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Evaluation of Management Options for Intermine Flow and associated Impacts in the Central Witbank Coalfield

by

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1 INTRODUCTION

1.1 ORIGIN AND SCOPE OF THE STUDY

The influence of coal mining on the water resources in the Witbank has been the focus of several previous studies (Grobelaar, 2001, Hodgson and Krantz, 1998). From these studies several areas of further study have been identified. This study forms part of a broader project initiated by Coaltech 2020 to quantify the long-term water quality and quantity of the Mpumalanga coalfields. The study area is shown below:

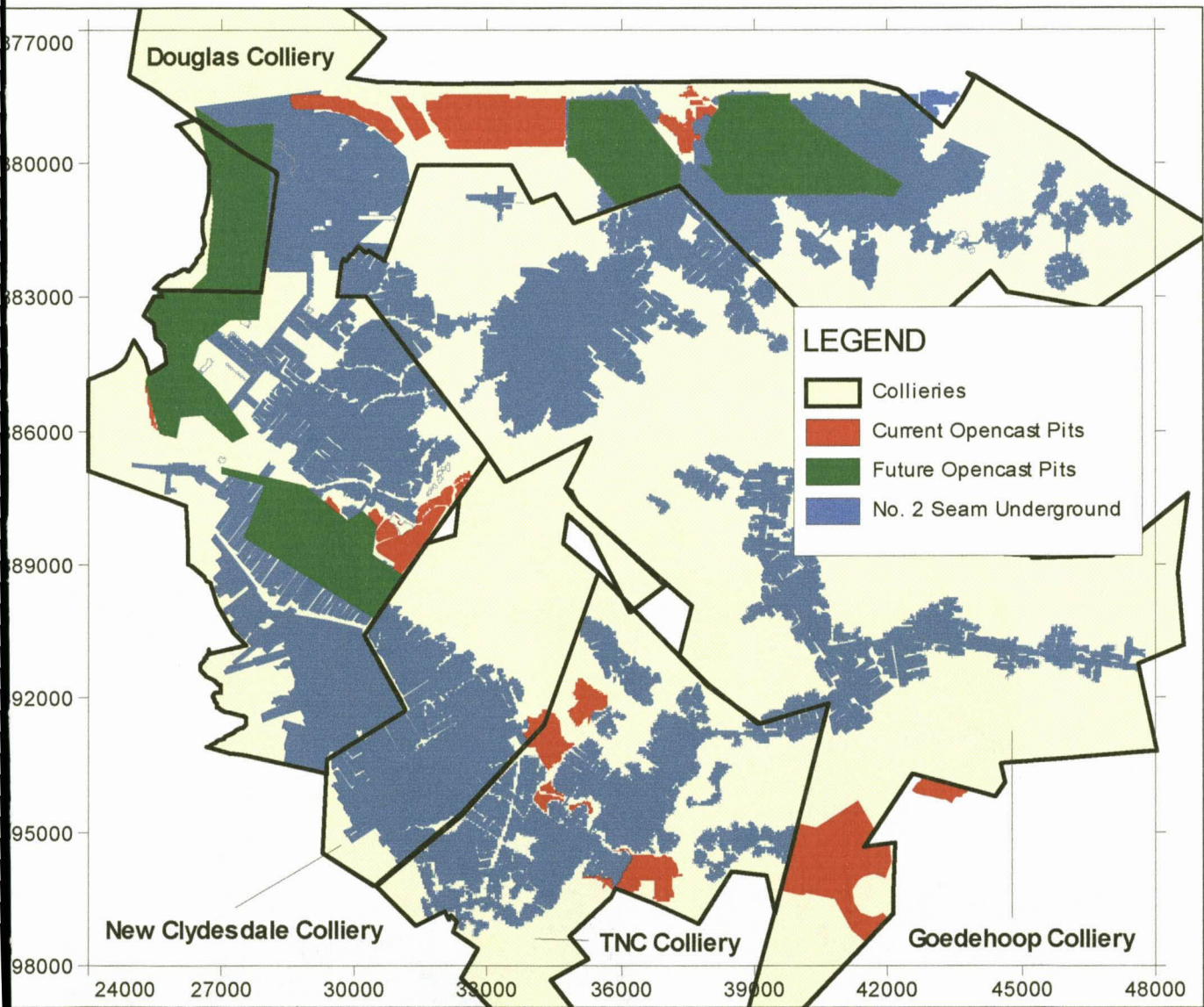


Figure 1-1. Map of study area (Central Witbank Coalfield).

The first phase of the Coaltech project was divided into three research segments:

- Data Collection and evaluation. It must be noted that data generation was not part of the scope of this phase of the Coaltech 2020 project.
- Construction of a data base within a GIS framework for the effected collieries,
- Modelling of the Base Case Situation to quantify the intermine flow in terms of flow direction and flow volume and hydrochemical impact.
- Identification of alternative water management strategies.

Grobbelaar, 2001 and Grobbelaar *et al.*, 2001, have previously identified the possible areas of intermine flow. The focus of this thesis is the quantification of these intermine flow areas in terms flow volumes and flow directions so that the impact of the intermine flow on the hydrochemistry of affected colliery's and the region can be evaluated. From this possible management strategies to limit the impacts are identified and discussed in terms of their influence and viability.

Aims of this thesis, as part of the above-mentioned project, can be summarised as:

- Development of a quantitative prediction of long-term intermine flow in the central Witbank coalfield, using the available data collated in the project.
- From the quantification of these flows and different hydrochemical techniques to determine likely water quality profiles at these collieries.
- Evaluate water management treatment strategies that will minimise the long-term influence of coal mining on the groundwater and surface water quality.

In terms of management focus of this thesis is to appraise practicable water management options that will minimise the impact or costs in the longterm. Treatment technologies are constantly emerging and Van Niekerk has recently completed a major study, (2002) to evaluate these. As such this thesis will instead look at ways of reducing the deterioration of quality or minimising treated volumes in the longterm.

1.2 METHODOLOGY

The first part of the study was to construct useable integrated information systems of the data provided to the researchers by the mines. This entailed the conversion of a host of data formats and structures into a single data format. The WISH software (Windows Interpretation System for Hydrologist) was selected to do the data comparison and spatial integration. An evaluation of the available data in terms of its ability to lead to the successful attainment of the long-term aims was also done. Several data deficiencies were identified for further research.

Quantification of the expected flows within and between the collieries in the central Witbank area was done using volumetric, analytical and numerical methods. For the numerical modelling the Modflow code (Harbaugh and McDonald, 1996) using the PMWIN interface (Chaing & Kinzelbach, 1999) was used. The following areas were modelled:

- TNC/Goedehoop Collieries
- Goedehoop/Douglas Collieries
- TNC/New Clydesdale/Douglas Collieries

Based on these results the interaction and volumetric implication of intermine flow could be obtained. The hydrochemical impact of these flows was evaluated using traditional methods such as standard hydrochemical assessments techniques. A mass balance method taking the degree of flooding within underground workings was developed to determine empirical sulphate production rates. This method was then employed to make predictions of future hydrochemical development and also to evaluate selected management options. Practical management options were evaluated in terms of their effect on water quality or quantity to be treated and recommended actions outlined.

1.3 STRUCTURE OF THESIS

- **Chapter 1:** Introduction to Thesis.
- **Chapter 2:** Background Information of Study Area. In this chapter a general overview is given on the geology, climate, geohydrology, determination of hydrological properties (tracer tests) and mining methods of the study area.
- **Chapter 3:** Numerical Modelling. In this chapter a brief description of the modelling software, modelling methods and model parameters used in the different scenarios is given.
- **Chapter 4:** Quantification of the Intermine Flow. In this chapter the intermine flow is modelled to quantify the flow direction as well as the flow volume of the different intermine flow scenarios.
- **Chapter 5:** Hydro chemistry of Opencast Pits and Underground Workings affected by Intermine Flow. In this chapter the effect of intermine flow in terms of water chemistry as well as the effects on surface hydrology (decanting on surface by opencast pits) are discussed.
- **Chapter 6:** Management Options. In this chapter different management options and strategies are discussed to limit the effects of intermine flow as well as strategies to yield optimum groundwater qualities.
- **Chapter 7:** Conclusions and Recommendations.

2 BACKGROUND INFORMATION

2.1 GEOLOGY OF THE CENTRAL WITBANK COALFIELD

The Witbank Coalfield extends from the Brakpan/Springs area (**Figure 2-1**) in the west to Belfast in the east and covers an area in excess of 568 000 ha.

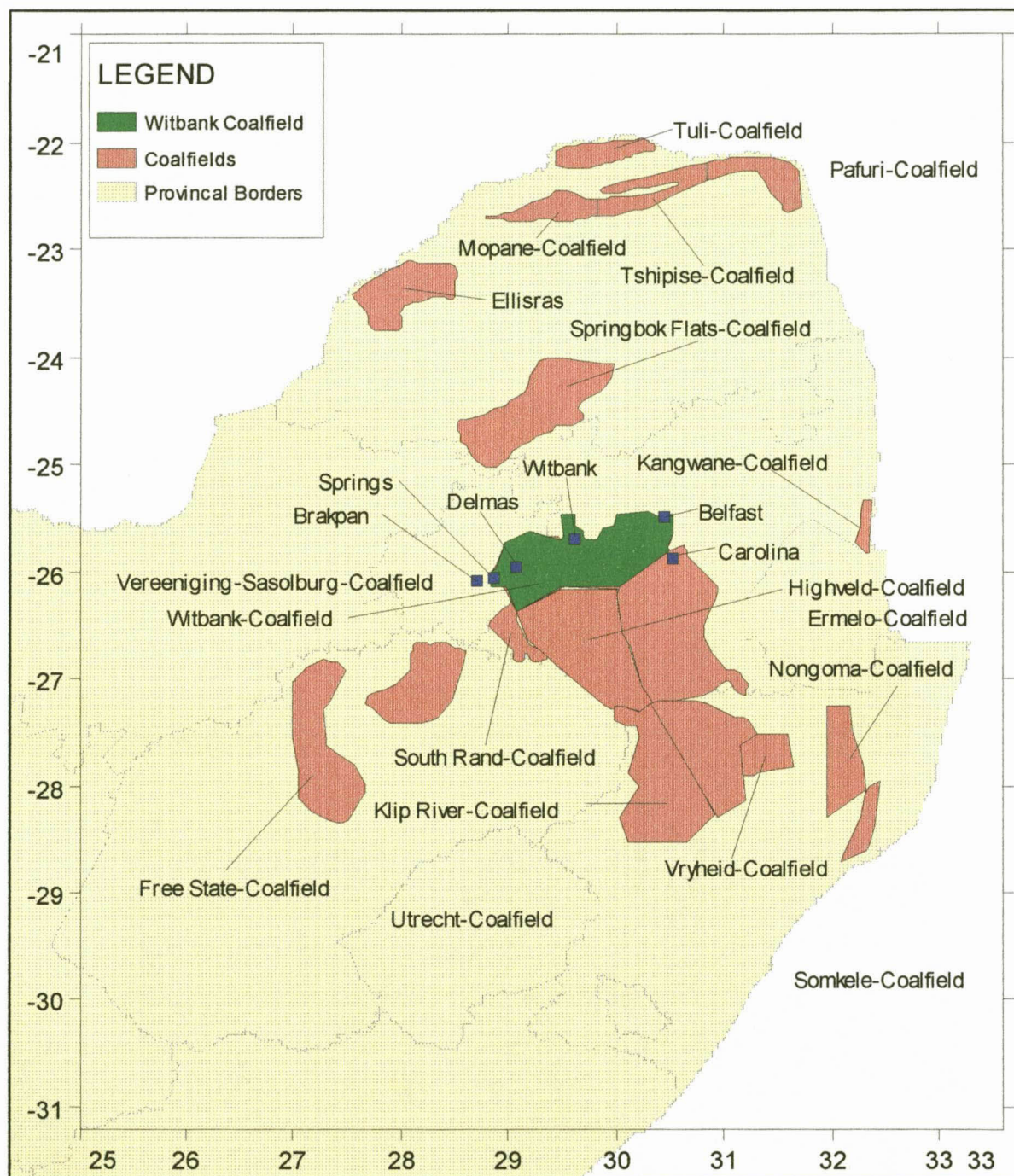


Figure 2-1. Distribution of the coalfields in the northern part of the Karoo Basin.

The southern boundary is formed by a series of inliers of Rooiberg felsite, known as the Smithfield ridge (Smith and Whittaker, 1986). The coal Seams are contained in a 70 m thick succession, consisting predominantly of sandstone with subordinate siltstone and mudstone. The distribution and altitude of the No. 1 and 2 Seams are largely determined by pre-Karoo topography, and the distribution of the No. 4 and 5 Seams is controlled by the present-day surface, parts of these Seams have been eroded away.

Dykes and sills are ubiquitous. The Ogies Dyke (**Figure 2-2**) is about 15 m thick. It devolatilized the coal on either side over a distance of up to 300 m, suggesting that it probably acted as a magma conduit for a considerable length of time (Snyman, 1998).

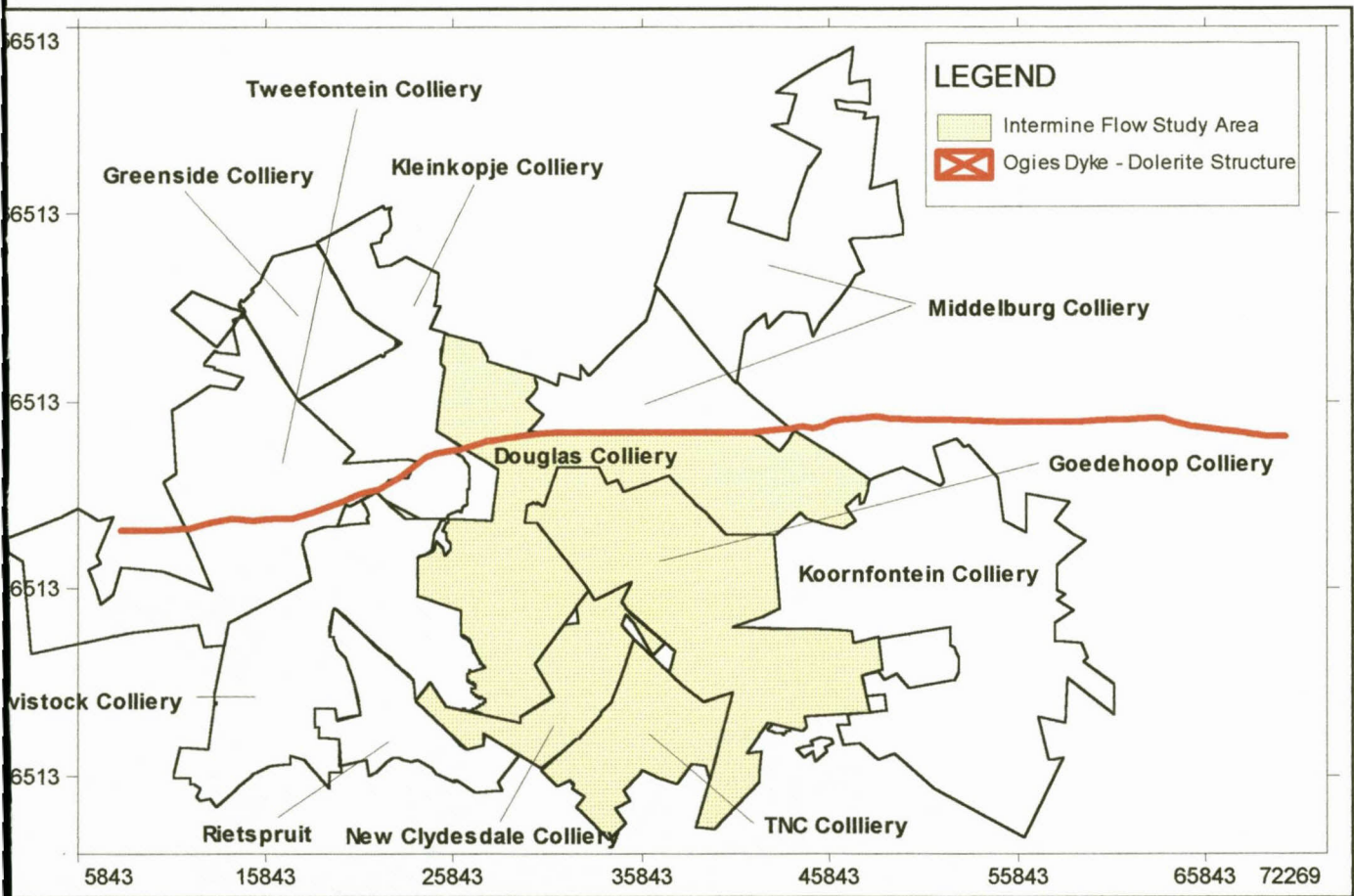


Figure 2-2. Map of the Collieries of the Witbank Coalfield as well as the Ogies Dyke and intermine flow study area.

The non-porphyrific dolerite sills attain a thickness of 50 m and the porphyritic sills a thickness of about 15 m. Both of these devolatilize the coal and displace the coal Seams into compartments as can be seen in **Figure 2-3** where the relative positions of dolerite structures and Goedehoop Colliery's No. 2 Seam are shown.

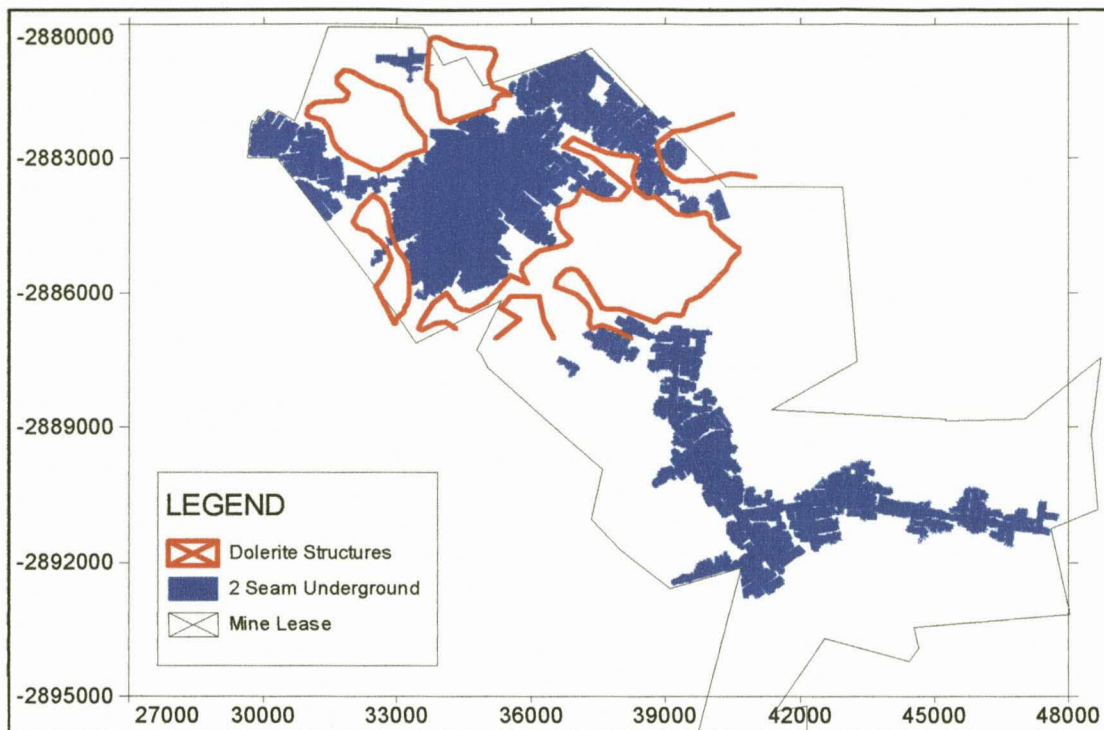


Figure 2-3. Map of Goedehoop Colliery's No. 2 Seam underground workings and dolerite structures.

Table 2-1. Table of physical parameters of the coal seams of the Central Witbank Coalfield (Data from Coaltech 2020, 2001). The table cells containing the hash symbol had no data available at that time.

Seams	Physical parameters	Douglas Colliery	Goedehoop Colliery	New Clydesdale Colliery
Seam 1	Average Thickness (m)	2.39	#	#
	Depth (m)	56	#	#
	Mining Height (m)	2.39	#	#
Seam 2	Average Thickness (m)	3.61	6	3.94
	Depth (m)	44	4.15-130	54
	Mining Height (m)	3.8	4.5	3.14
Seam 4	Average Thickness (m)	2.69	2.8	#
	Depth (m)	28.99	15-75	#
	Mining Height (m)	#	3	#

Five major coal Seams have been identified, numbered from 1 to 5. Coal Seam No. 5 are closest to the surface and Coal Seam No. 1 is at the bottom. General descriptions of physical parameters of the coal Seams are given in **Table 2-1**.

The No. 1 coal Seam is variably developed and only represents about 2% of the *in situ* demonstrated resources in the coalfield. It mostly consists of dull coal and is often indistinguishable from the No. 2 Seam.

The No. 2 Coal Seam (**Figure 2-8**) is the most extensively mined in the area. The Seam reaches its maximum development south, east and west of Witbank where it exceeds 6 m in thickness (**Figure 2-1**). The Seam is clearly defined from Delmas eastwards towards Carolina (**Figure 2-1**). It is on the No. 2 Coal Seam that the South African export coal industry was founded. The Seam has been mined extensively and is nearing its limit (Barker, 1999). The lower three benches can be mined separately for the production of low ash metallurgical coal (coking coal) and steam coal export (Snyman, 1998).

The No. 4 Seam is generally of poorer quality and of variable thickness. It is often split into a number of sub-Seams with a variety of partings often comprised of sandy mudstones and siltstones. Where the coals are thick enough to mine selectively underground, such as at Goedehoop Colliery, the Seam has a yield of about 60 % for the washed steam coal with less than 14% ash. Since the 1980's the No. 4 Seam has been used to bulk out the No. 2 Seam, even though it has a much lower yield (Barker, 1999, Snyman, 1998).

2.2 CLIMATE OF THE STUDY AREA (WESTERN MPUMALANGA)

The province of Mpumalanga has summer rainfall. Closer to the Kruger National Park, conditions are mild to hot subtropical. The summer monthly average temperatures range from 22 to 24°C and the winter average temperatures range from 15 to 17°C. **Figure 2-4** shows a graph of Mpumalanga's yearly rainfall averages as measured at Goedehoop Colliery.

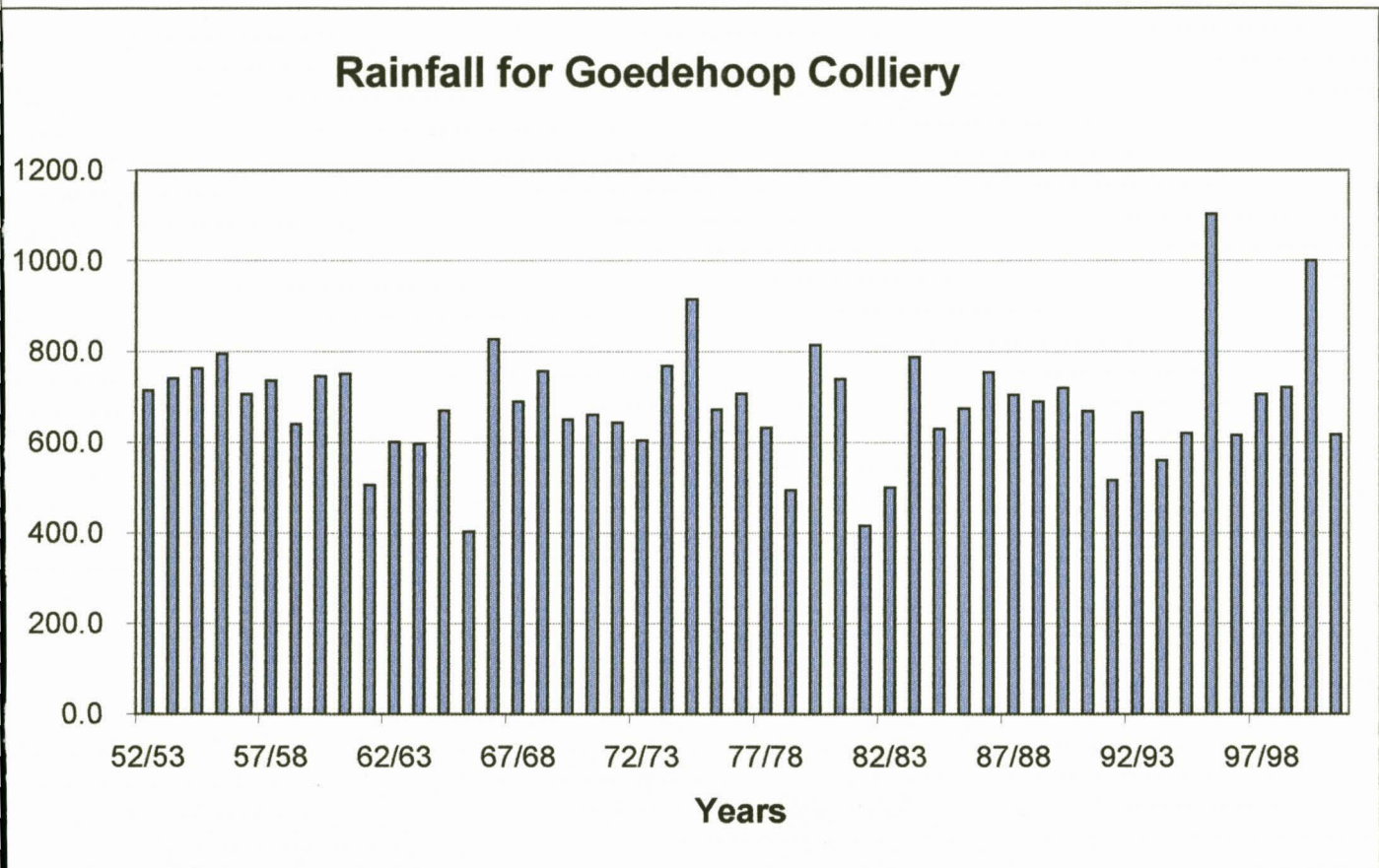


Figure 2-4. Graph of yearly rainfall for Goedehoop Colliery.

The average rainfall for Goedehoop was 686 mm/a over a period of 49 years (1952 – 2001), (**Figure 2-4**), (Data from Goedehoop Colliery). A rainfall of 700 mm/a was taken as an average rainfall for the Central Witbank Coalfield.

2.3 GEOHYDROLOGY OF CENTRAL WITBANK COALFIELD

Three distinct superimposed groundwater systems are present. They are the upper weathered Ecca aquifer, the fractured aquifers within the unweathered Ecca sediments and the aquifer below the Ecca sediments.

2.3.1 New Clydesdale Colliery

Two aquifers were identified in the vicinity of New Clydesdale (Groundwater Consulting Services, 1998). A perched aquifer is formed by silty sand, sand and clays in the upper 5 – 7 metres of the geological succession. Groundwater levels in the perched aquifer vary between 2.14 and 6.01 mbgl (meters below ground level). The perched aquifer is a seasonal phenomenon and is formed by the infiltration of rainwater (recharge) into the subsurface. It is expected that this aquifer may be dry during the winter months and will be replenished during the rainy season. The base of the perched aquifer has a low permeability but is hydraulically connected to the deeper fractured rock aquifer. As such it plays a role in recharge to the underlying fractured rock aquifer.

2.3.2 Koomfontein Colliery

To provide a broader base of understanding regarding the geohydrological regime of the area, Koomfontein Colliery, which is situated immediately to the west of Goedehoop Colliery was used. The geohydrological character of Koomfontein Colliery is described in a report by Groundwater Consulting Services, 2000.

2.3.2.1 The Weathered Aquifer

The weathered aquifer is found in the upper 10 meters of the geological succession and is formed by weathered sandstone, shale and siltstone. The aquifer base is formed by clays, which act as an aquitard between the two aquifers and retard the vertical infiltration of rainwater. The aquifer is not uniform over the mining area, but is developed in pockets of weathering. Groundwater levels in this aquifer are shallow; on average 3 mbgl. The weathered aquifer is significant as it contributes to the base flow of streams and rivers. The aquifer is also an important recharge mechanism to the underlying fractured rock aquifer. Rainwater is recharged into the weathered zone from where it moves slowly and vertically into the underlying fractured rock aquifer. The two aquifers are considered to be geohydrologically connected, i.e. there is no aquiclude present between the two aquifers.

Aquifer tests (pump tests and packer tests) were undertaken on the deep monitoring boreholes penetrating both the weathered aquifer and deeper fractured aquifer.

From these tests it is clear that the transmissivity of the weathered aquifer varies over the area. This is indicative of the heterogeneous nature of the aquifer and typical of fractured Karoo aquifers. (Botha et al., 1998) (**Error! Reference source not found.**).

Table 2-2. Transmissivity for the weathered aquifer (adapted from GCS report, 2000).

Borehole Names	Transmissivity (m/d)
KFTN6	0.002
KFNT7	0.09
KFTN8	0.55
KFTN9	0.17
KFTN10	0.26
KFTN12	0.12
KFTN14a	0.32
KFTN21	0.46
KFTN24	0.73
KFTN26	0.73
KFTN32	2.36
KFTN34	2.33
KFTN37	0.12
KFTN48	0.11

The average transmissivity (**Table 2-2**) in weathered aquifer is 0.00896 m/d and the storativity values are given in (**Table 2-3**).

Table 2-3. Storage characteristics for Koornfontein Colliery (adapted from JMA, 1998). The table cells containing a hash symbol had no values available at this time.

Lithology	Porosity	Effective Porosity	Storativity
Shallow Weathered Zone	0.05	#	0.03
Integrated Sandstone Layers	0.0062	0.05	0.0036
Dolerite	0.001	#	#
No. 2 Coal Seam	0.005	0.08	#

2.3.2.2 *Fractured Rock Aquifer*

The second aquifer is found at a depth greater than 15 mbgl. This is a fractured rock aquifer, which is formed by fractures, joints, bedding planes and the contact between intrusions (dolerite sill) and the sandstones, siltstones, shales, and coal seams in the geological succession. Piezometric levels in this aquifer are deeper; on average 8.8 mbgl. The three economical coal Seams occur within the fractured rock aquifer.

The most water strikes were encountered within the upper part of the fractured rock aquifer, from depths of 16 – 30 meters. The majority (70%) of the water strikes are associated with sandstone, shale, siltstone and coal Seams in the fractured rock aquifer. Only 30% of the water strikes are associated with the dolerite sills.

2.3.2.3 *Packer Test Results for Koornfontein Colliery*

In order to obtain a better understanding of the permeability of the aquifers, and specifically of the dolerite intrusions, packer tests were undertaken on four of the deep monitoring boreholes. The results of the packer test indicate that:

- The permeability of the aquifers decreases with depth.
- The permeability of the aquifers is relatively low (**Table 2-4**) and is typical of Karoo-type aquifers, which normally have low aquifer potentials.
- The permeability of the dolerite is mostly lower than the host rock, indicating that it does not act as an aquifer.
- The zones of contact between the dolerite and the host rock is often associated with higher permeability.

Table 2-4. Permeabilities obtained from packer tests (adapted from GCS, 2000).

Borehole Names	Permeability (m/d)	Permeability (m/d)	Permeability (m/d)	Permeability (m/d)
Aquifer Types	Weathered aquifer	Fractured Rock Aquifer	Dolerite Intrusion	Total for Entire Sequence
KFTN16	9.64E-05	2.70E-04	7.25E-05	4.39E-04
KFTN30	2.69E-02	5.87E-04	2.24E-02	4.99E-02
KFTN38	1.24E-02	1.30E-03	3.75E-06	1.37E-02
KFTN45	1.61E-05	1.01E-04	6.66E-05	1.84E-04

There was a large variation in transmissivity for the fractured rock aquifer. This is typical for fractured rock aquifers where flow mainly occurs in discrete zones

(fractures, joints, contact zones and bedding planes). These zones have a higher transmissivity than the rock matrix. The average (geometric mean) transmissivity for the fractured rock aquifer, calculated from the recovery data is 0.268 m²/d, which is slightly lower than the weathered aquifer.

2.3.3 Douglas Colliery

The available data on the hydrology of the Douglas Colliery was adapted from an EMPR report on the Boschmanskrans Pillars Project (JMA, 1998).

Three different aquifer types occur in the study area, namely the shallow perched aquifers, shallow weathered zone Karoo aquifers and the deep fractured rock karoo aquifers. The shallow perched aquifers are essentially restricted to the soil horizon and usually display unconfined conditions. The host rock for the other two-aquifer types is Karoo sediments and coal Seams. The shallow weathered aquifer displays unconfined to semi-confined conditions, hence the springs, while the deep fractured rock aquifer displays predominantly confined conditions.

At Boschmanskrans section the major dolerite structures are dykes of which the most significant is the Ogies dyke (see **Figure 2-2**). This dyke forms aquifer boundary perpendicular to the dyke in the north south direction and most probable forms preferred pathway on the contact zones in east west direction. See **Table 2-5** and **Table 2-6** aquifer parameters of Douglas Colliery.

Table 2-5. Aquifer parameters of Douglas Colliery.

Parameters	Storativity	Hydraulic Conductivity (m/d)
Aquifer of Douglas Colliery	0.05	0.0015 to 0.035
Opencast Pit (Boschmanskrans))	0.25	10
Recharge estimated at between 1 to 3%		
Porosity for shallow weathered zone aquifer - 5%		
Porosity for deep Karoo aquifer - 0.5%		

Table 2-6. Aquifer thickness of Douglas Colliery.

Thickness of Aquifers	
Aquifer Type	Thickness (m)
Shallow Perched Aquifer	1 - 2
Shallow Weathered Zone Karoo Aquifer	7 - 27
Deep Karoo Aquifer	30 - 50

2.3.4 Determination of Hydraulic Properties in the Witbank Coalfield through Tracer Tests

2.3.4.1 Single Well Tracer Tests

The use of tracer tests for the determination of aquifer parameters is not a common practice. Tracers test were preformed at Eikeboom Colliery on five observation boreholes in January 2002. The data derived from the tracer test were also brought into consideration for the model parameters. Detailed methodologies for conducting tracer tests can be found in Van Wyk, 1998 and Riemann, 2002. The following data have been collected and analysed:

Table 2-7. Table containing the point dilution data.

Time	Conc. mS/m	Time	Conc. mS/m	Time	Conc. mS/m
1	82	21	266	105	228
2	130	22	262	110	227
3	227	23	260	115	226
4	270	24	257	120	223
5	302	25	254	125	222
6	323	30	252	130	222
7	307	35	251	135	222
8	307	40	253	140	222
9	309	45	254	145	223
10	301	50	252	150	222
11	295	55	252	155	218
12	301	60	251	160	216
13	293	65	251	165	212
14	288	70	253	#	#
15	284	75	244	#	#
16	288	80	243	#	#
17	281	85	239	#	#
18	280	90	239	#	#
19	278	95	238	#	#
20	277	100	234	#	#

The first part of the tracer test is the point dilution whereby a measured mass of salt is circulated in a 2 m section of the borehole. The theory behind a point dilution test is that the salt will move by advection into the joints and cracks in the rock strata. As the tracer moves through the cracks and joints the salt is transported into the porous matrix of the rock strata through the process of matrix diffusion (Dennis, 2001). As the tracer moves into the porous rock the concentration should decrease over time, hence the electrical conductivity should also decrease (see **Table 2-7** and **Table 2-5**).

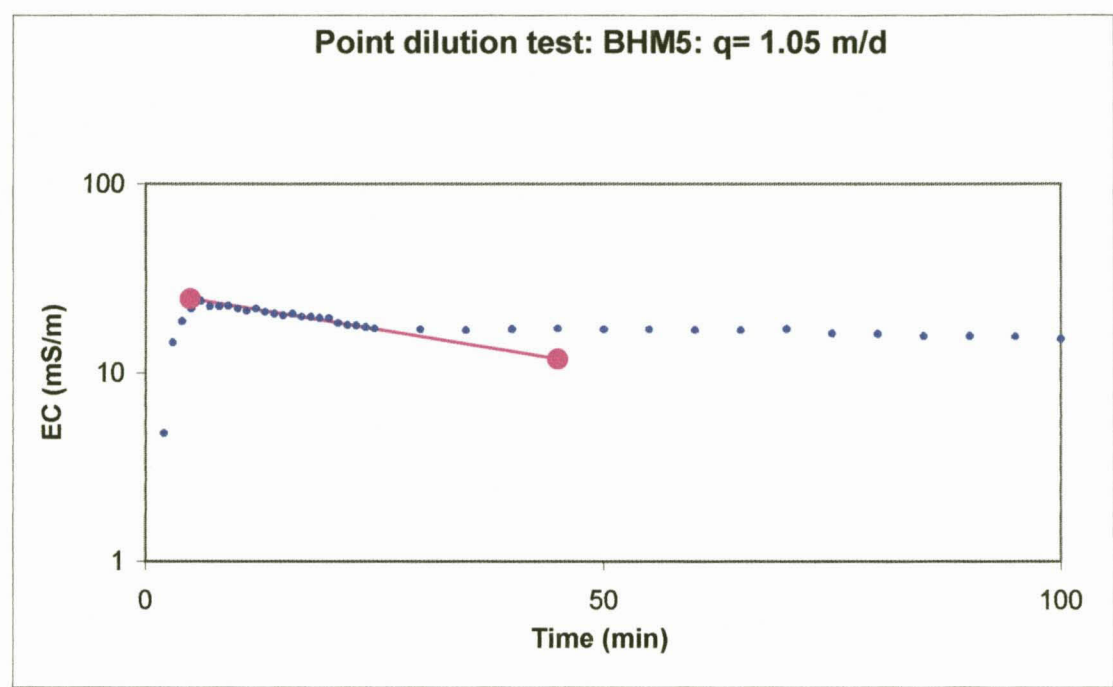


Figure 2-5. Graph of the point dilution single well test for concentration over time.

From the first part of the tracer test the Darcy velocity [q_n (m/d)] can be derived (see **Equation 2-1**). By using the calculated Darcy velocity a porosity value can be approximated (Riemann, 2002). For example **Figure 2-5** a Darcy velocity of 1.05 m/d has been calculated.

Equation 2-1. $q = \frac{W}{\alpha A t} \ln\left(\frac{C_o}{C}\right)$ (**Dorst and Neumaier, 1974**)

W – volume of fluid contained in the test section.

A – cross sectional area normal to the direction of flow.

C_o – tracer concentration $t=0$

C – tracer concentration at time $t=1$.

α - borehole distortion factor (between 0.5 and 4; = 2 for an open well.

(Note that $q\alpha = v^*$, where v^* = apparent velocity inside well)

t – time when concentration is equal to C.

2.3.4.2 Injection-Withdrawal Test

The second part of the tracer test is the injection withdrawal part. The groundwater is no longer circulated but pumped out of the borehole. In this phase of the tracer test the salt that was injected initially is being recovered. By using the data produced by the injection-withdrawal phase a seepage velocity can be derived. In theory the tracer moves out of the pores of the rock strata by the process of diffusion. As soon as the salt is in the joints and cracks advection takes over. The tracer will move slowly out of the pores over a long period. This is the reason why pump and treat does not work as a remediation practice in Karoo-type aquifers.

Table 2-8. Injection-withdrawal data of the tracer test.

Time	Conc. mS/m	Time	Conc. mS/m	Time	Conc. mS/m	Time	Conc. mS/m
0.5	208	11	97	26	110	40	117
1	208	12	92	26.5	107	45	99
1.5	207	13	88	27	115	50	90
2	207	14	85	28	118	55	82
2.5	203	15	83	29	122	60	62
3	201	16	84	30	124	65	57
3.5	194	17	82	31	123	70	54
4	181	18	83	32	129	75	53
4.5	177	19	84	33	135	#	#
5	165	20	80	34	130	#	#
6	148	21	81	35	129	#	#
7	141	22	99	36	118	#	#
8	125	23	101	37	121	#	#
9	110	24	102	38	117	#	#
10	102	25	104	39	121	#	#

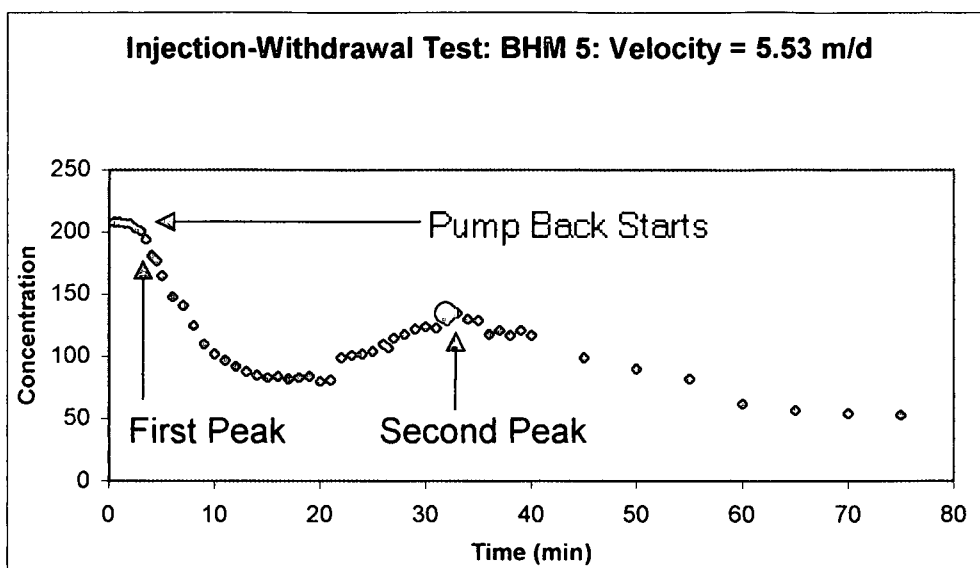


Figure 2-6. Graph of the injection withdrawal single well test for concentration over time.

Theoretically the electrical conductivity should increase (second peak in **Figure 2-6**) as the tracer is removed from the pores of the rock and joints. The first peak is the salt in solution in groundwater that is in circulation and therefore there is a drastic decrease in concentration when this water is pumped out of the well in the pump back phase, and fresh water flows into the borehole. After most of the salt is extracted by pumping, the electrical conductivity will decrease (**Figure 2-6**). From the second part of the tracer test the Seepage velocity [V_n (m/d)], can be derived (see **Equation 2-2**, Riemann, 2002). By dividing the Darcy velocity through the seepage velocity an porosity can be approximated. The approximated porosity is 0.19.

Equation 2-2.
$$v = \frac{\sqrt{Qt_p / \Pi \varepsilon D}}{t_d} \text{ (Leap and Kaplan, 1988)}$$

V – seepage velocity.

Q – pumping rate during recovery of tracer (m^3/d).

t_p – time elapsed from start of pumping until the center of mass of the tracer is recovered (d).

ε - kinematic porosity.

t_d – time elapsed from injection of tracer until the centre of mass of the tracer is recovered (d).

2.3.4.3 Results of Tracer Tests at Eikeboom Colliery

Table 2-9. The values derived from the tracer tests at Eikeboom Colliery.

Eikeboom Colliery	Point Dilution Test	Injection Withdrawal Test	Approximate Porosity
Borehole Name	Darcy Velocity (m/d)	Seepage Velocity (m/d)	
BHM1	0.72	7.23	0.10
BHM2	1.22	8.15	0.15
BHM3	1.39	3.47	0.40
BHM4	0.89	2.23	0.40
BHM5	1.05	5.53	0.19
Geometric Mean	1.03	4.8	0.21

The average value of the Darcy velocity for the rocks occurring in the area is 1.039m/d. The average seepage velocity for the rocks occurring in the area is 4.8 m/d. It must be noted that the seepage velocity calculated in the injection withdrawal is for the cracks and joints and thus is a worst-case scenario for the movement of pollutants. The seepage velocity has to be averaged to be representative of the whole rock formation and the averaged value is usually much smaller due to the density of the matrix as a whole. The same applies to relative large approximate porosities, which reflects on the porosity of the cracks. The above data were used to approximate the time it will take sulphate-polluted groundwater from opencast pits to reach the Olifants River (see chapter 5).

2.4 MINING METHODS IN THE STUDY AREA

See **Figure 2-2** for the location of the mines in the study area.

2.4.1 Douglas Colliery

Mining commenced at Douglas Colliery in 1945. Douglas Colliery’s mine lease area (see **Figure 2-7**) is 15556 ha. Coal Seams No. 1, 2 and 4 are mined at Douglas Colliery. Opencast mining as well as underground mining techniques are used to extract the coal. The underground mining technique used is bord and pillar mining. Mining by blasting was done up to 1995 and presently bord and pillar mining is done by mechanical means. A square pillar is about 16 m by 16 m and the bord about 6.5 m wide. At the Boschmanskrans section the pillar size is about 6 – 9 m (Coaltech 2020, 2001).

The initial extraction ratios (Coaltech 2020, 2001) for the coal Seams are:

- No. 1 Seam – 66%
- No. 2 Seam – 66%

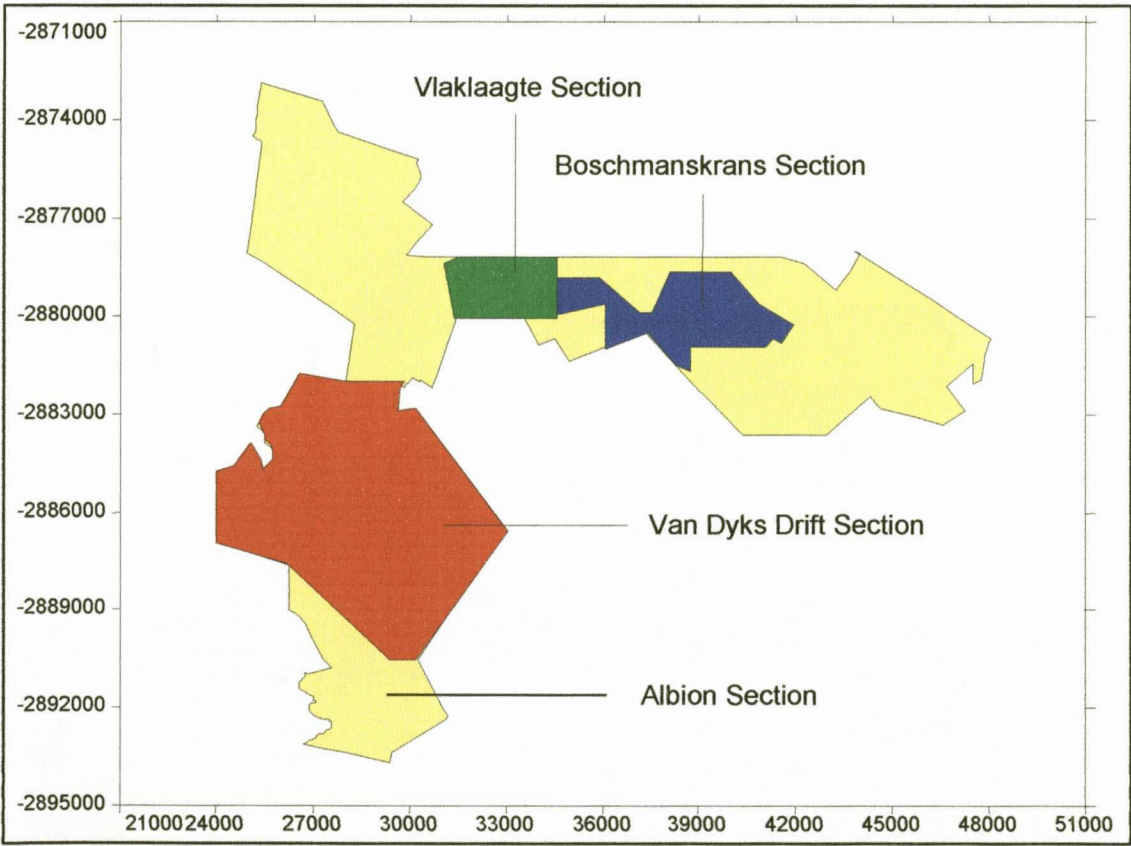


Figure 2-7. Map showing some of the sections of Douglas Colliery.

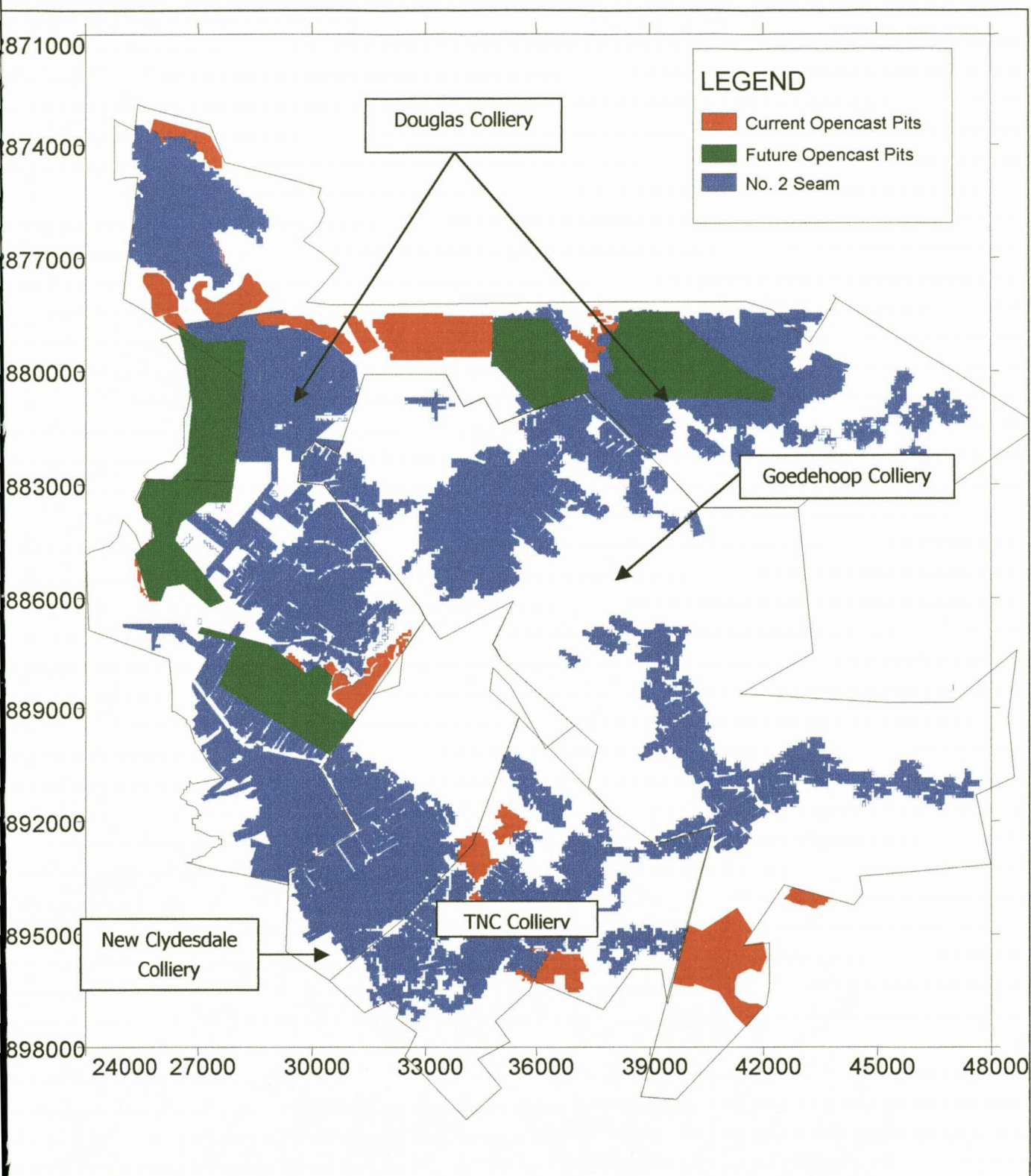


Figure 2-8 Map showing the mining activities in the Central Witbank Coalfield based on latest mining plans available.

The final extraction ratios for the coal Seams are:

- No. 1 Seam – 70%
- No. 2 Seam – 70%

The initial extraction is by bord and pillar and the final extraction is when some of the pillars are removed by stooping.

Douglas Colliery is currently extracting the pillars of the Boschmanskrans No. 2 Seam underground workings. They also plan to extract the pillars left in the Van Dyks Drift No. 2 Seam underground by means of re-mining through opencast mining methods.

2.4.2 Goedehoop Colliery

Mining commenced at Goedehoop Colliery in 1976. Goedehoop Colliery's mine lease area is 13536 ha. Coal Seams No. 2 and 5 are mined at Goedehoop Colliery. Opencast mining as well as underground mining techniques are used to extract the coal. The underground mining technique used is bord and pillar mining. The bords (the space between pillars) are about 6.5 m wide and centers about 14 to 24 m apart. The 4A -, 4U - and No. 3 Seams are too thin or of too poor quality to mine at Goedehoop Colliery (**Table 2-8**, Coaltech 2020, 2001).

2.4.3 New Clydesdale Colliery

Mining commenced at New Clydesdale Colliery in 1956. New Clydesdale Colliery's mine lease area is 3285 ha. Coal Seam No. 2 is mined. Opencast mining as well as underground mining techniques are used to extract the coal. The underground mining technique used is bord and pillar mining. The bords are about 6.5 m wide and the centre about 20 m apart. The initial extraction ratio for the coal Seam is 62% and the final extraction 65% (**Figure 2-8**, Coaltech 2020, 2001).

