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QUANTIFICATION AND MANAGEMENT OF INTERMINE FLOW IN THE WESTERN WITBANK COALFIELD: IMPLICATION FOR MINE WATER VOLUMES AND QUALITY

by

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Abstract

The collieries in the Western Witbank Coalfield have geometries such that there are several areas where this intermine flow is possible. Identification of intermine flow areas in the Witbank Coalfield was previously done by Grobbelaar, (2001). Research into the identification, quantification and impact assessment of the intermine flow on the groundwater- and surface water quality of the Western Witbank Coalfield was undertaken as part of broader research initiatives sponsored by COALTECH 2020. The larger project aims to provide water management strategies for optimal water quality and quantities in South Africa's coalfields. The focus in this thesis is on the Western Witbank coalfield. The main aims were to quantify the intermine flow in this study area and determine the impacts on regional water qualities and quantities. The impact of different management options was evaluated.

The research showed that the paleogeologic conditions of coal deposition and formation can explain currently observed hydrochemical and hydrogeological phenomena.

Numerical flow modeling and analytical or empiric approaches were used to quantify flow directions, flow volumes and filling times. This research showed that numerical models such as Modflow can be fruitfully used to understand the hydrologic interactions that occur in typical intermine flow areas. Comparison between the approaches yielded similar answers in several cases, but numerical models allow the evaluation of changing conditions and resolve complex situations satisfactorily. This thesis has highlighted certain instances where the answers obtained must be used with circumspection. A specific example dealt with, occurs in some underground mining situations which are overlain by saturated media. Due to moving boundary conditions in such situations conventional models can produce erroneous results. Refilling times for underground models using saturated flow models, should be checked for consistency using volumetric /inflow calculations.

Comparison of mass transport approaches and mixing cell approaches using a geochemical model provided similar results, with mass transport more insightful in intermine flow assessment due to the spatial variation in concentration change. By using PHREEQC to evaluate almost 2000 samples at two collieries, it is clear that sulphate concentrations are often limited by the saturation of gypsum. An upper limit of around 3000 mg/l is suggested by these evaluations.

Intermine flows have been shown to vary considerably in the area with values ranging from more than 1.5 Ml/d (Wolwekrans/Kleinkopje and Greenside/ Kleinkopje) to less than 10 m³/d (Kriel /Tavistock). Evaluation of the situation around the Rietspruit pit showed that due to the immense perimeter and thin unmined barrier, significant flows are expected into the adjacent underground workings. This leakage results in very long projected fill up times of more than 200 years for N3 pit.

An evaluation of management options has shown that an inter-colliery option of piping the decant from Kriel to Tavistock's 4 Seam workings will have mutually beneficial results. Among the other options investigated, it was illustrated that impermeable barriers will not be effective in preventing flow between Rietspruit and the adjacent underground workings. From the research done recommendations for future work include more detailed water balances at the collieries, site - specific investigations into critical considerations such as aquifer parameters, effective recharge and localized intermine management plans.

1 INTRODUCTION

1.1 BACKGROUND INFORMATION AND SCOPE OF INVESTIGATION

Coal mining in the Witbank Coalfield has been in existence for more than a century. Due to the scale of these operations in aerial extent and the time period of operation, these activities have altered the geohydrological environment in the area. These impacts are not only limited to the operational life of the mines, but are expected to continue for several years after mining has ceased. As such, an understanding of these interactions is vital if appropriate management options are to be exercised in the area.

One of the key areas of concern is the phenomenon of intermine flow. Previous researchers, (for example, (Grobbelaar et al., 2001 and Grobbelaar, 2001), have investigated intermine flow. After the closure of mines, water in the mined-out areas will flow along the coal seam floor and accumulate in the lower-lying areas. These man-made voids will fill up with water and hydraulic gradients will be exerted onto peripheral areas (barriers) or compartments within mines. This results in water flow between mines, or onto the surface. This flow is referred to as intermine flow (Grobbelaar, 2001). Due to the potential long-term impact of intermine flow in terms of water quantities and qualities, the Department of Water Affairs and Forestry regards intermine flow as one the most important challenges in the mining industry (Postma and Schwab 2002).

In order to address these issues, the individual mining houses undertake periodic and ongoing research into water quantity and quality issues. Through the collaborative research organisation COALTECH 2020, a research project was launched to address several of these issues to provide more quantitative solutions to these problems. This thesis forms part of an initial phase of this Coaltech project.

The aims of this study include the following:

- Evaluation of paleogeological conditions in the Witbank Coalfield to ascertain if present observations can be related to these conditions.
- The collation of available information in the Witbank Coalfield in order to construct a unified database of information and graphical representation thereof, using appropriate techniques.
- Understanding of the regional groundwater flow and simulation of regional and intermine flows the study area using empirical and numerical methods.
- To provide filling times for the opencast and underground areas as well as flow volumes in the intermine flow areas.

-
- By making use of the calculated flow volumes, do quality calculations to predict improvement or deterioration of the pits and workings.
 - To find possible management options to enhance or prevent intermine flow to improve the quality of mines.

1.2 APPROACH TO THE RESEARCH

The first step towards achieving the aims was the collection and collation of available data. This included large quantities of data from different mines in different forms and also a review of available literature on topics related to the research. This information was combined into databases and formatted to be compatible with the WISH software package.

The study area was divided into three hydraulic units. The grouping of the three units were done in terms of current flow directions by making use of the floor contours of the area as well as on predictions in terms of intermine flow in the study area. Figure 1-1 was prepared to stipulate the locations of the three hydraulic units.

Three flow models were constructed to predict intermine flow in the hydraulic units of the Western Witbank Coalfield. The three models are the following:

- Kriel-Tavistock scenario
- Rietspruit-Tavistock scenario and
- Greenside-Kleinkopje-Wolwekrans scenario

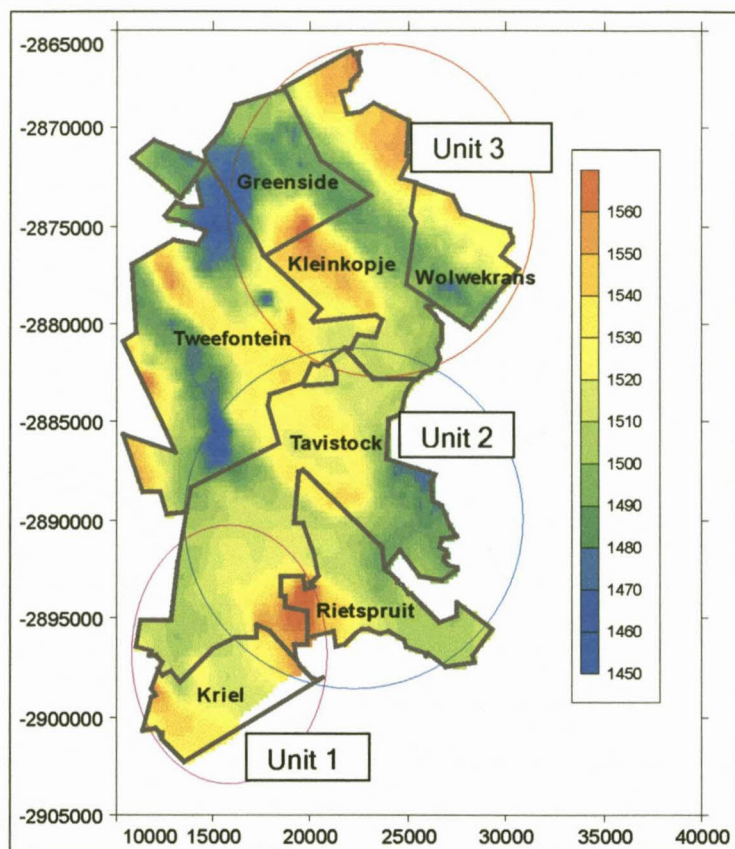


Figure 1-1 Study area and the grouping of the three hydraulic units.

Kriel-Tavistock scenario was done to predict the possible intermine flow between Pit 6 and the 4 seam underground workings at Tavistock Colliery.

Rietspruit-Tavistock-Tweefontein scenario was done to predict intermine flow between the opencast and underground areas of the unit.

Greenside-Kleinkopje-Wolwekrans scenario was done to predict flow volumes over the coal barriers between Wolwekrans and Kleinkopje and between Kleinkopje and Greenside and visa versa.

An evaluation of the volumes and potential flows was done using volumetric determination techniques and also extensive review of available geographical information. The three models will enable us to predict filling times of the mining pits and workings according to the in- and outflows, as well as the amount of flow through the coal barriers.

The borders of the study area on the southern and eastern side was set as follows:

Only the Wolwekrans section of Douglas Colliery was used to calculate the flow over the coal barrier between Wolwekrans and Kleinkopje. Just the two future opencast pits at Kriel colliery were added to the study area, because of the possible intermine flow between the latter and Tavistock Colliery. It was decided to set the border there and not to including the underground area of Kriel. There is no interaction between the underground area and the opencast pits because of the distance between the mining areas.

Based on the outcome of the model calculations, two issues were selected to be investigated in greater detail viz. the current chemistry of the area as well as the impact that intermine flow might have on the chemistry of the area. Two methods were used to predict the chemistry of the area, namely Mass Transport modelling and Phreeqc (Parkhurst and Appelo, 2001). Mass Transport simulations were run by making use of the original flow model and by superimposing expected mine water concentrations on these flows, using the MT3D module with PMWIN.

Phreeqc, a geochemical modelling package, enabled the calculation of current saturation states and predicts pit water chemistries, using thermodynamic approaches. These two methods were compared to see which is more suitable for these specific calculations and predictions.

Potential management options that would lessen the potential environmental impact over the long term are proposed and discussed. The proposed management options were incorporated into the flow models to see the effect over time, and to gauge its practical implications.

1.3 STRUCTURE OF THIS THESIS

This thesis consists of six chapters. The first chapter is an introduction to the scope of the research. Chapter 2 gives an introduction to the palaeo environments and sedimentation of coal in South Africa, specifically of the Witbank Coalfield. Chapter 3 explains the motivation behind the investigation as well as the development of the flow models. Chapter 4 explains the influence of these flows on the chemistry of the area. Chapter 5 deals with management options that can enhance the quality of the mine water. Chapters 6 and 7 contain the overall conclusion, recommendations and list of reference.

2.1 INTRODUCTION TO THE WITBANK COALFIELD

The Springs-Witbank Coalfield extends over a distance of some 180 km from the Brakpan and Springs areas in the west to Belfast in the east, and about 40 km in a north-south direction and can be seen in Figure 2-1 (Smith and Whittaker, 1986). The Witbank Coalfield is located in the Springs-Witbank Coalfield.

The Springs-Witbank Coalfield currently accounts for 53% of the country's coal production, including supplies used in generating 41% of the Republic of South Africa's electricity. Most of the major power stations in the area are located in the Springs-Witbank Coalfield (Smith and Whittaker, 1986).

The boundaries between the individual coalfields are largely based on historical and geographical considerations, and not necessarily on pronounced geological differences.

The southern boundary of the Witbank Coalfield is considered to run from about 5 km south of Delmas Colliery in an east-northeast direction until about 5 km south of South Witbank Colliery. From this point eastwards, for about 60 km, a natural boundary is formed by a series of inliers of Rooiberg felsite.

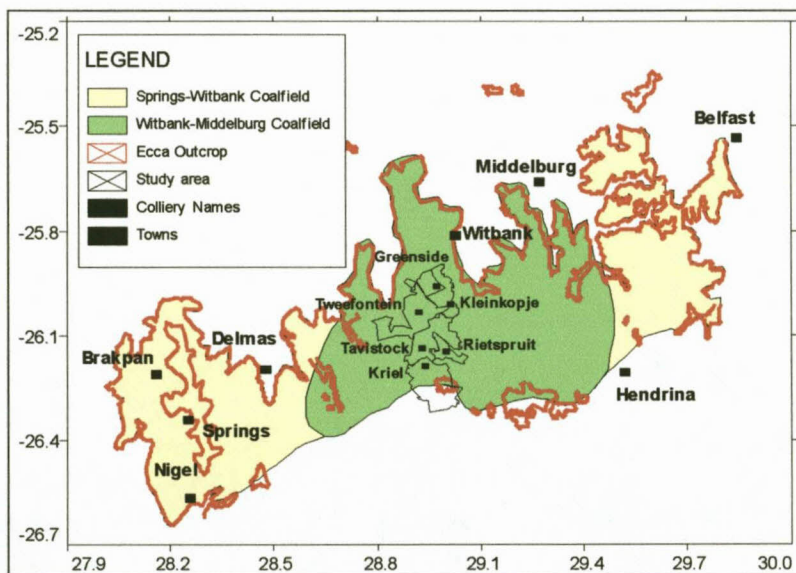


Figure 2-1 Distribution of the major coalfields in the Springs-Witbank area (From Smith and Whittaker, 1986).

Mining commenced in the Witbank Coalfield in 1895. The Witbank Coalfield developed into the most important coalfield in South Africa. Witbank hosted 28 collieries during the 1970s and 37 in 1995 (Snyman, 1998). The Witbank Coalfield is currently the largest coal producer in Africa.

The economic coal seams are contained at depths ranging from a few metres to about 300 m in the largely horizontal Ecca Series of the Karoo Geological System, which consists mainly of reasonably soft sandstone, shale and mudstone.

A considerable amount of regional geological data, in the form of borehole logs and arid sample results, is available. It is estimated that some 30 000 boreholes have been drilled in this area (Smith and Whittaker, 1986).

Estimated South African coal production in 2000 was 224.3 million short tons. During the year 2000, 260.8 million tons of saleable coal was produced in the Western Witbank Coalfield (Chamber of Mines, 2000).

2.1.1 Historical and geological background

The earliest records of the existence of coal in the Transvaal (as it was then known) are from 1868, when coal was worked by farmers along the road between Pretoria and Trichardt, in the neighbourhood of Bethal. Outcrop coal was probably opened in many places prior to the discovery of the Witwatersrand. The first coal brought into Johannesburg came from Steenkoolspruit. The first mines were opened in the Middelburg-Witbank district when four small collieries, Brugspruit, Steenkoolspruit, Maggies Mine, and Douglas Colliery, were opened in 1889 (Smith and Whittaker, 1986). The first geological work on the Witbank Coalfield was undertaken in 1906 by Mellor (Smith and Whittaker, 1986).

2.2 PALEOGEOLOGY OF THE STUDY AREA

The paleogeology of the Witbank Coalfield was included in this study to ascertain if any understanding can be extrapolated to the current hydrogeology and hydrochemical conditions, and if the conditions of deposit and preservation of different coal seams could provide clues to the current observed phenomena. In other coal mining regions of the world researchers (e.g. Brady *et al.*, 1999) have done a great deal of work on extrapolating paleogeologic conditions to modern day occurrences. This section does not attempt to provide a detailed assessment, but rather highlights some pertinent facts and the need for more in-depth research on this topic.

2.3 ORIGIN OF COAL

Coal is a readily combustible sedimentary rock containing more than 50% by mass and more than 70% by volume carbonaceous material, and is formed by the accumulation, compaction and induration of variously altered plant remains (Snyman, 1998).

According to Plumstead (1957) coal is "a compact stratified mass of mummified plants". The vegetable origin of coal was established in 1778 (Plumstead, 1957) but more than a century later geologists were still arguing about the manner of its accumulation and the relative merits of the "*in situ*" and "Drift" theories, i.e. whether the coal had formed from plant matter that accumulated where it grew or from vegetable debris drifted by floods and currents to the present site. The first theory is almost universally accepted, but for a long time many people in South Africa believed that only a "Drift" origin could explain the higher percentage of mineral matter which is a feature of most South African coals. Data from the Department of Minerals and Energy indicate that in this area the percentage of inert material is often around 50%, reaching as high as 56% for Landau coals (DME, 2001).

2.4 CONDITIONS DURING THE ORIGIN OF COAL

2.4.1 Basin subsidence and transgression during the formation of the coal seams.

In order for peat to accumulate and be preserved, subsidence must occur or, alternatively, the water table must be sufficiently maintained to prevent peat destruction. Slight variations in water depth would result in thin, but widespread lower quality (high ash) bands within a seam, produced by oxidation due to lowering of the water level or drowning of the swamp by increased water depth. Subsidence was not as greatly pronounced in the northern parts of the Karoo Basin as in other coal basins. Mild epeirogenic subsidence in the Karoo Basin resulted in marked lateral sedimentation patterns rather than the vertical stacking of facies normally associated with rapid downwarping.

2.4.2 Chemistry and Microbial activity associated with South African coal

Apart from peat types and contemporaneous clastic depositional processes, swamp water pH is a significant parameter in the determination of the ash content of coal. The rate and degree of plant degradation during peatification is primarily pH-controlled. Microbial activity plays a critical role during the peat stage and is to a large degree pH-controlled. It is shown geochemically that the ash content of coal is dependent on pH-controlled levels of bacterial activity in the ancestral swamps. Microbial activity becomes increasingly effective above a pH of approximately 4.5. Coals are low in mineral matter

and were derived from peat that accumulated under highly acid conditions of $\text{pH} < 4.5$. If the peat swamp pH is > 5 , then microbial activity is so vigorous that it precludes sufficient organic material to produce coal. Peat accumulation in swamps with $\text{pH} > 5$ would only produce black, highly carbonaceous shales or impure bone coal ($> 33\%$ ash) or, if unfavorable conditions were only short-lived, a coal parting. This would explain the presence of carbonaceous shale partings that persist over vast areas in a coal seam with little or no change in thickness. These represent the degraded peat surface subjected temporarily to non-ideal conditions of peat preservation.

