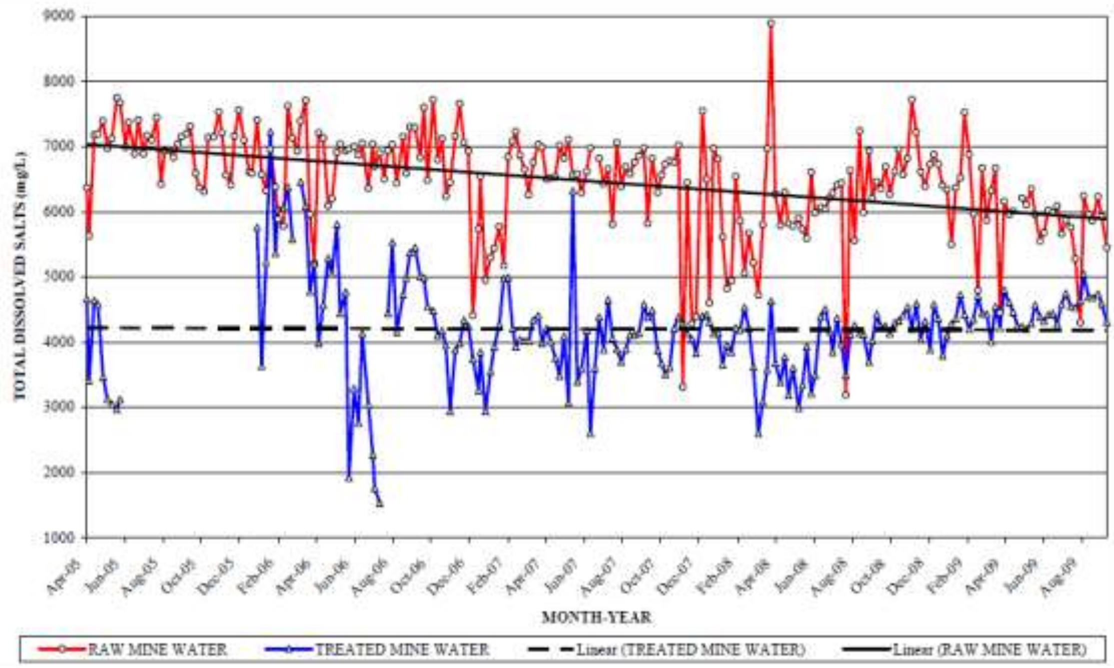


Figure 6.18: Long-term trend of TDS in raw and treated/discharged mine water (Hobbs, 2011).

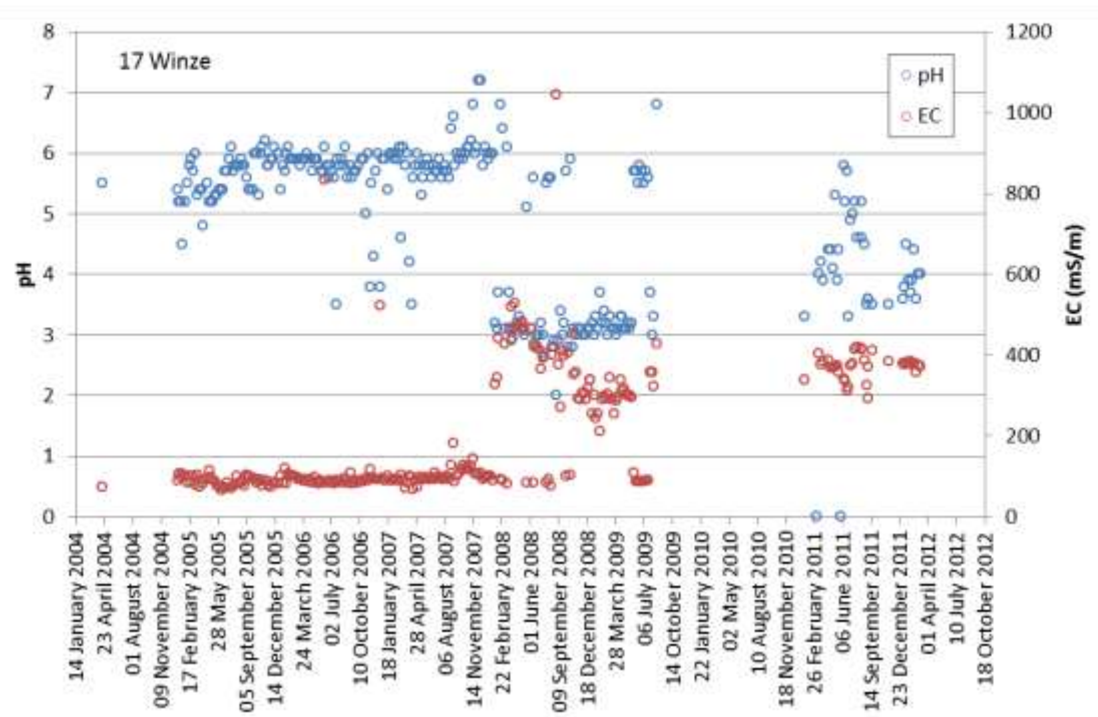


Figure 6.19: Chemical change of the Winze 17 water.

At 18 Winze, the water shows a continuous improvement (decrease) in EC (**Figure 6.20**), as well as a rise in pH. It is possible that some mixing of AMD and dolomite water is taking place at this site, as suggested by the high pH measured in 2011.

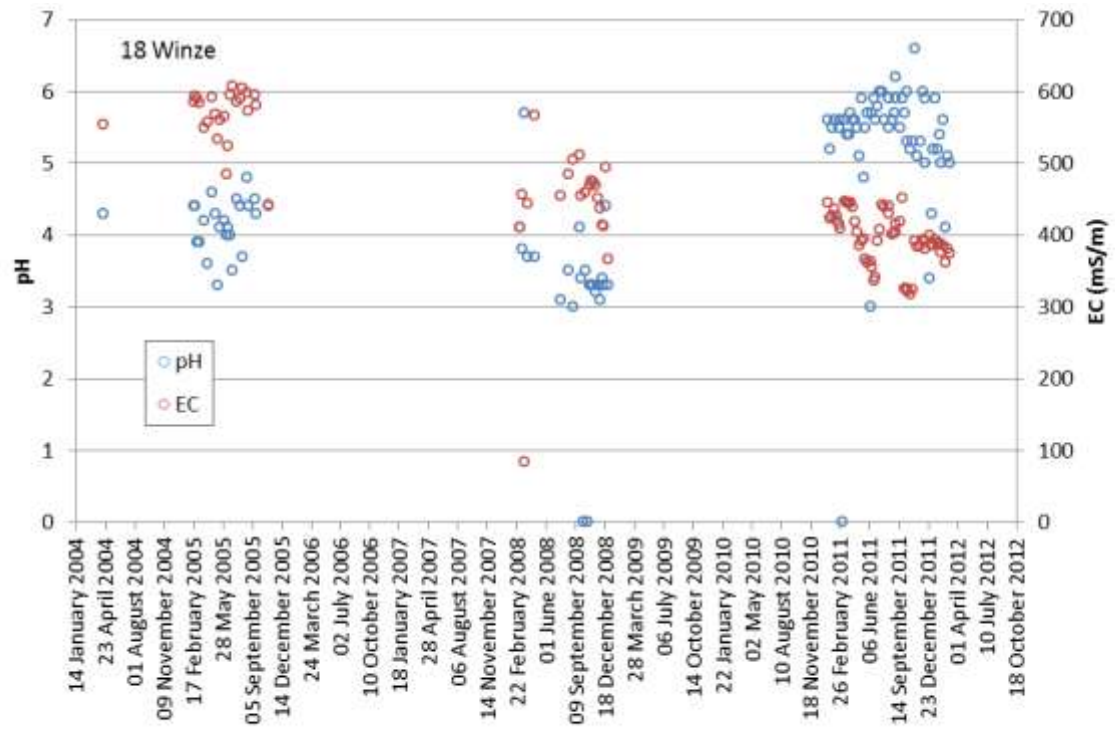


Figure 6.20: Chemical change of the Winze 18 water.

At the BRI, the water quality is more consistent over time than at the winze sites (**Figure** 6.21). The EC values are improving, whereas the pH values are at more alkaline levels. The buffering effect of dolomite is inferred from the high Mn contents of the BRI water (**Figure 6.22**) relative to winze surface decant water.

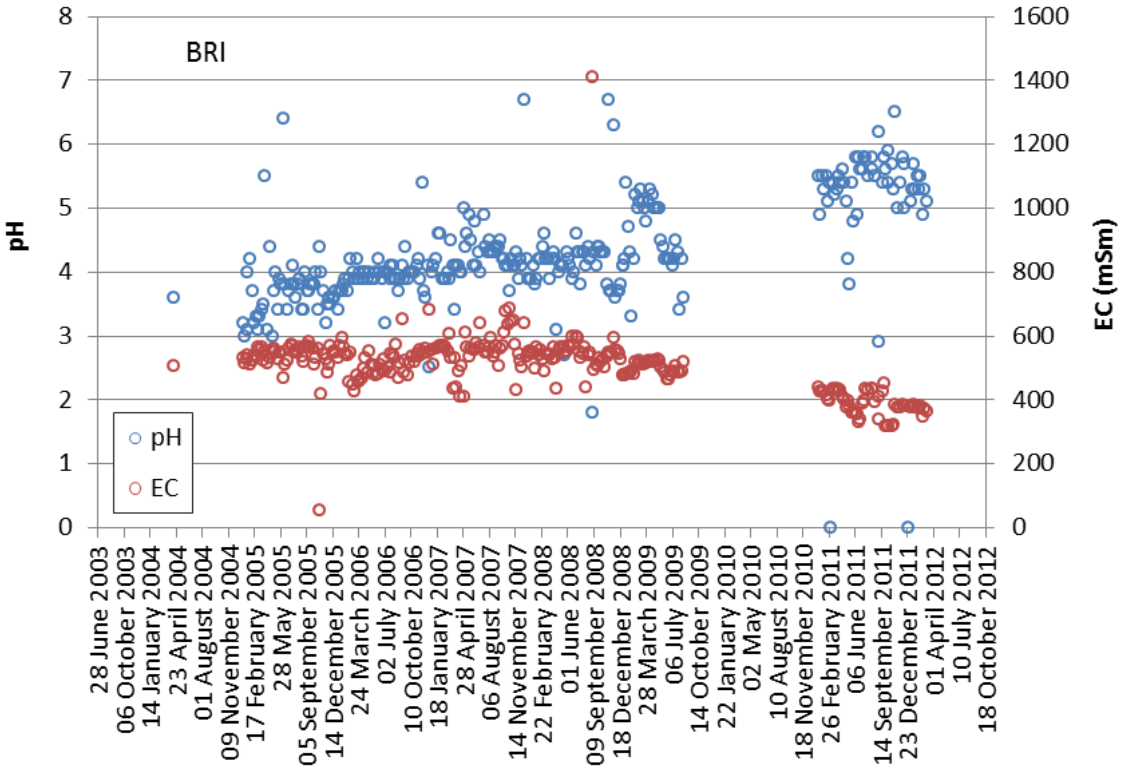


Figure 6.21: Chemical change of the BRI water.

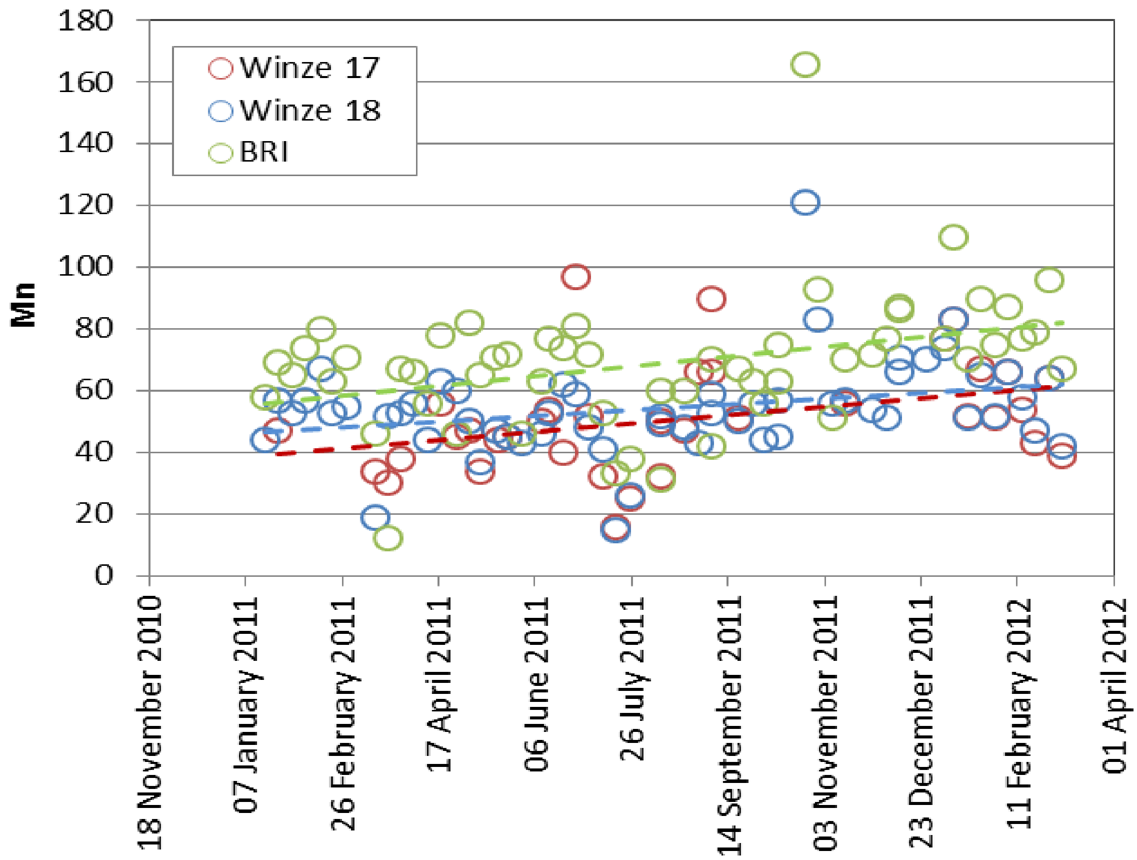


Figure 6.22: Mn contents (µg/l) of the surface decant water of the Western Basin.

On a note of caution, it must be pointed out that in Figures 6-17 and 6-18, the initial ECs measured approached 550 to 600 mS/m. If the model conversion equation (TDS ~ 11*EDC) is applied, the TDS estimates come to between 6000 and 6600 mg/l, which are much higher than measured elsewhere in the Western Basin. This observation underscores the inherent AMD variability that could possibly be expected during the pumping process.

6.8 Summary and Recommendations

6.8.1 Water levels and ECL

In the Western Basin, to reduce the associated risks to the Sterkfontein dolomite aquifer that hosts the Cradle of Humankind due to decant from the void into the Tweelopies Spruit, the water level could be lowered to the TOL which equates to the proposed ECL of 1600 m amsl and held there for an appropriate duration to establish whether the current situation downstream improves. It is noted that, depending on the rate of pumping it could take 1 to 2 years to reach equilibrium across the void. If leakage of direct AMD in the lower reaches of the Tweelopies Spruit ceases then the water could be held at this level, if not it could be lowered further to the more conservative 1550 m amsl ECL proposed in the TCTA Report (2011a).

6.8.2 Ingress

The ingress control measures that could theoretically be implemented (i.e. reducing ingress from the open and backfilled pits and removal/re-working of tailings dams) would reduce ingress by about 11 Mℓ/day, although this is not likely to be realistically achievable. Assuming less than half of these inflows can be removed, it is considered that a total ingress reduction of 5 Mℓ/day may be possible. The remainder of the ingress sources would be difficult and very costly to control and hence have not yet been taken into account. A detailed follow-up study would be required to assess the practicality as well as cost implications.

A summary of the ingress predictions with and without ingress control measures are given by source of information in **Table 6.13**.

Table 6.13: Summary of predicted ingress volumes, Western Basin.

Information source	Predicted ingress volume (Mℓ/d), No ingress control		Predicted Ingress Volumes (Mℓ/day), with improved Ingress Control	
	Average	Range	Average	Range
WUC Report (2009)	18	16 - 20	13	11-15
This Study	(23)	19 – 27	(18)	14-22
TCTA (planned average pumping rate)	27	23 -35	22	18-30

The following observations are made from **Table 6.13**:

- Data from this study compares well with the WUC data;
- The TCTA planned pumping rates are well in excess of the predicted ingress volumes and would also cater for possible climate change and wetter than average years.

6.8.3 Pumping rates

To account for the accumulated water in the shallow dolomite aquifer (Section 6.6.1), an initial pumping rate of up to 60 Mℓ/day from the immediate solution and short term pumps is proposed. This would affect the lowering of the water levels to 1600 m amsl in approximately one year if required. However, once the required TOL is reached, the pumping rate could be lowered to attain steady state conditions. Data indicates that this longer-term required pumping rate would probably level off at about 20 to 27 Mℓ/day an average of 23 Mℓ/day is proposed for use in other components of the study. Based on the interconnectivity with the mine void, the selected STI abstraction point at Rand Uranium Shaft No. 8 is considered to be appropriate for the long term solution.

6.8.4 Water quality

The Western Basin AMD currently is in a narrow band at an EC of ca. 350 mS/m, which represents about 3850mg/ℓ of total dissolved solids (TDS), with the 95th percentile reporting at an EC of 426 mS/m (about 5400mg/ℓ TDS). Recorded pH values vary between 2 and 7, depending on the degree of neutralisation that probably reflects differing degrees of interaction with dolomitic water. However, the slow oxidation of ferrous iron to insoluble ferric hydroxide may also account for the persistence of low pH's downstream of the surface decant.

7 CENTRAL BASIN

7.1 Geological Setting

The Central Basin extends from Durban Roodepoort Deep (DRD) in the west, where the reefs terminate against the Roodepoort Fault, to East Rand Proprietary Mines (ERPM) in the east, a distance of about 55 km. The West and Central Rand Group strata dip towards the south at dips varying from vertical (even occasionally overturned) to as little as 20° (**Figure** 7.1).

The Black Reef and the overlying dolomite of the Transvaal Supergroup outcrop well to the south of the Witwatersrand Supergroup rocks and are mostly separated from them by volcanic rocks of the Ventersdorp Supergroup except for a small region in the west (south of DRD) where the Black Reef fills a deep syncline in upper Central Rand Group rocks. The separation of the Black Reef from the main gold-bearing strata means that the dolomite has no impact on mine water in this basin.

7.2 Hydrogeological Setting

Figure 7.2 shows the conceptual hydrogeological model in a cross-section through the Central Basin from North to South. Since the dolomite is essentially absent within the Central Basin, only the shallow weathered aquifer associated with the Witwatersrand and Ventersdorp rocks is present. Hydraulic connectivity to the mine voids is via joints, faults and intrusive dykes.

According to Brink (1979), there is a trough-like depression along the total strike of the Jeppestown Subgroup that was occupied by pans and marshes before development in the area, indicating a shallow groundwater table. Even after the reefs were mined, the groundwater strike depths and rest-water elevations are normal for this climatic region (Hodgson, 1993). This suggests that no wide cone of dewatering of the shallow weathered aquifer has developed around the mines. This shallow aquifer is nevertheless used locally as borehole water mostly for irrigation of gardens, golf courses in the highly urbanised Central Basin and also provides base flow to the streams and rivers that originate in the Witwatersrand quartzite ridges and ultimately flow into the Vaal River catchment. For this reason, protection of this shallow aquifer must be considered and the underlying mine void water should ideally remain below the “bottom” of the weathered aquifer estimated to be a maximum of 100 metres below ground level.

The weathered intrusions in the old workings at shallow depths (<300m) were zones of seepage, providing preferential flow paths. When the mine development cut through these rocks, the preferential flow was called an inrush. Typically, the flows would have diminished as the storage drained from the more permeable structures into the void. At deeper levels, these fractures would have been sealed by grouting.

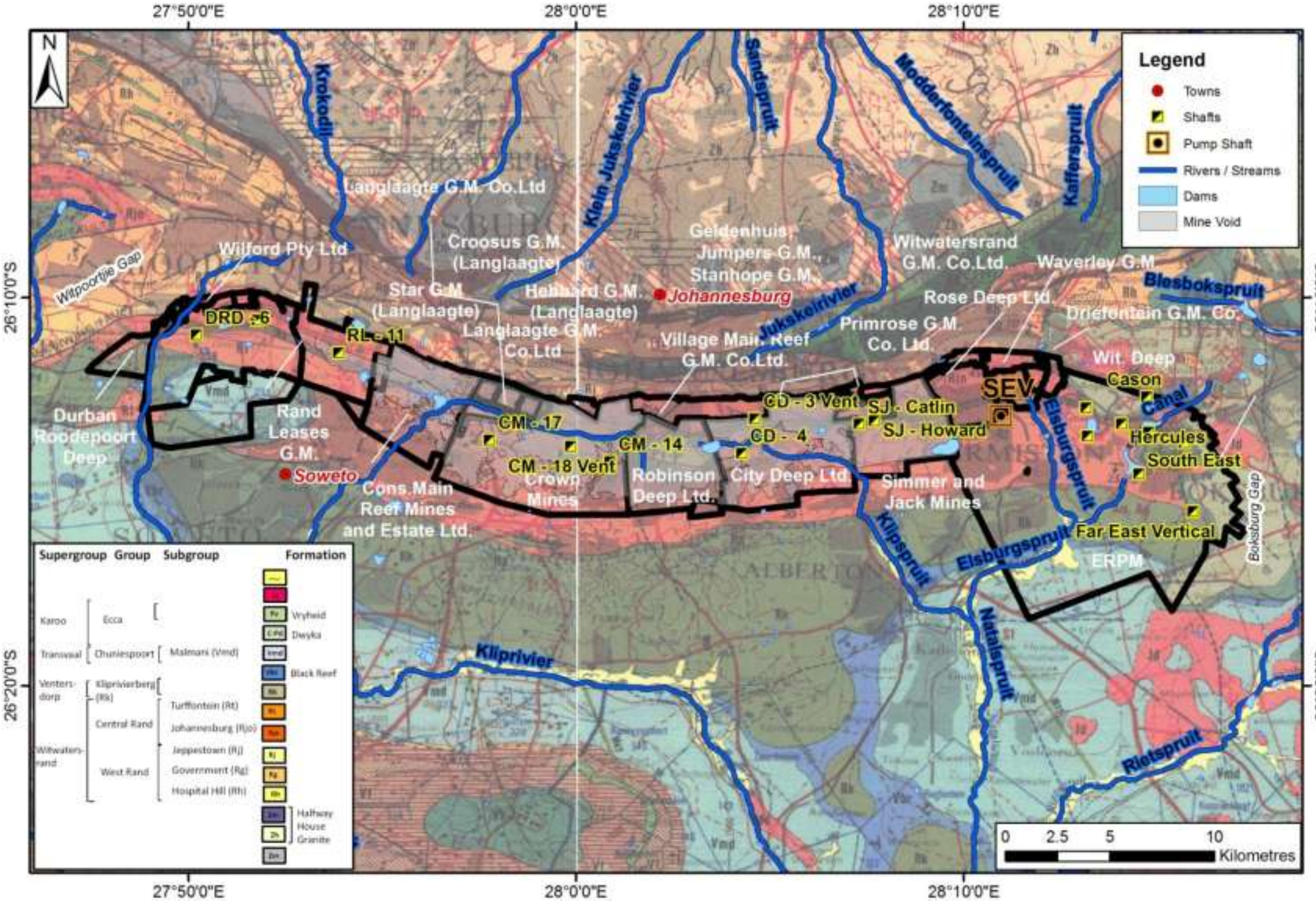


Figure 7.1: Geological map of the Central Basin showing mine boundaries and selected shaft.

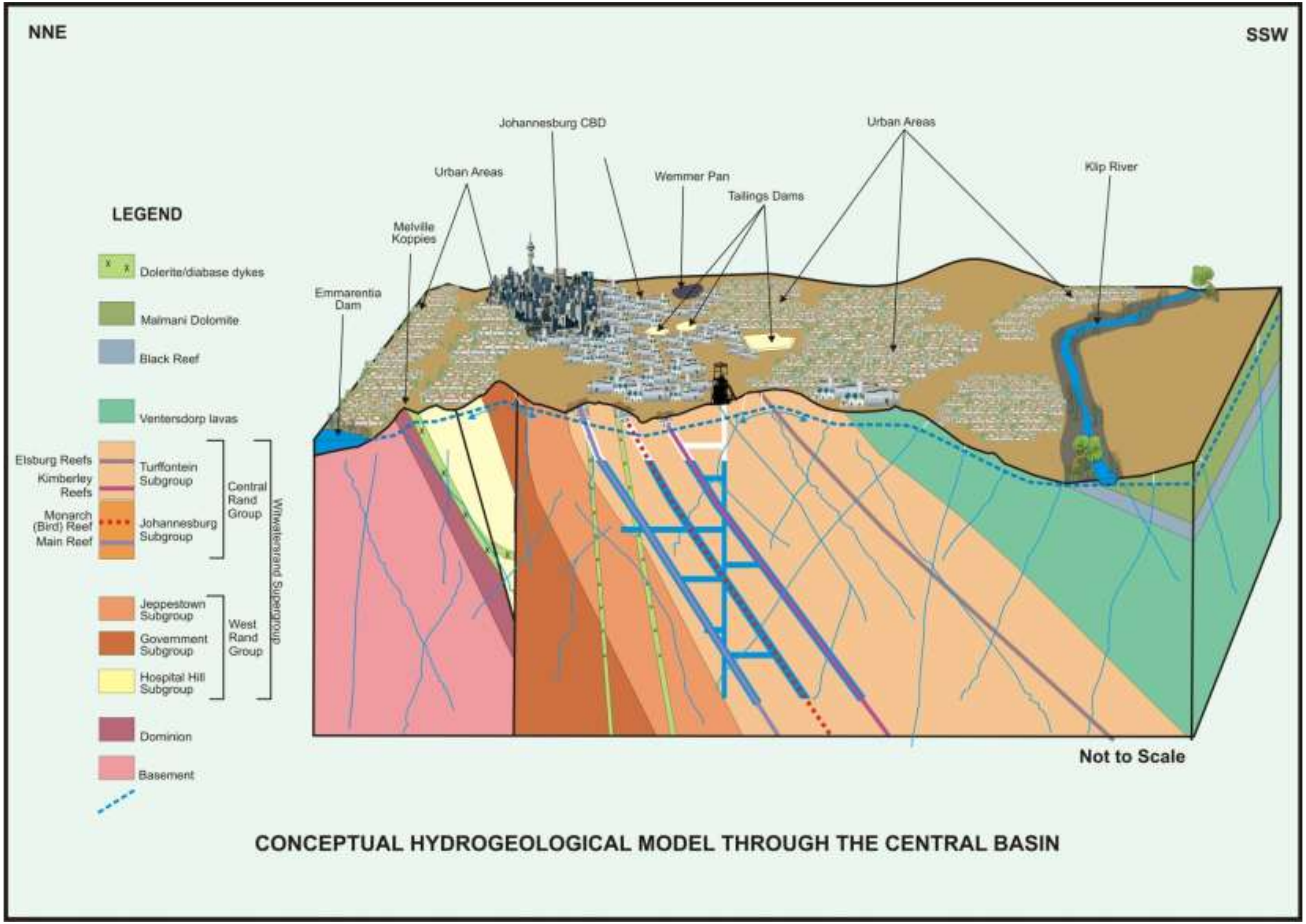


Figure 7.2: Schematic illustration of a conceptual hydrogeological model for the Central Basin.

7.3 Mine Voids

7.3.1 History, distribution and connectivity

Mining operations commenced in the Central Basin in 1886 and, over its long history, numerous mining companies were active. Because of increasing depth and higher costs, mines amalgamated, leaving only a few larger players in the field. Starting in the 1950s, these mines began to close, the last two being DRD in 1999, and finally ERPM, which ceased deep level operations in 2008. The impact of this progressive closure of the mines on the extraction of water has been well documented in several reports (e.g. Scott, 1995; Boer et al., 2004; Winde, 2011) and will not be repeated here.

In the Central Basin, the major gold-bearing strata were those of the Main Reef Group (South, Main Reef Leader and Main Reef) and to a much lesser extent the Kimberley Reef (**Figure 7.3**). The Bird Reef was sporadically mined in the west, as was the Ventersdorp Contact Reef (VCR) in the southern Roodepoort area.

The multiple reefs of the Main Reef group of conglomerates (South, Main, Main Reef Leader and North Reef) progressively converge towards the eastern end of the Central Basin. In the eastern portion of ERPM only a single reef is developed, known as the Composite Reef. This convergence of the reefs coincides with the western flank of an anticlinal structure (the Van Dyk anticline) which forms part of the Springs Monocline that marks the western limit of the Eastern Basin. In the Eastern Basin, only a single reef, the Nigel or Main Reef, is developed at this stratigraphic level.

The payability of the Composite Reef evidently also declined towards the east and the reef was therefore not mined along the far eastern portion of ERPM, a region known as the Boksburg Gap. To the east of this zone, payability improved and extensive mining took place on the Main Reef in the Eastern Basin. The two areas are separated by a minimum of 500m of solid rock, which constitutes a substantial pillar (Arnold, et al., 2005).

By the time the operating mines had dwindled to just DRD and ERPM, it was evident that the mine void could be divided into several discrete sub-basins which were separated by boundary pillars that had been plugged. Once DRD ceased pumping, its void filled and water began to cascade over the boundary pillars towards the last remaining mine in the east (ERPM). This mine ceased pumping in 2008 and the water level in the compartments in the central and eastern regions began to rise. They have now equilibrated and the water level across the basin appears to be rising in unison, with the exception of the Far East Sub-compartment at ERPM, which is described below.

Zones of fairly high payability on the Composite Reef were found to extend in a south-easterly direction and to access the down-dip extensions of this zone of payable gold reef, the Far East Vertical (FEV) Shaft system of ERPM was sunk (**Figure 7.3**). This became a quasi-independent section of ERPM and was connected through to the older mine workings

on only a few relatively deep levels. The ore reserves on the older mining areas began to be depleted and the possibility of a cessation of mining and hence pumping was looming. For mining operations at FEV to continue, strategically placed plugs were installed on 68, 58 and 42 levels. These plugs were intended to protect the FEV Shaft operations from flooding when routine pumping from 24 level at South West Vertical Shaft (SWV) ceased. The Far East workings are therefore completely separated from the ERPM Hercules Compartment.

Mining has since ceased in the Far East Sub-compartment and it is now slowly flooding. Since it is apparently no longer connected to the remaining portion of ERPM and ingress is restricted, the rate of rise of the water level in the FEV is far slower that in the Central Basin as a whole. However, it should be noted that the FEV Shaft collar elevation is one of the lowest in the Central Basin (approximately 1605 m amsl ±10 m). Regular monitoring of the water level in this shaft is therefore strongly recommended.

It is assumed that, at the shallower levels that are now filling, there is free and open connection across the mine void from DRD to ERPM (e.g. Winde, 2011). However, examination of mine plans indicates that the mined out area is transected by numerous large dykes and zones of fault loss where mining was not carried out. These structures were penetrated by haulages, but often these haulages were partially sealed by ventilation doors or even brick walls. The locations and frequency of these barriers is unknown and if present in sufficient numbers they could impede, although not prevent, lateral flow of water through the void. The effect of these obstacles on the flow of water in the void will only become known once pumping commences.

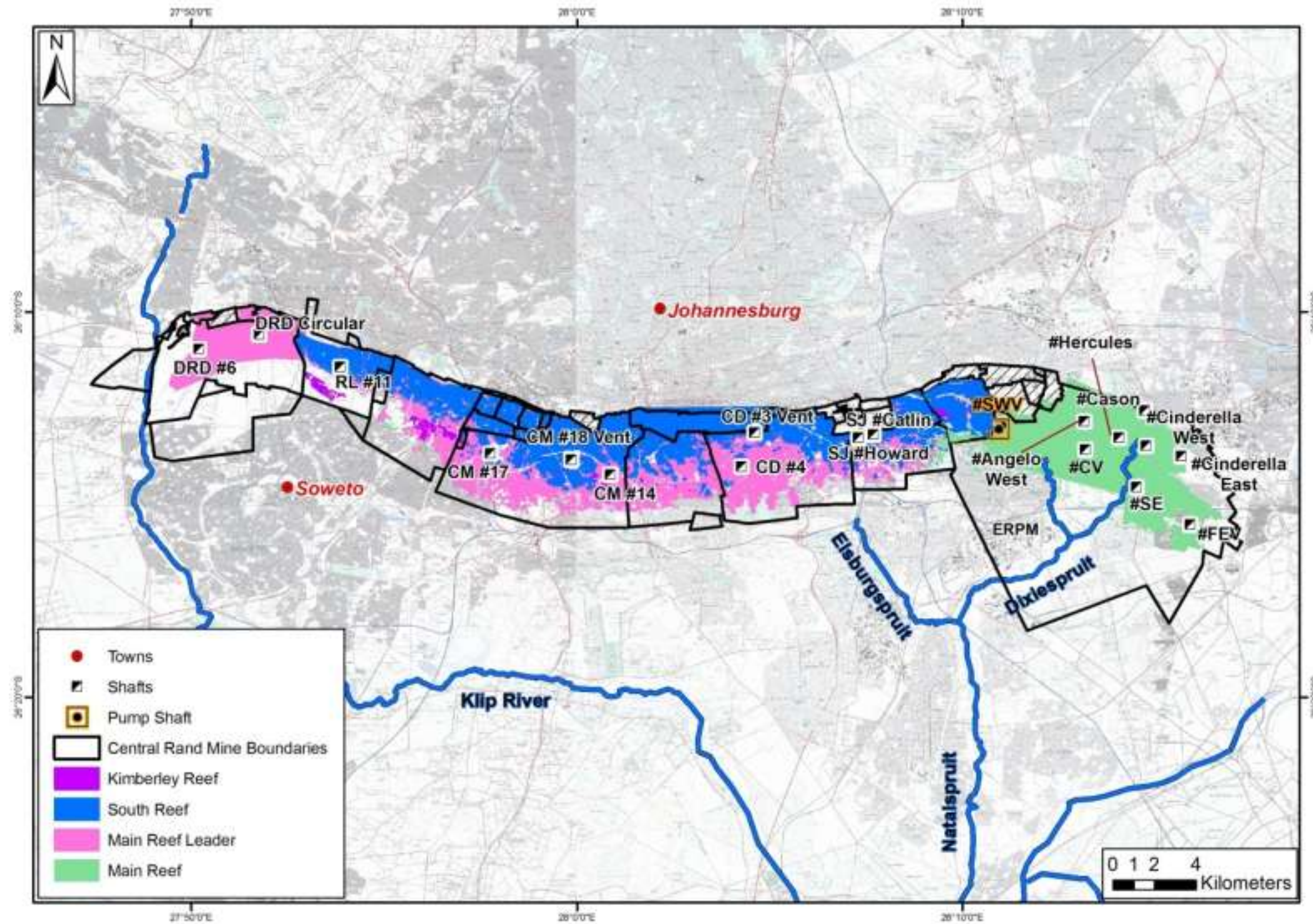


Figure 7.3: Map showing mined out area of the Central Rand. Hashed areas were mined but no void data is currently available. Note the Main Reef in the ERPM area is a Composite Reef comprising Main Reef Leader and Main Reef.