2.4.4 Transvaal Navigational Colliery

Transvaal Navigational Colliery ceased mining activities in 1991. The opencast pits were rehabilitated (250 ha mined). The underground workings were mined by bord and pillar method and stooped in places. The No. 2 coal Seam was mainly mined in underground blocks (1710 ha). The final extraction ration was 0.6 for the underground workings. The mining height was 3 m for the No. 2 coal Seam underground workings. Underground high extraction of coal through stooping was executed in 22% (350 ha) of the underground area (Hodgson *et al.*, 2000).

3 NUMERICAL MODELLING

Numerical modelling was used to quantify the intermine flow in terms of flow volumes and fill up times of underground workings and opencast pits. The software suite PMWIN (processing Modflow for Windows) was used to model the intermine flow scenarios.

3.1 MODELLING SOFTWARE

PMWIN version 5.1.7 modelling software (Chaing and Kinzelbach, 1999) was used to model the intermine flow scenarios.

The applications of MODFLOW, a modular three-dimensional finite-difference groundwater model of the U. S. Geological Survey, to the description and prediction of the behaviour of groundwater systems have increased significantly over the last few years. The "original" version of MODFLOW-88 (McDonald and Harbaugh, 1988) or MODFLOW-96 (Harbaugh and McDonald, 1996) can simulate the effects of wells, rivers, drains, head-dependent boundaries, recharge and evapotranspiration. Since the publication of MODFLOW numerous investigators have developed various codes. These codes are called packages, models or sometimes simply programs. Packages are integrated with MODFLOW. Each package deals with a specific feature of the hydrologic system to be simulated, such as wells, recharge or river. Models or programs can be stand-alone codes or can be integrated with MODFLOW. A stand-alone model or program communicates with MODFLOW through data files. The advective transport model PMPATH (Chiang and Kinzelbach, 1994, 1998).are examples of such modules used in this investigation.

Assumptions and Parameters for Modflow Models constructed for this study include:

- **Mesh Size:**

- **Goedehoop Colliery – TNC (Transvaal Navigational Colliery) Intermine Flow Scenario:** A cell size of 100 m by 100m was used and then refined at intermine flow areas to a cell size of 25m by 25 m.
- **Goedehoop Colliery – Douglas Colliery Intermine Flow Scenario:** A cell size of 100m by 100m was used and then refined at intermine flow areas to a cell size of 50m by 50m.
- **TNC – New Clydesdale Colliery – Douglas Intermine Flow Scenario:** A cell size of 100m by 100m was used and then refined at intermine flow areas to a cell size of 50m by 50 m.

- **Layer Type:** A two-layer model was used. The layer type used was confined for all three models.
- **Boundary Condition:** Fixed heads were used in the steady-state running of the model, but during the transient-state modelling fixed heads were only used to simulate decant points when water levels reached the decant height, for example at the Goedehoop Colliery's new opencast pit.
- **Layer Construction:** For the all flow models the floor layer was formed by the No. 2 Seam floor contours and for the top of the models the surface contours were used. The lower layer was used to simulate the underground workings and layer one was used for the opencast pits.
 - **Goedehoop Colliery – TNC (Transvaal Navigational Colliery) Intermine Flow Scenario:** A layer thickness (layer 2) of 3 m was used for the TNC underground workings and a layer thickness of 4.5 m was used for the Hope workings (Coaltech 2020, Geological/Geophysical Needs Analysis, 2000)
 - **Goedehoop Colliery – Douglas Colliery Intermine Flow Scenario:** A layer thickness (layer 2) of 3.8 m was used for the Douglas Colliery underground workings and a layer thickness of 4.5 m was used for the Hope workings (Coaltech 2020, Geological/Geophysical Needs Analysis, 2000).
 - **TNC – New Clydesdale Colliery – Douglas Intermine Flow Scenario:** A layer thickness (layer 2) of 3.8 m was used for the Douglas Colliery underground workings and a layer thickness of 3 m was used for New Clydesdale and TNC Collieries respectively (Coaltech 2020, Geological/Geophysical Needs Analysis, 2000).
- **Initial Hydraulic Heads (water levels):**
 - **Goedehoop Colliery – TNC (Transvaal Navigational Colliery) Intermine Flow Scenario:** The southern part of Hope underground workings is dewatered due to mining activities. The new opencast block at the southern tip of the mine lease area of the Goedehoop Colliery was taken as empty. The rest of Hope underground workings is at a water level elevation of 1511 mamsl (borehole UG 04, 01/02/2001). For the Welstand underground block and the rest of the other underground workings and opencast pits the water level as measured in March 2002 was used.
 - **Goedehoop Colliery – Douglas Colliery Intermine Flow Scenario:** The underground workings of the Van Dyks Drift Section and the Boschmanskrans Section were taken as dewatered due to the future opencast pits that will be mined into the underground sections, to mine

the pillars that have been left. The water level in the underground section of the Springbok Section was taken as approximately 1523.5 mamsl (borehole UG 11).

- **TNC – New Clydesdale Colliery – Douglas Intermine Flow Scenario:** The underground workings of Douglas Colliery's Albion Section's No. 2 Seam underground workings is empty (latest water level data available). The New Clydesdale Colliery's No. 2 Seam underground workings water level was taken at 1521 mamsl (water level from only one borehole, thus there is a measure of uncertainty) and the TNC Colliery's Welstand underground Block has a water level of 1521.5 mamsl.
- **Horizontal Hydraulic Conductivity:** A hydraulic conductivity for the unmined areas was taken between 0.0015 m/d (layer 1), (Douglas Colliery, EMPR, 1998, JMA). A hydraulic conductivity of 5000 m/d and 100 m/d for the underground workings and opencast pits was used respectively; this value is not precise but was used in contrast with the 0.0015 value to simulate areas of high hydraulic conductivity and the underground voids. A geometric mean hydraulic conductivity of 0.1017 m/d (Hodgson *et al.*, 1998) was taken for the unmined coal seam in layer 2 of the model.
- **Vertical Hydraulic Conductivity:** A vertical hydraulic conductivity of 0.00001 – 0.000035 m/d was used for the unmined areas. The same value used for the horizontal conductivity was used in the underground voids and opencast pits.
- **Storage Coefficient:** The following storage coefficients were used for all three models:
 - Unmined areas – 0.05 (Douglas Colliery, EMPR, 1998, JMA)
 - Underground workings – 0.6 – 0.7 (Bord-and-Pillar) (Geological/Geophysical needs analysis, Coaltech 2020, 2001)
 - Opencast pits – 0.25 (Rehabilitated), (Douglas Colliery, EMPR, 1998, JMA, Hodgson and Krantz, 1998).
- **Drains:** Drains were used to simulate the surface water interaction; in this case the rivers with the groundwater (see section 3.2).
- **Horizontal Flow Barriers:** Horizontal flow barriers were used to simulate dykes and sills as well as the unmined areas between underground workings that form a type of flow barrier between the underground workings.
- **Recharge:** The following recharge rates were assumed with an annual rainfall of 700 mm.

- Unmined areas – 1.5 %
- Underground workings – 3 % (Bord-and-Pillar), (Hodgson *et al.*,1999).
- Underground workings – 6 % (Stooped), (calculated from TNC water balance)
- Opencast pits – 20 %, rehabilitated, (Hodgson and Krantz, 1998).

3.2 GROUNDWATER AND SURFACE WATER INTERACTION SIMULATION USING MODFLOW'S DRAIN PACKAGE

The interactions of the rivers were simulated by using the drainage package in Modflow. The reason for using the drainage package was to prevent the build-up of groundwater in the lowest topographic areas in the model and to simulate the groundwater decanting into the river. The drains are placed into the model cell by cell along the path of the river, usually at the lowest elevations. For each cell a hydraulic conductivity and elevation height (mamsl) is specified. If the hydraulic conductivity assigned to the cells is too high, the model will not run for the full specified time duration, due to numerical errors or the fact that the model may run dry. To estimate the average hydraulic conductivity for the cells forming the river, the Darcy equation is applied.

$$Q = T \cdot i \cdot L$$

Q - Rate of Groundwater Flux (m³/d)

i - Gradient

L - Distance over which flux is taking place (m)

The influx of groundwater into the river can be approximated by using the Darcy equation. The flux calculated by the Darcy equation must then be divided by the number of cells simulating the river in the model. By doing this an average hydraulic conductivity for the drain cells can be calculated.

Table 3-1. Water budget of the Goedehoop – TNC intermine flow model at decant level.

ZONE 1 IN LAYER 1			
FLOW TERM	IN	OUT	IN-OUT
STORAGE	0.00E+00	2.13E-01	-2.13E-01
CONSTANT HEAD	0.00E+00	0.00E+00	0.00E+00
HORIZ. EXCHANGE	2.97E+00	4.84E+00	-1.87E+00
EXCHANGE (UPPER)	0.00E+00	0.00E+00	0.00E+00
EXCHANGE (LOWER)	1.14E+00	4.16E+00	-3.02E+00
WELLS	0.00E+00	0.00E+00	0.00E+00
DRAINS	0.00E+00	4.87E+05	4.87E+05
RECHARGE	5.53E+05	0.00E+00	5.53E+05

Fixed head cells were used to simulate decant from opencast pits. When the water level head in the model reached the decant level calculated, a fixed head cell was placed on the decant position to remove the water as the opencast pit decant. It was found that 80% to 90% of the water that decants is from recharge and the other 10% - 20% is from the substrata (groundwater flowing through the pit walls), (see **Table 3-1** as an example from Goedehoop's new opencast pit).

In the model a drain cell was placed on the decant position of the new Goedehoop opencast pit. The drain cell removed the water from the pit that will decant, thus preventing the water level in the model from rising above the surface level of the model. The volume of water removed by the drain thus represents the decant volume (see **Table 3-1**).

Decant Percentage = $4.87\text{E}+05/5.53\text{E}+05 = 0.88 = 88 \%$ of the decant of the pit is from recharge.

According to the calculation of the flow model, 88% percent of the recharge decants and flows to the river, where as 12% of the recharge seeps into the river via the groundwater flow component.

3.3 REGIONAL MODEL VERSUS LOCAL MODEL EVALUATION

Two models were constructed for the intermine flow area between Goedehoop Colliery's Hope workings and TNC Colliery's Welstand underground block to evaluate the effectiveness of the horizontal flow barrier package of Modflow. The first model was a small local model and the second was a regional model. The small model should give more accurate results due to a much greater grid density. The regional model will have fewer cells per area unit and hence should be less accurate. The unmined barrier between the Hope workings and the Welstand block was simulated in the local model with at least 7 cells and in the regional model with one cell and the horizontal flow barrier.

The regional model (for model area see **Figure 3-1**) includes all the TNC's underground blocks and opencast pits as well as Goedehoop's Hope workings. The local model area only includes the intermine flow area (intermine flow area for the local model is defined in **Figure 3-1**) between the Welstand block and the Hope workings.

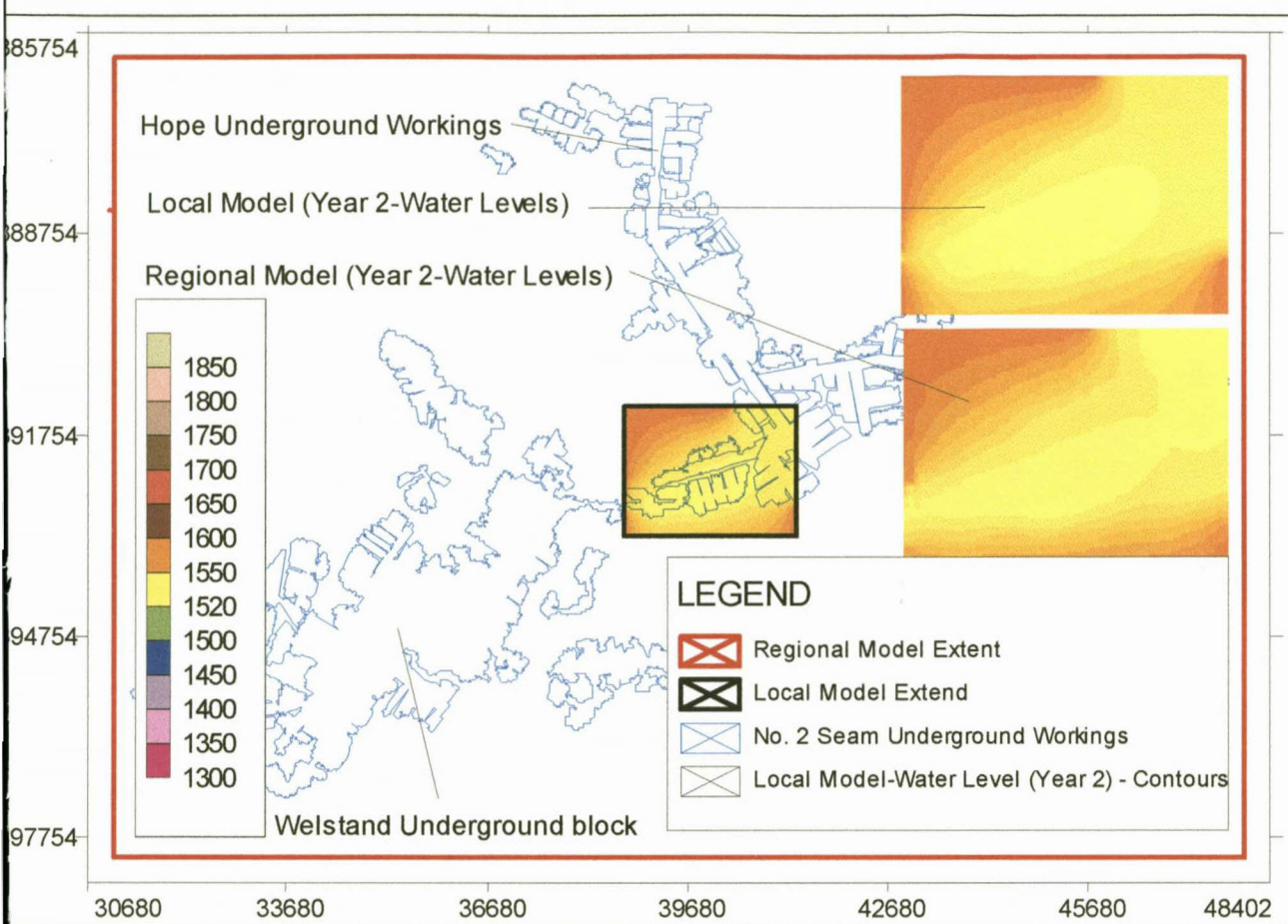


Figure 3-1. Map of model area of the regional model and local model as well as the water level contours.

5000	5000	5000	5000	0.06	5000	5000	5000	5000	=	Horizontal Flow Barrier Package	0.06
5000	5000	5000	5000	0.06	5000	5000	5000	5000	=	Harmonic Mean	0.18
5000	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	=	Harmonic Mean	0.07

Table 3-2. Diagram showing the unmined area (barrier formed by unmined section between the two underground voids) between the Goedehoop No. 2 Seam Hope workings and the TNC's Welstand No. 2 Seam underground workings assigned of number cells and the hydraulic conductivity the model will calculate to use according to the number of cells in the barrier (model uses harmonic mean).

The local model has a refined grid size of 5m by 5m in the intermine flow zone, where the regional model has a refined grid size of 30m by 30m. The local model's average cell number in the unmined area (barrier) between the underground workings is about 4 to 7 cells, while the regional models has only one cell to form the unmined area (barrier) between the two underground blocks.

The problem in the case of the regional model's number of assigned cells is that the Modflow package uses the harmonic mean to calculate an average for the hydraulic conductivity of the unmined area. The regional model only has one cell forming the average thickness.

A solution to this would be additional grid refinement. This is not always an easy undertaking since the boundaries between mines are irregular and often oblique to any generated grid.

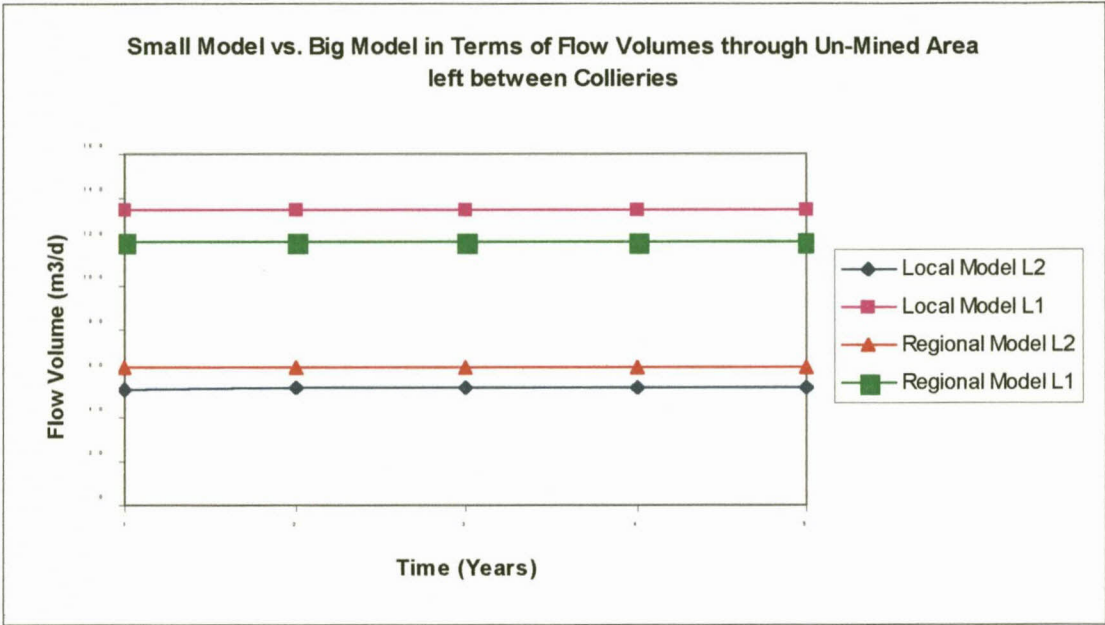


Figure 3-2. Graph showing the flow volumes through the unmined area between the two underground workings, simulated in the regional model and local model.

The solution to the problem of the unmined area's hydraulic conductivity in the regional model is to use Modflow's horizontal flow barrier package. By assigning horizontal flow barriers to the cells forming the unmined area between the two undergrounds, the model does not use the harmonic mean over the unmined area to calculate the average hydraulic conductivity, but uses the value directly as it was assigned to the cells in the first place; thus water level contours and flow volume (**Figure 3-1** and **Figure 3-2**) in the regional model are more or less the same as the local model through the unmined area.

The disadvantage of the local model is the boundary conditions. If the boundary conditions are simple or well understood a local model can be fruitfully used. In the case where the boundary conditions are not well known, a regional model must be used.

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3.4 A HYDRAULIC DESCRIPTION OF THE INTERACTION OF GROUNDWATER WITH COLLIERIES

When mining occurs, underground workings form a separate aquifer, thus a two-aquifer system is formed. The one aquifer in the system is the natural aquifer (top aquifer) and the other aquifer is the manmade void (underground workings – bottom aquifer) where the groundwater seeps into. While the void fills up through seepage from the top and sides, piezometric pressures are created (depending on the slope of floor contours of the seam), which enables the underground workings to mix their water with the rest of the aquifer below the piezometric pressure. Therefore mixing of unpolluted and polluted mine water can take place due to piezometric pressures developed as a function of the slope of the floor contours (see **Figure 3-3**). This piezometric pressure can also enable underground workings to decant on the surface. When the underground working is completely filled with groundwater the original aquifer system is restored, since a fluid continuum is re-established between the two entities.

Opencast pits after rehabilitated forms a high permeability and recharge zone. It is for this reason that the decant volumes from opencast pits are usually higher than for underground workings of the same size. The opencast pit does not form a second aquifer due to its unconfined nature.

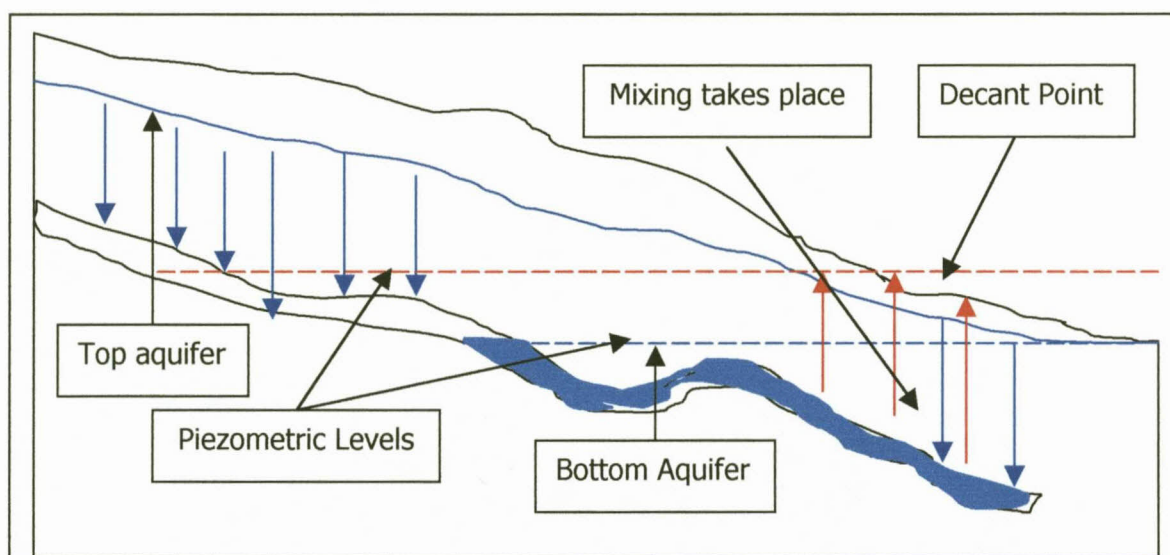


Figure 3-3. Conceptual model showing that the top aquifer will leak towards the bottom mine aquifer until the water level of the bottom mine aquifer is higher than the water level of the top aquifer.

Intermine flow will take place as soon as the water level heads in the underground workings is at a elevation, which will create a hydraulic gradient from the one void to the other. The intermine flow will only take place if the unmined barrier between the two voids is thin enough to let intermine flow take place between the voids or if this

"barrier" is transmissive enough. Fractures on the contact zones between the coal and the other sediments can help to facilitate the intermine flow.

To accommodate these two mining methods (opencast pits and underground workings) into one model requires a two-layer model, the first layer of the model is to accommodate the opencast pits or overlying aquifer in the overburden. The second model layer is to accommodate the underground workings. In this research the model layer types could not be selected as Unconfined/Confined with a T-value that varies (according to water level elevation), which would have been the correct layer type. The reason for this layer types is that Modflow cannot handle unsaturated flow and therefore the model creates a huge number of numerical overflows. The model layers were therefore selected as confined, which have a disadvantage. The disadvantage is that if, the second layer's starting water levels are not horizontal (steep floor contours) the model will automatically make the water level horizontal after one time step in running the model. This is due to the fact that the second layer got a very high hydraulic conductivity (1000 – 5000 m/d) to simulate the underground voids, therefore if the model floor has a severe slope the model margin of error will be great. If the model floor is not sloping that much the margin of error may be acceptable. It is therefore advisable to check all answers by non-numerical methods to try and determine the error, so that more accurate and acceptable answer can be obtained.

4 QUANTIFICATION OF INTERMINE FLOW

4.1 INTERMINE FLOW AND ASSOCIATED PROBLEM IN MODELLING THE SCENARIO

4.1.1 Definition of Intermine Flow

In all the collieries of the central Witbank Coalfield, sufficient connectivity exists between mining levels and the surface for intermine flow (Grobelaar *et al.*, 2001). The post-mining scenario has been modelled for the intermine flow areas.

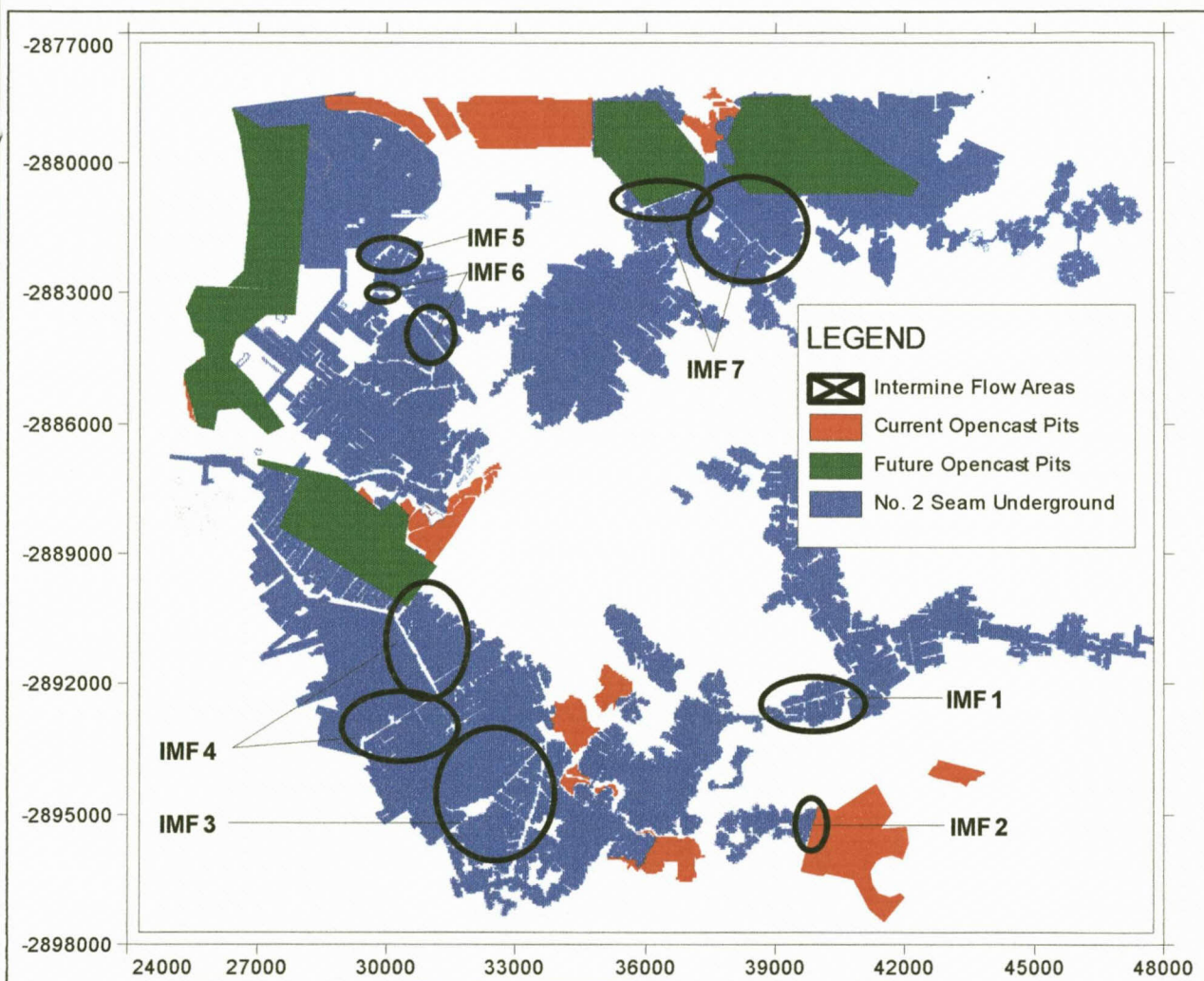


Figure 4-1. Regional map of the intermine flow (IMF) occurrences of study area. IMF 1 & IMF 2 - intermine flow between Goedehoop Colliery and Transvaal Navigational Colliery, IMF 3 - intermine flow between TNC Colliery and New Clydesdale Colliery (NCC), IMF 4 - intermine flow between New Clydesdale Colliery (NCC) and Douglas Colliery's Albion section, IMF 5 & IMF 6 - intermine flow between Goedehoop Colliery and Douglas Colliery's Van Dyks Drift section, IMF 7 - intermine flow between Goedehoop Colliery and Douglas Colliery's Boschmanskrans section.

Intermine flow is therefore defined as the flow of water in mine voids (underground workings and opencast pits) from one void to another or the flow of mine water from the void to the surface, where it decants into streams and rivers. In terms of decanting water from underground workings, areas of greatest risk for environmental impact are (according to Grobbelaar et al., 2001):

- Low topographic areas such as at streams and rivers.
- Areas of low coal seam elevations, which will constantly receive water from higher mining elevations.

4.1.2 Using numerical models to quantify intermine flow

Intermine flow quantification was done through modelling. The Modflow software package was used as model program. Modelling was a necessity to quantify the intermine flow direction and volumes and was applied in the scenarios where analytical methods were not applicable.

4.1.2.1 Associated Problems Encountered in Numerical Modelling of Intermine Flow Areas

Problems encountered in Modelling:

- Lack of site-specific aquifer parameters of each intermine flow area. It is recommended that follow-up studies be done to determine the site-specific parameter, for instance the hydraulic conductivity for the coal seam of the unmined barrier between the workings, through which the intermine flow takes place, as well as the site-specific recharge to the underground workings to determine fill-up times of the voids more accurately.
- Limitations on the Modflow modelling package due to multi-layer models. The model layer type used was confined, which posed the problem that in the second layer which simulated the underground workings, (high K-value to simulate the underground void) the water table on the seam floor will equalise to a horizontal level in the steady state running of the model. This problem to running a confined layer is only significant if the floor angles steeply. If the floor contours is level, the error is less significant.

4.1.3 Non-Numerical Methods Applied

The non-numerical methods applied were the usage of stage curves and empiric or analytical inflow/outflow methods. Stage curves are graphs that delineate the volume of the void versus the water level in the void. Spreadsheets were used to calculate the time that voids (underground workings and opencast pits) took to fill up, based on void volumes and expected inflows from recharge and surrounding aquifers. Identical recharge values and hydraulic parameters were used where possible to

compare numerically derived answers with the other approaches. The analytical calculated fill-up time was then used to check numerical modelling fill-up time. The Darcy equation was used to check the intermine flow volumes of the model. Where significant differences occur, the reasons for these differences were investigated. Typical reasons for discrepancies lie in the basic assumptions in the models or calculations or, very importantly, in the fact that the non-numerical methods can often not accommodate the host of interactions that need to be considered. In such cases numerical models offer the best hope at understanding the system so that appropriate water management measures can be implemented.

4.2 TRANSVAAL NAVIGATION COLLIERY (TNC) – GOEDEHOOP COLLIERY FLOW MODEL SCENARIO

The intermine flow area between TNC Colliery and Goedehoop Colliery was modelled to quantify the intermine flow in terms of flow direction and flow volume for the post-mining scenario.

4.2.1 Conceptual Model

The model area (**Figure 4-2**) of this intermine flow model comprises the Goedehoop Colliery's Hope Workings, the opencast pit in the south of the mine lease area, and TNC's Welstand underground block as well as the Block C underground workings. The average thickness of the unmined area between the two underground workings is approximately 50 m.

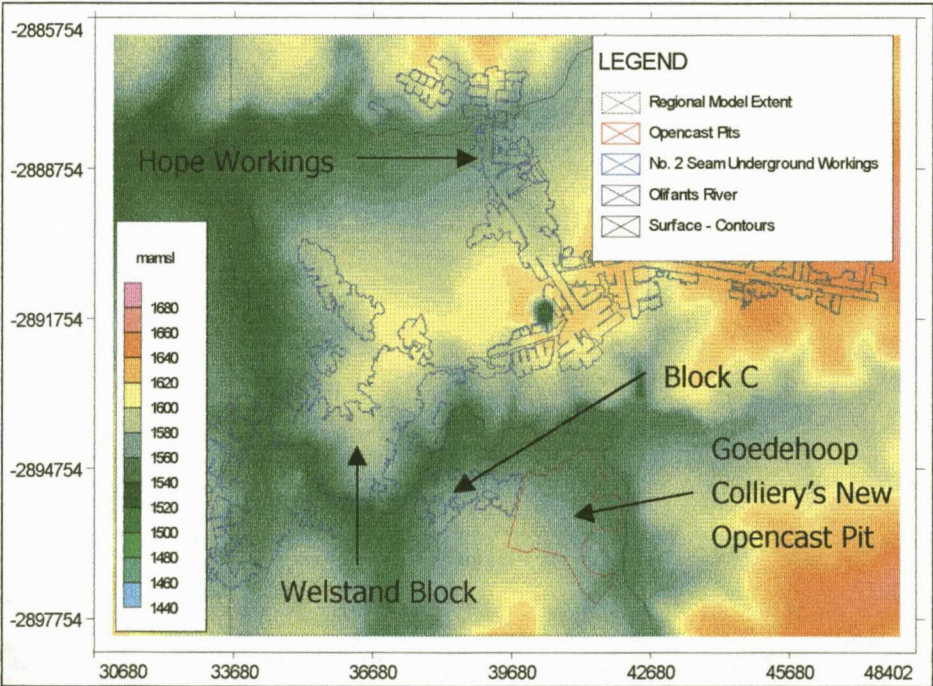


Figure 4-2. Map of the model extent and underground workings as well as opencast pits.

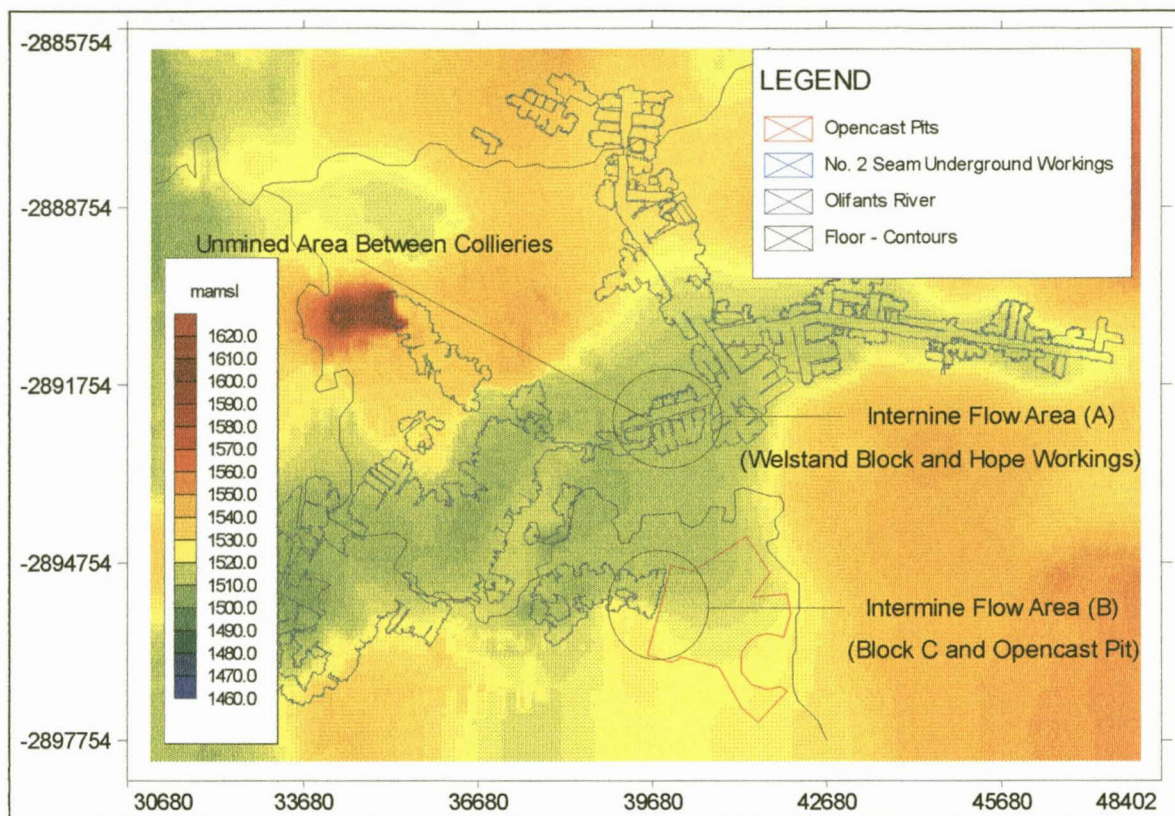


Figure 4-3. Map of intermine flow areas in the TNC-Goedehoop Flow Model and floor contours.

In **Figure 4-3**, two intermine flow areas can be identified, namely intermine flow area (A) – (TNC’s Welstand Block and Goedehoop Colliery’s Hope Workings) and intermine flow area (B) – (TNC’s Block C underground workings and Goedehoop Colliery’s opencast block).

The Hope underground workings are dewatered due to underground mining activities (thus Welstand Block will flow into the Hope Workings as long as the area is kept empty by pumping). The new opencast block at the southern tip of the mine lease area of the Goedehoop Colliery was taken as empty due to future mining activities. In the modelling of intermine flow for the Welstand underground block and the rest of the underground workings and opencast pits, the latest water level as measured in March 2002 was used. The TNC Welstand underground block is flooded to about 1521.5 mamsl.

Conceptually TNC’s Welstand Block (intermine flow area A) will initially (when mining has stopped and pumps are switched off) flow into the Hope Workings and the water levels will equilibrate. After a period of inflow the water level in the Hope Workings will then rise above the water level head of the Welstand Block and thus water will flow into the Welstand Block from the Hope underground workings. This is due to

the higher elevation of the floor contours in certain parts of the Hope Workings (see **Figure 4-3**).

As for TNC's Block C underground workings, it will flow into Goedehoop Colliery's opencast pit. Block C will most probably decant through the opencast pit.

4.2.2 Model Results - Transvaal Navigation Colliery (TNC) – Goedehoop Colliery Flow Model Scenario.

4.2.3 Calculation of Flow Volume Range in Flow Models

The flow volumes (m^3/d) for the intermine flow were modelled with a mean K-value of 0.1017 m/d (Hodgson *et al.*, 1998). To calculate a maximum flow scenario, the standard deviation was added to the mean and a K-value of 0.2312 m/d was used. For example the initial intermine flow from the Welstand Block to Hope Workings will be in the order of 200 m^3/d (K-value of 0.1017 m/d) while the worst-case scenario will be in the order of 440 m^3/d (K-value of 0.2312 m/d). From this it must be noted that the range of possible flow can be very big, depending on the site-specific horizontal hydraulic conductivity. Model

4.2.4 Results - Transvaal Navigation Colliery (TNC) – Goedehoop Colliery Flow Model Scenario

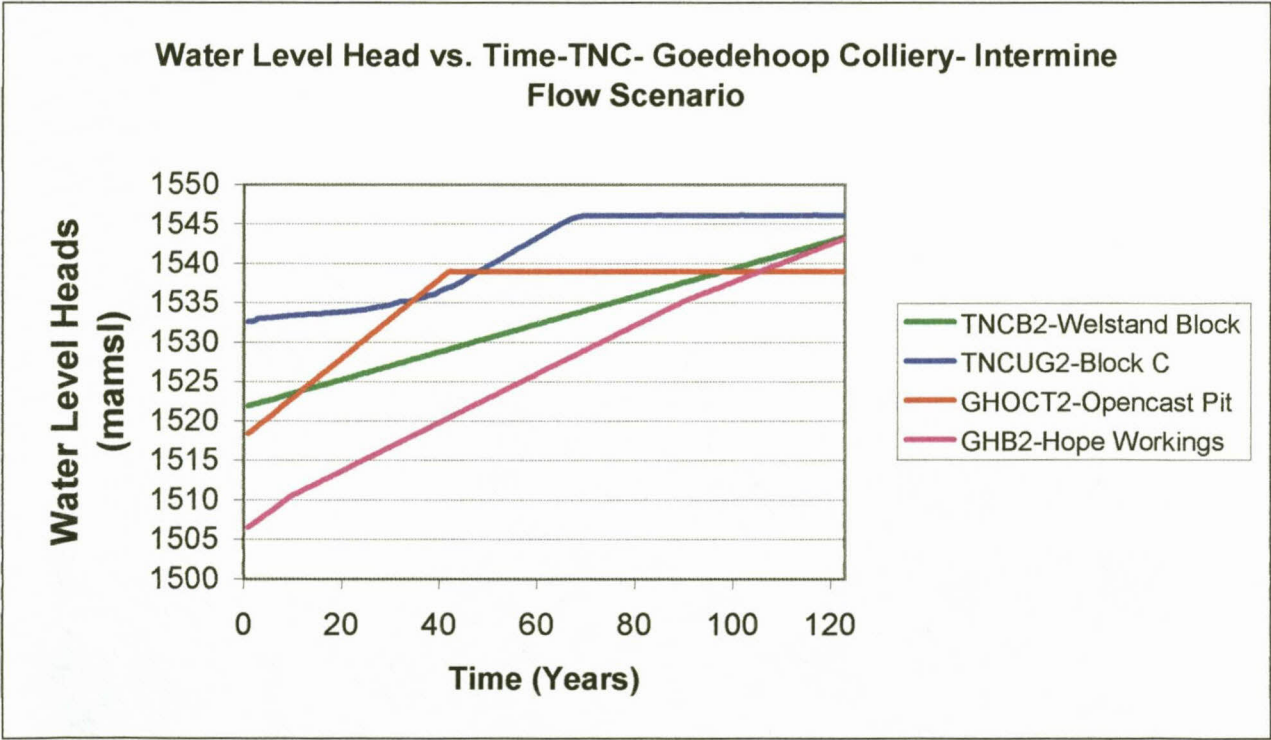


Figure 4-4. Graph of water level heads versus time of the two intermine flow areas A and B of the TNC - Goedehoop Colliery intermine flow scenario (GHB2 – water level heads in the Goedehoop Colliery's Hope underground workings and TNCB2 – water level heads in the

TNC's Welstand underground block), (GHOCT2 – water level heads in Goedehoop Colliery's new opencast pit and TNCUG2 – water level heads in TNC's Block C underground workings).



Figure 4-5. Map of model grid showing the particle tracking (particles in red correspond to the groundwater flow) of groundwater flowing from the Hope underground workings to the Welstand Block (intermine flow area A).

Intermine Flow Area (A): Modelling results show that after all mining has stopped the Welstand underground block will initially flow at an average rate of 200 m³/d, and a worst-case flow volume of 440m³/d into the Hope underground workings, due to the different water level heads (see **Figure 4-4**).

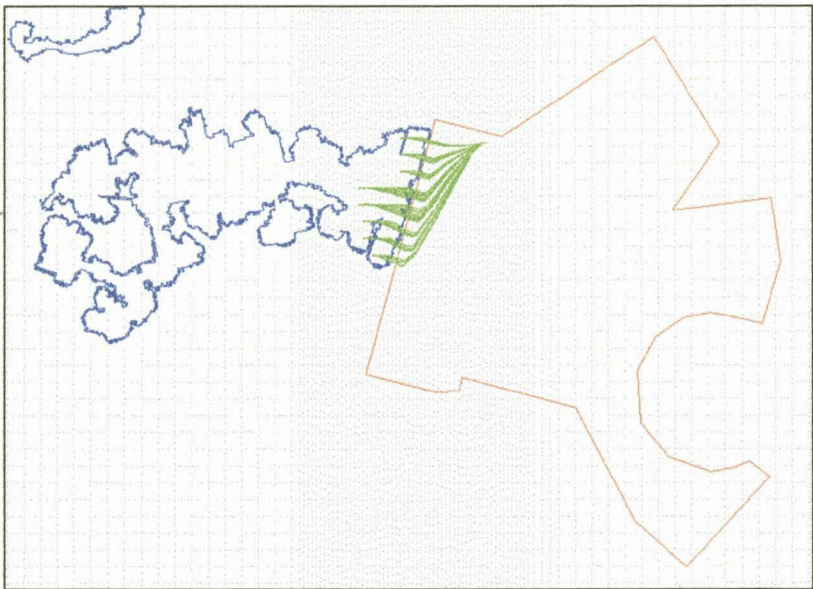


Figure 4-6. Map of model grid showing the particle tracking (particles in green correspond to the groundwater flow) of groundwater flowing from the Block C underground workings to the Goedehoop Colliery's new opencast pit (intermine flow area B).

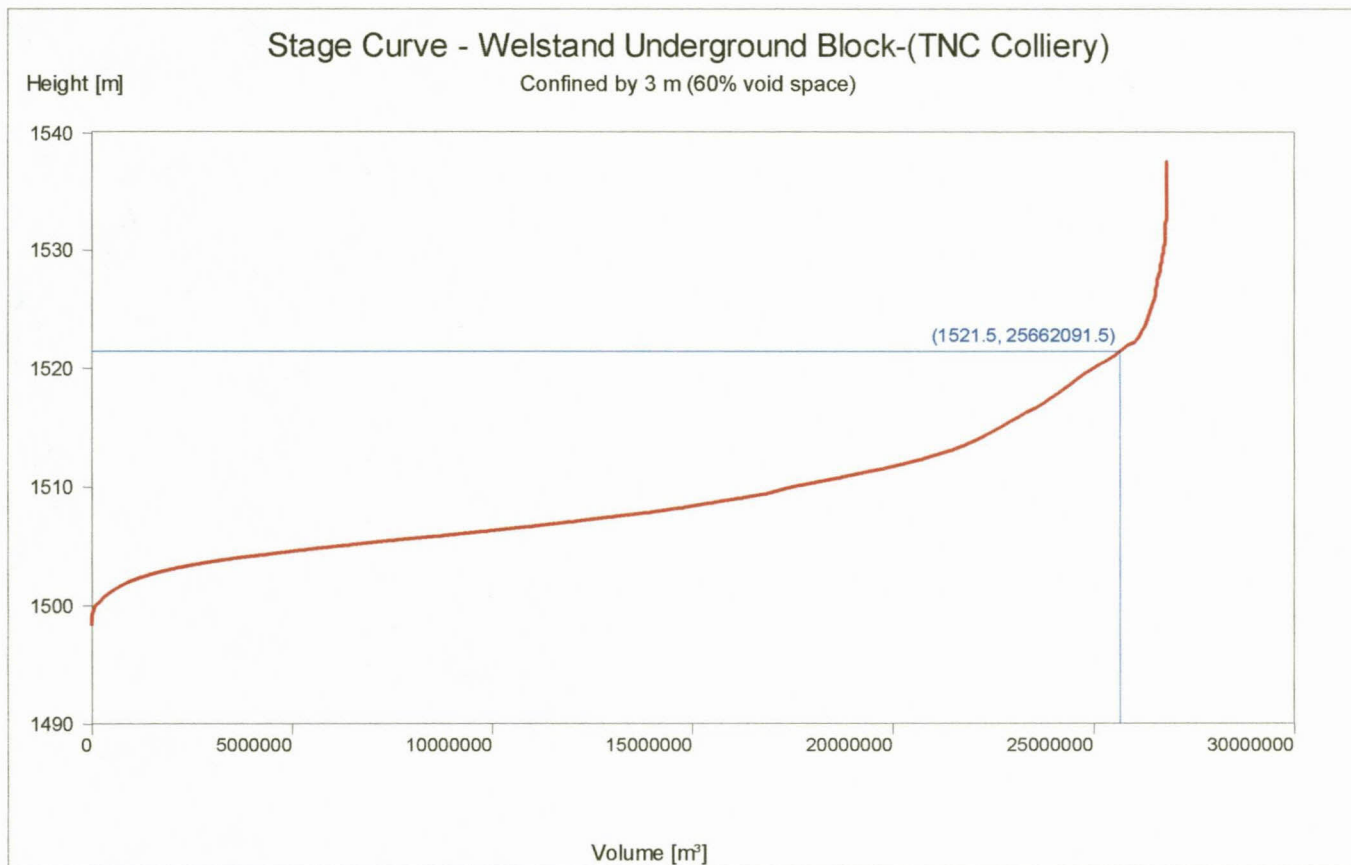


Figure 4-7. Stage curve for the Welstand underground block.

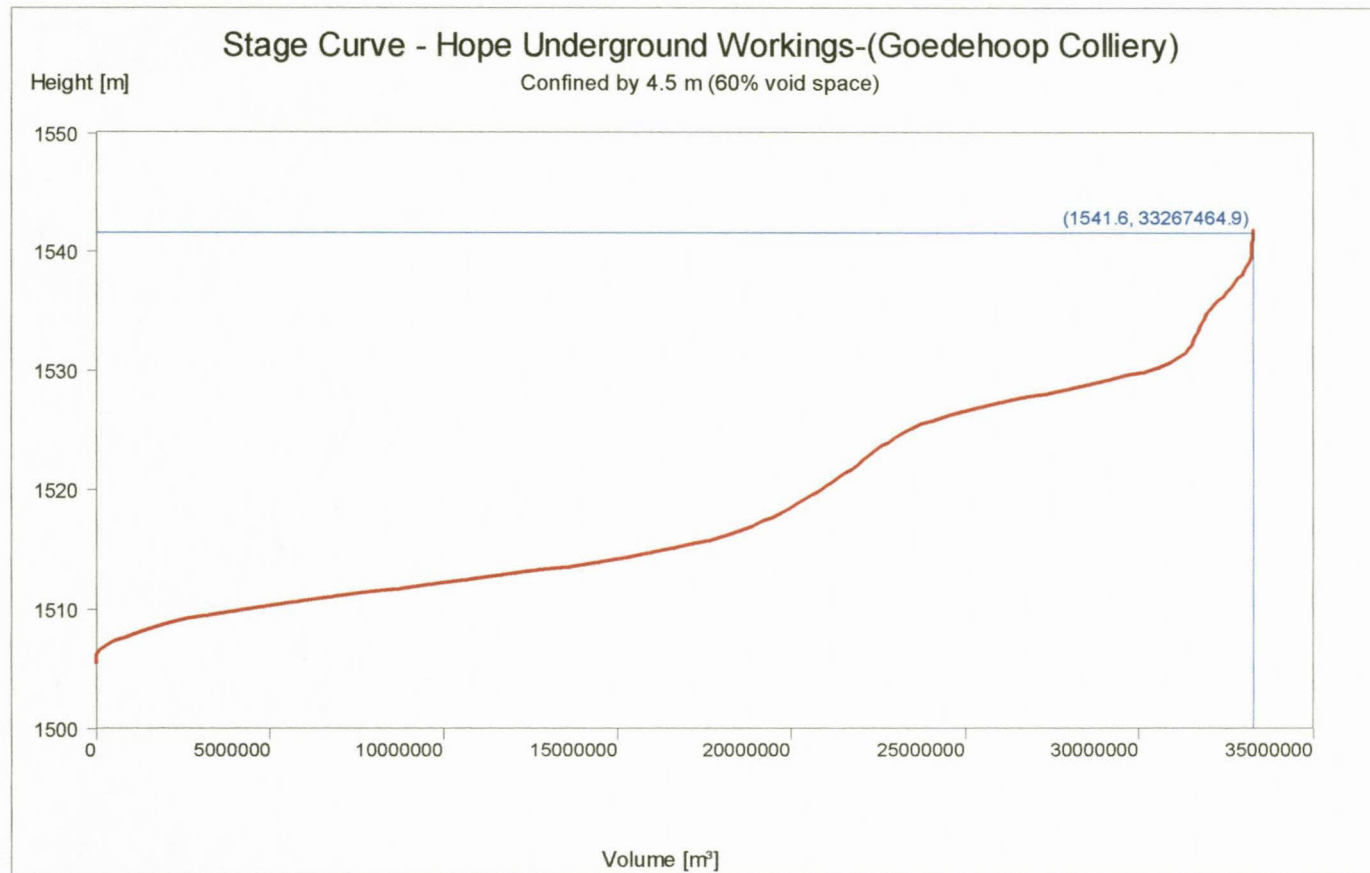


Figure 4-8 Stage curve for Hope underground workings.

TNC's water level is currently at 1521.5 mamsl and Welstand underground block is about 95% flooded (see **Figure 4-2** for stage curve, a stage curve is graph of water level (mamsl) in void versus volume of water in void), whereas the old Hope underground workings were taken as empty, the flow gradient is initially in the direction of Goedehoop Colliery. The flow direction will remain in the direction of the Hope Workings until the water level heads in the two voids equalise (**Figure 4-4**). As the water level heads equalise, the flow volume will decrease (**Figure 4-9**). Hope Workings will be filled with water up to a water level of approximately 1541.6 mamsl. It will take Hope Workings approximately between 110 - 123 years to fill up at 3% recharge, and as long as 185 years with 2% recharge. Therefore site-specific recharge values are very important. The TNC Welstand Block will be filled completely at a level of 1530.5 mamsl.

Intermine Flow Area (B): Block C will flow into Goedehoop's (see **Figure 4-4**) new opencast pit. The Goedehoop's water level will be on the floor due to mining activities and Block C's water level is currently at 1532.5 mamsl. Average projected flow volumes are around $130\text{m}^3/\text{d}$ (see **Figure 4-9**), while the worst-case estimate can be as high as $300\text{ m}^3/\text{d}$). The Block C underground flow volume into the opencast pit decreases (see **Figure 4-9**) over time as the difference in water levels diminishes. After 35-40 years the water level heads in the pit and underground will have stabilised and the opencast pit will flow into the Block C underground. After 39 to 42 years (see **Figure 4-9** and **Figure 4-11**) the opencast pit will decant at a decant level of 1539.79 mamsl, if the pit is not flooded by flood events or filled from a river. The water level in the opencast pit of Goedehoop Colliery will remain stable at 1539.7 mamsl but the water level in TNC's underground block C will still rise and reach the level of the opencast pit in approximately 48 to 53 years. Block C underground will once again flow into the opencast pit. The flow volume will then increase to about $60 - 80\text{ m}^3/\text{d}$ (see **Figure 4-9**) as the water levels in the pit remain stable at 1539 mamsl, and the water level in Block C rises to its decant level of 1546 mamsl.