As microbial and bacterial activity can be temperature dependent, the pH of the No. 1 and the No. 2 Seam swamp water may have been greater than 4.5, which were obtained from warm climate modern-day swamps. The cooler temperature thereby inhibiting peat degradation under higher pH -values would therefore have suppressed bacterial activity. It seems that when the lowermost coal seams were deposited, acidic water conditions were already present in the areas.

These pH -conditions are very important in understanding the observed minerals commonly associated with the coal seams in Mpumalanga. If it is assumed that the conditions under which the peat were reserved were fairly anoxic (otherwise there would have been heightened bacterial metabolism of the organic material) and that the pH -conditions were such that peat preservation could occur, the presence of pyrite in these seams should be investigated. Berner (1970) outlines the following broad process for pyrite formation:

- Bacterial sulphate reduction
- Reaction of the reduced S (probably in the form of H_2S) with sedimentary iron minerals
- Reaction of the non-sulphide iron minerals with elemental or other forms of S to form Pyrite.

The important factors for pyrite formation are therefore the presence of metabolisable organic matter, the diffusion of sulphate in the reacting sediments, the total concentration and reactivity of iron minerals and the production of elemental sulphur. Figure 2-2 indicates the process as seen by Goldhaber and Kaplan (1982).

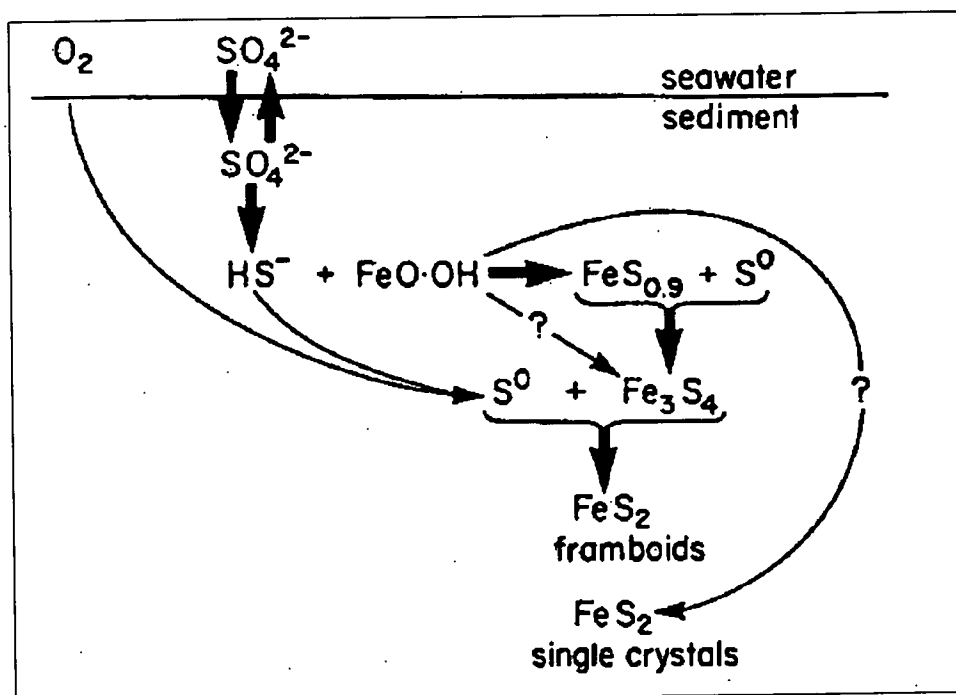


Figure 2-2 Pathway of sedimentary pyrite formation (from Goldhaber and Kaplan, 1982).

The likely redox and pH-conditions under which pyrite is stable are also worth considering. Figure 2-3 and Figure 2-4 indicate the stability field of pyrite under different conditions. Figure 2-3 indicates the conditions under which elemental sulphur and pyrite could co-exist. This indicates that pore waters trapped within these coal layers are expected to have a lower pH and to be in reduced states. As time precedes processes such as ion exchange, reaction with the carbonate system, minerals and dissolved solids will alter this chemistry to eventually reflect a sodium carbonate nature.

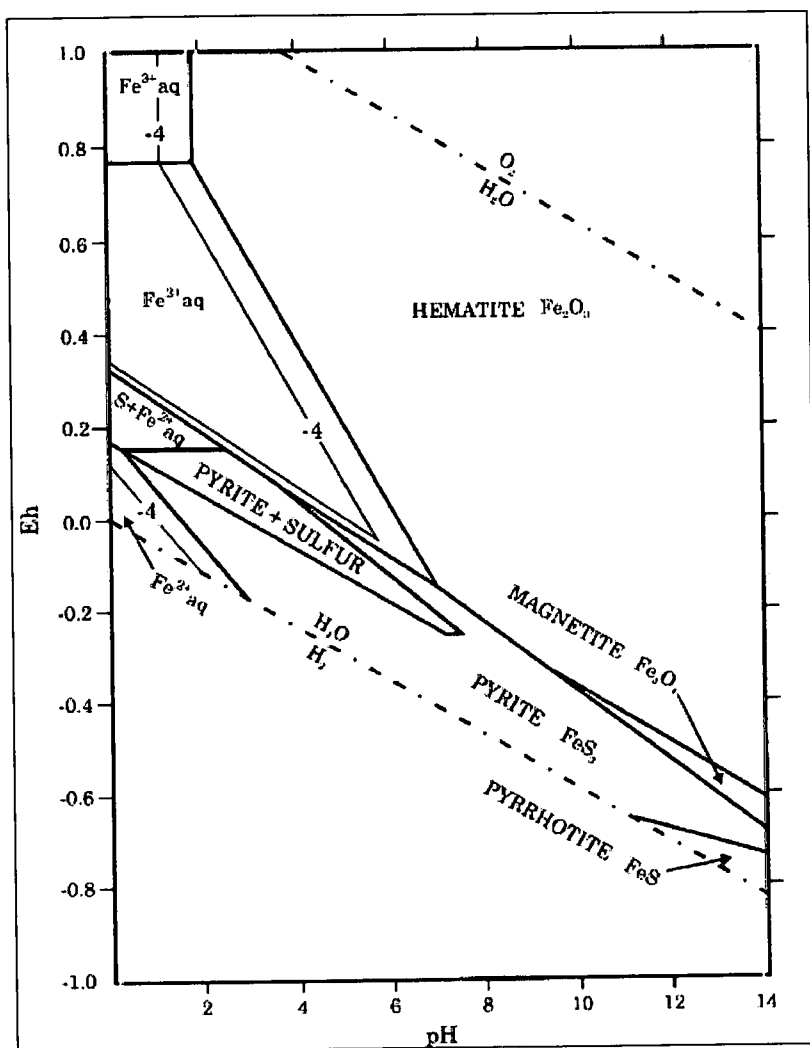


Figure 2-3 Eh-pH diagram showing stability fields of iron oxides and sulfides, when total sulphur = 10 M. Plot at 25C

When the effect of carbonate in the water from dissolution of calcite, and or dolomite, and atmospheric CO_2 dissolution via Henry's law is taken into account, the stability fields look rather different, as shown in Figure 2-4.

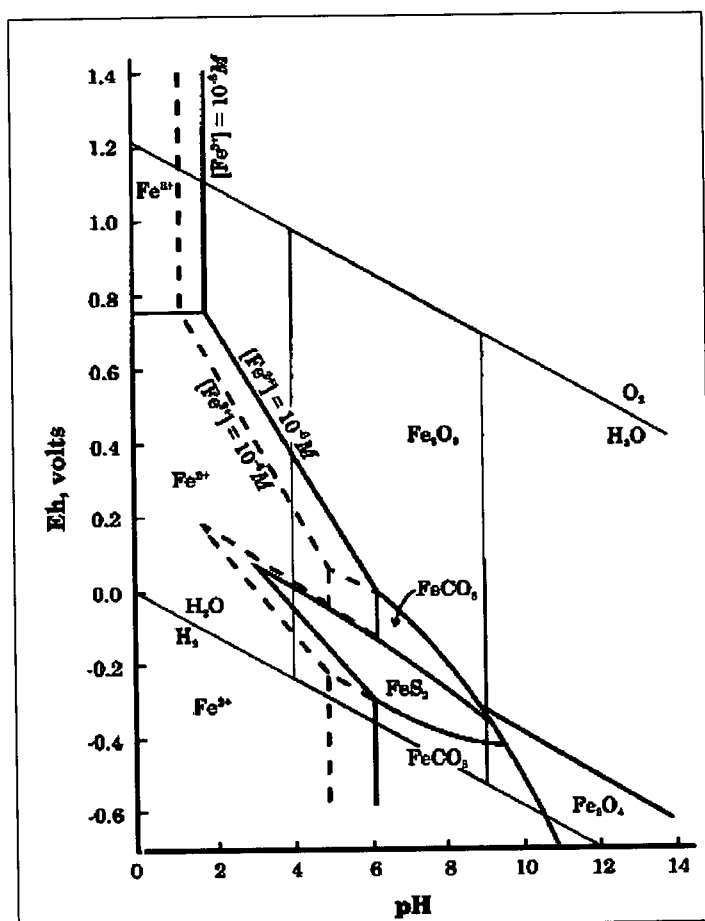


Figure 2-4 Eh-pH diagram showing the stability fields of common iron minerals. Total activity of dissolved carbonate 1M, of dissolved sulphur 10^{-6} M. Solid boundaries represent 10^{-6} M iron; dashed lines 10^{-6} M.

From these diagrams it is clear that the pyrite stability field lies in the neutral to acidic pH-value range, and in fairly reducing conditions. The higher pH-values are also consistent with the higher temperature stability for the peat discussed earlier. The pH-Eh conditions present explain the formation of coal, the formation pyrite and carbonate minerals.

2.5 DISTRIBUTION OF COAL IN SOUTH AFRICA

The Karoo Supergroup is a thick and extensive group of rocks that was deposited on land and in fresh water, almost continuously from the Late Carboniferous to late Triassic age. The Karoo Supergroup hosts all the South African coal deposits. The coal deposits were formed in the great Gondwana basin.

The South African Coalfields extend from the Southern Cape Province to the Southern Transvaal, and in isolated patches northwards as far as the Congo and Uganda.

The South African coal deposits are found in two major tectonic settings, namely stable cratonic platforms and fault-bounded rift basins. The main Karoo Basin is typical of a stable cratonic platform and the northern parts of South Africa are typical of a fault-bounded rift basin.

In the Karoo Supergroup itself there are four subdivisions, three of which are coal-bearing in places (

Figure 2-5 and Table 2-1). The late Carboniferous to early Permian Glaciogene Dwyka group occupies the base of the Karoo Supergroup. The Dwyka Series is approximately 900m thick and 280 million years old. The Dwyka Series consists of a variety of glacial to periglacial sediments. These include logment tills, terrestrial moraine, glaciolacustrine and fluvioglacial conglomerates, sandstones and mudrock as well as submarine to subaerial outwash diamictites, sandstone and mudrocks. These glacial deposits are easily recognised in borehole cores and form an excellent marker below which coal is not found.

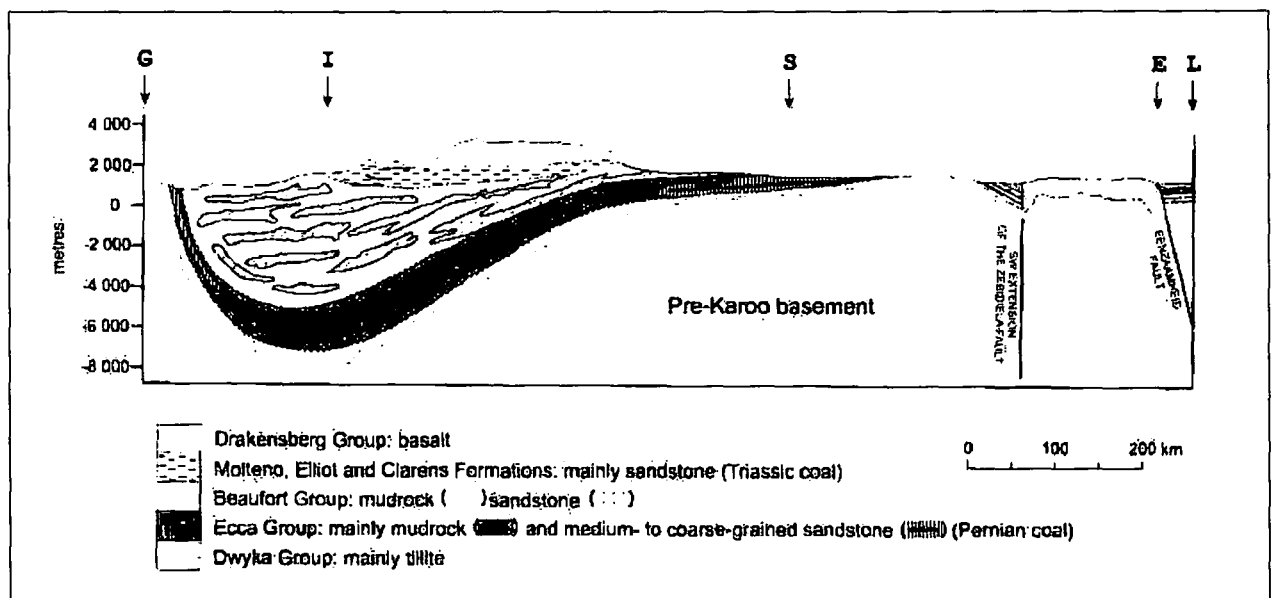


Figure 2-5 Schematic cross section from Grahamstown (G), through Ingwe (I), Standerton (S) and Ellisras (E) to the Limpopo River (L), showing the stratigraphic and tectonic setting of the coal deposits (Snyman, 1998).

The Ecca series of the lower Permian Age is by far the most important coal-bearing in Africa, but this is true only east of longitude 25 °E and north of latitude 29 °S.

South African coal deposits are confined to the area east of 26°E. Within the main Karoo Basin, coal is present in the Vryheid Formation of the Ecca Group and the Normandien Formation of the Beaufort Group north of 29°S, and also in the Molteno Formation in the Eastern Cape (Snyman, 1998).

The Beaufort Group records fluvial sedimentation by highly sinuous, suspension-load streams, in a setting of increasing aridity and active subsidence. Fluctuating water tables resulted in different degrees of oxidation, which produced multi-coloured mudrocks and sandstones. Although the animal and plant fossils signify the presence of appreciable vegetation during the deposition of the Beaufort Group, very little of this appears to have been preserved as coal (Snyman, 1998).

The Molteno Formation rests on the Beaufort Group and hosts the uppermost coals of the Karoo Supergroup. The climatic conditions during the Molteno sedimentation were not ideal for peat formation. The coal seams in this area are lenticular, of low grade and not economically viable under present conditions.

As a result of increasing aridity the sediments of the Elliot Formation were deposited by ephemeral streams and those of the Clarens Formation by aeolian activity. The development of the Karoo Supergroup ended with the eruption of the basaltic lavas of the Drakensberg Group. A significant proportion of the Drakensberg magma intruded the sedimentary rocks of the Karoo Supergroup as dykes, concordant sills and transgressive sills of dolerite. The coal close to the intrusion has devolatilised. Transgressive sills are especially troublesome in coal mining, as they displace the coal seams over a distance equal to the apparent vertical thickness of the relevant sill. In some places strongly undulating sills form domes and basins cause severe mining problems (Snyman, 1998).

Table 2-1 Lithostratigraphy of the Karoo Supergroup in the Main Karoo Basin (Snyman, 1998).

Formation or group	Southwestern Facies	Northeastern Facies	Age
Drakensberg	Flood Basalts	Flood Basalts	Middle to Early Jurassic - 180 Ma
Clarens	Aeolian Sandstone	Aeolian Sandstone	Early Jurassic
Elliot	Red mudstone and Sandstone	Red mudstone and Sandstone	Late Triassic
Moltino	Sandstone, mudstone, minor coal	Sandstone, mudstone	Late Triassic - 210 Ma
Beaufort	Greenish, bluish and reddish mudstone, grey sandstone	Mudstone and shale: Driekoppen Formation Conglomerate, coarse- to medium-grained sandstone: Verkykerskop Formation. Sandstone, mudstone, coal: Normandie Formation	Early Triassic
Ecca	Grey to black shale and mudstone, subordinate sandstone	Shale and mudstone: Volksrus Formation Feldspatic sandstone, shale, mudstone, coal: Vryheid Formation Shale, mudstone: Pietermaritzburg Formation	Late to Early Permian - 260 Ma
Dwyka	Tillite, minor sandstone and shale	Tillite, fluvioglacial conglomerate, varved shale; also drop stones	Early Permian to Late Carboniferous - 320 Ma

2.6 SOUTH AFRICAN PALAEO-GEOLOGY AND DEPOSTIONAL CONDITIONS

Data from over 1200 borehole logs were used to determine the palaeoenvironmental controls on coal distribution (Le Blanc Smith, 1980). The coalfield borehole cores drilled through the coal-bearing sediments of the Witbank Coalfield and many other coalfields show a distinct lack of uniformity.