7.3.2 Water Levels

The Central Basin is essentially subdivided into three sub-basins or compartments: the western DRD-RL (Durban Roodepoort Deep - Rand Leases) sub-compartment, the central CMR-SJ sub-compartment (Consolidated Main Reef – Simmer & Jack) and the East Rand Proprietary Mines (ERPM) sub-compartment (Rison Consulting, 2001). **Figure 7.4** schematically illustrates the compartmentalisation of the Central Basin and shows key shaft, haulage and plug positions (note that the water level shown is as per 2001, after pumping ceased at DRD but prior to cessation of pumping at ERPM). The historic water flow and management in the Central Basin is illustrated in **Table 7.1**. East of the main ERPM compartment is the Far East sub-compartment, which is isolated by plugs from the rest of the Central Basin.

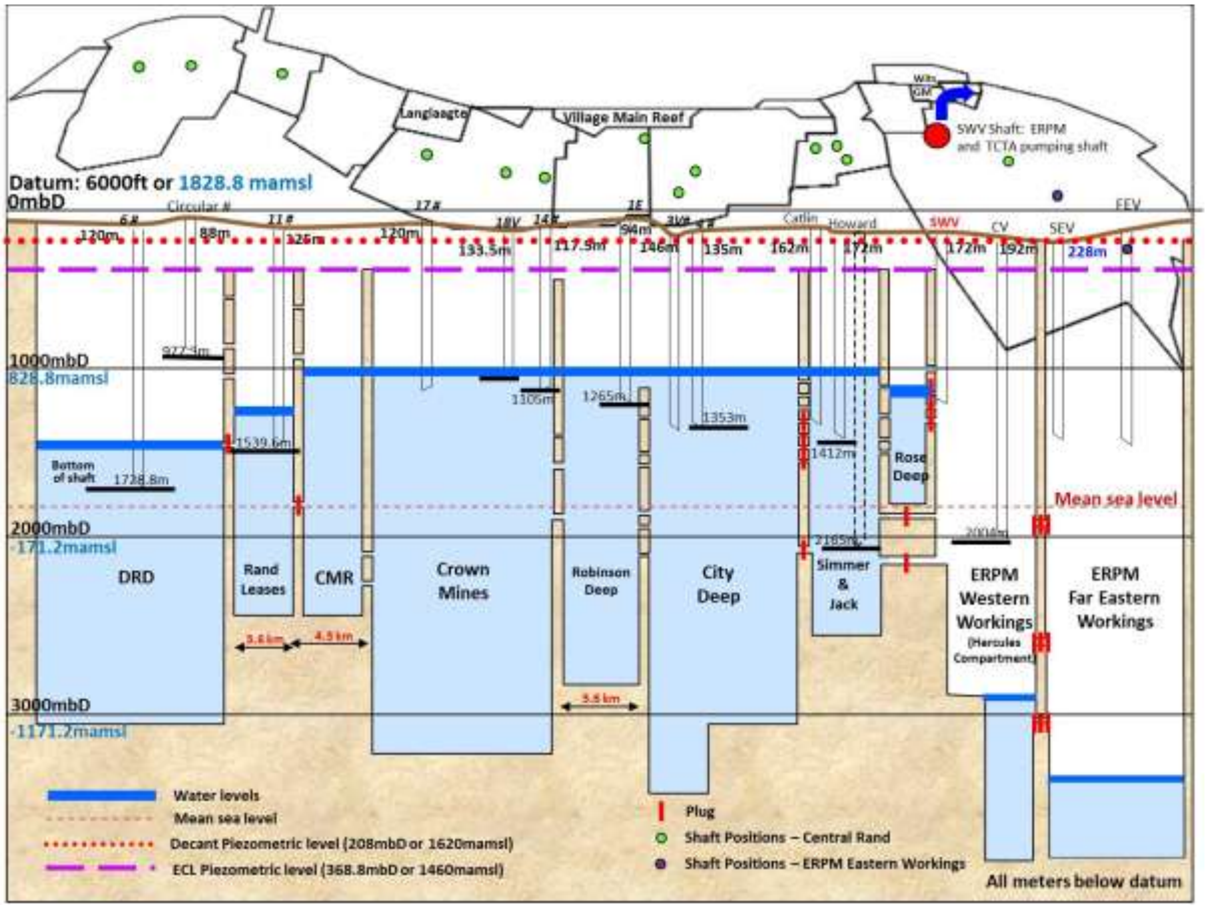


Figure 7.4: Sub-compartments in the Central Basin mine void (note water levels as per 2001).

Table 7.1: Historic water flow (Mℓ/day) and management in the Central Basin. (DRD – Durban Roodepoort Deep; RL – Rand Leases; CMR – Consolidated Main Reef; CM – Crown Mines; RoD – Robinson Deep; CD – City Deep; SJ – Simmer and Jack; RsD – Rose deep; ERPM – East Rand Proprietary Mines Limited).

Year	DRD_5	RL	CMR	CM	RoD	CD	SJ	RsD	ERPM _Herc	ERPM _SWV
1952	4.9	3.7	7.1	7.4	4.4	7.4	4.4	4.5	10.4	
1953	6	4.3	6.4	7.6	4	8.6	3.8	5.1	10.2	
1954	6.1	3.1	7.6	7.1	3.6	8.2	4	4.4	11.6	
1955	7.9	6.1	6.6	10	4.4	10.1	5.2	5.6	12.7	
1956	7.4	4.3	6	9.2	4.5	9.6	4.1	5.4	11.6	
1957	7	4.4	8.1	9.4	4.8	9.3	4.3	5.9	11.9	
1958	5.7	5.2	5.8	8.7	4.4	7.1	4.4	5.6	12.3	
1959	7.3	3.2	6.8	8.2	4.3	6.8	4.1	3.3	11.9	
1960	nr	nr	nr	nr	nr	nr	nr	nr	12.9	
1961	nr	nr	nr	nr	nr	nr	nr	nr	12.5	
1962	nr	nr	nr	nr	nr	nr	nr	nr	11.2	
1963	nr	nr	nr	nr	nr	nr	nr	nr	10.2	
1964	nr	nr	nr	nr	nr	nr	Closure	nr	11.9	
1965	nr	nr	nr	nr	nr	nr		Closure	nr	
1966	nr	nr	nr	nr	Closure	nr			nr	
1967	nr	nr	nr	nr		nr			nr	
1968	nr	nr	nr	nr		nr			6.9	
1969	nr	nr	nr	nr		nr			17.6	
1970	nr	nr	nr	nr		nr			19.7	
1971	nr	Closure	nr	nr		nr			21.4	
1972	8.1		nr	nr		nr			19.6	
1973	8.3		nr	nr		nr			14.2	
1974	9.6		nr	nr		nr			18.3	
1975	11.5		Closure	nr		nr			nr	
1976	18.9			nr		Closure			16.2	
1977	18.7			Closure					12.7	33.2
1978	21.6								13.9	33.4
1979	16.9								14.6	23
1980	17.2								17.5	27.8
1981	17.9								18.4	29
1982	17.1								17.9	25.9
1983	15.8								17.9	24.6
1984	16								18.8	22.2
1985	nr								nr	nr
1986	14.3								19.1	25.6
1987	17								20.9	33.7
1988	21.4								nr	28.9
1989	nr								18.4	26.8
1990	19.2								17.8	19.9
1991	nr								nr	37.6
1992	nr								nr	37.5
1993	nr								nr	39.6
1994	22.4								nr	42.7
1995	18.1								16	31.1
1996	17								nr	nr
1997	18								18	16.2
1998	nr								44.8	
1999	stopped								nr	
2000									nr	nr
2001									16.4	33.4
2002									15.2	36.3
2003									15.5	38.5
2004									stopped	35
2005										
2006										41.3
2007										39.7
2008										54.1
Oct-2008										stopped

The historic and most recent water level data in the Central Basin are presented in **Figure** 7.5. This diagram is based on multiple datasets (L.du Plessis, Gold Reef City, 2012; H.Coetzee, CGS, 2012; V.Labuschagne, ERPM, 2012) and illustrates the gradual decrease in the filling rate (m/day) as successive compartments merged and the volume of the void increases. This decrease in filling rate may also in part be due to the gradual reduction in the hydraulic gradient. The merging of the CMR-SJ sub-compartment (green arrow in **Figure** 7.5) with the ERPM sub-compartment at about 820 m amsl reduced the rate of filling (lowering in the slope of the black arrows). The same effect is observed when the DRD-RL sub-compartment (blue arrow) equalised at 1049 m amsl with the larger CM-ERPM basin.

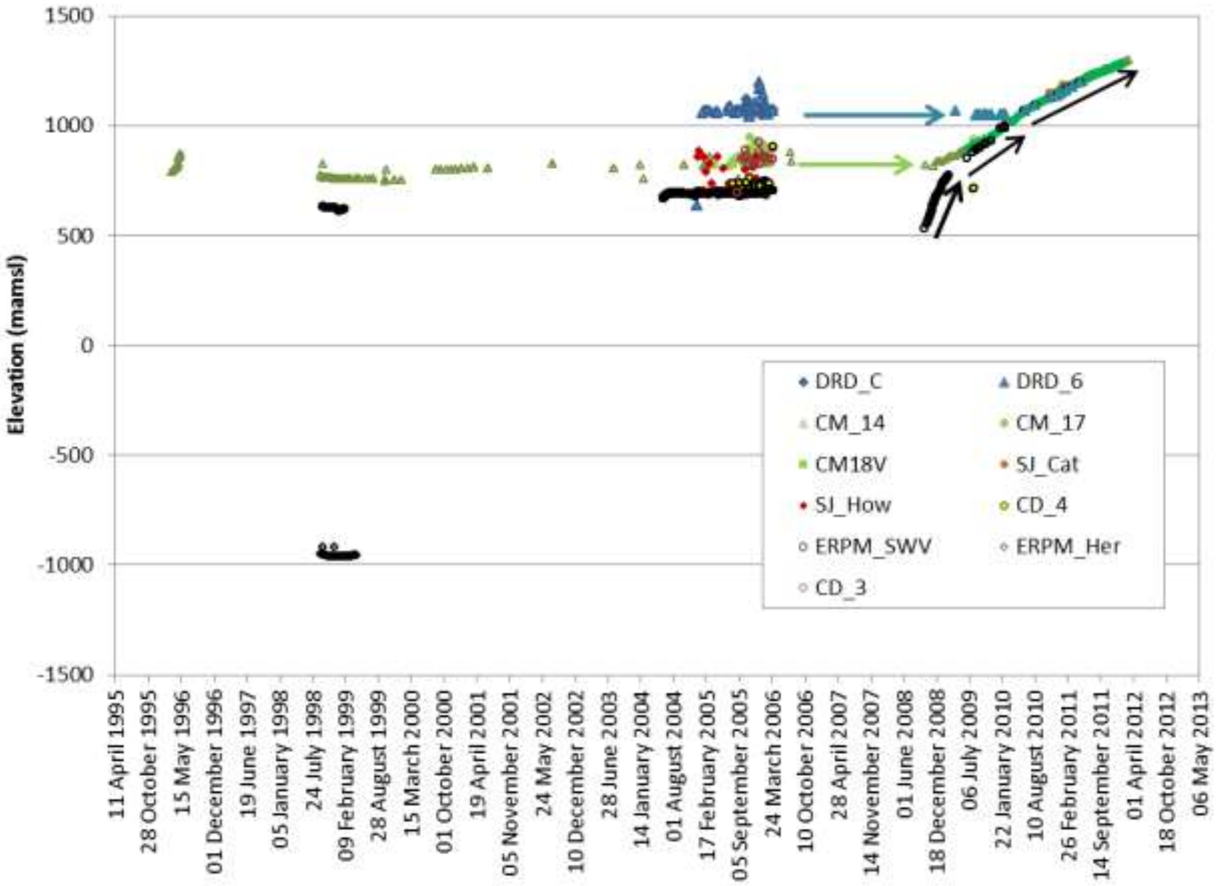


Figure 7.5: Historic water level rise and filling of the Central Basin.

7.3.3 Predicted Decant

The elevation of the outcrop of the Main Reef essentially decreases from west to east and the lowest points accessing the mine void occur at ERPM in the east. The TCTA Report (2011a) identified Cinderella East Shaft to be the expected surface decant site at an elevation of 1617 m amsl. From our investigations, the shafts accessing the mine void (that have not been subsequently filled) with the lowest collar elevations are Cinderella East (1627 m amsl) and Cinderella West (1621 m amsl). These elevations are based on Google Earth elevations, since Winde (2011) found that in open terrain such as the mining belt, this

data closely matched the surveyed shaft collar elevations, with an average deviation of only 20 cm. Other ERPM shafts, which have similar elevations, are also potential surface decant sites even though they have been filled with rubble. These include Hercules (1621 m amsl), Angelo West (Vent; 1620 m amsl), Angelo Deep (1629 m amsl) and Central Vertical shaft (1639 m amsl).

Decanting on surface, if allowed to occur, will take place at one or more of these shafts, or possibly at points where fractures connected to the mine void allow water to escape at a lower elevation (**Figure 7.6**).

Winde (2011) undertook an investigation of the Central Rand surface decant locations and more detail can be obtained from that report. If report identified Cinderella West at 1613.7 m amsl is the lowest shaft elevation. However, the current project team found that Cinderella Dam is located at this height and ERPM survey data places Cinderella West Shaft at 1625 m amsl, or 1621 m amsl according to Google Earth. The DWA is currently in process of re-surveying all of the key shafts in this area, which should provide the definitive collar elevation data that is much needed.

The final merging, at 1049 m amsl, of the water levels in all three compartments of the Central Basin occurred in May 2010, meaning that there is connectivity across the basin. New data allows a revised estimate of the surface decant and ECL dates (**Figure 7.7**). Keeping in mind the risks of excessive extrapolation, the current estimate for the water levels in the Crown Mines 14 Shaft to reach the ECL proposed by TCTA (1467 m amsl) is estimated at about January 2014 with decant sometime in 2015. This contrasts with the TCTA original estimate of August 2012 for breaching the ECL. Water levels as measured in the Crown Mines 14 Shaft rose at a rate of 0.3 to 0.4 m/day during February 2012, and, although somewhat tenuous, appears to show a small decreasing trend with time (**Figure** 7.8).

If the mine water was allowed to rise and decant there would be contamination of significant areas of near surface aquifers and the objective set by the IMC of protecting the aquifers would not be met. It is therefore necessary to set an ECL.

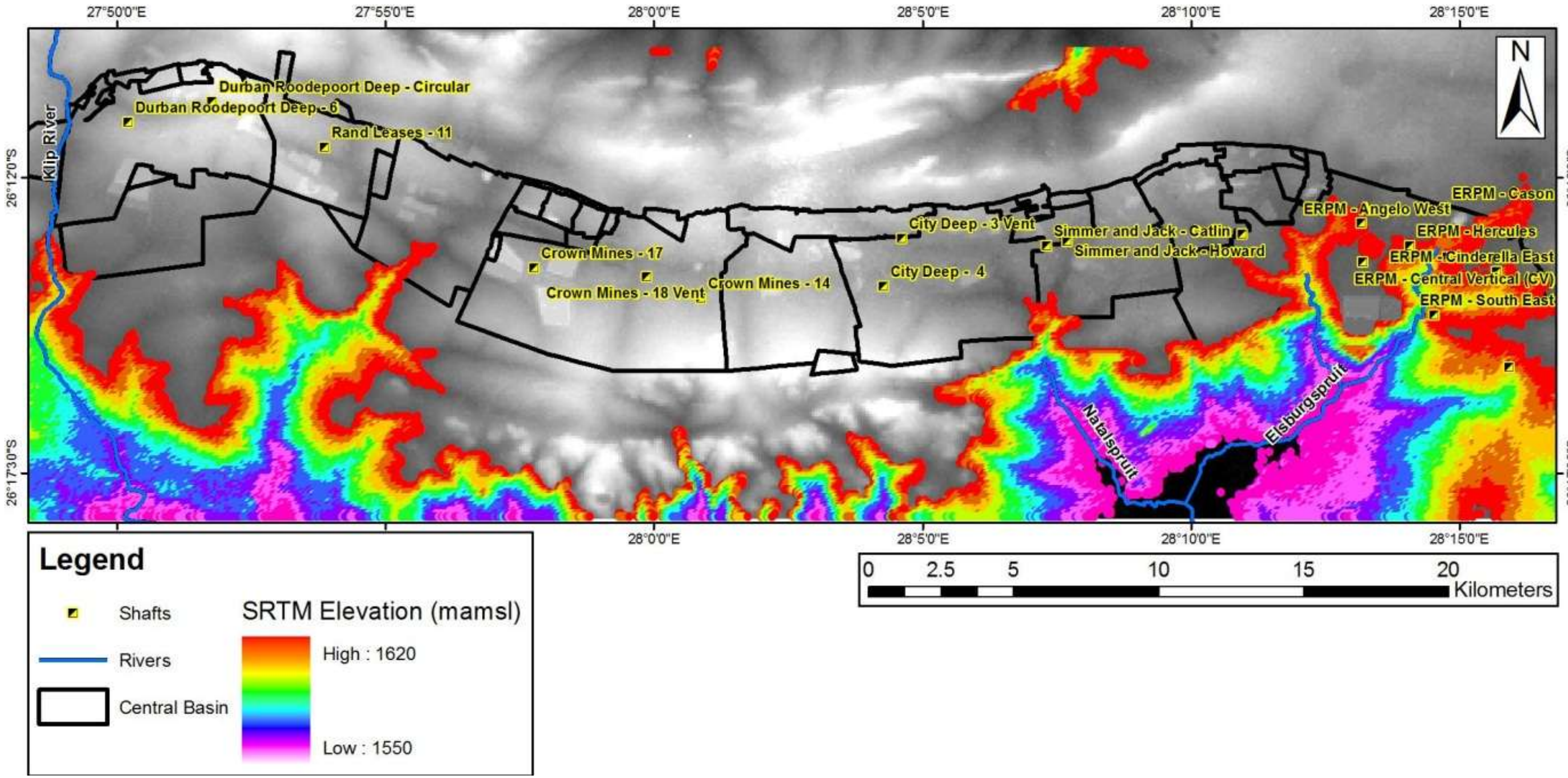


Figure 7.6: Elevations in the Central Rand below 1620 m amsl defined by Shuttle Radar Topography Mission (SRTM) data.

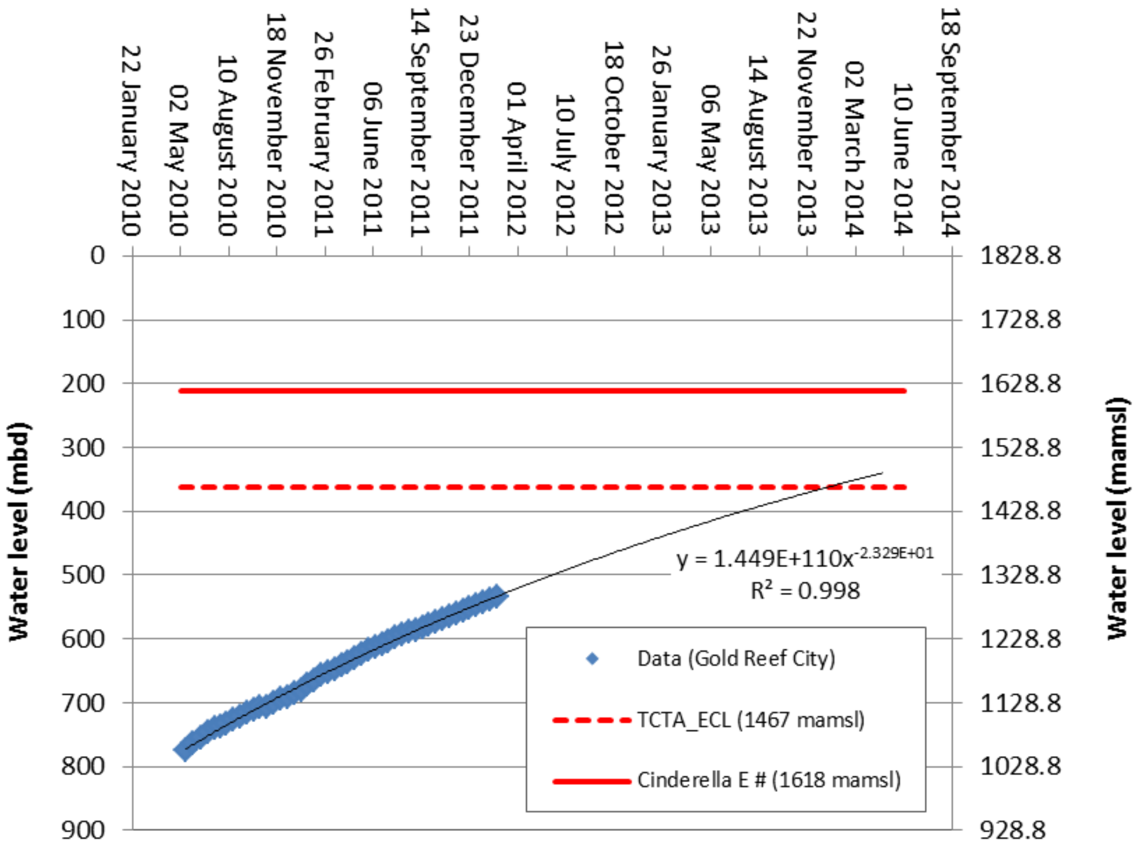


Figure 7.7: Estimated surface decant and ECL dates for the Central Basin.

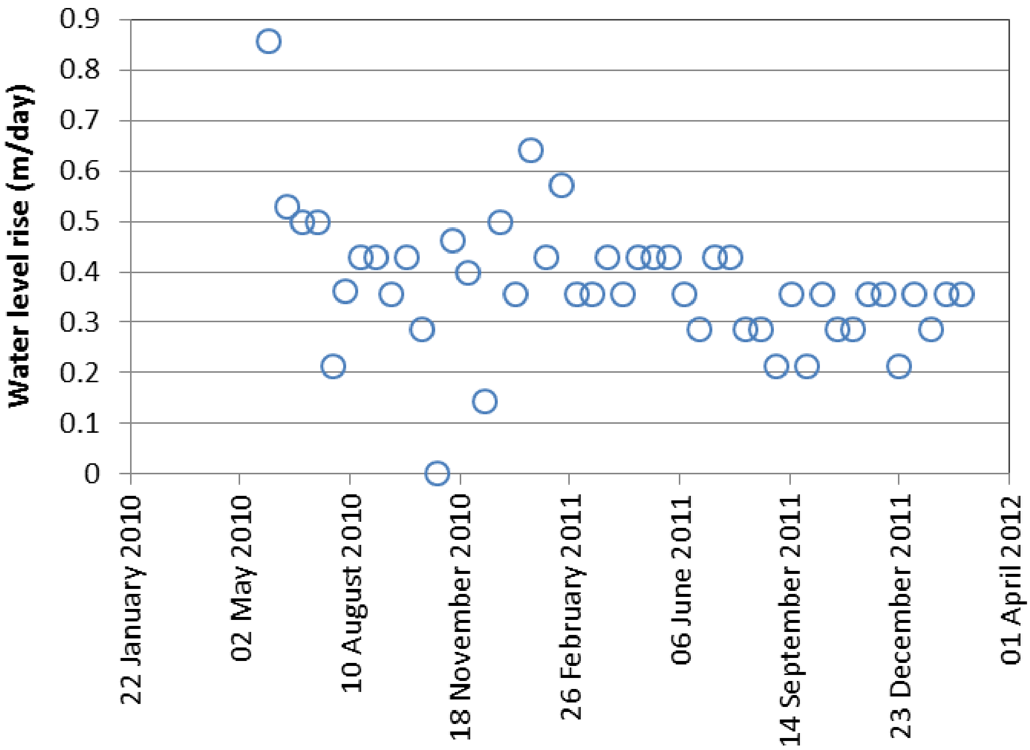


Figure 7.8: Water level rise in the Central Basin

7.4 Critical Water Levels

7.4.1 Proposed Environmental Critical Level

The TCTA Report (2011a) proposed a 1467 m amsl ECL or a depth of 150m below their assumed surface decant elevation (1617 m amsl) at ERPM, with the stated objective to protect groundwater resources. This critical water level was designed to account for a 50 m buffer with the shallow weathered and fractured aquifer only considered to extend to '80-100 m below the surface' (Annexure B, TCTA Report, 2011a).

The depth to water from available borehole data is indicated to be generally shallow in the Central Basin region, typically less than 20 m. The ECL is therefore proposed at an elevation of 1520 m amsl (**Figure 7.9**), which is based on an estimated depth of 100 metres below the potential surface decant at ERPM (section 7.3.3), and should adequately protect the shallow weathered aquifer. This ECL does not incorporate a substantial 'buffer', such as proposed in the TCTA Report (2011a), as this will be considered in the definition of a TOL in the Pre-Feasibility Report.

A program of drilling across the Central Basin is recommended to improve definition of the depths of the shallow aquifer, since much of the currently available data is not directly above the mine void. This will enable a more accurate elevation to be set for the ECL.

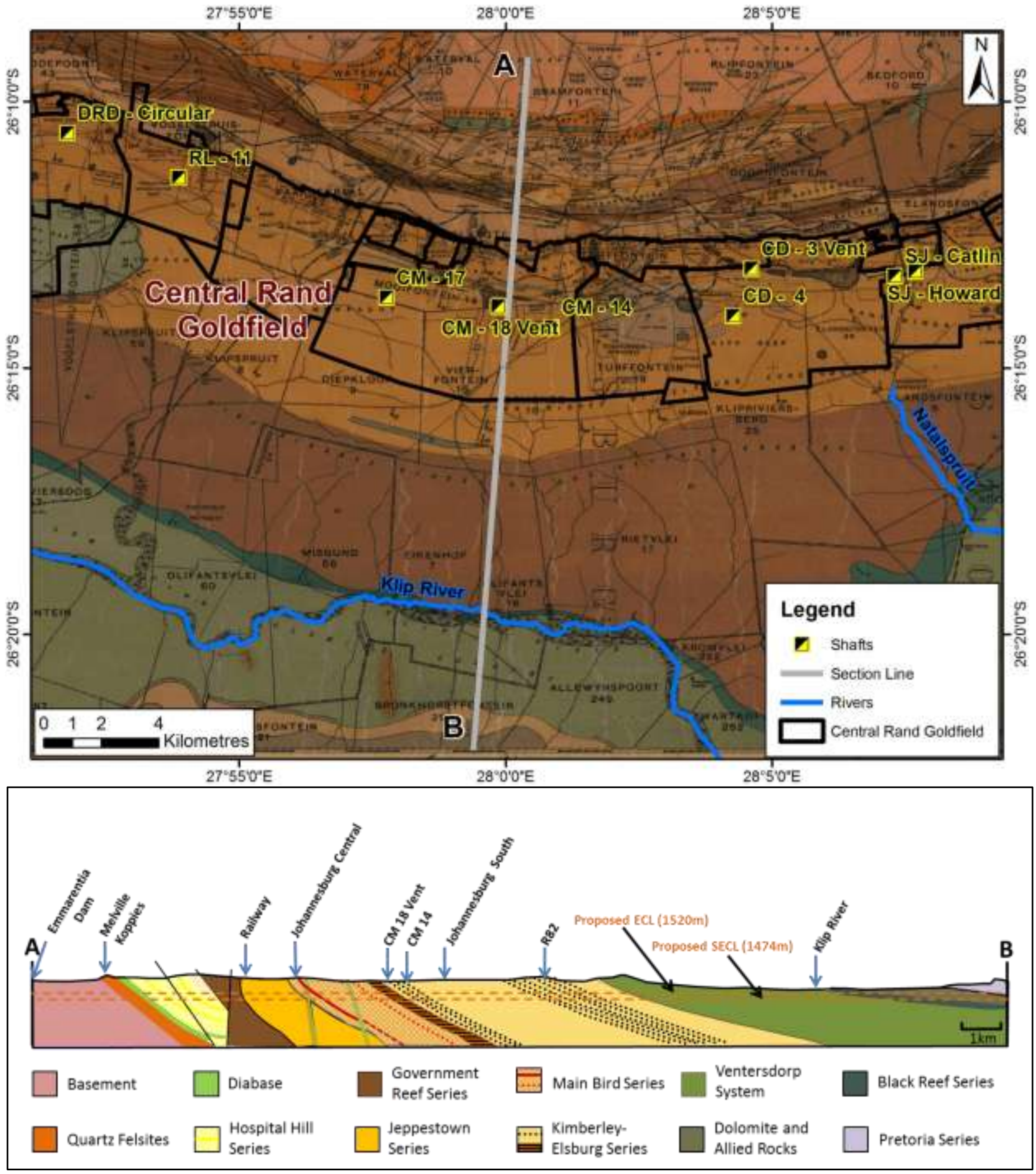


Figure 7.9: Geological map of the Central Basin, with a cross section along the centre. Cross section shows ECL as proposed in the TCTA Report (2011a), and the ECL/SECL as proposed in this study.

7.4.2 Proposed Socio-Economic Critical Level

The IMC set the ECL (now defined as the SECL) at 1503 m amsl in the Central Basin so as to protect the historic underground museum at 14 Shaft (CM14) at Gold Reef City (GRC). This would now be defined as an SECL. Although the TCTA Report (2011a) defined the

1467 m amsl ECL to protect groundwater resources, this static water level would also protect the GRC underground museum.

Based on the latest survey data from the Department of Water Affairs, the collar elevation of CM14 has been definitively set at 1699 m amsl (E. van Wyk, pers. comm.). According to several sources, including historic mine plans and sections, the 5 Level museum historic mine workings are at 215 m below surface (1484 m amsl). To protect 5 Level, and providing for additional space to house the double-decker conveyance and minor errors in elevation/depth data, an SECL of 1474 m amsl is proposed (**Figure 7.9**).

Figure 7.10 illustrates the location of the TCTA ECL and proposed SECL in the form of a north-south cross section through CM14 Shaft and workings. It should be noted that Gold Reef City management are conducting detailed contingency investigations into the relocation of the mining museum facility to 2 Level, 75 m below surface (1624 m amsl). Whilst this would be suitably protected at the proposed ECL of 1520 m amsl (section 7.4.1), it would offer very little freeboard in the event of natural decant at approximately 1620 m amsl. It should also be noted that 5 Level was once an active working level on the mine, and it is appropriate that it be preserved. Redevelopment would require the excavation of new tunnels from the shaft to the Kimberley Reef stopes, and would be, in a sense, artificial. If at all possible, the actual places where miners spent their working days should be preserved for posterity.

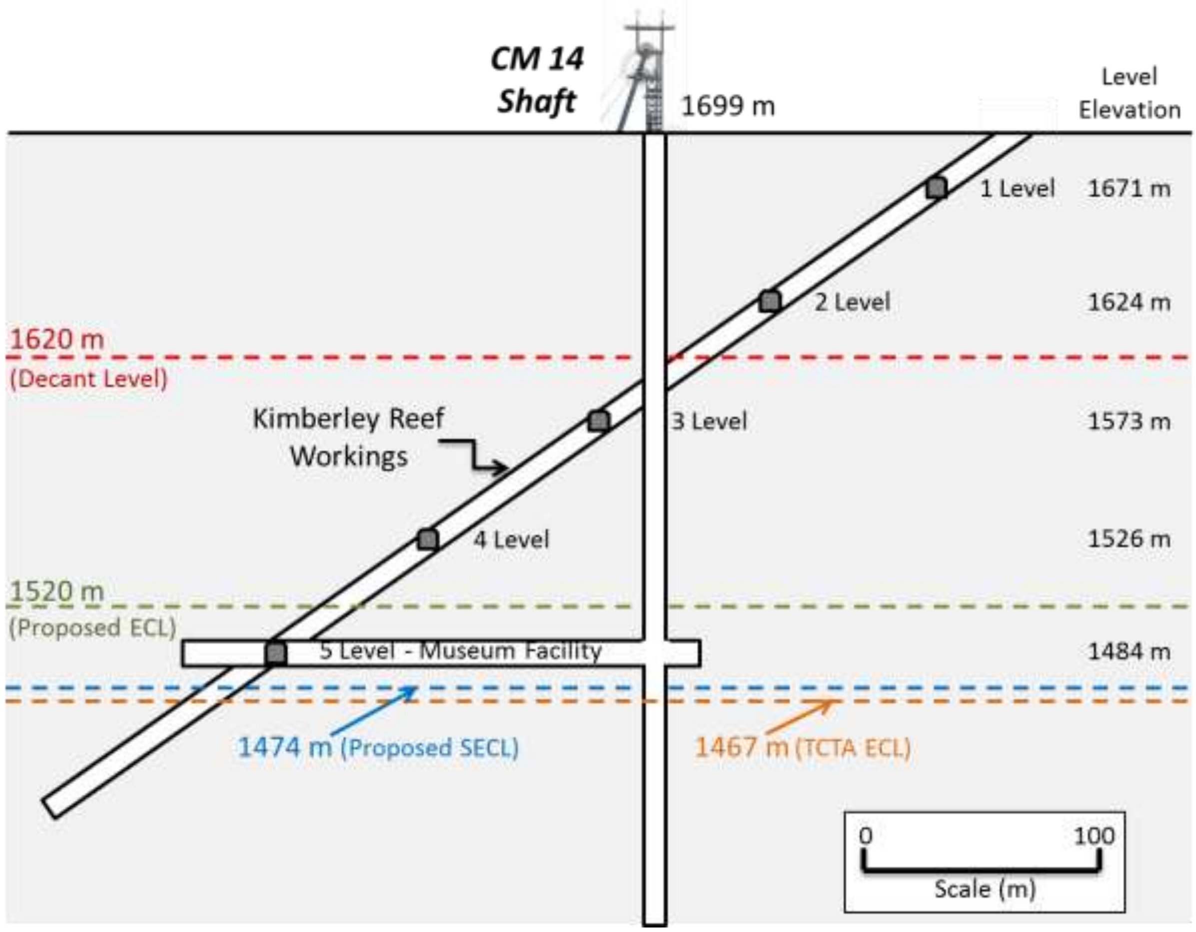


Figure 7.10: Schematic cross-section of CM 14 Shaft showing the location of various water levels and the Gold Reef City 5 Level museum facility.