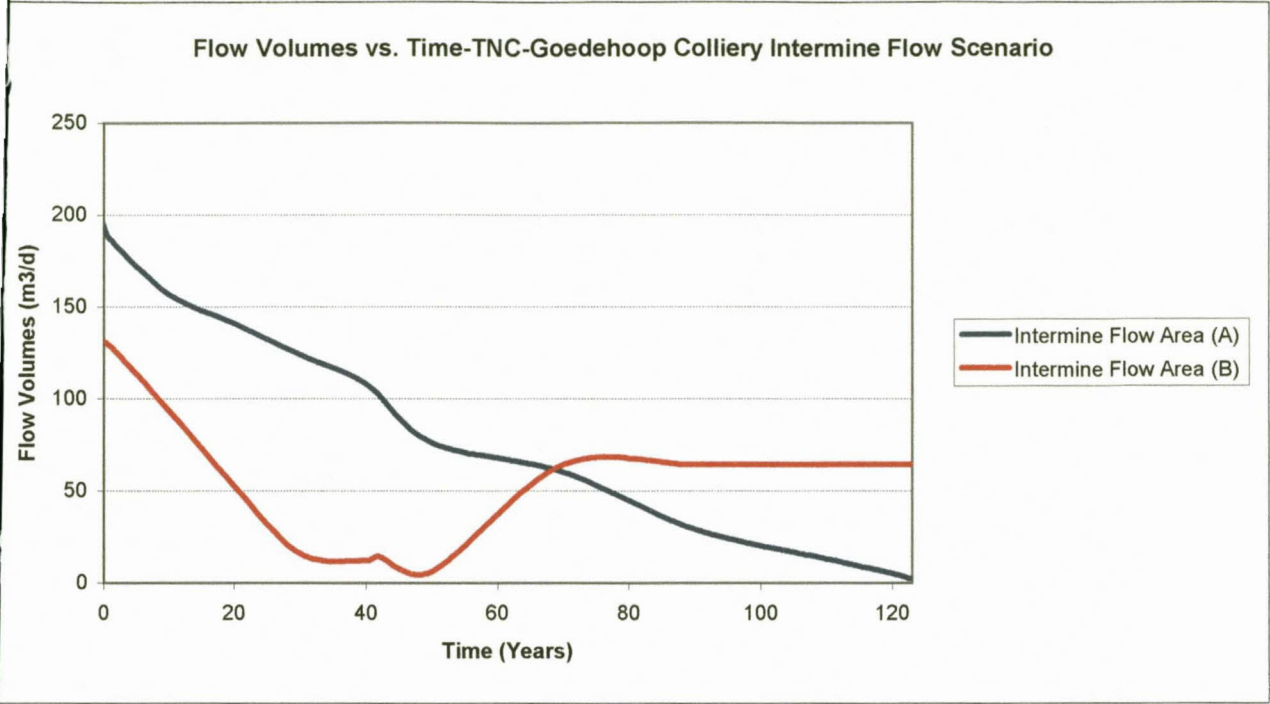


Figure 4-9. Graph of flow volumes in the intermine flow areas in the TNC-Goedehoop Colliery scenario.

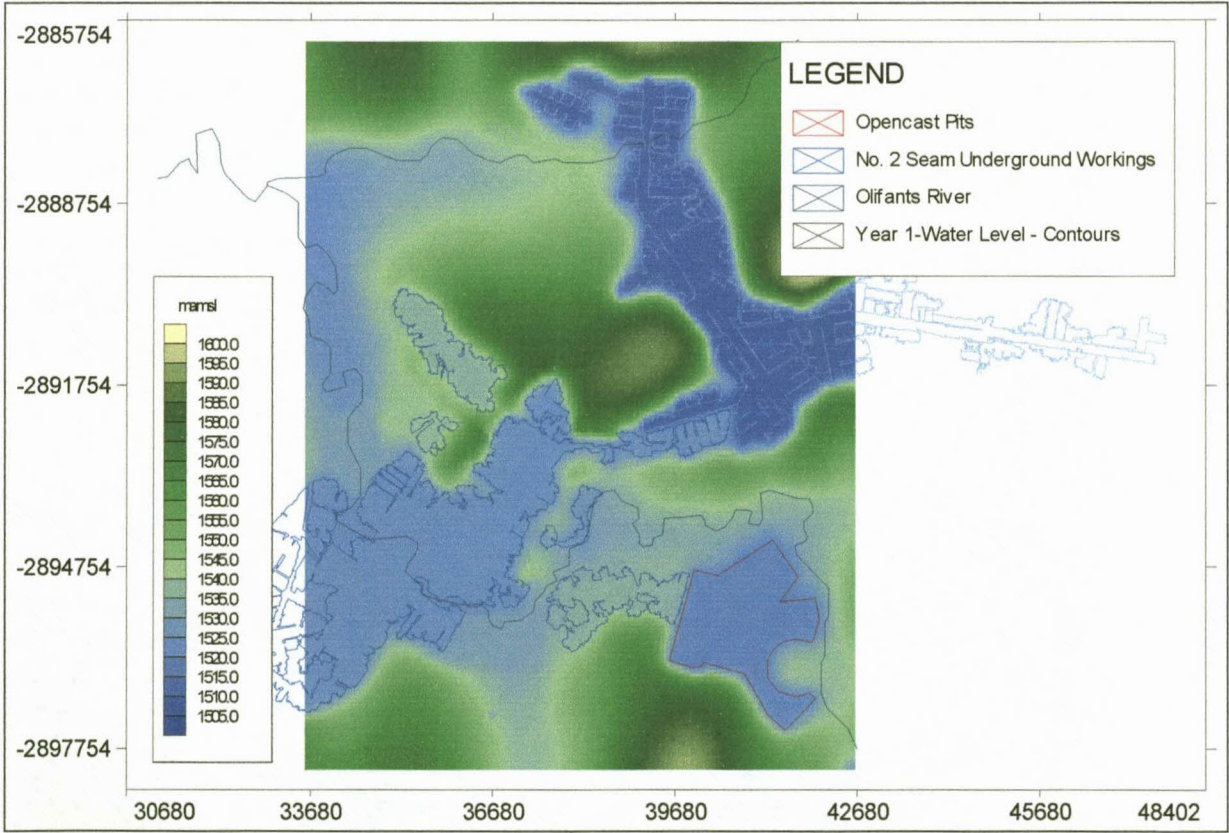


Figure 4-10. Contour maps showing the changing water level scenario of the TNC – Goedehoop Colliery scenario flow model (Year 1 water levels).

In **Figure 4-10** and **Figure 4-11** the changing contour levels as well as the decant positions can be seen. **Figure 4-11** shows decant contour levels of Goedehoop Colliery's new opencast pit in year 42.

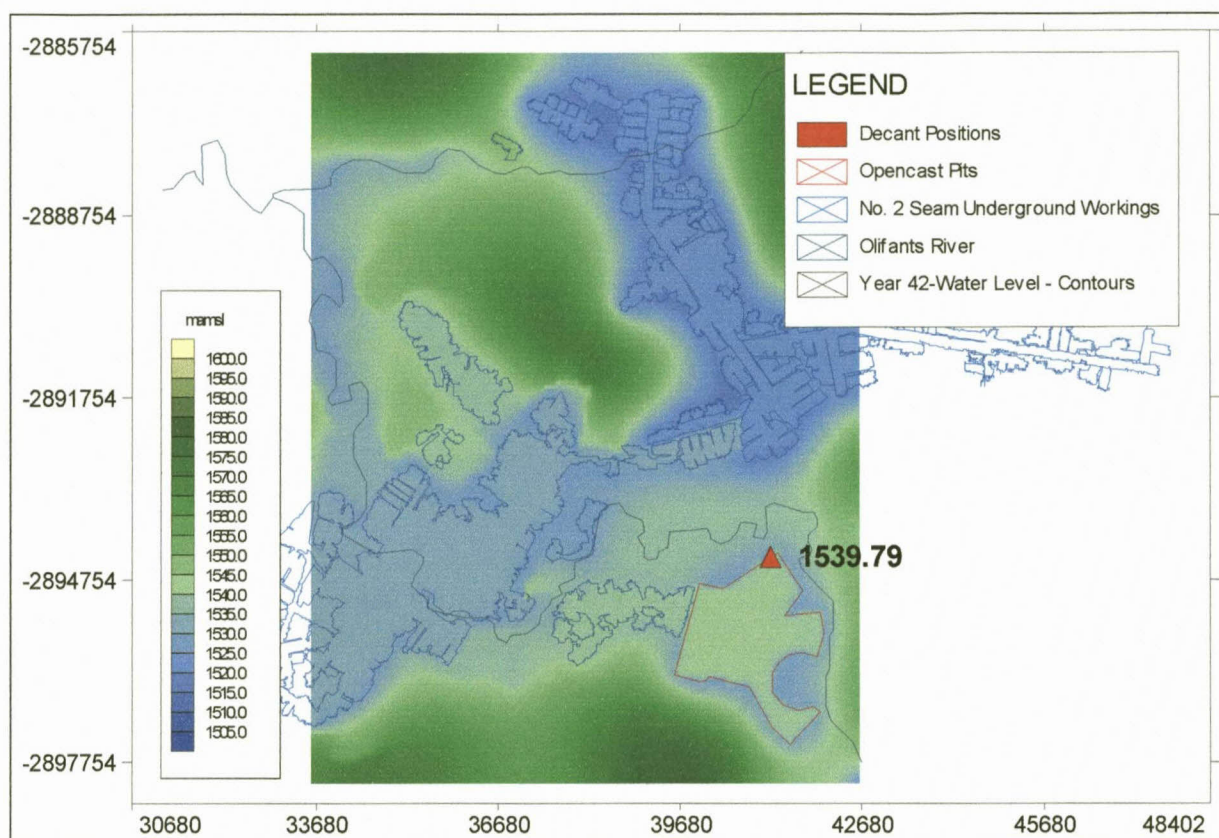


Figure 4-11. Contour maps showing the changing water level scenario of the TNC – Goedehoop Colliery scenario flow model (Year 42 water levels – opencast pit at decant level).

4.3 DOUGLAS COLLIERY – GOEDEHOOP COLLIERY FLOW MODEL SCENARIO

This section of the chapter describes and quantifies the intermine flow between Douglas Colliery and Goedehoop Colliery for the post-mining scenario.

4.3.1 Conceptual Model

In the model area (**Figure 4-12**) two possible intermine flow areas have been identified. The first area of possible intermine flow is intermine flow area A, which includes the Springbok No. 2 Seam underground workings of Goedehoop Colliery and the Van Dyks Drift No. 2 Seam underground workings and the North Shaft workings of Douglas Colliery.

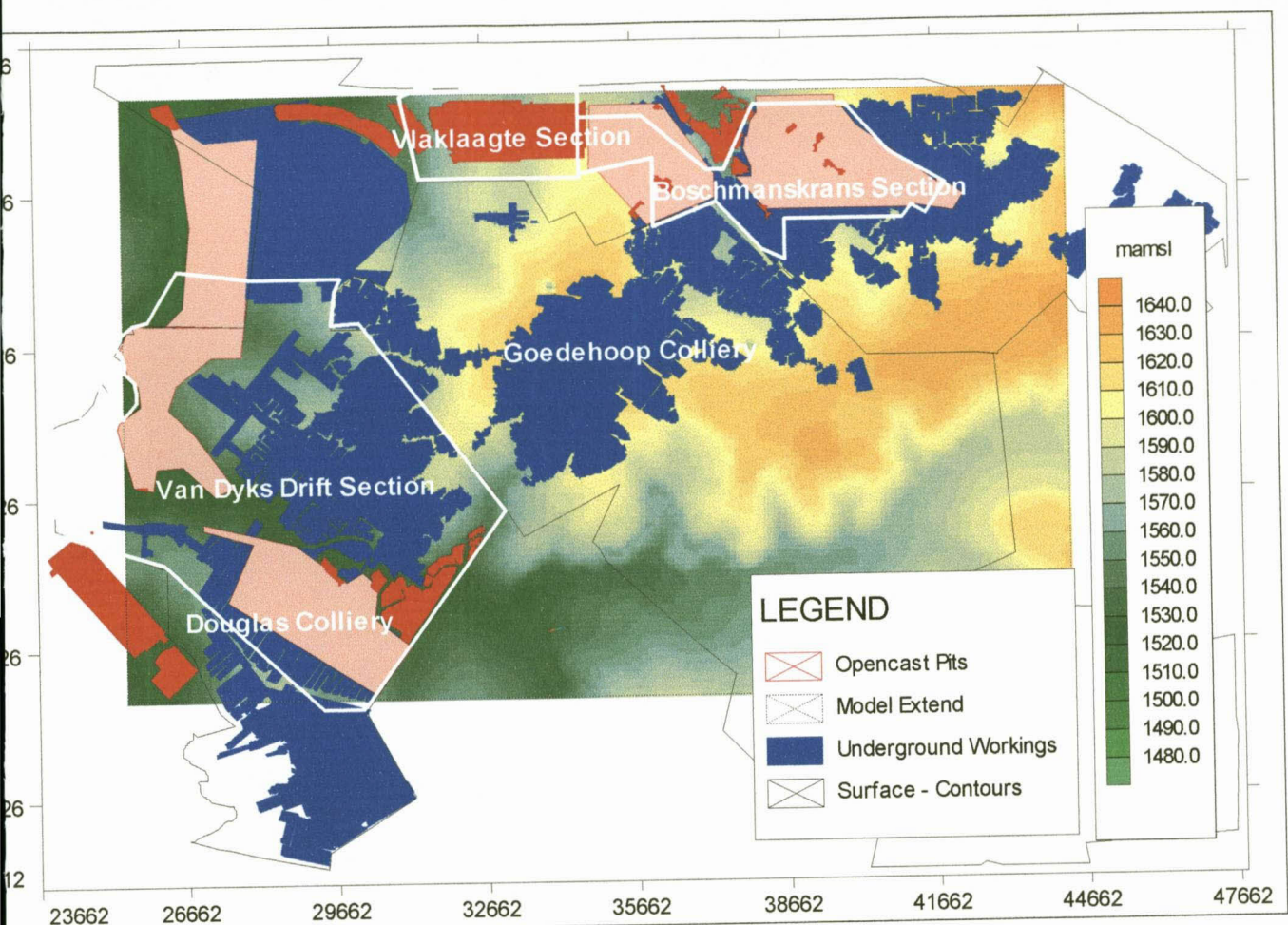


Figure 4-12. Map of the model extent (Goedehoop – Douglas intermine Flow Model) and underground workings as well as opencast pits.

The second area (intermine flow area B), includes the possible flow of water from Goedehoop's Springbok underground No. 2 Seam Section to Douglas Colliery's No. 2 Seam Underground workings in the Boschmanskrans Section. The future opencast pits (Boschmanskrans East and West Pit) are going to be mined into the Boschmanskrans underground workings to remove the pillars left during underground mining.

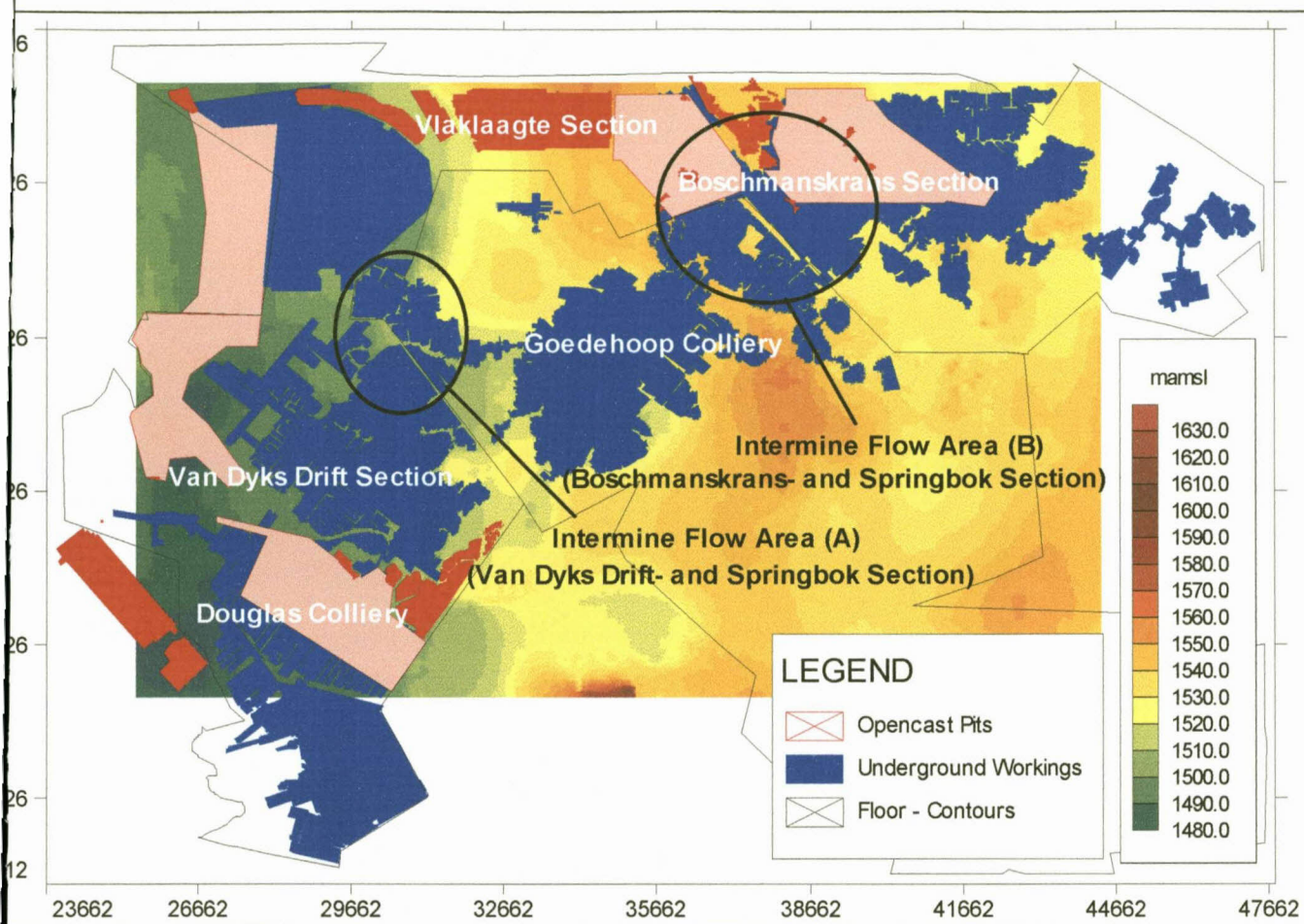


Figure 4-13. Map of intermine flow areas in the Douglas - Goedehoop Intermine Flow Model and floor contours.

In modelling, the underground workings of both of Douglas Colliery's sections have been taken as dewatered, due to the future opencast pits that will be mined into these underground workings, thus necessitating the dewatering of the underground workings. The Goedehoop Underground Springbok section's current water levels were used as starting water levels for the model. According to the Douglas mining plans (2002) the mining duration of the Boschmanskrans Pillar mining project will go on until 2014. The Springbok section of Douglas was allowed to fill up at with a 3% recharge value in the flow model.

Due to the dewatering in the Douglas underground workings the groundwater flows from the Goedehoop underground No. 2 Seam workings into the Van Dyks Drift Section and Boschmanskrans section via their No. 2 Seam underground workings. Eventually, due to the higher recharge through the opencast pits spoils after mining has ceased at the Douglas Sections, Boschmanskrans Section will flow into Goedehoop Colliery's No. 2 Seam underground sections (intermine flow area B). In intermine flow area (A) the flow direction will initially be from Springbok underground workings to the Van Dyks Drift section.

4.3.2 Model Results - Douglas Colliery – Goedehoop Colliery Flow Model Scenario

Intermine Flow Area (A): Modelling results indicate that mine water from the Springbok underground workings will initially flow into the Van Dyks Drift underground workings (**Figure 4-14** and **Figure 4-15**). The flow volume is initially 400 m³/d (0.1017 m/d) and 900 m³/d for a worst case scenario modelled with a hydraulic conductivity of 0.2312 m/d (**Figure 4-17**), but the flow volume decreases as the water level heads in the Springbok No. 2 Seam underground and the Van Dyks Drift No. 2 Seam underground approach the same level.



Figure 4-14. Picture showing a detailed map of intermine flow area (A), which includes Springbok underground workings, Van Dyks Drift underground workings and the North Shaft underground workings.

The flow of water from Goedehoop's underground to the Van Dyks Drift section will continue for about 38 – 42 years (**Figure 4-1**). The water level head in the Van Dyks Drift workings will then rise above the water level head of the Springbok underground section, the flow direction will reverse and mine water will flow from Van Dyks Drift underground workings to the Springbok underground workings. Eventually the water levels will recover and the natural gradient of flow will be in the direction of the Van Dyks Drift No. 2 Seam underground. As for the intermine flow interaction between the North Shaft underground workings and the Springbok underground workings (**Figure 4-14**), the Springbok underground workings will flow into the North Shaft underground workings (**Figure 4-15**).

The rate of flow while mining continues will be in the order of 400 - 600m³/d with a partly filled No. 2 Seam underground.

Water Level Head vs. Time-Douglas Colliery-Goedehoop Colliery Intermine Flow Scenario

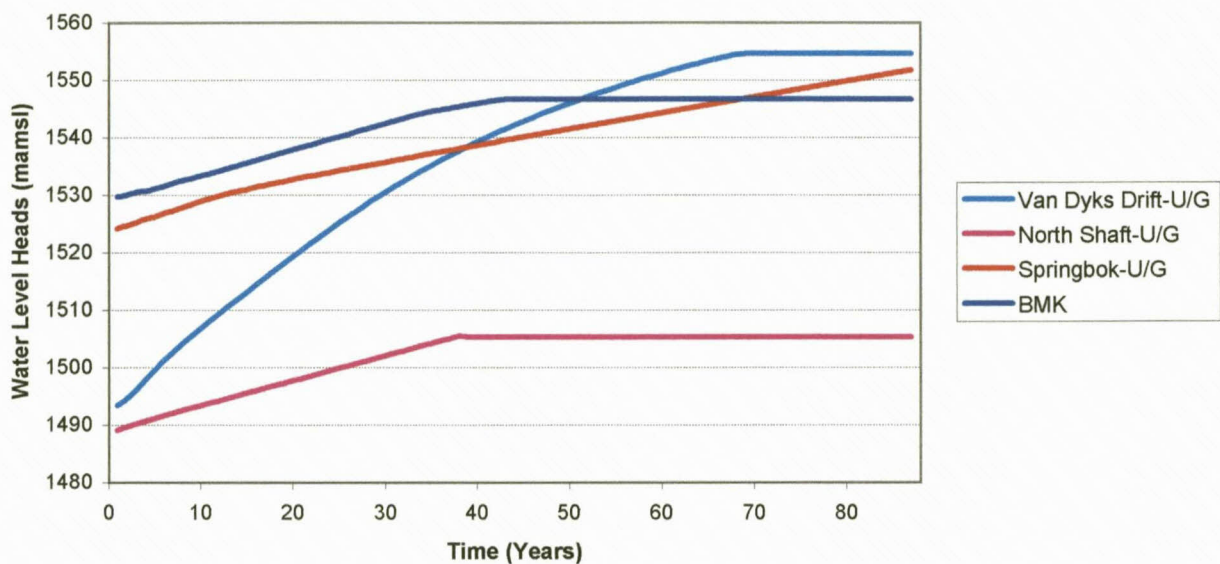


Figure 4-15. Graph of water level heads versus time of the two intermine flow areas A and B of the Douglas Colliery - Goedehoop Colliery intermine flow scenario (intermine flow area A: Are water level heads in the Goedehoop Colliery's Springbok No. 2 Seam underground workings (Springbok-U/G) and water level heads in the Van Dyks Drift No. 2 Seam underground workings (Van Dyks Drift-U/G) as well as the North Shaft underground workings (North Shaft-U/G)), (intermine flow area B: water level heads in the Goedehoop Colliery's Springbok No. 2 Seam underground workings (Springbok-U/G) and water level heads in the Boschmanskrans No. 2 Seam underground workings (BMK) and Opencast Pits namely the Boschmanskrans East- and West Pit).

After mining has stopped in the North Shaft underground, the rate of flow will initially be in the order of 400 to 500 m³/d, if the area is allowed to fill up. Since the future planned Steenkool Spruit/Kleinkopje opencast pit extent is right next to the North Shaft underground workings, the opencast pit and the underground workings will be hydraulically interconnected. This means that the North Shaft underground workings will decant through the Steenkool Spruit/Kleinkopje opencast pit at 1507 mamsl. The water level head in the North Shaft underground workings can never rise above the 1507 mamsl level if it is connected to the Steenkool Spruit/Kleinkopje opencast pit. Due to this, the intermine flow direction can only be in the direction of the North Shaft undergrounds. Consequently with the rise in water level head in the Springbok No. 2 Seam undergrounds, the flow volume will increase over time from 500 to 600 m³/d.

Fill-up times of opencast pits and underground workings for intermine flow area (A): The Springbok No. 2 Seam underground, which is partly flooded, will start to fill up further. After the mining of the pillars (2015) into the underground workings via opencast pit methods, dewatering will cease. The Van Dyks Drift underground will then be connected to two future opencast pits and will start to fill up with water. The opencast pit together with the No. 2 Seam underground workings will be totally filled up to decant level (1554.64 mamsl) in about 85 - 90 years (NWVDD) (Figure 4-16). The eventual decant volume will be about 2000 - 2300 m³/d. The Van Dyks Drift underground workings will decant partly through the Steenkoolspruit/Kleinkopje opencast pit and the opencast pits where the pillars of the Van Dyks Drift underground workings were extracted. The Steenkool spruit/Kleinkopje opencast pit and connected North Shaft underground workings will fill up and decant in about 38 to 42 years (SKP) (Figure 4-16 and Figure 4-19). The decant volume will be about 4000 – 5000 m³/d at a level of 1507 mamsl. Goedehoop Colliery's Springbok underground workings will take about 55 – 65 years to fill up with groundwater at a level of 1546.6 mamsl.

Intermine flow area (B): The initial intermine flow direction will be to Goedehoop No. 2 Seam underground (The opencast pits are connected due to the pillar project and will most probably be connected to each other through the Boschmanskrans No. 2 Seam underground workings. After mining has stopped, the water level in the Boschmanskrans No. 2 Seam underground and connected opencast pits (Boschmanskrans East- and West Pits) will rise and the flow volume will increase. The initial flow volume in the first year will be in the order of 320 m³/d to a worst case of 700 m³/d. The water level head in the Boschmanskrans underground and opencast pits will rise faster than in the Goedehoop underground workings. The flow volume of groundwater will increase from about 320 m³/d to approximately 420 m³/d (Figure 4-17) in approximately 43 years after mining has ceased. The underground will most probably decant through the Boschmanskrans East Pit at a decant level of (1546.65 mamsl). When this decant level has been reached, the water level will stay stable and the water level head in the Goedehoop No. 2 Seam will still rise while the flow volume will decrease. Eventually the heads will equalise and the Goedehoop No. 2 Seam underground will rise above that of the head of the Boschmanskrans underground, and the flow direction will reverse. Accordingly the flow direction will be from Goedehoop No. 2 Seam underground to the Boschmanskrans No. 2 Seam underground and Boschmanskrans East Pit in about 65 to 75 years (Figure 4-15). The intermine flow volume from the Goedehoop No. 2 Seam underground to the Boschmanskrans underground workings and East Pit will be in the order of 300 m³/d.

Water Level heads vs. Time-Full up Times of Douglas Colliery's Opencast Pits and connected Underground Workings

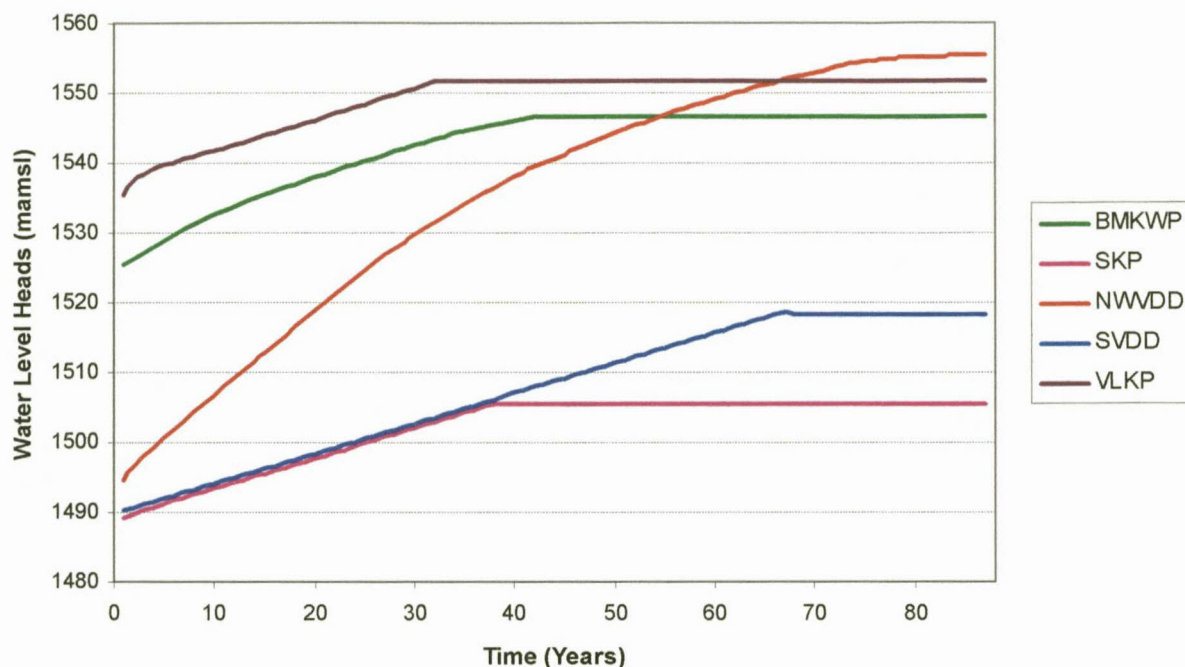


Figure 4-16. Graph of the water level head versus time of the fill-up times of Douglas Colliery's opencast pits and connected underground workings (BMKWP-Boschmanskrans connected West and East pit via the Boschmanskrans No. 2 Seam underground workings, SKP- Steenkool Spruit/-Kleinkopje opencast pit, NWVDD-The part north of the Olifants River of the Van Dyks Drift section that includes the Van Dyks Drift connected No. 2 Seam underground workings and two opencast pits, SVDD- The part south of the Olifants River of the Van Dyks Drift section that includes the interconnected No. 2 Seam underground workings and the VDD South opencast pit, VLKP-Vlaklaagte pit.

Fill-up times of opencast pits and underground workings for intermine flow area (B): The Boschmanskrans East and West opencast pit as well as the connected No. 2 Seam underground (BMKWP) will take between 38 to 43 years to fill up to a decant level of 1545.33 mamsl (Figure 4-16 and Figure 4-20). The underground and West Pit will decant through the East Pit if they are connected through the No. 2 Seam underground, which will most probably be the case due to the pillar project at the Boschmanskrans section. The combined decant volume will be in the range of 3900 - 4900 m³/d.

Fill-up times of other opencast pits and underground workings: The Van Dyks Drift South opencast pit is also mined into the Van Dyks Drift No. 2 Seam underground workings to extract the pillars left behind. The opencast pit and connected underground workings (SVDD) will fill up to decant level (1518.33

mamsl) in about 60 to 70 years (**Figure 4-21**). The decant volume will probably be in the order of 2000 to 3000 m³/d. Vlaklaagte opencast pit will decant at a level of 1551.63 mamsl. The Vlaklaagte opencast pit will take about 28 to 32 years to fill up (**Figure 4-17** and **Figure 4-18**) and the decant volume will be in the order of 1300 to 1400 m³/d.

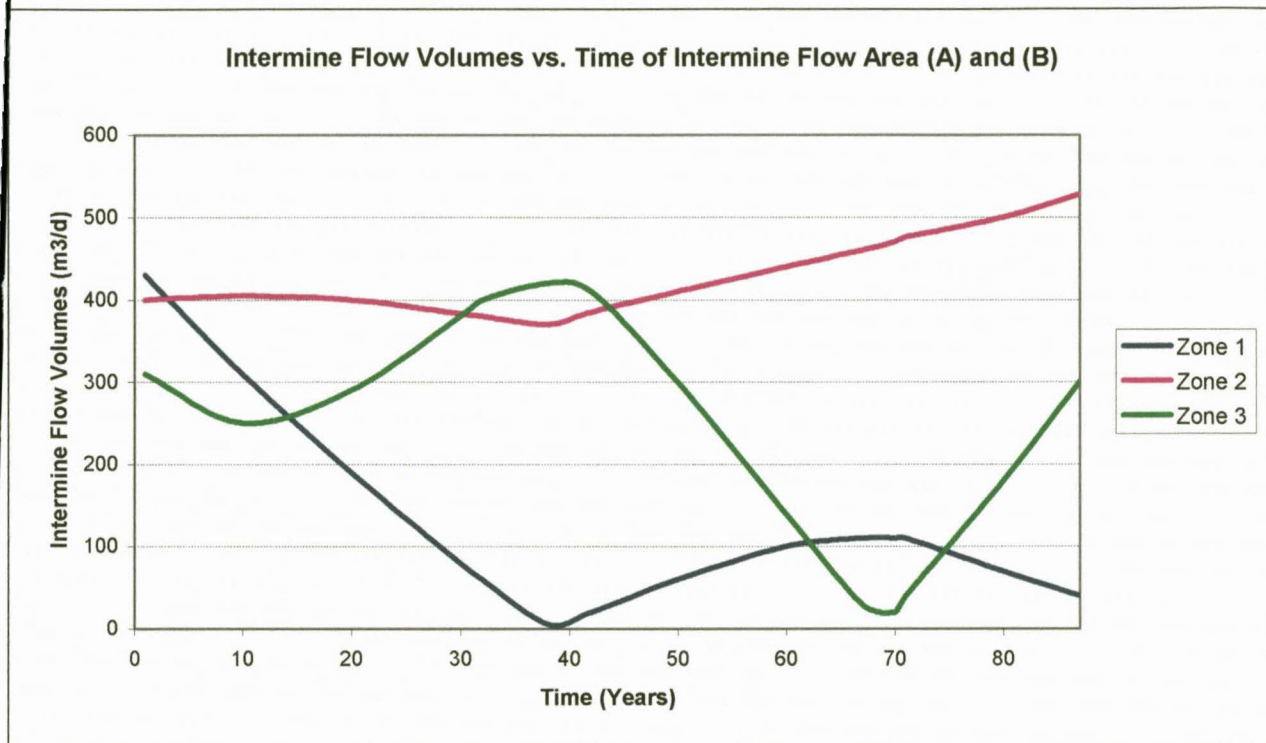


Figure 4-17. Graph of intermine flow volumes versus time (Zone 1 – Intermine flow between Springbok No. 2 Seam underground and Van Dyks Drift No. 2 Seam underground, Zone 2 – Intermine flow between Springbok No. 2 Seam underground and the North Shaft No. 2 Seam underground, Zone 3 – Intermine flow between Goedehoop No. 2 Seam underground and the Boschmanskrans No. 2 Seam underground and Boschmanskrans East Pit.

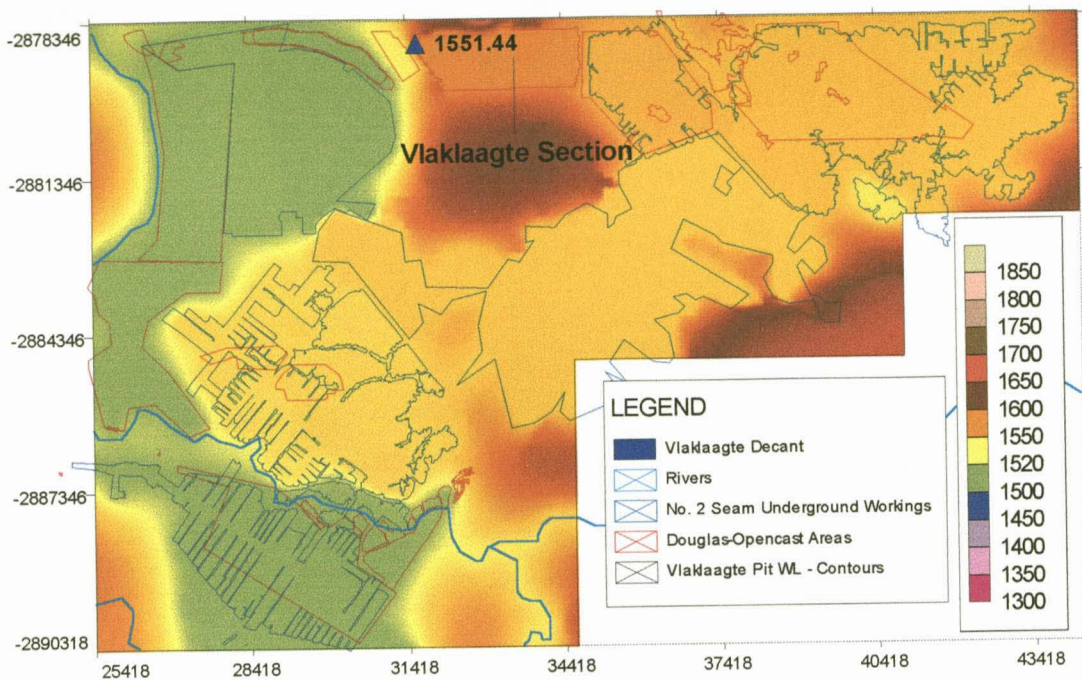


Figure 4-18. Contour Map with the decant position (1551.44 mamsl) of the Vlaklaagte opencast pit and the model water levels of year 32, which is the decant water level for the above-mentioned opencast pit.

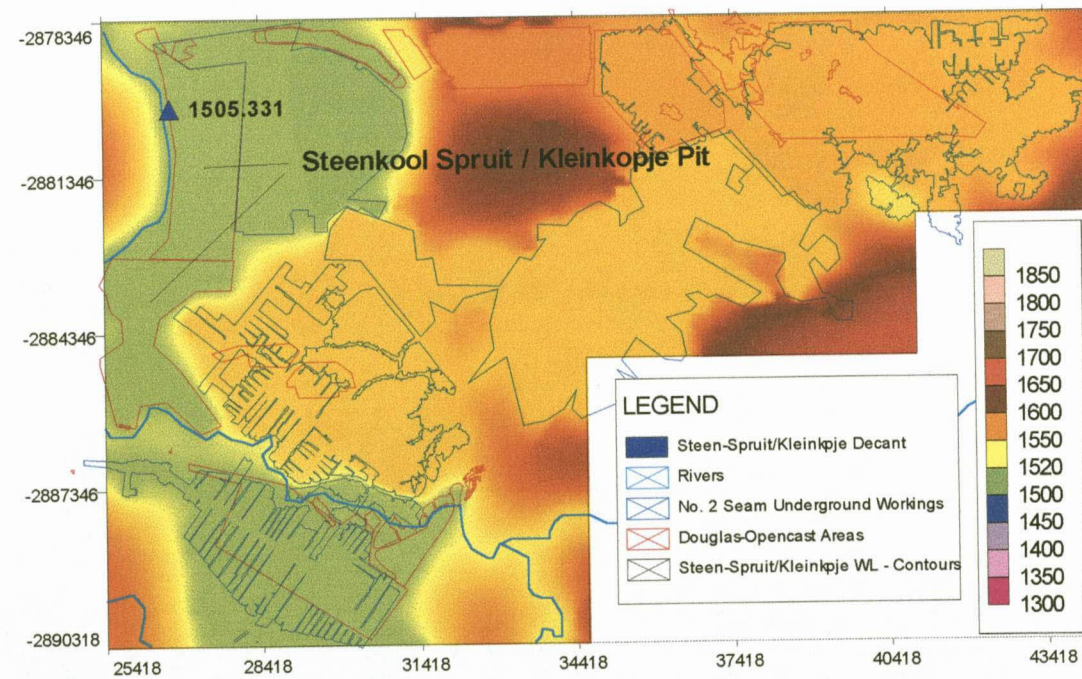


Figure 4-19. Contour Map with the decant position (1505.331 mamsl) of the Steenkool Spruit/Kleinkopje opencast pit and the model water levels of year 38, which is the decant water level for the above-mentioned opencast pit.

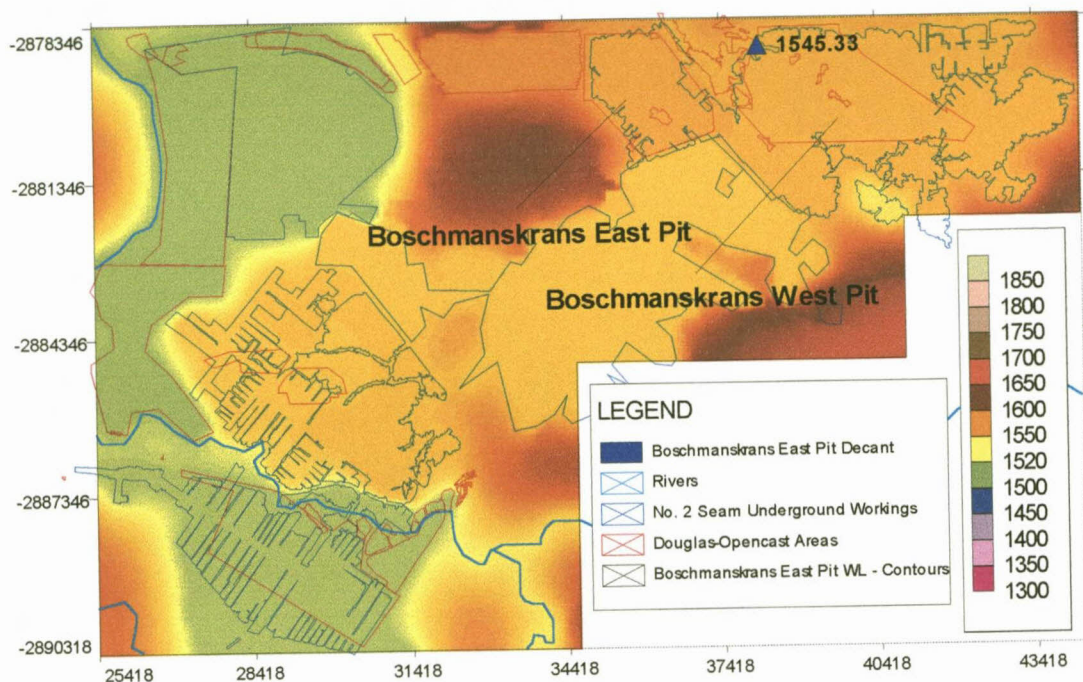


Figure 4-20. Contour Map with the decant position (1545.33 mamsl) of the Boschmanskrans West opencast pit and the model water levels of year 42, which is the decant water level for the above-mentioned opencast pit.

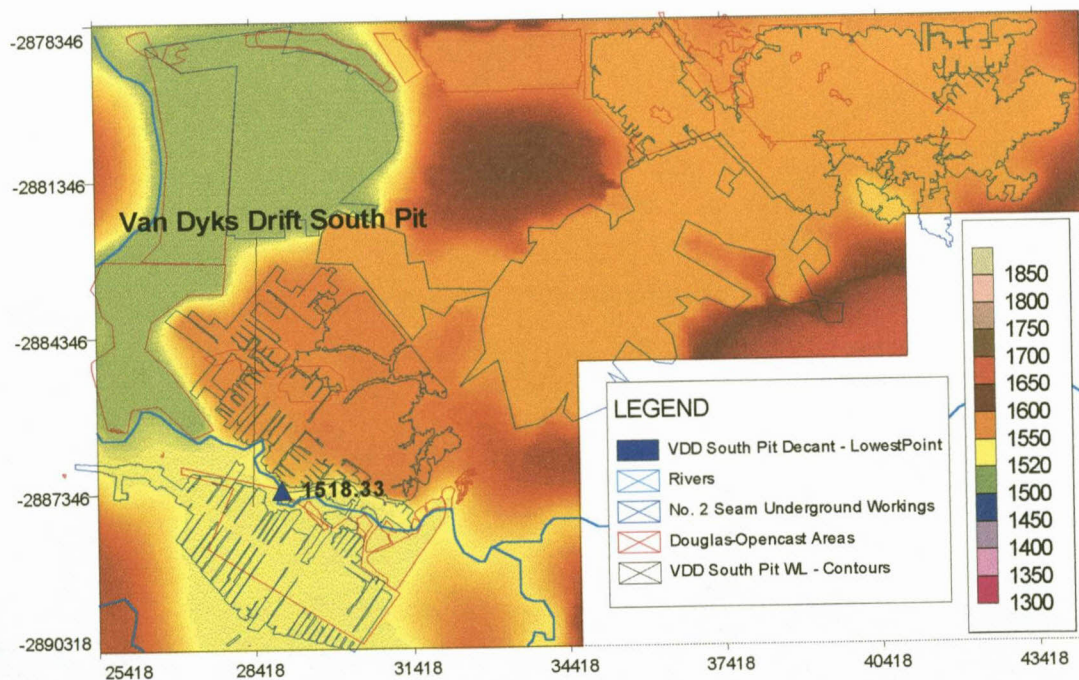


Figure 4-21. Contour Map with the decant position (1518.33 mamsl) of the Van Dyks Drift South opencast pit and the model water levels of year 68, which is the decant water level for the above-mentioned opencast pit.

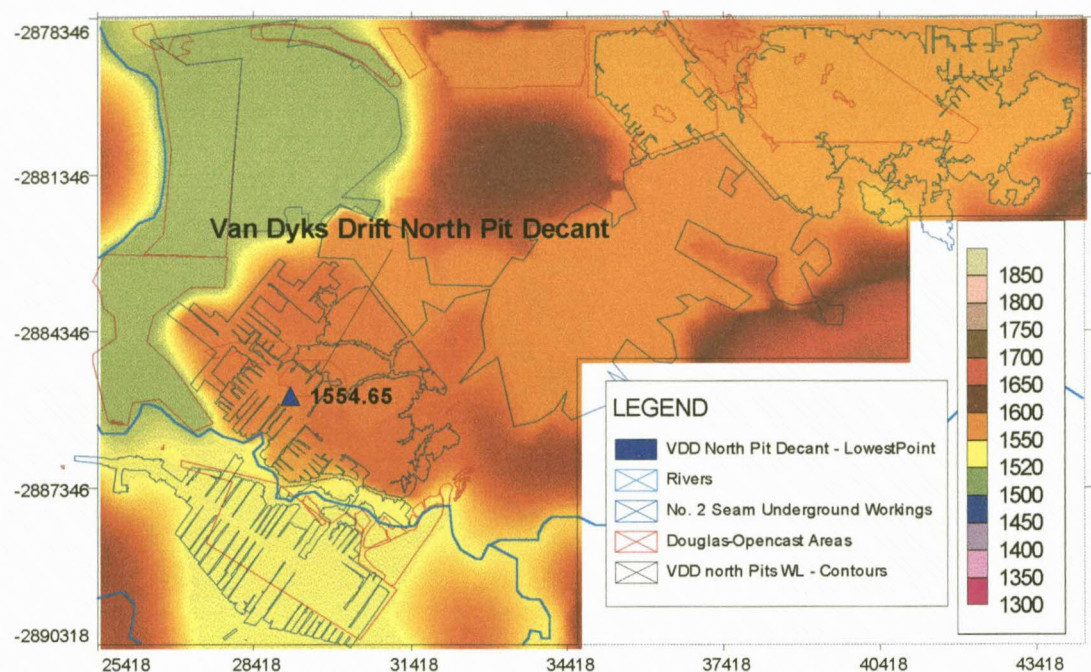


Figure 4-22. Contour Map with the decant position (1554.65 mamsl) of the Van Dyks Drift North Pit opencast pit and the model water levels of year 87, which is the decant water level for the above-mentioned opencast pit.

Table 4-1. Summary of decant elevations, decant volumes and fill-up times calculated.

Void Name	Decant Elevation (mamsl)	Decant Volumes (m3/d)	Fillup Times (years)
Van Dyks Drift No. 2 Seam U/G and Connected Pits	1554.64	2000 - 2300	85 - 90
enkoolspruit/Kleinkopje Pit and Connected North Shaft U/G	1507.00	4000 – 5000	38 - 42
Boschmanskrans East and West Pit and Connected U/G	1545.33	3900 - 4900	38 - 43
Van Dyks Drift South Opencast Pit and Connected U/G	1518.33	2000 - 3000	60 - 70
Vlakraagte Opencast Pit	1551.63	1300 - 1400	28 - 32

4.4 TRANSVAAL NAVIGATION COLLIERY (TNC) – NEW CLYDESDALE COLLIERY AND DOUGLAS COLLIERY FLOW MODEL SCENARIO

This section of the chapter quantifies the TNC, New Clydesdale and Douglas Colliery post-mining intermine flow scenario.

4.4.1 Conceptual Model

The model area consists of the Welstand No. 2 Seam underground block, the New Clydesdale No. 2 Seam underground workings and the Albion Section (Douglas Colliery) No. 2 Seam underground workings (**Figure 4-23**). The thickness of the unmined area between Albion section and New Clydesdale is on average 64 m. The variable thickness of the unmined area between TNC and New Clydesdale is on average approximately 46 m.

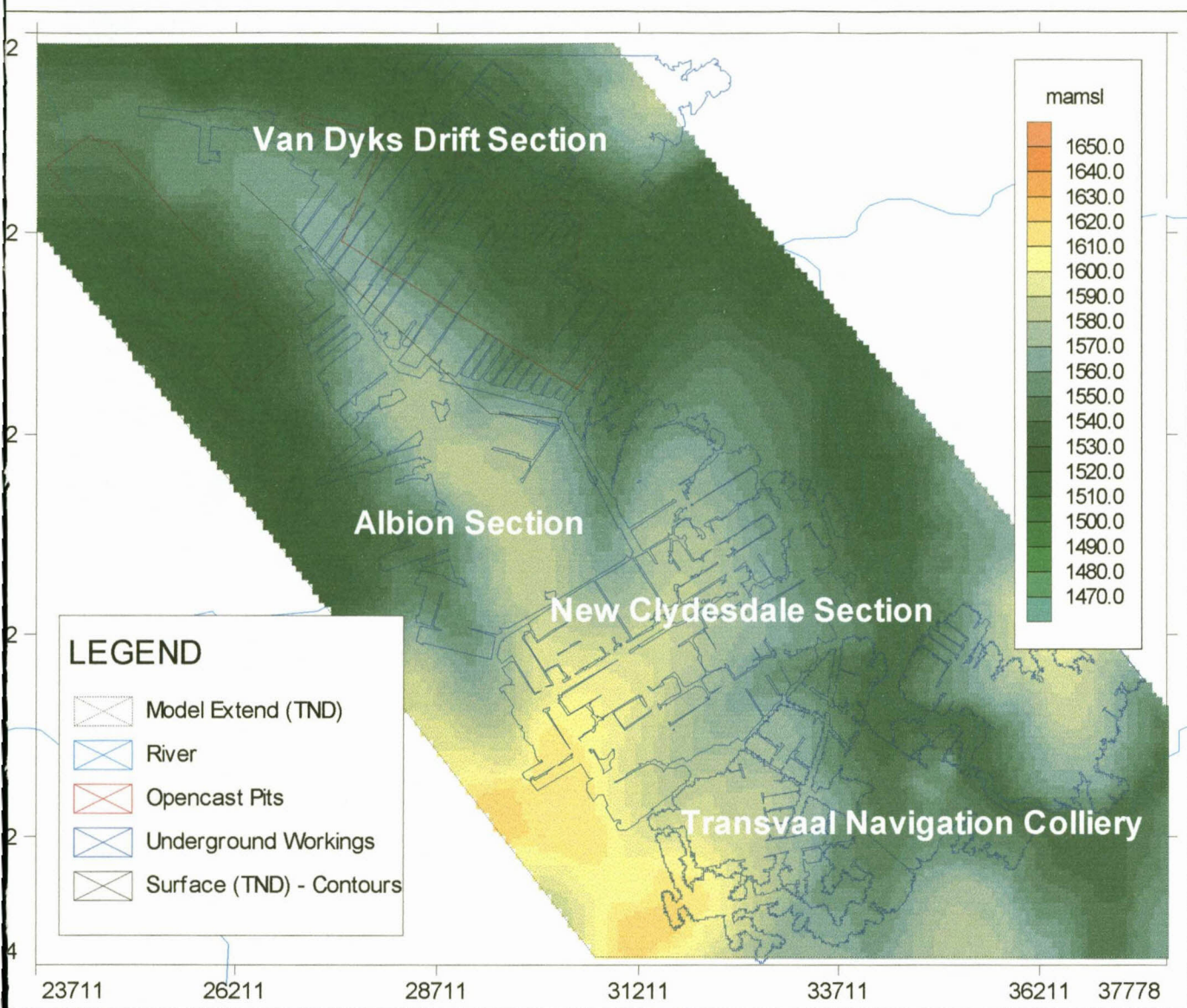


Figure 4-23. Map of the model extent and underground workings as well as opencast pits.