Geological evidence indicates that vastly different climates prevailed in the coal areas of the southern and northern hemisphere during the later part of the Palaeozoic Era. In each of the southern continents the coal period followed closely after a great ice age. Following climatic amelioration during later Permian times, the ice sheet melted, and glaciogene sediments comprising outwash sands and gravel moraine predominated. During the Dwyka period the ice sheet moved across this landscape from the north, removing loose soil and polishing and striating the floor. Some of the ancient glaciated pavements can still be seen in the vicinity of the Witbank Collieries. The loose rock debris was dumped in ridges and mounds further to the south, and in out-wash plains of glacial till wherever the ice melted and as the ice sheet gradually retreated northwards. This moraine masked all except the projecting hills (ridges), but many badly drained basins (valleys) remained. Some were rock basins scooped out by the ice; other mounds of moraine acted as barriers and prevented free drainage. The landscape, in fact, must have resembled northern Canada or Siberia (Plumstead, 1957). A figure was included by Grobbelaar *et al.*, (1998) to show the ridges and valleys that formed in the Witbank Coalfield. See Figure 2-6 for the palaeodrainage channels and ridges of the Witbank Coalfield.

In the more sheltered of these drained basins, vegetation was established and gradually reached peat bog dimensions. These basins were small in extent at first, and had uneven floors, which were frequently interrupted by ridges. Some of these ridges can still be seen projecting through the coal measures, e.g. the hillocks of red Waterberg sandstone in the vicinity of Witbank and the partly covered ridge of felsite that marks the boundary between the Witbank and Bethal Coalfields. Others, which are lower, only interrupted the lower seams, which are often uneven and undulating with the irregularities of the floor.

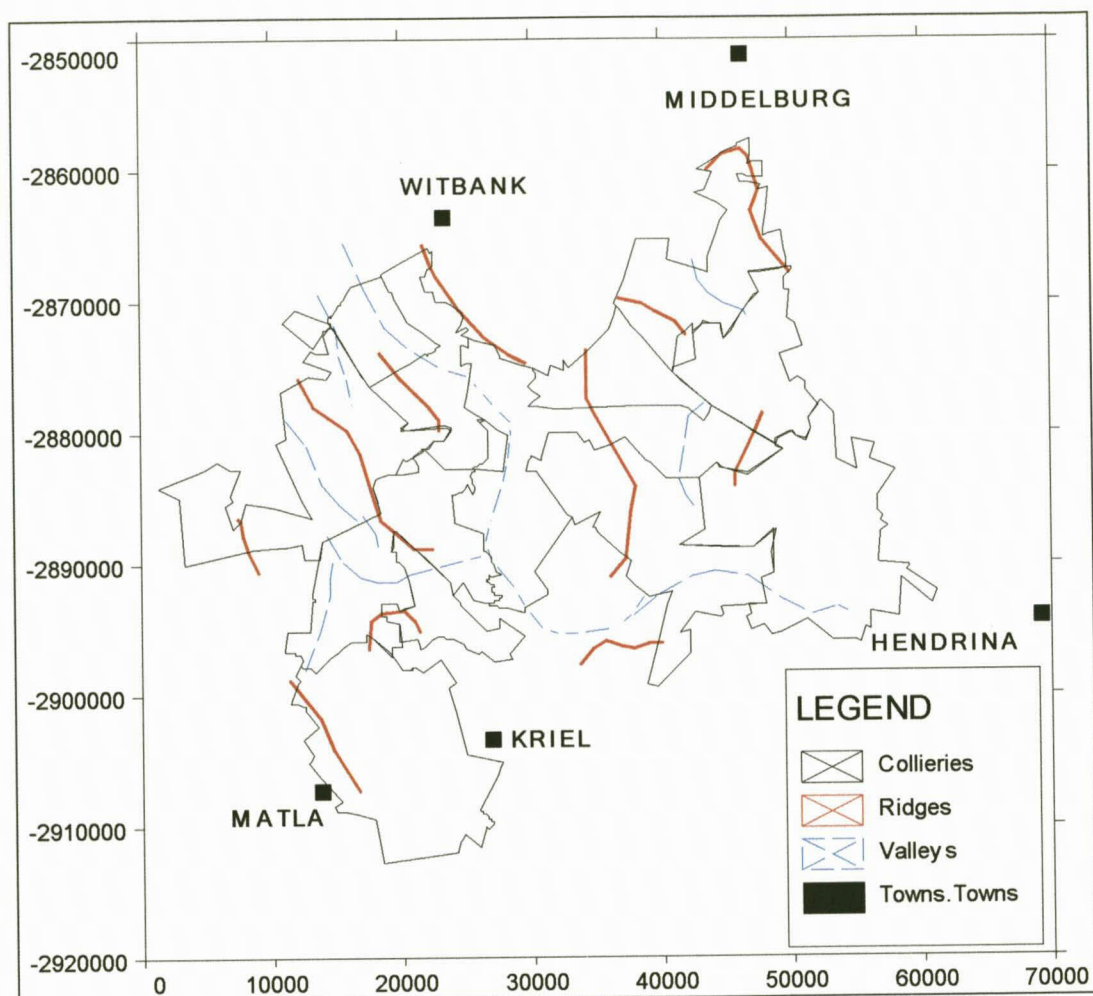


Figure 2-6 Paleodrainage channels and ridges of the Witbank Coalfield (from Grobbelaar et al., 1998)

The barren hills and the higher land strewn with glacial moraine would, for a long time, have supported co-vegetation, and in such a landscape the rain-wash would be unchecked by the plant cover (Plumstead, 1957). The soil erosion would be considerable and the streams and run-off water would sweep the unconsolidated products of glaciation into the low-lying basins where the peat was forming.

2.7 DWYKA SEDIMENTARY REGIME

The Dwyka glaciation started at latest during the Early Carboniferous and ended more or less during Early Permian. The magnetic pole movement during this interval was from the northwest, swinging to the southeast across southern Africa. This pole movement can be interpreted in terms of the drift of the African continent past the rotational pole. The Dwyka glaciation can thus be interpreted as a climatic response to the tectonic displacement of the continental plate (Rust, 1975).

During the later part of the Palaeozoic, the geomagnetic pole positions suggest that the climate in South Africa changed from glacial to periglacial (Figure 2-7).

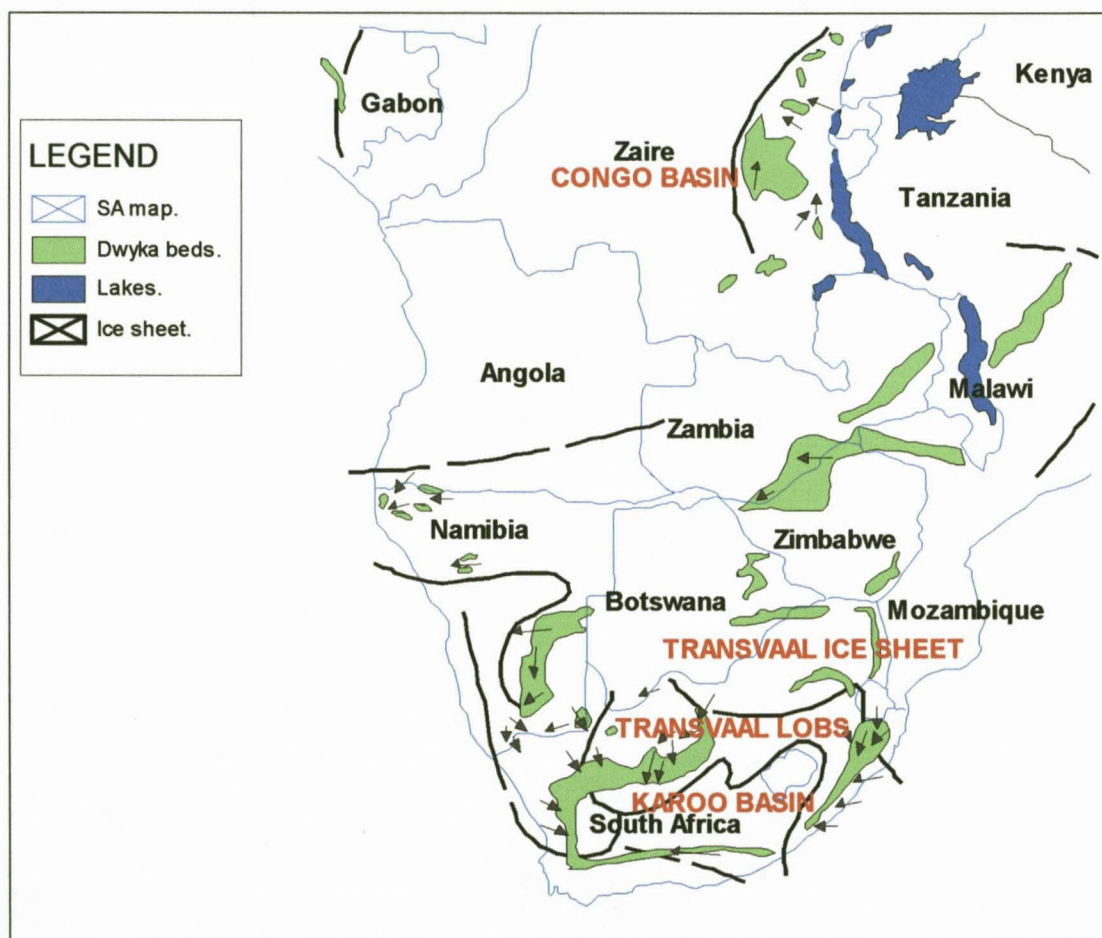


Figure 2-7 Late Palaeozoic glaciation in Southern Africa (from Rust, 1975).

A major ice sheet centered over Zambia, Zimbabwe and Mpumalanga and radiated several lobes (Figure 2-8).

Although this area was probably elevated somewhat, the topography was apparently fairly mature. Most workers report a topography of the order of 100 to 150 m or less, but others refer to it as 'rugged topography', 'very uneven', and even 'mountainous' (Rust, 1975).

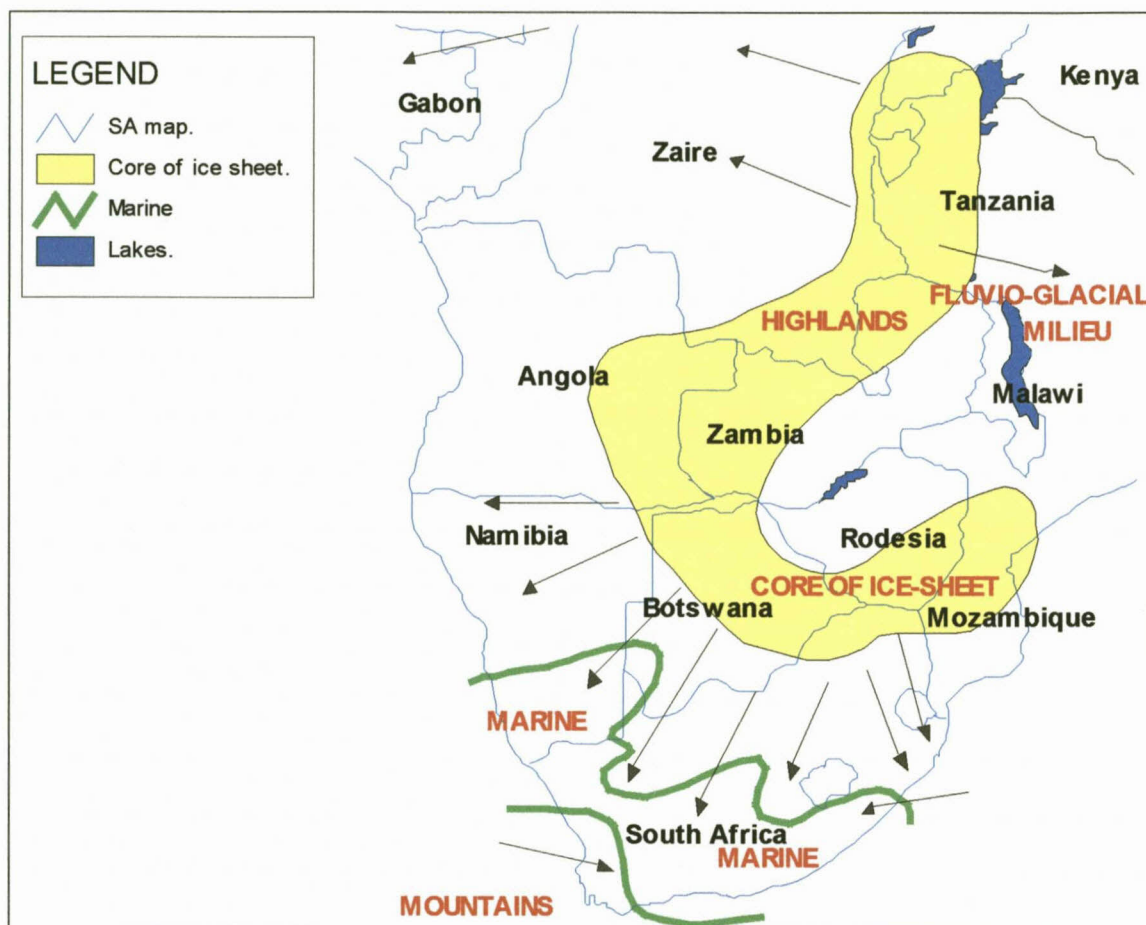


Figure 2-8 Dwyka glaciation. The central core of the Dwyka ice cap may have been continuous from the Congo to Rhodesia. A marine shelf environment existed to the south (from Rust, 1975).

Along the eastern boundary of the main Karoo Basin an ice center lay off the present coast of Natal. Likewise an extra-continental centre was developed on some presumably elevated land to the west of the Karoo Basin. In the case of the western source there is strong evidence that elevated land existed in that area from at least Ordovician to Early Devonian times (Rust, 1975).

The centres of deposition of glacial debris in central Africa were mainly determined by pre-existing drainage as well as lowlands produced by ice scouring. Several glacial advances and retreats have been recorded in various places and following the gradual

reduction of the ice load, caused extensive denudation and redeposition. Swamps formed in these lowlands where redeposition took place.

Major downwarps developed quite early in Dwyka time and paved the way for the accumulation of glaciogene sediments up to 1000 m thick. These sediments accumulated by various processes, such as ground moraines, end moraines, mud slumps, gravity slidings, rafting and fluvio-glacial processes.

2.8 THE ECCA SEDIMENTARY REGIME

The Lower to Middle Permian Ecca sequence consists of water-laid clastic sediments, part of which contains vast reserves of coal (Figure 2-9).

Ryan (1968) recognises three major facies in the Ecca of the type Karoo Basin and each of these facies can be subdivided vertically into three broadly similar lithologies: shale in the lower and upper units and sandstone in the middle unit. Although some regard the lower, middle and upper units as approximately isochronous, no reliable time-planes have been demonstrate so far (Rust, 1975).

The shape of the middle Ecca Coalfields is like a horseshoe, one tip lying near Ladysmith in Natal, curving northwards through Witbank at the apex, and swinging back through Vereeniging to reach the other tip of the horseshoe near the Free State Goldfields. The map of the Ecca (Figure 2-9) indicates that the location of the Lesotho rise was a controlling feature in determining the gross shape of the original coal swamp area.

It is important to know that the middle Ecca sediments were deposited under shallow-water fluvial conditions with an average sediment transport direction towards the west.

The tectonic framework of the Karoo tectono-sedimentary terrain during the Ecca time was essentially uncomplicated and similar to the situation that developed during the Dwyka time. Over most of the area mild tectonic movement was in the southern geosynclinal trough, and to a much lesser extent the Natal downwarp. The sedimentary environment varied appreciably, ranging from a typical turbidite environment to a coal swamp deltaic complex. Most of the Ecca sediments were deposited in a lake environment (Rust, 1975).

During Ecca times the sedimentary pattern was mainly of a delta-floodplain-lake type. The sedimentary cycles during Ecca times are interpreted as upward coarsening and upward fining respectively, as resulting from deltaic and fluvial deposition.

Based on the relative proportion of the deltaic and fluvial cyclic arrangements, the Middle Ecca is subdivided into (1) the lower delta-dominated succession; (2) a middle fluvially-dominated succession; and (3) an upper delta-dominated succession. As illustrated in Figure 2-10, upward-fining cycles occur above thick deltaic sequences. This is explained as resulting from incision and fluvial sedimentation following progradation. Superimposed delta sequences are probably a consequence of delta switching and subsidence followed by renewed progradation.

Coal in the Ecca Group of the main basin is restricted to the northeastern area of terrestrial deposition on a gently subsiding shelf platform. This proximal platform facies is represented by widespread, mainly coarse, fluviodeltaic sandstones, derived from the north, which become thin and eventually wedge out into siltstone and mudstone facies towards the south. Elongated valleys scoured into the pre-Karoo basement by the Dwyka glaciers and continental ice sheets determined the course of the southerly flowing rivers. After the northward retreat of the ice sheets these glacial valleys were dammed up by terminal moraines, and were partly filled by fluvioglacial sediments so that shallow proglacial lakes were formed, which in time were transformed into swamps. This resulted in the formation of the lower coal seams. In the Witbank, Free State, Vereeniging-Sasolburg, South Rand and Highveld Coalfields the lowermost seam generally occurs close to the scoured pre-Karoo floor, and may even lie directly on the sediments of the Dwyka Group. The topography of the pre-Karoo floor thus played a crucial role in determining the distribution of the lower seams and their associated clastic rocks, and the lower seams narrow towards and eventually pinch out against palaeohighs.

The topography of the Dwyka is therefore still a crucial factor in the current hydrogeology of the area. The floor of the coal seams is the initial control on water build-up, during the initial stages of water accumulation. The shape of the pre-coal environment is thus of utmost importance for current understanding.