Should the proposed higher level ECL of 1520 m amsl be applied in the Central Basin it may be possible to retain the museum facility on 5 Level by plugging CM14 Shaft. Pumping facilities would also have to be installed. Any other voids that connect the Kimberley Reef workings with the Main Reef workings on the mine would also have to be sealed. The water level is currently at 1330 m amsl (as of 13 July 2012: L. du Preez, pers. comm.) and therefore close to submerging 8 Level (at approximately 1340 m). At these rising water levels, plugging may be a very challenging operation due to the multiple connection points at 5 Level with the flooded workings below (**Figure 7.11**). Failure of a plug could, of course, have catastrophic consequences and public perception may be such that this would not be a viable solution even if technically feasible.

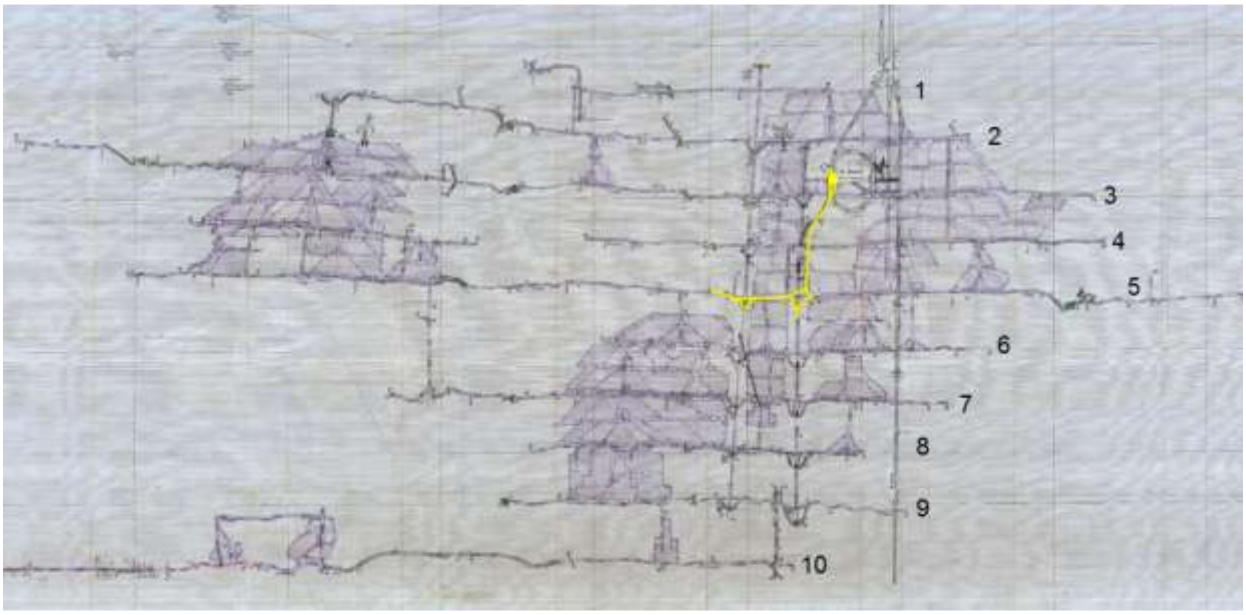


Figure 7.11: Crown Mines Kimberley Reef mine plan. Numbers indicate mining levels; yellow indicates CM14 Shaft and 5 Level museum facility.

7.5 Surface Water Ingress

Within the Central Basin, streams originate in the W-E striking unmined ridges of the West Rand Group of the Witwatersrand ridges and drain southwards towards the Vaal River system. The Klipriver and Klipspruit drain the western portion of the Central Basin. The central portion of the basin is drained by the Natalspruit, and the eastern portion of the basin by the Elsburgspruit.

The land use in the immediate vicinity of the study area consists primarily of urban development. This includes commercial, industrial and residential development, with the city of Johannesburg being the most prominent urban feature. The built-up areas are mainly concentrated to the north of the outcrop of the gold-bearing reefs. The surface excavation of the shallow reefs along their outcrop, with a strike length of approximately 15 km, resulted in topographically lower lying areas with highly disturbed land coverage, allowing a higher rate of infiltration of precipitation. Land use to the south of the mines comprises predominantly agricultural land for grazing and maize crop production. It should also be noted that the runoff due to rainfall in this basin has a fairly low effect on the ingress volumes due to the already constant flow within the watercourses due to leaking sewer lines and stormwater drainage systems.

For each of the ingress sources described in Section 4.3, a percentage of recharge (ingress) of the rainfall and surface water run-off was estimated taking into account the existing geological formations as well as potential ingress sources as listed above to predict the expected ingress volumes into the mine workings. In addition to this, relevant and applicable rainfall records needed to be established before being able to determine the ingress volumes.

7.5.1 Meteorology

The major source of inflow to the basin is rainfall onto open mine workings, as well as runoff from catchments draining into the mine areas. For this basin, several rainfall stations within the greater Johannesburg region have been used to define the average as well as minimum and maximum monthly rainfall within the basin (WUC Report, 2009), which at the time of this study was the most up to date information.

The extracted monthly average rainfall data is presented in **Table 7.2** and the annual minimum and maximum rainfall is presented in **Table 7.3**.

Table 7.2: Monthly rainfall figures in the Central Basin (WUC Report, 2009).

Month	Average Rainfall (mm)	Minimum Rainfall (mm)	Year Recorded	Maximum Rainfall (mm)	Year Recorded
October	73.59	13.47	1999	200.5	2001
November	112.2	8.3	1951	214.95	1998
December	118.34	45.45	1984	265.15	1949
January	131.86	42.53	1956	314.35	1978
February	101.28	21.75	2007	281.7	2000
March	88.45	15.5	1966	337.68	1997
April	48.32	2.16	1991	126.34	1990
May	17.26	0	Often	83.9	1997
June	7.29	0	Often	50.47	1963
July	4.87	0	Often	65.33	1957
August	6.55	0	Often	58	1979
September	22.79	0	1953;2008	148.44	1987
Total	**732.8**				

Table 7.3: Annual minimum and maximum rainfall figures in the Central Basin (WUC Report, 2009).

Month	Driest Year - 1984 (mm)	Wettest Year -2000 (mm)
October	79.7	98.7
November	100.18	111.6
December	45.45	124.15
January	60.2	148.03
February	22.5	281.7
March	82.25	185
April	9.08	22
May	1.83	22.53
June	8.53	1.33
July	15.2	0
August	0.58	2.4
September	11.55	27.48
Total	**437.05**	**1024.92**

In addition to the above rainfall used in the WUC Report (2009), an independent assessment of the average monthly rainfall as well as possible minimum and maximum monthly rainfall has been carried out as part of the review. Two stations were compared: station 0475881W with 98 years of records and station 0476012W with 63 years of records (**Figure 4.3**). The computed average of the two rainfall stations was calculated and is summarised in **Table** 7.4.

Table 7.4: Average monthly rainfall data (Independent rainfall station).

Month	Average Rainfall (mm)	Minimum Rainfall (mm)	Year Recorded	Maximum Rainfall (mm)	Year Recorded
October	18	0	1977	87	1942
November	18	0	1953	131	1917
December	24	0	1974	106	1956
January	65	7	1940	264	1993
February	116	11	1941	451	1917
March	125	17	1948	275	1949
April	130	20	1942	470	1908
May	110	17	1962	464	1943
June	93	10	1903	258	1996
July	48	1	1938	194	1902
August	23	1	1912, 1946	124	1935
September	12	0	1967	82	1943
Total	**783**				

The following observations are made when comparing the above rainfall tables:

- Comparison of the reviewed MAP with that of the WUC report shows the reviewed rainfall to be very similar, with the reviewed MAP being about 6% higher than the WUC MAP;
- The maximum monthly rainfall based on the review is higher at 470 mm (39%) when compared to the WUC value of 337 mm. This could possibly be due to a more accurate and patched rainfall record used for the review study, which is based on the rainfall database used by DWA for all resource modelling (Middleton and Bailey, 2005);
- It is noted from **Figure 4.3** that the expected average rainfall could increase by about 40% over the Gauteng region due to climate change. Given the short length of the rainfall record used, in terms of meteorological time scales, the potential impact of climate change should still be taken into consideration in any further predictive studies of ingress.

7.5.2 Review and verification of ingress volumes

An important aspect is the review and validation where possible of the expected ingress of surface water into the mine workings. This has a marked influence on the abstraction

requirements and hence pumping and maintenance costs. In view of the above, two approaches have been adopted in verifying the predicted ingress volumes:

- Determination of the total ingress into the mine void based on surface flow rates, as well as assumptions on the percentage infiltration of surface water into the mine void from various geological formations, mine infrastructure and natural drainage systems**;**
- Determination of the total ingress into the mine void based on mine void volume, water level and pumping data, described in Section 7.5.3.

7.5.2.1 Sources of ingress and estimated volumes

A summary of ingress areas based on estimates from different surface sources, within the Central Basin is given in **Table 7.5** and shown in **Figure 7.12.**

Table 7.5: Summary of ingress areas.

No.	Ingress area	Comments
1	Undisturbed geology /Shallow aquifers	Ingress through the shallow aquifer above the mine void has been estimated as between 69% to 40% of total ingress by different reports (Winde 2011) However, as no dolomite aquifers overlying the mine void and extensive urbanisation reduces recharge of shallow aquifers, so we have assumed this estimate to be too high.
2	Surface water (dams, rivers, wetlands)	Water discharged to the Elsburgspruit and Boksburg Canal could ingress to the mine void. Where surface streams and tributaries of the upper reaches of the Klipspruit cross undermined areas, or structures such as dykes, faults as it flows parallel to strike (E to W) over the void. Ingress from streams has been estimated to account for 26.7 % to 40.4% of the total ingress by different reports (Winde 2011)
3	Municipal infrastructure (leaking mains and sewerage, stormwater run-off)	The Central Basin is highly urbanised (Johannesburg and Ekurhuleni Municipalities) so a larger component of water leaking from municipal services adds to the volume of water entering the mine void. In addition, irrigation of mine golf courses, vegetated slimes dams etc., adds to sub-surface seepage
4	Surface mine workings (open pits, shafts, inclines)	Extensive historic pits along the strike of the Central Basin have been poorly back-filled allows high infiltration varying from 1.2 to 12.5 Mℓ/day or 4 to 14% of total ingress into void according to different studies.
5	Tailings dams and mine dumps	Ingress of water from mine residue deposits (at least 15 identified) which were placed directly on top of disturbed reef, over shafts, or on dykes or faults connected to the void. There are reports of tailings pumped directly into the mine void resulting in an ingress of >3.5 Mℓ/day, although this practice has been discontinued (Winde 2011). Reclamation of mine dumps results in active disposal at 3 existing slimes dams at Nasrec with estimated 10 Mℓ/day seepage losses, Seepage rate of 7 Mℓ/day estimated from Cooke slimes dams (from Winde 2011). Water used to hydraulically mine the dumps is also a source of ingress but this will reduce once the dumps have been removed.

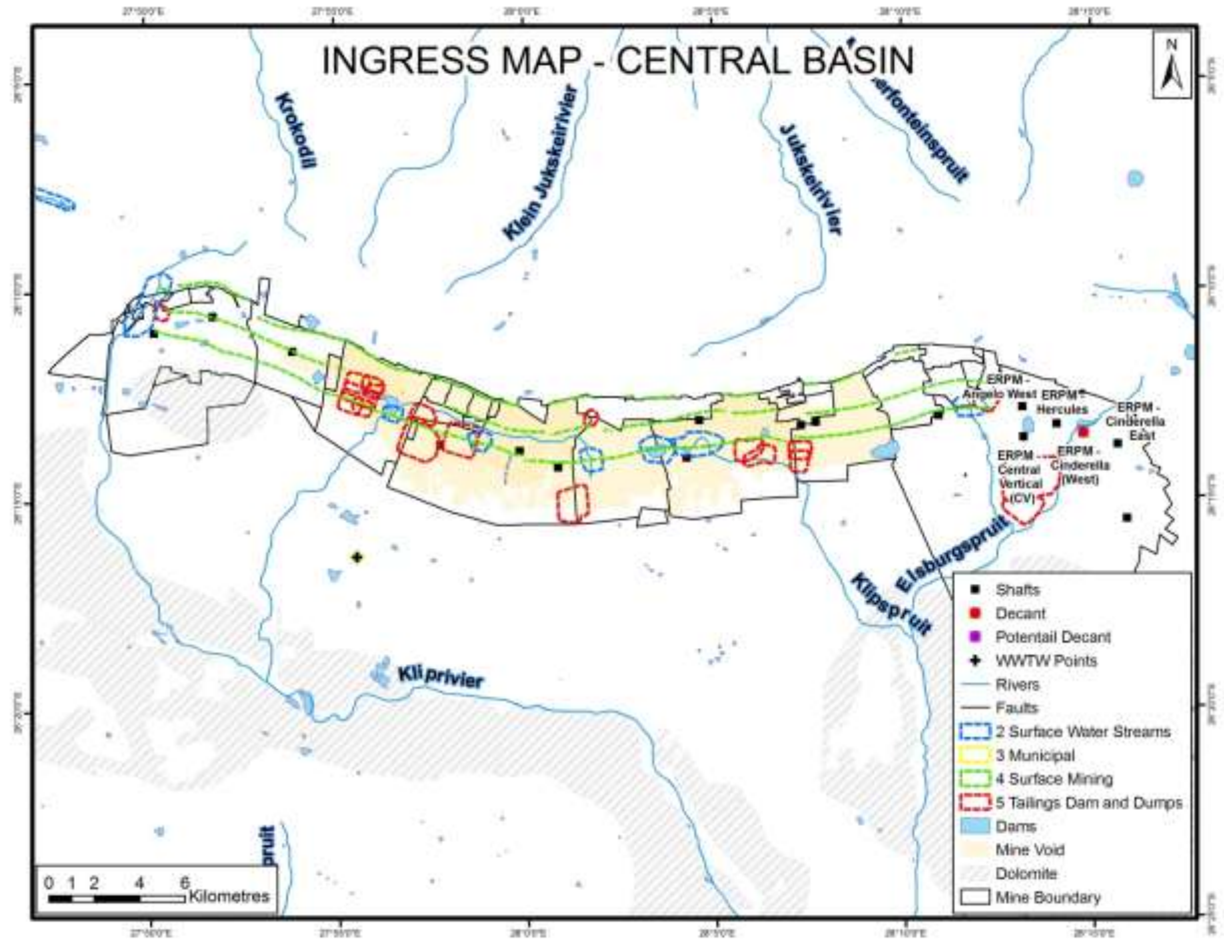


Figure 7.12: Major ingress areas in the Central Basin. Numbers in legend refer to source type in the preceding table.

In this section, relevant data and assumptions made has been abstracted from the WUC report (WUC Report, 2009) on the Central Basin. In addition to this, the changes in rainfall have also been reviewed in order to determine the impact of the rainfall variation on the ingress volumes.

Based on the average rainfall data as given in **Table 7.4**, as well as flow monitoring, the expected ingress volume for the entire basin is estimated to be about 57-59 Mℓ/day. The approximate percentage distribution of each of the sources is given in **Table 7.6**.

Table 7.6: Predicted ingress volumes and sources (average rainfall) (WUC Report, 2009).

Source	Percentage of Total Ingress volume	Ingress Volume (Mℓ/day)
Groundwater recharge via undisturbed geology	41	24
Ingress through reef outcrops	11	7
Underground disposal of tailings	4	2
Sand dumps	0	0
Shallow perched aquifers above mine void	30	18
Ingress from rivers, drainage systems & water bodies	14	8
TOTAL	**100**	**59**

It is also important to take into account the impact of rainfall variations on the ingress volume. For this purpose, **Table 7.7** giving extreme rainfall variations has been used to predict expected changes in ingress volumes. The prediction has been based on the Goldsim Model utilised by Golder & Associates (WUC Report, 2009).

A summary of the expected ingress volume variation is given in **Table 7.7** and also shown in **Figure 7.13**.

Table 7.7: Rainfall variation impact on ingress volume.

Rainfall	MAP (mm)	Change in MAP (%)	Predicted Ingress Mℓ/day	Change in Ingress (%)
Average	732	0.00	59	0.00
Dry Season	437	-40.30	34	-42.37
Wet Season	1025	40.03	66	11.86
Extremely Wet	1413	193.31	73	24
Climate Change	1025	40.00	66.00	11.86

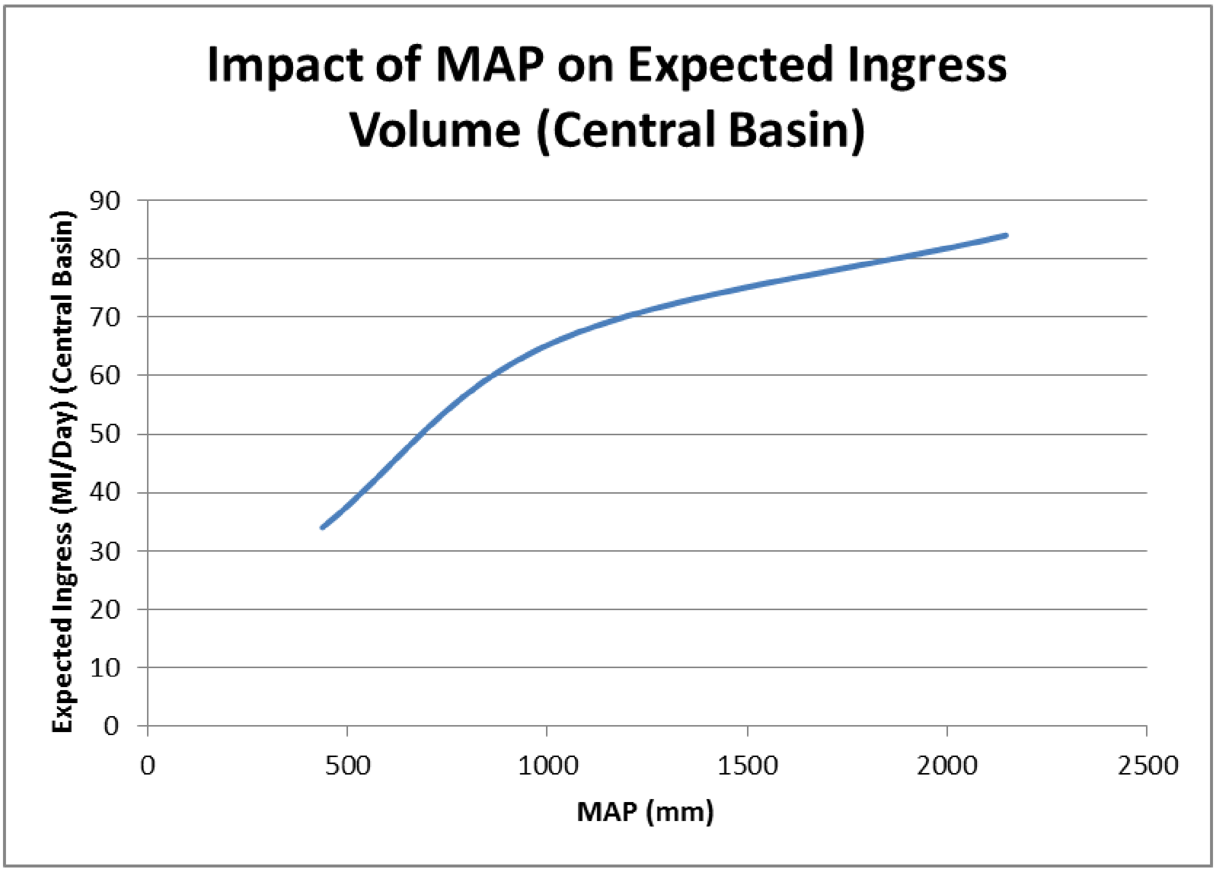


Figure 7.13: Rainfall and ingress variations.

The following observations are made:

- The change in MAP has a fairly significant effect on the predicted ingress volume;
- For an average change in MAP of 40% the predicted ingress volume changes by as much as 12%;The potential change in MAP of about 20 to 40% due to climate change could possibly change the ingress volume by about 12%.

7.5.3 Estimations based on pumping rates and void volume

Water ingress into the mine void has been the focus of a number of studies, notably that of the Ferret Mining and Environmental Services (Boer et al., 2004) and Krige (2001). An important source is rain and local run-off entering via the disturbed zone in the vicinity of the outcrop. A second source is inflow from streams that cross the disturbed zone. The strike of the reef outcrops run more or less parallel to the watershed and hence there are several streams that cross the outcrop zone. Because of the proximity of the outcrop to the watershed, stream discharge is small and many of the streams are seasonal, carrying most of their annual discharge in short duration storm events. However, sustained flow does occur in several streams due to anthropogenic causes.

Notwithstanding the existence of an extensive mine void across the Witwatersrand, the shallow groundwater aquifer remains relatively undisturbed across the region. In the

Johannesburg area, the depth to the water table in this aquifer varies from 0.5 m to about 30 m (Scott, 1995). Some of the water in this aquifer is highly contaminated by plumes that arise from tailings dumps (e.g. Naiker et al., 2002). It is likely that in the vicinity of the disturbed zone, water from this aquifer discharges into the mine void. Finally, water also enters the mine void at depth due to depressurisation via water-bearing structures which are linked through to the shallow aquifer above.

At the time Scott carried out his investigation (pre-1995), both DRD and ERPM were in operation and he had access to a large amount of data from these sources (2 and 12 years of records respectively). At ERPM the pumping situation was rather complex and involved extracting water from two separate compartments. The first of these involved water pumped from the Hercules compartment where mining was still taking place. The total volume pumped averaged 16.02 Mℓ/day of which 8.93 Mℓ/day was service water provided by Rand Water: i.e. 7.09 Mℓ/day of extraneous inflow. The second source of pumped water represented inflow from the defunct mines to the west of ERPM (CMR to Rose Deep). The volume of this water amounted to 13.84 Mℓ/day (Scott allowed for some return flow from tailings that were being discharged into the mine void at that time). The total ingress volume pumped from ERPM thus amounted to 20.93 Mℓ/day.

Only two years of pumping records from DRD were available to Scott. The pumped water represented water from DRD itself (which was still in production) and leakage from neighbouring Rand Leases. Scott (1995) reported that 18.06 Mℓ/day was pumped from DRD, which he inferred was made up of 10.23 Mℓ/day ingress into DRD, 4.74 Mℓ/day ingress into Rand Leases and 3.09 Mℓ/day of service water.

The total ingress into the Central Rand in the period pre-1995, representing the sum of non-service water pumped from ERPM and DRD, thus amounted to about 35.9 Mℓ/day.

Boer et al. (2004) carried out an assessment of sources of ingress into the defunct mines of the Central and Eastern Basins which included, inter alia, pumping records which were extracted from company annual reports. The pumping records for the Central Basin mines are shown in **Table 7.1**. In the period 1978 to 1989 when only DRD and ERPM were still operating and records were relatively complete, pumped volume ranged from 44.9 to 71.5 Mℓ/day, averaging 59.1 Mℓ/day. It is not clear whether service water was deducted, but it appears that this was not taken into account. According to Scott (1995) total service water for DRD and ERPM amounted to 13.7 Mℓ/day, and hence the net ingress volume from the data compiled from the Boer et al. (2004) analysis is 45.5 Mℓ/day for the period 1978 to 1989. The data in the period after the closure of DRD (post-1999) indicate a rise in pumped volume to about 50 Mℓ/day. The reason for this sudden increase is not clear.

Scott (1995) investigated the relationship between rainfall and pumping volumes and plug pressures at ERPM and found an extremely weak correlation suggesting a 4 to 7 day response time between plug pressure and rainfall. He suggested that this reflected direct ingress from streams crossing the disturbed zone. Pumping volumes appeared not to

correlate with rainfall, which he attributed to the pumping regimen adopted by the mine, e.g. pumping during the night and weekends to reduce costs.

Krige (2001), based on flow measurements in the Klip River and its tributaries, arrived at an estimated ingress of 32.51 Mℓ/day. Total ingress into the Central Basin as implied by the studies of Scott (1995) amounted to 27.5 to 35.0 Mℓ/day. Winde (2011), largely following Scott (1995), calculated the total ingress to be 33.92 Mℓ/day. The estimated total ingress of 76 (dry season) to 99 (wet season) Mℓ/day derived by Van Biljon and Walker (2001) is higher than the average pumping rates of ca. 60 Mℓ/day and is therefore regarded as unrealistic.

As is evident from the latest data available, the water levels of the entire Central Basin equalised in May 2010 when the water in the eastern parts of the Central basin reached the perched level of the DRD compartment (**Figure 7.14**). Utilising this fact, it is possible (following the approach as in Section 7.5.3) to calculate the ingress rate in the Central Basin from the void curves of Rison Consulting **Figure 7.15** and **Figure 7.16**) (TCTA Report, 2011a) combined with the water level rise statistics of the Central Basin as measured at Crown Mines 14 Shaft. The "conservative" curve in **Figure 7.16** is based on the data as presented by Rison Consulting, whereas the "progressive" line (red dotted line) allows for possible overestimation in the void volume reduction between 1000 and 1400 m amsl. The latter represents a worst case scenario.

The results of the calculations are presented in **Figure 7.17** and **Figure 7.18**.

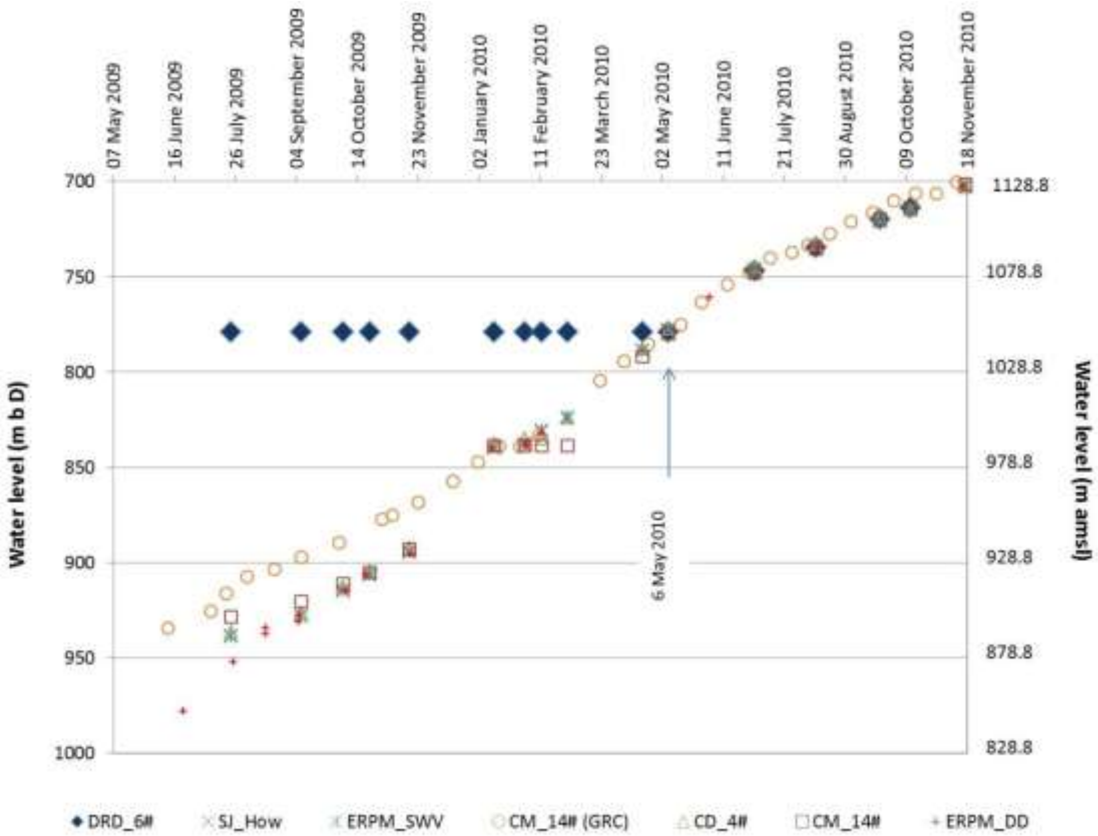


Figure 7.14: Detail of merging of the DRD compartment with the CM and ERPM compartments.

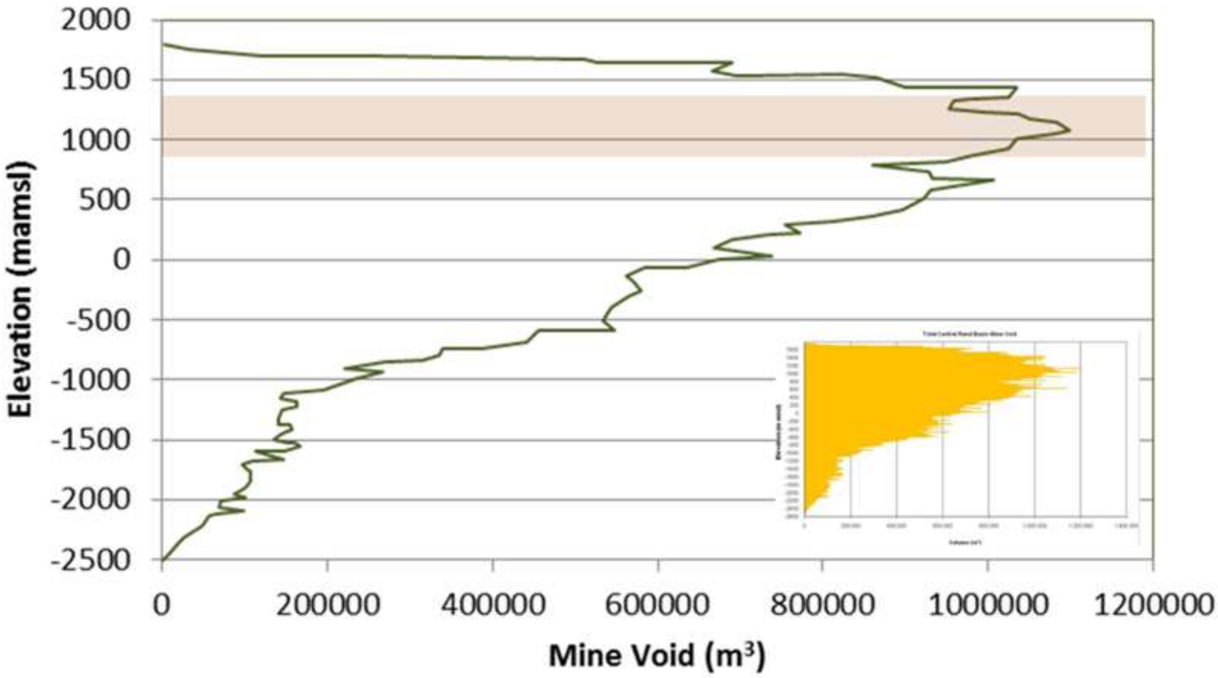


Figure 7.15: Digitised void curve for the Central Basin. Shaded area covers the water levels since merging of the sub-basins. Inset is the void curve of Rison Consulting.

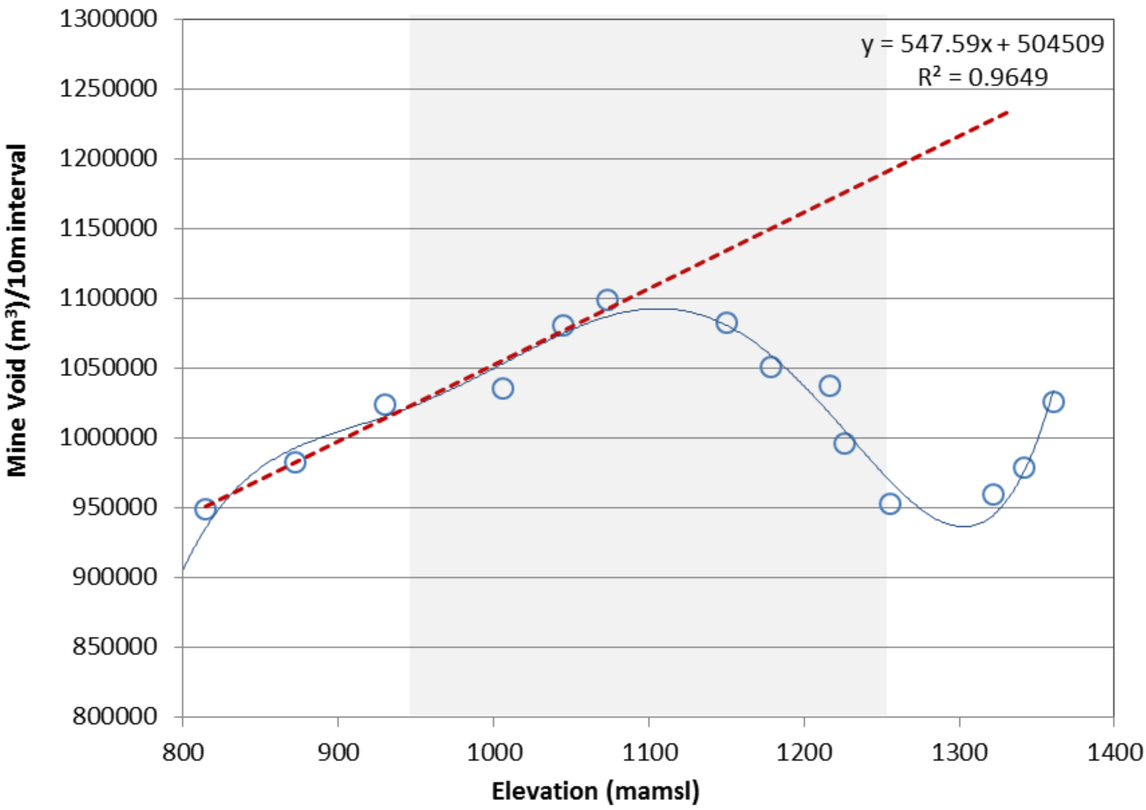


Figure 7.16: Detail of the digitised void volume over the elevation interval (shaded grey).Trend lines: Curved line (conservative) and red dotted lines (progressive).