During modelling the initial water levels for the TNC Welstand underground block were taken at 1521.5 mamsl, which is also the water level measured in April 2002. As for the New Clydesdale No. 2 Seam, the initial water level that was used was 1521 mamsl. Currently the Welstand underground block flows into the New Clydesdale underground block, while the Albion No. 2 Seam underground workings are currently empty, based on the latest water levels. The Welstand Block is considered to flow into the New Clydesdale underground workings as well as the Goedehoop Hope Workings (section 4.2.1), while New Clydesdale underground workings flow into the Albion underground section, which is currently empty.

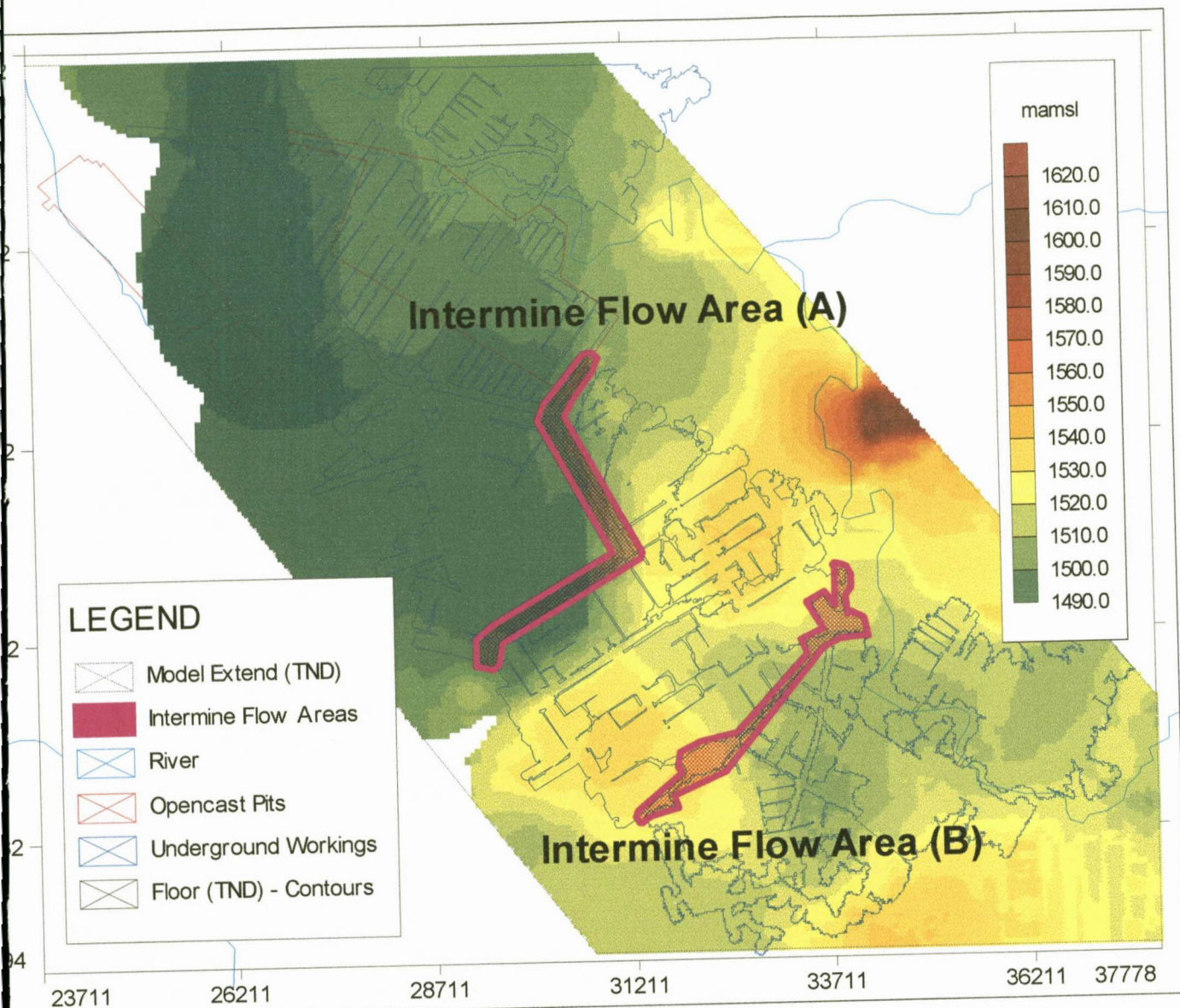


Figure 4-24. Map of intermine flow areas in the TNC, New Clydesdale and Douglas Intermine Flow Model and floor contours.

In the TNC-New Clydesdale-Douglas intermine flow model, two intermine flow areas have been delineated, namely area (A) that includes the intermine flow between Douglas Colliery's Albion Section No. 2 Seam underground workings and New Clydesdale Colliery No. 2 Seam underground workings. The second intermine flow area in the model is area (B), which includes the flow between the TNC Welstand No. 2 Seam underground block and New Clydesdale Colliery's No. 2 Seam underground workings.

4.4.2 Model Results - Transvaal Navigation Colliery (TNC) –Douglas Colliery Flow Model Scenario

Intermine flow area (A): The New Clydesdale No. 2 Seam underground workings are partly flooded to the level of about 1521 mamsl (Aug 2002) (This water level was measured at only one borehole, so there is uncertainty about the water level in the other compartments of the underground workings. Unfortunately New Clydesdale Colliery could not supply more information. The Albion No. 2 Seam underground workings are currently empty, according to water level data (Aug 2002).

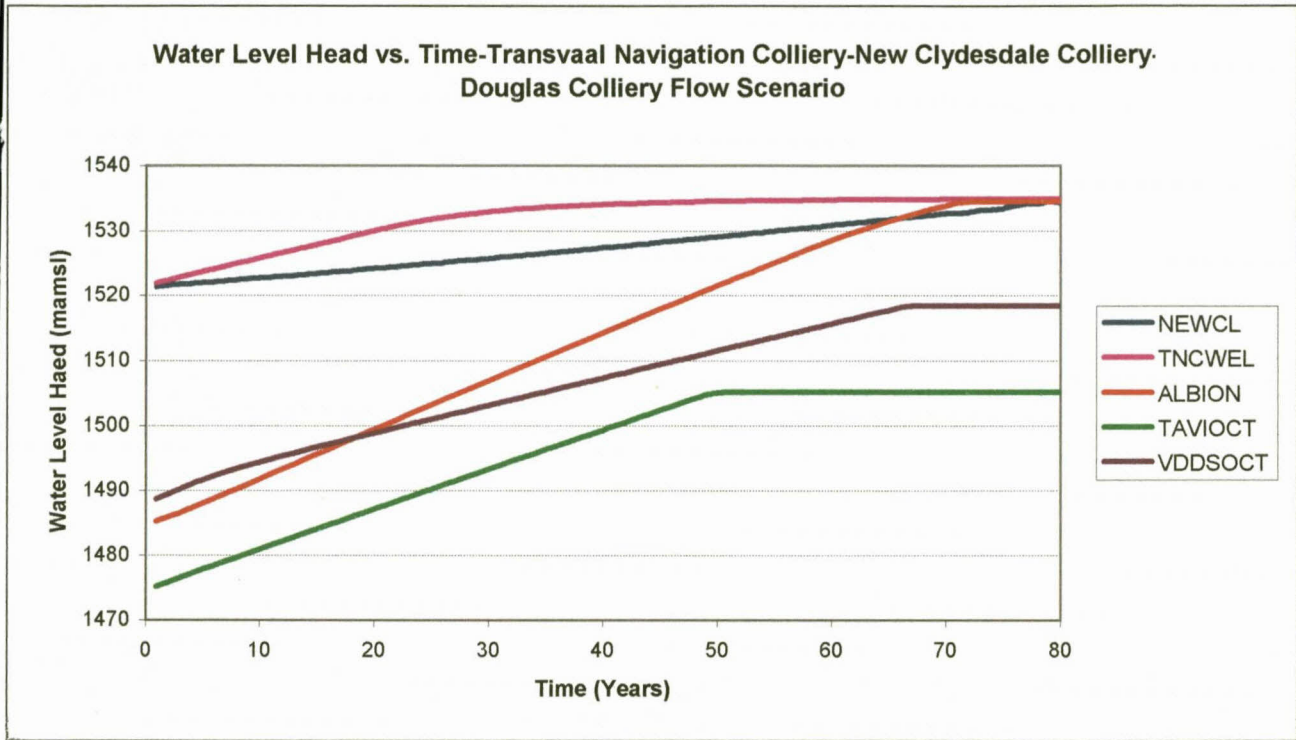


Figure 4-25. Water level head versus time graph of the in New Clydesdale underground workings (NEWCL), TNC's Welstand underground block (TNCWEL), Albion section's underground workings (ALBION), Tavistock opencast pit (TAVIOCT) and Van Dyks Drift south opencast pit (VDDSOCT).

Due to the water level information, the water flow gradient is in the direction of Albion section. The model's head versus time graph (**Figure 4-25**) shows that the New Clydesdales Colliery No. 2 Seam underground (NEWCL) groundwater flows into the Albion section's (ALBION) No. 2 Seam underground workings. The flow volume indicated by the model is initially in the order of $1000 \text{ m}^3/\text{d}$ (**Figure 4-26**). This intermine flow direction will remain in the same direction until the water level heads have equilibrated in both workings. As Albion section fills up with water the difference in hydraulic head will diminish in the underground workings, which will cause the flow volume (**Figure 4-26**) to decrease over time (**Figure 4-25**).

Fill-up times of opencast pits and underground workings for intermine flow area (A): New Clydesdale will take about 75 to 80 years (**Figure 4-25**) to fill up with water, assuming the current water level of 1521 mamsl. New Clydesdale underground workings will not decant on the surface due to the No. 2 Seam floor contours, of which the relative position and elevation do not provide a piezometric pressure to force the water in the workings to decant to the surface or mix with the groundwater in the aquifer above the void. New Clydesdale's No. 2 Seam underground will be completely filled at the level of approximately 1533 mamsl. Albion section will be filled up with water in about 47 to 55 years (**Figure 4-25**). Albion section's No. 2 Seam underground workings will also not decant at the surface and will be filled totally at a water level of 1526.3 mamsl. After the void is filled with water the aquifer will react as a single entity again. The water in the void will move slowly out of the void at the rate dictated by the natural flow gradient of the area.

Intermine flow area (B): The current water level in the TNC Welstand underground block is at 1521 mamsl (May 2002). TNC's Welstand No. 2 Seam underground workings water level is approximately at 1521.5 mamsl, thus the initial intermine flow direction is from the Welstand (TNCWEL) block to the New Clydesdale Colliery No. 2 Seam underground workings (Albion). The flow direction according to the model will remain the same until the water level heads equalise. The flow volume will initially be small due to the almost equal water level heads in both undergrounds. The water level head increases in the Welstand Block, but climbs slowly in the New Clydesdale underground workings due to the water loss in the Albion section (the water level increases in the New Clydesdale Colliery No. 2 Seam workings due to the fact that the recharge to the workings is more than the intermine flow to Albion section and therefore the flow gradient increases, and the flow volume increases to 120 m³/d (**Figure 4-26**). The flow volume decreases from a volume in the order of 120 m³/d (**Figure 4-26**) after year 35, to a volume that almost approaches zero as the water level heads equalise after approximately 80 years.

Fill-up times of opencast pits and underground workings for intermine flow area (B): TNC Welstand Block is approximately 95% flooded. The current water levels are due to a flood in the Olifants River (Feb 2000), which allowed increased influx into TNC. The surface water flowed through boreholes connected to the underground workings. The flow gradient between the surface and the underground workings is unity; hence there was a high inflow rate to the underground workings, which almost filled up the workings.

Flow Volumes vs. Time-Transvaal Navigation Colliery-New Clydesdale Colliery-
Douglas Colliery Intermine Flow Scenario

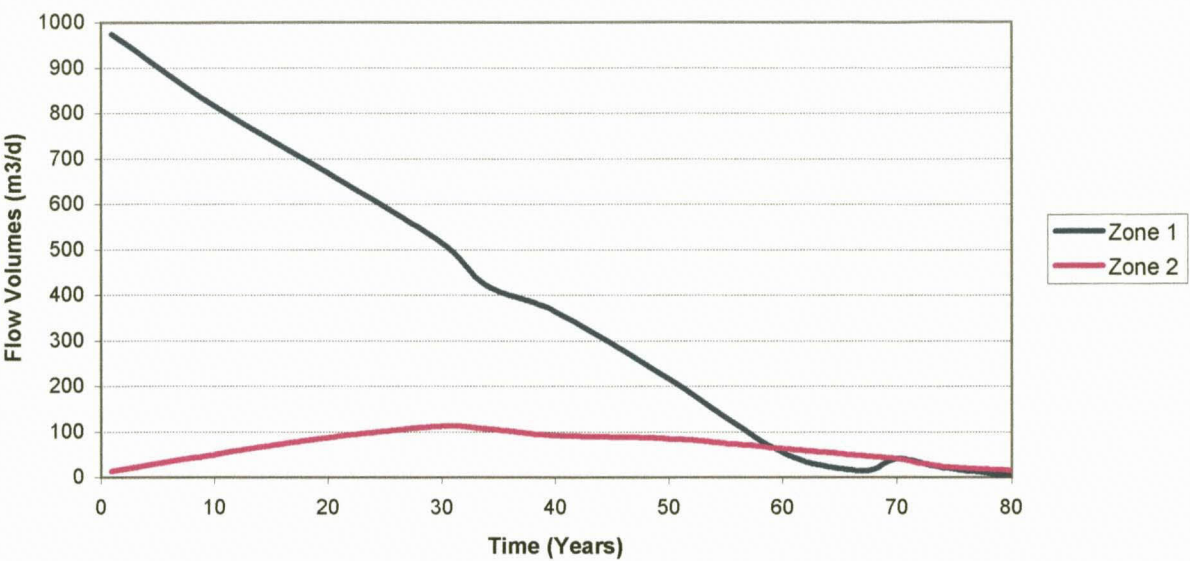


Figure 4-26. Graph of intermine flow volumes versus time for the TNC-New Clydesdale-Douglas intermine flow model (Zone 1-Intermine flow area (A) between Albion section and New Clydesdale Colliery, Zone 2-Intermine flow area (B) between TNC and New Clydesdale).

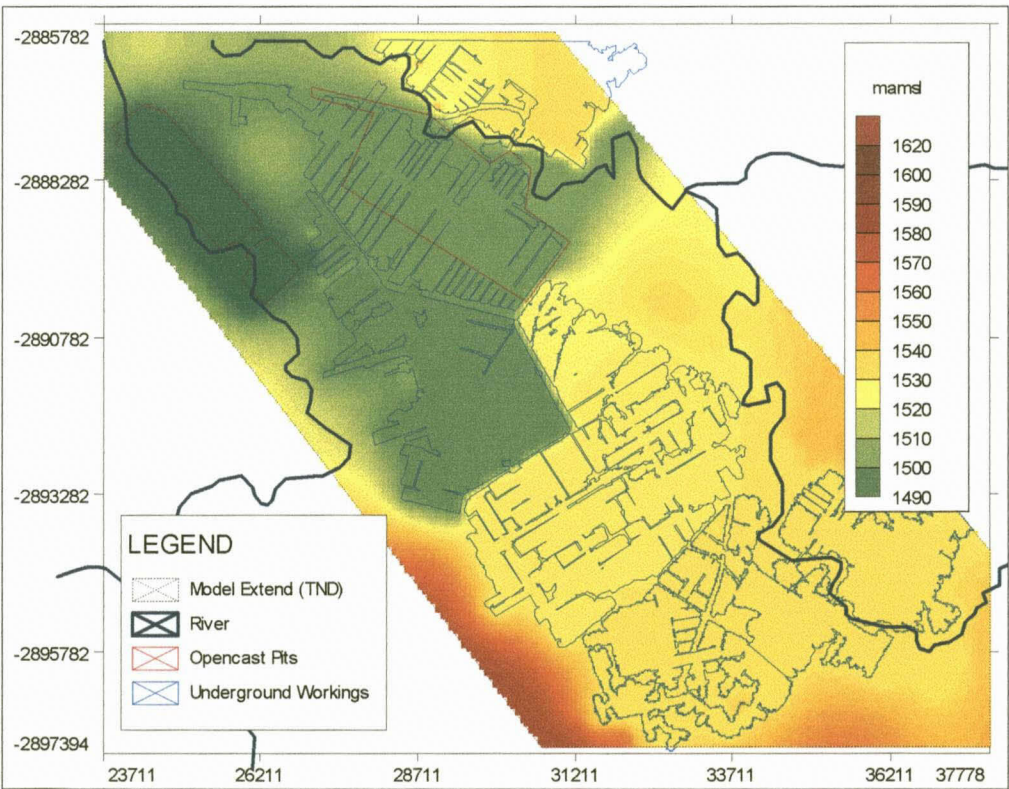


Figure 4-27. Map of the year 10 water levels of the TNC-New Clydesdale-Douglas model.

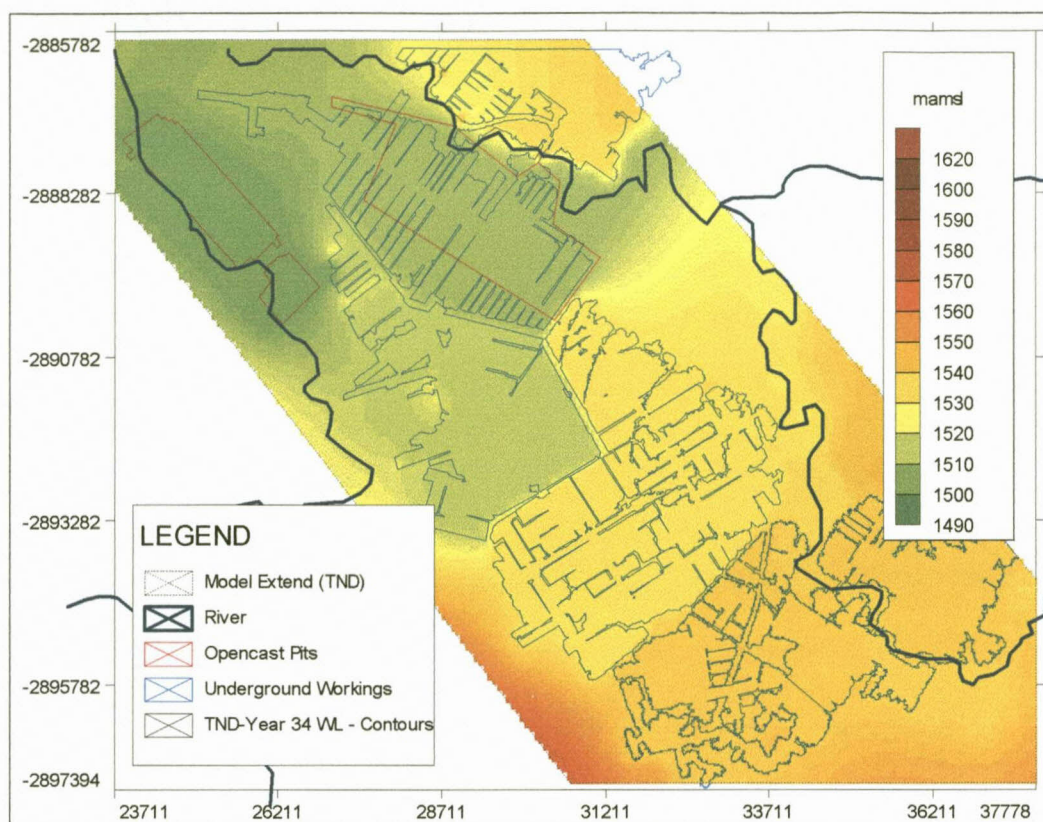


Figure 4-28. Map of the year 34 water levels of the TNC-New Clydesdale-Douglas model.

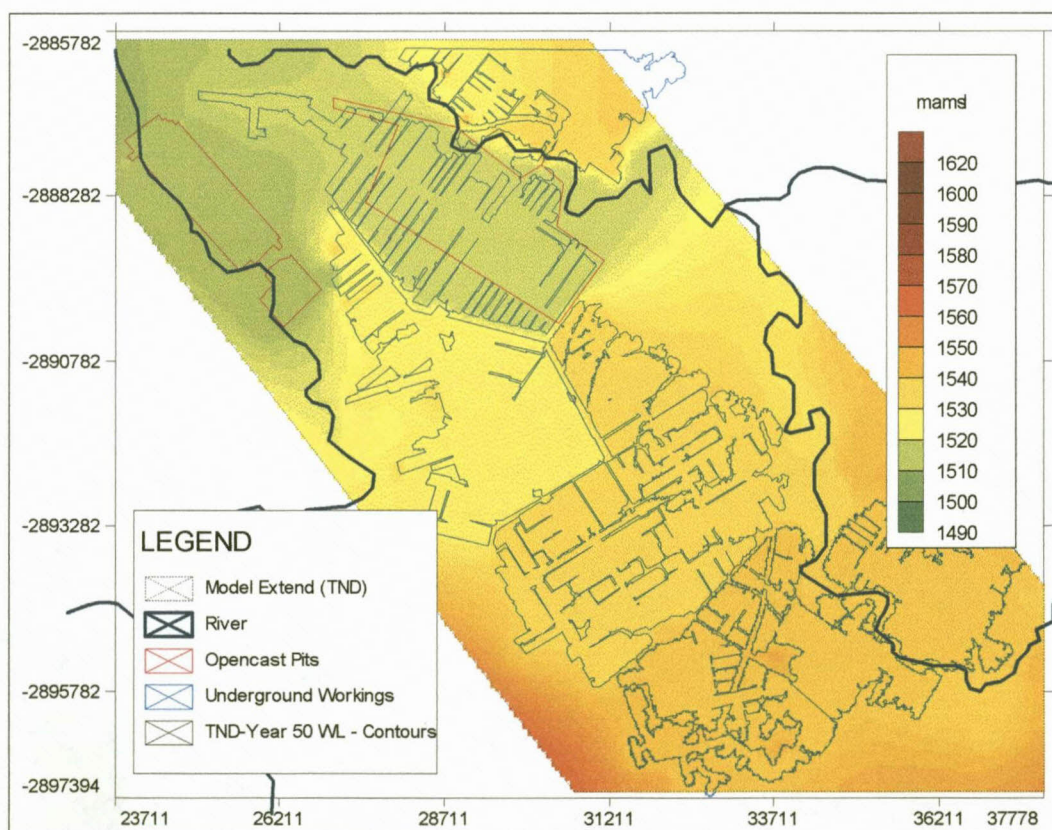


Figure 4-29. Map of the year 50 water levels of the TNC-New Clydesdale-Douglas model.

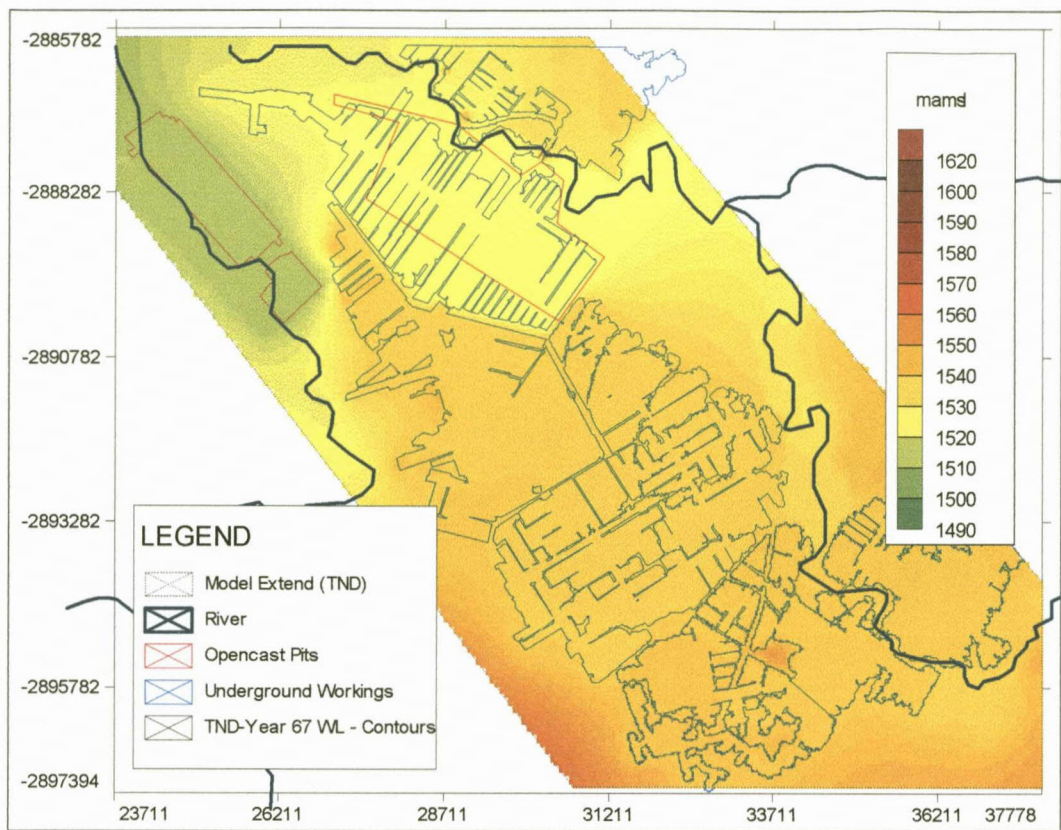


Figure 4-30. Map of the year 67 water levels of the TNC-New Clydesdale-Douglas model.

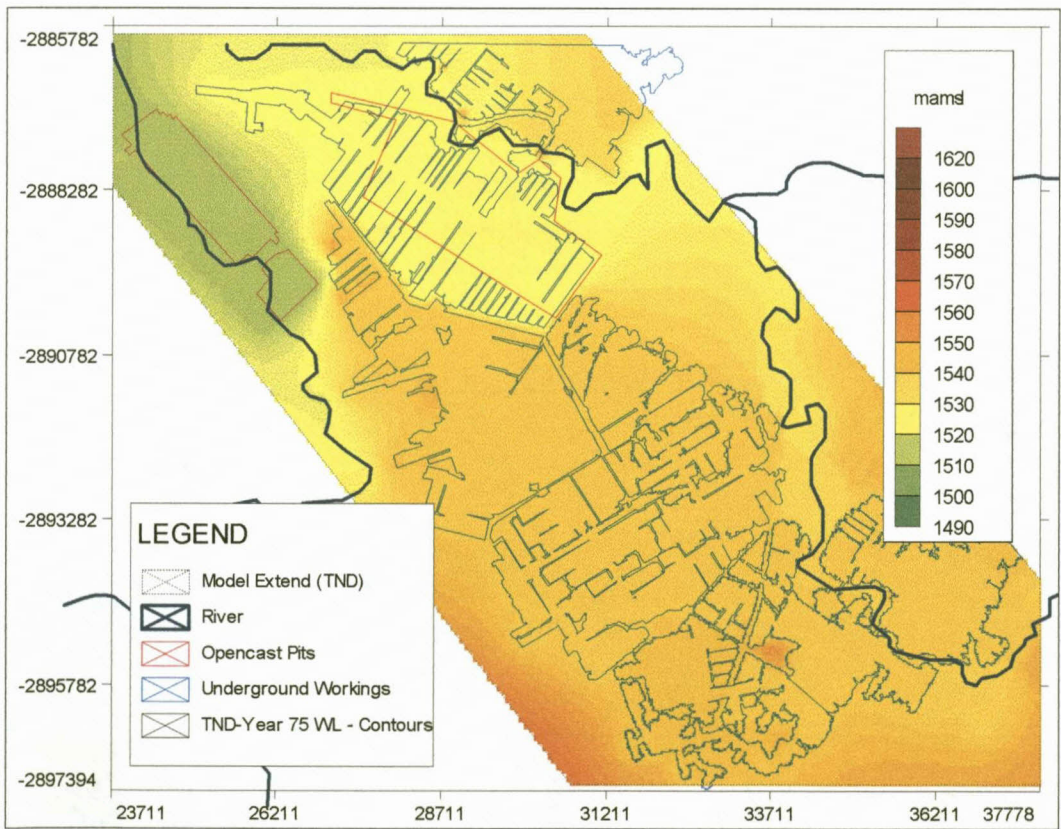


Figure 4-31. Map of the year 75 water levels of the TNC-New Clydesdale-Douglas model.

5.1 SURFACE WATER CHEMISTRY

This section discusses the surface water chemistry to give the reader an overview of the current water quality state of the Olifants River, Steenkoolspruit and the Koringspruit. In the next subsection about mining the influence of opencast mining on the Olifants River is discussed. The decant waters of the opencast pits that is flowing directly into the Olifants River can be detrimental to the surface water in the rivers and dams in terms of the salt loads and the acidic water can decrease the pH-values. Hodgson *et al.* (1998) reported that there is a general rise in salt concentrations within the water of the Loskop Dam and that sulphate concentrations are presently the main concern. It is also concluded from this report that a correlation exists between mining and surface water qualities in the area. The degree to which sulphate is present in the chemistry of the Olifants waters is illustrated in **Figure 5-1**. The data used in this section were obtained from the Department of Water Affairs and Forestry.

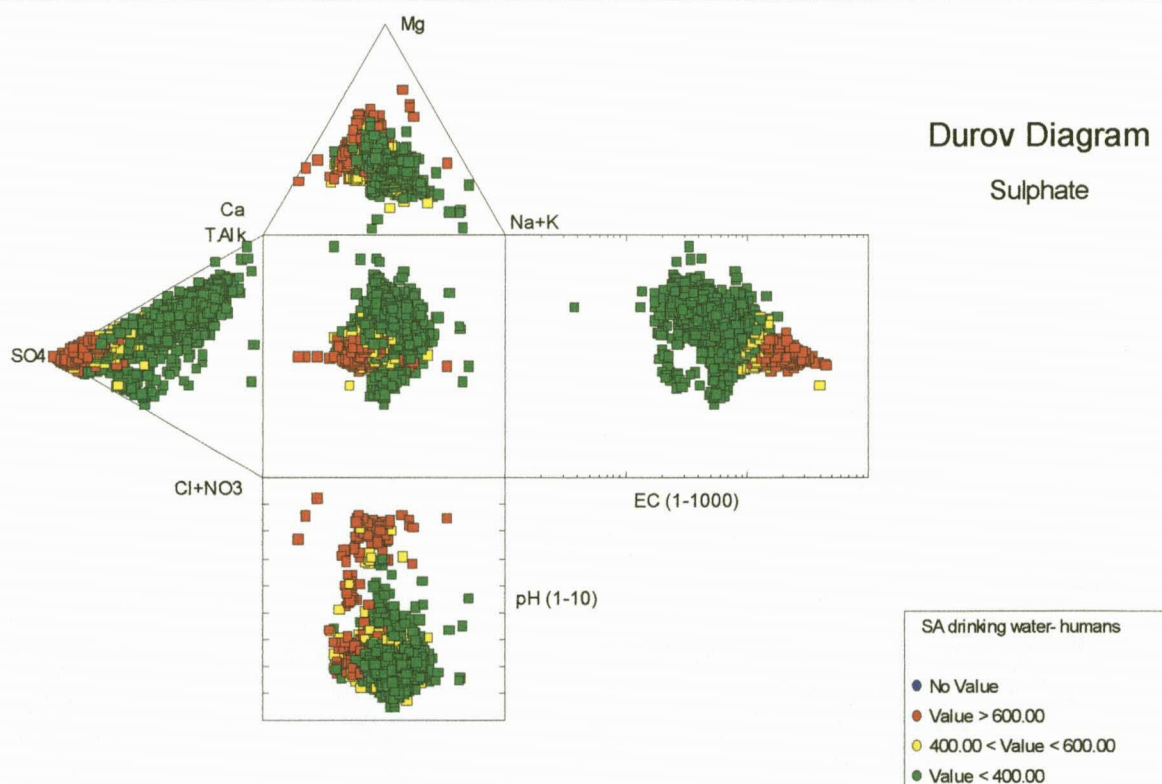


Figure 5-1. Durov diagram of the water chemistry of the Olifants River and tributaries.

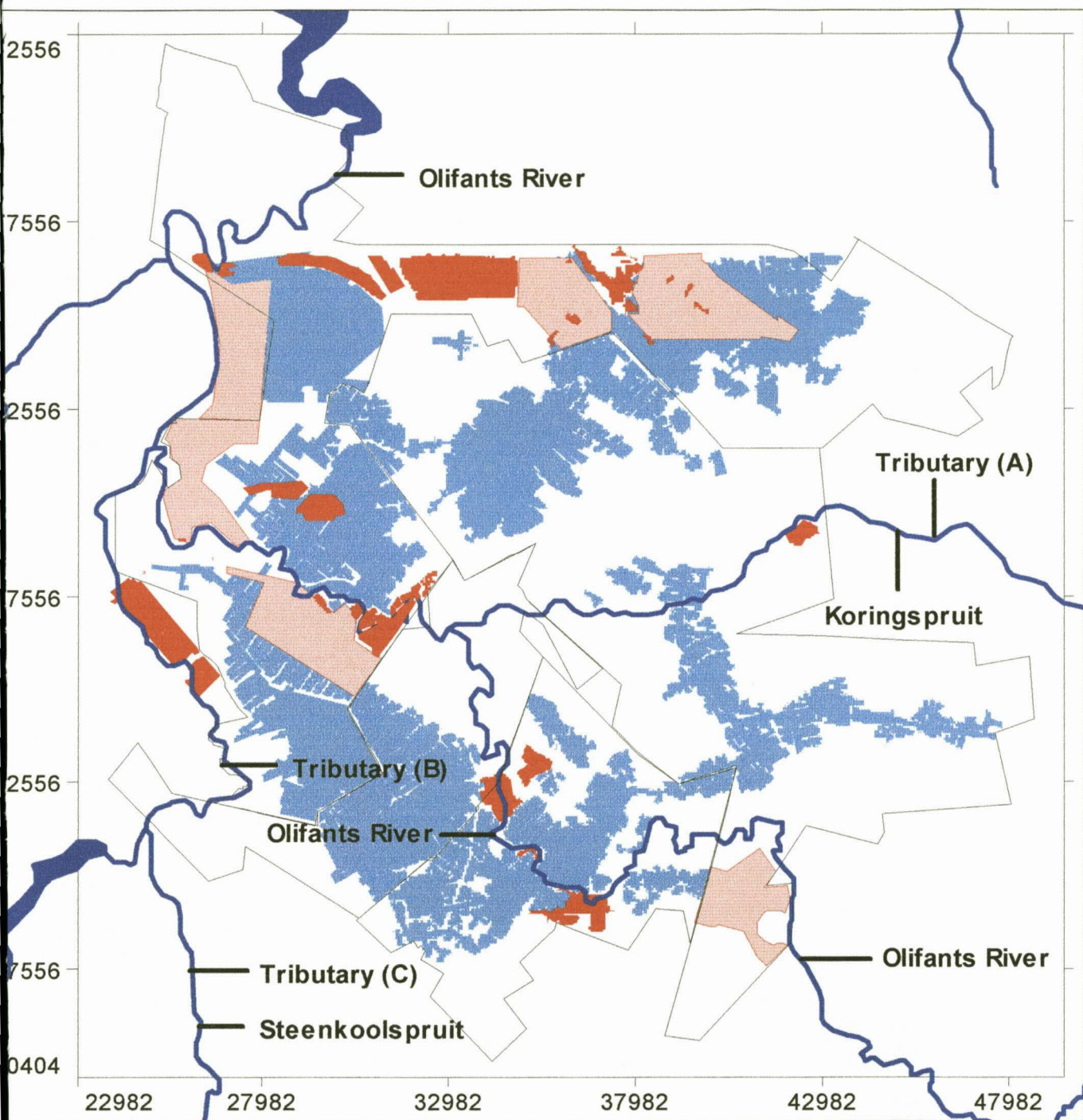


Figure 5-2. Map of rivers and dams of the central Witbank Coalfield.

Tributary - (A) - Koringspruit: As the Koringspruit moves into the mine lease area of Goedehoop Colliery the sulphate concentration upstream of the current opencast pit is 269 mg/L (WG10) (**Figure 5-3** and **Figure 5-4**) and downstream of the opencast pit the value decreases slightly to 257 mg/L. This value can increase dramatically if oxidising conditions allow AMD-reactions and decant occurs from this opencast pit.

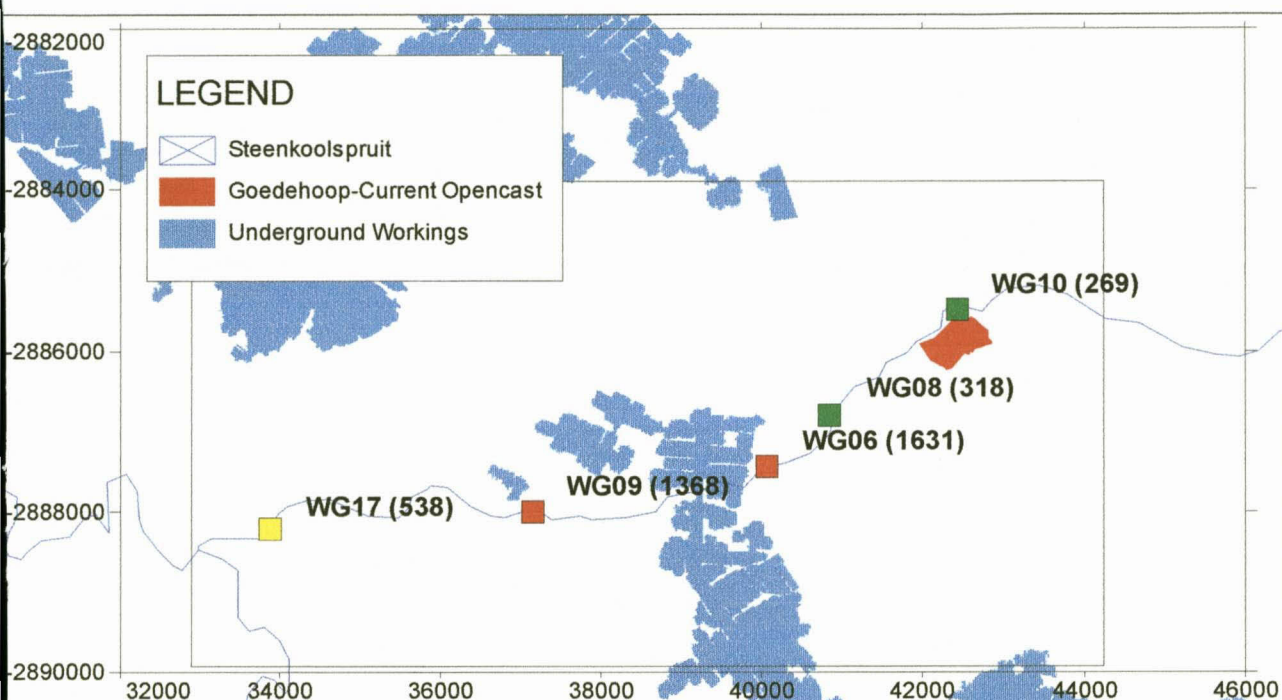


Figure 5-3. Map of the Koringspruit (tributary A) as it flows through Goedehoop Colliery showing the sulphate concentration in mg/L (The red colour shows the concentration is above the SA water drinking standards, where the green colour shows that the concentration is within the SA drinking water standards. The yellow colour is for concentrations above the recommended standard).

As the surface water flows past the Goedehoop plant there is a drastic increase in the sulphate concentration from 318 to 1631 mg/L (from WG8 to WG6) (**Figure 5-3** and **Figure 5-4**) and a corresponding drop in the pH-levels to 4.5. Possible sources for the increase in sulphate loads in the surface water are the pollution control dam and the return water dam.

Magnesium concentrations also increase from 33 – 169 mg/L. The increase in magnesium in solution may be due to buffer reactions in the water chemistry (buffer reactions – dissociation of dolomite to increase the alkalinity to neutralise the acid in the water). Alkalinity of effluents is controlled mostly by carbonate minerals (Limestone – CaCO_3 as well as Dolomite – $\text{CaMg}(\text{CO}_3)_2$). The factors that effect CaCO_3 solubility are pH and pCO_2 . The concentration of Ca (Mg) reflects the level of alkalinity in water since the mass-balance reveals that any Ca quantity (moles)

released from CaCO_3 must be accompanied by similar quantity (moles) of CO_3 (Evangelou, 1995).

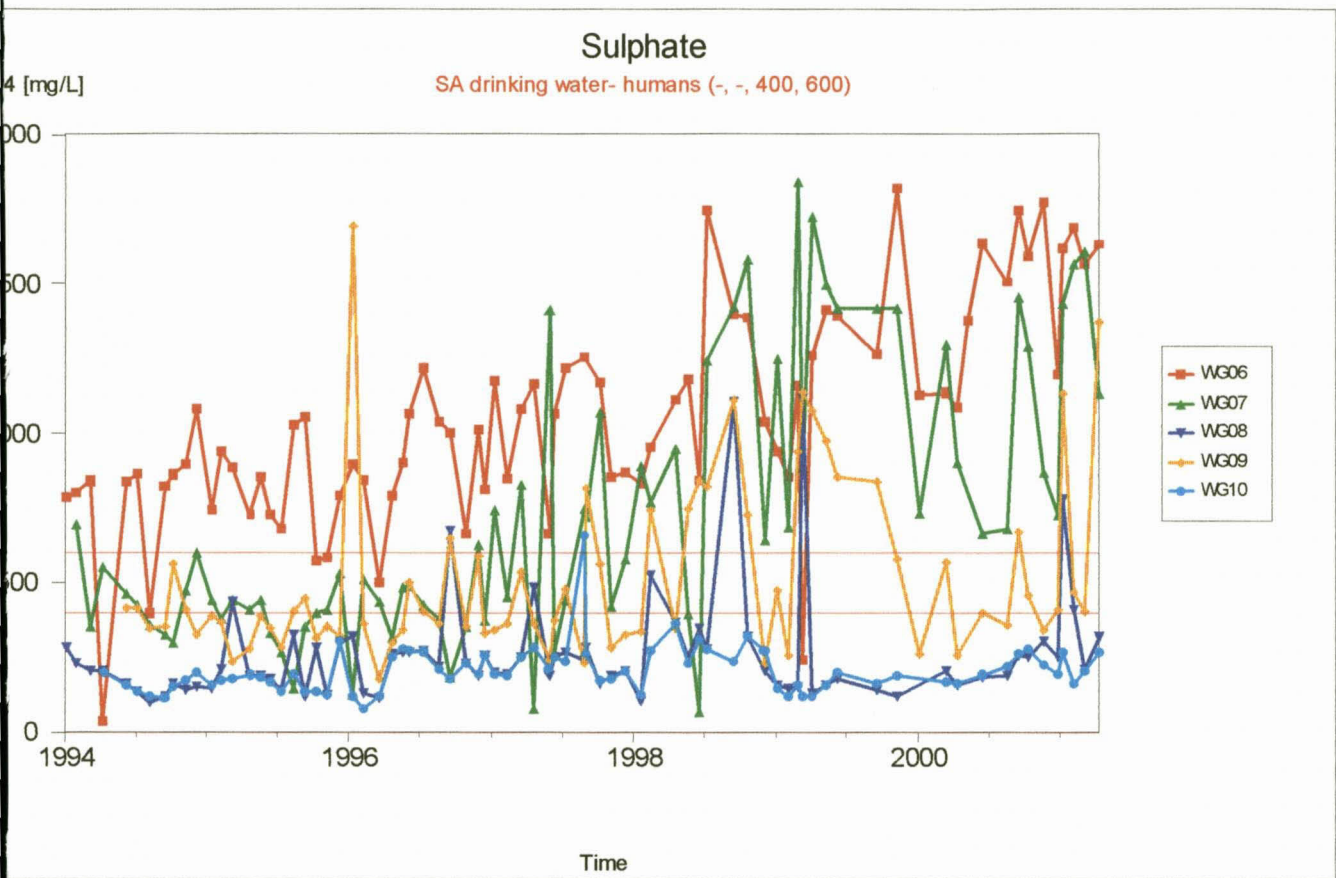


Figure 5-4. Graph of sulphate and electrical conductivity for the Koringspruit as it flows over the Goedehoop Colliery mine lease.

Downstream the sulphate concentration in the water decreases from 1631 mg/L to 538 mg/L but have actually increased in concentration from observation WG10 with a pH of 6.3 (from WG6 to WG17) (**Figure 5-3** and **Figure 5-4**); thus there is a net elevation in sulphate concentration and a decrease in pH as the Koringspruit moves through the Goedehoop Colliery mine lease. Downstream (WG4, WG15, WG9 and WG16) the magnesium values remain high, in the region of 150 mg/L, [the sodium (70 mg/L), calcium (260 mg/L) and potassium (6 mg/L). The reason for the higher calcium and magnesium relative to potassium and sodium is that calcite and dolomite are being disassociated in the buffer reactions, which elevates the cations in surface water.

The Koringspruit flows from Goedehoop Colliery to New Clydesdale Colliery. The sulphate concentration before the Koringspruit flows into the Olifants River is 334

mg/L. In conclusion Goedehoop Colliery increased the net sulphate load in the river, hence there is a correlation between mining and the quality of the stream water.

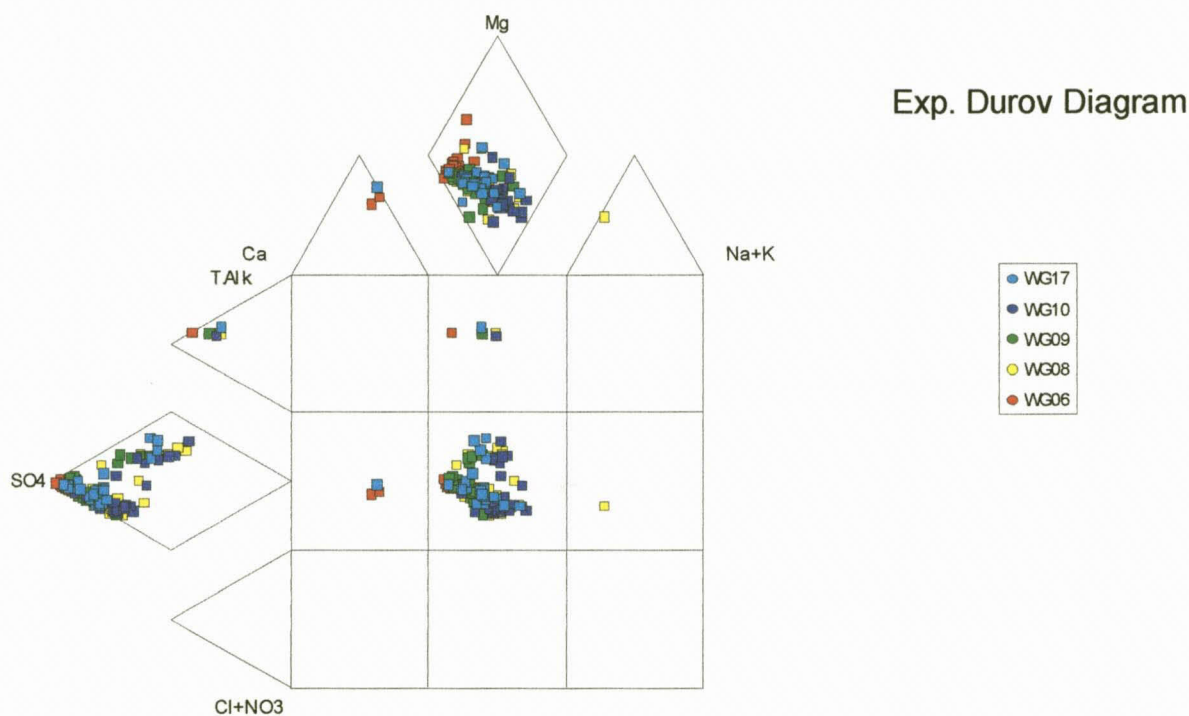


Figure 5-5. Expanded Durov diagram of the Steenkoolspruit water as it flows through Goedehoop Colliery.

The expanded Durov diagram (**Figure 5-5**) indicates that the water in the sampled section of the Steenkoolspruit is definitely being influenced by mine water from Goedehoop Colliery. Most of the points plot in the centre sector, which indicates SO_4 enriched waters. The pH-values are still neutral for most cases, indicating sufficient neutralisation of the AMD-reactions in the short term.

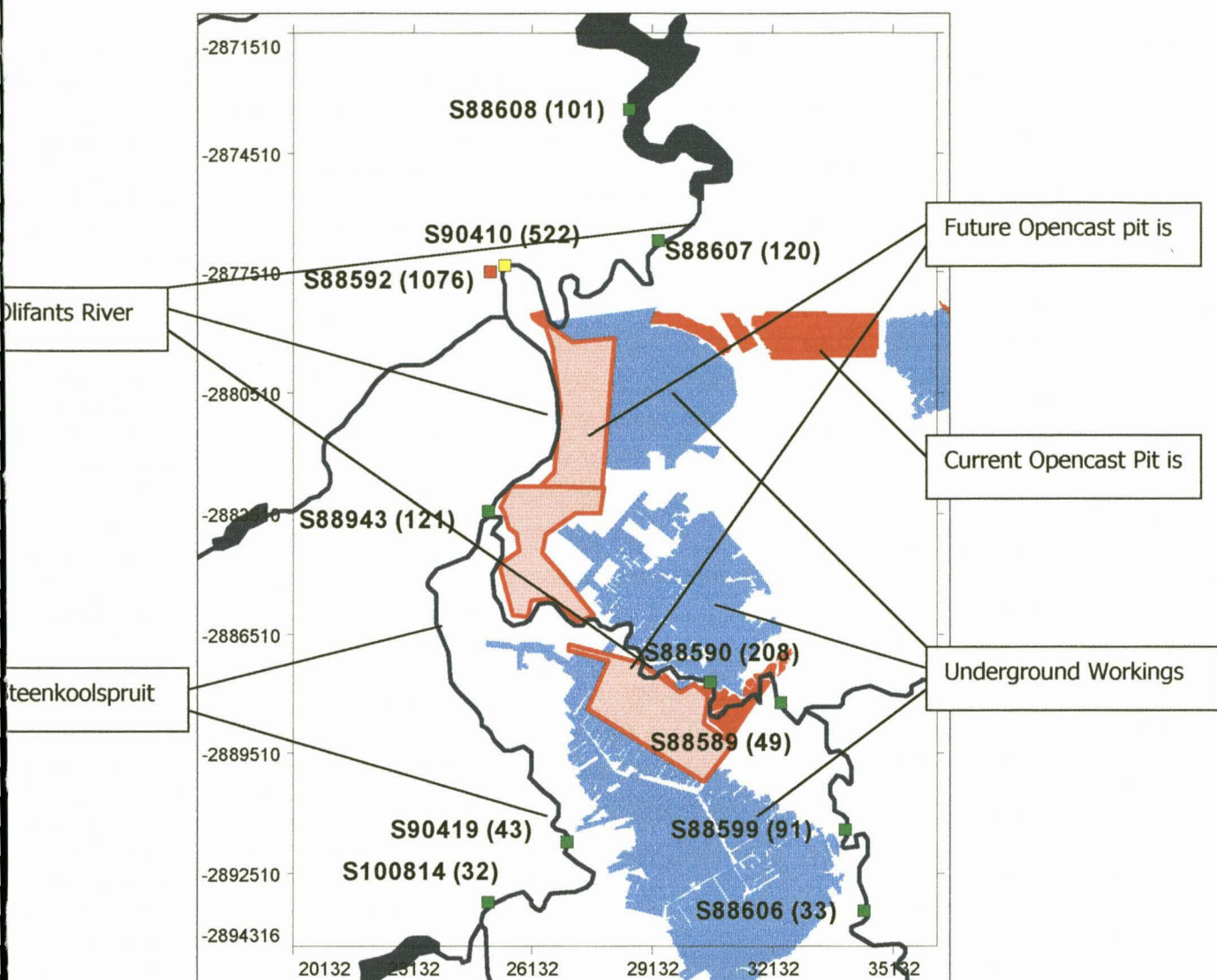


Figure 5-6. Map of tributary (B) Olifants River section displaying the sulphate concentration (mg/L) at different surface monitoring points (The red colour shows the concentration is above the SA water drinking standards, where the green colour shows that the concentration is below the SA drinking water standards. The yellow colour is for concentrations above the recommended standard).