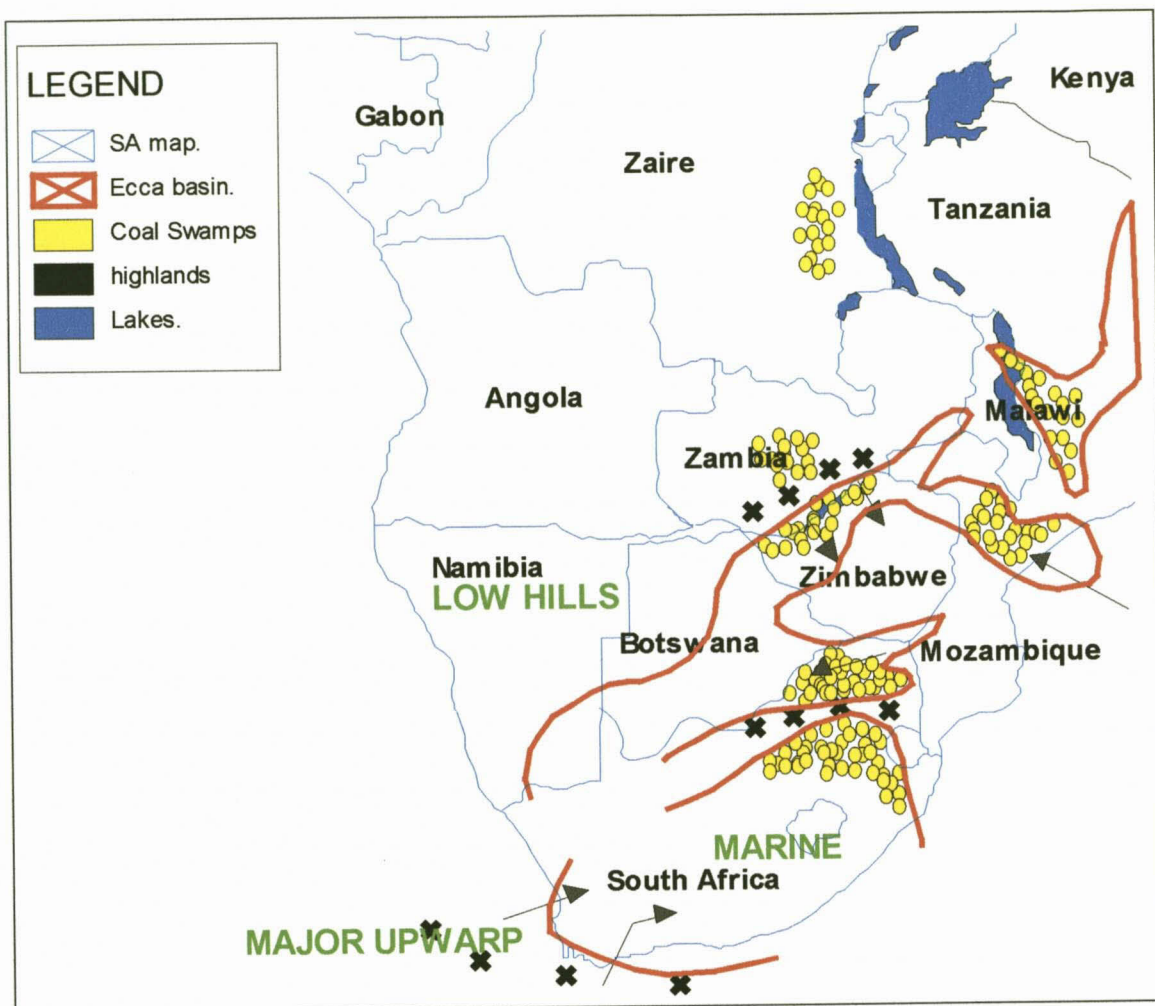
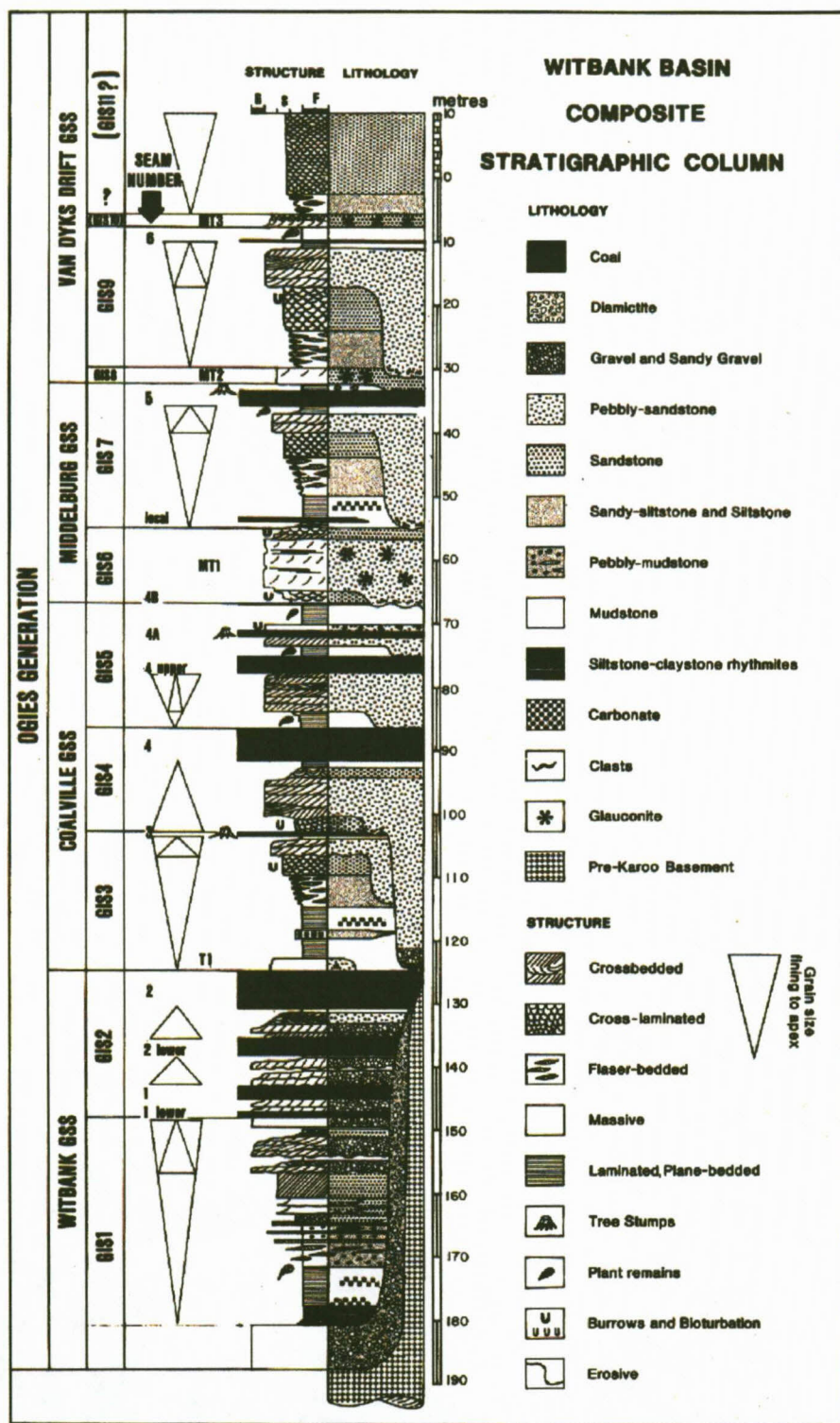


Figure 2-9 Ecca Basin. The tectonic situation of the Ecca Basin is dominated by major upwards movement in the extreme south, in the Transvaal Highlands. A flysch environment developed in the southern marine embayment but elsewhere coal swamps were widespread (from Rust, 1975).



2.9 THE DEPOSITION OF SEAMS

2.9.1 Seam information

Mellor (1906) established the nomenclature of the five seams, as they are known today, and recognised many of the more important stratigraphic, sedimentary, and structural features of the rocks (Smith and Whittaker, 1986).

The five classically recognised coal seams of the Witbank Coalfield, numbered from the base up as Nos. 1, 2, 3, 4 and 5 respectively, are contained within a 70 m succession. The succession consists predominantly of sandstone with subordinate siltstone and mudstone.

The parting thickness between the seams remains remarkably constant over most of the field, but towards the northern limits of the coalfield, stratigraphic units become generally thinner.

Within the main basin the number of coal seams in the Witbank Coalfield varies from one coalfield to another, and although individual coal seams cannot always be correlated, it is possible to correlate smaller depositional sequences, based on upward-fining (fluvial) and upward-coarsening (deltaic) cycles.

In the Witbank Coalfield the lowermost seam generally occurs close to the scoured pre-Karoo floor, and may even lie directly on the sediments of the Dwyka Group. The topography of the pre-Karoo floor thus plays an important role in determining the distribution of the lower seams (Snyman, 1998).

2.9.1.1 Number 1 Seam

The No. 1 Seam is the least important of the four economically mineable seams (See Figure 2-11 and Figure 2-12 for detail). In general, the No. 1 Seam is patchily developed and thin. It represents about 2% of the *in situ* demonstrated resources in the coalfield. The seam consists of lustrous to dull coal with local shaly sandstone partings, giving rise to a local No. 1 Lower Seam.

The seam at Kleinkopje and Rietspruit is a source of high-grade steam coal, suitable for export after beneficiation. In the future, this seam could also provide a feedstock of low ash coal for farmed coke production.

2.9.1.2 Number 2 Seam

The No. 2 Seam is located mainly in the north-central part of the basin near Witbank Mellor (1906). The No. 2 Seam is divided into 0,3m of silky, dull "gas" coal at the base, overlain by 1m of bright, low-ash "smithy" coal and 1 to 2m of "splinty" dull coal, followed by approximately 3m of "upper" banded steam coal. At present these zones in the No. 2 Seam still play an important role in the production of metallurgical coal, and export and domestic steam coal (Smith and Whittaker, 1986).

In the Witbank Coalfield the No. 2 Seam has been the most extensively mined and remains the most economically important coal seam. It contains some of the best quality coal, and some 69% of the *in situ* demonstrated resources in the coalfield (See Figure 2-11 and Figure 2-12 for detail).

In the main central part of the coalfield, the seam averages approximately 6,5m in thickness. In the Witbank area it displays well-defined zoning, with up to 5 zones of coal of differing qualities. The three basal ones are currently being mined to a height of approximately 4m at mines such as Landau and Greenside, for the production of low ash metallurgical coal, and steam coal for export. Patches of thicker coal (up to 10m) occur mainly to the south of the Ogies Dyke.

Underground mining conditions are usually good with 1 to 2m of coal being left in the roof. When true roof shales are exposed it can cause poor conditions in the mine, e.g. collapsing of the mine roof. In the eastern part of the field, where the seam is thinner locally, due to widespread regional scouring, the roof beds are competent sandstones. Here, underground mining problems have been encountered where seam thickness varies markedly over short distances (Smith and Whittaker, 1986). The distribution and altitude of the No's. 1 and 2 Seams are largely determined by pre-Karoo topography.

2.9.1.3 Number 3 Seam

The thin No. 3 Seam (usually less than 0,5 m thick) has been considered uneconomic in the past.

The No. 3 Seam is commonly absent from the stratigraphic record in the study area. In such cases, the stratigraphy reflects a continuous sedimentary sequence from the No. 2 Seam into the sandstone floor of the No. 4 Seam (Cairncross and Cadle, 1987).

Distinguishing the No. 3 Seam from local splits of the No. 4 Seam is difficult, as the No. 3 Seam is not always present. Crossbedded sandstone separates the No. 3 Seam from the No. 4 Seam, and where the No. 3 Seam is absent, a stratigraphically equivalent

carbonaceous siltstone is present. This No. 3 to No. 4 Seam parting averages 5m in thickness and exceeds 12m in places.

2.9.1.4 Number 4 Seam

The seam varies in thickness from approximately 2.5m in the central Witbank area to over 6.5m elsewhere (See Figure 2-11 and Figure 2-12 for detail). The seam contributes about 26% of the *in situ* demonstrated resources. The coal is predominantly dull.

The seam contains numerous shale and sandstone partings. In addition to the No. 4 Seam, the coal zone generally contains a 4 Upper and 4A Seam, neither of which are at present of economic importance, due to their thinness, sporadic development, and poor quality.

The mining horizon is generally restricted to the lower 3,5 m of a 5 m seam because of the poor quality of the upper section and mining roof, if the normal shale roof is exposed.

The coal is most suitable as power station feedstock. It is also sold as domestic steam coal by some of the producers (Smith and Whittaker, 1986).

The most distinctive and widespread component of the No. 4 Seam sequence is the upward-coarsening sequence, which comprises, from the base upwards, carbonaceous siltstone, argillaceous lenticular laminated siltstone-sandstone, interlaminated siltstone-sandstone, and medium-grained cross-bedded sandstone, capped by either the No. 3 or No. 4 Seams.

The No. 4 Seam is composed of coal up to 2 m thick, which can be split into several sub-seams, or may be absent from the geological column. Seam splitting is erratic and occurs over distances of less than 1 km. These intra-seam partings comprise carbonaceous siltstone, which has gradational contacts, above and below, with No. 4 Seam splits (Cairncross and Cadle, 1987).

2.9.1.5 Number 5 Seam

The No. 5 Seam accounts for about 4% of the *in-situ* demonstrated resources in the Witbank Coalfield. It consists predominantly of bright coal, and has an average thickness of about 1.8 m. It has been extensively eroded over large areas (See Figure 2-11 and Figure 2-12 for detail). The seam is approximately 1.8 m thick in areas currently being mined, and seldom attains a thickness in excess of 2 m. The seam consists of mixed, mainly bright, banded coal, with thin shale and mudstone partings in a few localities. The

laminated sandstone roof usually constitutes a fair to weak mining roof, requiring extensive support.

The No. 5 Seam sequence consists of the strata from the top of the No. 4 Seam to the top of the No. 5 Seam and above. The lithologies separating the No. 4 Seam from the No. 5 Seam consist of massive granulestone-sandstone, cross-bedded granulestone, cross-bedded sandstone and lesser amounts of interbedded carbonaceous siltstone. Planar cross-bedding is the dominant sedimentary structure and stacked, erosively based upward-fining sequences constitute up to 15 m of this interval.

In the eastern part of the study area there are several areas where the No. 4 Seam or No. 5 Seam are not present. This is due to two factors: (1) non-deposition of peat in these areas, and (2) erosion of these coal seams by the overlying stacked upward-fining sedimentary rocks (Cairncross and Cadle, 1987).

The No. 5 Seam is mined as a source of blend coking coal for Iscor and other metallurgical coal users.

The higher rank coals ($R_oV_{rand} > 0,7\%$) occur in two arcuate zones, convex towards the southeast; one runs from Ogies through Greenside Colliery to Witbank and the other from Rietspruit Colliery through Goedehoop Bank Collieries to near Middelburg (Snyman, 1998).

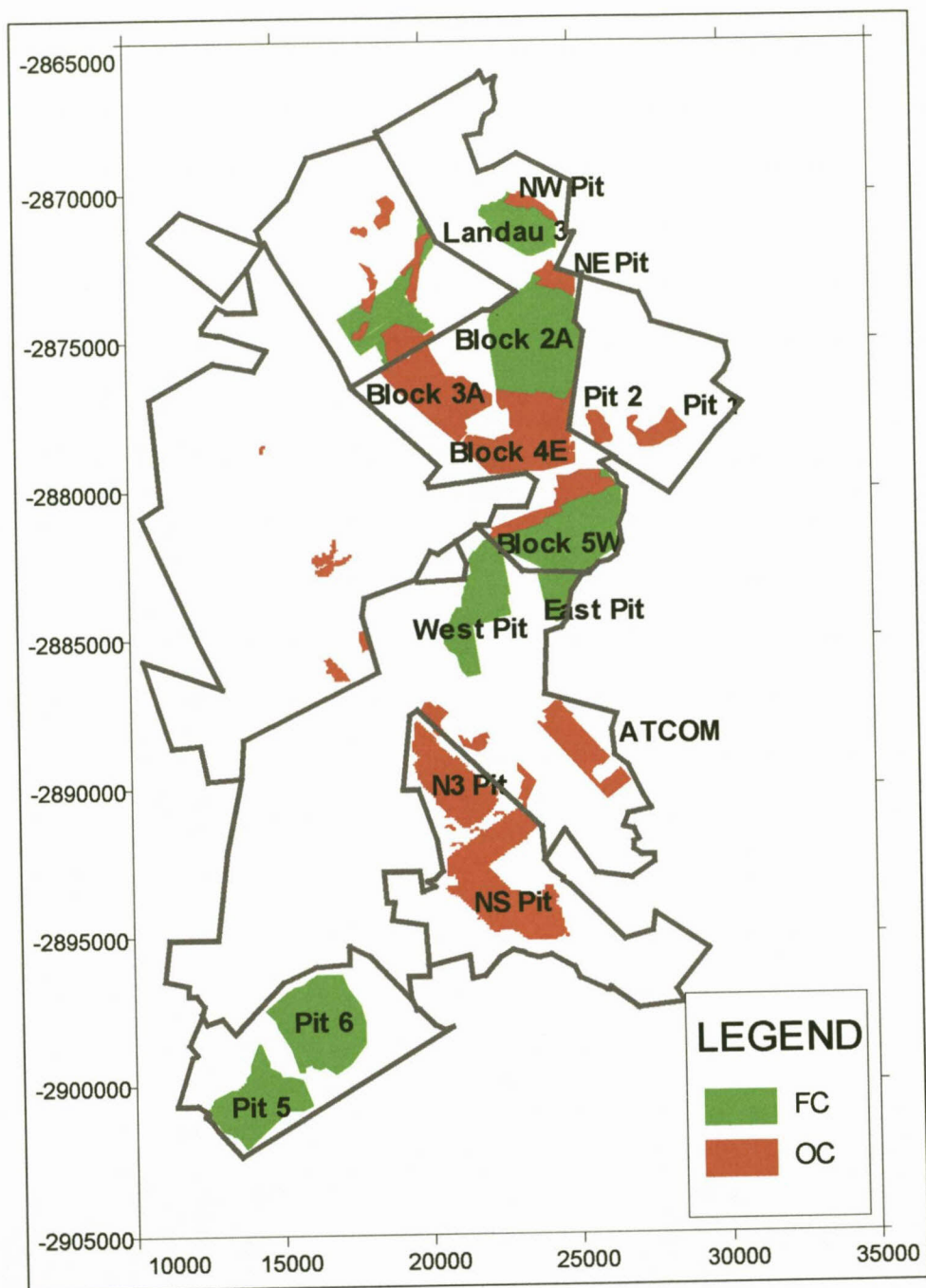


Figure 2-11 Opencast and future opencast mining in the Western Witbank Collieries.