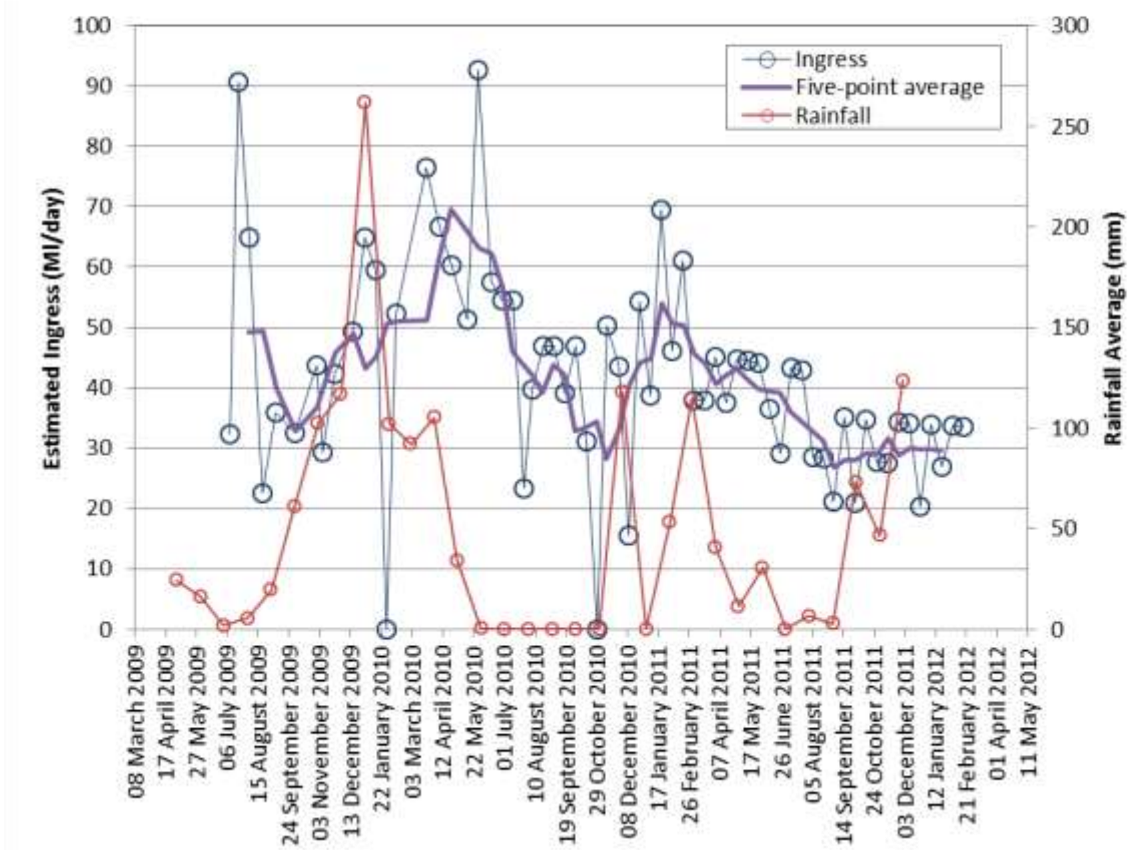


Figure 7.17: Estimated total ingress with time in Central Basin, derived from the rate of water level rise and the curved line of conservative best fit (Figure 7.16) of the void volume.

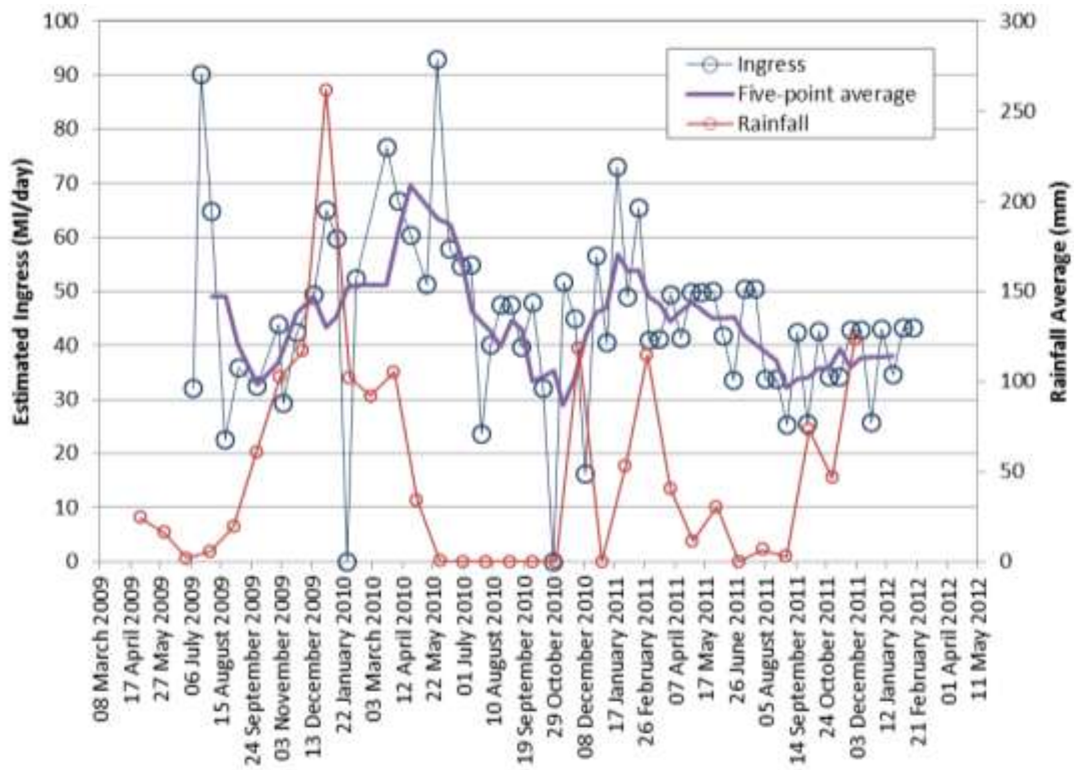


Figure 7.18: Estimated total ingress with time in Central Basin, derived from the rate of water level rise and the red stippled line of progressive best fit (Figure 7.16) of the void volume.

Keeping in mind that the void volume curve might not be accurate to the detail used here, scrutiny of **Figure 7.17** and **Figure 7.18** suggests that:

- The short time range of the data does not allow any firm inferences to be made on the relation between the seasonal trends and the regional rainfall pattern (the average of three stations, Springs, OR Tambo and Botanical Gardens, Emmarentia). However, the periods of increasing ingress (e.g. September 2009 to April 2010) correspond to periods of higher rainfall. The excessive rainfall event in 2010 was not repeated in later years (**Figure 7.18**).
- Following Krige (2001), the seasonal variation may be largely the effect of relatively slow ingress of "imported water" due to human activities during summer months, rather than abrupt inflow during rainstorms, hence the slow and somewhat inconsistent response of the ingress curve to the rainfall data.
- Ingress maxima appear to be gradually decreasing with time. This may be in part due to increasingly smaller summer rainfall spikes over the time period considered, or to the expected lowering of the hydraulic head of water flowing into the void from fracture aquifers, or both.
- The ingress minima decrease at an average rate of approximately 5 Mℓ/100 m rise in the water level. This decrease is interpreted to give an indication of the maximum decrease in the rate of flow of fracture water into the mine void.
- The current ingress averages to about 30 to 38 Mℓ/day (depending on which void model is accepted, as well as the accuracy of the void volume data). This finding is in agreement with the estimates of Scott (1995), Krige (2001) and Winde (2011) and within the wide range of 34 to 84 Mℓ/day estimated in the WUC Report (2009).

7.5.4 Minimising surface water ingress

It is considered that the ingress in the Central Basin appears to be more susceptible to wet and dry seasons due to direct ingress of infiltration through the extensive shallow mine excavations along strike and the numerous surface water bodies. A rate of 46 Mℓ/day has been used as the nominal ingress rate to allow for higher inflows during the wetter periods (see later discussion on equilibrium pumping rates in section 7.6.1). In order to minimise surface water ingress if possible, an initial prioritisation of the main categories of sources as defined in **Table 6.4** has been made for the Central Basin, as shown in **Table 7.8**.

As can be observed from **Table 7.8**, the majority of ingress is via tailings and dumps (44%). Municipal leaks could account for 24% of the water entering the void and 14% from surface water bodies crossing more permeable zones.

Table 7.8: Prioritisation of ingress control measures

Source	Percentage of Total Ingress volume	Expected Ingress Volume (Mℓ/day)	Priority of improved ingress control[2]
Undisturbed geology[1] /Shallow aquifers	7	3	5
Surface water (dams, rivers, wetlands) (WUC)	14	7	1
Municipal infrastructure (leaking mains and sewerage, stormwater run-off)	24	11	2
Surface mine workings (open pits, shafts, inclines) (WUC)	11	5	3
Tailings dams and mine dumps (Winde)	44	20	4
Total	100	46	

1: The remaining water not included in WUC and Winde is an estimate on the basis that the Central Basin is highly urbanised so there is more run-off to stormwater and sewer and less recharge through the undisturbed geology. Recharge through the undisturbed geology has been estimated as 5% of the MAP over the 15kmx6km area of the Central Basin.
2: A priority "5" has been given to the "Groundwater recharge via undisturbed geology" and "underground disposal of tailings" as no practical and feasible improvements to ingress control can be used for this source

The water bodies that cross major faults, dykes and shallow undermined areas, should be canalised across these more permeable structures. Krige (1999) and others (WUC Report, 2009) have identified a number of areas of water ingress into the Central Basin, particularly those areas where surface streams cross areas of shallow undermining. Canalisation of these streams, as well as grouting within these areas could also reduce the ingress of water into the zone of shallow undermining. Krige (1999) estimates that as much as 32.5 Mℓ/d of ingress could be stopped. The construction of a canal to the south of Florida Lake is currently underway, and additional sites for canal construction have been identified.

The loss/leakage of water from the municipal water supply networks (attributable to decaying infrastructure), as well as tree root growth into municipal systems, sewerage and storm-water reticulation systems are suspected to contribute to ingress into the Central Basin. These possible sources will need to be investigated in collaboration with the Johannesburg and Ekurhuleni metropolitan councils.

As the tailings dams are re-worked, the source of water will be reduced, and ingress into the voids will decrease. Implementation of priorities 1 to 3 could theoretically reduce the ingress by 20 Mℓ/day and again assuming that only half of this is achievable, the ingress could be reduced by by 10 Mℓ/day. Removal of the mine dumps as is currently underway, could reduce ingress further.

It should be noted that before any of the above control measures are implemented further detailed and site specific cost-benefit studies would need to be undertaken. This would aid the client in determining the net benefit of implementing the control measures in relation to initial capital expenses and a reduction in long term operating and maintenance cost of the decanting pumps, as well as the water treatment works and waste material handling facilities.

7.6 Pumping Volumes and Abstraction Points

7.6.1 Pumping volumes required

The main objective of the pumping exercise is to keep the water in the mining void below a pre-determined level. Since the ingress is variable (Section 7.5.3; **Figure 7.17**), having reached levels of 70 Mℓ/day in the wet season of 2010, adequate free board and spare pumping capacity must be provided to prevent excessive water level fluctuations in the mine void during such periods. Scrutiny of **Figure 7.17** suggest that during the dry months the ingress stabilises at ca. 30 to 35 Mℓ/day, which gives an indication of the base flow volumes, suggesting that the abstraction rate will be larger than this number.

During pumping, the water level fluctuation will be a function of the ingress, the pump rate and mine void volume at a given elevation:

Water level rise/day (m amsl) = (Ingress (m^3/day) – Abstraction (m^3/day))/Void Surface Area at ECL (m^3/m).

The estimated ingress rate over a three year period (**Figure 7.17**), and the void volumes determined by Rison Consulting (2001) allow the required pumping volumes to be modelled. The results are illustrated in **Figure 7.19**. For this model a constant void surface area of 1.1×10^5 m^2 at the preferred water level (ECL) of 1467 m amsl has been assumed.

At an abstraction rate of 35 Mℓ/day the water levels in the mine void is expected to rise at an average rate of about 0.1 m/day. At 45.5 Mℓ/day, a state of equilibrium is maintained, with water levels fluctuating within approximately 25m from the ECL and on average pumping rate of 46 Mℓ/day is proposed. However, pumping at that rate during excessively wet seasons, the water level in the void will rise and with insufficient freeboard may inundate the Gold Reef City (GRC) tourist facility. Pumping at 50 Mℓ/day would tend to lower the water level in average conditions, below the preferred level (ca. 40 m over 965 days) with increased costs. Allowing for maintenance and other contingencies a minimum pump capacity of 50 Mℓ/day is recommended. It should be noted that pumps with an average capacity of 46 Mℓ/day (in 19h00 as proposed by TCTA) will be able to pump 58 Mℓ/day in 24 hours.

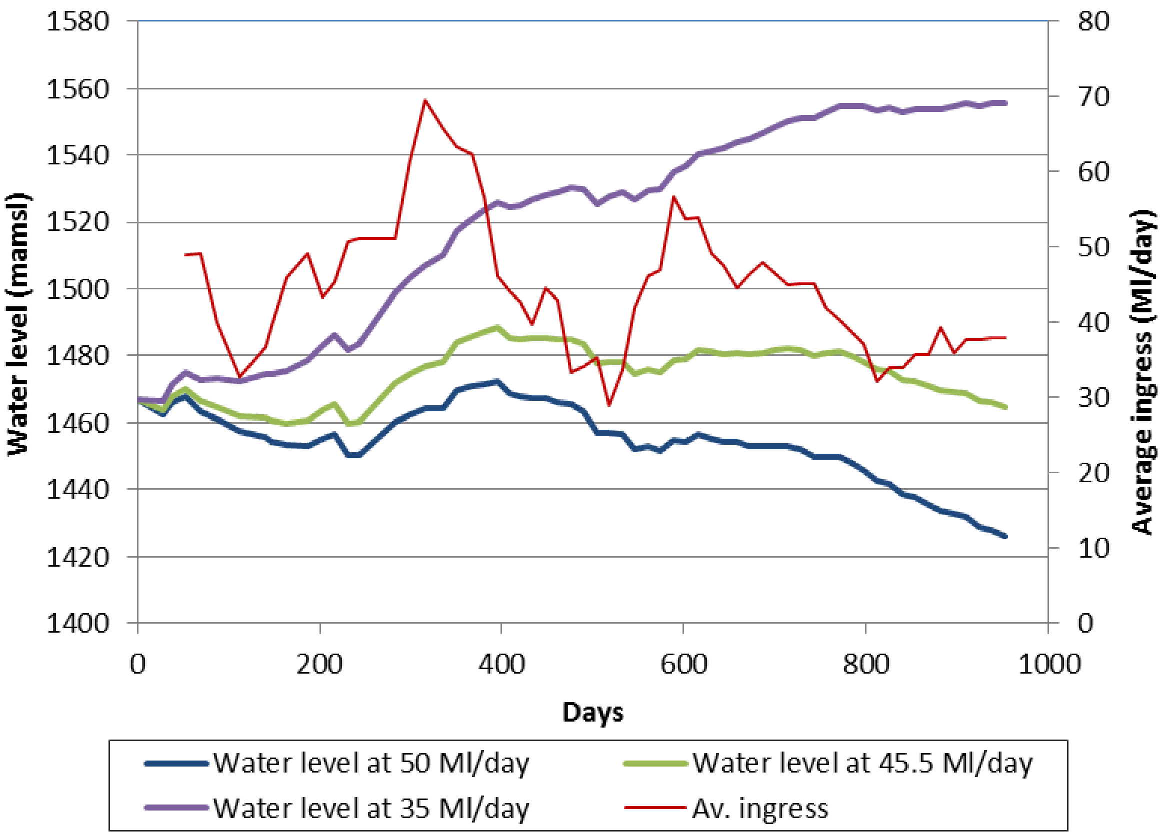


Figure 7.19: Pumping models for the Central Basin.

In applying these results, the following sources of variance need to be considered:

(1) The rainfall patterns may vary from one period to the next. The 965 day period considered here includes a particularly wet season (2010) and what appears to be more normal rainfall seasons (2011 and 2012).

(2) Furthermore, the "progressive" model (Section 7.5.3, **Figure 7.18**) was selected in the calculation. The "conservative" model produces water levels on average about 20 m lower (after the 965 day run) compared to those for the "progressive" model

(3) The pumping volumes proposed here are based on the void volume estimates of Rison Consulting and the pumping volume accuracy is therefore directly related to that of the void volume estimates.

(4) A possible gradual decrease in direct ingress into the mine void of fracture aquifers due to increasing hydraulic equilibrium has not been considered. Crude estimates based on the calculated ingress minima (winter months) suggests a decrease of ca. 5 Mℓ/day over a 100 m elevation change. Since the current water level in the Central Basin is about 150 m below the accepted ECL of 1467 m, the pumping rates suggested above may be reduced by 5 to 8 Mℓ/day. However, monitoring is required before such reductions can be applied.

7.6.2 Suitability of shafts for pumping

South West Vertical (SWV) Shaft at ERPM was identified in the TCTA Report (2011a) as the site where the pumps will be installed, largely because much of the necessary infrastructure was already in place there. It should be noted, however, that much of the pumping infrastructure has subsequently been removed. A major disadvantage of this shaft is considered to be that the connection with the mine void is very deep (24 level, 1080 m below surface) and the haulage at this level will have to carry the entire void discharge. A collapse in this haulage could have serious consequences. In a long term solution, other pumping strategies should be investigated which could involve multiple extraction points which have greater connectivity with the void at a shallow level.

A preferable long term approach would be to abstract at SWV and up to four other locations. Most of the vertical shafts still accessible today on the Central Rand intersect the void at great depth, much like SWV Shaft. The reason for this is that most of the shallower reefs were accessed by incline shafts. A detailed investigation of potential vertical shafts that may have greater interconnectivity would require a detailed study of multiple criteria and is beyond the scope of this study. However it is not recommended approach.

An advantage of an incline shaft is that it is connected directly to the mine void at shallower depths, on multiple levels and even without headgear can be accessed easily, compared to a vertical shaft. The chances of stope or haulage collapse at shallow depths (less than 500 m) are also greatly reduced.

However, preparing and equipping an incline shaft would require considerable lead times and the use of pumps capable of operating at an inclined orientation. There is also some risk with regards shaft stability, when considering incline shafts over vertical shafts, which would have to be evaluated on a case by case basis in the options analysis. Another important consideration is that the pump scenario should be able to manage pumping from different water levels. Therefore submersible pumps would be recommended.

One such incline shaft which may be suitable for pumping, but is currently being worked by ERPM, is Cason Shaft. This shaft is approximately 1000 m deep intersecting the mine void on multiple levels right up to 1599 m amsl (**Figure 7.20** and **Table 7.9**). Note that both Hercules and Central Shafts may have been filled.

Given the preference for multiple abstraction parts, the problematic connectivity of shafts and he risks and uncertainties of equipping and pumping from shafts and initiates the preferred strategy is to drill a number of new boreholes into carefully selected locations in the mine void, with good connectivity at shallow and other depths. This is considered further to the Pre-Feasibility Report.

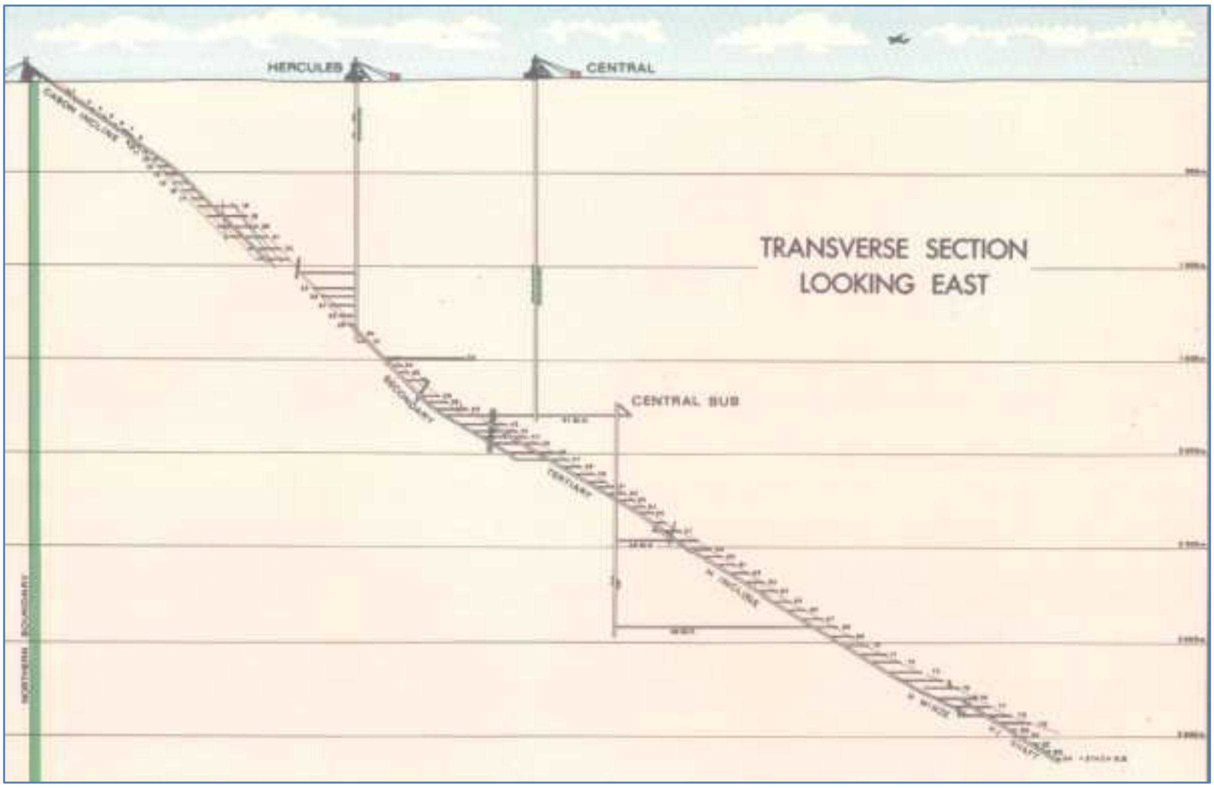


Figure 7.20: North South cross section of Cason Shaft. Note primary incline is well connected and extends approximately 1000 m below surface.

Table 7.9: Summary of level elevations in Cason Shaft..

Cason shaft	Elevation	Elevation
Collar: 1643m amsl	Below datum	m amsl
1 level	230	1599
2 level	256	1573
3 level	289	1540
4 level	317	1512
5 level	361	1468
6 level	405	1424
7 level	432	1396
8 level	460	1369
9 level	488	1340
10 level	514	1315
11 level	548	1281
12 level	584	1245

7.6.3 Alternative options to pumping

Passive solutions allowing natural surface decant at preferred ECL's, rather than pumping were identified. A tunnel designed to intersect the Central Vertical (CV) Shaft at ERPM has previously been proposed, allowing Central Basin water to decant naturally into the Elsburgspruit (Boer et al., 2004). It was established at that stage that a 2km long tunnel option from 110m below collar at CV Shaft to a point along the Elsburgspruit (1570 m amsl) would offer the most practical and cost effective solution. Although at the time of the original study the mine was still operating at CV Shaft, unfortunately this shaft has subsequently been filled. The length of the tunnel would now likely be far longer than previously conceptualised due to the practice of shaft filling in the ERPM area. An in-situ pumping or siphon solution may also be required to lower the water level to the required ECL. However, there is sufficient elevation difference between the surface decant point and the Elsburg wetland to allow for the construction of a treatment plant.

It should be noted that should this option be considered, the ECL would have to be at 1520 m amsl and the Gold Reef City tourist level would be flooded unless 14 Shaft is plugged to isolate the tourist level from the mine void.

7.7 Water Qualities

7.7.1 Data Utilised

Water quality data was synthesised from three principal sources, described below and summarised in **Table 7.10**:

(1) Shaft sampling:

Two types of sampling techniques have been developed for waters in vertical shafts:

- Underground samples collected at the water surface in the shaft barrel accompanying water level monitoring.
- A depth point sampler that collected water samples at various depths in the shaft water column. This aimed to quantify potential stratification in the shaft water column.

(2) Underground sampling:

Underground samples were collected between 2005 and 2006 from two sites accessed from SWV Shaft on ERPM, Witwatersrand Gold Mine (Wits GM) overflow and Rose Deep plug. These sites represent stope water collected from approximately 1080 metres below surface.

(3) Surface sampling:

A number of surface samples were taken from ERPM during 2005 to assess the quality of ingress water into the Hercules compartment at ERPM. The surface sample sites range from streams to tailings dams and surface water bodies.

Table 7.10: Water quality sampling data utilised in the Central Basin.

Mine	Location	Sample Type	Source	n
DRD	06#, Circular	Shaft Sampling, Depth profile	CGS	62
Crown Mines	14#, 14# incl	Shaft Sampling	CGS	16
Crown Mines	17#	Shaft Sampling, Depth profile	CGS	18
City Deep	03Vent#, 04#	Shaft Sampling	CGS	45
Simmer and Jack	Catlin#, Howard#	Shaft Sampling	CGS	26
ERPM/Wits GM	Various	Surface Monitoring Point	CGS	22
ERPM	Central Vertical#	Shaft Sampling	CGS	8
ERPM	Wits GM overflow and Rose Deep plug	Underground	CGS	12
			Total	113

= Shaft, n = Number of samples

7.7.2 Water chemistry

The water quality of the Central Basin at different sample localities is summarised in **Table** 7.11. Except for the DRD 6 Shaft and ERPM CV Shaft, the water in the Central Basin is generally acidic with high levels of dissolved solids. **Table 7.12** presents the summary composition ranges (as percentiles) of the combined water quality dataset.

It is considered likely that the extensive shaft sampling data (**Table 7.11**) reflect dilution from surface ingress and possibly some degree of reaction with shaft cement linings. **Table 7.13** presents percentile values for the underground mine water samples only. Should pumping take place from deeper areas, such as proposed for the STI at SWV Shaft, then these are more likely to be broadly representative water qualities.

Table 7.11: Water quality (95th percentiles) of the Central Basin

Elements	Units	Shaft									Underground		Surface
		DRD 6#	DRD Circular#	CM 14#	CM 17#	CD 03Vent#	CD 4#	SJ Catlin#	SJ Howard#	ERPM CV#	WitsGM Overflow	Rose Deep	ERPM Surface
n		23	18	7	13	14	23	8	1	1	6	6	23
pH*		7.2	3.0	3.4	3.9	4.3	4.4	3.3	5.0	7.4	2.4	2.6	3.4
EC	mS/m	94	189	264	350	196	309	377	327	301	412	473	575
TDS^	ppm	980	1828	2525	3867	1085	2215	4507	2695	2263	4251	4478	4364
Temp	°C	25.4	25.3	27.0	30.8	27.5	27.6	28.4	19.8	21.0	24.5	27.2	32
Tot Alk	mg/l $CaCO_3$	129	16	25	49	29	40	41	89	44	3	37	271
P Alk	mg/l $CaCO_3$	46	91	50	62	34	46	35	52	16	97	95	70
Na	mg/l	56	69	153	195	72	172	209	106	243	172	169	225
Mg	mg/l	46	78	93	170	66	102	232	160	153	261	208	205
Al	mg/l	2	51	1	11	10	2	1	10	20	195	106	36
K	mg/l	4	4	11	13	6	9	18	10	36	5	13	49
Ca	mg/l	113	209	323	490	132	317	626	354	551	281	629	650
Fe	mg/l	1	14	71	214	2	3	173	75	5	48	114	127
Mn	mg/l	0	4	13	22	5	18	23	48	7	50	46	11
F	mg/l	1	3	4	6	2	2	0	2	nd	4	4	5
Cl	mg/l	37	35	57	68	57	61	75	166	108	147	136	259
NO^3	mg/l	42	19	26	39	53	19	37	31	9	34	28	37
SO^4	mg/l	675	1328	1769	2631	671	1504	3107	1724	1124	3029	3005	2750
Li	µg/l	47	120	137	199	126	167	290	198	24	448	504	262
Be	µg/l	1	16	1	2	4	2	1	9	1	26	19	4
B	µg/l	850	591	714	559	1109	689	451	1225	50	350	938	3529
V	µg/l	3	3	1	2	2	3	6	1	19	14	5	9
Cr	µg/l	131	154	77	56	85	132	173	76	175	160	96	131
Co	µg/l	18	1956	136	522	749	722	341	2634	536	5814	4397	1164
Ni	µg/l	132	7017	326	1671	1623	915	772	2440	737	12935	9853	2027
Cu	µg/l	64	744	86	232	151	242	82	802	48	377	310	324
Ga	µg/l	40	50	27	66	45	47	56	43	8	72	71	6
As	µg/l	42	31	31	42	34	32	22	116	25	33	155	1
Se	µg/l	11	12	8	11	12	14	10	22	13	46	45	12
Rb	µg/l	6	8	28	33	17	26	42	34	26	19	45	50
Zn	µg/l	2	4	3	4	4	3	6	7	4	12	10	3
Sr	µg/l	581	433	309	794	532	562	510	776	1054	698	639	510
Mo	µg/l	8	3	3	3	3	3	3	3	5	3	3	6
Ag	µg/l	5	6	2	8	2	2	1	1	5	15	15	1
Cd	µg/l	1	8	1	4	11	5	3	8	6	16	12	3
Te	µg/l	1	1	1	1	1	1	1	1	1	1	1	1
Ba	µg/l	798	1078	701	1396	903	909	1601	855	2870	1753	1819	105
Tl	µg/l	1	1	1	1	1	1	1	1	5	1	1	1
Pb	µg/l	156	547	461	205	324	282	1109	153	418	131	354	399
Bi	µg/l	1	1	1	1	1	1	1	1	3	4	1	1
U	µg/l	7	231	13	64	69	19	13	57	30	703	569	567

*5th Percentile ^Estimated by summation of reported salts Numbers rounded

Table 7.12: Water quality range (percentiles) of the combined data for the Central Basin.

Parameter	Unit	n	Percentile				
			95th	90th	50th	10th	5th
T	°C	119	28.4	27.3	23.1	20.4	19.3
pH#		119	3.2	3.3	5.0	7.7	8.1
EC	mS/m	119	354	333	187	84	82
TDS	mg/l		3695^	3056^	1624^	557	544
Tot Alk	mg/l $CaCO_3$	110	125	120	25	3	3
P Alk	mg/l $CaCO_3$	110	85	73	25	14	12
Bicarb_Alk	mg/l	110	88	79.2	0	0	0
Carb_Alk	mg/l	110	61	42	3	0	0
Hydrox_Alk	mg/l	110	150	101	15	0	0
Na	mg/l	109	185	171	72	41	39
Mg	mg/l	109	161	147	64	35	33
Al	mg/l	109	44	40	0.8	0.05	0.05
K	mg/l	109	14	11	5	1	1
Ca	mg/l	109	483	402	180	89	86
Fe	mg/l	109	177	162	1	0.05	0.05
Mn	mg/l	109	20	18	5	0.03	0.02
F	mg/l	109	3	3	0	0	0
Cl	mg/l	109	69	64	46	19	18
NO3	mg/l	109	49	44	18	4	1
SO4	mg/l	109	2464	2037	1083	289	266
Li	µg/l	109	194	171	88	19	16
Be	µg/l	109	12	11	1	1	1
B	µg/l	109	916	540	165	25	25
V	µg/l	109	4	3	1	1	1
Cr	µg/l	109	147	123	39	5	5
Co	µg/l	109	1858	1669	423	8	4
Ni	µg/l	109	6617	5699	598	106	93
Cu	µg/l	109	688	552	70	3	3
Zn	µg/l	109	4019	3316	1237	374	319
Ga	µg/l	109	49	42	3	3	3
As	µg/l	109	37	34	1	1	1
Se	µg/l	109	13	11	3	3	3
Rb	µg/l	109	36	31	16	3	3
Sr	µg/l	109	638	574	485	320	256
Mo	µg/l	109	6	5	3	3	3
Ag	µg/l	109	4	2	1	1	1
Cd	µg/l	109	6	5	1	1	1
Te	µg/l	109	1	1	1	1	1
Ba	µg/l	109	1031	903	26	5	5
Tl	µg/l	109	1	1	1	1	1
Pb	µg/l	109	506	302	75	18	13
Bi	µg/l	109	1	1	1	1	1
U	µg/l	109	219	198	11	6	5

^Estimated Data rounded
pH values in reverse percentile order, e.g. 95^{th} percentile is 5^{th} percentile

Table 7.13: Water quality range (percentiles) of the Central Basin underground data.