Tributary - (B) – Olifants River: Upstream from B1H018Q01 (Olifants River at Middelkraal) monitoring point the sulphate concentration is 62 mg/L. No data are available for the surface water as it flows past the Goedehoop new opencast pit development. However if this opencast pit is not well managed, the decant water from this pit can drastically increase the salt loads in the Olifants River downstream from the Transvaal Navigational Colliery. The sulphate value decreases to 33 mg/L at monitoring point S88606 as it flows into the TNC mine lease (Olifants River old weir on Vaalkrans on the TNC mine lease area). From TNC the Olifants River flows into the New Clydesdale Colliery mine lease and the sulphate concentration increases even further to 91 mg/L at monitoring point S88599 (Olifants River at Vaalkrans).

The Koringspruit then joins the Olifants River. Downstream of where the Koringspruit joins the Olifants River at monitoring point S88589 (Olifants River at van Dyks Drift bridge on Vaalkranz) the sulphate concentration is 49 mg/L. This decrease in the sulphate concentration from 334 mg/L in the Koringspruit as it flows into the Olifants River is due to mixing with much lower concentration sulphate waters of the Olifants River. At monitoring point S88590 (Olifants River at Van Dyks Drift pump station) the sulphate is 208 mg/L and this increase is probably due to the rehabilitated opencast pit is past which the Olifants River flows. The salt loads will most probably increase sharply as mining commences on the planned Van Dyks Drift south opencast pit as well as the Steenkoolspruit/Kleinkopje opencast pit. Consequently the rehabilitation of these massive opencast pit is should be done with care to ensure that water quality deterioration is minimised. If the decant from these opencast pit is of poor quality it could dramatically increase the sulphate loads in that stretch of the Olifants River. The Steenkoolspruit joins the Olifants River (see **Figure 5-6**). Whereas the Olifants River flows into the Douglas Wolwekrans section there is a sharp increase in sulphate concentration at monitoring point S88592 to (Landau vlei draining complex) 270 mg/L. The sulphate concentration then increases to 522 mg/L downstream at monitoring point S90410 (Olifants River at Wolwekrans Section). The sulphate concentration goes down even further to 120 mg/L at monitoring point S88607 (Upstream from Duva Power Station on the Wolwekrans Section). At monitoring point S88608 (Duva Pump Station at Witbank Dam) the sulphate concentration is 101 mg/L, thus the sulphate concentration has decreased even further due to mixing.

Tributary - (C) – Steenkoolspruit: The sulphate concentration at New Clydesdale Colliery at monitoring point S100814 is 32 mg/L (**Figure 5-6** and **Figure 5-7**). Further downstream at monitoring point S90419 (Steenkoolspruit at Middeldrift) the sulphate value is 43 mg/L. At monitoring point S88943 (Phoenix off-take from Steenkoolspruit), (**Figure 5-6** and **Figure 5-7**) the sulphate concentration increases to 121 mg/L possibly due to the mining activities at the Tavistock opencast pit situated next the Steenkoolspruit. Further downstream the Steenkoolspruit joins the Olifants River.

Conclusions from this section are:

- There is a correlation between mining (opencast mining methods) and the stream water quality.
- There are elevated sulphate and other salt concentrations in the Olifants River and its tributaries.
- Future opencast pits that are linked to undergrounds through pillar extraction, which in turn are then linked to the underground workings of other Collieries (intermine flow scenarios) can possibly increase the sulphate load in the

Olifants River drastically if management and remediation are not done properly.

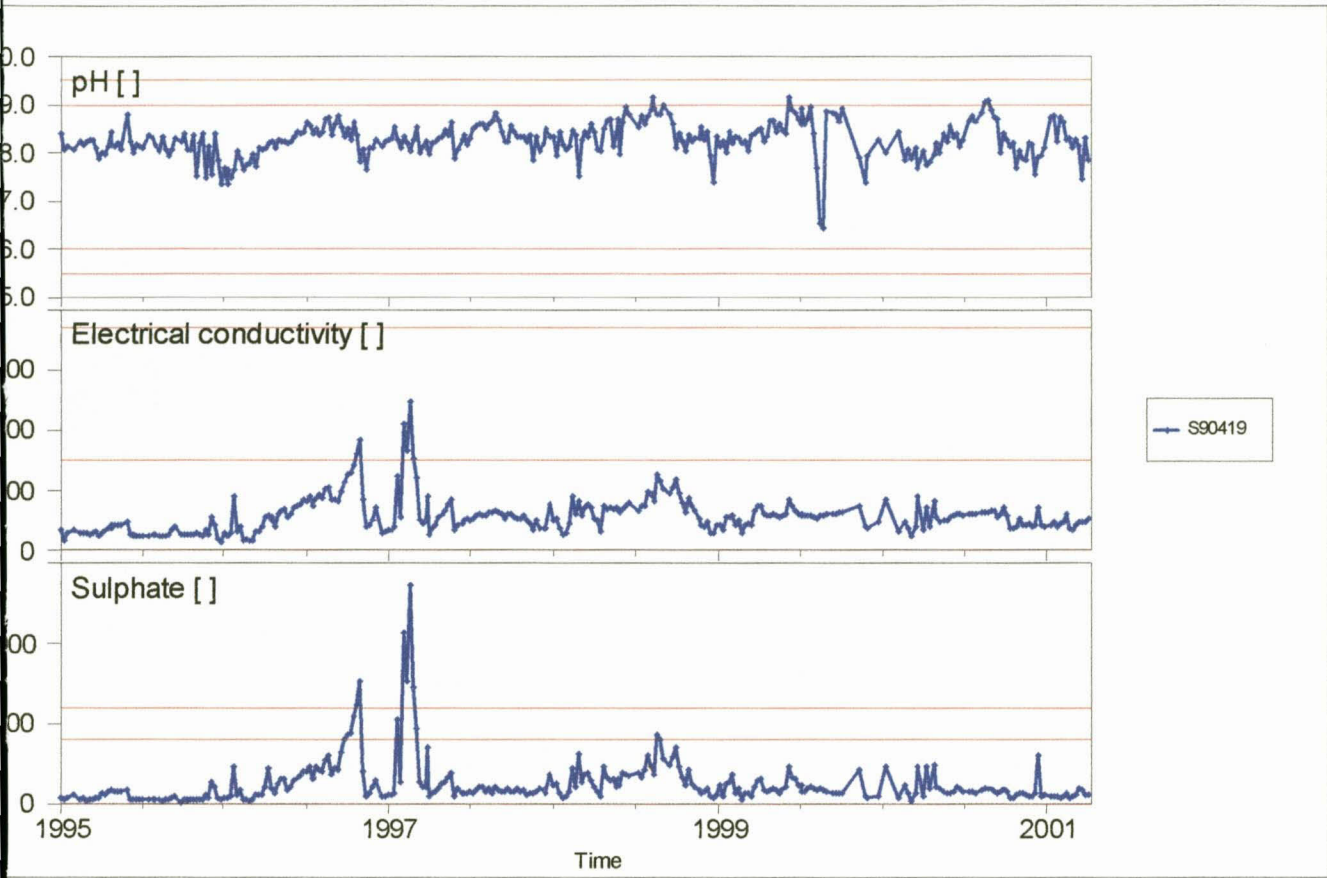


Figure 5-7. Graph of sulphate concentration (mg/L) electrical conductivity (mS/m) and pH-values over time for the Steenkoolspruit at monitoring point S90419.

5.2 MINING HYDROCHEMISTRY

5.2.1 Hydrochemistry of Opencast Pit

5.2.1.1 Goedehoop Colliery Opencast Pit

In this section of the chapter the current hydrochemistry (current opencast pit), future hydrochemistry (intermine flow between Goedehoop Colliery’s new opencast pit and TNC’s Block C underground workings) and the future impact of new opencast pit of Goedehoop Colliery on the Olifants River will be discussed (see **Figure 5-8**).

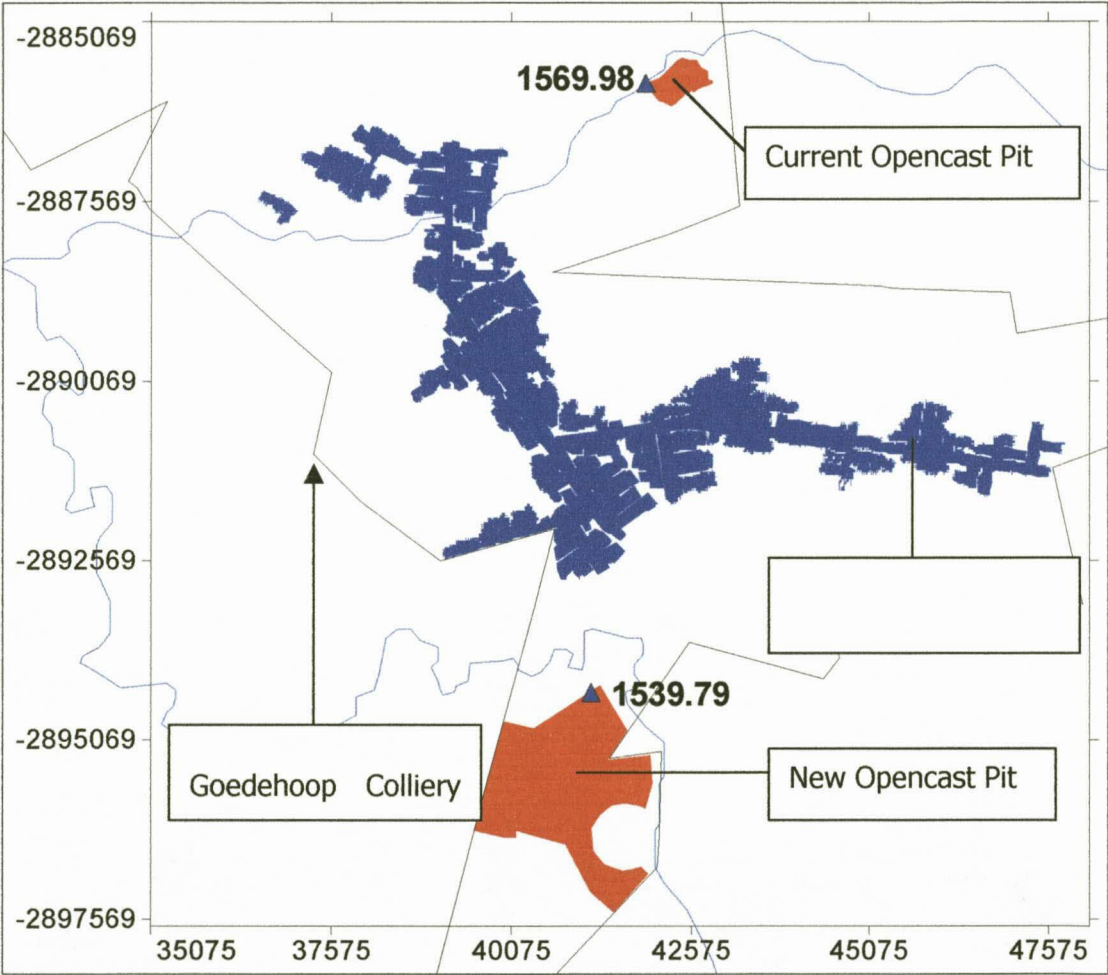


Figure 5-8. Map showing the future planned opencast pit and the current opencast pit. (Also show position so of the monitoring boreholes on this figure)

5.2.1.1.1 CURRENT OPENCAST PIT GOEDEHOOP COLLIERY

The sulphate values are currently low (**Figure 5-10**) for boreholes WG10, WM 13 and WM31, which occur near the current opencast pit of Goedehoop Colliery. Monitoring boreholes WM31 and WM 13 are up-gradient from the opencast pit while WG 10 is down-gradient (**Figure 5-9**). Therefore WG 10 (269 mg/L) has a much higher sulphate concentration than WM 13 (29 mg/L) and WM31 (58 mg/L), due to the flow of the affected groundwater away from the pit.

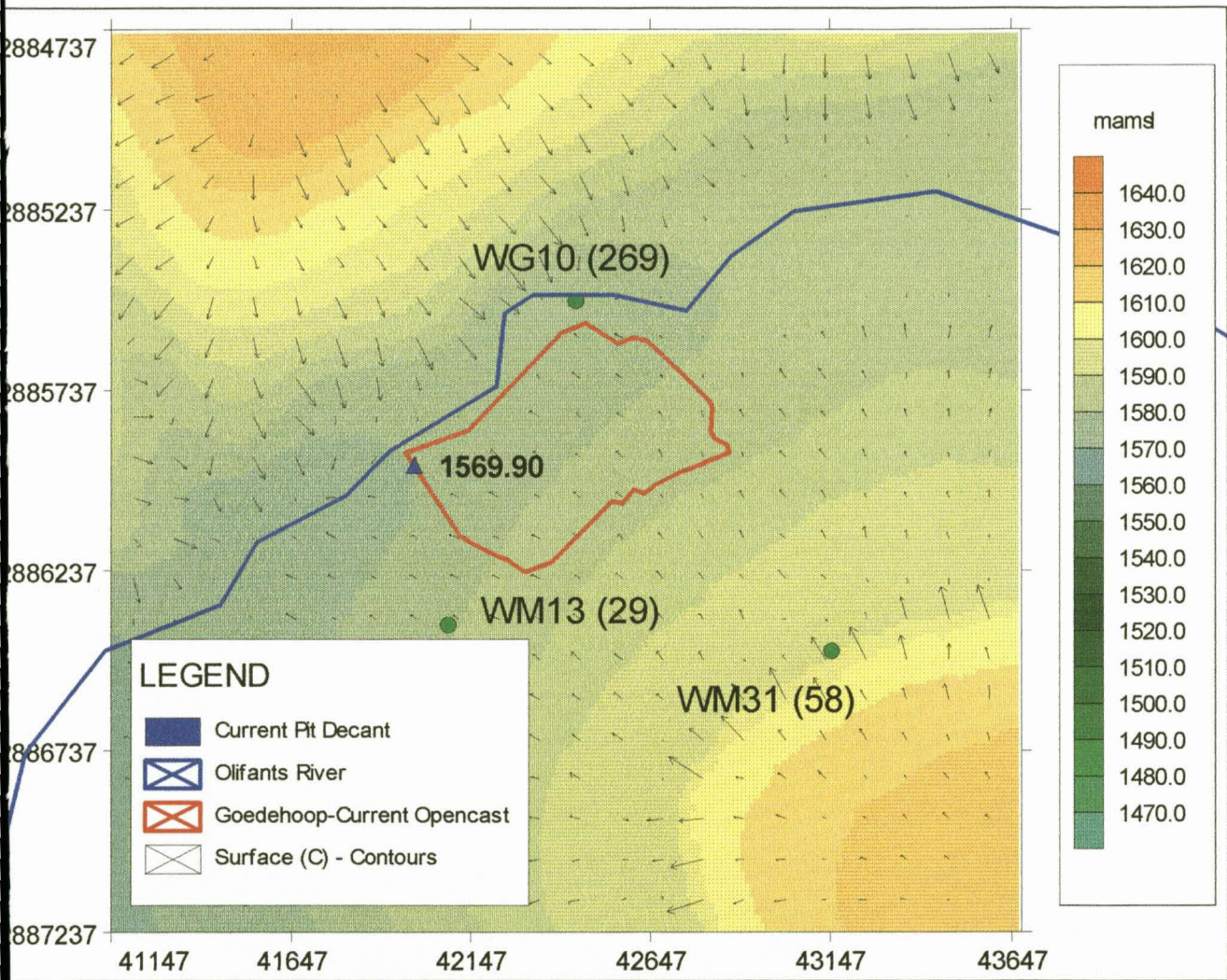


Figure 5-9. Map showing the Goedehoop Colliery current opencast pit as well as the monitoring boreholes displaying the current sulphate concentration and the decant level of the pit (1569.90mamsl). The arrows indicate the groundwater flow direction.

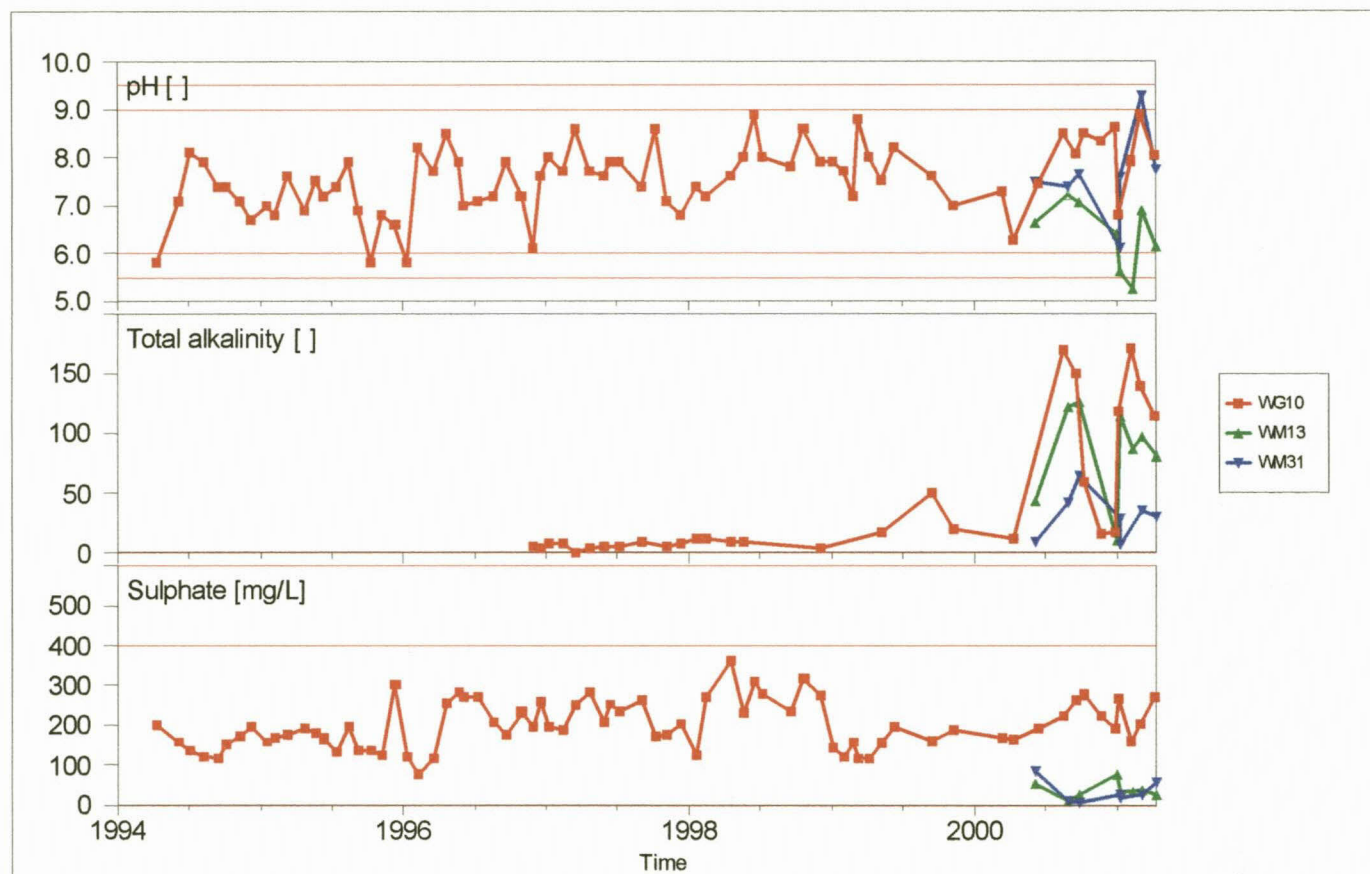


Figure 5-10. Graph of sulphate, total alkalinity and pH-values for boreholes around the current opencast pit.

In **Figure 5-11** most of the points plot in the centre sector of the expanded Durov diagram. This sector delineates groundwater from opencast pit is (Minimum Requirements for Waste Disposal by Landfill, 1998). The sulphate ion is also the dominant ion (**Figure 5-11**), suggesting that current opencast pit of Goedehoop Colliery is undergoing oxidation. The alkalinity values of boreholes WM13 (81 mg/L CaCO_3) and WM31 (31 mg/L CaCO_3) are lower than borehole WG10 (114 mg/L CaCO_3) (**Figure 5-10**). A possible reason for the higher alkalinity of borehole (WG10) is that oxidation reactions in the opencast pit acidifies the groundwater, which puts the alkalinity of the groundwater under stress, prompting a release of CaCO_3 or dolomite from the spoils and pushing the alkalinity values higher.

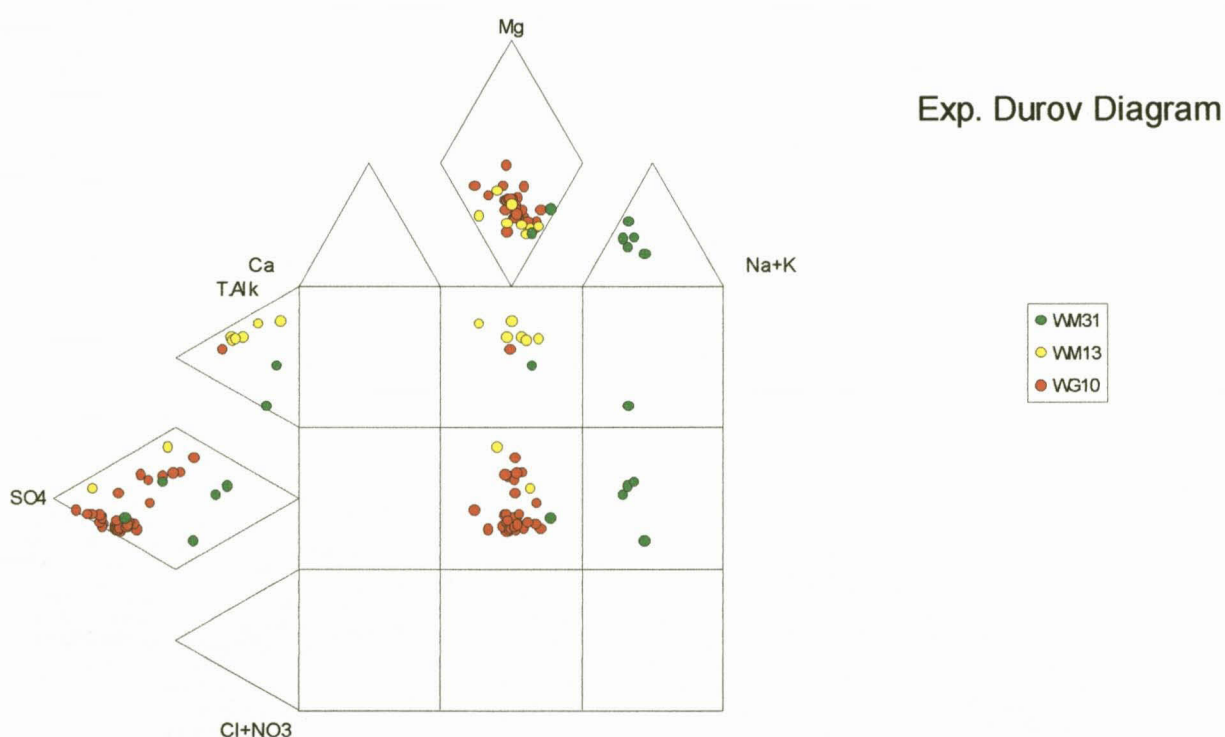


Figure 5-11. Expanded Durov of the boreholes around the current opencast pit.

The pit will decant at 1569.90 mamsl (**Figure 5-9**) and the volume at decant in the pit is 1.6 Mm^3 (mined to No. 2 Seam). Decant is the groundwater decanting on the surface at lowest elevation on the opencast pit. From there the decant water flows from the opencast pit's decant point to the river in the form of a small surface stream. The decant volume will be in the order of 150 – 200 m^3/d . The decant volume can be separated in two components, namely the polluted water that decants into the Olifants River from the decant point (surface leachate) as well as the

groundwater component that moves through the strata to the river. The groundwater component contributes 4 - 8% of the volume (polluted water) whereas the surface decant contributes about 88 - 96% of the salt load to the river. The decant component is the groundwater that decants on the surface and the groundwater component is the groundwater that contains the salt loads and seeps in to the river through the strata, like a groundwater pollution plume The groundwater component assessment was done by approximating the groundwater flow volume to river from the opencast pit by using the Darcy Equation (Equation 5-1. $Q = TiL$) and using the Reserve Software (Van Tonder, 2002). The range of sulphate generation is 5 – 10 kg/d per hectare in an opencast pit (Hodgson & Krantz, 1998). An average generation of 7 kg/d of sulphate per hectare was used to calculate the possible decant quality. Based on this, the possible decant quality ranges from 1600 to 2400 mg/L for the current opencast pit at Goedehoop Colliery.

5.2.1.1.2 NEW OPENCAST PIT OF GOEDEHOOP COLLIERY

Monitoring borehole BLK03 is down-gradient from the new opencast pit (**Figure 5-13**). In **Figure 5-12** the sulphate concentration and the total iron content in the groundwater are seen to increase over time. This data correspond to oxidation reactions starting to take place as mining progresses in the new pit. Therefore acidification takes place and the pH drops. The oxidation reactions will most probably accelerate.

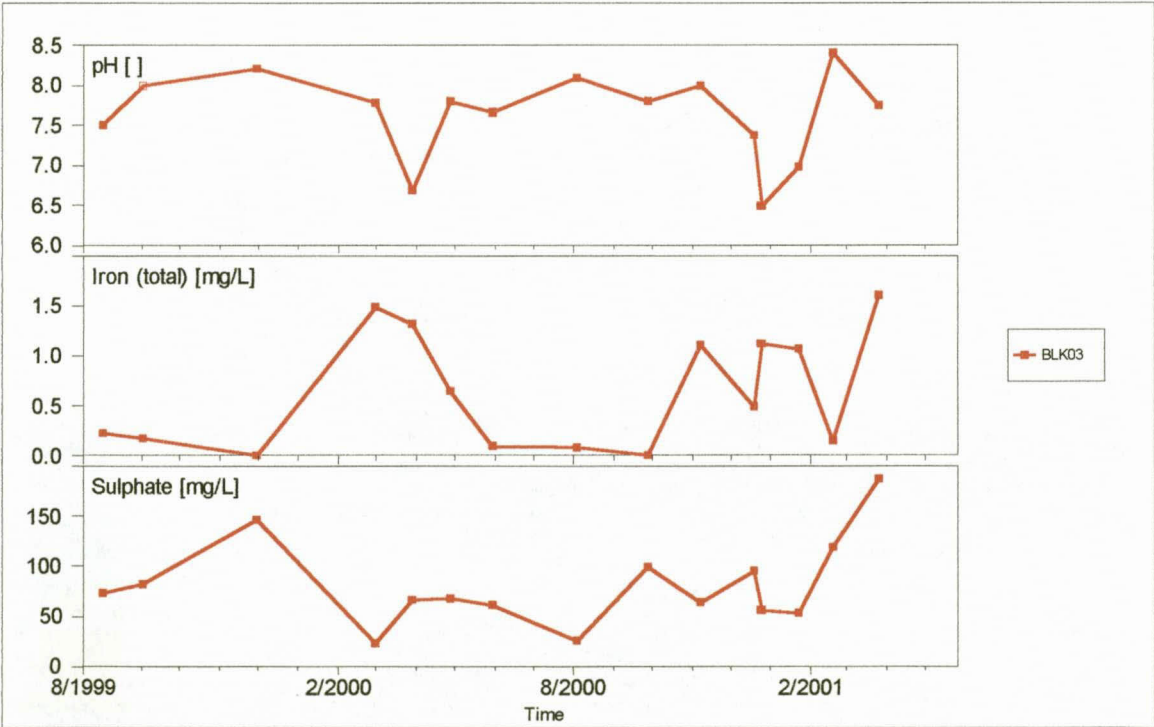


Figure 5-12. Graphs of pH-, iron (total) and sulphate values from monitoring borehole BLK03, down-gradient of the new opencast pit of Goedehoop Colliery.

The pit will take about 38 to 42 years to fill up with water. The natural fill-up time is long and gives ample time for AMD reactions to take place, which will most probably deteriorate the groundwater quality significantly over time. If the pit is flooded with the Olifants River, as is the case with TNC Colliery’s opencast pit is (natural flooding in 2000), this deterioration of groundwater quality in the new opencast pit can be halted. See the management chapter for further information (see Chapter 6).

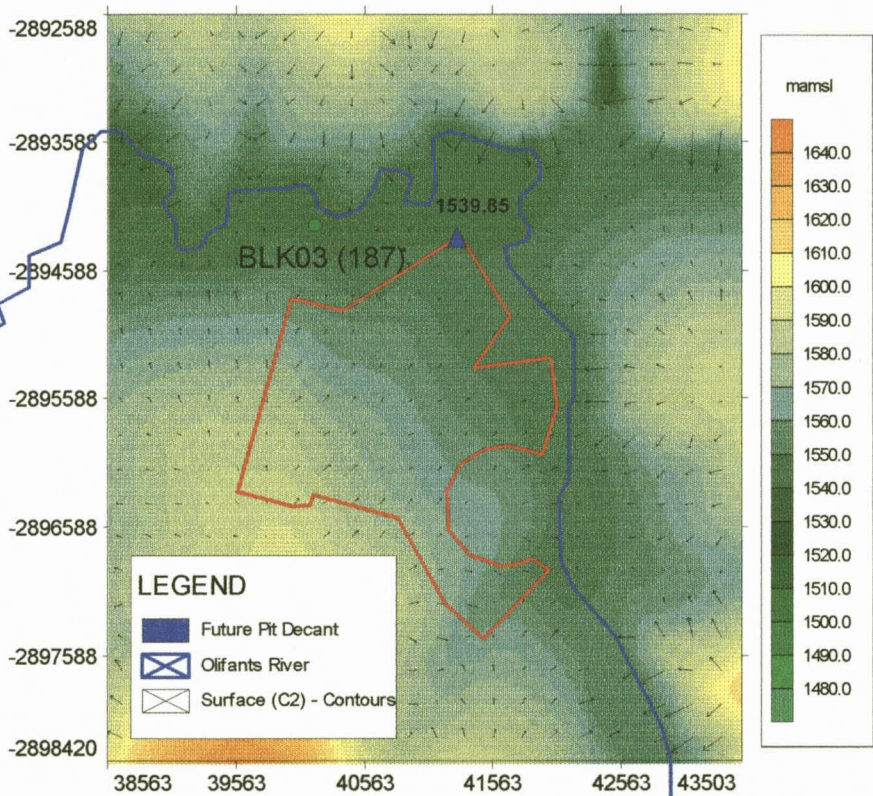


Figure 5-13. Map of the new opencast pit of Goedehoop Colliery as well as monitoring borehole BLK03 with a sulphate concentration value. The arrows indicate the groundwater flow paths while decant is taking place.

The pit decant elevation will be at 1539.7 mamsl (**Figure 5-13**) and the volume at decant is expected to be 23.1 Mm³ (mined to No. 2 Seam, see **Figure 5-14**). The decant volume is about 1600 - 1800 m³/d. Once again the groundwater component is small in the decant volume into the river (see section 5.2.1.1.1). The possible decant quality ranges from 1700 to 2400 mg/L for the current opencast pit at Goedehoop Colliery (7 kg/d/ha, Hodgson & Krantz, 1998) if the pit is allowed to fill up naturally with recharge.

The future influence that the new opencast pit may have on the Olifants River has been predicted using the Groundwater Reserve Program (Version 1.0), Van Tonder, 2002).

The Goedeheop Colliery's new opencast pit will increase the sulphate concentration in the river by 5 – 10 mg/L through the groundwater flow component. The increase of concentration was calculated by taking the calculated future decant quality and assuming this concentration for the whole pit and then by using the Ogata equation (see below) in combination with the Reserve software to calculate the effect of concentration on the Olifants River. The expected decant component that flows into the river will probably increase the concentration in the river by 105 mg/L on average (range 90 – 120 mg/L). The worst-case scenario for the decant component to increase the sulphate concentration in the Olifants River is 320 mg/L on average (range 270 – 370 mg/L). The worst-case scenario will only come in effect if the river's flow volume decreases dramatically to about 0.1 Mm³/month. The sulphate load flowing into the Olifants River from Goedeheop Colliery's new opencast pit will be in the order of 3000 kg/d (range 2600 – 3300 kg).

The Ogata equation was used to approximate the time it will take the sulphate-polluted groundwater from Goedeheop Colliery's new opencast pit to reach the river and at what concentration. The flow volume data in the river were obtained from the Department of Water Affairs and Forestry. The flow data range from 1972 to 1988. The surface water resources of South Africa of 1990, (Midgley *et al.*, 1994) were used to rework the flow data for each catchment.

Equation 5-2.
$$\frac{C}{C_o} = \frac{1}{2} \left[\operatorname{erfc} \left(\frac{1-v}{2\sqrt{D_i t}} \right) + \exp \left(\frac{vl}{D_i} \right) \operatorname{erfc} \left(\frac{1+vt}{2\sqrt{D_i t}} \right) \right] \text{ (Ogata, 1970)}$$

from Freeze and Cherry, 1998).

l – the distance along the flow path

v – is the average linear water velocity

t – time

C – is concentration at time *t*

C_o – is initial concentration

D – is the coefficient of molecular diffusion, for the solute in the porous medium

The above equation can be used to compute the shapes of the breakthrough curves of the concentration profiles (**Figure 5-15** and **Figure 5-16**).

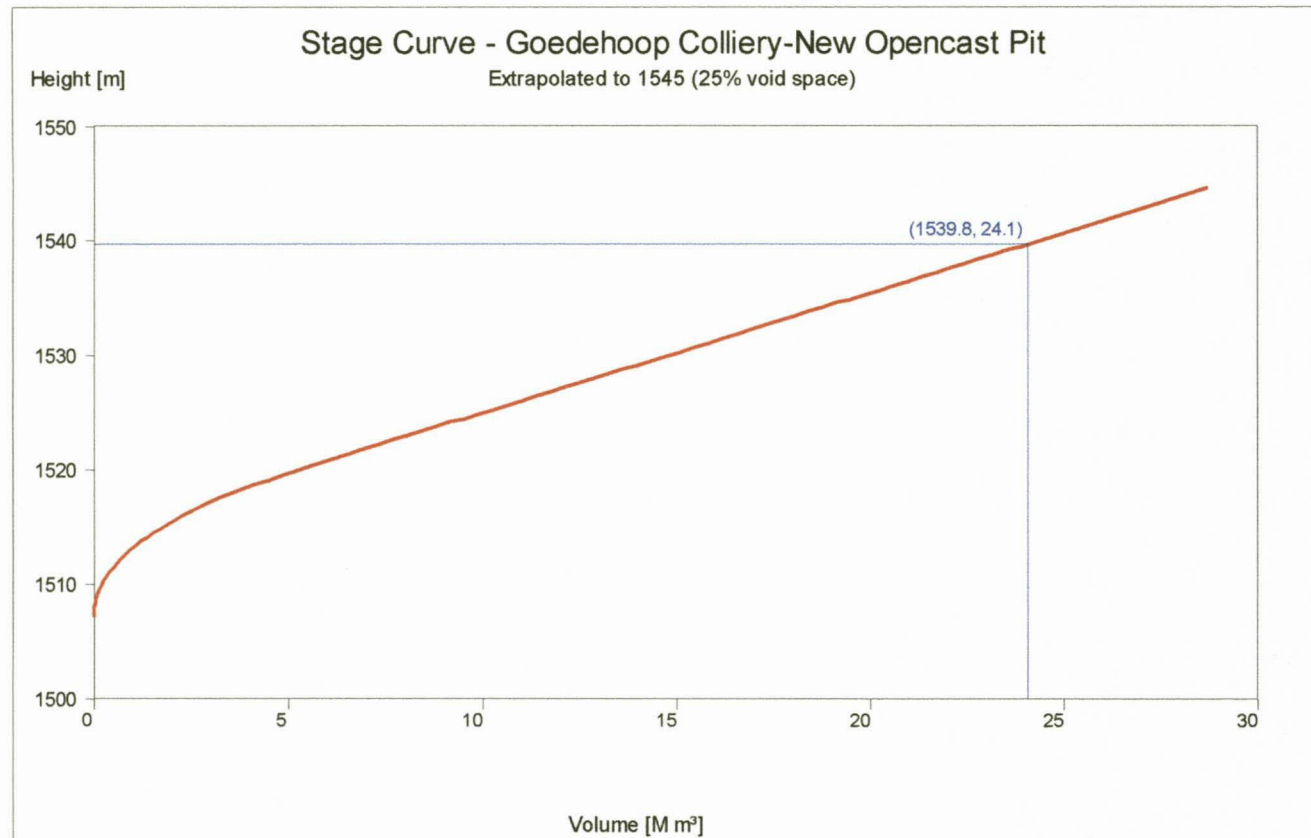


Figure 5-14. Stage Curve for the new opencast pit of Goedehoop Colliery in (Mm³).

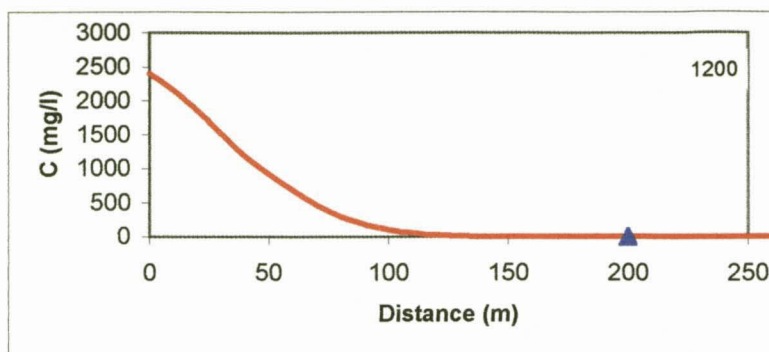


Figure 5-15. Graph of the breakthrough curves for the groundwater flowing from the Goedehoop Colliery's pit to the Olifants River on day 3200 (3.28 years). It must be noted that time on graph is time the groundwater takes to reach the river. This time starts from when the groundwater gradient is in the direction of the river until the affected water reaches the river.

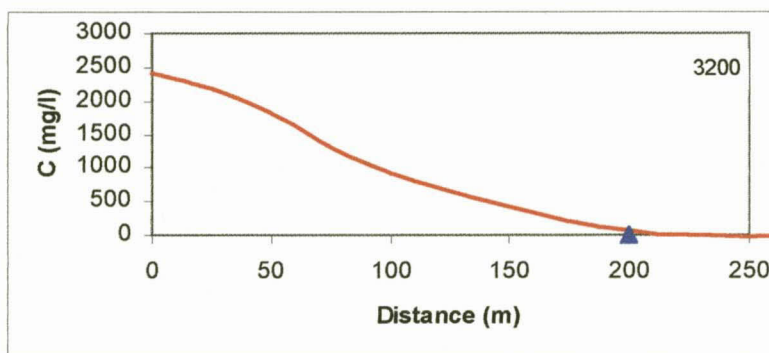


Figure 5-16. Graph of the breakthrough curves for the groundwater flowing from the Goedehoop Colliery's pit to the Olifants River on day 3200 (8.76 years). It must be noted that time on graph is time the groundwater takes to reach the river. This time starts from when the groundwater gradient is in the direction of the river until the affected water reaches the river.

The distance to the Olifants River from the Goedehoop Colliery's new opencast pit is from 100 m to 200 m on average.

The influence of the intermine flow between the new Goedehoop Colliery opencast and the Transvaal Navigational Colliery's Block C underground workings is negligible. The reason for this is that the Block C underground flows into the opencast for the majority of the intermine flow period. The intermine flow volumes are small (chapter on Quantification of the intermine flow volumes). The Block C underground is also filled to about 90%, thus oxidation is limited, due to the limited availability of oxygen to the reactive surfaces. The current quality of the groundwater in Block C underground void is of relatively good quality (sulphate – 578 mg/L, pH – 7.82 and soluble iron – 0.0545 mg/L). It is expected that the quality of the groundwater in the

new Goedehoop Colliery's opencast pit will be of worse quality due to the larger reactive surfaces exposed to the spoils, which will increase the oxidation rate (Morin *et al.*, 1997). Therefore although the Block C underground flows into the opencast pit, it is expected that the quality of intermine flow groundwater flowing into the Goedehoop opencast pit will be better than the water in the pit, thus the quality of the groundwater in the opencast pit should not be negatively impacted on because of the intermine flow water. The small intermine flow volume makes this even more unlikely, that the receiving Colliery should be negatively impacted on.

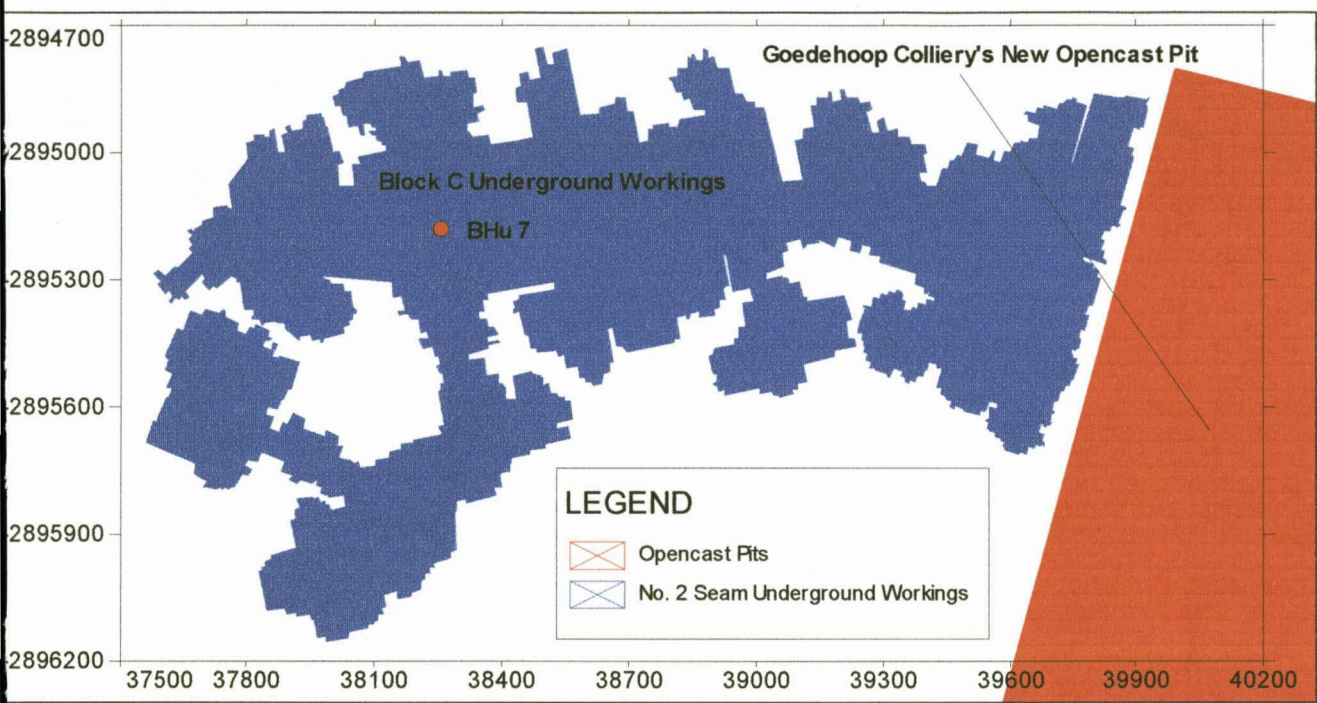


Figure 5-17. Map of TNC's Block C underground and the Goedehoop Colliery's new opencast pit. The observation borehole Bhu 7 for the Block C underground workings is also shown.

5.2.1.2 Transvaal Navigational Colliery Opencast Pits

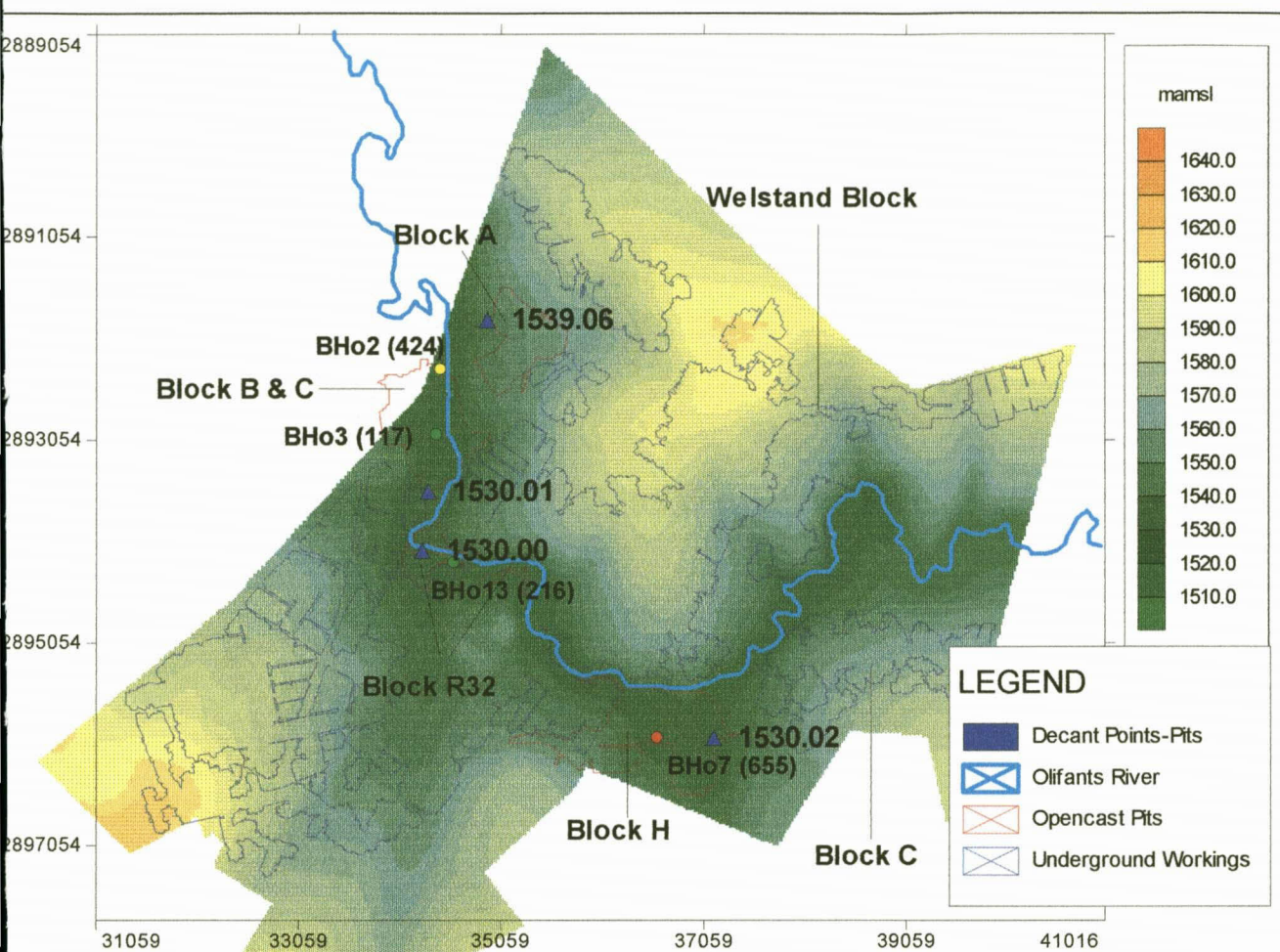


Figure 5-18. Map of TNC's opencast pits and the Welstand underground block as well as the monitoring boreholes for the opencast pits showing sulphate values (The red colour shows the concentration is above the SA water drinking standards, where the green colour shows that the concentration is below the SA drinking water standards. The yellow colour is for concentrations above the recommended standard).

TNC's opencast pits were flooded in the 2000 flood. Block H opencast pit has a sulphate concentration of 655 mg/L, Block R32 has a sulphate concentration of 216 mg/L and Blocks B & C have a sulphate concentration of 424 mg/L. After the flood the sulphate concentration decreased in all monitoring boreholes due to the diluting effect of the flooding. Consequently the mine will have lower iron and sulphate concentrations, and higher net alkalinity and pH-values (Evanangelou, 1995). The benefits of flooding points to a solution to water quality in the area. The possibility is clearly illustrated by this situation of artificially flooding pits from rivers if more than 85 - 95% of the spoils are flooded. If the spoils can only be flooded partially the oxidation reactions will continue, but a large part of the reactive surface will be

inundated and the oxygen will be cut off from the reactive surface, thus limiting the oxidation reaction and sulphate production rate. The flooding could also alter the pH of the opencast pit's water thus creating an environment where Fe^{3+} must precipitate and therefore cannot be used as an oxidant to oxidise the pyrite minerals. Ultimately inundation will improve the water quality (Evanangelou, 1995).

5.3 MASS BALANCE APPROACH FOR THE PREDICTION OF SULPHATE PRODUCTION RATES IN UNDERGROUND WORKINGS THROUGH EMPIRICAL METHODS

The Transvaal Navigational Colliery's underground workings have been used to predict the production rates of sulphate generation at Block C, Block F and Welstand Block (**Figure 5-19**). The production rates are estimated by taking underground voids in different stages of fill-up. The volumes in the underground voids are taken with sulphate increases over time and from this value a production rate is calculated for sulphate generation. The method therefore provides a means to extrapolate future chemistry in the area.

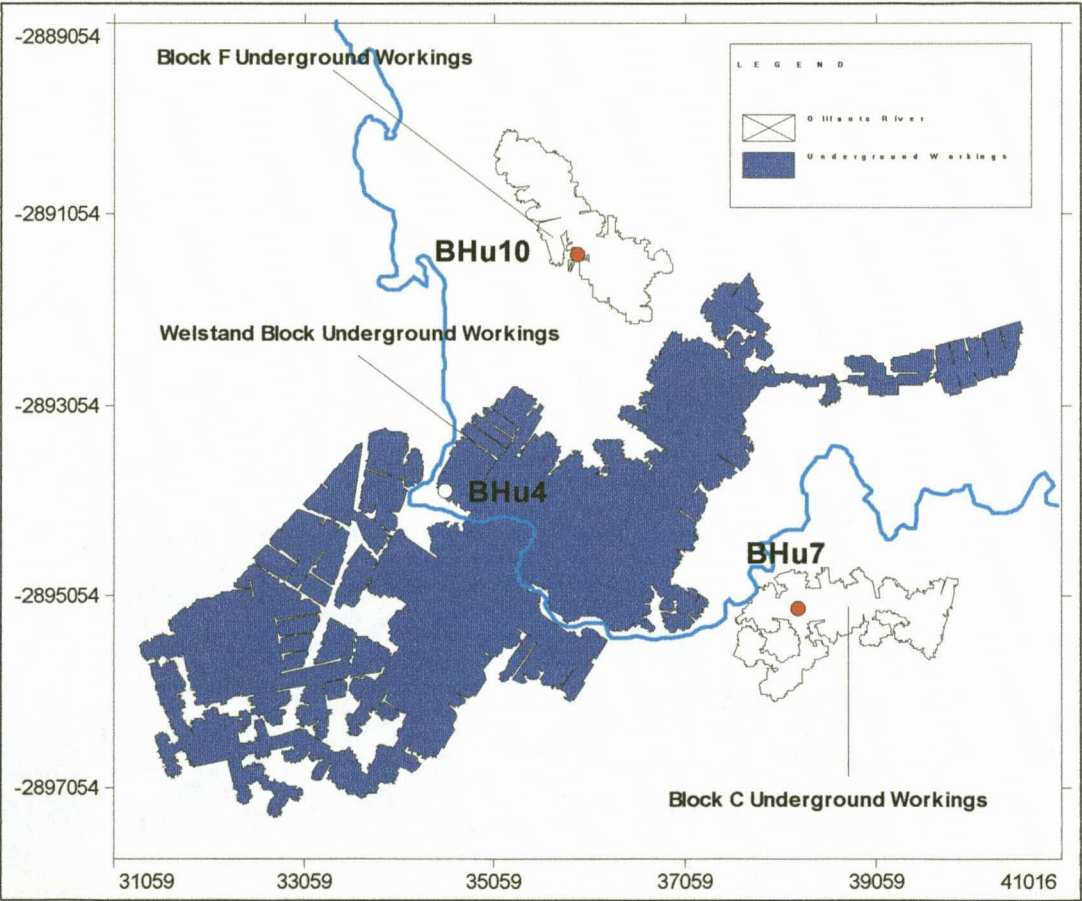


Figure 5-19. Map of TNC's underground workings used to calculate the Sulphate Production Rate also indicated are the positions of the monitoring boreholes.

Welstand Underground Block: Welstand Underground Block is about 95% flooded. Two dates with sulphate concentrations and water levels were selected to calculate the sulphate increase and water volume increase in underground workings (see **Table 5-1**). The sulphate increase over the 750-day period is 101 mg/L, while the water level has increased by 0.94 m, and the increase in volume in the underground void was 3.73×10^8 litres. The Sulphate Production Rate calculated with these data was 0.343 kg/ha/d.

Table 5-1. Table of values used in the Welstand Block reaction rate calculations via the mass balance approach.

Borehole-BHu4	Sulphate Concentrations (mg/L)	Water Levels (mamsl)	Volume in Void (L)
Point 1 (Day-1)	967	1520.99	2.51E+10
Point 2 (Day-720)	1068	1521.93	2.55E+10
Difference in Values	101	0.94	3.73E+08
Void 95 % Flooded			

Block C Underground Workings: Welstand Underground Block is about 90% flooded. Two dates with sulphate concentrations and water levels were selected (**Table 5-2**) to calculate the sulphate increase and water volume increase in underground workings. The sulphate increase of the 720-day period is 6.4 mg/L, while the water level has increased by 13.375 m and the increase in volume in the underground void was 8.01×10^4 litres. The Sulphate Production Rate calculated with these data was 0.422 kg/ha/d.