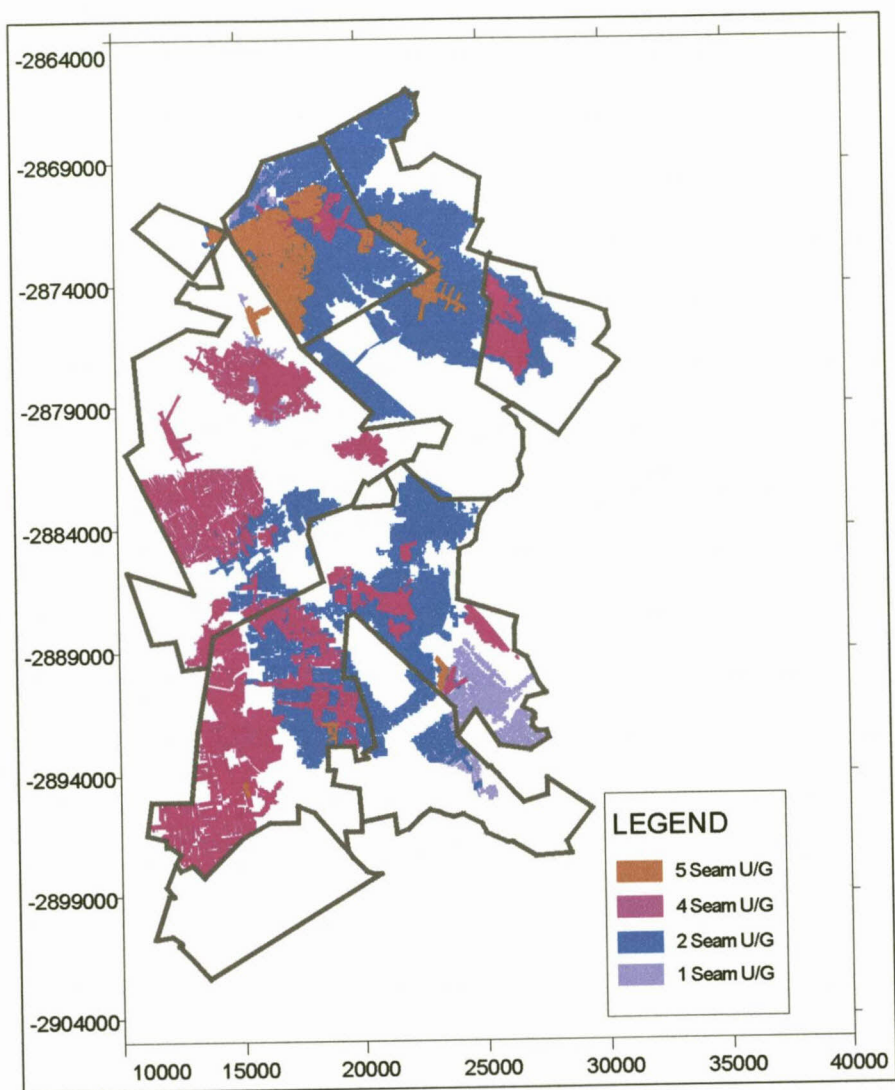


Figure 2-12 Underground mining in the different seams in the Western Witbank Collieries.

2.9.2 Palaeogeographic synthesis of the deposition of seams (from Cairncross and Cadle, 1987).

The sequence of depositional events that took place in most of the coalfields of South Africa can be classified into several terrigenous clastic pulses punctuated by periods of low clastic deposition. These periods were characterised by the accumulation and preservation of vegetation resulting in the formation of coal seams.

After the northward retreat of the ice sheets, coarse-grained sediments were transported into the basin from northern and northwestern granite source terrains. The bedload dominated glaciogene fluvial systems deposited sediments as a blanket-sand sheet over the underlying pre-Karoo basement and Dwyka diamictite. Channelised glaciofluvial systems transported boulders, gravel and coarse sand into the basin. This northward retreat is important to note since previous workers, e.g. Grobbelaar (2001) intimated that the paleochannels were in a north-south direction.

The abandonment of the river system that perhaps caused by the encroachment of vegetation and accumulation of peat, gives rise to the No. 1 Seam (Figure 2-13 A) (Cairncross and Cadle, 1987).

A short period of instability related either to short-lived basin subsidence and/or transgression, caused the drowning of the No. 1 Seam peat. This led to the spread of a thin, but laterally persistent veneer of transgressive granulestone over the peat surface.

Ephemeral fluvial activity transported coarse to very coarse sand and granule grains across the No. 1 Seam peat (Figure 2-13 B). The temporary clastic influx soon succumbed to swamp impingement and swamp vegetation. This gave rise to the deposition of the No. 2 Seam peat.

Unlike the deposition of the No. 1 Seam when the peat-swamp was relatively free of clastic contamination (and hence, seam splitting), the No. 2 Seam contains numerous dispersed as well as laterally persistent partings. These are related primarily to a low-sinuosity fluvial system. This system invaded the peat swamp from the northwest and deposited channel sand and associated overbank sediment into the adjacent backswamp (Figure 2-13 C). Vertical profiles and lateral geometry of the channel sand typifies bed-load braided river deposits. This resulted in the anomalous situation of a braided river system. Easily erodable banks, impounded by vegetation, stabilised channel margins, characteristically flank this system. The lateral migration of the system will be reduced and deposition results from vertical accretion within the channel. Smaller scale fluvial channels occur elsewhere in the No. 2 Seam. This is interpreted as anastomosed river deposits. It is therefore proposed that the larger-scale braided

channel represents the upstream equivalent of the smaller anastomosed channels located further into the basin. As the gradient, flow velocity and carrying capacity of the system diminished, this trunk stream would have digitated into a network of subsidiary anastomosed channels.

Following the abandonment of the fluvial sequence in the study area, vegetation encroached over the channel sand to form the No. 2U Seam peat. Plants, however, did not colonise the elevated areas of maximum channel-fill, but contained a highly carbonaceous siltstone instead. The non-colonisation of these topographically high areas may be attributed to the preferential zonation of vegetation and peat within swamps. This is a fairly common phenomenon in swamps.

The vertical decrease in the coal quality and the transformation of the uppermost peat to highly carbonaceous siltstone can be attributed to a gradual but continuous drowning of the No. 2 Seam swamps (Cairncross and Cadle, 1987). The water depth remained relatively shallow during this time while the disseminated plant debris associated with this unit attest to a nearby continental source.

An interesting focus for further research would be to ascertain the mineralogical variation in the No. 2 Seam. If the minerals are distributed variably due to their depth of burial beneath a fluctuating, paleo-water table, zones of variable acid and neutralisation potential might exist. This could provide targets for selected handling or mining of different horizons.

A major regressive deltaic progradation succeeded the basinal transgression above the No. 2 Seam (Figure 2-13 D). A sequence of depositional events from fine-grained lower delta-plain deposits is overlain by transitional delta-plain, to upper delta-plain and fluvial systems.

The No. 4 Seam sequence formed as a result of lower to transitional delta plain progradation. This process produced an upward increase of sand within the sequence. These deltaic deposits were fluvially dominated and probably resembled the short-headed stream deltas. The coarse-grained sandstones which overlie the No. 4 Seam and No. 5 Seam sequence, represent fluvial plain deposits. These deposits migrated basinward across the underlying deltaic platform.

Climatic constraints played a significant role; cool temperate climate deltas for example typically consist of braided fluvial channels characterised by high bed-load to suspended-load ratios.

Above the No. 4 and No. 5 Seams, shallow-water, high-constructive lobate deltaic deposits are present.

In some parts of the Witbank Coalfield, glauconite is absent in the strata immediately above the No. 4 and No. 5 Seams. This suggests essentially non-marine conditions during the deposition of this sedimentary sequence. The fluvial plain, in this particular location, was most likely beyond the reach of the marine transgressive processes responsible for glauconite deposition. For the rest of the Witbank Coalfield glauconite is present above the No. 4 and No. 5 Seams, which can be interpreted as marine transgressive deposits.

If more detailed sampling of water encountered is done as mining progresses, regional trends attributable to these different paleoclimatic conditions could provide clues for observed hydrochemical trends. Thus the apparent enrichment of sodium in a southerly direction as alluded by Hodgson (1999) and Hodgson and Krantz (1998) could be explained by the marine or non-marine nature of the sedimentation and the depth or burial in the geologic past, relative to present shallow aquifers, or by ion exchange reactions as referred to earlier.

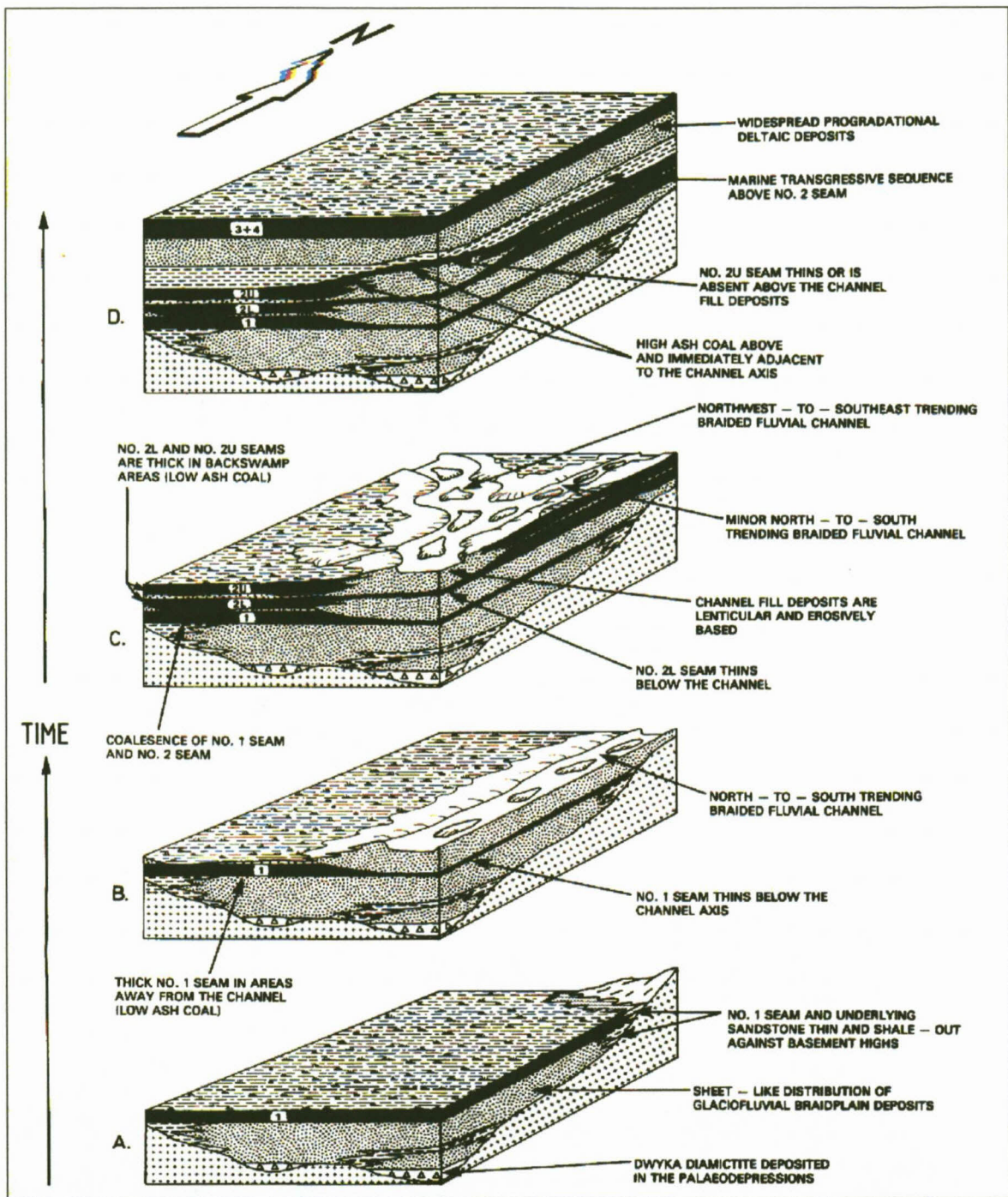


Figure 2-13 Reconstruction of the depositional events from the pre-Karoo basement to the No. 4 Seam (from Cairncross and Cadle, 1987).

2.9.3 Structural intrusions

The coal seams in the Witbank Coalfield are mainly flat to gently undulating, with a general southerly dip of about 1 in 100. Coal seam topography and aerial distribution are commonly controlled by pre-Karoo topography. Steep dips of as many as 1 in 8 are encountered where seams abut against pre-Karoo hills, such as the No. 2 Seam at Greenside and Landau (Kleinkopje) Collieries (Smith and Whittaker, 1986). Figure 2-14 represents the palaeo hills and channels in the Greenside and Landau area.

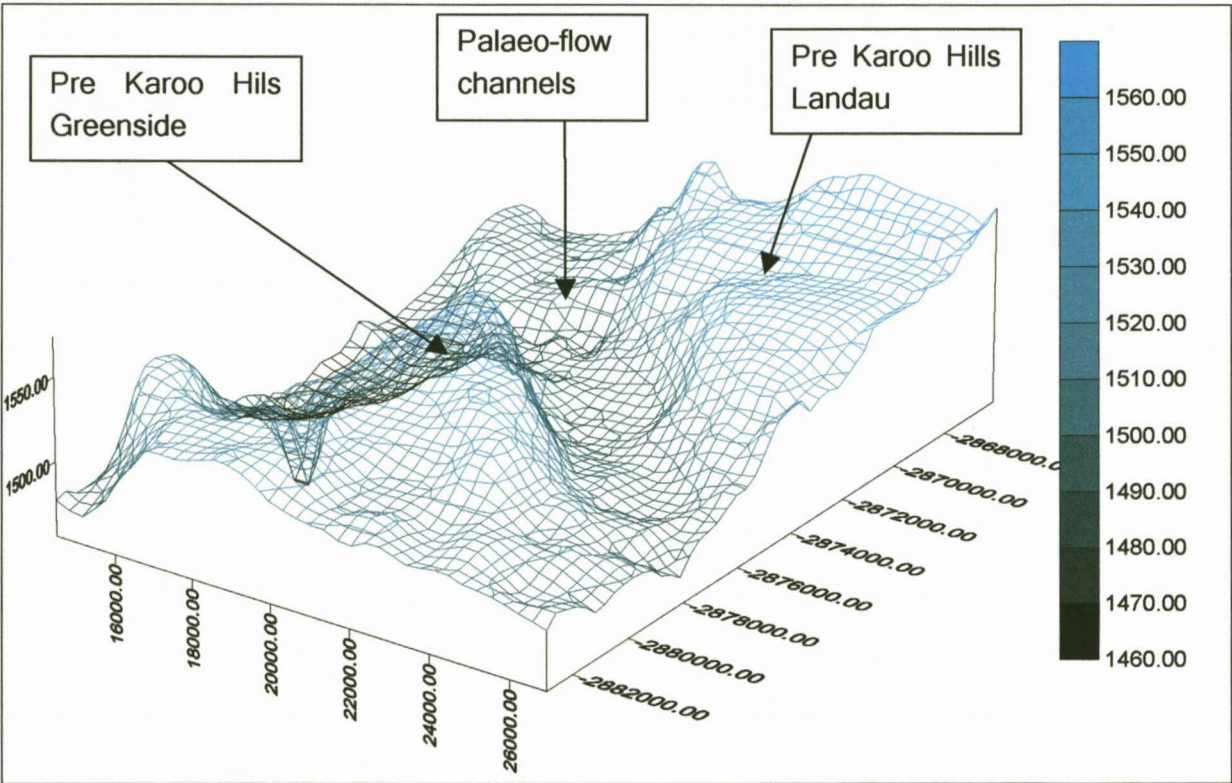


Figure 2-14 Palaeo Hills and channels in the Greenside Landau area.