Parameter	Unit	Percentile						
		5th	10th	50th	60th	75th	90th	95th
T	°C	21.7	22.0	22.9	23.2	25.3	26.3	26.8
pH		2.4	2.5	3.0	3.7	4.2	4.3	4.4
EC	mS/m	371	371	397	405	412	450	465
TDS^	mg/l	3644	3896	4247	4319	4429	4561	4592
Tot Alk	mg/l CaCO3	2.5	2.5	2.5	2.5	8.9	28.9	34.0
Na	mg/l	108	110	122	134	169	170	171
Mg	mg/l	118	159	172	177	201	249	258
Al	mg/l	10	21	122	129	133	184	193
K	mg/l	3	3	5	5	7	12	13
Ca	mg/l	241	243	279	351	403	459	563
Fe	mg/l	1	2	40	41	48	94	108
Mn	mg/l	13	24	47	47	49	50	50
F	mg/l	0	0	1	2	2	4	4
Cl	mg/l	84	87	137	138	141	144	146
NO_3	mg/l	10	12	23	26	29	33	34
PO_4	mg/l	0	0	0	0	0	11	15
SO_4	mg/l	2429	2597	2831	2879	2953	3041	3062
Li	µg/l	274	290	372	`	428	450	495
Be	µg/l	2	4	20	21	23	24	25
B	µg/l	214	245	280	300	318	361	712
V	µg/l	1	1	1	1	4	9	12
Cr	µg/l	5	5	87	100	129	130	148
Co	µg/l	601	1200	4684	4923	5205	5637	5760
Ni	µg/l	1268	2600	10589	11122	11669	12633	12850
Cu	µg/l	28	40	328	332	371	375	376
Zn	µg/l	1046	1991	9122	9195	9625	11174	11736
Ga	µg/l	3	3	3	3	19	79	88
As	µg/l	1	1	31	33	39	55	115
Se	µg/l	6	10	40	42	45	46	47
Rb	µg/l	15	15	19	19	25	38	42
Sr	µg/l	443	493	634	638	661	693	697
Mo	µg/l	3	3	3	3	3	3	3
Ag	µg/l	1	1	1	1	15	15	15
Cd	µg/l	1	1	11	11	12	12	15
Te	µg/l	1	1	1	1	1	1	1
Ba	µg/l	5	5	11	18	442	2053	2213
Tl	µg/l	1	1	1	1	1	1	1
Pb	µg/l	5	7	28	35	80	132	276
Bi	µg/l	1	1	1	1	1	1	2
U	µg/l	56	123	606	645	657	682	695
Number of samples = 12	^ Estimated	Numbers rounded						

7.7.3 Change of water quality with time

No meaningful data on this aspect for the Central Basin could be sourced. However, the general considerations (discussed in more detail in Section 10.3) apply equally well for the Central Basin. It can be expected that the AMD that formed initially, will be inhomogeneously distributed and layered due to localised dilution by uncontaminated water. Near the upper reaches of the void, surface water can be expected to form deep columns in the shaft voids. The DRD No. 6 shaft is a good example, where the relatively good quality water recorded (**Table 7.11**) most likely comes from the surface via human activity.

Another factor that needs to be considered here is that before 1930, mine workings were filled to a depth of several hundred metres with sand and rubble, but mainly with ash derived from the many steam engines used in stamp mills, hoists and locomotives (Scott, 1995). This practice physically reduced the mine void but can also be expected to have an influence on the water chemistry. The alkaline nature of coal ash that can lead to pH values of between 10 and 12 would tend to neutralise the early-formed AMD. However, the degree of interaction of the ash with void water over time is unknown.

Considering the above, it would be prudent to expect that unless the abstraction rate keeps pace with the ingress, the water quality would at first deteriorate (as exemplified by the water quality over time in 17 Winze of the Western Basin; **Figure 6.19**). Prolonged pumping will tend to stabilise the chemistry, depending on the degree of mixing and the extent to which channelling is effected during the pumping exercise. It is not possible to predict how the water quality might fluctuate over relatively short time periods when pumping commences and the flow regime established itself. Quantification of only long term changes (improvement) is also not possible.

7.8 Summary and Recommendations

7.8.1 Critical Water Levels

The ECL is determined to be at an elevation of 1520 m amsl. This is based on an estimated depth of 100 metres below surface at ERPM, and should adequately protect the surface aquifer.

The museum floor level (1484 m amsl) in Crown Mines 14 Shaft at Gold Reef City (GRC) was taken to be the critical factor in determining the SECL. The SECL is set at an elevation of 1474 m amsl to accommodate the lowering of the double decker conveyance and to ensure that the museum can still be visited as a heritage site. If the SECL is used, then the TOL must ensure that there is sufficient freeboard to allow for potential slow flow rates between GRC and the pump site.

7.8.2 Ingress

A summary of the ingress predictions by various studies is given in **Table 7.12**, with and without ingress control measures. For this study, it is assumed that a reduction in ingress of at least 10 Mℓ/day could be achieved by canalising surface water features crossing shallow workings, dykes and faults, by continuing to upgrade the ageing water reticulation and sewerage systems and by on-going re-working of the mine dumps (as a conservative estimate, half the estimated ingress from these sources has been applied). Additional reduction in the ingress volume could possibly be obtained by applying ingress control measures to the remaining sources. The practicality and cost implications can however only be established once a more detailed study is undertaken.

Table 7.14: Summary of predicted ingress volumes, Central Basin.

Information source	Predicted ingress volume (Mℓ/d), No ingress control		Predicted Ingress Volume (Mℓ/day) with improved ingress control (10 Mℓ/day)	
	Average	Range	Average	Range
WUC Report (2009)	59	47 - 102	49	37 – 92
This Study	46	34 - 84	36	24 - 74
TCTA (planned pumping rate)	57	34 -84	47	24 - 74

- The TCTA planned pumping rates compare well with the predicted range of ingress volumes and would also cater for possible climate change (as described in section 4.2).
- Realistically, the ingress volume could be reduced by about 10 Mℓ/day if the ingress control measures as described above can be implemented.

7.8.3 Pumping rates

Calculations based on estimated void volumes and ingress rates (this study) indicate that a state of equilibrium could possibly be maintained at a pumping rate of 46 Mℓ/day, with water levels fluctuating within approximately 25 m from the ECL.Pumping at 50 Mℓ/day would tend to lower the water level below the preferred static water level, but is the recommended minimum pump capacity to enable high flows to be managed without an excessive freeboard. This might be a preferred volume to abstract, allowing for freeboard, maintenance and other contingencies.

There are concerns regarding the STI pumping site at South West Vertical Shaft due to its very deep connection with the mine void and that one will have to carry the entire void discharge. A collapse in the haulage could have serious consequences. In a long term solution, other pumping strategies should be investigated which could involve multiple extraction points which have greater connectivity with the void at a shallow level. Incline shafts, such as Cason Shaft, or preferably boreholes intersections incline shafts or other suitable areas of the void should be considered as potential alternative pumping sites as they offer a greater connectivity to the mine void at shallower levels.

7.8.4 Water quality

The Central Basin data is scattered over a wide field, reflecting the diversity of samples within the database, ranging from extremely contaminated surface samples to water within the potable range. However, the water quality of the Central Basin is generally acidic with high levels of dissolved solids. Prolonged pumping will tend to stabilise the chemistry, depending on the degree of mixing and the extent to which channelling is effected during the pumping exercise. **Table 7.13** is considered to reflect the best approximation available of the likely water quality should pumping take place from moderate-deep levels within the mine void.

8 EASTERN BASIN

8.1 Geological Setting

The geology of the Eastern Basin differs substantially from the Western and Central Basins. Here, the Witwatersrand strata form a fairly shallow, oval shaped sub-basin about 30 km long and 20 km wide in which dips of strata are relatively shallow. It is connected to the main Witwatersrand Basin in the west across a zone of steepened dip known as the Springs Monocline. Structurally, the basin is marked by prominent folding, and a number of major faults transect the area, notably the Vogel's, Jeffrey's and Grootvlei tear faults. These tear faults tend to strike East-West, while another major fault-set strikes northwest – southeast. Gold bearing conglomerates, which were extensively mined from surface down to depths in excess of 2500m, outcrop at two localities in the East Rand Basin, i.e. at the old Van Ryn and Gravelotte mines (Benoni), and again near Nigel.

The Witwatersrand rocks are almost entirely overlain by younger strata, notably the Transvaal and Karoo Supergroups, and very little of the Witwatersrand strata exposed on surface (**Figure** 8.1). Approximately 90% of the Eastern Basin is covered by Karoo Supergroup rocks, in particular the Vryheid Formation of the Ecca Group and the Dwyka Formation. Economic coal layers, which were mined at a number of localities, occur within some of the strata (e.g. Largo Mine). Although the Transvaal Supergroup is extensively developed it is largely covered by Karoo strata and the Transvaal rocks (mainly the dolomite) are only exposed along river courses, especially along the Blesbokspruit.

A number of intrusive bodies occur throughout the basin. The most prominent of these are diabase and syenite dykes and sills, with a general strike of northwest to southeast.

8.2 Hydrogeological Setting

Figure 8.2 shows the conceptual hydrogeological model for the Eastern Basin in a cross section from NW to SE.

The Karoo sequence is susceptible to preferential weathering relative to the Transvaal or Witwatersrand units, and shallow perched aquifers occur mainly in the sandstone and mined-out coal horizons. Clay as well as coal seams have and will be mined from Karoo sediments. Minor aquifers are associated with the weathered zone as well as the coal seams. Successful boreholes yield on average between 0.1 and 0.5 l/sec and are used extensively for irrigation and domestic water supplies to farmers in the area. Hydraulic interconnectivity between the Karoo and underlying Witwatersrand formations could occur via major faults/fractures and even historical exploration boreholes. Indeed indications are that some of the bords of the Largo Colliery in the area near Marievale have collapsed and are filled with water. Water from the coal mining void probably already contributes to the total sulphate load in the Eastern Basin.

The Blesbok Spruit, which flows through the Eastern Basin, has eroded through the Karoo unit, and exposed the Malmani dolomite of the Chuniespoort Group of the Transvaal Sequence for the majority of its course. This brings the surface water in direct contact with the dolomite aquifers, improving groundwater recharge rates. The low gradient and wide ponding areas within the Blesbokspruit also contribute to accelerated groundwater recharge. Scott (1995) has estimated that groundwater flows from the dolomites to underground workings represents the bulk of all water ingresses to the mines. The following is relevant to the dolomite aquifers:

- Chert layers serve as barriers to flow resulting in compartmentalisation of the dolomite aquifers;
- Fractures and faults provide hydraulic connection from the dolomites to the mine voids
- Sills serve as horizontal barriers limiting downward flow upon which groundwater accumulates;
- Dykes which have alteration halos along the contacts are more permeable and allow vertical flow along the contacts but prevent horizontal flow across the dykes.

Two distinct dolomite aquifers occur within the Eastern Basin:

- In the northern part of the area, the dolomite overlies the Witwatersrand sediments where it is up to 200m thick. A prominent set of sills occurs in this dolomite below 60m referred to as the Green Sill. These sills have resulted in the development of a perched water table characterized by relatively shallow water levels. In spite of major fissures occurring within the dolomite allowing leakage into the mine void (particularly in the Black Reef workings), the Green Sill prevents complete dewatering of the dolomites as inflows are greater than the outflows through the Silt;
- In the south-western portion of the area, the dolomite aquifer overlies the Ventersdorp Supergroup rocks. The latter forms a hydraulic barrier between the water-bearing dolomite and the Witwatersrand sediments.

The Witwatersrand quartzites, which are not well exposed in the Eastern Basin, are not susceptible to deep weathering with low permeability and allow water through mainly via faults and fractures and along intrusive dykes.

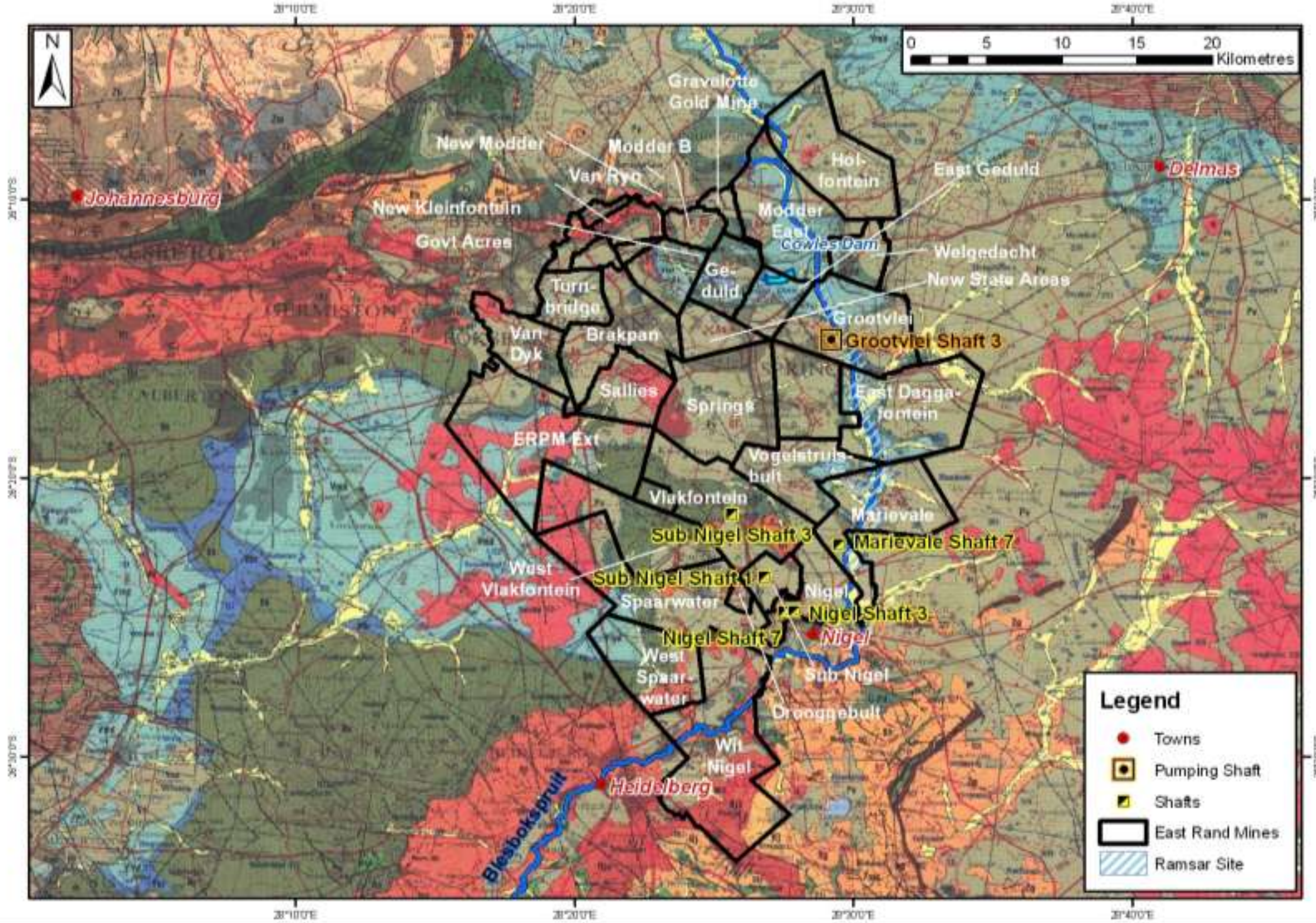


Figure 8.1:Geological map of the Eastern Basin showing mine locations and selected shafts.

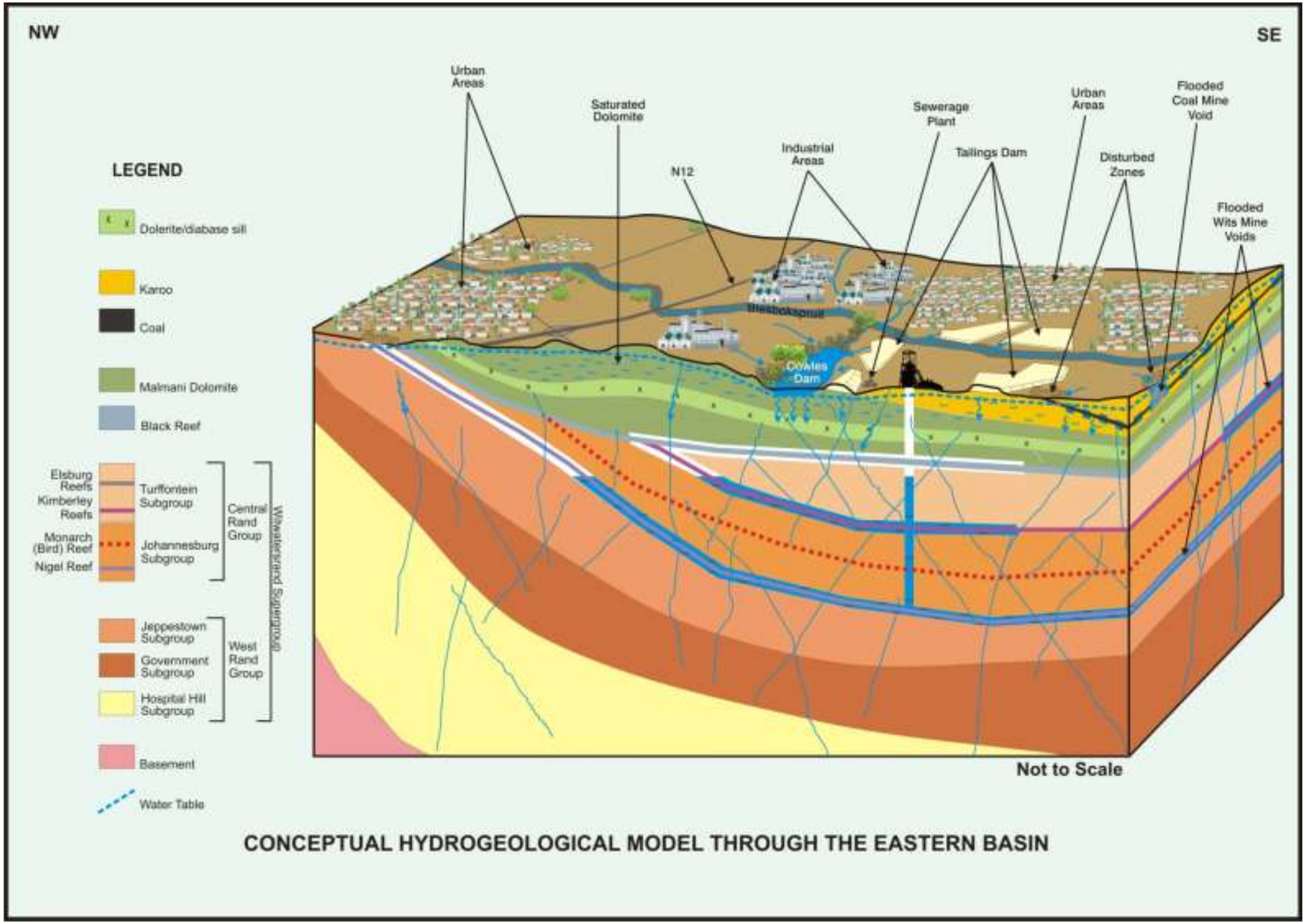


Figure 8.2: Schematic illustration of a conceptual hydrogeological model for the Eastern Basin.

8.3 Mine Voids

8.3.1 History, distribution and connectivity

Gold mining in the Eastern Basin commenced soon after the discovery of gold in 1886 and peaked in the 1950s. Active mining is still taking place in the basin. In addition to gold, several coal mines operated in the area from as early as the 1890s. The last of these (Largo Colliery) closed in 1947. The main focus of gold mining was the Nigel (or Main) Reef which was extensively mined (Error! Reference source not found.). The deepest workings on the Nigel Reef were located at Vlakfontein Gold Mine at a depth of about 2300 m below surface. Of secondary importance was the Kimberley Reef where mining was more sporadic (Error! Reference source not found.). Limited mining was also carried out on the Black Reef.

Pumping was historically carried out from numerous locations during the peak of mining activity in the 1950s to 1960s. By the late 1970s, dewatering was only from Sallies No.1 Shaft and Grootvlei No's 3 and 4 shafts (Scott, 1995). Pumping stopped at Sallies in 1991 and at Grootvlei in January 2011.

8.3.2 Water levels and predicted decant

Scott (1995) investigated likely surface decant points in the event of the entire void filling. The lowest shaft collar elevations occur in the southern portion of the basin because of the generally southerly slope of the land surface. The lowest shafts occur on Nigel and Sub Nigel mines. Reference to Error! Reference source not found. shows that these mines occur in a north-westerly trending zone of more sporadic mining compared to the more extensive, continuous mining carried out to the northeast.

The dolomite aquifer is the main source of ingress (Scott, 1995) and is located above this zone of more extensive mining. The bulk of this water will need to flow across to the zone of more fragmented mining to a surface decant point on Nigel mine. Scott investigated the connections between the mines and noted that there was only limited interconnection between the two groups of mines. He identified a haulage linking the Marievale Mine (the topographically lowest mine in the area of continuous mining) to Sub Nigel (61 Level 8 haulage) and concluded that ingress water would have to flow via this route to reach the low shafts on Nigel Mine. He concluded that this was the only link between the two mining zones. If the flow is restricted in this haulage, water from the mines in the north-eastern zone will decant at Marievale No's 4 and 7 shafts (1565 and 1564 m amsl) on surface. In the event of free flow via the haulage, surface decant will occur at Nigel No. 3 shaft (collar elevation 1549 m amsl estimated from a 1:10 000 orthophoto (Scott, 1995) or 1553 m amsl according to Google Earth). This is an incline shaft that is partially filled with rubble and the roof has also collapsed. It is unlikely to be completely sealed, but rate of flow could be reduced.

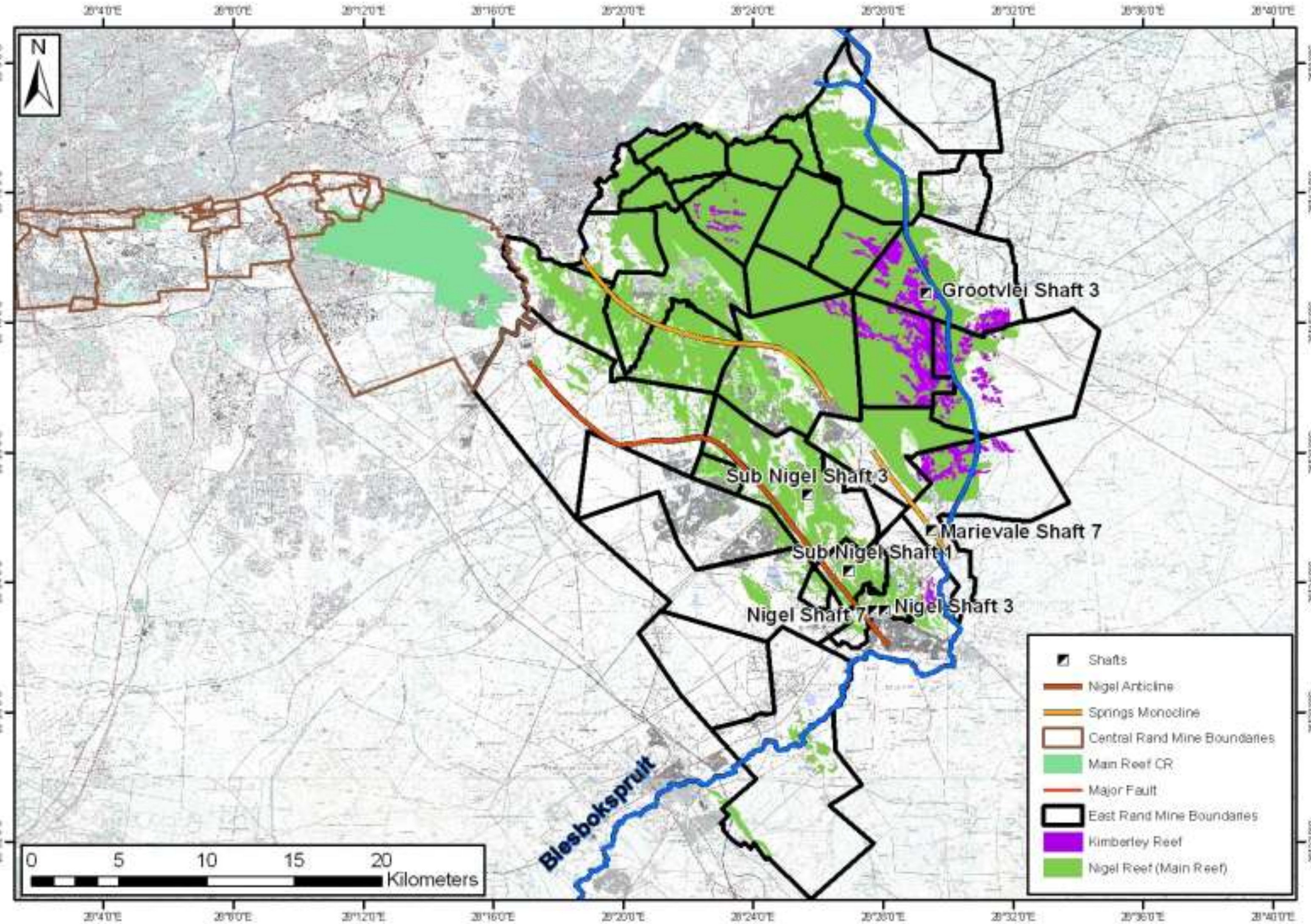


Figure 8.3: Mine voids of the Eastern Basin with significant shafts annotated. Note the gap in the Main/Nigel Reef mine void (Boksburg Gap) between the Central Basin (CR) and Eastern Basin.

Alternative surface decant points are Nigel No's 2 and 10 shafts at 1559 m amsl, and Nigel No's 7 and 13 and Sub Nigel B and CV shafts, all at 1558 m amsl (elevations estimated from 1:10 000 orthophotos). Notwithstanding the uncertainties, the linkages between the two sections of the Eastern Basin are such that the water level in the western portion has been effectively controlled by the pumping at Grootvlei in the east. However, ingress volumes into the mines in the western section are probably much smaller than into the eastern mines, and it is uncertain if the linkages could sustain flow in the opposite direction, given its likely larger volume.

The water level as measured in the Sub-Nigel No.1 shaft is currently rising at approximately 0.3 to 0.4 m/day (**Figure 8.5**). The single data point, suggesting a water level decrease, is considered spurious due to the multiple sources of the data.

The TCTA Report (2011a) predicts that the ECL will be reached between December 2014 and May 2015.

Recent measurements in the Sub-Nigel No.1 Shaft indicate that the water levels in the Eastern Basin have reached 1025 m amsl in April 2012 (**Figure 8.4**) and it is thus predicted that the ECL, set at 1280 m amsl (TCTA Report (2011a)), will be reached by middle 2014. This estimate is seen as somewhat uncertain and conservative (the given ECL will probably be reached much later) because of the expected decrease in the rate of water level rise with elevation. Again, the estimates are based on excessive extrapolation from more than one data source and may be in error.

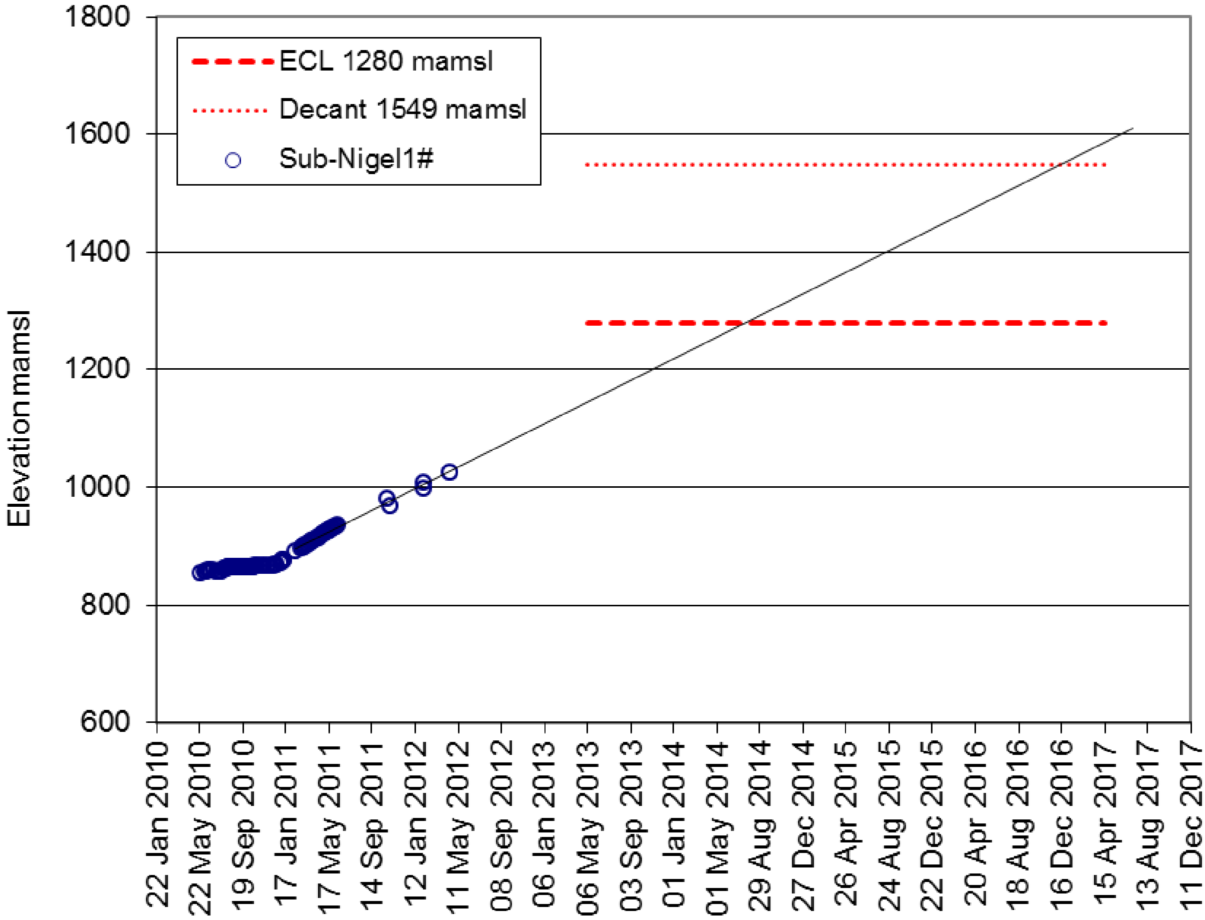


Figure 8.4: Estimated surface decant and ECL dates for the Eastern Basin.

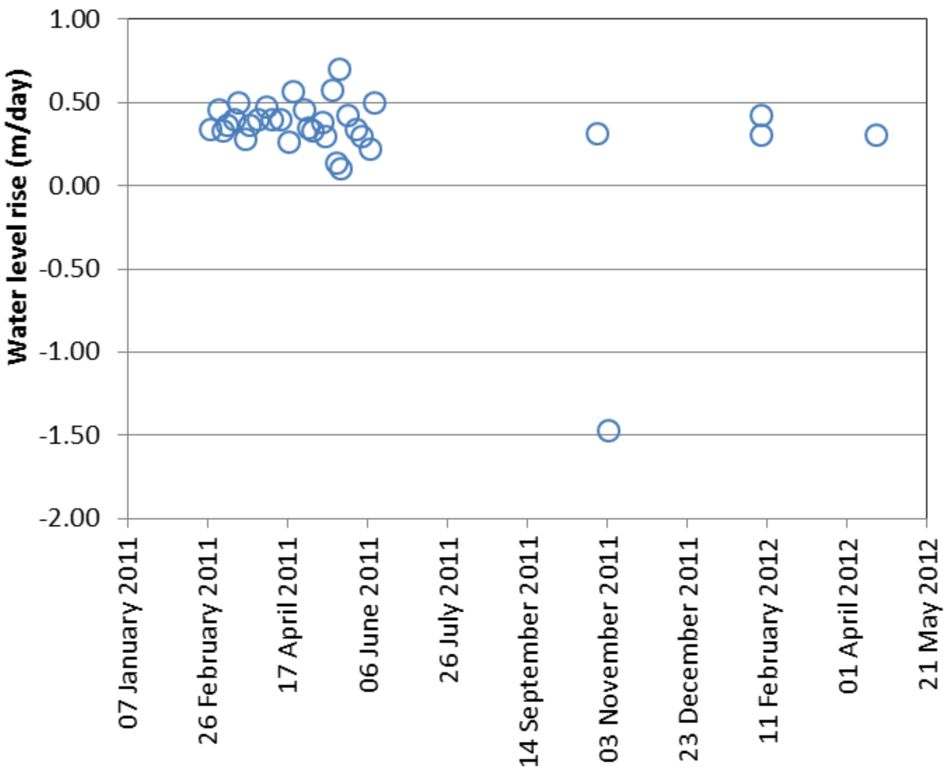


Figure 8.5: Water level rise in the Eastern Basin.

8.4 Critical Water Levels

The ECL chosen by the TCTA for the Eastern Basin is 1280 m amsl, which was chosen to keep the water level in the mine void below the base of the dolomite of the Transvaal Supergroup. The ECL elevation would place the water level at 290 m below the collar at the pumping shaft (Grootvlei No. 3 shaft) and about 270 m below the expected surface decant point at Nigel No. 3 shaft. This ECL is thought to be highly conservative and could possibly be safely raised.

8.4.1 Proposed Environmental Critical Level

The dolomite aquifer is fully flooded and was so throughout the period of active mining and pumping in the Eastern Basin. The water table in the dolomite aquifer along the Blesbokspruit is at surface, which in the region of Grootvlei No. 3 shaft is about 1573 m amsl, and away from the river it is probably shallow (Scott (1995) notes a figure of 15 m below surface). The ECL is shown in relation to the geology in **Figure 8.6**, a cross section aligned more or less along the Blesbokspruit, which is approximately the topographically lowest portion of the basin. For the STI it is prudent to be conservative and to keep the ECL below the base of the dolomite at the TCTA suggested level. However, it should be noted that even at this ECL, deep keels of dolomite protrude through the chosen level.

An alternative is the possibility of raising the ECL to 1470 m amsl (i.e. a depth of 100 m at Grootvlei) which would result in a substantial cost reduction. Although it does introduce a risk of mixing the dolomitic water with AMD, the shallower ECL would still be about 70 m lower than the water table in the dolomite compartment and it is probable that this would produce a net flow from the dolomite into the underlying Witwatersrand rocks and the mine void. (**Figure 8.6**). We therefore suggest that the ECL of 1280 m amsl be maintained until adequate monitoring of the water quality from boreholes in the dolomite establishes a baseline water quality. The water level can then be allowed to rise in say 20 m increment and maintained for a period of 3 months. If no change in Water Quality is detected the level can be raised further 20 metres. As the 1470 m amsl is reached 10 metre increment should be adopted consideration be given to raising the ECL to 1470 m amsl under conditions of careful monitoring of water quality in surface boreholes at sites throughout the basin, especially along the Blesbokspruit.