Table 5-2. Table of values used in the Block C underground reaction rate calculations via the mass balance approach.

Borehole-BHu4	Sulphate Concentrations (mg/L)	Water Levels (mamsl)	Volume in Void (L)
Point 1 (Day-0)	571.6	1519.258	2.30E+06
Point 2 (Day-990)	578	1532.633	2.38E+06
Difference in Values	6.4	13.375	8.01E+04
Void 90 % Flooded			

Block F Underground Workings: Welstand Underground Block is about 84% flooded. Two dates with sulphate concentrations and water levels were selected (**Table 5-3**) to calculate the sulphate increase and water volume increase in underground workings. The sulphate increase of the 730-day period is 7 mg/L, while the water level has increased by 0.704 m, and the increase in volume in the underground void was 4.32×10^4 litres. The Sulphate Production Rate calculated with these data was 0.532 kg/ha/d.

Table 5-3. Table of values used in the Block F underground reaction rate calculations via the mass balance approach.

Borehole-BHu4	Sulphate Concentrations (mg/L)	Water Levels (mamsl)	Volume inVoid (L)
Point 1 (Day-0)	973	1533.493	2.04E+06
Point 2 (Day-730)	980	1534.197	2.08E+06
Difference in Values	7	0.704	4.32E+04
Void 84 % Flooded			

To refine the above-calculated values more data are needed that were not available at the time of calculation. It is recommended that more of these values (reaction rate values and percentage underground filled over time) be generated. With more reaction rate values the trend function could be estimated more accurately. Therefore it is recommended that this method should be thoroughly investigated and further research should be done.

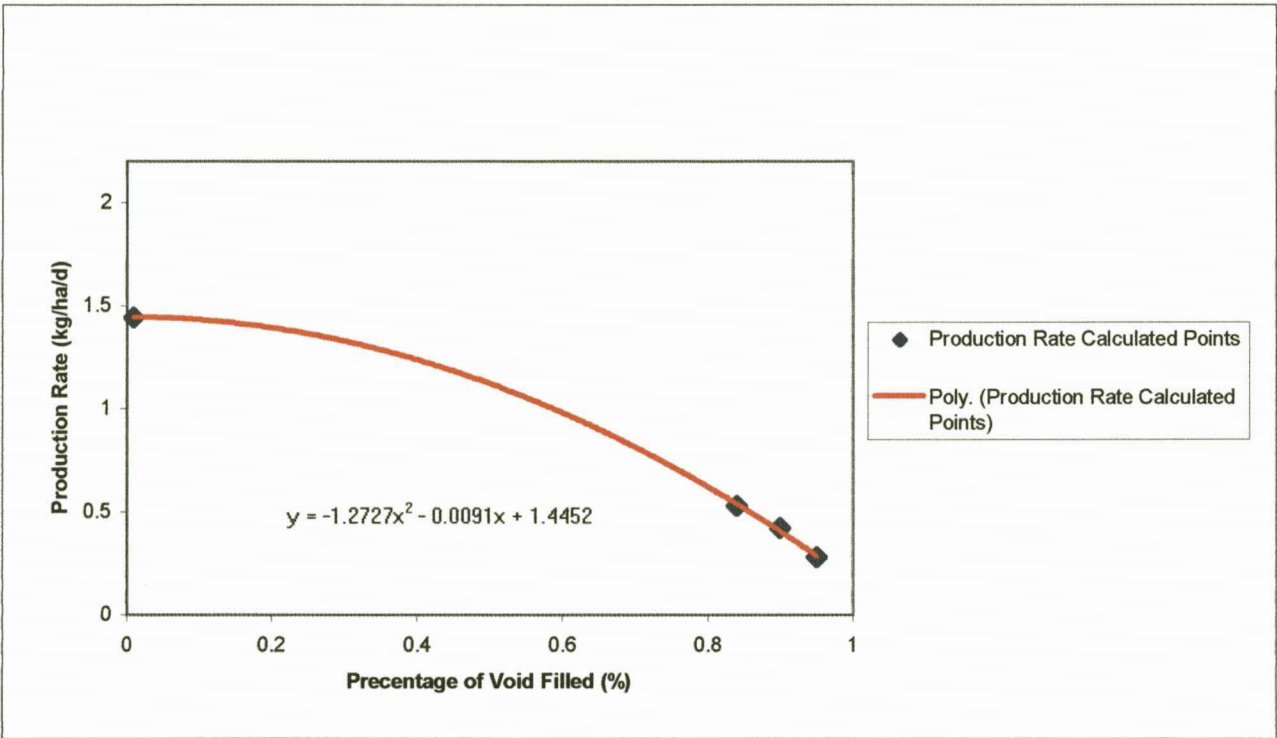


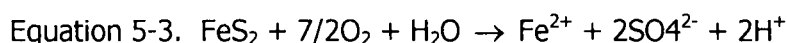
Figure 5-20. Graph of the calculate reaction rate points, trend line and polynomial function.

The reaction rate points were plotted on a graph (**Figure 5-20**) and a trend line fitted to the data points by means of a second order polynomial function of the form:

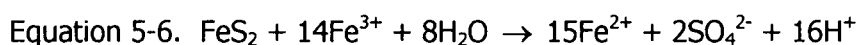
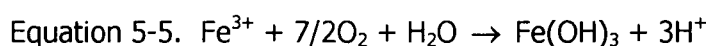
$$y = -1.2727 (x)^2 - 0.0091 (X) + 1.4452.$$

It can be concluded from **Figure 5-20** that the reaction rate decreases as the underground void fills up with groundwater. The reason for this is that as the void fills up with groundwater the oxygen is cut off from the reaction surface as can be

seen in **Equation 5-3** and **Equation 5-4**. Oxygen is a necessary oxidant and if it is limited the AMD process will be inhibited. The first increment of water level rise is very important because the mining floor and rubble around the pillars will be inundated first, depriving a large part of the reaction surface of oxygen (Evanangelou, 1995).



Oxygen diffusion to pyritic material is greatly reduced upon inundation because the diffusion coefficient of O_2 through the covering water is only 1/10000 of that through the atmosphere. Hence, the rate of O_2 consuming reactions becomes low and rate limiting, and bacterial oxidation of pyrite becomes slow or nil (Evanangelou, 1995).



Kleinmann and Crerar (1979) confirmed that there was no significant growth of T. ferrooxidants in saturated environments. However, complete inhibition of pyrite oxidation by flooding may never be possible because of the availability of Fe^{3+} (**Equation 5-5** and **Equation 5-6**) as an alternate oxidant (Evanangelou, 1995). The concentration of Fe^{3+} will most probably be minute, due a relatively neutral pH (when underground void is filled with groundwater) and under this state Fe^{3+} will most probably precipitate or be reduced to Fe^{2+} (**Figure 5-21**).

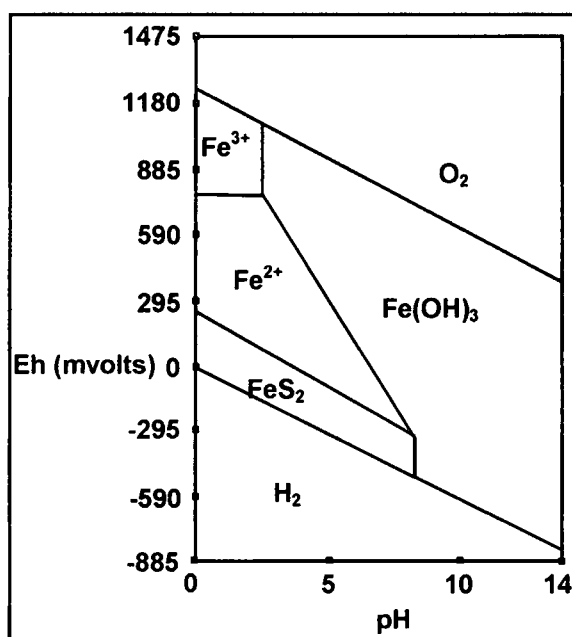


Figure 5-21. Pyrite Stability Diagram (After Brown, 1985).

The mass balance approximation is a method that needs further research to refine the sulphate generation rates. This method can be used to predict what could happen for future scenarios. When the sulphate generation rate for the opencast pits (5 –10 kg/ha/d) of Hodgson is compared to the mass balance production rate the generation rate (0.1 – 1.5 kg/ha/d) for underground, it is concluded that the sulphate generation rate for the underground workings is an order smaller. This can be due to the much smaller reaction surface in the underground workings when compared to that of an opencast pit. It must also be noted that the sulphate generation rate might be lower than that of the opencast but sulphate concentration in underground (bord-and-pillar areas) might be higher than that of the opencast pit due to slow water ingress. The recharge to an underground working is much lower than that of the recharge of an opencast pit.

The mass balance approximation have been used to predict the future void chemistries rather the geochemical modelling due to lack of availability chemistry data for the model package.

5.4 THE HYDROCHEMISTRY OF THE HYDRAULICALLY INTERCONNECTED UNDERGROUND WORKINGS AND OPENCAST PITS BY MEANS OF PILLAR EXTRACTION

In this section of the chapter the mass balance approximation is applied to the hydraulic interconnected opencast pits and underground workings of Douglas Colliery in an attempt to predict the future sulphate salt generation and concentrations. It must be noted that the method needs further verification, but it is felt that it can provide an indication for what might happen in the future. Further data and research are needed to refine the mass balance approximation to sulphate production rates.

5.4.1 Douglas Colliery Combined Underground Workings and Opencast Pits

5.4.1.1 *Boschmanskrans Section Future Opencast Pits mined into the Boschmanskrans No. 2 Seam Underground Workings*

In the Boschmanskrans Pillar project two opencast pits, namely the West pit and East pit are going to be mined respectively into the Boschmanskrans No. 2 Seam underground workings to extract the pillars left by the underground bord-and-pillar mining.

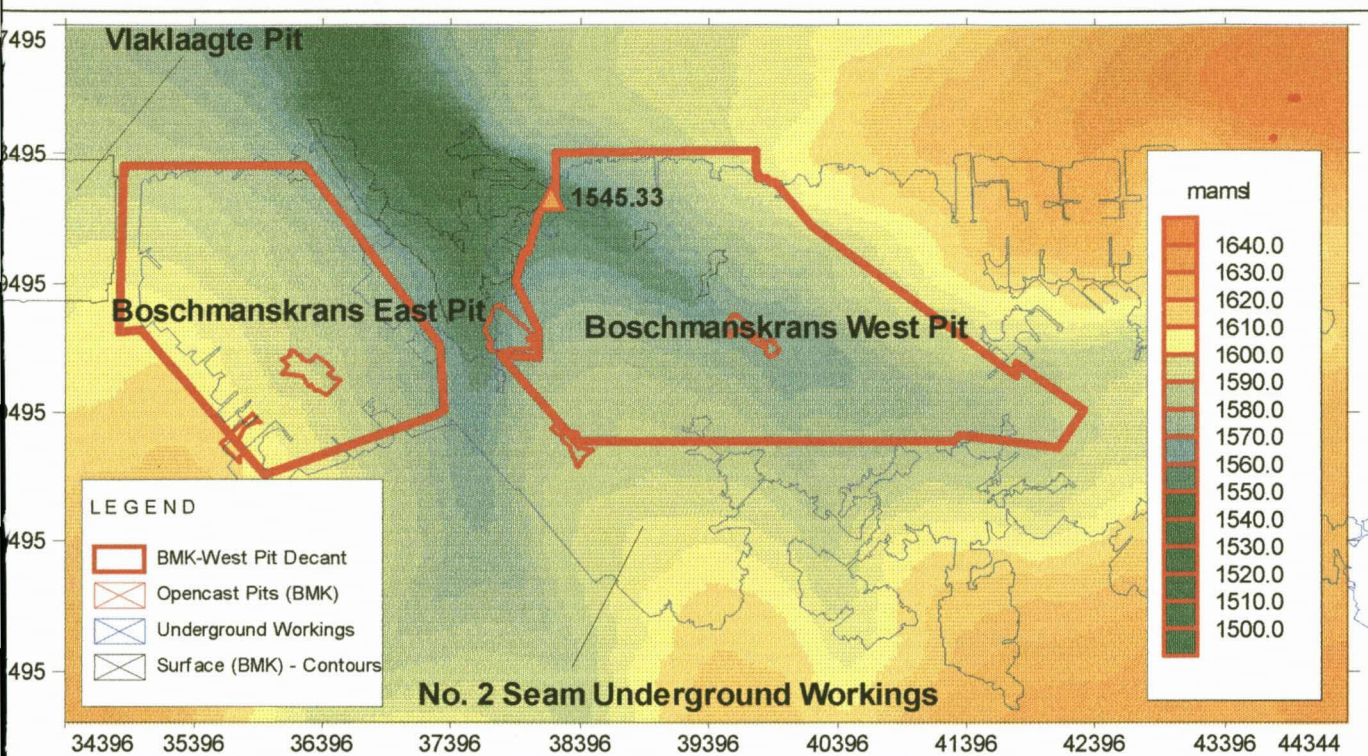


Figure 5-22. Map of the future Boschmanskrans East and West opencast pits.

As a result the two opencast pits will eventually be connected to each other hydraulically by the No. 2 Seam underground workings. Due to the hydraulic connection the underground workings and the two opencast pits will decant at one decant point, based on current mining plans.

The pit decant is at 1545.33 mamsl (**Figure 5-22**) and is situated on the Boschmanskrans west opencast pit. The combined decant volumes from the underground and pits are between 3900 – 4900 m³/d. The possible decant quality ranges from 1750 to 2300 mg/L (5 - 10 kg/ha/d, Hodgson & Krantz, 1998) if the pit is allowed to fill up naturally with recharge. The Boschmanskrans No. 2 Seam underground workings therefore could contribute about 17 – 20% (mass balance approximation) of the total sulphate generated by combined opencast pits and Boschmanskrans complex. 80 – 83% of the sulphate mass is generated by West- and East Boschmanskrans opencast pits. The reason for this is that the sulphate generation rate in an opencast pit is a factor greater due to the much larger reactive surface of the spoils versus the underground mines floor and pillar surfaces.

Concentration Value Approximation through the Mass Balance Approach for the Springbok no. 2 Seam Underground Workings.

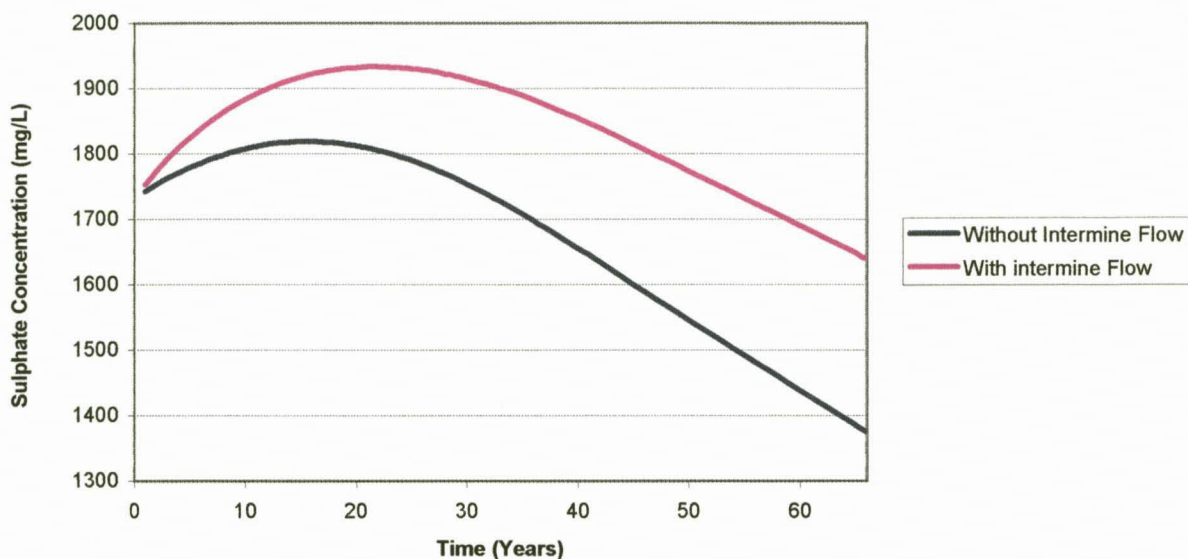


Figure 5-23. Graph of concentration over time for an intermining flow scenario and for a scenario without intermining flow for the Goedehoop Colliery's Springbok **No. 2 Seam** underground workings.

Intermining flow will take place between the Boschmanskrans No. 2 Seam underground and Goedehoop Colliery's No. 2 Seam underground (see chapter on the quantification of intermining flow). The current sulphate concentration in the Springbok No. 2 Seam workings is 1731 mg/L. The Springbok No 2 Seam underground currently is about 38 – 42% flooded. The total mass of sulphate in the Springbok No 2 Seam workings is approximately between 36300 – 38300 tons. The intermining flow volume from the Boschmanskrans complex via the Boschmanskrans No 2 Seam underground to the Springbok No 2 Seam underground workings is initially 320 m³/d and increases to about 420 m³/d. If the Boschmanskrans reaches a worst-case sulphate concentration of 2300 - 2400 mg/L (worst case calculated at 15% recharge to the opencast pit system) the sulphate load transferred to the Springbok No 2 Seam underground will be in the order of 0.5 – 0.7 tons of sulphate per day. The Springbok underground workings will generate approximately 2.6 tons a day (mass balance approximation). The total amount of sulphate added to the Springbok No 2 Seam workings over the period the intermining flow has taken place in the direction of the Springbok workings, is approximately 20% of the total sulphate generated by the workings and the sulphate already present in the workings. This contribution was calculated with the mass balance approach to sulphate production rate prediction and the 5 – 10 kg/ha/d approximation (Hodgson & Krantz, 1998),].

By using the 5 - 10 kg/ha/d for the opencast sections (Hodgson & Krantz, 1998) and the mass balance approximation for the underground workings it is concluded that the intermine flow from the Boschmanskrans section could have a detrimental effect on the water quality of Springbok No 2 Seam underground workings. The concentration of the Springbok No 2 Seam underground workings will increase to between 10 - 360 mg/L with the intermine flow from Boschmanskrans. The predicted concentration without intermine flow for the Springbok No 2 Seam workings will be 1350 mg/L. The projected concentration of the Springbok No 2 Seam workings with intermine flow is 1700 mg/L, based on a mass transfer calculation. This calculates to a predicted approximation of 20% increase to Springbok No 2 Seam underground workings in terms of sulphate load.

The acid-base accounting (Hodgson et al., 1998) that was done on the Boschmanskrans section suggests the following (see Figure 5-24):

- The sediments above the No 2 Seam have a low probability of acidification (see **Figure 5-24**).

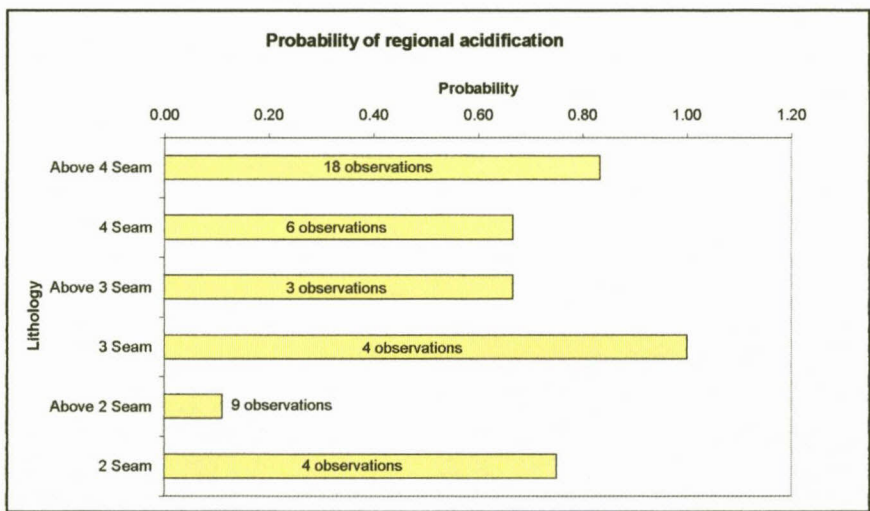


Figure 5-24. Graph of the probability of regional acidification

- The sediments above the No. 2 Seam have a high probability of acidification and a low neutralising potential (see **Figure 5-24**).
- The fresh sediments above the No. 3 Coal Seam generally have excess acid potential (see **Figure 5-24**).
- Leaching tests show that a wide variety of heavy metals will leach from the rock under acid conditions. It is therefore imperative that the spoil at Boschmanskrans be managed in such a way that the chances of acidification are minimised (see **Figure 5-24**).

- The sediments above the No. 4 Seam have a 65% probability of acidification (see **Figure 5-24**).
- The sediments above the No. 2 Seam have a 65% probability of acidification and a low neutralising potential (see **Figure 5-24**).

It is concluded from the above that if the spoils in the Boschmanskrans Section are not managed correctly, acidification can take place and therefore the intermine flow to Springbok Colliery could be detrimental to the water quality of the water in the Springbok No 2 Seam underground workings.

5.4.1.2 Van Dyks Drift Section's (VDD) Planned South Opencast Pit mined into the Van Dyks Drift No. 2 Seam Underground Workings and the Steenkoolspruit/Kleinkopje Pit

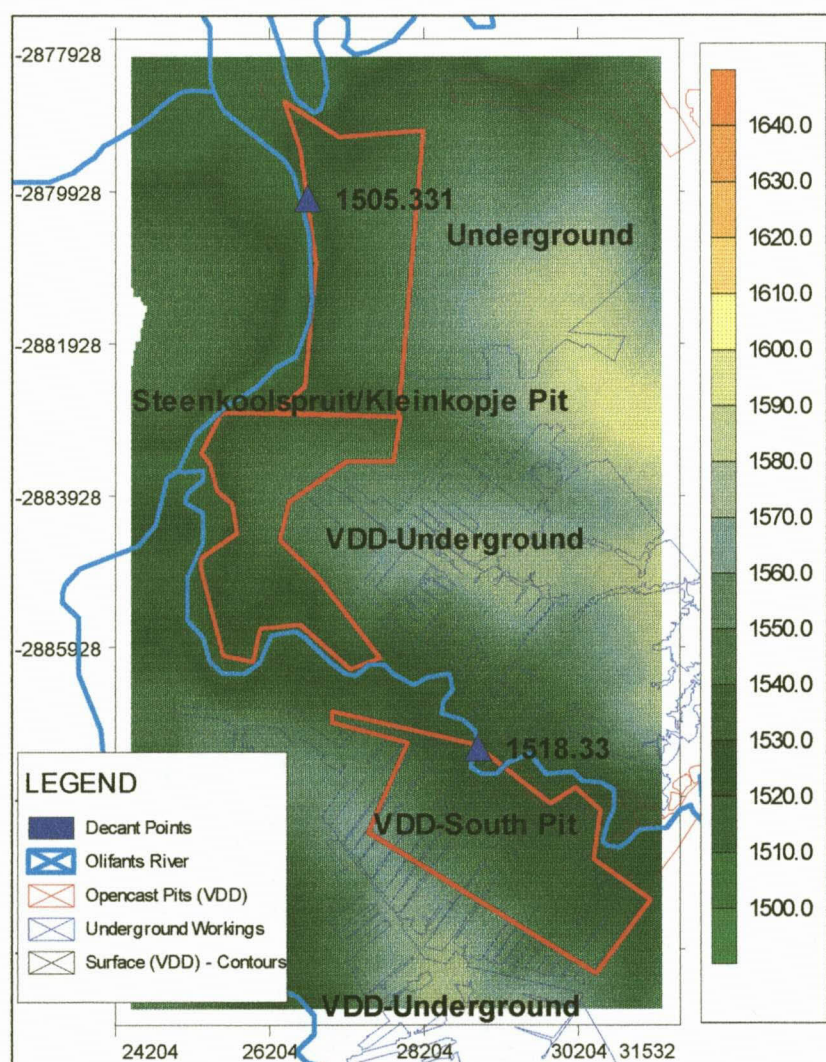


Figure 5-25. Map of Van Dyks Drift section's (VDD) South opencast pit and the Steenkoolspruit/Kleinkopje opencast pit.

The planned Van Dyks Drift South opencast pit is going to be mined into the Van Dyks Drift No. 2 Seam underground workings to extract the pillars left by the underground mining. As in the case of the Boschmanskrans East- and West Pit, the Van Dyks Drift underground workings will decant through the Van Dyks Drift South planned opencast pit.

The Van Dyks Drift South pits decant is at 1518.33 mamsl (**Figure 5-25**) and the combined volume at decant of the pit and underground workings is 77.3 Mm³ (mined to No. 2 Seam pillars). The decant volume is about 1950 - 2500 m³/d. The possible decant quality ranges from 1750 to 2300 mg/L for the current opencast pit at Goedehoop Colliery (7 kg/d/ha, Hodgson & Krantz, 1998) if the pit is allowed to fill up naturally with recharge. Several studies have been done on the Van Dyks Drift section (Hodgson *et al.*, 1998 and JMA, 1998), but the data used to determine the decant qualities are not valid in the planned Van Dyks Drift South Opencast Pit, due to radically changed future mining plans.

The decant quality can possibly be improved by flooding the pit from the Olifants River (see section 5.2.1.2).

The future influence that the Van Dyks Drift South opencast pit may have on the Olifants river has been predicted by using the Groundwater Reserve Program (Version 1.0, Van Tonder, 2002). The Van Dyks Drift section's South opencast pit will increase the sulphate concentration in the river by 10 – 15 mg/L through the groundwater flow component. The expected decant component that flows into the river will probably increase the concentration in the Olifants River by 110 mg/L (range 80 – 140 mg/L) on average. The worst-case scenario for the decant component to increase the sulphate concentration in the Olifants River is 360 mg/L (range 260 – 450 mg/L) on average. The worst-case scenario will only come in effect if the river's flow volume decreases dramatically to about 1.78 Mm³/month. The mass of sulphate flowing into the Olifants River from Van Dyks Drift South opencast pit will be in the order of 4500 kg/d (range 3300 – 5800 kg/d).

The Steenkoolspruit/Kleinkopje opencast pit is going to be mined to right next to the North Shaft underground workings. The Steenkoolspruit/Kleinkopje opencast pit decant is at 1505.33 mamsl (**Figure 5-25**) and the combined volume at decant of the pit and underground workings is 63.4 Mm³ (mined to No. 2 Seam pillars). The combined decant volume is about 3800 - 4900 m³/d. The possible decant quality ranges from 1700 to 2400 mg/L for the current opencast pit at Goedehoop Colliery (7 kg/d/ha) (Hodgson & Krantz, 1998) if the pit is allowed to fill up naturally with recharge.

The decant quality can possibly be improved by flooding the pit from the Olifants River (see section 5.2.1.2). The future influence that the Steenkoolspruit/Kleinkopje

planned opencast pit may have on the Olifants River have been predicted by using the Groundwater Reserve Program. The Douglas Colliery's Steenkoolspruit/Kleinkopje planned opencast pit will increase the sulphate concentration in the river by 10 – 20 mg/L through the groundwater flow component. The expected decant component that flows into the river will probably increase the concentration in the Olifants River by 180 mg/L (range 130 – 230 mg/L) on average. The worst-case scenario for the decant component to increase the sulphate concentration in the Olifants River is 590 mg/L (range 420 – 760 mg/L) on average if the flow decreases dramatically (0.18 Mm³/month). The mass of sulphate flowing into the Olifants River from Van Dyks Drift South opencast pit will be in the order of 9000 kg/d (range 6464 - 11800 kg/d).

5.5 APPLICATION OF THE MASS BALANCE APPROXIMATION TO THE PREDICTION OF SULPHATE PRODUCTION RATES TO UNDERGROUND WORKINGS IN THE CENTRAL WITBANK COALFIELD

This section of the chapter discusses water quality impacts of intermine flow on the affected underground workings. The mass balance approximation to predicting sulphate production rates was used to predict the future chemistry scenario.

5.5.1 Groundwater Hydrochemistry of Goedehoop Colliery No. 2 Seam Underground Workings

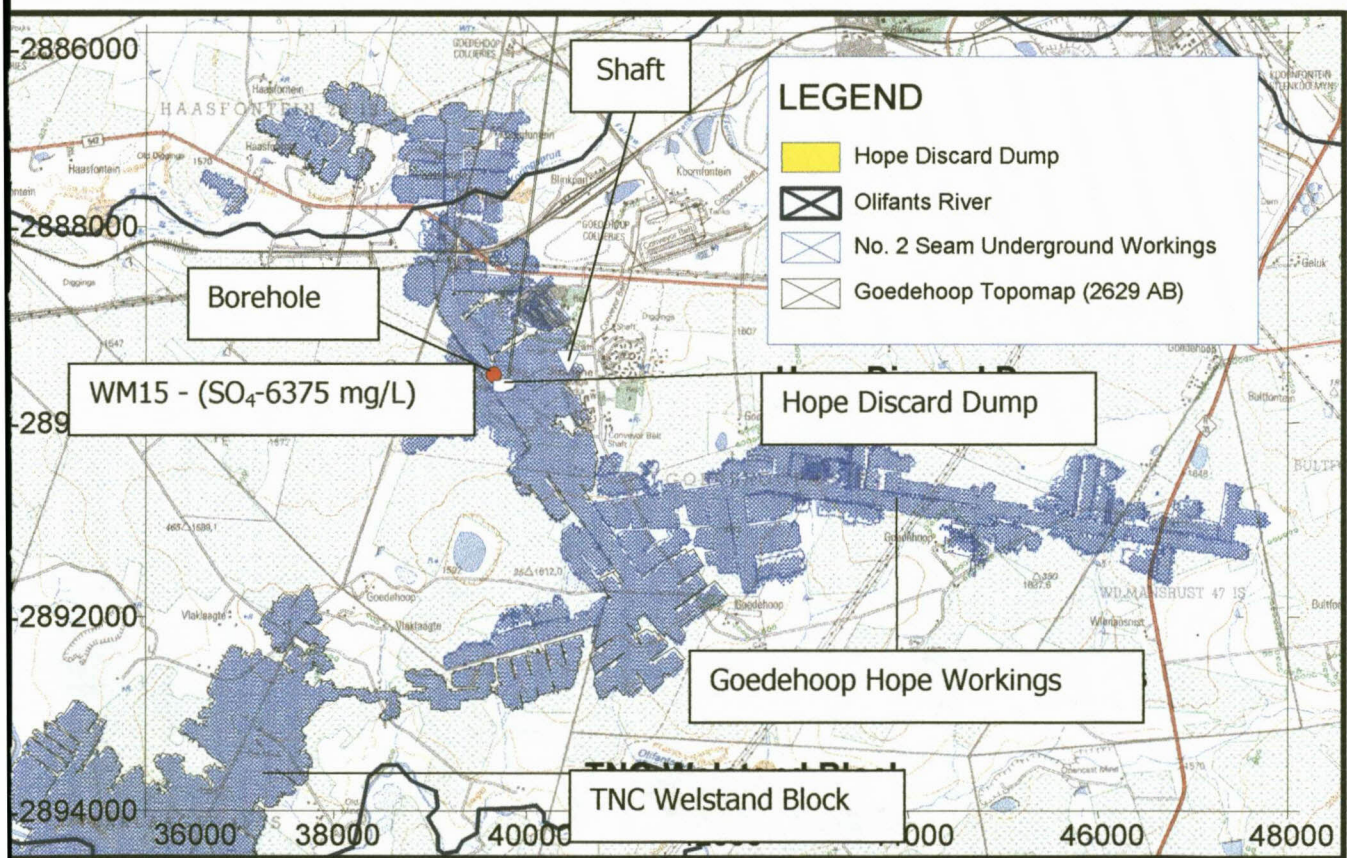


Figure 5-26. Map of Hope Underground Workings of Goedehoop Colliery showing the positions of the shaft, Hope discard dump as well as monitoring borehole WM15 showing the sulphate concentration that monitors the groundwater of Hope discard dump.

The latest sample (2001/04/11) in

Figure 5-26 indicates that the groundwater down gradient from Hope discard dump has a high sulphate value (6375 mg/L) at borehole WM15. This value has an ion balance error of -40 and is therefore incorrect. The other sulphate concentrations (5480 mg/L) taken at dates before the latest sample also show large sulphate concentrations with an ion balance error. Therefore it could be assumed that this is most probably the order of the sulphate concentration. Discard dumps usually have high sulphate values due to the pyrite minerals that which are enriched in discards, oxidised rapidly due to the exposure to oxygen the atmosphere.

The Hope Underground workings are currently unfilled due to mining activities, but may contain small amounts of water in some areas (UG04 is most likely in such a compartment). The Mass Balance Approach to Predicting Sulphate Production Rates (Section 5.3) was applied to predict the sulphate concentration for the future scenario when the mining activities have ceased.

Concentration in Hope Underground Workings vs. Percentage of Workings Filled over Time

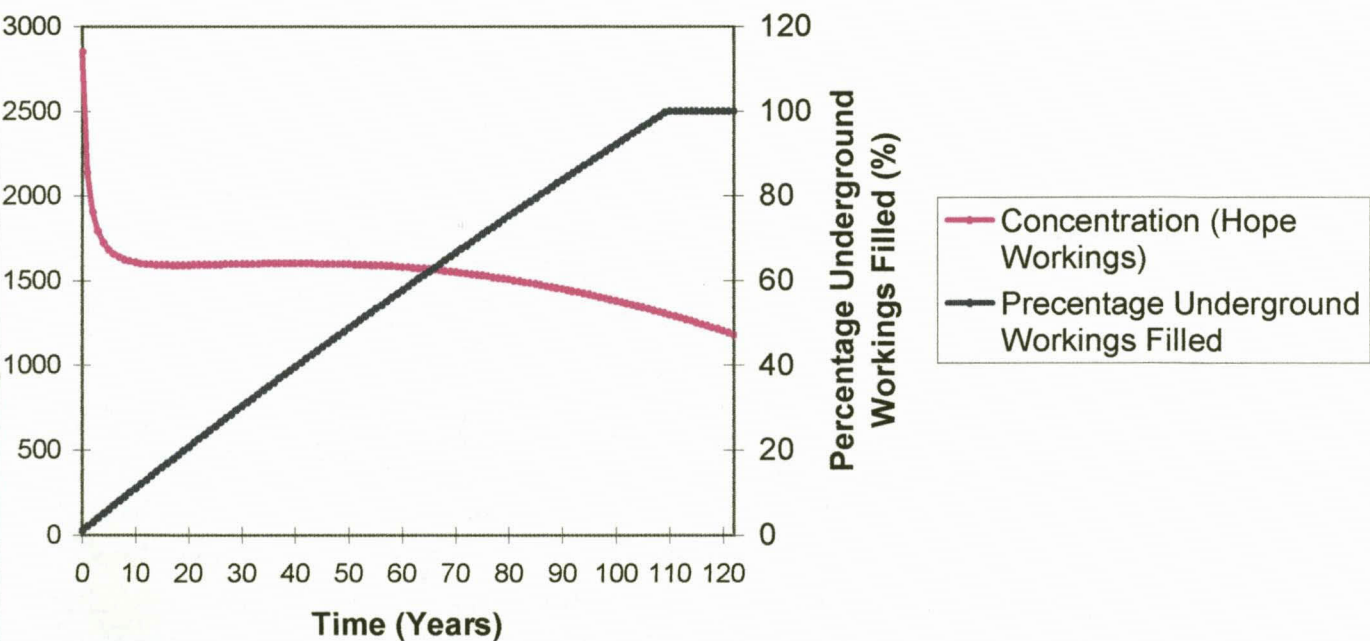


Figure 5-27. Graph of sulphate concentration in underground and percentage of underground workings filled with groundwater over time.

Initially when the underground void starts to fill up, there are large amounts of oxygen available and much of the reactive surface is exposed to oxygen. The pillars (bord-and-pillar mining) in the case of Goedehoop Colliery's Hope underground workings and the discard materials (pyrite containing rubble) left around the pillars ensure an initial high rate of oxidation. During the mining phase the mine is kept empty but in some compartments there is a small amount of groundwater in pools (sometimes a function of the shape of the floor) and thus oxidation takes place. Due to the small volume of water in the compartment and the high oxidation rate (large reaction surface exposed to oxygen) a very high sulphate concentration is produced in the pool. SI calculations have been done by using PHREEQC (Parkhurst and Appelo, 1999) and the following are the results:

Calculated with PHREEQC database: SI-Index = -0.11, IAP = -4.69, log KT = -4.58 $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. The SI-Index indicates that the Gypsum phase is under-saturated.

Calculated with the Minteq database: SI-Index = 0.15, IAP = -4.69, log KT = -4.85 $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. The SI-Index indicates that the Gypsum phase is over-saturated.

Gypsum precipitation however limits the production of sulphate. The two databases are thus not in total agreement and contradict each other. This difference in SI-Index answer could be attributed to the different experimental results when the two databases were compiled. This is a very important observation that should be kept in mind when applying or interpreting results from geochemical models. Appelo (Pers comm., 2002) suggests that users should be aware of these differences and interpret results accordingly.

For example observation borehole UG04 currently has a sulphate concentration of 2800 mg/L. This borehole UG04 is most probably situated in a compartment with a small amount of water due to the fact that Hope underground workings are mostly pumped dry due to mining activities. Accordingly the initial concentration of sulphate will be high (**Figure 5-27**). Over time the sulphate concentration will decrease cumulatively. Eventually as the underground void (Hope Workings) fills up with groundwater the oxygen is cut off from the reactive surface (**Figure 5-28**). The calculated (Modflow) intermine flow from TNC's Welstand Block should be so small that sulphate introduced to the Hope underground workings would be about 4 – 6% of the total amount of sulphate generated by the Hope workings itself. The average sulphate concentration of the Welstand underground block is currently about 600 mg/L, therefore the intermine flow from TNC will dilute the concentration of sulphate in the Hope workings. In the long term the intermine flow volume from the Welstand No. 2 Seam underground workings (see chapter on quantification of intermine flow)

should not be excessively detrimental to the Hope No. 2 Seam underground workings.

In other words the oxygen diffusion to pyrite material in the floor, pillars and rubble around the pillars is greatly reduced as the underground void fills with groundwater. Therefore, the rate of O_2 consuming reactions becomes low and rate limiting, and bacterial oxidation of pyrite becomes slow. As these oxidation reactions are slowed

the rate at which sulphate is produced. Thus the rate slows down (**Figure 5-28**) and the concentration of sulphate diminishes with time as the reaction rate slows down. The recharge filling the underground workings also dilutes the sulphate load in the void itself and hence the concentration will decrease over time as the pit fills up (**Figure 5-28**).

Concentration in Hope Underground Workings vs. Sulphate Production Rate over Time

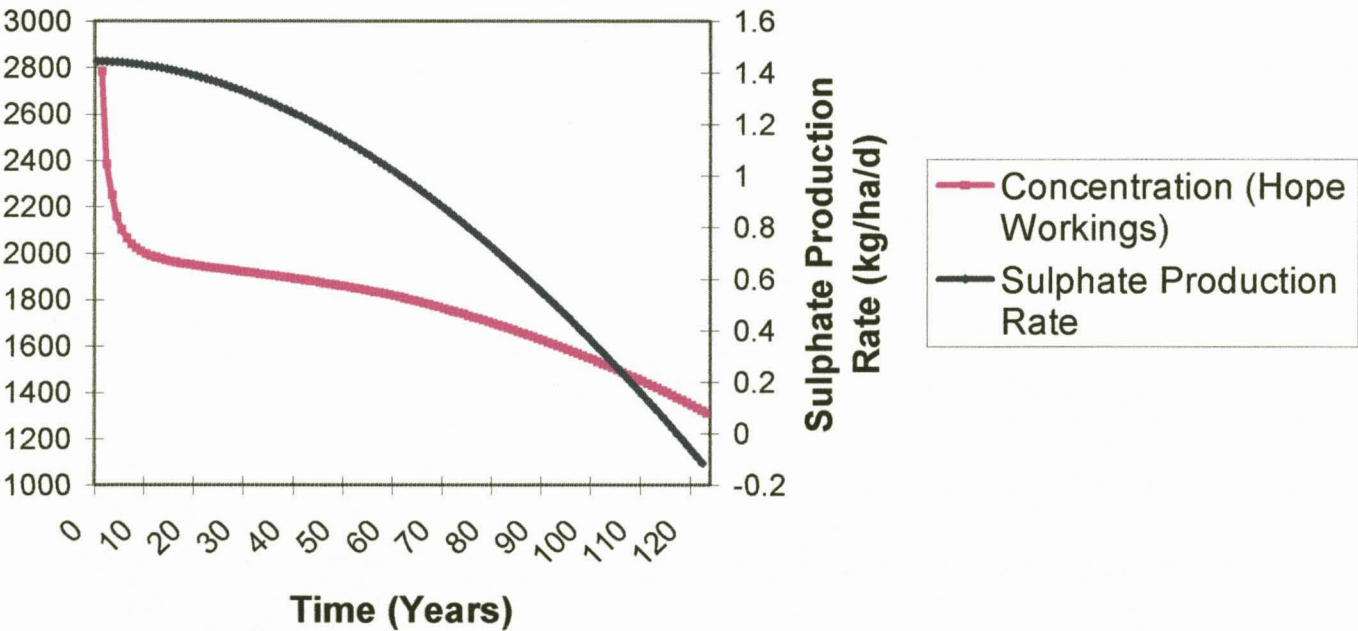


Figure 5-28. Graph of Sulphate Production Rate and concentration versus time of Goedehoop Colliery's Hope Underground workings.

5.5.2 Groundwater Chemistry of New Clydesdale Colliery No. 2 Seam Underground Workings

For the monitoring boreholes drilled in the perched and fractured rock aquifers (Groundwater consulting Services, 1998) the following chemistry was available (see **Figure 5-29**):

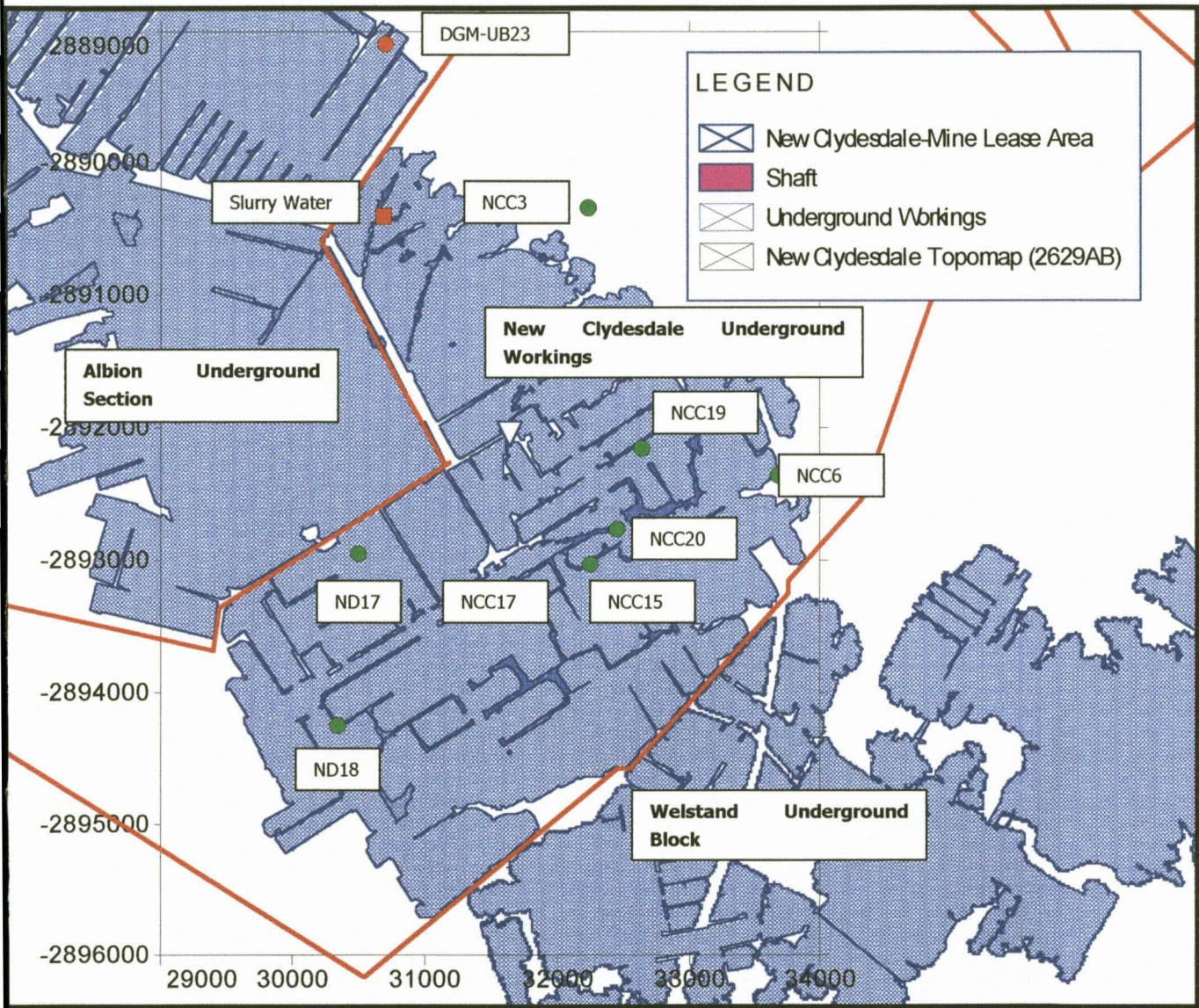


Figure 5-29. Map of New Clydesdale Colliery's No. 2 Seam underground workings as well as Albion Section's No. 2 Seam underground workings and monitoring boreholes.

The concentrations of sulphate and calcium fall within the SA drinking water standard. No trends can be deduced due to the once-off nature of the data. The pH-values are generally neutral. The groundwater in the vicinity of the slurry water is the exception and the groundwater at the monitoring borehole has a high sulphate value (1214 mg/L), and oxidation is most probably taking place in the slurry waste.

In the expanded Durov diagram most points plot in the sectors designated for unpolluted groundwater (**Figure 5-30**). Therefore according to the once-off data the groundwater of the upper perched and lower fractured rock aquifer is still fairly unpolluted.

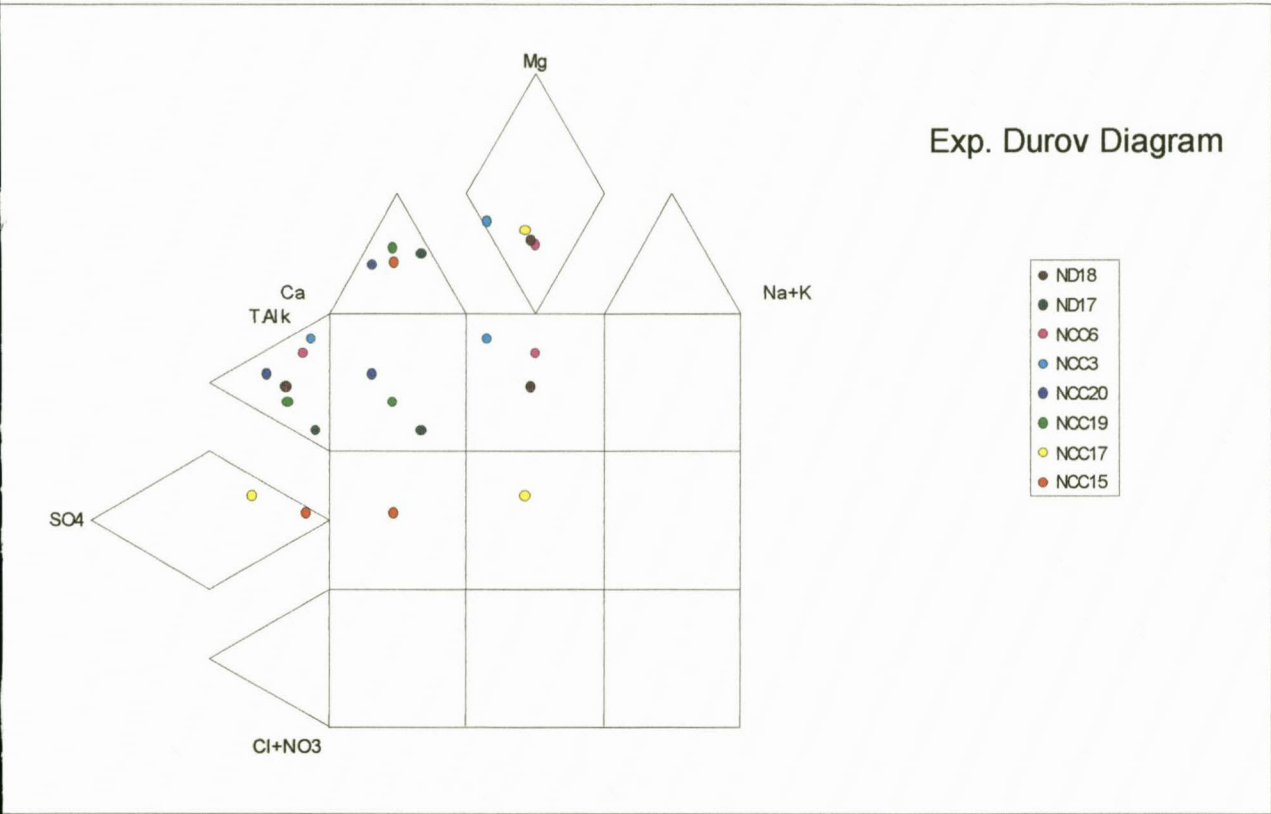


Figure 5-30. Expanded Durov diagram.

The groundwater chemistry data of New Clydesdale Collieries are very limited for the No. 2 Seam underground workings. Therefore the sulphate mass balances approach was applied to try and estimate the concentration of sulphate in the underground workings for the future scenario.

The current concentration of sulphate in the New Clydesdale underground workings was taken at an average of 1500 mg/L (Groundwater Consulting Services, 1998).

By applying the mass balance approach to the New Clydesdale No. 2 Seam underground workings, it is found that the New Clydesdale workings will probably have a maximum future sulphate concentration of approximately between 2000 – 2500 mg/L), (see **Figure 5-31**).

Concentration in New Clydesdale Underground vs. Percentage Workings Filled over Time

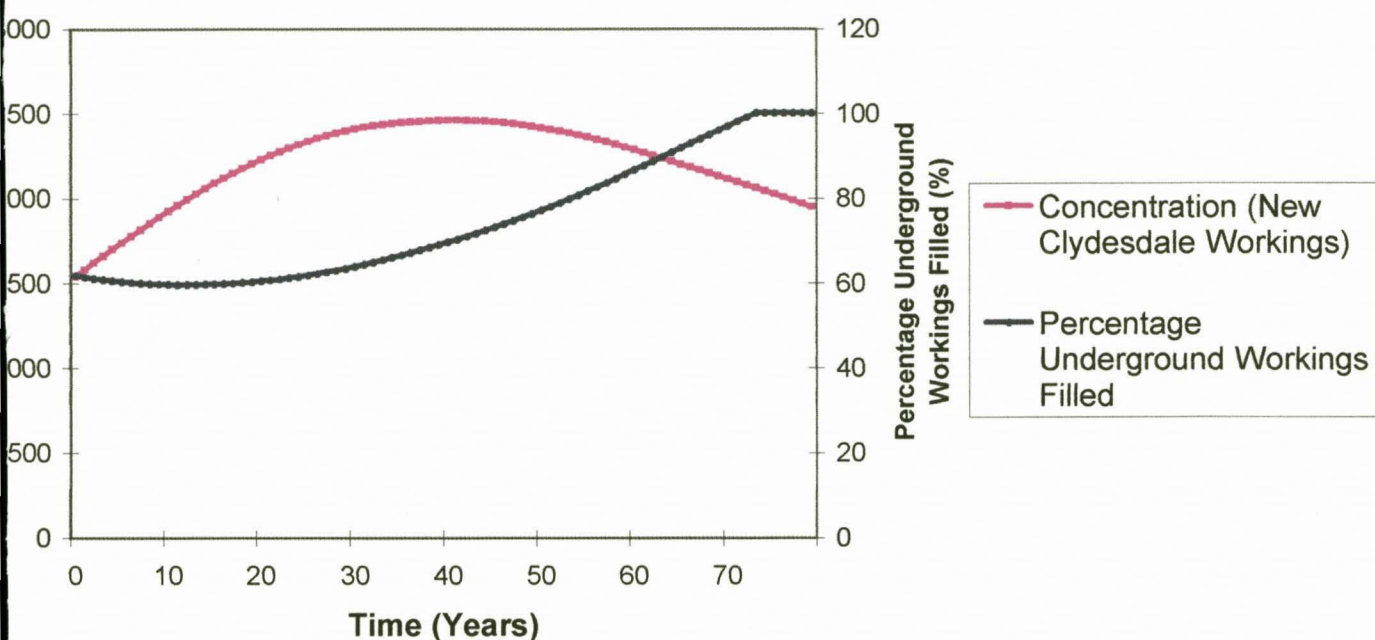


Figure 5-31. Graph of sulphate concentration in underground and percentage of underground workings filled with groundwater over time.