The Karoo strata in the Springs-Witbank Coalfield are virtually unfolded and have not been subjected to marked displacements, except where they are transgressed by dolerites. Small faults with throws of less than 0.5 m are rare and faults with throws larger than this, exceptional. Where faulting does occur in the coal seams it is usually associated with steeper dips on the flanks of pre-Karoo valleys or hollows such as those occurring where dolomite comprises the basement immediately below the lower seams in the Springs area (Smith and Whittaker, 1986). This is important in the currently observed flows, since folding/faulting may have enhanced vertical K-values and modified the regional flow hydraulics.

Dolerite intrusions in the form of dykes and sills have adversely affected some areas of the coalfield. Large areas of coal seams have been burnt and rendered useless for exploitation, and the intrusions have caused significant displacement of seams, which seriously affects mining in many areas. Dykes are ubiquitous throughout the area. The main trends of the dykes are east, northeast and north.

The most prominent of all the dykes is the Ogies Dyke. Figure 2-15 shows the location of the Ogies Dyke, which has been traced on surface over a strike length of approximately 100 km, and is about 15 m thick. It strikes west-east, extending from Ogies in the west to the south of Arnot Colliery in the east. This dyke is approximately 15 m thick. The sediments in this area are folded within 20 m on either side of the dyke, which is near-vertical. The Ogies Dyke devolatilised 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.

To the north of the Ogies Dyke small dykes and sills are less common than to the south. In mine workings to the north of the Ogies Dyke, dykes are commonly 0,5 to 1 m thick, with two preferred orientations north and northeast. To the south, dykes up to 5 m thick have been traced over relatively longer strike distances, and their orientation is predominantly east-west, with subordinate northeast and northwest orientations. The dykes at Riespruit and Tavistock Colliery are all northeast oriented. the dykes are located in the South Pit and the underground workings of Rietspruit and Tavistock. The dykes in the opencast mines were mined with the coal, but in the underground areas parts of the dykes have been left in place, while the others were extracted with the coal. This coal that is left in place can for example cause an underground area to fill irregularly, because water will be sealed or blocked in some compartments.

Dolerite dykes are less common in the Springs area and the eastern part of the Witbank Coalfield. Burning associated with dykes varies considerably. Elsewhere dykes have burnt zones of less than 10 m wide with a maximum width of about 100 m. The width of a burnt zone does not necessarily relate to the thickness of the dyke. The degree of burning is influenced by factors such as temperature of intrusion, period of molten flow and attitude of intrusion.

Dolerite dykes can act as impervious (solid) or semi-impervious (eroded) boundaries. Groundwater will normally dam against the barriers, but in some places the dykes can be fractured or mined through and can cause water to flow through freely.

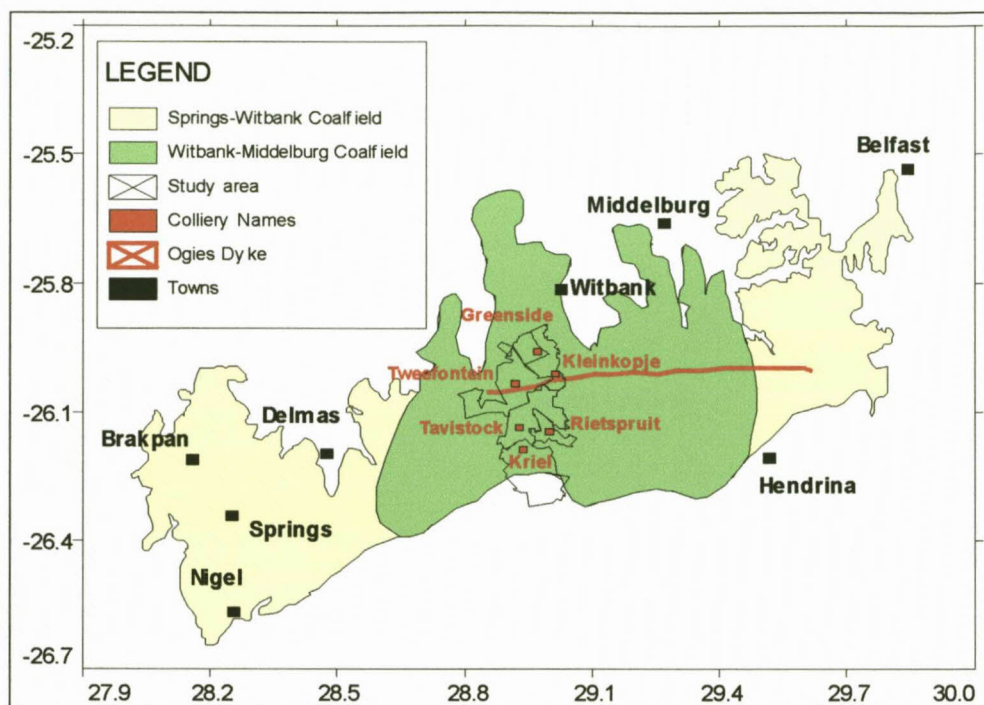


Figure 2-15 General location plan of the Coalfields. The figure also shows the exact position of the Ogies Dyke (From Smith and Whittaker, 1986).

Dolerite sills, which are both conformable and transgressive in attitude, probably underlay the whole of the coalfield prior to erosion. As with the dykes, sills are more numerous south of the Ogies Dyke in the central part of the coalfield. The non-porphyrific sills attain a thickness of up to 50 m, in places comprising a series of splits of up to 25 m individual thickness. The porphyritic sills, generally about 15 m thick, occur preferentially in the west-central part of the field.

As illustrated in Figure 2-16 and Figure 2-17, the dolerite sills commonly transgress the strata comprising the coal measures. The resultant tilting and displacement of coal seams has had serious consequences for mining, particularly where blocks of coal are present at different elevations. The amount of displacement of a coal seam by a transgressive sill is usually equivalent to the thickness of the sill. The degree and extent of coal burning associated with sill intrusion presents a more serious problem to mining and coal resource estimation than that resulting from seam displacement. On some mines and undeveloped coal properties, as much as 20% of the *in situ* coal may have been destroyed. Sills underlying seams appear to have had a more destructive effect than overlying sills of similar thickness and distance from the seam.

2.10 MINING METHODS

Coal extraction has been ongoing in the Mpumalanga Coalfields for more than 100 years. At first, mining was mainly to the west of Witbank. Many of these mines have already closed down.

Through the years, mining extended from its original position to the south and east. Many new collieries commenced with mining, particularly during the past 30 years. Since 1970, mining has increasingly been mechanised. Different mining methods have been used at all the coalmines over the past thirty years. Mining methods are usually chosen as a function of seam thickness and mining depth. The three major mining methods in South Africa are:

- Bord-and-pillar extraction (Figure 2-18),
- Underground high extraction through longwall and shortwall methods and
- Opencast mining, using openpit and strip mining (Figure 2-19).

In the study area, bord-and-pillar and opencast mining are the dominant mining methods.

Initial underground mining was relatively shallow, in the range of 10 - 50 m below surface. Mining was mainly through underground methods. Access to the underground workings was commonly through inclined shafts.

The coal seams deepen toward the south. Access to the deep mines is through vertical shafts.

Bord-and-pillar is one of the major underground coal mining methods used in South Africa (Snyman, 1998). In bord-and-pillar mining coal pillars are left as support, although they may be extracted at a later stage.

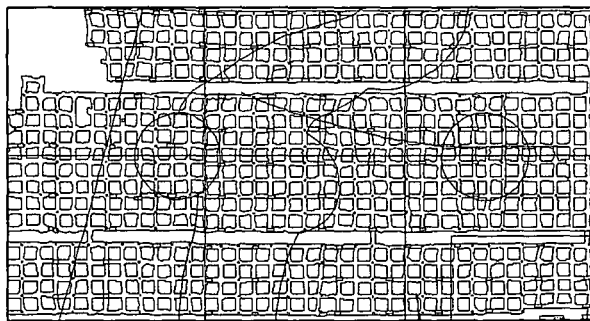


Figure 2-18 Example of bord-and-pillar mining in a modern underground colliery.

Two opencast methods are used, viz. open-pit and strip mining (Snyman, 1998). In the present study area open-pit mining is dominant. In open-pit mining a large hole is excavated to expose the coal. The hole is enlarged in whatever direction is necessary to expose more coal as the coal itself is extracted. The overburden is dumped at a suitable spot that is not underlain by coal. To ensure the stability of the sides of the pit, the overburden is removed in a series of benches, the width and height of which depend on the properties of the overburden.

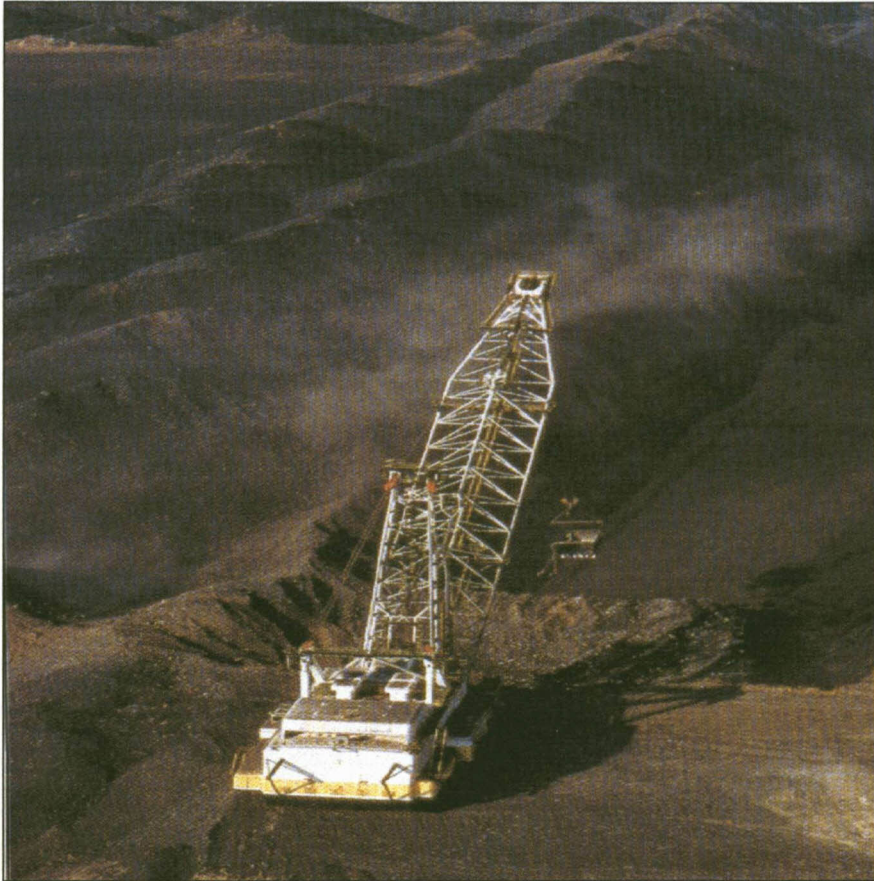


Figure 2-19 Dragline mining in an opencast pit (from Snyman, 1998, Optimum Colliery).

The choice of mining method is primarily a function of seam thickness and mining depth, but geological factors play a very important role, e.g. a very dislocated field with fairly shallow coal could render even opencast mining uneconomic.

Geological factors affecting the choice of mining method include the following (Snyman, 1998):

- Thickness of the overburden; in the case of bord-and-pillar mining the percentage extraction decreases with increasing depth and above a certain thickness of overburden total extraction can be considered, provided

cognizance is taken of possible damage to surface structures and of the effect on the water table due to carving;

- Thickness of the partings between the seams; in general the upper seams are extracted first, and in the case of bord-and-pillar mining interpanel pillars should be superimposed;
- Seam thickness,: seams between 0.75 and 3.5 m in thickness can be mined in stages by means of either top or bottom coaling, but substantial variation in seam thickness may result in coal losses, due to the unsuitability of available equipment;
- Variations in the elevation of the seam floor due to palaeotopography or displacement of the seam affect mine planning and mining methods, as mechanical miners in general cannot operate on inclinations of more than 1:4 and for some types of equipment the inclination restrictions may be considerably less;
- Floor rocks such as mudstones may lead to an uneven, slippery floor, which adversely affects the operation of mechanised equipment;
- In-seam partings and coal wash-outs (rock-rolls) lead to accelerated wear and tear on coal cutting equipment, especially picks, and also enhance the possibility of underground gas explosions as a result of frictional heat;
- Weak roof rocks such as thinly bedded, poorly cemented sandstone and slaking mudstones, immediately above the seam, obviously create roof problems;
- Pronounced discontinuities, such as faults, dolerite dykes and cross-cutting dolerite sills break up the coal reserves into smaller, irregular blocks, eventually making some mining methods like longwalling and the use of continuous miners impractical. Dolerite intrusions devolatilise the coal, and in some cases nature coke is formed at contact with the dolerite, adversely affecting its strength close to the contact. In many instances this changes the dolerite to so-called white trap by the assimilation of carbonaceous material, which results in the formation of various carbonate and clay minerals such as calcite, siderite, dolomite and kaolinite, thus leading to the lowering in strength of the altered dolerite. This process is vital into the overall neutralisation potential of the strata.

The composition and thickness of the roof strata, especially dolerite sills, determine the way in which mining-induced stresses are redistributed, and thus influence overall mine design and layout.

A short description of the different mining methods practiced at the western Witbank Coalfield is provided below.

2.10.1 Kleinkopje

There are four economically exploitable seams present, namely the No.1, No. 2, No. 4 and the No. 5 Seams. Coal is presently mined by opencast operations at Kleinkopje Colliery.

The Kleinkopje coal reserves are mainly contained in the No. 1 and No. 2 Seams. The No. 5 and No. 4 Seams are present in the deeper parts of the Landau III and Block 2A areas.

The Landau I and II areas were previously mined by underground methods and the No. 2 and No. 5 Seams are mined. The underground bord-and-pillar mining operations at the Landau III Colliery ceased during 1991 (see Figure 2-20 for details). The NW and NE minipits were mined by opencast methods. Mining in these pits stopped in 1989 and 1993 respectively.

Current opencast mining is performed in the Block 2A, 3A, 4E and 5W area, and opencast stripping currently takes place in Block 2A, 3A and 5W.

The life of Kleinkopje Colliery is expected to terminate in 2025, based on the present definition of economic reserves within Block 2A and 5W. Additional coal reserves are situated north of Block 2A and Block 3A (EMPR, 2001).

Statistics show that 989.4 million tons of coal was produced at SACE (Kleinkopje and Greenside Colliery) in 2000 (Chamber of Mines).

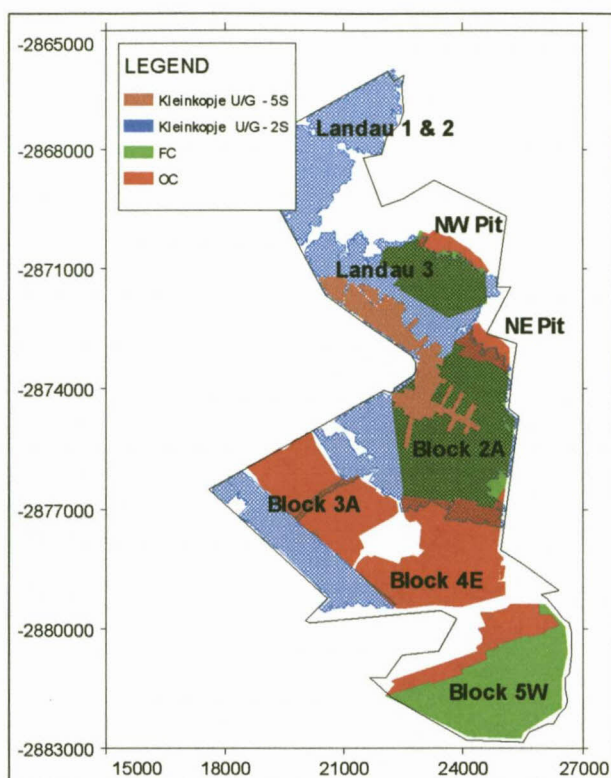


Figure 2-20 Seams mined and mining methods used at Kleinkopje Colliery

Table 2-2 gives a summary of the seams mined and mining methods at Kleinkopje Colliery.

Table 2-2 Summary of the seams mined and mining methods at Kleinkopje Colliery.

Kleinkopje	Mining method	Area (Ha)
Kleinkopje OC		3545
Kleinkopje UG 2S	bp	3426
Kleinkopje UG 5S	bp	354

2.10.2 Tweefontein

At Tweefontein the Nos. 1, 2, 3, 4 and 5 Seams are presently being mined. Bord-and-pillar is the principle mining method. Tweefontein Colliery has an expected lifespan of 14 years. The life span of the colliery could be extended by 5 years if additional reserves are extracted from abandoned workings by removing the pillar structures and using opencast methods (EMPR, 1995) (See Figure 2-21 for details on mining methods and seams mined in the areas).

Tweefontein Colliery produced 360.9 million tons of coal in 2000.