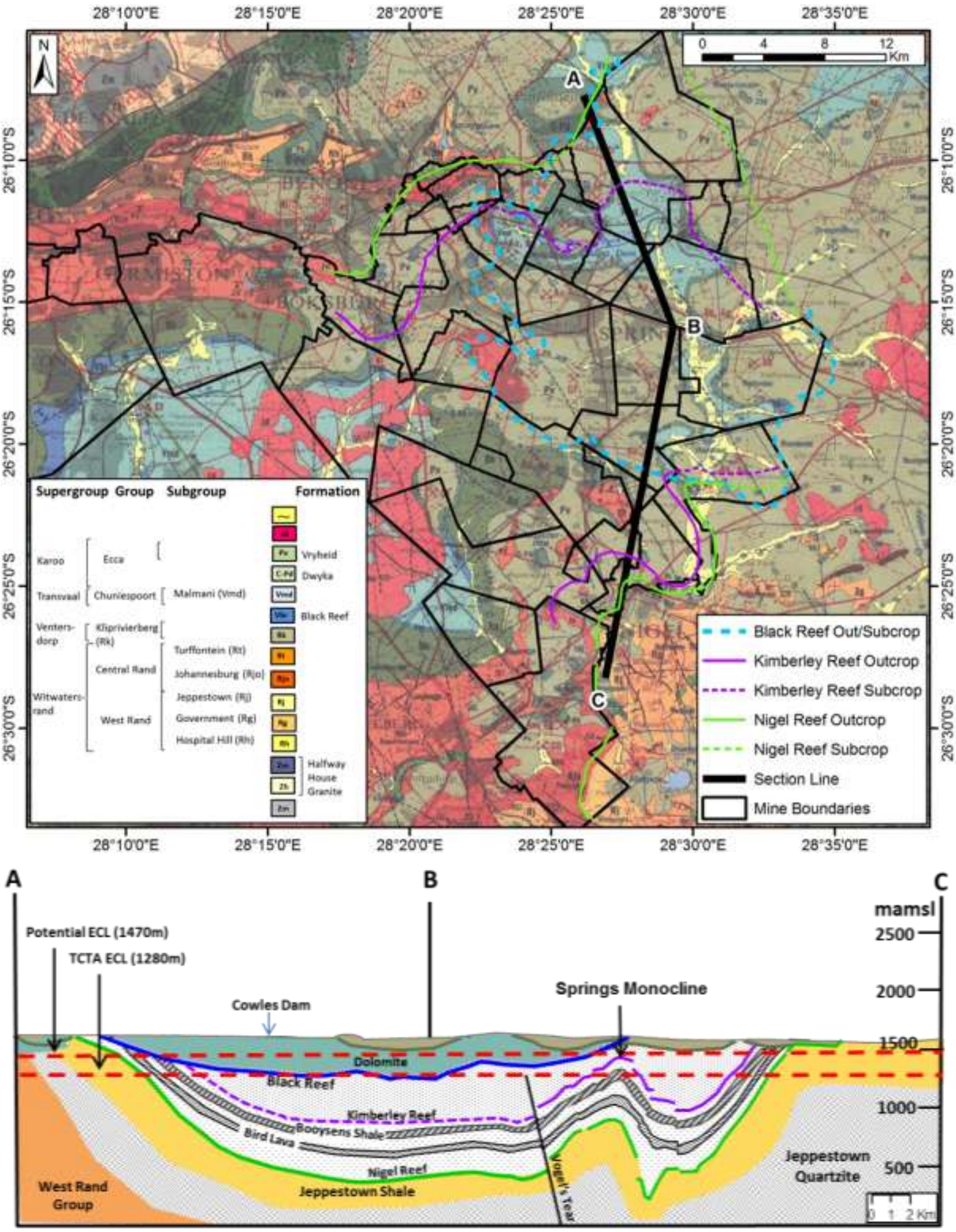


Figure 8.6: Geological plan and cross-section in the Eastern Basin in the vicinity of the Blesbokspruit, showing the current ECL as per the TCTA Report (2011a) at 1280 and potential ECL at 1470m.

8.5 Surface Water Ingress

The northern and eastern portions of the Eastern Basin are primarily drained by the Blesbokspruit while the Rietspruit drains the central and western portions of the basin. Both rivers eventually flow into the Vaal River.

For each of the ingress sources described in Section 4.3, a percentage of recharge (ingress) of the rainfall and surface water run-off was estimated taking into account the existing geological formations as well as potential ingress sources to predict the expected ingress volumes into the mine workings. In addition to this, relevant and applicable rainfall records needed to be established before being able to determine the ingress volumes.

8.5.1 Meteorology

For the Eastern Basin, 3 stations were used in the Benoni and Brakpan area (WUC Report, 2009). The extracted monthly average rainfall data is presented in **Table 8.1** and the annual minimum and maximum rainfall is presented in **Table 8.2**. At the time of the WUC study, this was the most up to date data.

Table 8.1: Monthly rainfall figures in the East Rand Basin (WUC Report, 2009).

Month	Average Rainfall (mm)	Minimum Rainfall (mm)	Year Recorded	Maximum Rainfall (mm)	Year Recorded
October	74.32	15.27	1999	182.18	2001
November	111.02	10.73	1951	213.2	1998
December	117.08	37.88	1984	253.8	1949
January	131.28	55	1962	324.1	1978
February	98.25	14.8	2007	294.36	2000
March	88.68	14.32	1966	317.27	1997
April	45.64	0.53	1991	133.03	1958
May	17.85	0	Often	104.55	1997
June	7.8	0	Often	60.68	1963
July	4.59	0	Often	69.7	1957
August	6.5	0	Often	59.68	1979
September	24.13	0	1955	154.78	1987
Total	**727.14**				

Table 8.2: Annual minimum and maximum rainfall figures in the East Rand basin (WUC Report, 2009).

Month	Driest Year - 1984 (mm)	Wettest Year - 1997 (mm)
October	81.4	41.55
November	106.08	148.05
December	37.88	104.13
January	74.2	107.58
February	23.6	64.93
March	84.34	317.27
April	10.78	27.52
May	0.58	104.55
June	6.88	8.73
July	15.4	7.63
August	0.82	5.98
September	10.72	52.47
Total	**452.68**	**990.39**

In addition to the above, rainfall used in the WUC Report (2009), an independent assessment of the average monthly rainfall, as well as possible minimum and maximum monthly rainfall, have been carried out as part of the review. Two stations were compared: station 0476736W with 81 years of record and station 0476766W with 81 years record (**Figure 4.3**). The average of the two rainfall stations was computed and is summarised in **Table 8.3**.

Table 8.3: Average monthly rainfall data (independent rainfall station).

Month	Average Rainfall (mm)	Minimum Rainfall (mm)	Year Recorded	Maximum Rainfall (mm)	Year Recorded
October	68.7	9.05	1917	200.8	1993
November	110.1	20.1	1935	276.4	1917
December	117.4	19.15	1944	276.6	1942
January	128.9	29.5	1989	393	1977
February	100.5	23.6	1976	370.1	1943
March	92.3	7.05	1964	288.7	1924
April	44.2	0	Often	176.5	1957
May	20.7	0	Often	151.2	1935
June	7	0	Often	65.3	1988
July	7.2	0	Often	73.1	1956
August	7.1	0	Often	69.7	1978
September	25.5	0	Often	164	1986
Total	**729.5**				

The following observations are made when comparing the above rainfall tables:

- Comparison of the reviewed MAP with that of the WUC report shows the reviewed rainfall to be very similar, with the reviewed MAP being about 0.5% higher than the WUC MAP;
- The maximum monthly rainfall based on the review is somewhat higher at 393 mm (24%) when compared to the WUC value of 317 mm. This could possibly be due to a more accurate and patched rainfall record used for the review study, which is based on the rainfall database used by DWA for all resource modelling (Middleton and Bailey, 2005);
- It is noted from **Figure 4.4** that the expected average rainfall may increase by about 40% over the Gauteng region due to climate change. This is above the 24% increase as determined from the comparison of extremely wet months that occurred during the rainfall record under review. It is noted that the rainfall record used is only 81 year which is short in terms of meteorological time scales. Due to this, climate change should still be taken into account when predicting ingress into the mine voids.

8.5.2 Review and verification of ingress volumes

An important aspect is the review and validation where possible of the expected ingress of surface water into the mine workings. This has a marked influence on the abstraction requirements and hence pumping and maintenance costs. In view of the above, two approaches have been adopted in verifying the predicted ingress volumes:

- Determination of the total ingress into the mine void based on surface flow rates as well as assumptions on the percentage infiltration of surface water into the mine void from various geological formations, mine infrastructure and natural drainage systems.
- Determination of the total ingress into the mine void based on water level and pumping data, described in Section 8.5.3;

In the Eastern Basin, mined-out reef outcrops as potential ingress sources occur to a very limited extent whereas the dolomite aquifer above the mine void is a significant contributor to ingress into the mine void as described below.

Surface water bodies serve as additional sources of water ingress to underground works. The ingress sources are summarised in **Table 8.4** and specific areas investigated with quantified water ingress are indicated in **Table 8.5** below and shown in **Figure 8.7**.

Table 8.4: Summary of ingress areas in the Eastern Basin.

No.	Ingress area	Comments
1	Undisturbed geology /Shallow aquifers	Dolomite is relatively thick in this basin, The prominent Green Sill has intruded the dolomite which act as aquicludes, preventing dewatering of the dolomite whilst allowing accumulation of water as major reservoirs which seep into the mine workings along faults and fissures. The Modder East dyke, and the associated faulting occurs towards the west, and is associated with high underground inflows.
2	Surface water (dams, rivers, wetlands)	Major surface water bodies e.g. Blesbokspruit and Cowles Dam are in the vicinity of major faults, dykes and open cast areas (Largo Colliery). Effluent disposal by other industries contributes a steady year-round flow of water to the dam and the Blesbokspruit system.
3	Municipal infrastructure (leaks, stormwater run-off etc.)	The upper reaches of the Eastern Basin is highly urbanised (e.g. Boksburg, Benoni) and leaking occurs from ageing infrastructure. Stormwater inflows are channelled into Leeupan (located over the Boksburg Gap).
4	Surface mine workings (open pits, shafts, inclines)	The bulk of mining was underground at depths varying from 250 to 500m due to poor reef exposure. West pit, and Gravelotte are surface pits that mined the reef. Largo Collieries mined the shallow coal seam of the Karoo and the voids are now flooded and subsidence is evident on surface.
5	Tailings dams and mine dumps	Ingress of water from mine residue deposits to the void.

Table 8.5: Water ingress zones and quantified volumes of water (CGS, 2008 in preparation).

Ingress Map Reference	Identified Ingress area	Seepage to subsurface/ groundwater body (Mℓ/d)
2	Leeupan	4.1
2	Cowles Dam	5.6
2	Van Rhyn	1.4
4	Gravelotte	0.2
4	Largo	0.6
2	North Blesbok (Northern Area)	1.4
2	North Blesbok (Southern Area)	0.7
2	Central Blesbok	3.9
2	South Blesbok	5.7
4	West Pit	7- 10

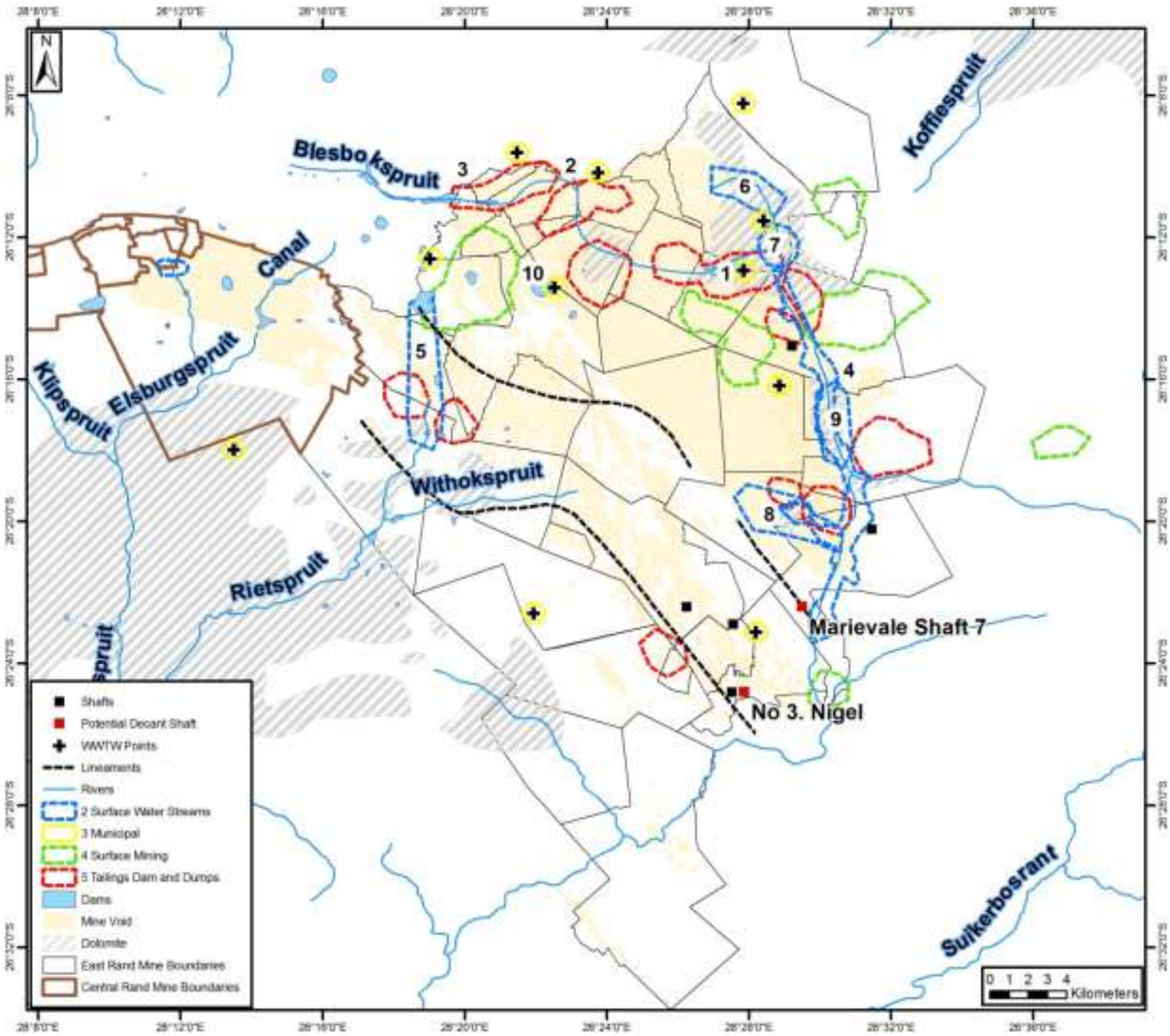


Figure 8.7: Major ingress areas in the Eastern Basin (modified after CGS, 2006). Numbers in legend refer to source type in the preceding table.

In this section, relevant data and assumptions made have been abstracted from the WUC Report (2009) on the Western Basin. Based on the average rainfall data, as given in **Table** 8.1, as well as flow monitoring, the expected ingress volumes for the entire basin is about 82 Mℓ/day. The approximate percentage distribution for each of the sources is given in **Table 8.6**.

Table 8.6: Predicted ingress volumes and sources (average rainfall) (WUC Report, 2009).

Source	Percentage of Total Ingress volume	Expected Ingress Volume (Mℓ/day)
Dolomite aquifer seepage into mine void	42	34
Surface mine workings	16	13
Shallow undermined areas (Largo colliery)	30	25
Natural geological structures/rivers/water bodies	12	10
TOTAL	**100**	**82.0**

It is also important to take into account the impact of rainfall variations on the ingress volume. For this purpose, **Table 8.2** giving extreme rainfall variations and climate change have been used to predict expected changes in ingress volumes. The prediction has been based on the Goldsim Model utilised by Golder & Associates (WUC Report, 2009).

A summary of the expected ingress volume variation is given in **Table 8.7** and also shown on **Figure 8.8**.

Table 8.7: Rainfall variation impact on ingress volume.

Rainfall	MAP (mm)	Change in MAP (%)	Predicted Ingress Mℓ/day	Change in Ingress (%)
Average	727	0.00	82	0.0
Dry Season	452	-37.83	77	-6.1
Wet Season	990	36.18	87	6.1
Extremely Wet	1439	198.07	108	31.7
Climate Change	1100	40	90	9.8

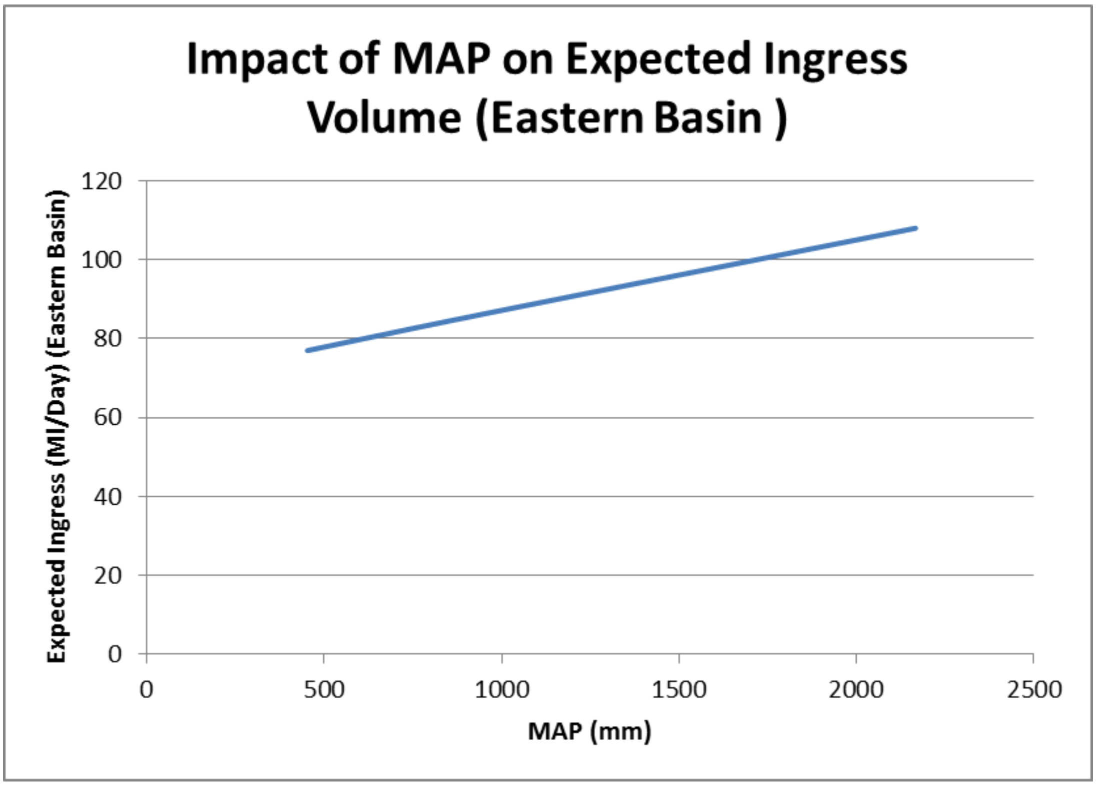


Figure 8.8: Rainfall and ingress variations.

The following observations are made:

- The change in MAP has a fairly significant effect on the predicted ingress volume;
- The potential change in MAP of about 20 to 40% due to climate change could possibly change the ingress volume by about 10% and hence need to be taken into account in future studies regarding ingress predictions.

8.5.3 Estimations based on pumping rates and void volume

An analysis of mine pumping records carried out for the period 1952 to 1959 showed that of the 19 mines operating at that time, 12 were situated directly below dolomite outcrop and pumped 85% of the total pumped volume (Dolan, 1961, reported in Scott, 1995). Notwithstanding the extensive pumping taking place from the mine void, the shallow groundwater aquifer in the overlying rocks, including the dolomite, has remained undisturbed.

Scott (1995) has shown that recharge from rainfall directly on the exposed dolomite is sufficient to sustain the natural groundwater aquifer, notwithstanding major ingress into the mine void below. Recharge of the dolomitic aquifer also occurs via seepage from tailings dumps and this water is highly contaminated (Ntsume and McCarthy, 2005). The Blesbokspruit was originally a seasonal stream, responding to seasonal fluctuations in the water table. However, this situation has now changed primarily due to the discharge of effluent from municipal sewage works into the spruit and it is now a perennial river (a portion has been declared a RAMSAR site).

Scott investigated the relationship between rainfall and pumping rate from the mines and found that the correlation was extremely weak. The best correlation (0.7) was obtained by lagging the rainfall by 7 months, indicating an extremely slow response between rainfall and ingress. He concluded that direct recharge was a very minor contributor to total ingress and that the large storage capacity of the dolomite aquifer strongly modulated the effect of rainfall.

Flooding of the deeper levels of the Eastern Basin commenced in August 1991 when pumping stopped at Sallies No. 1 shaft. By August 1994, the water level had risen by 385 m, an average of 0.34 m/day (Scott, 1995). Analysis of the rate of rise during this period showed it to be linear which led Scott (1995) to conclude that ingress was primarily via fissures and weathered fracture zones.

Although the deeper levels (Main Reef workings) were allowed to flood, mining on the Kimberley Reef continued and a new pump station was installed at Grootvlei No. 3 shaft where pumping would resume once the water reached about 798 m amsl. Water level in the void was thereafter maintained at about 800 m amsl at a pumping rate of ca. 80 Mℓ /day (**Figure 8.9**). Pumping at Grootvlei finally ceased in January 2011 when the water level was at 877 m amsl at Sub_Nigel No1# and the remaining void is now filling.

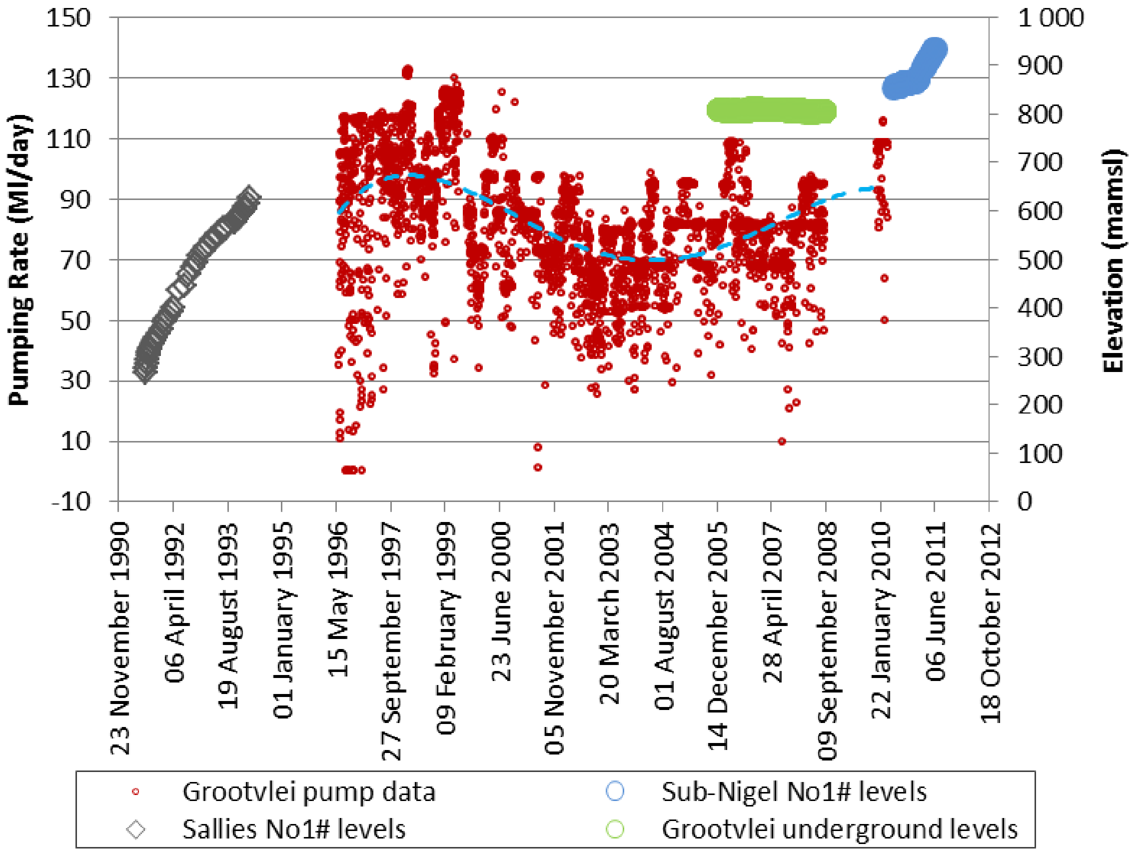


Figure 8.9: Eastern Basin pumping rates and underground water levels.

8.5.4 Minimising surface water ingress

Based on **Table 8.6**, an initial prioritisation of the main sources causing the ingress of 80 Mℓ/day into the Eastern Basin void was compiled, as shown below in **Table 8.8**.

Table 8.8: Prioritisation of ingress control measures

Source	Percentage of Total Ingress volume	Expected Ingress Volume (Mℓ/day)	Priority of improved ingress control
Undisturbed geology /dolomites (WUC)	42	34	5
Surface water (dams, rivers, wetlands) (CGS)	33	26	1
Municipal infrastructure (leaking mains and sewerage, stormwater run-off)	5	4	3
Surface mine workings (open pits, shafts, inclines) (CGS)	14	11	2
Tailings dams and mine dumps	6	5	4
Total	100	80	

1: A priority "5" has been given to the "Dolomite aquifer seepage" and "Shallow undermined areas" as it is at this stage not known whether any practical and feasible improvements to ingress control can be used for these sources.

As can be observed from **Table 8.8**, the majority of the inflows is from the dolomites through fractures in the Green Sill into the void but there is no practical method for reducing these inflows. Sources of surface water ingress amounts to nearly 33% of the total ingress volume and open pits or shallow mine workings making up 14% of the total ingress.

Theoretically if the ingress sources prioritised as 1 to 3 (**Table 8.8**) could be reduced, a maximum reduction of 42 Mℓ/day into the void could be realised. Using the same logic as applied for the Western and Central basins, at best only half of this volume (21 Mℓ/day) may be effectively stopped from entering the mine voids by implementing methods outlined in Section 4.3.

In the Eastern Basin, various options were identified and evaluated to prevent surface water ingress into the underground works (Mafanya and Esterhuyse, 2011). The options varied from lining the water sources (dams and spruits) to building of canals and diversion of culverts. The first operation on implementation of the management plans on prevention of water ingress into underground workings started in 2005, with West Pit at Grootvlei Mine, which was noted to contribute high volumes of water ingress. From the prevention plan implemented in West Pit, it was modelled that about 8 Mℓ/d of water ingress will be prevented from entering underground workings. The option has been implemented successfully and about 6 Mℓ/d of water ingress reduction was reported. The management plan to be followed to prevent water ingress into underground workings might not provide 100% prevention of

water ingress but is believed to prevent large volumes of surface water (± 80%) from ingressing.

Although there will be a reduction in volumes of water ingress once the management options to prevent water ingress into underground works are implemented, surface decanting is still likely to occur once pumping is ceased, as the recent volumes pumped at Grootvlei (80 Mℓ/d) were significantly higher than the volume of ingress which can realistically be prevented.

It is furthermore established that the opening up of culverts under roads in the Blesbokspruit to prevent ponding of water and the consequent ingress to the underground mine void could start immediately. Other ingress prevention actions have been identified (WUC Report, 2009) and will require focused study and urgent implementation, noting that stream flows are greatly increased above their historical levels owing to other discharges, in particular treated sewage discharges (Scott, 1995). In the Nigel area, the possibility exists to install more culverts under the R42 road which should lessen ingress.

Ingress volumes at the Cowles Dam site are similar to those recorded at West Pit (7-10 Mℓ/d). There are future plans to drain the dam in order to mine the slimes, at which point flow would be diverted around Cowles Dam. This action has to be monitored in order to build up pre-engineering data to be able to determine if ingress decreases once the dam is drained.

In some areas in the Eastern Basin the mine void is in contact with a dolomitic aquifer located immediately above the Black Reef workings. At this interface clean dolomitic groundwater has been observed flowing into the mine void. In its passage through the mine void to the pumping station, this water becomes contaminated and acidified. Interception of this water before it becomes polluted via a well field or in-mine infrastructure would make a source of clean water available for use and also reduce the volume of water from the basin that needs to be pumped and treated. This pumping will need to be approached with caution to prevent subsidence effects that could be triggered by dewatering of the dolomite.

The above mentioned option (of abstracting groundwater before it becomes contaminated) is also mentioned in the report on the regional mine closure strategies for the Eastern Basin (Mafanya and Esterhuyse, 2011), but it is stated that due to the drawbacks to this option, it is not recommended for implementation. It must however be noted that most of the drawbacks relate to outstanding information (such as abstraction rates and costs).

Site specific control measures as recommended by Mafanya and Esterhuyse (2011) are summarised in **Table 8.8** below.

Table 8.9: Site specific ingress control measures (Mafanya and Esterhuyse, 2011).

Ingress area	Proposed Actions
West Pit	Build canal AND unblock culvert
Cowles Dam	Mine sediments and divert flow around the dam
South Blesbok	Unblock or enlarge culverts AND divert flow over certain portions – significant volume to be saved
Leeupan	Reduce the grey water entering the pan by collecting the water and discharging the water to the sewage reticulation network. Line pan, Ekhurhuleni is in an advanced stage of developing the pan as nature reserve, flow diversion will nullify purpose of nature reserve
Central Blesbok	Unblock and enlarge culverts AND Divert flow over certain portions – significant volume to be saved
North Blesbok (northern area)	Unblock and enlarge culverts AND divert flow over certain portions – significant volume to be saved
North Blesbok (southern area)	Unblock and enlarge culverts
Van Rhyn (ponding)	Repair channel which will remove the dam - Should reduce ponding significantly, getting rid of the unnatural dam
Van Rhyn (direct runoff)	Close cracks and stabilize openings
Largo	Close openings – foam
Gravelotte (opencast mine, open shaft)	Shaft closing costs low enough, costs to close opencast mine too high to be feasible. Construct upstream bunds
New Kleinfontein	Repair channel

8.6 Pumping Volumes and Abstraction Points

8.6.1 Pumping volumes required

The Eastern Basin presents a special problem in that the mine void underlies a perched dolomite aquifer. The water in the latter was never significantly influenced by pumping during the mining activities, maintaining a water table close to surface in the Blesbokspruit. All indications are that water from this dolomite aquifer leaks into the mine void over a wide area, maintaining a flow of ca. 80 Mℓ/day. Pumping at this rate allowed Grootvlei Mine to steady the water level in the mine at about 800 m amsl. It appears logical that the average pumping rate from the Eastern Basin should be 80 Mℓ/day. Considering breakdowns and other off-times, a pump capacity of 100 Mℓ/day may be prudent.

8.6.2 Suitability of shafts for pumping

According to the Appendix J of the TCTA Report (2011a), all mining at Grootvlei was done on the Kimberley and Nigel (Main) reefs. The intersection of the Kimberley reefs in the chosen TCTA shaft, Grootvlei No. 3 Shaft, is at approximately 710 m below surface and the area around the shaft has not been mined (the shaft pillar is intact). A plug has been installed at approximately 790 m below surface so there is reduced connectivity with the Nigel Reef (the largest portion of the mine void). The Nigel Reef intersects the shaft at 1 000 metres below surface, which is also the shaft bottom (pers. com. Trouw, 2011).

The shaft has however proven to be connected to the entire Eastern Basin and has in the past maintained the water levels in all the sub compartments. The collar elevation of Grootvlei No. 3 Shaft is 1570 m amsl (according to the TCTA Report (2011a) and 1577 m amsl according to Google Earth). This equates to a 20 m elevation difference between the lowest shaft in the greater Eastern Basin at Marievale and the pumping shaft. The cost of pumping the extra 20 m may be reduced if pumping were to take place from a lower elevation.

The Grootvlei No. 3 Shaft is also located on the Blesbokspruit wetland, which is a known ingress source into the mine void. The discharge of the neutralised water into the Blesbokspruit will mean that this water will be recycled and, until desalination commences, some of the salts will be returned to the void. By pumping from further south in the Eastern Basin and discharging the water after the wetlands and dolomites will prevent this recycling by reducing the opportunity for recycling. This solution will increase the chances of flushing the system and improving water quality until desalinisation commences. This could be done by pumping from a borehole arrangement drilled into the void at the lowest elevations rather than shafts if the shafts in this area are found to be sealed/filled or structurally not sound.

The lowest level for pumping would be at the Sub Nigel Shaft. However due to the concern that the haulage between Marievale and Sub Nigel may not be sufficient to dewater the greater Eastern Basin from Sub Nigel alone, another option would be to also use a shaft at Marievale Mine or a borehole into the mine void. The southern portion of Marievale is also located south of the dolomite and wetlands therefore release of water there will avoid any return flow into the mine void.

8.6.3 Alternative options to pumping

Due to the topography of the land it is highly unlikely that passive solutions, allowing natural surface decant at preferred ECL's, would be possible in the Eastern Basin. A tunnel length of more than 30 km long would be required which is prohibited by time and cost.

8.7 Water Qualities

8.7.1 Data Utilised

The bulk of the sampling data for the Eastern Basin were collected by Grootvlei No 3 Shaft between 1997 and 2008 as surface discharge and underground raw mine water. Water quality data was synthesised from two principal sources:

(1) Surface sampling:

These samples were collected from a flume at Grootvlei No 3 Shaft after treatment at a HDS plant prior to discharge into the Blesbokspruit.

(2) Underground sampling:

The majority of raw water underground samples are from Grootvlei No 3 Shaft. The remaining underground samples were collected on behalf of CGS from various locations in the East Geduld, Geduld and Government Areas Gold Mines.

Table 8.10: Water quality sampling data utilised in the Central Basin.