The intermine flow rate to Albion Section's No. 2 Seam underground is quite high and in the order 800 – 1000 m³/d initially (see chapter on the quantification of intermine flow) and from TNC to New Clydesdale it is 60 – 120 m³/d on average (see chapter on the quantification of intermine flow). Due to the intermine flow New Clydesdale's underground workings lose a large volume of groundwater to the Albion Section. This intermine flow prevents the void from filling up and thus exposes larger proportions of reaction surface to oxygen for longer periods of time. Thus the cumulative sulphate generation will increase proportionally. Higher maximum sulphate concentration can then be generated. Than if the underground workings had no intermine flow areas, in which case it would have filled up faster.

The high intermine flow volume to Albion underground section could potentially be detrimental to the New Clydesdale No. 2 Seam underground workings due to the increase time the New Clydesdale workings could take to fill up, thus creating a more oxidising environment for longer periods of time. This assumption is based on the 1500 mg/L concentration of sulphate in the New Clydesdale No. 2 Seam underground workings, from which a sulphate load to the Albion section in conjunction with the model flow volumes is calculated.

5.5.3 Groundwater Chemistry of Douglas Colliery's Albion Section's No. 2 Seam Underground Workings

Observation borehole DGM-UB23 is drilled into the Albion underground section (see **Figure 5-29**).

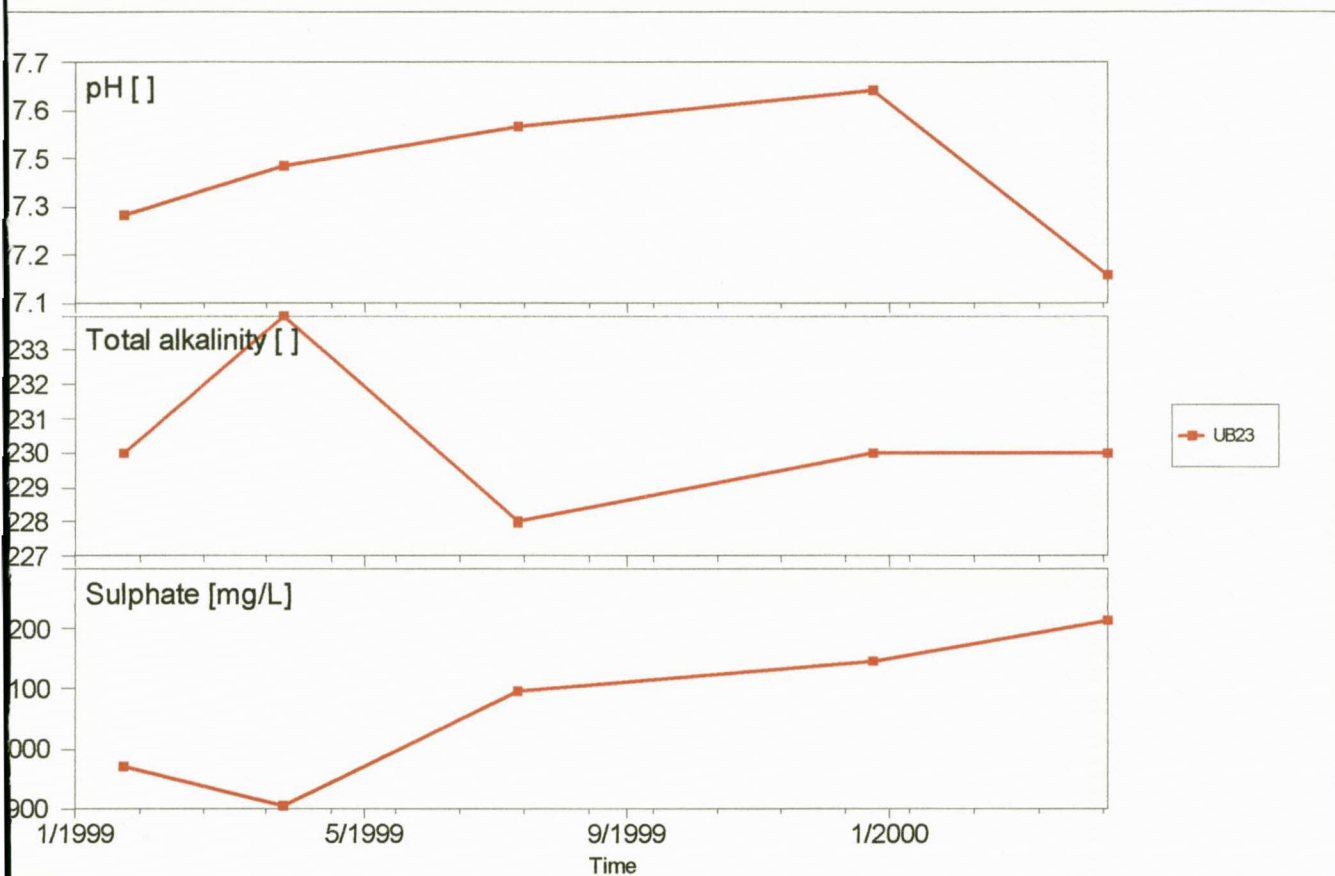


Figure 5-32. Graph of pH-values, alkalinity and sulphate concentration for Albion underground section's DGM-UB23 observation borehole.

The Albion underground section is for the most part completely empty (due to mining activities). The compartment into which the DGM-UB23 (**Figure 5-29**) is drilled, is partially filled, and therefore the groundwater samples taken in this particular observation borehole can give some idea of the current chemistry of the compartments. The sulphate concentration increases over time, which indicates that oxidation is taking place. The pH-values remain fairly constant and neutral. The alkalinity is 230 mg-CaCO₃/L on average, which makes the groundwater sufficient to buffer the increased acidity produced by oxidation reactions and stabilise the pH (see **Figure 5-32**) (<http://bcn.boulder.co.us>). The indication of the relatively high alkalinity may possibly be due to the presence of base materials in the geology (usually shale layers and sandstone layers), (Azzie, 2002).

Graphs of Concentration in Albion Section Underground Workings vs. Sulphate Reaction Rate over Time

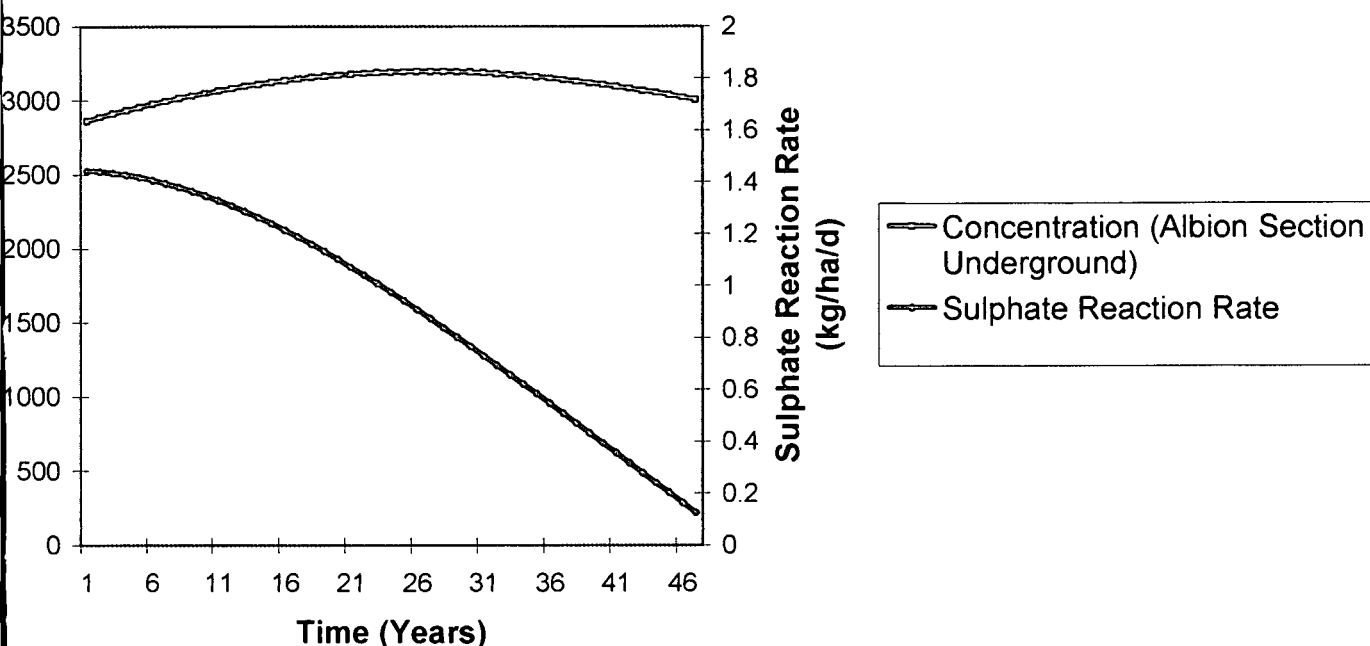


Figure 5-33. Graph of Sulphate Production Rate and concentration versus time of Douglas Colliery's Albion Section's Underground workings.

As discussed in chapter 4, New Clydesdale No. 2 Seam underground workings flow into the Albion section's No. 2 Seam underground. The intermine flow rate is initially high (in the order of 800 – 1000 m³/d). A benefit of the high intermine flow volume is that the Albion void will be filled up more rapidly with water, consequently cutting off oxygen to the reactive surface and accordingly restricting the oxidation of pyrite. Unfortunately the sulphate concentration of the New Clydesdale underground is about 1500 mg/L and therefore the Albion Section underground intermine flow contributes about 38% of the sulphate, resulting in a sustained high concentration of sulphate in the Albion section workings (**Figure 5-33**). Although the reaction rate should slow down as the underground void fills up with groundwater, concentrations remain high (**Figure 5-33**), due to the high sulphate concentration. The intermine flow from New Clydesdale Colliery would most probably be detrimental to Albion Section's underground water quality, projected with New Clydesdale current water quality.

5.5.4 Groundwater Hydrochemistry of Douglas Colliery's Van Dyks Drift Section's No. 2 Seam Underground Workings

The Van Dyks Drift No. 2 Seam northern part (north of the Olifants River) underground workings are currently dry (DGM-UB72, 2002/01/20). There is a lack of hydrochemical data, due to the fact that the northern parts of the workings are dewatered. The mass balance approach (section 5.3) was taken to approximate the mine water quality for a post-closure scenario. The intermine flow between the Springbok No. 2 Seam and Van Dyks Drift section's northern part of the No. 2 Seam underground workings was also taken into account.

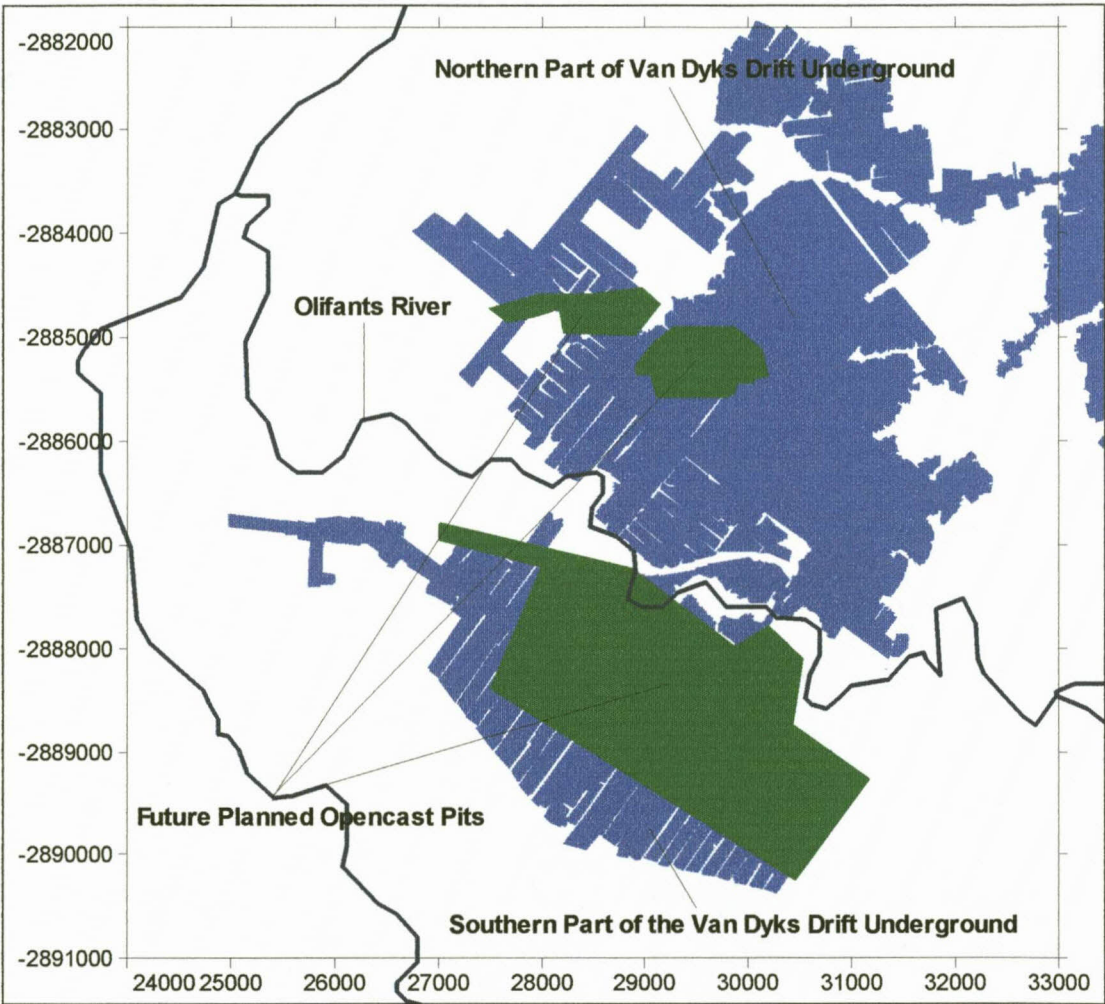


Figure 5-34. Map showing the van Dyks Drift **No. 2 Seam** underground workings and the planned future opencast pit is.

Intermine flow will take place between Van Dyks Drift No. 2 Seam (north of the Olifants River) underground workings and the Springbok No. 2 Seam underground workings of Goedehoop Colliery.

Concentration Values Approximation through the Mass Balance Approach for the Northern Part of the Van Dyks Drift Underground Workings.

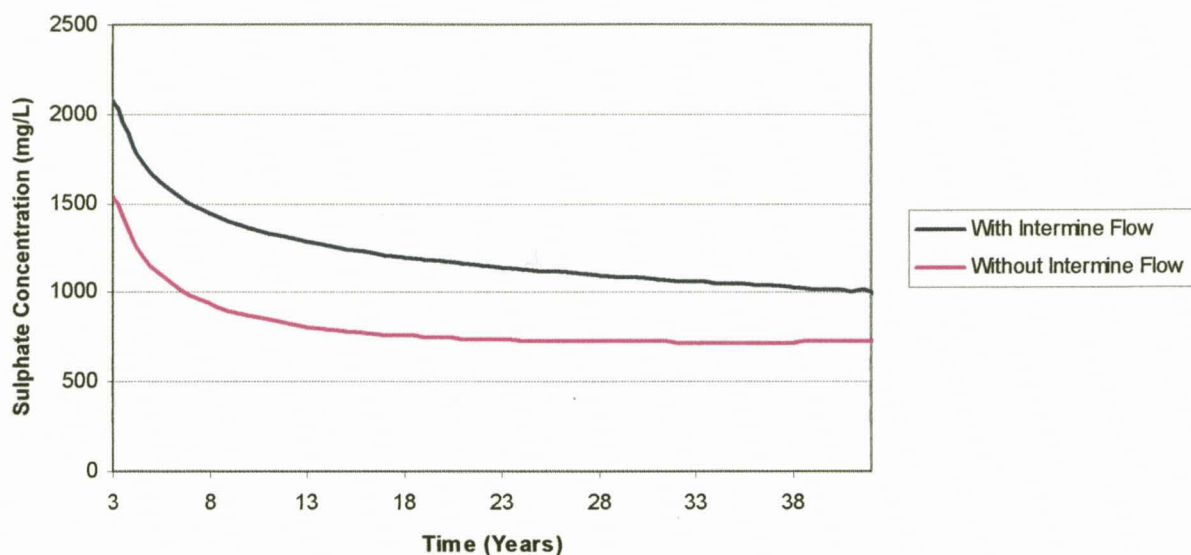


Figure 5-35. Graph of concentration over time for an intermine flow scenario and for a scenario without intermine flow for the northern part of the Van Dyks Drift **No. 2 Seam** underground workings.

The intermine flow direction will be initially in the direction of the Van Dyks Drift No. 2 Seam underground workings. If the water quality in Springbok (the Springbok water quality will most probably will deteriorate due to the slow fill-time leaving ample time for oxidation and salt generation in the workings) voids be of a poorer quality, the intermine flow volumes could adversely influence the groundwater in the Van Dyks Drift No. 2 Seam workings in the post-closure environment. This is due in part to intermine flow volume of $400 \text{ m}^3/\text{d}$ initially and tapering down to an average of $250 \text{ m}^3/\text{d}$ (see chapter on the quantification of intermine flow), which is a considerable amount, if considered that the recharge at maximum is in the order of $1100 \text{ m}^3/\text{d}$. In **Figure 5-35** it can be seen by using the mass balance approximation the sulphate concentration can be increased (on average about 300 mg/L increase in sulphate) by intermine flow from the Springbok No. 2 Seam workings with the current groundwater quality of the Springbok No. 2 Seam workings, which is 1731 mg/L .

In conclusion the water in the Springbok void has a high sulphate concentration and the intermine flow will transfer a significant load, which could be detrimental to the water quality in the Van Dyks Drift section's northern part No. 2 Seam workings.

5.5.5 North Shaft No. 2 Seam Underground Workings of Douglas Colliery

The north shaft No. 2 Seam underground workings are still actively mined (**Figure 5-25**). The North Shaft underground workings will be mined on current plans into the planned Steenkoolspruit/Kleinkopje future planned opencast pit. The No. 2 Seam floor slopes to the direction of the Steenkoolspruit/Kleinkopje opencast pit. This means that the water recharging the North Shaft underground will flow into the opencast pit. The opencast pit will fill up faster than the underground, which will cause the water from opencast to move into the North Shaft underground, which will mean degradation of the underground workings water quality. This is due to the higher oxidation rate in the opencast pit due to the much larger reaction (Morin *et al.*, 1997) surface exposed by the spoils, than the pillars and floor. Accordingly the Steenkoolspruit/Kleinkopje opencast pit will affect the North Shaft underground if they are mined into each other. Therefore the North Shaft workings' future groundwater chemistry will be representative of the chemistry of the Steenkoolspruit/Kleinkopje planned opencast pit at that time.

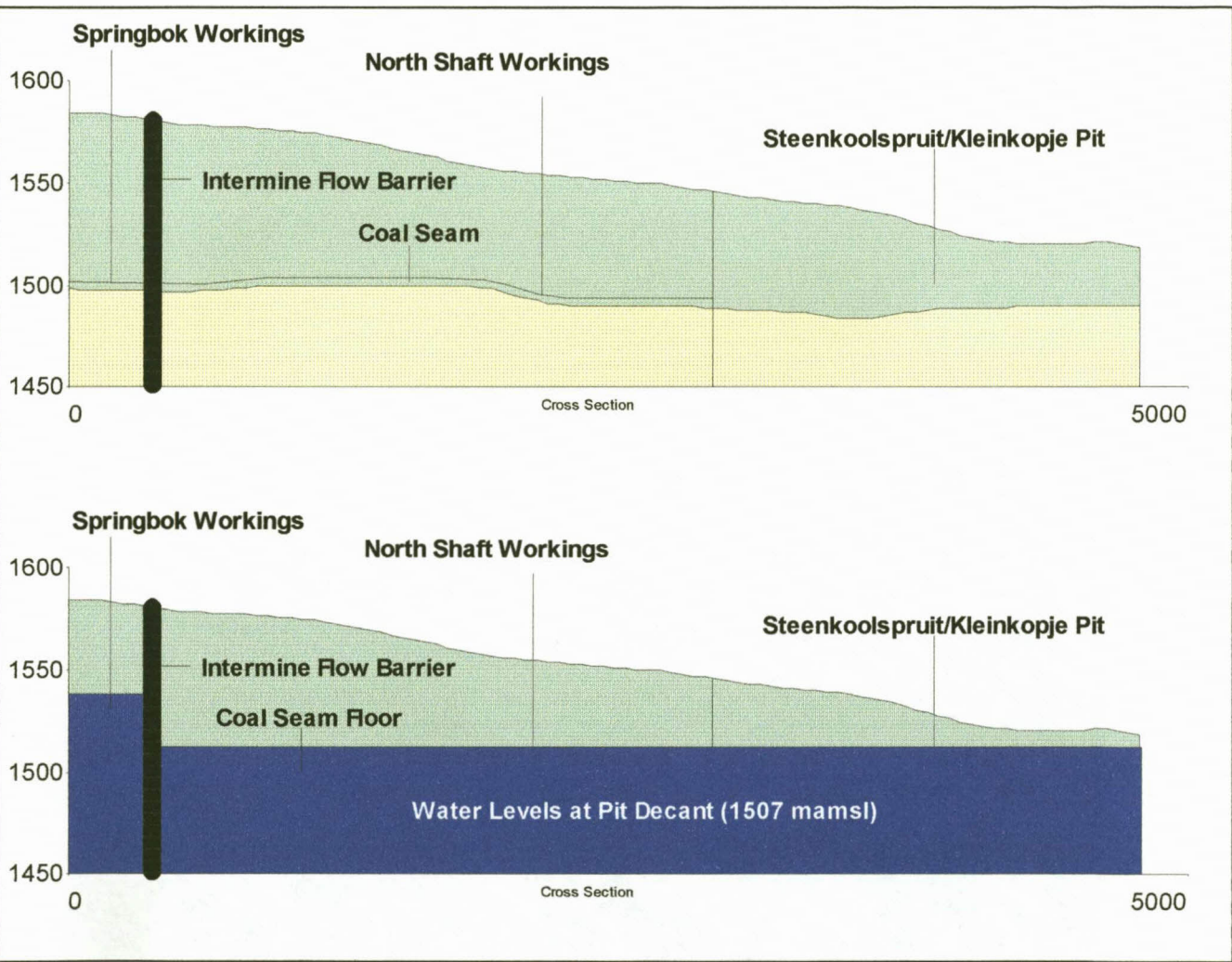


Figure 5-36. Cross sections of the intermine flow scenario between Springbok workings and the combined North Shaft workings-Steenkoolspruit/Kleinkopje pit complex.

Intermine flow will take place between the North Shaft No. 2 Seam underground workings and the Springbok No. 2 Seam underground workings. The current sulphate concentration of the Springbok workings is 1731 mg/L. The intermine flow volume to the North Shaft No. 2 Seam underground is in the order of 500 – 600 m³/d. The intermine flow effect on the North Shaft No. 2 Seam underground workings will be minimal and will increase the sulphate concentration only by about 60 - 140 mg/L (calculated by the mass balance approach). The effect is minimal because the average sulphate value in the Steenkoolspruit/Kleinkopje opencast pit is calculated at 1460 mg/L, and without the intermine flow from Springbok No. 2 Seam workings, at 1380 mg/L. The respective contributions of sulphate salt load to the Steenkoolspruit/Kleinkopje pit-North Shaft workings are: 6% for the North Shaft No. 2 Seam workings, 2% due to intermine flow from Springbok No. 2 Seam workings and 92% from the planned Steenkoolspruit/Kleinkopje opencast pit.

5.6 CONCLUSIONS

It is concluded that intermine flow will only have a real impact if the intermine flow volumes are large enough. As for the intermine flow water quality impacts, the following was concluded:

- Decant of future planned opencast pits, if not managed well, could have a negative impact on sulphate loads in the Olifants River.
- The intermine flow between TNC's Block C underground and the new opencast pit of Goedehoop Colliery could have an impact on Block C underground if the quality in the opencast pit is poor. The opencast pit can also increase the concentration of the Olifants River for the section at decant.
- The mass balance approximation has been used to predict the future void chemistries rather than the geochemical modelling, due to a lack of chemistry data for the model package.
- Mass transport was also not used because the sulphate generation rates of the opencast pits and the underground workings cannot be simulated by the MT3D mass transport package of Modflow. Therefore the answer in the mass transport are only a mixing sum and do not take into account the sulphate generation rates.
- The intermine flow from Boschmanskrans to Goedehoop Colliery could have a detrimental effect on the Springbok No. 2 Seam workings if the spoils of the new opencast pits is not managed to yield optimum water qualities.
- The intermine flow from TNC will dilute the concentration of sulphate in the Hope workings. In the long term the intermine flow volume from the Welstand No. 2 Seam underground workings (see chapter on quantification of intermine flow) should not be excessively detrimental to the Hope No. 2 Seam underground workings.

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- The high intermine flow volume to Albion underground section could potentially be detrimental to the New Clydesdale No. 2 Seam underground workings due to the increase time the New Clydesdale workings could take to fill up thus creating a more oxidising environment for longer periods of time.
 - The intermine flow from New Clydesdale Colliery would most probably be detrimental to Albion Section's underground water quality projected with New Clydesdale current water quality.
 - The water in the Springbok void has a high sulphate load and the intermine flow between these two voids could be detrimental to the water quality in the Van Dyks Drift section's northern part No. 2 Seam workings.
 - The intermine flow effect on the North Shaft No. 2 Seam underground workings will be minimal and will increase the sulphate concentration only by about 60 - 140 mg/L (calculated by the mass balance approach). The Steenkoolspruit/Kleinkopje opencast pit will have a far larger impact on the underground workings than the intermine flow from Goedehoop Colliery.

6 MANAGEMENT OPTIONS

This chapter discusses the possible management options (in terms of groundwater flow and quality) that could be applied to the intermine flow areas to improve general water qualities in the study area.

6.1 A BRIEF DESCRIPTION OF THE MANAGEMENT OPTIONS CONSIDERED

Based on an extensive literature review of methods the following options are considered viable in the central Witbank area:

- Development of High Recharge Areas
- Mine Seals as a Management Option
- Maximising Daylighting
- Regrading and Revegetation
- Inundation of Spoils and Underground Workings
- Selective Spoil Layering
- Alkaline Treatment
- Inert Gas Blankets
- Development of High Recharge Areas

6.1.1 Development of High Recharge Areas

High recharge areas for underground workings can be constructed by drilling boreholes from the surface into the underground workings. By regrading the surface it is proposed to channel runoff into these boreholes to augment the volume of water that fills up the workings through recharge. The effect on the water quality in the workings should be similar to the effects on water quality if the workings is flooded from a river. The effect on water quality by using the development of high recharge areas would not be as effective as with flooding, due to the slower rate of filling, hence more reactive surfaces are exposed over a longer period of time.

High recharge areas for opencast pits can be constructed by leaving small sections of the spoils bare and channelling the runoff into these bare spoils. Due to the high hydraulic conductivity of these spoils the water will infiltrate freely into the spoils. The effect would be similar to flooding by cutting off oxygen from the reactive surfaces by inundating the spoils in water. The viability of this option is dependent on:

- How much faster the high recharge areas will fill the void in comparison to natural recharge. If the difference between the two fill-up times is not significant, this option is not worthwhile.
- The legality of this option in terms of the Water Act (Act No. 36 of 1998). For example by channelling the run-off into the spoils the runoff is cut off from the streams and this will minimise the water available to nearby streams, and the legality of this has to be examined in terms of the reserve.

6.1.2 Mine Seals as a Management Option

Mine seals are fitted to underground workings to primarily eliminate surface access. Surface access dry seals are used to minimise the infiltration of oxygen into the underground working in the post-closure scenario (Skousen *et al.*, 1998). By minimising the oxygen infiltration the AMD-reactions can be limited (Evangelou, 1995). It may not be practical due to the amount of points of entry (shafts, observation borehole and core boreholes) into the underground workings.

Hydraulic mine seals are installed in entries where significant hydrostatic pressure will be exerted on the seals. The primary functions of the seals are to control the flow of water in the different underground compartments, eliminate potential access to the abandoned workings following closure, minimise AMD production by limiting the infiltration of air and water into the deep mine, and to minimise AMD production by limiting the exfiltration of water and maximise inundation (Skousen *et al.*, 1998).

6.1.3 Maximising Daylighting

Daylighting is the remining of underground workings through opencast methods. The Boschmanskrans underground workings and the Van Dyks Drift underground workings are going to be remined through opencast methods (truck and shovel). Remining already commenced at Douglas Colliery's Boschmanskrans Section.

In general, daylighting as great an area of an abandoned underground mine as possible yields positive results in terms of reducing pollution loads. Daylighting can work both physically and geochemically to effect a pollution load reduction. First, and perhaps the most salient mechanism that works toward reducing pollutant loads, is the reduction of potential surface water infiltration zones (Skousen *et al.*, 1998).

Daylighting tends to eliminate large portions of subsided mine sections where considerable vertical groundwater infiltration into the mines occurs. The reduced infiltration rates in turn facilitate reduced loads. Surface-expressed subsidence features, such as exposed fractures and sinkholes, tend to collect surface and groundwater and divert it directly into the mine. When surface mining eliminates these subsidence features, water infiltration into the mine is significantly reduced.

Daylighting also eliminates substantial void spaces that serve as mine water storage areas, which tend to facilitate a more continuous source of lateral recharge to the adjacent reclaimed remining operation. Daylighting dramatically changes the groundwater flow system from open conduit-type of underground mines to the double-porosity system exhibited by mine spoils (Hawkins, 1998).

Once surface mining and reclamation have occurred, the groundwater flow system changes dramatically, and the strata encountered is reflective of the entire overburden quality. Rather than only encountering acidic strata exposed in the underground mine, groundwater will contact strata in the spoil that can be potentially alkaline or acidic or relatively inert. The amount of each type of rock intersected by the groundwater is directly related to the volume of the material in the spoil, and to some degree, the mining and reclamation methods. Daylighting operations may need to have special conditions to require mining to a predetermined overburden thickness to ensure that a sufficient amount of alkaline strata are encountered and spoiled. In most cases, daylighting successfully decreases the pollution loads (Egis Consulting, 2001).

6.1.4 Regrading and Revegetation

Regrading is to contour (building of terraces) the surface of the rehabilitated pits and revegetation to minimise erosion. Regrading and revegetation work hand-in-hand to decrease pollution loadings, both physically and geochemically. This BMP (best management practice) combination functions physically by reducing the amount of surface water introduced into the backfill and, geochemically by altering spoil pore gas composition that impacts the weathering of carbonates and pyrite.

Spoil regrading eliminates exposed, highly permeable material and closed contour depressions, both of which, when unchecked, facilitate direct infiltration into the spoil of surface water, and promote surface runoff.

The addition of soil and vegetative cover over regraded spoil also works to enhance the inhibition of surface water infiltration. Soils will allow some surface water infiltration, but a great deal of the infiltrating water will be held in the soil horizon until it is used by plants. The structure of soil cover is such that significant quantities of water are preferentially retained. The soil holds water close the ground surface, which permits direct evaporation (Egis Consulting, 2001).

The addition of vegetative cover further inhibits water infiltration into the underlying spoil. The plants, during the growing season, will take up the water in the soil and transpire it back into the atmosphere. Certain types of plants will promote additional runoff, especially during high intensity precipitation events. Use of bio-solids can greatly enhance the vegetative growth and cover percentage, which in turn will promote greater water use by the plants.

6.1.5 Inundation of Spoils and Underground Workings

Inundation of pyritic material is a conventional method generally used to curtail AMD. Oxygen diffusion to pyretic waste is greatly reduced upon inundation because the diffusion coefficient of oxygen through the covering water table is only 1/10000 of that of the atmosphere (Evangelou, 1995). Therefore the rate of oxygen consuming reactions becomes low and rate limiting, and bacterial oxidation of pyrite becomes slow or nil. However, complete inhibition of pyrite oxidation by flooding may never be possible because of the availability of Fe^{3+} as an alternate oxidant. See section 6.2.2.

6.1.6 Selective Spoil Handling

This method entails the selective placement of spoils as to limit AMD. An example is mixing the potential acid material with the potentially alkaline material to prevent acidification in the spoils. By placing the potential high risk acid forming material below the water table at the lowest possible elevation to inundate the material as soon as possible (Skousen *et al.*, 1998). The practicality of this method will depend on the distribution of the potential acidic sediments. If the potentially acidic sediments are distributed through the whole overburden, selective spoil layering will not work.

6.1.7 Alkaline Treatment

The alkaline treatment option is basically the neutralising and acidic water by addition of alkaline material to the system (spoils and acidic decant waters). Neutralisers as NaOH or CaCO₃ (fly ash also a source of alkalinity but must be handled with care due to the high heavy metal content of the material) can be used for the alkalinity component. Neutralisers such as sodium hydroxide have a high solubility and can be easily moved with percolating water deep in the strata to sites where acid drainage is produced (Evangelou, 1995).

6.1.8 Inert Gas Blanket

The use of an inert gas blanket (methane- or carbon dioxide gas), which involves the placement and retention of an inert gas (Skousen *et al.*, 1998) in the underground workings to prevent oxidation from taking place. If this method is employed, all connection the workings have with the atmosphere will have to be sealed. The inert gas blanket has great promise because it prevents the oxidation of acid material. If the mine can be sealed completely, little additional make-up gas will be necessary after the initial injection (Skousen *et al.*, 1998). The disadvantage is that, by using methane, which is a flammable gas, an explosion could occur which in turn will most probably destroy the mine seals or start underground coal combustion.

6.2 MANAGEMENT OPTIONS OF INTERMINE FLOW AREAS

6.2.1 Intermine Flow Area between Goedehoop Colliery's New Opencast Pit and TNC's Block C Underground Workings

Block C will flow into the opencast pit initially and according to the flow model the opencast pit will flow into the Block C underground workings for a short time. Thereafter Block C underground workings will flow into the opencast pit again (see chapter 4). The water quality of Block C is relatively good with a sulphate value approaching 600 mg/l and a near neutral pH. The intermine flow volume is small, in the order of 130 m³/d and an upper flow of 300 m³/d is projected. It is expected that the water quality of the opencast pit will be of poorer quality (projected to reach 1700 - 2400 mg/l SO₄) due to AMD reactions, hence the small amount of intermine flow water would actually dilute the sulphate concentration in the groundwater in the spoils of the pit. A potential problem could be the period when the opencast pit flows into the Block C underground workings. If the opencast pit's water quality is of a poor quality, it could be detrimental to the water quality of the water in the Block C, as would be expected after approximately 36 years. Therefore a few management options are proposed to yield optimal water qualities and quantities for the new opencast pit of Goedehoop Colliery.

In **Figure 6-3** the new opencast pit of Goedehoop Colliery can be seen. The opencast pit will decant at an elevation of 1539.89 mamsl and at this decant elevation the pit will contain 23.4 Mm³ of groundwater. Due to the topography a large proportion of the spoils in the opencast pit will not be flooded at decant level (**Figure 6-1**). The unsaturated zone above the water table will be rich in oxygen and the recharge into the spoils will also seep through this zone, hence creating a highly oxidising environment which can have a significant impact on the water quality in the pit (Morin *et al.*, 1997).

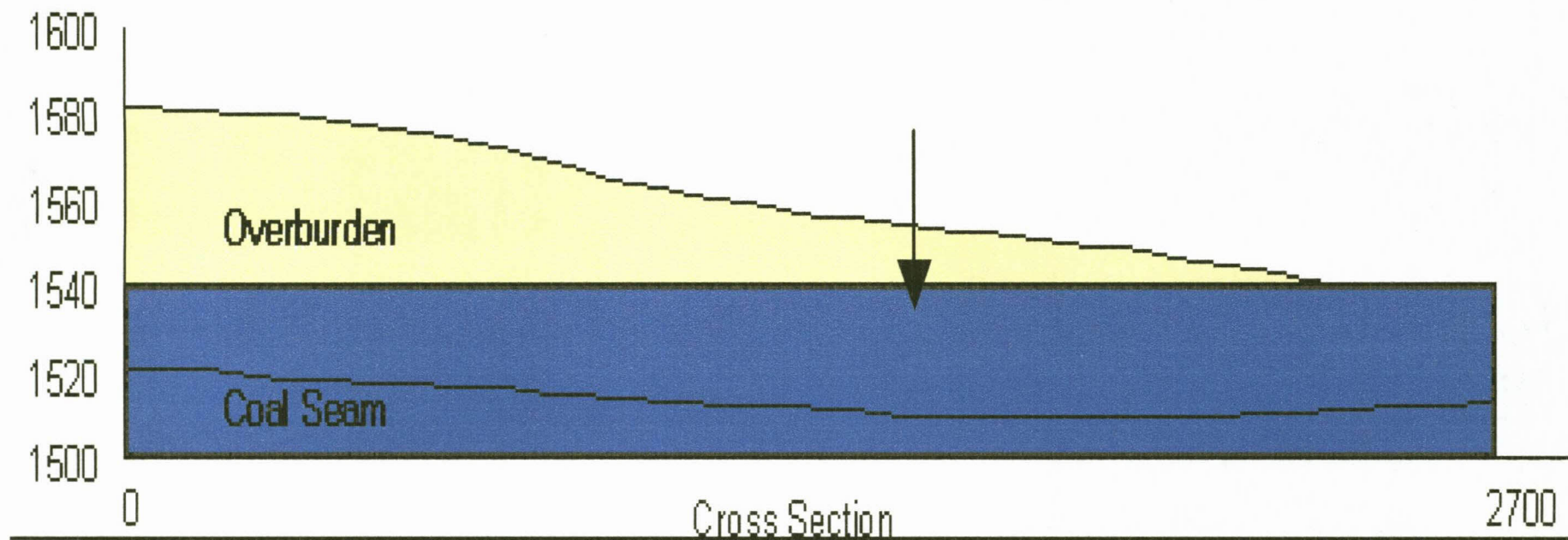


Figure 6-1. Cross section of cross section line1 of the new Goedehoop opencast pit showing the water table at a decant level of 1539.89 mamsl.

Dave and Vivyruka (1994) reported a case study on the design and full-scale implementation of tailings submergence of acid-generating tailings in the Elliot Lake Uranium district of eastern Canada. They noted the primary benefits of cover by submergence as follows:

- Limitation of oxygen
- Limitation of sulphate oxidation
- Formation of chemically reducing conditions for sulphate reducing and nitrate reducing bacteria.

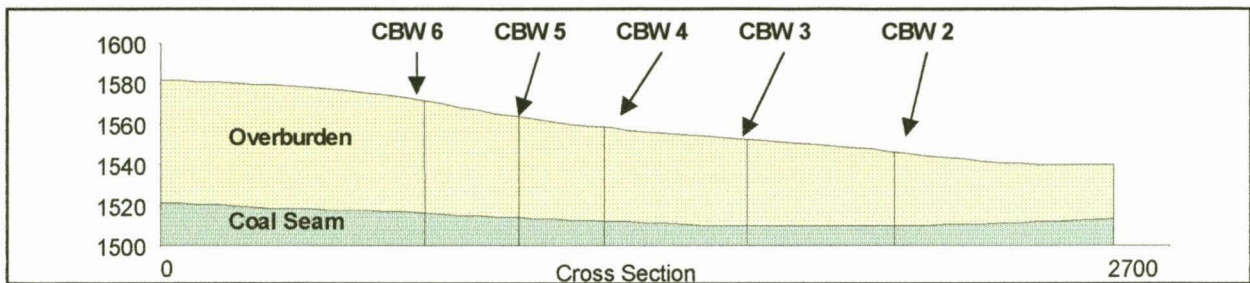


Figure 6-2. Cross section of cross section line 1 showing the proposed unmined areas to form the compartment barrier walls (CBW2 – CBW6).

To submerge most of Goedehoop Colliery's new opencast pit spoils, the pit will have to be divided into compartments. To do this effectively at low cost, certain parts of the opencast pit will have to be left unmined. These unmined areas will then effectively form compartment barrier walls (**Figure 6-2** and **Figure 6-3**). The thick black lines in **Figure 6-3** represents the unmined areas that will form the compartment walls. The distances between these unmined areas have been calculated for an increase in elevation of 6 m, thus for example from the one barrier wall to another the elevation has risen by 6 m.

The thickness of these unmined areas will depend on the hydraulic conductivity of the coal seam and the overburden. Hence the higher the hydraulic conductivity of the sediments, the thicker the unmined area must be to form an effective barrier. The flow through the barrier (Q in m^3/d) should be smaller than the recharge to the opencast compartment, so that damming in the mini-pit could be possible.

Table 6-1. Calculated thickness of compartment barrier walls (unmined areas left to from barrier walls).

Table with Data for the Compartment Barrier Wall Thickness		K-0.1027 m/d	K-0.075 m/d
Compartment Barrier Wall (CBW2-9)	Barrier Wall Length (m)	Barrier Wall Thickness (m)	Barrier Wall Thickness (m)
2	1930	37	35
3	1900	50	47
4	1900	55	47
5	2375	95	80
6	1255	60	50
8	300	30	23
9	520	60	60

In the first scenario an average K-value of 0.1 m/d (WRC Report No. 291/1/98, Hodgson *et al.*, 1998) for the coal seam and a K-value of 0.03 for the unmined strata (Douglas Colliery, EMPR, 1998, JMA). The K-value of the coal seam and the K-value of the unmined strata are used to calculate the thickness of the unmined barrier between the mini-pits. A second scenario was calculated with an average K-value of 0.0745 for the coal seam. The average thickness values are given in **Table 6-1**.

Table 6-2. Table showing the calculated amount of hectares left unmined to form the barrier walls between the opencast compartments.

K-0.1 m/d	K-0.075 m/d
Hectares lefts Unmined for Barrier Walls	Hectares lefts Unmined for Barrier Walls
6.755	4.825
8.93	6.65
8.93	6.27
19	13.5375
6.275	4.3925
0.69	0.48
3.12	2.08
Total hectares Unmined	Total hectares Unmined
53.7	38.235

If the K-value is 0.1 m/d the barrier walls will acquire about 53.7 hectares in total of the opencast pit to be left unmined, which is on average about 14% of the opencast pit's total surface. If the K-value is 0.074 m/d the barrier walls will acquire about 38.2 hectares in total of the opencast pit to be left unmined, which is on average about 10% of the opencast pit's total surface. If the K-value is smaller than 0.074 m/d, the thickness of the barriers will decrease even more drastically in thickness.

By compartmentalising the opencast pit, the effect is that mini-opencast pits are created with their own decant elevation that will maximise the amount of spoils submerged in groundwater.

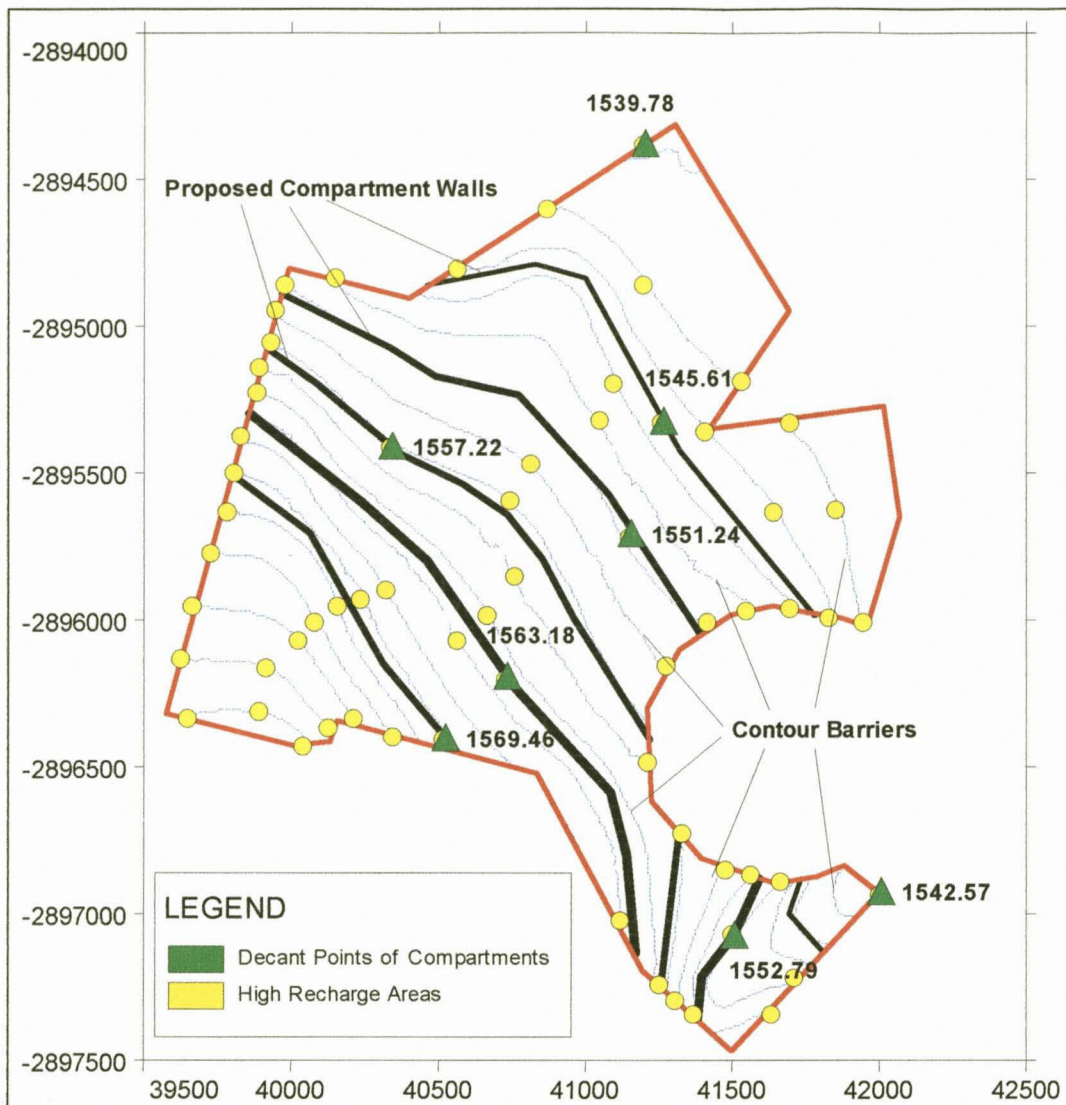


Figure 6-3. Map of Goedehoop Colliery's New Opencast Pit. (Please show the cross-section line On this diagram)

This effect is illustrated in **Figure 6-4**. By compartmentalising the opencast pit the pit will contain about 36.5 Mm³ of groundwater, which in turn will submerge almost all the spoils, thus greatly limiting the oxidation reactions by cutting off oxygen to the spoils (Morin *et al.*, 1997). The drawback of this method is that all the coal is not mined, but remainremains in the unmined barrier walls.

Another alternative to compartmentalising is to do selective spoil layering. To accomplish this, successful geochemical characterisation such as ABA will have to be done on the sediments and coal seams to determine which sediments are potentially acid-generating. When this is done the spoils are layered so that the acid-generating material is placed at an elevation below that of the decant elevation. This is done to ensure that acid-generating material remainremains inundated. A drawback of this method is that it is not always practically viable.

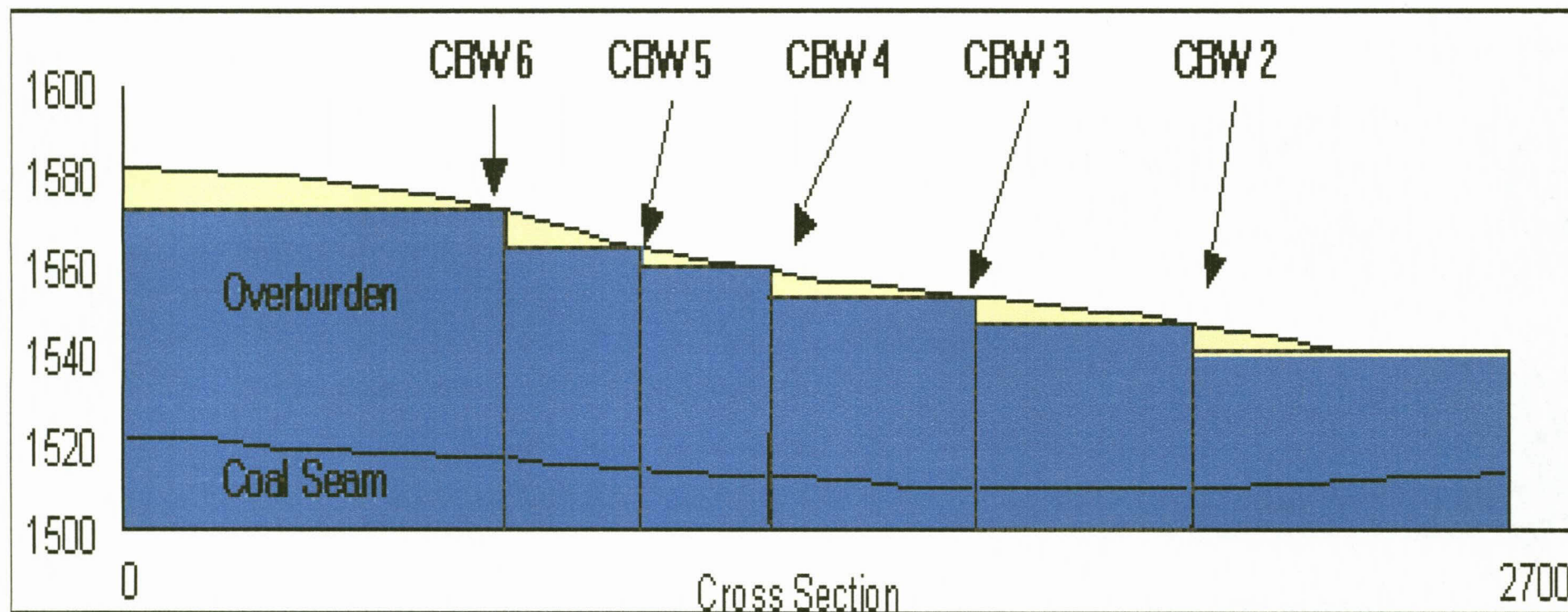


Figure 6-4. Cross section of cross section line1 of the new Goedehoop opencast pit showing the water tables for some of the mini opencast pits.

Another crucial aspect of submergences of the spoils is the rate at which the mini-opencast pits are filled up. The longer the opencast pit takes to fill-up, the longer the environment in the pit will remain oxidising, hence a much worse groundwater quality is found in the pit itself (Morin *et al.*, 1997). The decant quality is therefore also a function of the time taken before inundation can be achieved.

When opencast pits are rehabilitated, the spoils are covered with topsoil and grass is planted to prevent infiltration. The recharge to an opencast pit is on average between 15 -20% of the annual rainfall (Hodgson *et al.*, 1998). The calculated fill-up time (by modelling, see chapter on the quantification of intermine flow) of the Goedehoop Colliery new opencast pit is about 38 to 42 years. By proposing to build contour barriers to firstly prevent erosion and secondly to channel the precipitation into small areas that have no topsoil present. The groundwater will flow into these areas directly (channelled by the contour barriers, see **Figure 6-3**) into the spoils and the effect should be a increased recharge due to the high hydraulic conductivity values of the spoils, which is about 10 m/d (Douglas Colliery, EMPR, 1998, JMA). See Hodgson and Krantz for other estimation of spoils K.

See **Figure 6-3** for the proposed high recharge areas. The contour barriers will form recharge channels, but these recharge channels can be modified into alkaline recharge trenches. Neutralisers such as NaOH, CaO or Ca(OH)_2 or CaCO_3 can be used for the alkalinity component. This method of alkaline recharge trenches might prove too costly a measure, but warrants mention. By doing an ABA of the overburden, the sediments with a high neutralising potential can also be placed in the high recharge areas as the alkalinity component.