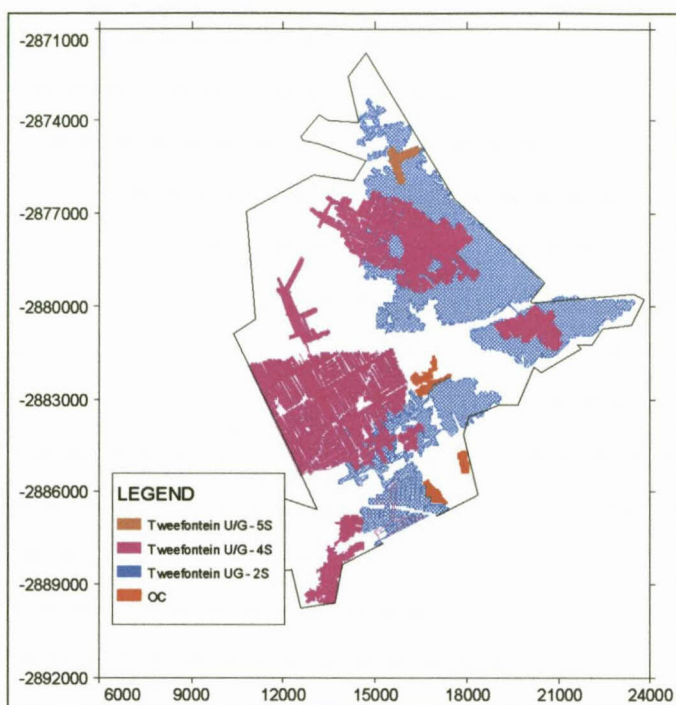


Figure 2-21 Seams mined and mining methods used at Twefontein Colliery

Table 2-3 gives a summary of the seams mined and mining methods at Twefontein Colliery.

Table 2-3 Summary of the seams mined and mining methods at Twefontein Colliery.

Twefontein	Mining method	Area (Ha)
Twefontein OC		89
Twefontein UG 1S	bp	315
Twefontein UG 2S	bp	602
Twefontein UG 4S	bp	3063

2.10.3 Tavistock Colliery

Five coal seams are present in the Tavistock Colliery area. These have dominantly been mined by underground methods. Two of the seams, namely the Nos. 2 and 4 Seams, are mineable over most of the area. The Nos. 1 and 5 Seams occur in mineable thicknesses in certain portions of the area.

Mining has been on the No. 4 Seam in the Arthur Taylor and South Witbank area.

Tavistock Colliery plans to mine the northern portion of their reserves by opencast methods. The northern portion will be known as the Northern Pit, which will consist of

two pits, namely a West and an East Pit. These two pits will be linked on the No. 2 Coal Seam horizon by existing mining (Hodgson and de Necker, 2001).

The North Pit (West and East Pit) at Tavistock Colliery will mine into an underground bord-and-pillar area. In terms of future mining prospects, Tavistock's coal reserves are vast. Mining at Tavistock Colliery is likely to continue for at least another 15 to 20 years (see Figure 2-22 for details on mining areas).

Analyses from the Chamber of Mines (2000) indicate that approximately 416.9 million tons of coal was mined in 2000.

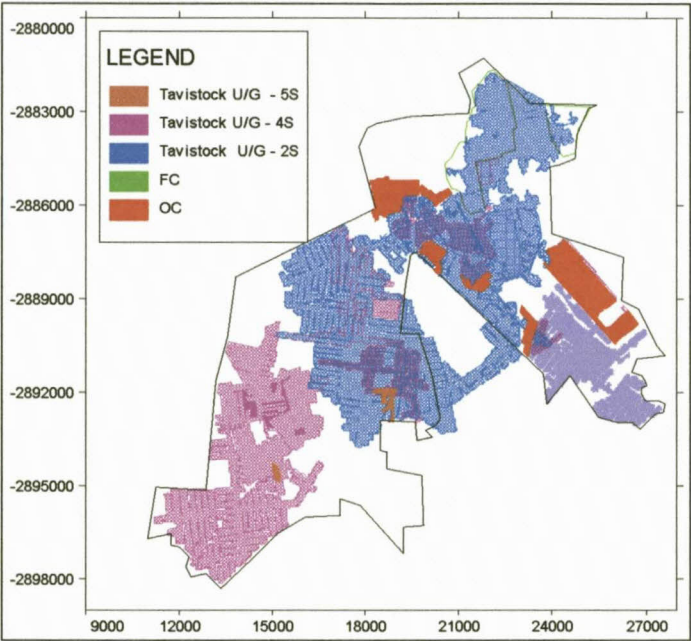


Figure 2-22 Seams mined and mining methods used at Tavistock Colliery

Table 2-4 gives a summary of the minable seams and mining methods at Tavistock Colliery.

Table 2-4 Summary of the seams mined and mining methods at Tavistock Colliery.

Tavistock	Mining method	Area (Ha)
Tavistock OC		1237
Tavistock UG 1S	bp	831
Tavistock UG 2S	bp	4314
Tavistock UG 4S	bp	3954
Tavistock UG 5S	bp	40

2.10.4 Rietspruit Colliery

The Rietspruit Colliery has four coal seams, namely the No's. 1, 2, 4 and 5 Seams.

The dominant mining method has been opencast, but underground methods were also used on a small scale. The No. 2 Seam has been mined extensively in the central and northern portions of the area. Opencast mining at Rietspruit Colliery has been done in the North-South pit as well as in the Third Pits.

The No. 1 and No. 2 Seams have also been mined by underground bord-and-pillar methods (See Figure 2-23 for detail on mining areas).

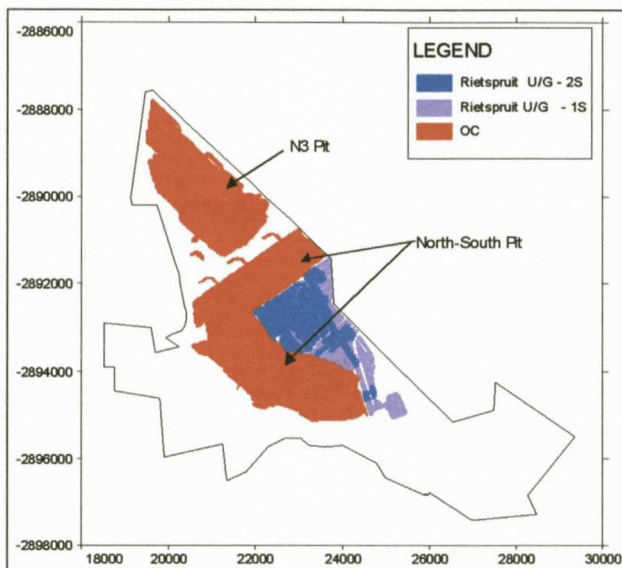


Figure 2-23 Seams mined and mining methods used at Rietspruit Colliery

Table 2-5 gives a summary of the minable seams and the dominant mining methods at Rietspruit Colliery.

Table 2-5 Summary of the seams mined and mining methods at Rietspruit Colliery.

Rietspruit	Mining method	Area (Ha)
Rietspruit OC		1087
Rietspruit UG 1S	bp	382
Rietspruit UG 2S	bp	252

2.10.5 Kriel Colliery

Two opencast pits, namely Pit 5 and 6, are to be mined in the northern area in the near future. The No. 4 Seam will be mined in both opencast pits (See Figure 2-24 for

details on mining areas). Statistics show that 870.7 million tons were produced during the period of 2000.

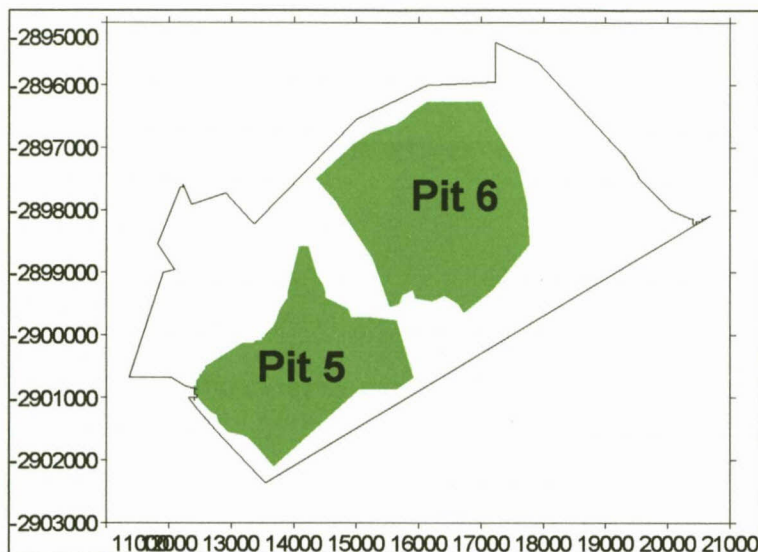


Figure 2-24 Seams mined and mining methods used at Kriel Colliery

Table 2-6 gives a summary of the minable seams and mining methods at Tavisotck Colliery.

A summary of the different mining methods and seams mined at the different collieries is given in Table 2-7.

Table 2-6 Summary of the seams mined and mining methods at Kriel Colliery.

Kriel	Area (Ha)
Kriel OC	1294

Table 2-7 Summary of the seams mined and mining methods at western Witbank Colliery.

Colliery	Seams mined and mining method	Mining method
Kleinkopje	1, 2, 4, 5	bp, oc
Rietspruit	1, 2, 4, 5	oc, bp
Tavistock	1, 2, 3, 4, 5	bp, oc, pe
Tweefontein	1, 2, 3, 4, 5	Bp, oc
Kriel	2	oc, bp

Pe = Pillar extraction, bp = bord-and-pillar, oc = opencast

3 MINE WATER FLOW IN THE WESTERN WITBANK COALFIELD

3.1 FLOW HYDRAULICS OF MINE WATER

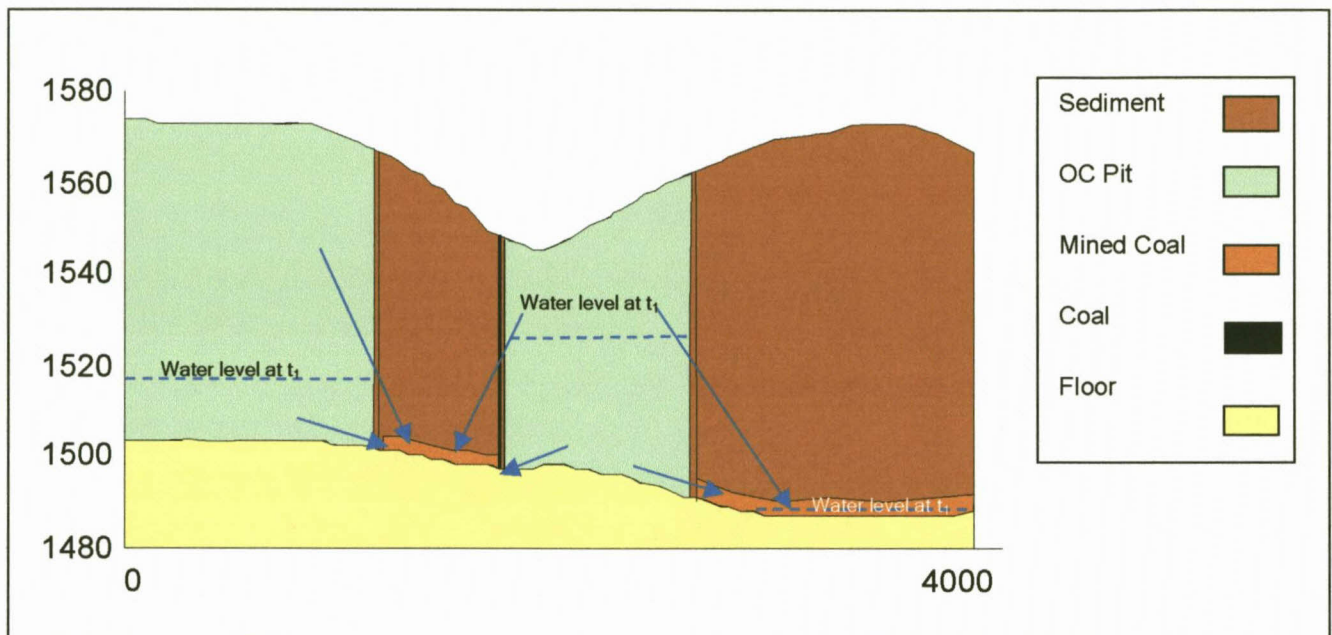


Figure 3-1 Example of the types of hydraulic interaction encountered in the study area (Northwest - Southeast cross section through the N3, Tavistock 2 Seam underground and the North-South Pit.)

The processes of water flow in the subsurface have been studied in mining environments for many years. Additional complications superimposed on the groundwater flow in typical Karoo aquifers, make the study and simulation of flows in these areas a challenging exercise.

Mine drainage is a common problem associated with coal mines. It begins during active mining operations, when water enters the mines from groundwater and/or surface water. In some cases this water is pumped from the mines while in other cases it drains freely from the mines to adjacent areas. In the case of mines for which pumping is used during active operations, water fills these mines upon closure and eventually discharges at the surface. Water that drains freely out of mines will continue to do so upon closure unless measures are taken to prevent it (Lambert, 2000).

Modelling flow through engineered structures such as channels, flumes, weirs, and tanks reactors is fairly simple, because man-built systems have the benefit of "knowns", such as regular geometry, measured inputs and outputs, volumes and velocities. Even flow through some natural underground systems such as homogeneous aquifers can easily be

modelled and validated. Flow in surface waters such as rivers and lakes can also be modelled with a few assumptions and idealisations.

Modelling flow through underground coal mines is difficult because it resembles all of these systems in some way. The system can be viewed as a groundwater system, where a highly conductive aquifer has been created that channels water to the surface. The conduits that have been created in the coal can be seen as underground pipes through which water travels. Finally, systems where large blocks of coal have been mined out and filled with water can be seen as pools, or underground lakes. An ideal model would combine all of these concepts. However, because the system is underground, the boundaries between the applicable flow domains are difficult to assess.

Despite the difficulties and limitations associated with creating a hydraulic model for a series of underground coal mines, there are important benefits associated with quantitative modelling. Hydraulic modelling provides a better understanding of water drainage from underground coal mines. Though the results may not be easily validated with field data, some specific questions, such as residence time and fate of water from different areas, can be answered. Also, hydraulic modelling serves as the platform for modelling the evolution of mine water chemical quality (Dzombak *et al.*, 2001).

3.1.1 Factors influencing flow in underground coal mines

The major factors that govern flow in coal mines include geometry of the mine, discharge elevation, extent of collapse and subsidence, coal unmined boundaries, the extent of fracturing, the general nature of overburden, and condition at the outcrop. The geometry of the mine determines whether the nature of flow will be in the downward direction toward a low elevation discharge, or out of a flooded mine at the lowest surface elevation. In a flooded mine, the elevation of the discharge controls the static water elevation. The undisturbed rock beneath the mined-out coal seam is assumed a lower boundary for water flow. In the Witbank Coalfield this lower limit is the floor of the lowest mine seam, often the Dwyka tillites underlying the 2 Seam in the Western Witbank Coalfield. Researchers such as Hodgson and Krantz (1998) have reported very low permeabilities for these sediments and flow through from the Dwyka is concerned to be negligible on a regional scale.

The extent of collapse and subsidence and the location of unmined coal boundaries influence the direction and velocity of flow in the subsurface. Collapse of material above the coal seam will direct water to some extent, though in some cases a significant void may still remain above the collapsed material and flow in the mine voids will not be hindered. Collapse accompanied by subsidence may create a significant flow. Hodgson *et al.*, (1982) cover this aspect in detail, while Grobbelaar *et al.*, (2001) allude to the increased recharge through collapsed areas.

3.1.2 Opencast flow hydraulics

Opencast coal mining has a big influence on the hydrological conditions associated with undisturbed strata. The following factors can influencing the normal hydraulic conditions of an opencast area:

- the exposure of unweathered strata to atmospheric conditions,
- increased gradients of groundwater flow, and
- higher hydraulic conductivities of disturbed strata.

Figure 3-2 illustrates the generalised hydrological conditions associated with an opencast environment. Normal groundwater movement still takes place in aquifers. Groundwater flow directions will necessarily be directed toward the pits, due to an artificial change in gradients on a local scale.

This normal groundwater flow, together with direct recharge into the spoils, will create a groundwater level in the heaped spoil until a decant level is reached. Water that decants out of the spoils as well as run-off from the surface of the spoils follows the natural gradient and flows to the nearest river or stream. See Figure 3-2 for the general geohydrological conditions of an opencast pit.

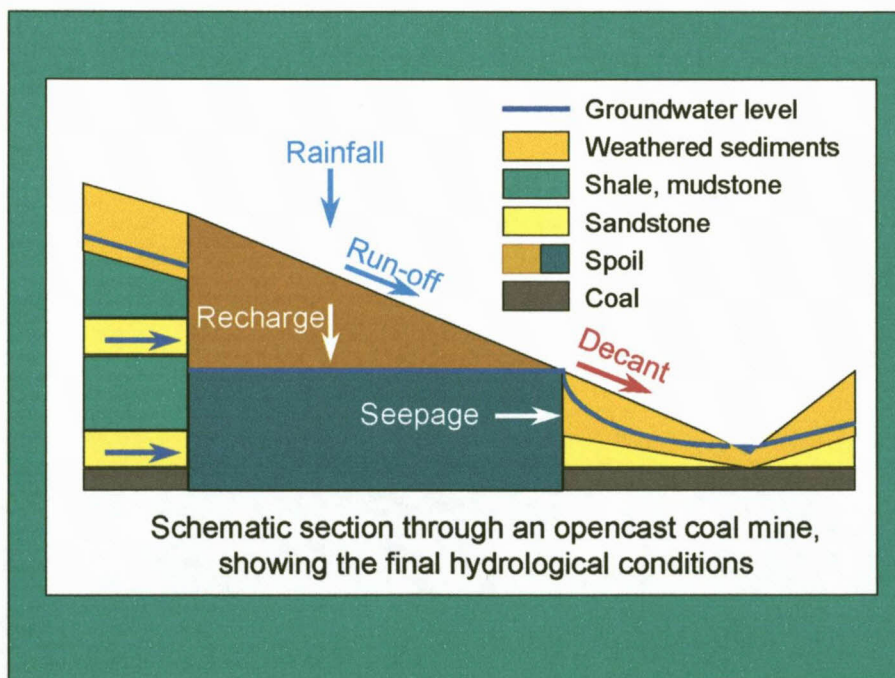


Figure 3-2 General geohydrological conditions of an opencast pit (Grobelaar et al., 2001).