Mine	Location	Sampling Type	Source	n
East Geduld	Various	Underground	CGS	12
Geduld	Various	Underground	CGS	11
Government Areas	Various	Underground	CGS	12
Grootvlei	Various	Underground	CGS	4
Grootvlei	Underground, pre-treatment	Underground	Irene Lea, Grootvlei	127
Grootvlei	Flume, treated discharge	Surface sample	Irene Lea, Grootvlei	3497
Total				39

n = number of samples

8.7.2 Water chemistry

The water quality of the Eastern Basin is summarised in **Table 8.11** to **Table 8.15**. Compared to the water of the Central Basin, the water is more neutral with notably higher Mn concentrations. The buffering effect of the dolomite is evident.

Table 8.13 presents the summary compositional ranges of underground sampling data only (as described in section 8.7.1 can therefore be considered as a reasonable approximation for the water qualities anticipated during pumping from the mine void

Table 8.14 and **Table 8.15** present raw water and HDS treated discharge qualities, respectively, from Grootvlei No. 3 Shaft (I. Lea, pers. comm.) which is the planned abstraction point for the STI.

Table 8.11: Water quality (95th percentiles) of the Eastern Basin.

Mine	Units	East Geduld	Geduld	Govt Acres	Grootvlei	Grootvlei	Grootvlei
Sampling Point		GH Series	GH Series	GH1	Underground	AD/GH Series	
Temp	°C	20.1	18.2	17.3	25.0	19.5	-
pH*		7.3	6.9	2.6	5.9	6.7	7.2
EC	mS/m	299	617	395	363	227	367
TDS**	mg/l	2126	1462	4777	3968	1818	3402
Alkalinity	mg/l $CaCO_3$	223	885	195	364	181	-
Dissolved Oxygen	mg/l	-	-	-	3	-	-
Salinity	mg/l	2	3	2	-	1	-
Li	mg/l	0.045	0.011	0.256	-	0.134	-
B	mg/l	0.126	0.476	0.719	-	1.969	-
Na	mg/l	177.1	276.0	73.7	260.0	321.0	-
Mg	mg/l	94.4	79.5	45.1	184.8	69.3	-
Al	mg/l	0.190	0.186	61.630	0.417	2.650	-
K	mg/l	5.2	5.7	6.3	-	6.5	-
Ca	mg/l	-	93.5	75.3	440.0	154.6	-
Fe	mg/l	0.5	0.6	53.5	248.5	2.0	1.8
Mn	mg/l	0.568	0.178	7.422	6.000	0.341	-
Co	mg/l	0.301	0.027	1.906	-	0.562	-
Ni	mg/l	2.301	0.416	3.407	0.433	4.413	-
Cu	mg/l	0.016	0.017	0.962	-	0.034	-
Zn	mg/l	1.288	0.701	5.671	-	4.927	-
Ga	mg/l	0.000	0.013	0.032	-	0.069	-
As	mg/l	0.121	0.063	0.179	-	0.027	-
Se	mg/l	0.130	0.027	0.009	-	0.062	-
Rb	mg/l	0.038	0.012	0.013	-	0.018	-
Sr	mg/l	1.103	0.566	0.392	-	2.392	-
Ag	mg/l	0.000	0.000	0.001	-	0.004	-
Cd	mg/l	0.006	0.003	0.024	-	0.003	-
Ba	mg/l	0.108	0.118	0.583	-	1.712	-
Pb	mg/l	0.021	0.016	0.050	-	0.177	-
U	mg/l	0.184	0.006	0.858	-	0.348	-
F	mg/l	-	1.000	0.000	-	0.000	-
Cl	mg/l	377	306	73	204	155	-
NO_2	mg/l	7.400	0.000	0.000	-	0.000	-
Br	mg/l	0.000	0.000	0.000	-	0.000	-
NO_3	mg/l	99	15	20	-	21	-
PO_4	mg/l	61	18	14	-	14	-
SO_4	mg/l	1298	665	4332	2624	1056	2268
Total Hardness	mg/l	-	-	-	1759	-	-
Chemical Oxygen Demand	mg/l O_2	-	-	-	180	-	-
* 5th Percentile **Estimated							

Table 8.12: Compositional ranges (percentiles) in the Eastern Basin.

Parameter	Unit	n	Percentiles				
			95th	90th	50th	10th	5th
T	°C	140	29.0	28.0	26.3	19.8	18.6
pH#		3613	7.1	7.2	7.5	8.1	8.2
EC	mS/m	1046	367	360	323	251	205
TDS	mg/l	234	4248	3962	2781	990	513
Alkalinity	mg/l CaCO3	63	541	326	168	27	1
Salinity	mg/l	40	1.7	1.5	0.9	0.4	0.3
Total Hardness	mg/l	23	1759	1749	1655	1500	1481
Na	mg/l	141	264	252	208	66	58
Mg	mg/l	53	165	163	52	0	0
Al	mg/l	81	2.4	0.8	0.2	0.07	0.05
K	mg/l	40	7	6	4	3	3
Ca	mg/l	63	421	406	73	0	0
Fe	mg/l	3632	3	2	1	0	0
Mn	mg/l	141	6	5	3	0	0
F	mg/l	40	0	0	0	0	0
Cl	mg/l	141	253	205	157	73	66
NO_2	mg/l	40	0.1	0	0	0	0
Br	mg/l	40	0	0	0	0	0
NO_3	mg/l	40	88	21	8	0	0
PO_4	mg/l	40	22	14	7	0	0
SO_4	mg/l	227	2581	2356	1488	619	286
Li	µg/l	40	144	95	16	5	3
Be	µg/l	35	1	1	1	1	1
B	µg/l	40	1144	574	98	68	60
V	µg/l	34	1	1	1	1	1
Cr	µg/l	36	5	5	5	5	5
Co	µg/l	40	680	401	41	0	0
Ni	µg/l	63	2432	1280	301	0	0
Cu	µg/l	40	455	49	0	0	0
Zn	µg/l	40	4317	3090	572	521	519
Ga	µg/l	40	42	21	0	0	0
As	µg/l	40	109	50	0	0	0
Se	µg/l	40	94	52	8	0	0
Rb	µg/l	40	33	29	11	7	5
Sr	µg/l	40	1394	1096	321	129	103
Ag	µg/l	40	1.3	0.0	0.0	0.0	0.0
Cd	µg/l	40	17	8	3	2	0
Ba	µg/l	40	1145	224	105	96	93
Pb	µg/l	40	80	31	16	14	14
U	µg/l	40	453	351	8	1	0
COD	mg/l	67	180	166	32	12	11
DO	mg/l	100	3	3	2	2	1
# pH values in reverse percentile order, e.g. 95th percentile is 5th percentile							

n = number of samples

Table 8.13: Compositional ranges (percentiles) of underground mine water in the Eastern Basin.

Parameter	Unit	n	Percentile						
			5th	10th	50th	60th	75th	90th	95th
T	°C	138	18.9	20.0	26.5	27.0	28.0	28.0	29.0
pH		101	5.9	6.1	6.5	6.5	6.6	6.9	7.1
EC	mS/m	144	98	161	280	292	312	349	360
TDS	mg/l	138	484	781	2292	2468	2840	3196	3358
Alkalinity	mg/l $CaCO_3$	61	12	32	168	187	232	327	560
Total Hardness	mg/l	23	1481	1500	1655	1692	1700	1749	1759
Salinity	mg/l	38	0	0	1	1	1	2	2
Na	mg/l	139	58	70	208	223	238	252	264
Mg	mg/l	51	0	0	54	62	119	163	166
Al	mg/l	79	0	0	0	0	0	1	2
K	mg/l	38	3	3	4	5	5	6	6
Ca	mg/l	61	0	0	77	129	379	407	421
Fe	mg/l	139	0	0	74	88	126	209	227
Mn	mg/l	139	0	0	3	3	4	5	6
Cl	mg/l	139	66	75	157	170	184	205	254
NO2	mg/l	38	0	0	0	0	0	0	0
Br	mg/l	38	0	0	0	0	0	0	0
NO3	mg/l	38	0	0	8	11	15	20	31
PO4	mg/l	38	0	0	7	8	10	13	19
SO4	mg/l	139	240	364	1148	1273	1610	1917	2289
Li	µg/l	38	4	6	17	23	39	95	147
B	µg/l	38	64	71	98	106	125	523	1170
Ni	µg/l	61	0	0	302	350	515	1318	2553
Co	µg/l	38	0	0	45	61	96	446	748
Cu	µg/l	38	0	0	0	0	9	73	499
Zn	µg/l	38	520	525	586	647	1021	3131	4416
Ga	µg/l	38	0	0	0	0	0	23	43
As	µg/l	38	0	0	0	0	10	46	112
Se	µg/l	38	0	0	8	14	29	56	94
Rb	µg/l	38	5	7	11	14	20	29	33
Sr	µg/l	38	126	179	336	461	616	1100	1433
Ag	µg/l	38	0	0	0	0	0	0	1
Cd	µg/l	38	0	2	3	3	3	9	18
Ba	µg/l	38	93	95	104	106	108	320	1146
Pb	µg/l	38	14	15	16	17	18	41	83
U	µg/l	38	1	2	10	21	92	357	470
COD	mg/l	67	11	12	32	38	53	166	180
DO	mg/l	100	1.3	1.8	2.4	2.5	2.6	3.1	3.4
Data rounded									

All underground data used except Grootvlei pre-Feb 1999 (due to concerns over data validity)

Table 8.14: Raw mine water (pumped at Grootvlei Mine) (Grootvlei Mine, 2012).

Parameter	Unit	Min	Max	Ave	95th %
pH	0	6	6.8	6.4	6.7
Temperature	°C	25	28	26.7	28
DO	mg/l	2	3.5	2.5	3.2
EC	mS/m	294	347	321.8	342.8
TDS	mg/l	1928	3138	2879	3053
Cl	mg/l	170	198	183.8	193.8
F	mg/l	NA	NA	<0.2*	NA
SO4	mg/l	930	2065	1383	1747
Na	mg/l	187	458	240	256
Ca	mg/l	385	493	422	435
Mg	mg/l	170	251	197	202
Al	mg/l	0.1	0.9	0.3	0.7
Fe	mg/l	82	210	135	206
Mn	mg/l	2.4	5.4	4.1	5
Zn	mg/l	NA	NA	0.01*	NA
Ba	mg/l	NA	NA	<0.001*	NA
Ni	mg/l	NA	NA	<0.003*	NA
COD	mg/l	12	80	35.4	80
* Not measured NA = Not available					

Table 8.15: HDS Treated Water (as discharged into the Blesbokspruit, 2002) (Grootvlei Mine, 2012).

Parameter	Unit	Min	Max	Ave	95th %	Current Permit
pH		7	7.9	7.52	7.89	6.5-8.5
Temperature	°C	25	28	26.7	28	0
EC	mS/m	294	333	315	329	<400
TDS	mg/l	2472	2653	2518	2601	0
DO	mg/l	NA	NA	NA	NA	>9
COD	mg/l	NA	NA	NA	NA	<35
Cl	mg/l	179	184	181.2	184	<210
SO4	mg/l	1306	1688	1499	1688	<2200
Na	mg/l	230	244	239	243	<290
Ca	mg/l	310	360	341	352	0
Mg	mg/l	108	123	117	123	0
Fe	mg/l	0.35	1.88	0.92	1.81	<1
Mn	mg/l	0.8	1.1	1.1	1	<1
Al	mg/l	NA	NA	NA	NA	0.5
Ni	mg/l	0.02	0.035	0.025	0.031	0
T-Hard	mg/l	1098	1228	1165	1216	0
T- Alk	mg/l	120	146	137	146	0
SS	mg/l	4	31	21	30	<25
NA = Not available DO = Dissolved Oxygen COD = Chemical Oxygen Demand						

8.7.3 Change of water quality with time

Monitoring of the water quality during the pumping operation at Grootvlei Mine suggested an improvement of water quality with time. This notion is illustrated in **Figure 8.10** with the trends observed in pH and EC levels. It would appear as if pH has stabilised at about 7.5, whereas the decrease in EC seems to level out at about 250 mS/m. The relatively high EC (TDS~2750mg/ℓ), however, indicates that a large proportion of the water still derives from the gold workings, or that water is being recycled through the dolomite aquifer. However, the relatively large ingress of water from the perched dolomite aquifer (Section 6.3.2) implies that at least partial flushing of the initially-formed AMD in the mine void is possible, provided practices avoiding recirculation of the pumped neutralised but saline water are in place.

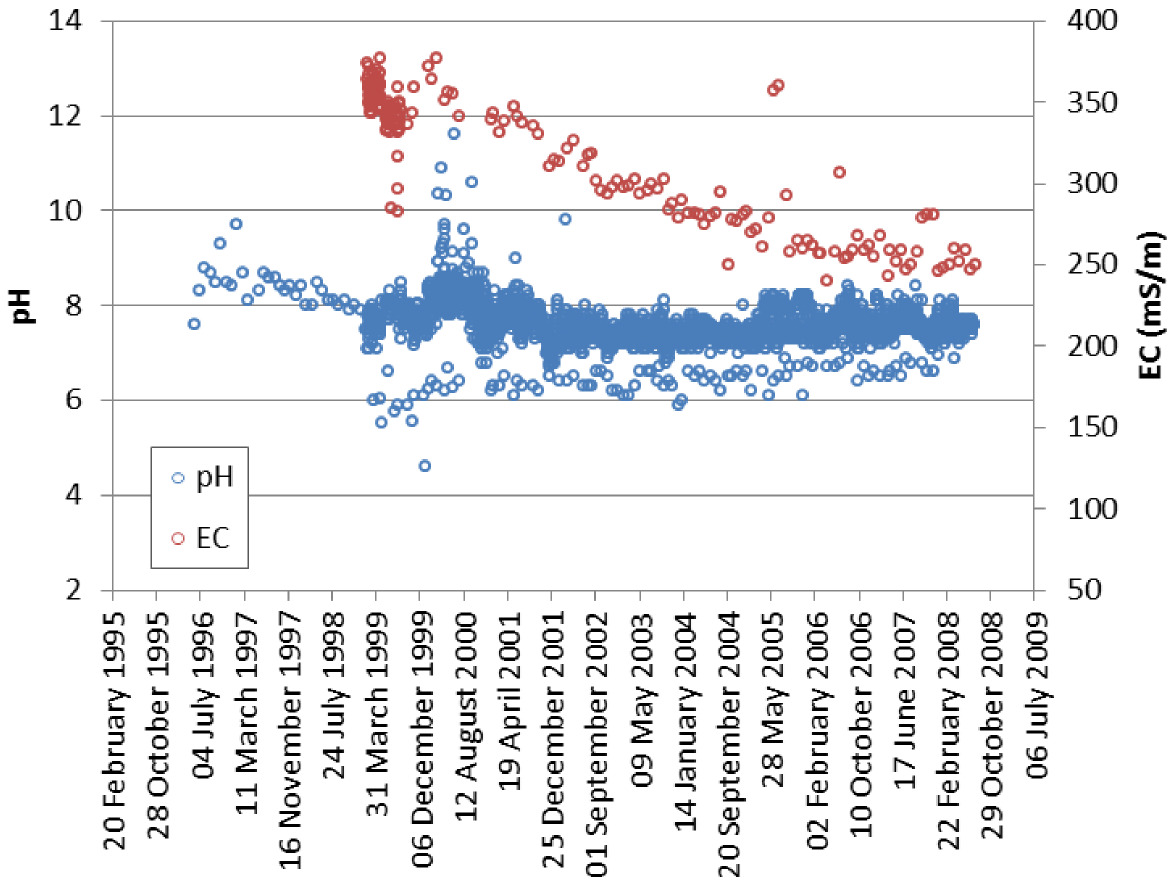


Figure 8.10: Water quality at Grootvlei Mine.

8.8 Summary and Recommendations

Water levels and ECL

In the Eastern Basin, the 1280 m amsl ECL, as proposed by the STI (TCTA Report, 2011a), is estimated in this study to be reached by middle 2014, which contrasts with the TCTA estimate of between December 2014 and May 2015. These differences may be due to extrapolation issues with limited data. This ECL is considered to be conservative and for the Short-Term solution it is therefore considered prudent to keep the water at this level below the base of the dolomite.

For the long term solution, consideration should be given to raising the ECL to 1470 m amsl under conditions of careful monitoring of water quality in surface boreholes at sites throughout the basin, especially along the Blesbokspruit. Although it does introduce a risk of mixing the dolomitic water with AMD, the shallower ECL would still be about 70 m lower than the water table in the dolomite compartment and it is probable that this would produce a net flow from the dolomite into the underlying Witwatersrand rocks and the mine void.

Ingress

The main source of ingress water is via the dolomite aquifers, especially along the zone where dolomite is exposed on surface. All indications are that water from the dolomite aquifer leaks into the mine void over a wide area, maintaining a flow of ca. 80 Mℓ/day. Because so little of the reef is exposed at outcrop, the amount of direct ingress via disturbed outcrop zones is very small.

A total ingress reduction of approximately 21 Mℓ/day is considered to be possible. This however needs to be studied in more detail to determine the effectiveness and financial implications. A summary of the prediction and source of information is given in **Table 8.16**, with and without potential ingress control applied.

Table 8.16: Summary of predicted ingress volumes, Eastern Basin.

Information source	Predicted ingress volume (Mℓ/d) No ingress control		Predicted ingress volume (Mℓ/d) With improved ingress control (21 Mℓ/day)	
	Average	Range	Average	Range
WUC Report (2009)	82	77-108	61	56 - 87
This study	80	70-100	59	49 -79
TCTA (planned pumping rate)	82	38-110	61	17 - 89

The following observations are made from **Table 8.16**:

- The estimated ingress volumes proposed in this study are in good agreement with the WUC estimations;
- The TCTA planned pumping rates compare well with the predicted range of ingress volumes and would cater both for an extremely wet season as well as expected climate change (as described in section 4.2).
- Ingress volume could be reduced by a maximum of about 30 Mℓ/day if all the planned ingress control measures are implemented and are 100% effective. A more realistic figure is estimated at approximately 21 Mℓ/day and includes the upgrade of municipal reticulation, sewerage system and stormwater controls as Priority 3 (**Table 8.8**).
- Control measures to the other ingress sources have not been considered at this stage as this is assumed that this would be difficult and impractical to implement.

Pumping rates

Pumping at a rate of ca. 80 Mℓ/day allowed Grootvlei Mine to steady the water level in the mine at about 800 m amsl. It seems logical that the minimum pumping rate from the Eastern Basin should be at least 80 Mℓ/day. Considering breakdowns and other off-times, a pump capacity of 100 Mℓ/day may be prudent.

The proven history of pumping at Grootvlei No. 3 Shaft supports its suitability as a pump site, despite concerns about its limited connectivity.

There are concerns that the haulage between Marievale and Sub Nigel may not be sufficient to dewater the greater Eastern Basin from Sub Nigel, the lowest point alone. Another option would be to use the contribution of abstraction point shafts at Grootvlei or Marievale Mine and Sub Nigel Shaft or boreholes into the mine void in each sub basin. The southern portion of Marievale is also located south of the dolomite and wetlands therefore release of water there will avoid any return flow into the mine void.

Water quality

Compared to the water of the Central Basin, the water is more neutral to slightly alkaline with notably higher Mn concentrations. The buffering effect of the dolomite is evident and a noted improvement of the water quality during pumping probably reflects the combined result of dilution and neutralisation by dolomite-equilibrated water. The water chemistry data from underground sampling is considered to provide the most reasonable approximation for likely water qualities to be abstracted from the mine void (**Table 8.13** and **Table 8.14**).

9 RISKS

Table 9.1 highlights identified risks and possible prevention and/or mitigation measures for mine water quantity and quality estimates, as well as the risks to dolomite in the region of potential AMD decant.

Table 9.1: Risk register for the hydrogeological aspects of the long term AMD scenarios.

Task / Component	Risk Description	Probability of Occurrence	Impact	Prevention Measures	Mitigation Measures
Mine Water Quantity	Unforeseen changes in the volume of the void as the water rises.	Possible	Significant	Ensure that pumping and treatment commence prior to water levels reaching ECL's	Measure water levels across the basins.
	The degree of connectivity across the mine void in the Central Basin remains uncertain and multiple surface decant sites might occur if connectivity is not sufficient.	Possible	Severe	Allow significant freeboard initially and reduce when hydraulic gradient is stable. Implement pumping strategy at multiple sites	Measure water levels across the basins to monitor for differential water levels. Identify suitable additional pumping sites and develop pumping strategy.
	Collapse of key water pathways in poorly connected shafts, or of the shaft itself, leads to cessation of pumping	Unknown	Severe	Implement pumping strategy at multiple sites. Select sites with a higher level of connectivity.	Identify suitable additional pumping sites and develop pumping strategy.
	Seismic events lead to reduction of interconnectivity or damage to pump sites.	Possible	Severe	Implement pumping strategy at multiple sites. Select sites with a higher level of connectivity.	Monitoring of seismicity. Identify suitable additional pumping sites and develop pumping strategy.

Task / Component	Risk Description	Probability of Occurrence	Impact	Prevention Measures	Mitigation Measures
	The timing of the water level reaching the ECL is difficult to predict, since rate of rise in the Eastern Basin is not properly quantified since data is insufficient.	Likely	Noticeable	Ensure that pumping and treatment commence prior to water levels reaching ECL's	Identify monitoring sites and measure water levels across the basin.
	Ingress exceeds the installed pumping capacity	Unlikely	Noticeable (EB, WB) Severe (CB)	Ensure that there is sufficient installed pumping capacity to cater for pump failures and abnormal ingress	
	Quantity of void water exceeds the treatment capacity of the plant, leading to contamination of surface water	Unlikely	Significant		Overflow facility
	Mines re-started/new mines planned with own pumping strategy, resulting in possible pump/treatment plant redundancies	Possible	Significant		Effective communication strategies between DWA and mining companies active in the Witwatersrand Basin
Mine Water Quality	Unacceptable pollution from AMD will continue to occur because of run-off from mine dumps, etc.	Likely	Significant	Remove mine dumps to safe storage sites.	DWA to enforce control management of surface sources of AMD
	Water contamination from industry	Very Likely	Noticeable		Ensure this does not affect treatment plant requirements

Task / Component	Risk Description	Probability of Occurrence	Impact	Prevention Measures	Mitigation Measures
	The rate of improvement in water quality is uncertain and quality could remain poor for a very long time	Likely	Noticeable		Underground experiment in a previously flooded mine, where mining recommences
	Pumping from a shaft with only deep connection to the mined area may prolong the pollution	Likely	Noticeable	Select sites with a higher level of connectivity at shallower levels.	Identify suitable additional/alternative pumping sites and develop pumping strategy.
	When pumping commences from newly flooded, shallow levels, water quality may be worse than anticipated	Likely	Noticeable		Design treatment for a range of water qualities that includes the poorest anticipated qualities
	Water qualities worse than predicted due to insufficient water quality data from within the mine void	Possible	Noticeable	Initiate water quality monitoring from multiple boreholes drilled directly into mine void	Design treatment for a range of water qualities that includes the poorest anticipated qualities
Dolomites	Sinkholes may develop due to water table fluctuations close to the dolomite aquifer, especially in the upper reaches of the Tweelopies Spruit in the Krugersdorp Game Reserve, including R24.	Possible	Severe		Identify and monitor existing sinkholes (ground geophysics).
	Excessive surface groundwater abstraction (i.e. for irrigation) causes interaction of mine void water with dolomites in the Eastern Basin	Unlikely	Noticeable	Maintain ECL at 1280 m amsl (TCTA) level until monitoring established.	Monitor agricultural abstraction points
	Sinkholes may develop due to AMD water flow through the dolomite geology	Possible	Noticeable		

10 CONCLUSIONS

Although there are some discrepancies and differences in certain areas, the status quo assessment as per the TCTA Report (2011a) is considered to be broadly acceptable in terms of proposed pumping rates and water quality (sections 10.2 and 0).

The uncertainties inherent in the data, and in particular in the detail of the void characteristics, do not allow for high accuracy predictions to be made. It is also impossible to describe any degree of confidence ot the predictions which are made. These uncertainties will best be solved by adopting an initially conservative approach and by a well-considered monitoring program established in advance of commencement of pumping as part of the short-term intervention. Feedback from the initial operations can be used to optimise the pumping and water treatment processes.

10.1 Critical Water Levels

It is considered that pumping should be considered from as shallow as possible to reduce the associated costs and to benefit from the expected improvement of water quality over time, without placing either the environment (specifically shallow water aquifers) or certain socio-economic features (e.g. Gold Reef City museum) at unacceptable risk. The proposed ECL and SECL (Table 10.1) are based on this premise.

The inherent uncertainties necessitate that these levels are kept under close review during pumping and on-going water quality and quantity monitoring should be implemented to determine whether any of the ECLs can be raised, or lowered if necessary. The SECL is dependent on future mining activities and could affect the TOL in the long term.

Table 10.1: Summary of the proposed critical water levels in this study (elevations in m amsl).

Basin	TCTA ECL	Proposed Initial ECL	Possible Long-Term ECL	Proposed SECL
Western	1550	1600	1550 if 1600 does not prevent pollution	-
Central	1467	1520		To suit mining or 1474
Eastern	1280	1280	Reuse to 1470 overtime if monitoring shows no ground water pollution	-

10.1.1 Western Basin

The ECL for the Western Basin is set at an elevation of 1600 m amsl to prevent the water from the mine void entering the dolomitic aquifer via the Black Reef mine workings at approximately 1610 m amsl. It is proposed that the water be kept at this level for an appropriate duration to establish whether the water quality downstream improves. If leakage of direct AMD ceases then the water could be held at this level; if not it could be lowered further, i.e. towards the 1550 m amsl ECL as recommended in the TCTA Report (2011a).

No SECL is currently anticipated, although as in all three basins under consideration there remains potential for new mining operations to become economically feasible, especially under an economic environment of increasing gold prices.

10.1.2 Central Basin

The ECL is determined to be at an elevation of 1520 m amsl. This is based on an estimated depth of 100 metres below surface at ERPM, and should adequately protect the surface aquifer.

The museum floor level (1484 m amsl) in Crown Mines 14 Shaft at Gold Reef City (GRC) was taken to be the critical factor in determining the SECL. The SECL is set at an elevation of 1474 m amsl to accommodate the lowering of the double decker conveyance and to ensure that the museum can still be visited as a heritage site. If the SECL is used, then the TOL must ensure that there is sufficient freeboard to allow for potential slow flow rates between GRC and the pump site.

10.1.3 Eastern Basin

The ECL of 1280 m amsl, as proposed in the TCTA Report (2011a), will ensure a positive downward flow from the elevated dolomite compartment into the void, and consequently prevent contamination of the aquifer above. It should be noted that the basal surface of the dolomite is not regular and deeper keels may be present that are not well defined. However, the risk of significant interaction with mine water is considered to be acceptable.

An alternative to this is the possibility of raising the ECL to 1470 m amsl (i.e. a depth of 100 m at Grootvlei) which would result in a substantial cost reduction. This would still be about 70 m lower than the water table in the dolomite compartment and it is probable that this would produce a net flow from the dolomite into the underlying Witwatersrand rocks and the mine void. However, this does introduce the possibility of mixing the dolomitic water with AMD and these risks are poorly understood and not quantifiable at this stage.

We therefore propose that the ECL of 1280 m amsl is retained, but that raising the ECL under conditions of careful monitoring of water quality in surface boreholes at sites throughout the basin, especially along the Blesbokspruit, should be considered.

The SECL is dependent on future mining plans and cannot be defined at present.

10.2 Water Quantity

The pumping rates as derived in this study are compared with those of the TCTA Report (2011a) in **Table 10.2**.

Table 10.2: Comparison of pumping rates.

Basin	Approx. Average Pumping Rates (TCTA) (Mℓ/day)		Proposed Pump Capacity and Rate (this study) (Mℓ/day)		
	Volume	Range	Capacity	Range	Average Rate
Western	27	23-35		23 - 27	23/25
Central	57	34-84	50	46 - 50	46
Eastern	82	38-110	100	80	80

Table 10.3: Expected ingress volumes (without and with ingress control measures).

Western Basin				
Information source	Predicted ingress volume (Mℓ/d) No ingress control		Predicted ingress volume (Mℓ/d), with improved ingress control	
	Average	Range	Average	Range
WUC Report (2009)	18	16 - 20	13	11 - 15
Shango Solutions (this study)	21	19 - 23	16	14 - 18
TCTA (planned pumping rate)	27	23 -35	22	18 - 30
Central Basin				
Information source	Predicted ingress volume (Mℓ/d) No ingress control		Predicted ingress volume (Mℓ/d) With improved ingress control	
	Average	Range	Average	Range
WUC Report (2009)	59	47 - 102	49	37 - 92
Shango Solutions (this study)	38	30 - 90	36	24 - 74
TCTA (planned pumping rate)	57	34-84	47	24 - 74
Eastern Basin				
Information source	Predicted ingress volume (Mℓ/d) No ingress control		Predicted ingress volume (Mℓ/d) With improved ingress control	
	Average	Range	Average	Range
WUC Report (2009)	82	77-108	61	56 - 87
Shango Solutions (this study)	85	70-100	59	49 - 79
TCTA (planned pumping rate)	82	38-110	61	17 - 89

10.3 Water Quality

Since the main sources of AMD are exposed pyrite-bearing reef in the mine void and surface tailings dumps, it is conceivable that the water quality of the mine void should for various reasons improve with time (Section 4; **Figure 5.1**):

- The AMD that formed during the initial filling of the void should become increasingly more diluted due to flushing by (mixing with) uncontaminated water ingress sourced from the surface and from deep fractures.
- The quality of surface water runoff down the void walls above the required ECL should gradually be less contaminated (depletion of pyrite and reduction in new AMD formation), provided runoff from tailings dams is contained (avoiding mixing).
- Progressive oxygen deficiency in the deeper levels should retard the oxidation of acid-producing minerals (reduction in new AMD formation).
- Sulphate-reducing and other bacteria may become active at deeper levels as long as nutrients are available (natural bio-mediated sulphate processing).
- Dolomite-equilibrated water will tend to reduce acidity of the AMD with time (mixing).

Due to the expected non-linearity of these quality-improving trends, the timing and extent of such improvements in water quality are near- impossible to quantify with reasonable confidence. Rough projections suggest that under ideal conditions several decades maybe necessary. A more aggressive approach to pollution control is required.

In **Table 10.4**, the current estimates on the chemistry of the AMD in the three basins are compared with that listed in the TCTA Report (2011a). As a general observation, it appears that the data sources consulted in this study report lower salt concentrations than that recorded in the TCTA Report (2011a). However, some variability in the water quality during the initial stages of pumping should be expected. This situation will stabilise when the systems approach dynamic equilibrium.

Table 10.4: Summary comparison of chemical data.

Water Quality Parameter	Units	TCTA Report			This Report		
		Basin			Basin		
		Western (95th percentile)	Central (95th percentile)	Eastern (flooded condition)	Western (95th percentile)	Central (95th percentile)	Eastern (95th percentile)
pH*	-	3.4-4.0#	2.3	5#	3	3.2	7.1
TDS	mg/ℓ	7174	7700	5500	5400^	3900^	4300^
Conductivity	mS/m	548	730	450	426	354	367
Calcium (Ca)	mg/ℓ	461	580	550	823	483	421
Magnesium (Mg)	mg/ℓ	345	380	230	-	161	165
Sodium (Na)	mg/ℓ	139	150	325	243	185	264
Sulphate (SO_4)	mg/ℓ	4556	5200	3275	3410	2464	2581
Chloride (Cl)	mg/ℓ	65	260	260	-	69	253
Acidity/Alkalinity	mg/ℓ	2560**	2425**	750**	1255+	125##	541##
Iron (Fe)	mg/ℓ	933	1,000	370	799	177	206
Aluminium (Al)	mg/ℓ	54	50	1	-	44	2
Manganese (Mn)	mg/ℓ	312	60	10	114	20	6
Uranium (U)	mg/ℓ	0.2	-	-	0.1	0.2	0.5
*5th percentile #Assumed 5th percentiles **Acidity - Calculated $CaCO_3$ +Acidity mg/l ##Alkalinity mg/l $CaCO_3$ ^Numbers rounded up All units as quoted in source documents							

As a reasonable approximation of the likely water qualities during abstraction, **Table 10.5** presents the 95th percentile water chemistry from underground samples only (or direct decant sites in the case of the Western Basin).

Table 10.5: Summary 95th percentile underground/decant mine water chemistry.

Parameter	Unit	Basin (95th Percentile)		
		Western	Central	Eastern
pH#	@ 25˚C	3.5	2.4	5.9
TDS^	mg/l	5434	5118	3358
Conductivity	mS/m @ 25˚C	442	465	363
Ca	mg/l	703	563	421
Mg	mg/l	-	258	165
Na	mg/l	227	171	264
SO4	mg/l	3623	3062	2624
Cl	mg/l	-	146	254
Acidity/Alkalinity	mg/l	1520	-	550
Fe	mg/l	954	108	227
Al	mg/l	-	193	2.4
Mn	mg/l	89	50	5.9
^Estimated # 5th percentile				

Principal component analysis of the water quality under discussion (detail not shown here) suggests a rather simple structure in chemical compositional space. The bulk proportion of the variance can be explained by three components, which have pH, the salt load (TDS as represented by Electrical Conductivity, EC) and Al as main variables. The Al-content is inversely proportional to the pH. These relationships are illustrated in **Figure 10.1**.

Following the general terms explained in Section 4, the following observations are relevant:

(1) Data cluster at K is regarded as the best average estimate of original Witwatersrand AMD. These samples have pH values of between 2 and 4, and TDS values of ca. 3850±1000 mg/ℓ.

(2) Most of the Western Basin AMD samples plot in a narrow band at an EC of ca. 350 mS/m, which represents about 3850mg/ℓ of total dissolved solids (TDS), and recorded pH values of between 2 and 7, depending on the degree of neutralisation (red arrow), probably by interaction with dolomitic water.

(3) The Central Basin data is scattered over a wide field, reflecting the diversity of samples within database, from extremely contaminated surface sample (EC ~ 1050 mS/m) to water within the potable range. A large number of samples plot at EC ~100 to 200 mS/m and pH between 2 and 6. The latter samples originate largely from the DRD Circular and CM 3 Vent shafts, and represent the dilution effect of surface ingress (blue arrow) on the AMD in the mine void.