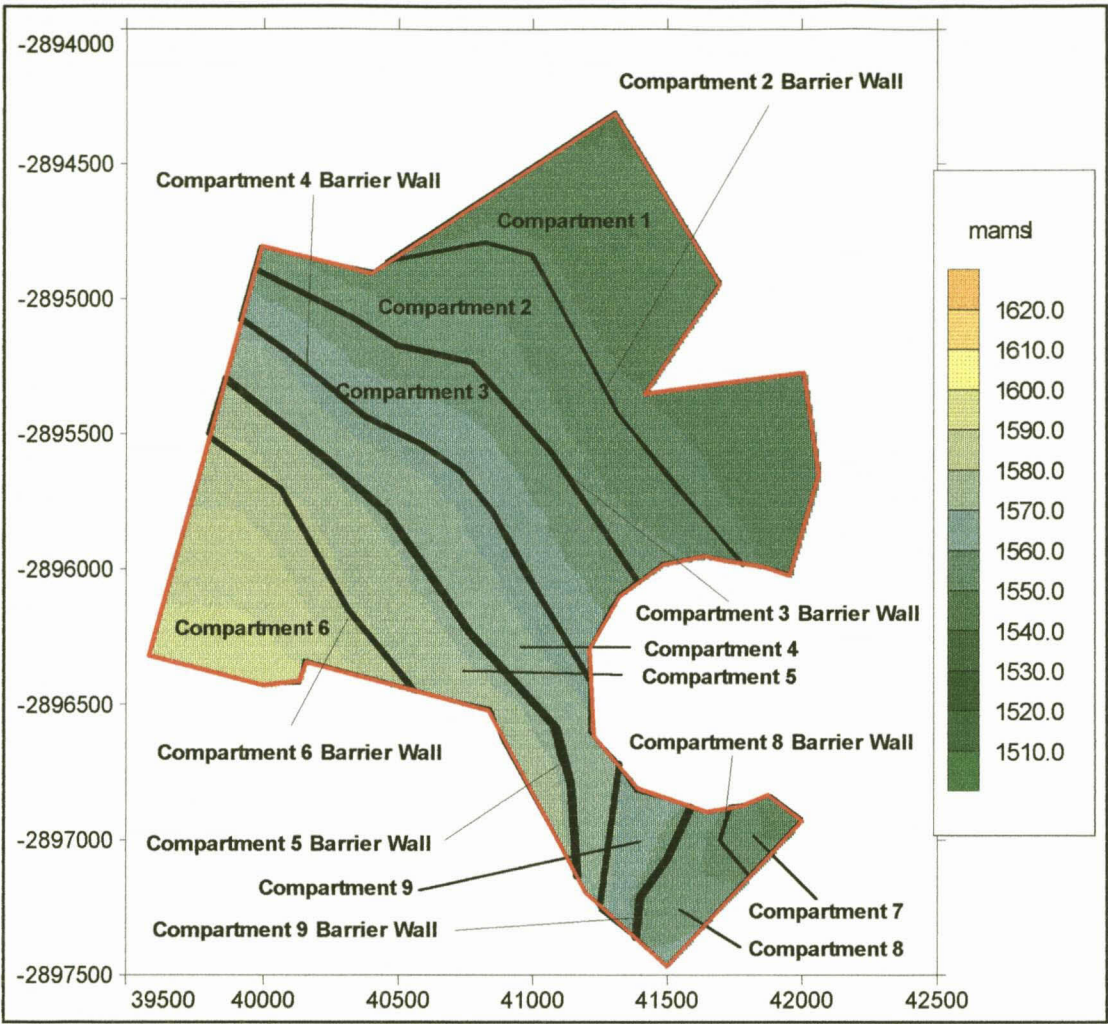


Figure 6-5. Map of Goedehoop Colliery’s new opencast pit showing the surface contours as well the opencast proposed compartments.

If this measure is put in effect the fill-up time can come down drastically. The fill-up times of the opencast compartments are given in **Table 6-3**.

Table 6-4. Table of fill-up times for the opencast compartments in Goedehoop Colliery’s new opencast pit.

Opencast Compartment Names	Total Time to Decant (years)
1	8-10
2	11-13
3	13-15
4	14-16
5	16-18
6	17-19
7	6-8
8	7-9
9	12-14

The drastically decreased fill-up times will limit the oxidation reactions and decrease the amount of time and surface of the reactive surface exposed to oxygen. The bacterial oxidation of pyrite becomes slow or nil (Evangelou, 1995).

Another method to inundate the spoils quickly is to use the Olifants River to flood time opencast compartments. If this measure is employed the water from the river should not be cascaded into the pit from the surface rim of the pit. The pipe that channels the water into the pit should rather be placed at floor elevation as to minimise the oxygen content of the water to minimise initial oxidation.

6.2.2 Intermine Flow Area between Goedehoop Colliery's Hope Workings and TNC's Welstand Block Underground Workings

According to the flow model (see chapter 4) the Welstand Block will flow into Hope Workings for much of the time. The water quality currently in the Welstand Block is relatively good, with an average sulphate concentration of 600 mg/L and a near neutral pH. The intermine flow volume to Hope workings is approximately 200 m³/d, and the sulphate load added to Hope workings will be in the order of 4 – 6%. It is expected that the water quality in Hope workings will be of poorer quality. This is due to the fact that the Welstand Block was almost filled after the Olifants River was in flood in 2000. Therefore the flood diluted the water already in the pit and decreased the salt concentrations in the workings. Accordingly the small intermine flow volumes to Hope workings from the Welstand Block should have a minimal effect on the water chemistry of the water in the Hope workings. A few management options are proposed to yield optimal water qualities for the Hope underground workings to minimise the effect of intermine flow and salt generation through AMD-reactions (see chapters on quantification of intermine flow and chemistry).

The Hope workings are currently kept empty for mining activities and to keep the conveyer belts operational to move the coal to the shaft. After underground mining has stopped and the pumps switched off the pit will start to fill up naturally with groundwater. The pit may take about 110 - 125 years to fill up and at that fill-up rate there is more time for oxidation due to the longer exposure to oxygen and sulphate generation (**Figure 6-6** and **Figure 6-7**).

Concentration in Hope Underground vs. Percentage of Workings Filled over Time

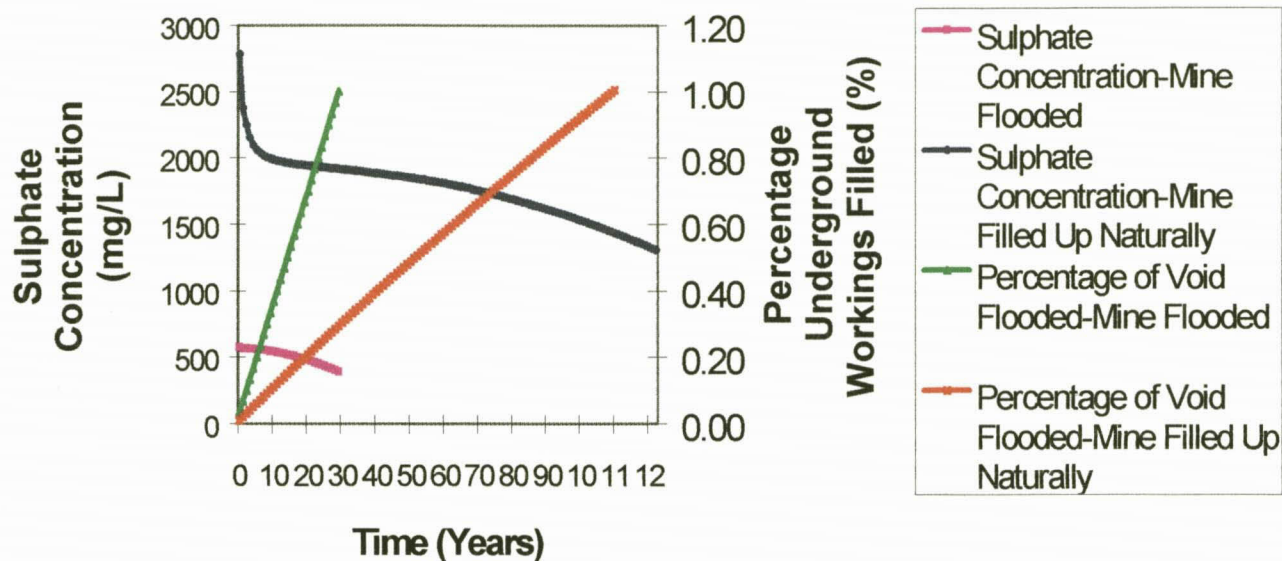


Figure 6-6. Graph of sulphate concentration and percentage of the underground void filled over time for the natural fill-up scenario of the void by recharge and the flooding of the void by means of the Koringspruit scenario.

Sulphate Production Rates vs. Percentage of Void Filled over Time

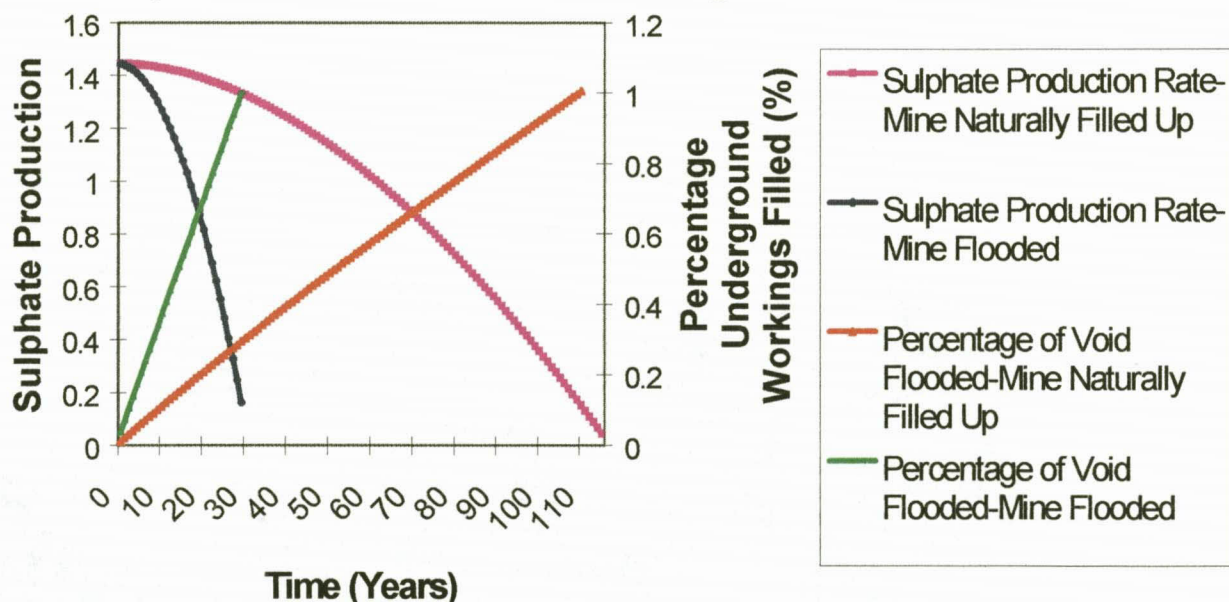


Figure 6-7 Graph of sulphate production rates versus percentage of void filled over time for the scenario where the void is filled up naturally by recharge and the second scenario where the void is flooded through the Koringspruit.

By using the sulphate mass balance approximation the sulphate concentration for the post closure scenario has been predicted. By flooding the Hope No. 2 Seam underground workings by using the Koringspruit may drastically reduce oxidation (**Figure 6-7**) in the underground void and severely limit the sulphate production rate (**Figure 6-6**). If the overlying rocks contain carbonate minerals, flooding may provide additional alkalinity by increasing the volume of alkaline strata in contact with mine water. As a result the groundwater quality in the underground workings would then have a better quality (Skousen *et al.*, 1998; Evangelou, 1995).

It is also proposed that the Hope underground workings should be fitted with surface access dry seals as to minimise the infiltration of oxygen into the underground workings in the post-closure scenario as well as to eliminate potential access to the abandoned mine workings (Skousen *et al.*, 1998). By minimising the oxygen infiltration the AMD-reactions can be somewhat limited (Evangelou, 1995).

An alternative to flooding would be to use an inert gas blanket, which involves the placement and retention of an inert gas blanket.

6.2.3 Intermine Flow Area between TNC's Welstand Block Underground Workings and New Clydesdale Colliery's Underground Workings

The intermine flow direction is from the Welstand block to the No. 2 Seam underground workings of New Clydesdale Colliery. The water levels between these two workings is almost even currently, therefore the intermine flow volumes are small at about 120 m³/d. The quality of the water currently in the Welstand Block is relatively good at about 600 mg/L. The quality of the new Clydesdale workings is about 1500 mg/L, therefore the water flowing into the New Clydesdale workings is of better quality. Coupled with the above statement and the small intermine flow volumes, the effect the intermine flow has on the New Clydesdale working will be very minimal, hence does not justify the spending of money on possible intermine flow management options.

6.2.4 Intermine Flow Area between New Clydesdale Underground Workings and the Albion Section's Underground Workings

The intermine flow direction at this intermine flow area is from New Clydesdale Colliery's No. 2 Seam underground to Albion section's No. 2 Seam underground workings. The Albion Section is currently empty, therefore the flow gradient to the Albion Section is quite large. The initial flow rate from the New Clydesdale workings is in the order of a 1000 m³/d and the current sulphate concentration is at 1500 mg/L. The intermine flow from New Clydesdale Colliery's workings might contribute about 38% of the sulphate load in Albion workings (note that it is a future estimation calculated by the mass balance approximation). The intermine flow therefore can influence Albion Section significantly.

To manage the intermine flow, a wall (5 km) that acts as a wet seal built on the Albion Section side of intermine flow barrier to seal the intermine flow barrier can be considered. This wall will have to be a hydraulic seal and will have to at least withstand 4-atmospheres worth of pressure (40 m head difference). This management option may not be viable due to the high cost of construction.

Another option is to flood the New Clydesdale workings from the Olifants River to improve quality of the water in the No. 2 Seam workings as was suggested in section 6.2.2 or to create high recharge areas as also discussed in section 6.2.2 (scenario as well as to eliminate potential access to the abandoned mine workings (Skousen *et al.*, 1998). By improving the water quality in the New Clydesdale workings the impact of the intermine flow on the Albion Section's No. 2 Seam workings is lessened. The current sulphate concentration in the New Clydesdale underground workings is currently 1500 mg/L. By flooding it the concentration can be decreased to approximately 1000 mg/L, assuming clean water is used to flood the mine and no further AMD reactions take place. The viability of this management option must be evaluated by looking at its legality in terms of the Water Act.

An alternative to flooding that can be employed at New Clydesdale Colliery's underground workings would be to use an inert gas blanket (methane or carbon dioxide).

6.2.5 Intermine Flow Area between Springbok No. 2 Seam Underground Workings and the North Shaft No. 2 Seam Underground Workings

Currently the Springbok No. 2 Seam is partially flooded. North Shaft underground workings is still in the process of being mined. In the post closure scenario the intermine flow direction will be from the Springbok No. 2 Seam workings into the North Shaft No. 2 Seam workings (initial intermine flow volume 400 m³/d) (**Figure 6-8**). The North Shaft workings are joined with the Steenkoolspruit/Kleinkopje planned opencast pit according to the latest mining plans. It is expected that the opencast pit will generate much more sulphate (5 - 10 kg/ha/d, Hodgson *et al.*, 1998) than the North Shaft underground. The current sulphate concentration of the Springbok No. 2 Seam workings is 1731 mg/L.

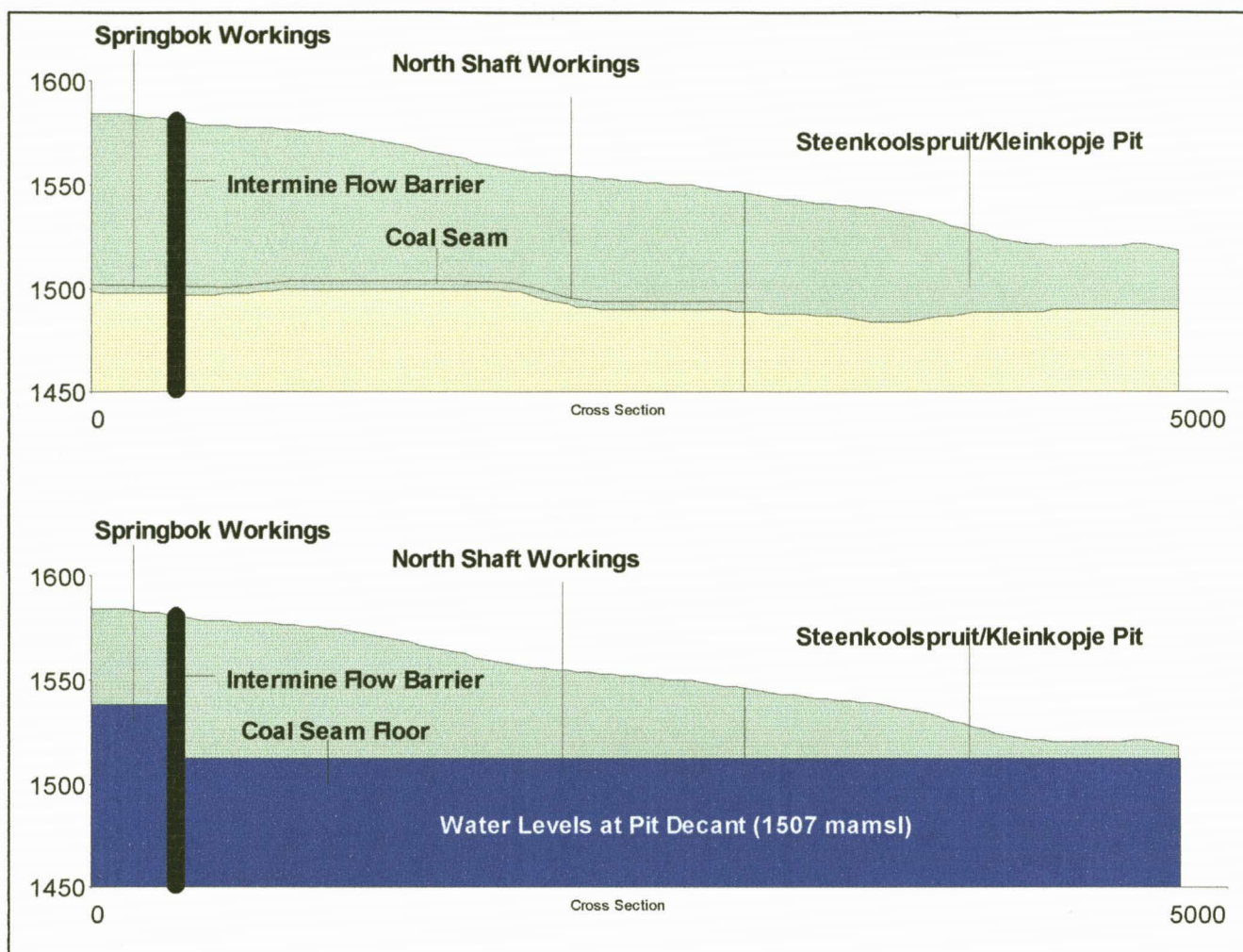


Figure 6-8. Cross sections of the intermine flow scenario between Springbok workings and the combined North Shaft workings-Steenkoolspruit/Kleinkopje pit complex.

The predicted contribution to the sulphate load via the intermine flow to the North Shaft-Steenkoolspruit/Kleinkopje combined underground-opencast pit complex is approximately 2%. The contribution of the opencast pit and the North Shaft underground workings are respectively 92% and 6% (these values have been calculated by using 5 – 10 kg/ha/d (Hodgson *et al.*, 1998) sulphate generation rate for the opencast pit, the sulphate generation rate for the underground section was calculated by using the mass balance approximation). The predicted impact of the intermine flow on the North Shaft-Steenkoolspruit/Kleinkopje combined complex is negligible small and therefore it does not warrant the implementation of management options.

6.2.6 Intermine Flow Area between Springbok No. 2 Seam Underground Workings and the Boschmanskrans Combined No. 2 Seam Underground Workings and Planned East- and West Opencast Pits

The initial intermine flow direction will be from the Boschmanskrans combined No. 2 Seam underground workings and planned east- and west opencast pits to the Springbok

No. 2 Seam underground workings. The initial intermine flow volume is in the order of 320 m³/d (high flow scenario 700 m³/d). The flow model projected that the time period that the Boschmanskrans combined No. 2 Seam underground workings and planned east- and west opencast pits will flow into the Springbok workings is approximately 50 years. The predicted added sulphate load to the Springbok No. 2 Seam workings is approximately 20%. From the acid-base accounting (Hodgson *et al.*, 1998) that was done on the Boschmanskrans section it was concluded that if the spoils in the Boschmanskrans section are not managed correctly acidification could take place and therefore the intermine flow to Goedehoop Colliery could be detrimental to the water quality in the Springbok No. 2 Seam underground workings (see chapter 5).

Suggested management options for the Boschmanskrans East- and West opencast pits to minimise the effect of the intermine flow on Springbok No. 2 Seam underground workings:

- The Boschmanskrans east- and west opencast pits are going to be mined by opencast methods into the No. 2 Seam underground workings to extract the pillars of the underground workings. Once surface mining and reclamation have occurred, the groundwater flow system in the Boschmanskrans underground workings will change dramatically and the strata encountered are reflective of the entire overburden quality. Rather than only encountering acidic strata exposed in the underground mine, groundwater will contact strata in the spoil that can be potentially alkaline, acidic or relatively inert. Therefore daylighting may facilitate mixing the alkaline sediments in the overburden to buffer acidification and sulphate generation.
- It is proposed that selective layering of the spoils be used as management option to reduce acidification and sulphate generation.
 1. According to the acid-base accounting report (Hodgson *et al.*, 1998) the weathered zone contains the least acid-generating potential of all sedimentary units in the Boschmanskrans Area. All of this material should be recovered and used for rehabilitation of the fresh, reactive spoil.
 2. As far as placement of the rest of the spoil is concerned, the best option is to mix the spoil from the different stratigraphic horizons. This will provide for an even spread of the neutralisation potential throughout the mine, thus counteracting the process of acidification. From a mining point of view, mixing of the spoil may, however, not be possible (since they are using truck and shovel it will be easier than using conventional dragline methods) (Hodgson *et al.*, 1998).
 3. It was also suggested in the ABA report that the pit ramps should be filled and rehabilitated as mining progresses. This will eliminate the bare slopes of

ramps along which oxygen can penetrate the fresh spoil (Hodgson *et al.*, 1998).

- Coal from the discard dump should be disposed of in the deepest portion of the pit to ensure that the waste material will be flooded by water. In the event that the discards are acid, slimes from the washing plant or lime water should be added to ensure disposal of the discards under alkaline conditions. Areas of discard disposal should afterwards artificially be flooded to ensure that oxygen is excluded from the discards as soon as possible. Monitoring of the water quality in these areas should be done through boreholes. If acidification takes place, this should be counteracted by the injection of lime water until the total pit can be flooded.
- When the Boschmanskrans East- and West Pit are rehabilitated, it is suggested that regrading and revegetation be incorporated in the rehabilitation phase. The more stable regraded surfaces will also function geochemically by inhibiting the introduction of oxygen at depth and by retaining carbon dioxide. Regrading of several spoil piles into one large backfilled area results in less surface area and fewer slopes for atmospheric exchange. In addition, thicker spoil will make it more difficult for oxygen to penetrate at depth. Soil cover and plant growth tend to further preclude oxygen infiltration and retention of carbon dioxide in underlying spoil. In addition, the decay of organic matter in the soil utilises oxygen, further suppressing deeper oxygen infiltration (Egis Consulting, 2001).
- Fly ash, which is highly alkaline, could also be mixed into the spoil to increase the alkalinity of the groundwater and to buffer the AMD reactions. The greatest shortcoming of this method is that if the system acidifies anyway the high heavy metal content of the fly ash will go into solution, which will in return create a much bigger problem.
- Development of high recharge areas by proposing to build contour barriers to firstly prevent erosion and secondly to channel the precipitation and runoff into small areas that have no topsoil present (high recharge areas where spoils are bare). The groundwater will be channelled to flow into these areas directly (channelled by the contour barriers, through regrading) into the spoils. The contour barriers will form runoff channels, but these recharge canals can be modified into alkaline recharge trenches (Evangelou, 1995). The high recharge areas placed at a location over the area where the discards were dumped can thus be modified to introduce lime treated water into the system as stated above to neutralise the highly acidic material if necessary.

Suggested management options for Springbok No. 2 Seam underground workings to minimise the effect of the intermine flow on Springbok No. 2 Seam underground workings:

-
- The development of high recharge areas is proposed on the Goedehoop Colliery Springbok Workings No. 2 Seam underground workings. The high recharge areas could be constructed by drilling boreholes (165 mm) from the surface into the underground workings. By regarding the surface it is proposed to channel runoff into these boreholes to augment the volume of water that fills up the workings through recharge. The effect on the quality of the water in the workings should be similar to the effects on water quality if the workings is flooded from a river. The effect on water quality by using the development of high recharge areas would not be as effective as with flooding due to the slower rate of filling, hence more reactive surfaces exposed over a longer period of time. The high recharge areas to fill the Springbok No. 2 Seam workings could be crucial to the intermine flow scenario. By filling the Springbok workings faster the hydraulic gradient from Boschmanskrans section to Springbok workings can be diminished thus decreasing the intermine flow volumes and possibly decreasing the effect Boschmanskrans combined opencast pits and underground workings will have on the Springbok workings.
 - An alternative option is to install a hydraulic seal to cut off the part of the Springbok No. 2 Seam workings receiving the intermine flow from the rest of the Springbok No. 2 Seam workings (**Figure 6-9** and **Figure 6-10**).

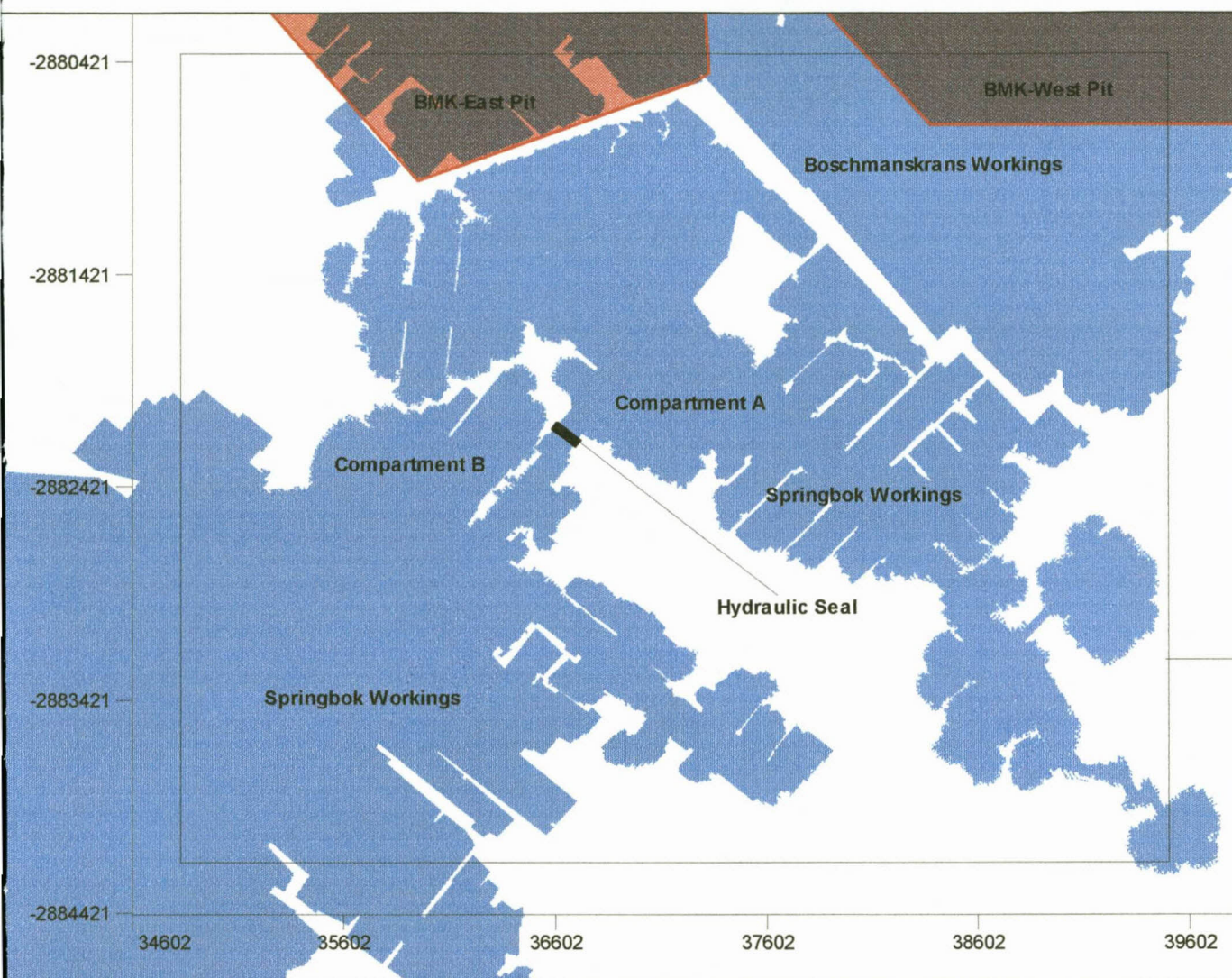


Figure 6-9. Map of the intermine flow area between Goedehoop Colliery and Boschmanskrans section, showing the position of the proposed hydraulic seal.

By doing this about 76% of the Springbok No. 2 Seam workings is cut off partially from the effects of the intermine flow from Boschmanskrans complex. The hydraulic seal will have to be engineered to withstand 12 m of head difference (about 1 atmosphere). The thickness of the unmined area between compartment A and B varies from 15 to 600 m and should form an effective barrier (**Figure 6-9** and **Figure 6-10**). Together with the seal and the unmined section between these two compartments the worst effects of the intermine flow could be limited to compartment A and should have a drastically diminished effect on compartment B in terms of sulphate loads and acidified intermine flow water from the Boschmanskrans combined No. 2 Seam underground and interconnected opencast pits (East- and West Pits). The above can be achieved through using the hydraulic seal which will cause compartment A to fill up faster due to the intermine flow volumes and therefore the hydraulic gradient will equilibrate faster which ultimately will lead to less intermine flow in the long run. Due to the partly filled No. 2 Seam workings

accessibility could be a problem and the seal can be remotely placed through drill holes (Skousen *et al.*, 1998).

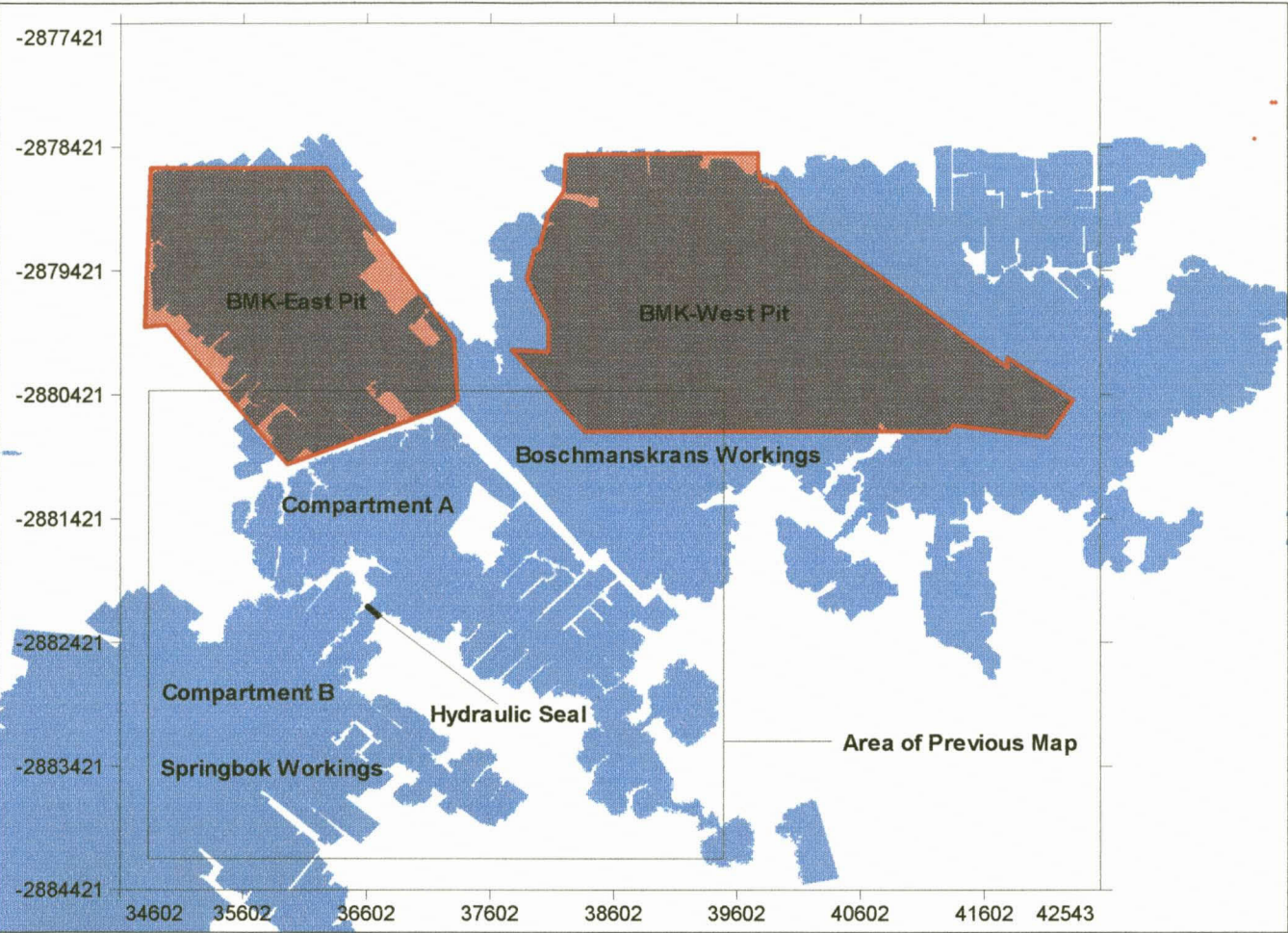


Figure 6-10. A regional map of the previous figure (**Figure 6-9**) also displaying the proposed hydraulic seal.

6.3 MANAGEMENT OPTIONS FOR NON INTERMINE FLOW AREAS IN THE STUDY AREA

6.3.1 Van Dyks Drift Planned South Opencast Pit

The VDD South opencast pit can also be flooded by the Olifants River to improve water quality by inundating the acid-generating material as discussed in section 6.2.1.

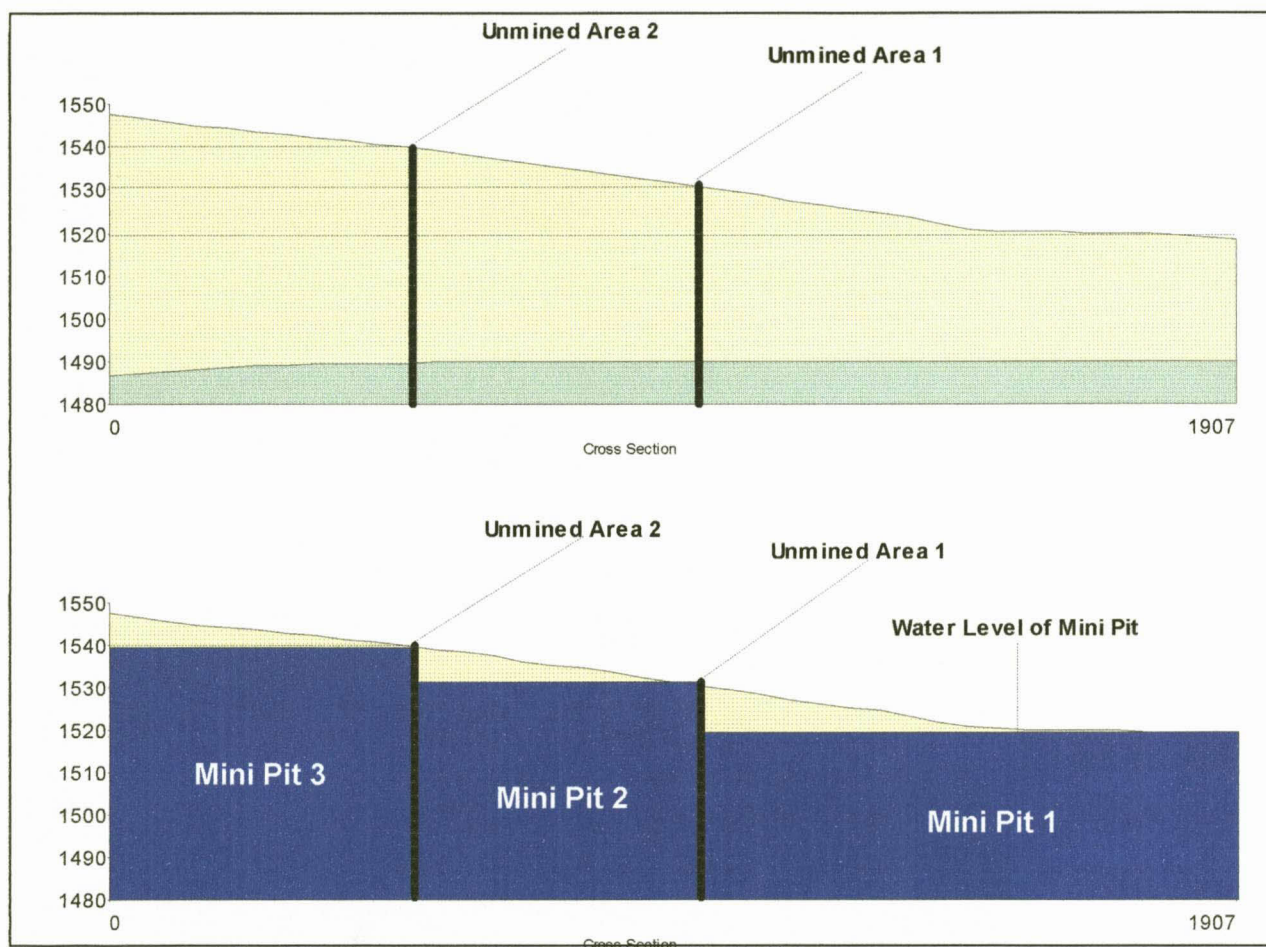


Figure 6-11. Cross Sections of Van Dyks Drift South to show the proposed unmined area to form the barrier walls of the mini-opencast pit as well as the final water level for the mini-opencast pits.

It is proposed that the at least two unmined sections be left in the VDD South Opencast pit to act as barriers to form mini-opencast pits to facilitated maximum spoils inundation (6.2.1). High recharge areas are also proposed as in section 6.2.1.

Another alternative method of flooding is to mine and rehabilitate the opencast pit in such a way that if the Olifants River should come down in flood that the VDD South opencast pit will be flooded by the flood event. The diluting effect of the fresh water

should improve the quality of the groundwater in the opencast pit's spoils considerably. For example the VDD South pit will take about 60 to 70 years to fill up and say 20 years after closure the pit is filled 30% and the water quality in the spoils is assumed at 1400 mg/L (Hodgson *et al.*, 1998). If the pit is flooded (with above-mentioned water quality) to decant level by a flood in the Olifants River the fresh water will dilute the assumed concentration of 1400 mg/L to 400 mg/L.

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

From this research the following conclusions can be drawn:

- Local models that do not include the whole extent of the underground workings in the model area will not simulate the intermine flow properly especially if the floor contours of the model floor slopes steeply.
- The horizontal flow barrier in Modflow is effective enough to simulate an intermine flow barrier between two mining voids.
- It was noted when Phreeq was used in a saturation calculation for gypsum the thermodynamic databases of Minteq and Phreeq gave different answers. This can be attributed to different K_{sp} values in the databases, derived from different sources.
- In this thesis an empiric sulphate generation rate method for underground areas was developed and applied. The method takes the relative degree of flooding into account and appears to hold promise for first order estimations of concentrations in underground areas in the Witbank coalfield
- It was determined that the sulphate generation rate in underground workings is between 0.1 to 1.5 kg/ha/d (on average between 0.1 – 1kg/ha/d). Compared to the 5 – 10 kg/ha/d (Hodgson *et al.*, 1998) sulphate generation rate for opencast pits, the underground workings have a much lower sulphate generation rate. This does not mean the sulphate concentration in the underground workings would be less than that of the opencast pits. Since the influx to underground voids is lower concentrations can often exceed those found at opencast pits. Reactive sulphate is also exposed to oxygen for longer periods time in the underground voids (longer period of oxidation) leading to high concentration of sulphate in the void despite the lower sulphate generation rate.

7.1.1 Conclusions for the Intermine Flow Scenarios

7.1.1.1 *Intermine Flow between Transvaal Navigational Colliery's Block C No. 2 Seam Underground Workings and Goedehoop Colliery's New Opencast Pit:*

- **Intermine Flow:** Block a C underground working is partially flooded (90%)while the opencast pit still is being mined. The Intermine flow will initially take place in the direction of the opencast pit (flow volume average 130 m³/d), after 35 to 40 years the water levels equilibrate and the intermine flow takes place in the direction of Block C (flow volume average 40 m³/d). Thereafter the opencast pit

decants (39 – 42 years) and the flow direction reverses again to the direction of the Block C underground.

- **Hydrochemistry:** The current sulphate concentration in Block C is relatively low (578 mg/L) and it is expected that the sulphate concentration in the opencast pit will be at least (projected sulphate concentration – 1700 – 2400 mg/L). Therefore it is concluded that the intermine flow from Block C will have a minimal impact on the opencast pit. The intermine flow from the opencast pit to Block C might have an impact if the water quality in the spoils is poor, but with the short time of intermine flow to the underground workings and the low intermine flow volume the impact should also be minimal. Decant from the opencast pit into the Olifants river could raise the concentration of sulphate in the river by 90 – 120 mg/L for an average flow volume in the river.

7.1.1.2 Intermine Flow between TNC's Welstand No. 2 Seam Underground Workings and Goedehoop Colliery's Hope No. 2 Seam Workings:

- **Intermine Flow:** The Welstand block is currently 95% flooded. The Hope workings is still being mined and therefore is kept empty. Intermine flow will take place in the direction of Hope workings (200 m³/d) from the Welstand Block, after the water levels have equilibrated the flow direction will reverse due to the natural flow gradient in the direction of the Welstand block
- **Hydrochemistry:** The Welstand block's current sulphate concentration is about 600 mg/L and the projected sulphate concentration for Hope workings is in the order of 1600 mg/L. Therefore the intermine flow from Welstand block should dilute the sulphate concentration in Hope workings. The intermine flow impact on Hope workings would therefore not be excessive. The intermine flow direction will reverse with time and the intermine flow from Hope workings could impact on Welstand block.

7.1.1.3 Intermine Flow between Albion Section's No. 2 Seam Underground Workings and New Clydesdale Colliery's No. 2 Seam Workings:

- **Intermine Flow:** The New Clydesdale working is partially flooded and Albion section's workings is considered to be empty. The intermine flow direction is to Albion section's workings and is in the order of 1000 m³/d initially. The flow volume decreases as the water levels equilibrates.
- **Hydrochemistry:** The benefit of the high intermine flow volume is that the Albion void will be filled up more rapidly with water, consequently cutting of oxygen to the reactive surface and accordingly restrict the oxidation of pyrite. Unfortunately the sulphate concentration of the New Clydesdale underground is about 1500 mg/L and therefore the Albion Section underground intermine flow contributes about 38% of the eventual sulphate, resulting in sustained high concentration of sulphate in the Albion section workings.

7.1.1.4 Intermine Flow between Van Dyks Drift No. 2 Seam Underground Workings and Goedehoop Colliery's No. 2 Seam Springbok Workings:

- **Intermine Flow:** The intermine flow direction will be initially in the direction of the Van Dyks Drift no. 2 seam underground workings (400 m³/d).
- **Hydrochemistry:** The current sulphate concentration of the Springbok workings is 1731 mg/L. The sulphate concentration can be increased in Van Dyks Drift no. 2 seam on average by about 300 mg/L by the intermine flow from the Springbok.

7.1.1.5 Intermine Flow between North Shaft No. 2 Seam Underground Workings and Goedehoop Colliery's No. 2 Seam Springbok Workings:

- **Intermine Flow:** The Springbok workings is partially filled while mining North Shaft workings is empty, the planned Steenkoolspruit/Kleinkopje is going to be hydraulically connected to North Shaft workings (current mining plans). The intermine flow will be from Springbok in the direction of the North Shaft workings (500 – 600 m³/d). The North shaft workings will decant (4000 – 5000 m³/d) through the opencast pit (current mining plans).
- **Hydrochemistry:** The effect of the intermine flow is minimal because the average future sulphate value in the Steenkoolspruit/Kleinkopje opencast pit is predicted for an average of 1460 mg/L. Without the intermine flow from Springbok no. 2 seam workings it is predicted to be 1380 mg/L. The respective contributions of sulphate salt load to the Steenkoolspruit/Kleinkopje pit-North Shaft workings are: 6% for the North Shaft no. 2 seam workings, 2% due to intermine flow from Springbok no. 2 seam workings and 92% from the planned Steenkoolspruit/Kleinkopje opencast pit.

7.1.1.6 Intermine Flow between Boschmanskrans No. 2 Seam Underground Workings/Interconnected East and West Opencast Pits and Goedehoop Colliery's No. 2 Seam Springbok Workings:

- **Intermine Flow:** The initial intermine flow direction will be from the Boschmanskrans Combined No. 2 Seam Underground Workings and Planned East- and West Opencast Pits to the Springbok no. 2 seam underground workings. The initial intermine flow volume is in the order of 320 m³/d (high flow scenario 700 m³/d). The flow model projected that the time period that Boschmanskrans will flow into the Springbok workings is approximately 50 years.
- **Hydrochemistry:** The predicted added sulphate load to the Springbok no. 2 seam workings is approximately 20%. The acid base accounting (Hodgson *et al*, 1998) that was done on the Boschmanskrans section it was concluded that if the spoils in the Boschmanskrans Section are not managed correctly acidification could take

place and therefore the intermine flow to Goedehoop Colliery could be detrimental to the water quality of the water in the Springbok no. 2 seam underground workings.

7.2 RECOMMENDATIONS

- It is recommended that more site-specific investigation (drilling of holes in the intermine flow barrier for pump test and tracer tests) could be done on aquifer parameters (hydraulic conductivities and recharge values) so that more accurate intermine flow modelling can be done.
 - It is recommended that the hydraulic conductivities of the site-specific coal seams be determined through packer test so that hydraulic conductivities of the unmined barriers between the voids can be calculated more accurately. This will also refine the intermine flow volume predictions more accurately.
 - Further research should also be done in terms of recharge values for each intermine flow area so that the fill up times of the voids can be calculated more accurately.
- It is also recommended that more investigation is done to refine the sulphate generation rates for the undergrounds.
 - Gathering of water level and sulphate concentrations data of underground workings so that more calculated sulphate generation points can be added to the graph on which the sulphate generation function is fitted. Therefore by adding more points a more accurate function can be derived.
 - More research must be done in terms of case studies to implement and evaluate the sulphate generation function for underground workings.
- The gathering of regular water level data and chemistry of mining voids in the study area to update and refine existing models. Water levels should be taken monthly and water samples for analyses should be taken quarterly (every three months) and on the minimum twice a year.
- It is also recommended that correct sampling techniques and correct sampling depths be standardized when sampling these voids. This is recommended due to the large amount of suspect chemical data received in this study.

7.2.1.1 TNC / Goedehoop New Opencast:

- Flooding and inundation through high recharge areas is proposed and due to the fact that the decant level of Goedehoop Colliery's new opencast pit is so low that a large extent of the spoils will not be inundated, compartmentalization of the pit is proposed. Selective spoil layering is also proposed to yield optimum water

qualities to limit the impact of intermine flow and that of the impacts decant could have on the river.

7.2.1.2 TNC Welstand / Goedehoop Hope:

- It is proposed that Hope workings be flooded from the Koringspruit over a period of 30 years to decrease sulphate generation and concentrations and to limit AMD reaction rates. It is also proposed that at Hope underground workings should be fitted with surface access dry seals as to minimize the infiltration of oxygen.).

7.2.1.3 TNC / New Clydesdale:

- The effect of the intermine flow on the New Clydesdale's workings will be minimal, hence it does not justify the spending of money on possible intermine flow management options.

7.2.1.4 Douglas Albion / New Clydesdale:

- Managing the intermine flow with a wall (5 km) that acts as a hydraulic seal (Albion Section side of intermine flow barrier). This management option may not be viable due to the high cost of construction and the groundwater will most probably seep underneath the wall. The other alternative is to flood the workings with the Olifants River, which may also be difficult to do because the current water act.

7.2.1.5 Boschmanskrans / Goedehoop:

Management Recommendations - Boschmanskrans Complex:

- Selective Spoil Layering
- Regrading and Revegetation
- Coal from the discard dump be disposed in the deepest part of the opencast pits.
- Mixing of fly ash with spoils to increase the alkalinity of the spoils.
- Development of high recharge areas.

Management Recommendations - Springbok No. 2 Seam Underground Workings:

- Placement of a hydraulic seal to separate 76% of the Springbok No. 2 Seam workings off from the intermine flow from the Boschmanskrans Complex.
- Development of high recharge areas.

The practical viability of these management options should be investigated, together with a cost/benefit analysis of each option.

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Abstract

Research into the identification, quantification and impact assessment of the intermine flow on the groundwater and surface water quality of the Witbank and Highveld coalfields was undertaken as part of broader research initiatives. The study area of this thesis included the coal collieries of the Central Witbank Coalfield. Intermine flow areas were previously identified in studies by Grobbelaar *et al.*, 2001 and Grobbelaar, 2001.

The aim of this thesis was to develop a quantitative prediction of long-term intermine flow in the central Witbank coalfield, using the available data collected in the project. From the quantification of these flows and different hydrochemical techniques, likely water quality profiles at these collieries were determined. The quantification on the intermine flow direction as well as the flow volume was predicted through numerical groundwater modelling using Modflow. Local and regional models were compared and it was found that regional models (relative to including the whole extend of the voids in the model area) yielded the most accurate answer of the two models in the study area. The quantification of the predicted impact on water qualities was done through the use of mass balance approximations and an empirical sulphate generation rate method (developed in this study for predicting future sulphate concentrations in underground workings) using available hydrochemical and acid base accounting data. It was calculated that the sulphate generation rate for the underground workings is in the order of 0.1 – 1.5 kg/ha/d depending on the degree to which the void is filled. An evaluation of water management strategies, which will minimise the long-term influence of intermine flow on the groundwater and surface water quality, was also done. A compartmentalization system to mining opencast pits has been suggested for opencast pits with low decant elevations, to inundate a maximum percentage of the spoils to limit AMD reactions. The implementation of artificially created, high recharge areas on opencast pits and underground workings also was investigated to reduce fill-up times of voids as to limit the exposure of oxygen to the acid generating materials.

The research indicates that intermine flow can be potentially detrimental to the groundwater- and surface water systems depending on the flow volumes and quality of the intermine flow water in the Central Witbank Coalfield. Flow volumes predicted through numerical modelling was quantified to be considerable enough to be potentially detrimental to mining voids into which the intermine flow water flows. It was also found that the intermine flow could influence the fill up times of the mining voids (both opencast pits and underground workings). The evaluation of different management options identified viable alternatives to manage intermine flow in such a way as to yield future optimal water qualities for the Central Witbank Coalfield.

Opsomming

Navorsing is gedoen om moontelike areas van inter-myn vloei te identifiseer, te kwantifiseer en om die impak daarvan op die grond- en oppervlak water te bepaal. Die studie area sluit die steenkool myne van die sentrale Witbank steenkool veld in. Meeste van die inter-myn vloei areas was deur Grobbelaar et al., 2001 en Grobbelaar, 2001 vasgestel in vorige studies.

Die doel van die studie was om kwantitatiewe voorspelings tegnieke en metodes te ontwikkel om die lang termyn impak van inter-myn vloei te bepaal deur die gebruik van bestaande data. Deur middel van die kwantifikasie en verskeie hidro-chemiese tegnieke is verskeie moontlike hidro-chemiese profiele vir die tesis bepaal. Die kwantifikasie van die inter-myn vloei is bepaal deur numeriese modellering, deur die gebruik van Modflow. Daar is geëksperimenteer met lokale en regionale grondwater modelle en dit is bevind dat die regionale modelle meer akkurate antwoorde lewer. Die kwantifikasie van die impak op die grondwater en oppervlak water is bepaal deur die gebruik van massa balanse, die empiries sulfaat generasie metode (ontwikkel vir voorspeling van sulfaat konsentrasies in die ondergrondse werke) en ander hidro chemies tegnieke, deur die gebruik van bestaande data. Dit is bepaal dat die sulfaat generasie tempo in orde van 0.1 – 1.5 kg/ha/d gekoppel aan die mate wat die ondergrondse werke gevul is met water. 'n Evaluasie van sekere grondwater bestuurs strategieë is gedoen om die lang termyn impakte van inter-myn vloei te beperk op die grondwater en oppervlak water bronne vir die studie area. In die tesis is 'n stelsel van kompartimentilisasie voorgestel vir oopgroef myne met 'n lae "decant" elewasie om sodoende die maksimum persentasie van die "spoils" onder water te hou om sodoende die suur generasie reaksies te beperk. Die implimentasie van verhoogde grondwater aanvullings areas om sodoende die ondergrondse werke sowel as die oopgroef seksie vinniger met water te vul om die blootstelling van suur produserende materiale aan suurstof te beperk.

Die navorsing toon dat inter-myn vloei potensiaal skadelik vir die grond- en oppervlak water kan wees, afhangende van die inter-myn vloei volumes en kwaliteite van die inter-myn vloei waters. Deur numeries modellering is vasgestel dat die vloei volumes groot genoeg is om potensiaal skadelik te wees vir die myn werke wat in die inter-myn vloei waters invloei. Dit is ook bevind dat inter-myn vloei die opvul tempo van die mynbou werke beïnvloed. Deur evaluasie van sekere bestuurs strategieë was dit bevind dat daar wel sekere bestuurs strategieë is wat geimplimenteer kan word om optimale water kwaliteite te verseker in die toekoms.