(4) The Eastern Basin samples cluster at an EC of about 300 mS/m (TDS ~ 3300) and pH between 5 and 8. These samples follow a trend (black arrow) which summarises the recorded improvement of the water quality during pumping.This improvement is probably the combined result of dilution and neutralisation by dolomite-equilibrated water.

(5) The water described by Holland and Witthueser (2009) are plotted for reference. Of interest is the water cluster that they referred to as influenced by anthropogenic sources (H&W Con in **Figure 10.1**) which overlap with water from the DRD 6 shaft. The latter also show high alkalinity and nitrate values and some form of human waste interaction is suspected.

(6) The salt load in the AMD shows relatively little variation in composition. The weight ratios of SO_4:Ca:Mg:Na:Fe:Al = 65:15:5:5:1:0.5 (ranges: 60-75:10-25:4-7:4-10:0.1-6:0-3), on average, determined on Central Basin data, seem to hold well for the other basins as well.

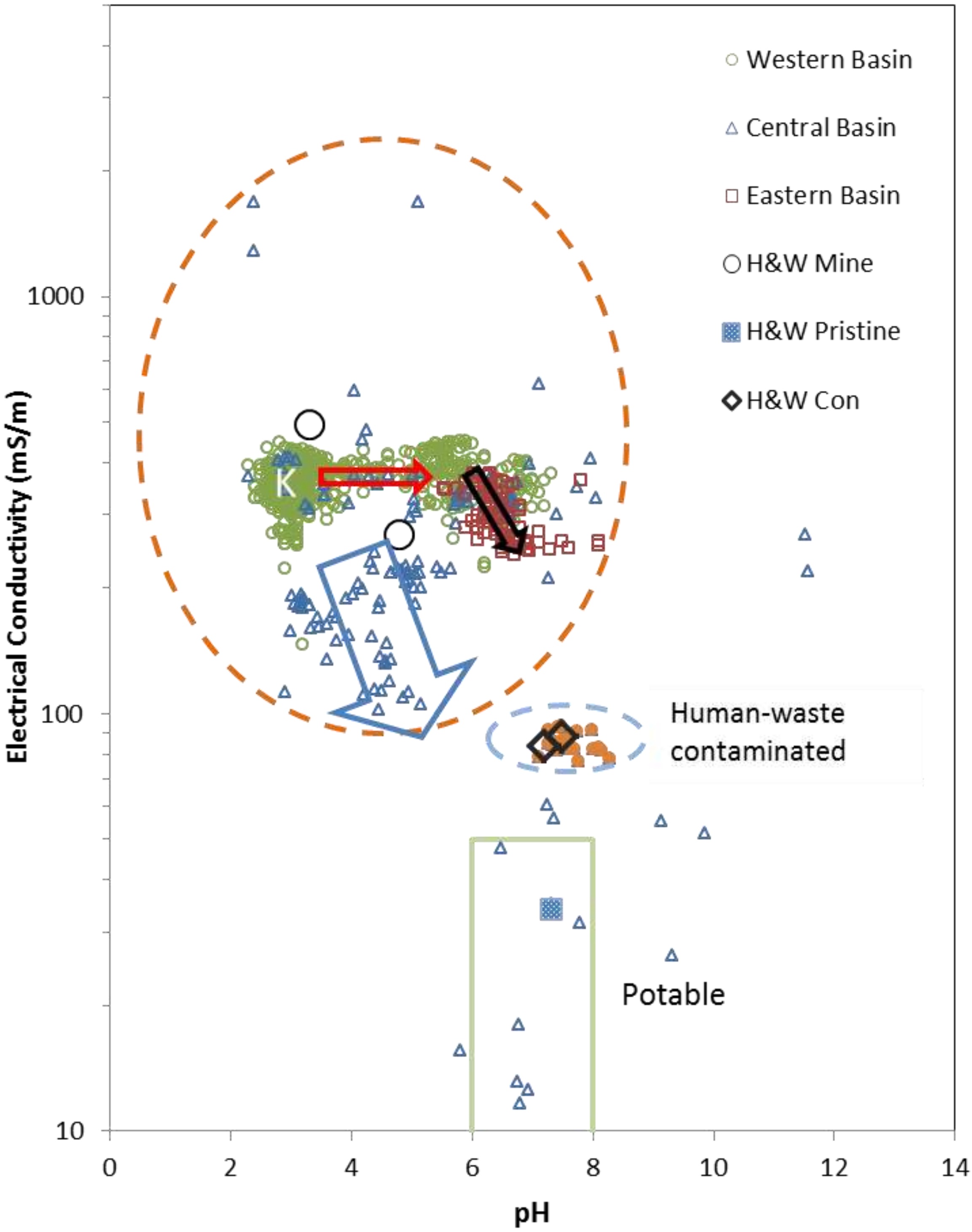


Figure 10.1: Simplified chemical relationships (H&W = Holland and Witthueser, 2009).

10.3.1 Data Considerations

In the interpretation of the chemical data presented in this report, it has to be considered that the data comes from a variety of sources and, as such, could be expected to be variable in purpose and quality. The following should hold true:

Variance $V^{total} = V^{analytical} + V^{inherent} + V^{sampling}$.

$V^{analytical}$ derives from the between- and in-laboratory differences in accuracy and precision. These differences are expected to be small relative to the other sources of variance.

$V^{inherent}$ includes a host of factors that affect the ultimate quality of the AMD, including, initial water-pyrite-oxygen ratio, degree of solids precipitation (e.g. ferric iron and other salts) effected by exposure to the atmosphere, degree of neutralisation/contamination due to wall rock reaction, activity of sulphate-reducing microbes, degree of dilution with fresh water ingress from surface or from groundwater sources, extent of isolation in shaft linings, human intervention, etc. By way of example, some highly contaminated AMD water has been recorded from surface ponds in the ERPM area, Central Basin (EC > 1000, **Figure 10.1**). These are most likely, in part, due to a proximity to mine dumps, and, in part, a response to evaporation. We also know that in both the Western and Eastern Basins, the observed AMD quality improved notably with time (Sections 6.7.3 and 8.7.3). In both instances, wall rock reaction and, possibly, some dilution with fresh water may have contributed to the overall effect. Also, the water sampled in the shafts in the Central Basin clearly shows dilution due to surface ingress (**Table 7.10**, comparison between shaft and underground water (**Figure** 10.1). Some degree of reaction with shaft linings is suspected in the water samples from the Central Basin.

In view of the possible inherent variations in AMD quality, $V^{sampling}$ expectedly represents a major source of variance, dominant among which probably are locality of sampling and sampling date relative to closure of mine. It should be obvious that AMD ponded on surface and exposed to evaporation will tend to increase the salt load to a point of saturation and precipitation of solids (e.g. gypsum), whereas water in the mine void, continuously mixing with either surface of underground water ingress, will tend to be diluted.

The planned pumping exercise may be considered as essentially a continuous sampling procedure and as such, depending on location and rate of abstraction relative to connectivity of the mine void in the direct vicinity of the pump station, may draw from a diverse range of AMD qualities. However, with time, as the water flow to the pumps reaches a dynamic equilibrium, the AMD reporting to the pump stations should converge to a more constant quality. However, the nature of this quality will depend on local conditions and can only be predicted in very broad terms.

It should be also be noted that the uranium values reported here reflect those that were included in overall water chemistry analyses and should be considered as indicative values only. Radiogenic water data will be assessed and described separately in the water treatment component of the Feasibility Study.

11 RECOMMENDATIONS

The STI as presented in the TCTA Report (2011a) is generally considered to be appropriate for addressing the immediate risks. Most of the recommendations addressed below are therefore pertinent only to the LTS. Only in the case of the Eastern Basin is there potentially sufficient time until the ECL is reached for the STI to consider these longer term recommendations.

11.1 Options analysis for this study

The following recommendations are for further investigation in the options analysis component of this Feasibility Study. It is understood that some of these recommendations may result in options being identified that are outside of the scope of the current study to define at the necessary confidence levels.

11.1.1 Abstraction sites

It is highly recommended that, for the Central and Eastern Basins alternative shafts be identified that may be suitable to use as pumping or monitoring sites and should therefore be secured for potential future use. Due to the constantly changing condition and status of shafts, in particular filling and capping, a comprehensive field investigation of potential sites would need to be undertaken as part of such a study.

In the Eastern Basin, consideration should be given to pumping from shafts in the south-eastern portion of the basin (Marievale) and Sub Nigel to reduce the pumping head.

11.1.1.1 Multiple pump sites

The current plan is to pump water from the Central Basin via a single shaft at ERPM. This has certain disadvantages, perhaps the most important of which are the deep level at which the shaft connects to the mine void and the fact that the pumps are situated at one end of the 50 km strike length of the void. This will mean that the pumps will perpetually draw water from deep in the void and moreover, ingress water entering in the west will have to flow the entire length of the void before being pumped to surface. These factors will inhibit shallow circulation in the void and the expected improvement in water quality that this could bring about.

As an alternative to pumping void water from a single, deep shaft, it has been suggested that a number of smaller pumps could be installed. This will reduce the risk from failure of a pump shaft due to collapse of the shaft itself or underground haulages. In addition, pumping from shallower levels is likely to result in a more rapid improvement in the pumped water quality. Ideally, shafts that are better connected to the mine void at multiple and preferably shallow levels are recommended. In the Central Basin, there are numerous incline shafts across the

length of the basin that could be investigated for their suitability as pump locations. However, many of these have been filled.

Access and infrastructural constraints may necessitate the consideration of large-diameter boreholes drilled into the mine void for pump installation. It should also be noted that serious obstructions have been encountered in some shafts during water monitoring, resulting in lost time and equipment; this could be considered as an additional argument in favour of dedicated boreholes for pump installation. The critical considerations for identifying potential borehole pump sites are:

- Determining optimum spacing for pump stations across the basin based on pump and treatment capacities;
- Sourcing and analysing accurate mine plans to identify suitable stopes and haulages with good interconnectivity at a shallow level;
- Identifying suitable sites for surface infrastructure.

The most suitable locations would be those that intersect places on incline shafts where large voids were made to accommodate pumping and other underground infrastructure. Most of the incline shafts are sealed near surface, but at likely pumping depths, these shafts will almost certainly still be open. The boreholes could be either inclined or vertical, making for easier siting in very developed areas.

The boreholes should intersect the void at a depth just below the bottom of the depth range envisaged in the Target Operating Level (TOL). The main disadvantage of this scheme is that the water level in the void will be variable only over a very small range, unless the holes penetrate the void at substantial depth (below the TOL), which will the offset the advantages of tapping the void at a shallow level. The boreholes should be designed to accommodate a nominal 200mm or 250mm (8 or 10 inch) pump with a total dynamic head of 300m and capable of pumping at 100 m 3/hr and should therefore be completed at a nominal diameter of 250mm or 300mm (10 or 12 inches).

In any of the multiple site scenarios described above, pipelines may have to be installed to convey water to central treatment plants in a similar manner to that employed by the companies that re-treat slimes dumps. The feasibility of installing small modular treatment plants should also be considered.

Pump capacity

As discussed in several sections of this report, the water levels in the Central and Eastern Basin should be initially maintained at the lowest safe ECL possible and then raised slowly, with careful monitoring (EC and water levels) throughout to optimise the ECL and TOL. Dewatering of the saturated dolomite aquifer in the Western Basin may require long lag times and/or additional pump capacity to reach the TOL. These factors will need to be considered during pump selection.

11.1.1.2 Alternative options to pumping

Controlled decant by means of a tunnel is a potentially viable option for the Central and Western Basins. This could be achieved by connecting the mine void to a point on surface at an elevation equal to or below the ECL/SECL.

The primary advantage of a controlled decant option is to remove or limit the need for pumping from surface. This would have a significant impact on the long term running and maintenance costs and be essentially self-sustaining.

The following aspects should be considered in the options analysis of the tunnel concept:

- The TOL for each tunnel option would need to be determined;
- Accurate Digital Elevation Models (DEM) would need to be sourced and investigated to establish the best surface outlet point for the tunnel;
- 1 in 50 and 1 in 100 year flood lines would need to be considered since the lowest elevations on surface will relate to drainage lines
- Sourcing and analysing accurate mine plans in order to establish the shortest distance between the decant point and the mine void
- Borehole drilling along the planned tunnel site to determine the geotechnical characteristics of the rock
- Evaluation of the potential surface decant sites for the placement of the water treatment plant.

11.1.2 Sludge disposal

As discussed in Section 5.1.1, it is not considered prudent to dispose of the HDS into the mine void, since under the acid environment, the metal oxides will dissolve into the void water over time. This will result in continual recycling of the more serious pollutants and the anticipated improvement in the quality of water being pumped from underground could be seriously delayed.

In addition to the chemical factors, there are also physical and economic arguments against the disposal of sludge into the mine void, including the sterilisation of areas that may become economically viable for renewed mining activities in the future.

Ideally, the sludge should be converted into a saleable form. If the iron could be separated from the gypsum, it could possibly be used as a pigment in paint or sold to scrap metal recyclers. Every effort should be made to achieve this goal. Co-disposal with tailings is considered to be a sensible option in the interim.

11.1.3 Central Basin SECL

A major point of concern regarding the SECL (and to a lesser extent, ECL) in the Central Basin is the fact that, under the current pump strategy, abstraction will take place only from the far eastern end of the void. Recharge, on the other hand, occurs across the full 55 km length of the basin. Should flow through the void be in any way impeded, the water level in the western and even the central portion of the Basin could rise above the set static water level. This could have dire consequences for the underground museum at Gold Reef City because there is so little freeboard between it and the pumping point on ERPM. Although the TOL will be finalised in the Pre-Feasibility Report, it is suggested that the pumps be installed at least 50 m below the SECL and that the water level in the void at various points across the basin be carefully monitored once pumping starts in order to obtain data on the lateral flow rate. If the flow rate is slow, the TOL may have to be adjusted to keep the water level in the void below the historic mine level.

If the water were allowed to decant at ERPM, the water in the void would rise to at least 1620 m amsl, leaving only 1 Level (approximately 1671 m amsl) safely above the water level and 2 Level (approximately 1624 m amsl) at significant risk. If the TOL was set based on the proposed 1520 m amsl ECL (which would be likely be a similar elevation should the tunnel option be applied), then the 5 Level museum facility would also be flooded (Figure 7.10). In this scenario, the static water level would be located just below 4 Level (approximately 1526 m amsl) and either redevelopment of the museum facility at a shallower mine level (e.g. 2 Level), or isolation of 5 Level from the flooded void via underground plugs would be necessary.

11.2 General Recommendations

11.2.1 Water Monitoring

We strongly endorse the water monitoring programme that is being developed by the Hydrological Monitoring Committee of the DWA. It is recommended that the monitoring strategy (levels and qualities) should include both the mine void and the surrounding natural groundwater. On-going monitoring of water levels across all basins is essential both in the period preceding the installation of the pumps by TCTA and especially thereafter.

Water quality data for the Central Basin is limited when considering mine void/stope data. Drilling boreholes into the mine void or using existing boreholes (drilled by Central Rand Gold) and sampling for water quality analysis is highly recommended to better understand the potential water quality expected for treatment.

Identifying more monitoring stations for the Eastern Basin is critical to determine the level of interconnectivity between the mines. Moreover, it is essential that regular monitoring of the raw water be carried out in all basins in order to detect changes in water quality with time.

11.2.2 ECL Evaluation and Review

In the Western Basin, it is strongly recommended that the water level is held at the 1600 m amsl (or respective TOL) during pumping to allow for sufficient lag time while the saturated shallow dolomite aquifer drains. This will permit the appropriate evaluation of the proposed ECL through water quality monitoring within the dolomite outlier and in the Lodge Spring area of the Cradle of Humankind. It is critical, however, that appropriate water quality monitoring stations are in place, otherwise the water should be held at the original TCTA recommended ECL of 1550 m amsl until such time as the monitoring stations are installed and operating.

A program of drilling across the Central Basin is recommended to define the depths of the shallow aquifer. This will enable a more accurate elevation for the ECL in the Central Basin.

Collar elevations for key shafts have been an issue, with some shafts reporting elevations with differences exceeding 10 m depending on the source. It is understood that the DMR is in process of completing such an exercise; this is strongly supported and should be completed across the basins.

11.2.3 Ingress control improvements

As identified in this study the ingress of surface water via various sources has a fairly significant effect on the expected pumping rates for each of the basins. At this point in time no detailed assessment as to the practicality and cost implication can be made for the control of ingress as this currently falls outside the scope of works. It is therefore recommended that follow-up studies be undertaken to define in more detail the ingress points and sources as well as the extent and practicality to reduce the ingress with an estimate of associated costs.

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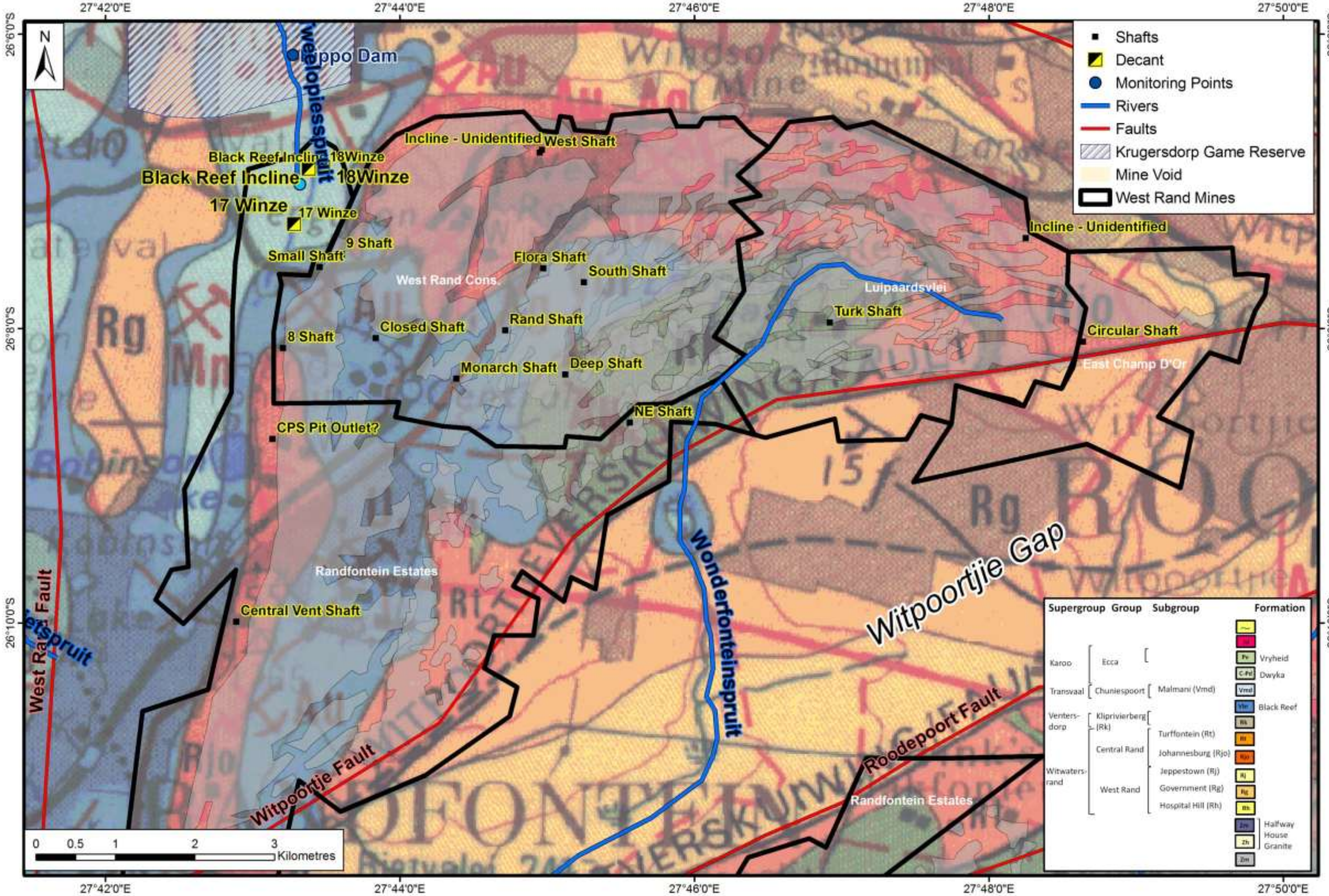
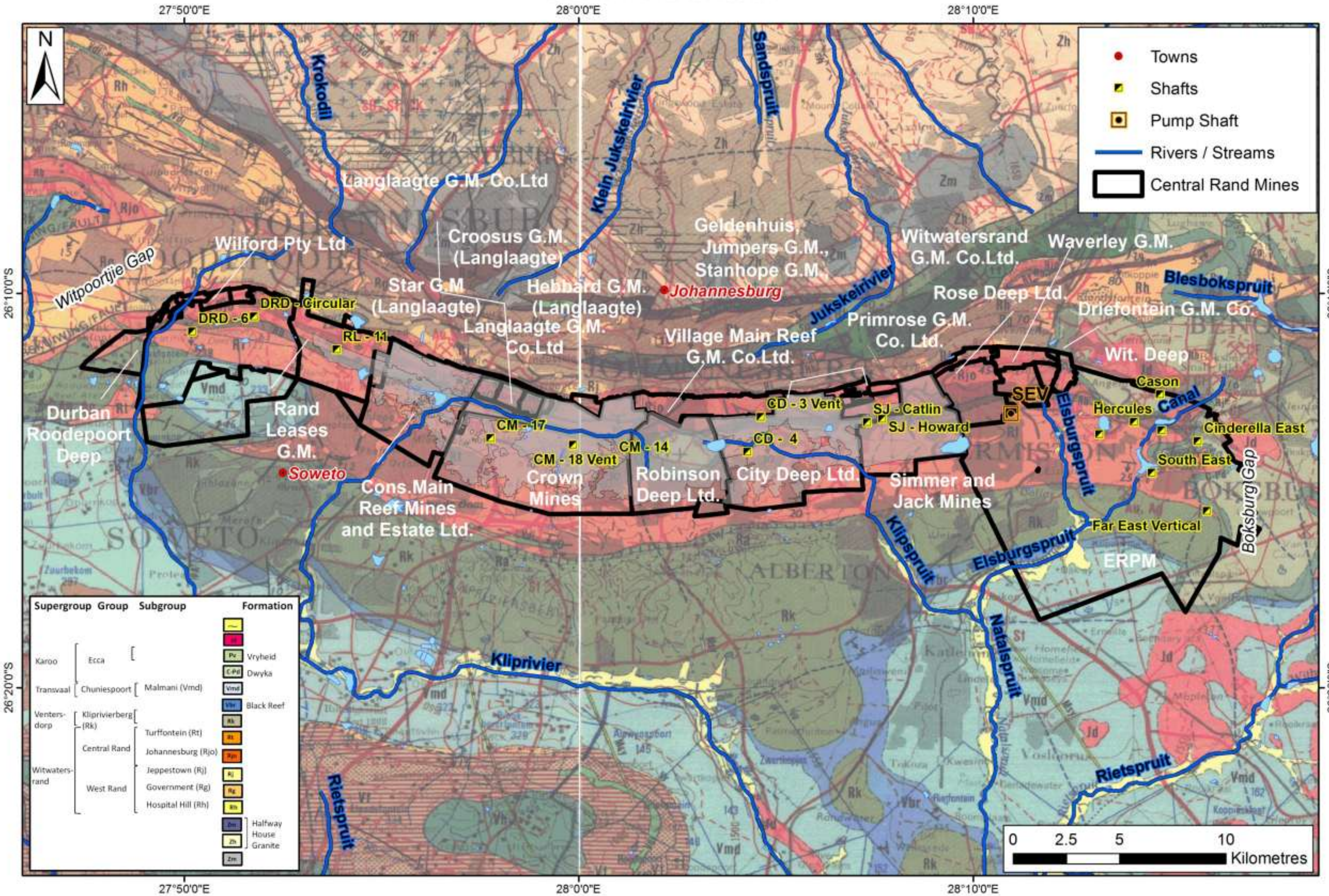
Appendix

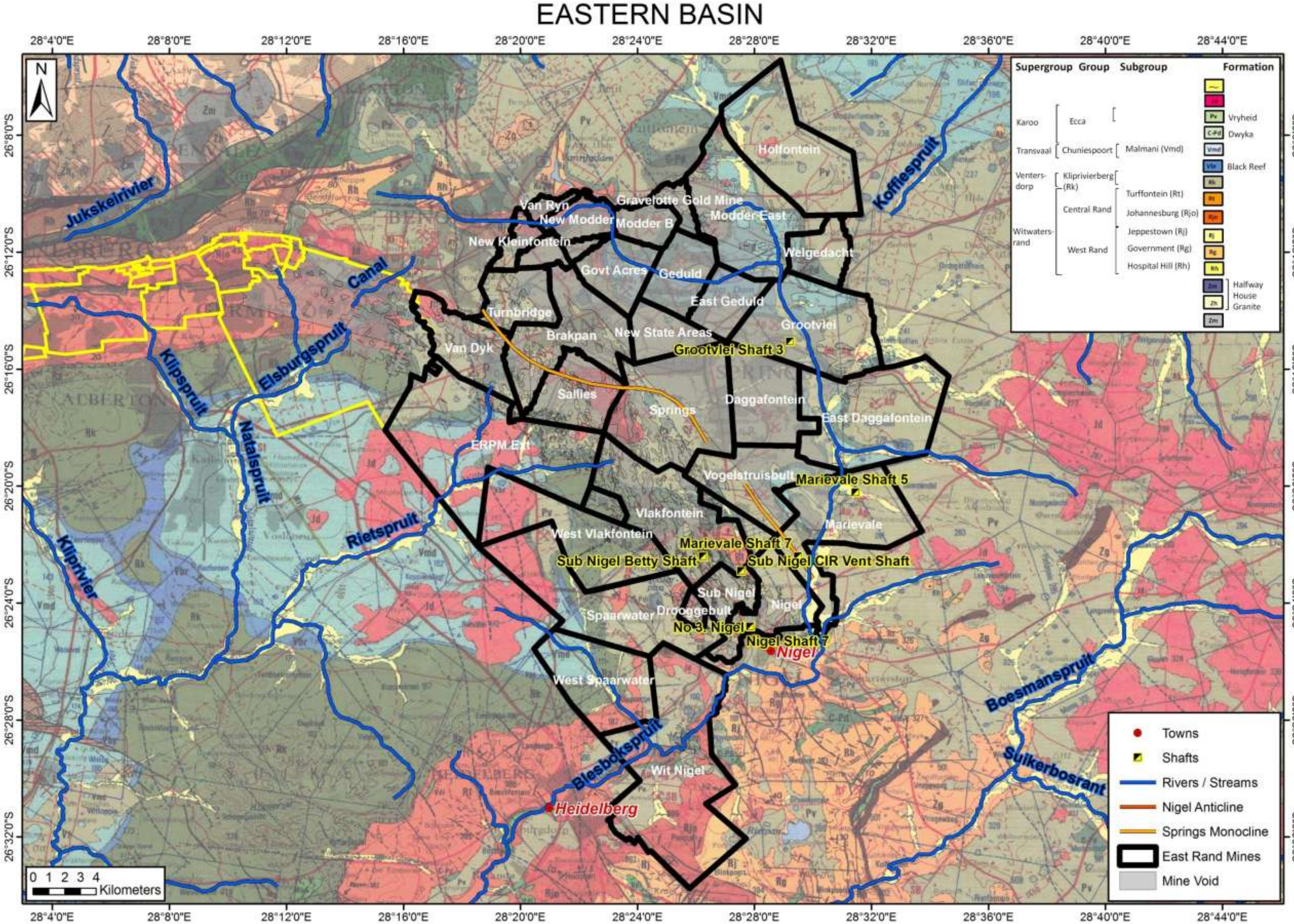
A1 Summary Plans

WESTERN BASIN



CENTRAL BASIN




EASTERN BASIN
Supergroup Group Subgroup Formation
Karoo
Ecca
Vryheid
Dwyka
Transvaal
Chuniespoort
Malmani (Vmd)
Black Reef
Ventersdorp
Klipriviersberg (Rk)
Witwatersrand
Central Rand
Turffontein (Rt)
Johannesburg (Rjo)
West Rand
Jeppestown (Rj)
Government (Rg)
Hospital Hill (Rh)
Halfway House Granite
Towns
Shafts
Rivers / Streams
Nigel Anticline
Springs Monocline
East Rand Mines
Mine Void
0 1 2 3 4 Kilometers
Jukskeirivier
Canal
Klipspruit
Elsburgspruit
Natalspruit
Rietspruit
Kliprivier
Blesbokspruit
Koffiespruit
Boesmanspruit
Suikerbosrant
Holfontein
Van Ryn
Gravelotte Gold Mine
New Modder
Modder B
Modder East
Welgedacht
New Kleinfontein
Govt Acres
Geduld
East Geduld
Turnbridge
Brakpan
New State Areas
Grootvlei
Grootvlei Shaft 3
Van Dyk
Sallies
Springs
Daggafontein
East Daggafontein
ERPM Ext
Vogelstruisbult
Marievale Shaft 5
Vlakfontein
Marievale
West Vlakfontein
Marievale Shaft 7
Sub Nigel Betty Shaft
Sub Nigel CIR Vent Shaft
Sub Nigel
Spaarwater
Droogebult
Nigel
No 3. Nigel
Nigel Shaft 7
West Spaarwater
Wit Nigel
Heidelberg

Appendix

A2 Suggested Ingress Reduction Measures for Each Basin

Suggested Ingress Reduction Measures for Each Basin

East Rand Basin

No.	Ingress area	Proposed Actions	Advantages	Drawbacks	Costs for preferred option	Reference
1	West Pit	Build canal AND unblock culvert		Change current ecology of stream		Regional mine closure strategies for the East Rand Basin, Table 1, p. 35. IMC Report Section 12.5.
2	Cowles	Mine sediments and divert flow around the dam		Change dam ecology; Destroy dam ecology (Sappi bird hide developed at Cowles dam)	R40 953 345	Regional mine closure strategies for the East Rand Basin, Table 1, p. 35. IMC Report Section 12.5.
3	South Blesbok	Unblock or enlarge culverts AND divert flow over certain portions – significant volume to be saved		Change ecology	R343 750	Regional mine closure strategies for the East Rand Basin, Table 1, p. 35. IMC Report Section 12.5.
4	Leeupan	Reduce the grey water entering the pan by collecting the water and discharging the water to the sewage reticulation network. Line pan, Ekurhuleni is in an advanced stage of developing the pan as nature reserve, flow diversion will nullify purpose of nature reserve		Water continues to ingress at a high rate; Change ecology	R50 344 989	Regional mine closure strategies for the East Rand Basin, Table 1, p. 35. IMC Report Section 12.5.
5	Central Blesbok	Unblock and enlarge culverts AND Divert flow over certain portions – significant volume to be saved		Change ecology	R5 833 985	Regional mine closure strategies for the East Rand Basin, Table 1, p. 35. IMC Report Section 12.5.
6	North Blesbok (northern area)	Unblock and enlarge culverts AND divert flow over certain portions – significant volume to be saved			R6 027 344	Regional mine closure strategies for the East Rand Basin, Table 1, p. 35. IMC Report Section 12.5.
7	North Blesbok (southern area)	Unblock and enlarge culverts				Regional mine closure strategies for the East Rand Basin, Table 1, p. 35. IMC Report Section 12.5.
8	Van Rhyn (ponding)	Repair channel which will remove the dam - Should reduce ponding significantly, getting rid of the unnatural dam			R34 205 241	Regional mine closure strategies for the East Rand Basin, Table 1, p. 35. IMC Report Section 12.5.
9	Van Rhyn (direct runoff)	Close cracks and stabilize openings			R6 908 400	Regional mine closure strategies for the East Rand Basin, Table 1, p. 35. IMC Report Section 12.5.
10	Largo	Close openings – foam		Foam might shrink?	R49 598 350	Regional mine closure strategies for the East Rand Basin, Table 1, p. 35. IMC Report Section 12.5.
11	Gravelotte (opencast mine, open shaft)	Shaft closing costs low enough, costs to close opencast mine too high to be feasible. Construct upstream bunds			R1 832 700	Regional mine closure strategies for the East Rand Basin, Table 1, p. 35. IMC Report Section 12.5.
12	New Kleinfontein	Repair channel			R10 297 172	IMC Report Section 12.5.

Central Rand Basin

No.	Ingress area	Proposed Actions	Advantages	Drawbacks	Costs for preferred option	Reference
1	Johannesburg and Ekurhuleni	Embark on a programme together with the relevant Metro Councils to alleviate risk.				IMC Report Appendix A.
2	Elsburg Spruit	Discharge point should be downstream of potential ingress area, or discharge should be via an impervious canal.				IMC Report Appendix A.

3	No specific location given	Proper waste management will reduce the risks				
4	Boksburg Canal	Assess ingress and feasibility of canal construction Canal construction				IMC Report, Section 12.5
5	Surface stream – City Deep to Consolidated Mine	Assess ingress and feasibility of canal construction Canal construction				IMC Report, Section 12.5
West Rand Basin						
No.	**Ingress area**	**Proposed Actions**	**Advantages**	**Drawbacks**	**Costs for preferred option**	**Reference**
1	No specific location given	Minimisation of ingress via open pits by backfilling with tailings (from reprocessing plants) and capping and shaping to prevent future ingress.				Regional Closure Strategy for West Rand Goldfields, p 90
2	No specific location given	Prevention of the flow of run-off from Dump 20 into the Millsite Pit. Investigation of and, if necessary, addressing of possible ingress along the Witpoortjie Fault after lowering of the void water level to the ECL.				Regional Closure Strategy for West Rand Goldfields, p 90
3	No specific location given	Identified diversion of stormwater into abandoned surface workings in Krugersdorp. Prevention of the flow of stormwater into open pits. Audit of possible ingress via urban stormwater system. Upgrading of stormwater management to prevent ponding, encourage run-off and ensure that stormwater is discharged to streams away from areas where ingress to the mine void is possible.				Regional Closure Strategy for West Rand Goldfields, p 90
4	No specific location given	Audit of possible reticulation and sewer losses.				Regional Closure Strategy for West Rand Goldfields, p 90
5	No specific location given	Investigation of potential ingress from existing residue deposits. Removal of residues and capping/shaping remaining deposits.				Regional Closure Strategy for West Rand Goldfields, p 90