3.1.3 State of Science: modelling water in mine voids

Modelling water in mine voids is not an established science. Mines that remain naturally unflooded have been of little interest to the scientific community thus far. Modelling of water in mine voids that flood naturally has been attempted. However, these attempts have been aimed at predicting the progress of water level rise during the process of mine flooding. Flooded mines have been evaluated for long-term improvements in water quality, both where flooding occurred naturally and where flooding was induced via mine seals, but hydraulic models that describe quantitatively the flow domain in such flooded mines have seldom been reported (Lambert, 2000). Researcher such as Adams and Younger (2001) and Banks (2001) describe methods to approach this complex problem.

Some modelling has occurred in relation to water flow in underground coal mines. The rate of infiltration into mine voids during the active mining process has long been of interest, and some related modelling has been performed. The USGS groundwater flow model Modflow has been used for site characterisation in several mine flooding studies (Adams and Younger, 2001).

3.1.4 Modelling flow in unflooded mines

Modelling of flow in unflooded mines has not been attempted very often. The majority of scientific literature that pertains to unflooded mines is focused on flooding unflooded mines. Flooding of mines has been generally accepted amongst regulators as the best available approach to induce long-term improvement of water quality in coal mines, through the limitation of oxygen supply. This approach has been known and practised for many years in the US coalfields (Dzombak, 1999).

3.1.5 Modelling flow in flooded mines

Modelling flow in long-flooded mines has not been widely attempted, though scientific research on mines that flood naturally has been significant. There is a general conceptual model that corresponds to flooded mines, that of the "pool" concept. Reference to abandoned coal mine "pools" is in the vernacular of coal miners, regulators, and researchers in the field. The pool concept is understood to mean the body of water that inundates abandoned mine voids in a mine that has a uniform hydraulic head over the area of the abandoned mine.

Much like the unflooded mines, research interest as to the hydraulics of flooded mines has been geared more toward the process of flooding, rather than the long-term state of flooded abandoned mines. In the United Kingdom, the prediction of flow in mines as they flood has been the focus of research in recent years. Prediction of the hydraulic behavior of groundwater entering abandoned coal mines has been addressed in research conducted by Younger (Sherwood and Younger, 1997), who expanded the "pond" concept and applied pipe flow equations to conduits of known geometry linking mine pools with different pool elevations. The Groundwater

Rebound in Abandoned Mineworkings (GRAM) model is used to predict mine water fate as abandoned workings fill. Other computer simulations predicting the time of the flooding process have been attempted, include Rogoz (1994). Modelling the infiltration rates during active mining has also been attempted. These have been motivated by mine safety considerations, and by the impacts of mining on regional groundwater. Fawcett (1984) describes various mathematical models used to predict quantities of water flowing into underground mines. These include well and aquifer models based on Darcy's law using finite differencing techniques. Toran (1988) constructed a two-dimensional finite difference mathematical model to represent drawdown and recovery in a well near an underground mine in order to predict observed hydraulic head distributions and groundwater discharge rates.

Some modelling has been carried out for water flow in abandoned mine networks for which a detailed site characterisation is available. The U.S. Bureau of Mines developed the MINEFLO program, which "simulates hydrologic flow systems" (Perry, 1993). Modflow (McDonald and Harbaugh, 1984), a USGS program developed to simulate flow in porous media, has also been used to simulate groundwater flow in three dimensions in projects of the Bureau of Mines (Perry, 1993). It has also been used by Bair and Hammer (1998) to help characterise site hydrogeology and assess the hydrogeologic impacts of grout injections into abandoned coal mines. Adams and Younger (1997) site other researchers who have used Modflow to model groundwater flow in a partially abandoned mine.

The challenges of modelling underground mines are manifold and the shortcomings of available tools have been discussed by several authors such as Younger (1997) and Banks (2001). Despite these caveats, attempts to understand the interactions of complex systems such as these often require a host of different tools to arrive at an appropriate answer. Numerical modelling is one of the most useful, due to the fact that it can accommodate a host of interactions simultaneously.

3.2 BACKGROUND TO INTERMINE FLOW

After the closure of mines they naturally start to fill up with water. As a result, hydraulic gradients develop between them and different hydraulic water pressures are exerted onto peripheral areas or compartments within mines. This results can be observed in water flow between mines, or onto the surface. This flow is referred to as intermine flow (Grobelaar, 2000).

DWAF sees intermine flow as the most important aspect in mining (Postma and Schwab, 2002). Thus the flow of water between adjacent mines has become a problem.

3.2.1 Water flow directions

Water in the mines initially migrates along the floor of the coal seams, dominated by the mining configuration and the floor slope, to accumulate in low lying areas.

In most of the collieries more than one seam has often been mined. Of all the coal seams, the No. 2 Coal Seam is mined the most extensively in the Lower Olifants Catchment Region (Grobbelaar *et al.*, 1998). It can thus be said with a fair amount of confidence that the flow of water will be dominant in this seam. It can also be assumed that the seams which overlie the No. 2 Coal Seam interconnect with the latter through prospect boreholes or shafts. Exceptions do occur and the No. 5 seam workings at Kleinkopje is a good example of mining which does not interconnect with the No. 2 Seam workings.

3.2.2 Problems concerning intermine flow

The interflow of water between adjacent mines is potentially a very important immediate and post-closure problem that needs to be addressed by the coal mining industry. Mined-out areas inevitably fill up with water, exerting hydraulic pressure on peripheral areas. This results in:

- Seepage of water from one mine to the next and the associated transfer of polluted mine water.
- Risk of failure of border pillars due to differential hydraulic pressures.
- Pollution of aquifers and surface water resources.

An understanding of the groundwater flow regime is essential to the design of specific monitoring plans, to determine the impact of mining on groundwater quality and the hydrologic balance.

Mine water in collieries will migrate out of these areas if conduits between the mining levels and other mines or the surface exist. In all the collieries in the Western Witbank Coalfield, sufficient connectivity exists between mining levels and the surface. In the few instances where isolated underground water bodies could establish, these will form part of the regional intermine flow. All mine water in this area is dynamic in nature and will surface or interact with shallow aquifers and contribute to base-flow at some stage in the future.

3.2.3 Areas of risk

Areas of greatest risk, which might be influenced by elevated water levels, are the following (Grobbelaar, 2001):

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

3.3 INTRODUCTION TO INTERMINE FLOW IN THE WESTERN WITBANK AREA

In the past, many studies have been done at positions where intermine flow might occur, but just on a regional basis. In this section the positions of possible intermine flow in the Western Witbank area will be stipulated and the amount of flow between the unmined boundaries will be calculated by making use of the following methods:

- Empiric and analytical solutions by making use of WISH stage curves, Darcy's flow equation and also Stochastic calculations.
- Flow models by making use of the model package Modflow.

3.3.1 Potential areas of Intermine flow in the Western Witbank area

Mining will progress for many years in much of the Western Witbank Coalfield. Mine layouts currently change almost on an annual basis.

To demonstrate the potential for interflow between mines, based on floor contours, Figure 3-3 has been compiled. In Figure 3-3 the 2 Seam contours were used to emphasize the natural groundwater gradients. As Grobbelaar (2001) states, this should not be seen as a quantitative depiction of potential flows since the true situation is more complex. Specific scenarios have to be investigated in detail before more definitive answers can be given.

- Tavistock/Kriel scenario
- Rietspruit/Tavistock/Tweefontein scenario
- Greenside/Kleinkopje/Wolwekrans scenario

As emphasized in chapter 1, this study draws upon information garnered from the individual mines, literature on the topic and other regional studies, and as such the conceptual models and answers provided are a function of the integrity and accuracy of supplied data.

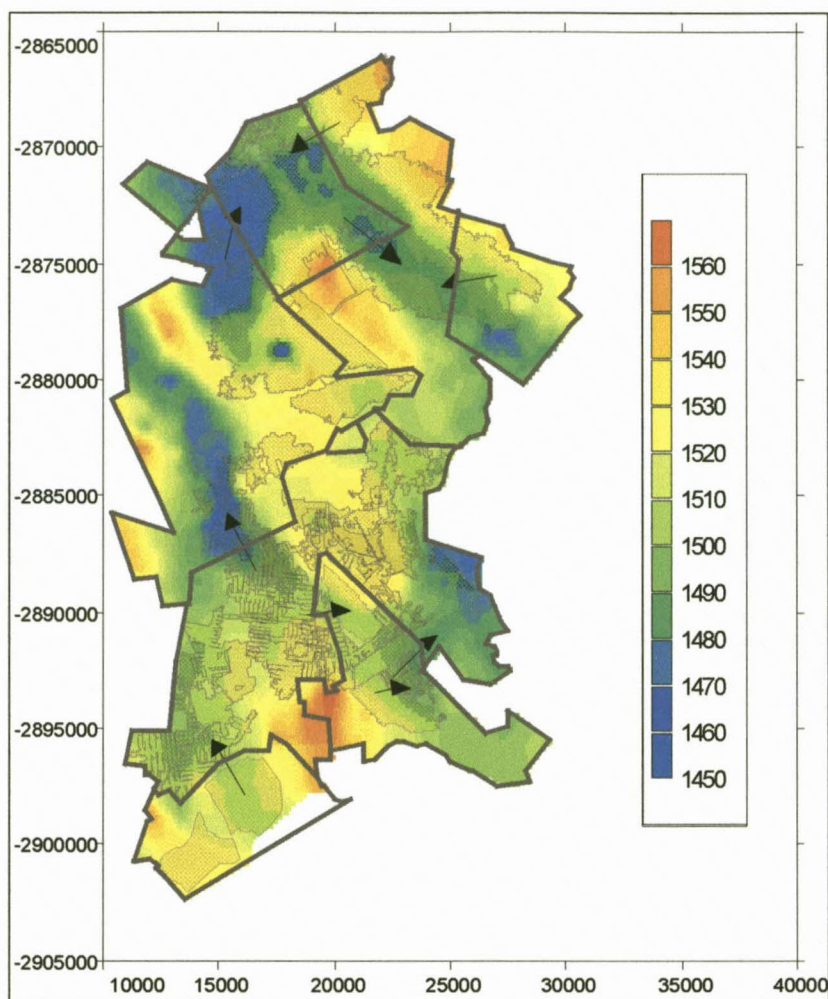


Figure 3-3 Arrows depicting directions of mine water flow across boundaries along the No. 2 Seam horizon.

3.4 NUMERICAL MODELS

Although the application of numerical groundwater models to solve groundwater related problems are quite a new field in the industry, many popular models were already published in the 1980's (Zhang, 2000).

In order to investigate the behaviour of aquifer systems in time and space, it is necessary to employ a mathematical model. Modflow is the software used during this investigation. Modflow, a modular three-dimensional finite difference groundwater flow model developed by the U.S. Geological Survey, is used to predict and simulate the behaviour of groundwater over time. Modflow is an internationally accepted modelling package, which solves the groundwater flow equation.

The "original" version of Modflow-88 can simulate the effects of wells, rivers, drains, head-dependent boundaries, recharge and evapo-transpiration. Since Modflow was developed, numerous investigators have developed various codes to be used with

Modflow. These codes are called packages, models or sometimes simply programs. These 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 was used to identify specific flow paths.

3.4.1 Relevance of Modflow

Modflow is a well known internationally accepted software modelling package. PMWIN comes with a professional graphical user-interface, the supported models and programs and several other useful modelling tools. The graphical user-interface allows you to create and simulate models with ease and fun. It can handle models with up to 1,000 stress periods, 80 layers and 250,000 cells in each model layer (Chiang and Kinzelbach, 1998). Listed below are a few reasons why Modflow was chosen as the modelling package and more specifically PMWIN as the graphical interface.

- It is accepted in many international courts.
- Modflow simulates steady and non-steady state flow in an irregularly shaped flow system in which aquifer layers can be confined, unconfined, or a combination of confined and unconfined.
- Flow from external stresses, such as flow to boreholes, aerial recharge, evapo-transpiration, flow to drains, and flow through river beds, can be simulated.
- Hydraulic conductivities or transmissivities for any layer may differ spatially and be anisotropic.
- The storage coefficient may be heterogeneous.
- Modflow is currently internationally the most used numerical model for flow problems.
- MT3D mass transport package runs together with Modflow. Simulation of the transfer of solutes can therefore be accomplished.

3.4.2 Shortcomings of Modflow

- Modflow makes use of the Finite Difference solution resulting in rows and columns. This makes it very difficult to simulate water through an irregular or angled boundary and considerable effort is required in mesh refinement on telescoping to achieve accurate simulations in such situations.
- PMWIN has the ability to import only 2000 points to simulate the surface and floor contours of the area. This causes the model to sometimes simulate the wrong elevation at a specific point.
- The systems modelled are often geometrically and hydraulically complex and the host of interactions can't always be accommodated in any numerical groundwater flow model.

3.5 BACKGROUND INFORMATION AND CONSTRUCTING A CONCEPTUAL MODEL

In every model study the natural system is represented by a conceptual model. A conceptual model includes designing and constructing equivalent but simplified conditions for the real world problem that are acceptable in view of the objectives of the modelling and the associated management problems. Transferring the real world situation into an equivalent model system, which can then be solved using existing program codes, is a crucial step in groundwater modelling. The following is included in a model:

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

Numerical groundwater models are an approximation, and the level of accuracy depends on the quality of the data that are available. This implies that there are always errors associated with groundwater models due to uncertainty in the data, the capability of numerical methods to describe natural physical processes. Numerical groundwater models are the best tool available to quantify groundwater and mass balances, which can be used to make decisions. The groundwater model in this investigation should therefore *not be seen as a predictive tool*, but rather as a prospective evaluation tool to determine the potential behaviour of the system with time, given a set of changing parameters.

3.6 MODEL INPUT PARAMETERS

3.6.1 Steady state and transient simulations

In order to obtain satisfactory results from any groundwater model, good quality data need to be entered into the model. Using the reports and information obtained from the mines, sufficient information was available to construct an initial groundwater model of the area.

Model calibration consists of changing values of model input parameters in an attempt to match field conditions within some acceptable criteria. The calibration process typically involves a steady state and transient simulation. With steady state simulations, there are no observed changes in hydraulic head or contaminant concentration with time for the field conditions being modelled. Transient simulations

involve the change in hydraulic head with time. Models may be calibrated without simulating steady state flow conditions, but not without some difficulty.

3.6.2 Discretisation

In Modflow, an aquifer system is replaced by a discretised domain consisting of an array of nodes and associated finite difference blocks (cells). In all three areas considered, the model area is represented by a spatial discretisation of the aquifer system with a mesh of cells and nodes at which hydraulic heads were calculated. The nodal grid forms the framework of the numerical model. Hydrostatigraphic units can be represented by one or more model layers. The thickness of each cell and the width of each column and row may be variable. The location of cells are described in terms of columns, rows and layers.

- Refinement of the mesh is also possible. If focus is to be placed on a specific area and the mesh in that specific area is too coarse, the mesh can be refined. This function will divide a block to any desired size. Thus instead of one block, a number of blocks are now located between the mining areas, depending on the refinement factor.

3.6.3 Layers

One- and two-layer models were constructed during the thesis. Confined conditions were used during the model simulations.

3.6.4 Layer Construction:

The surface and floor contours of the area are used to simulate the top and bottom of the aquifer.

In case of a two- or more layered model, mining heights are assigned for the different seams of the underground areas. Mining heights for the specific underground mining areas were taken from the Coaltech 2020 project (Jeffrey, 2002).

3.6.5 Boundary conditions

One of the first and most demanding tasks in groundwater modelling is identifying the model area and its boundaries. Boundary conditions express the way the area under investigation interacts with the rest of the environment. Conditions on the boundaries, however, have to be specified. Boundaries occur at the edges of the model area and at locations in the model area where external influences are represented, such as rivers, wells, and leaky impoundments.

Fixed heads were used to simulate decant positions. A fixed head will prevent the water level from rising above the decant level or water levels in the rivers.

3.6.6 Initial hydraulic heads

Initial hydraulic heads at fixed-head cells will be kept constant during the flow simulation. For transient flow simulations, the initial heads must be the actual values.

Ideally measured water levels should be available for each cell of the model. This is obviously not achievable for a large model area.

Two methods can therefore be used to simulate water levels over the entire model area:

- An interpolation technique, using the available data, can be used to simulate piezometric levels over the entire model area. The interpolation technique is referred to as Bayesian interpolation where piezometric levels are correlated with the surface topography. Note that the Bayesian interpolation is generally used in areas where borehole or sampling data are available for the whole area (See Figure 3-4 for example of a Bayesian interpolation graph).
- Where borehole or sampled water levels are available but not in a close range, an alternative method can be used to calculate water levels. An average water level is calculated for each cell of the model. The water level will thus correlate with the surface area of the model.

These initial heads are then used to simulate the initial conditions and the flow of water in the model area.

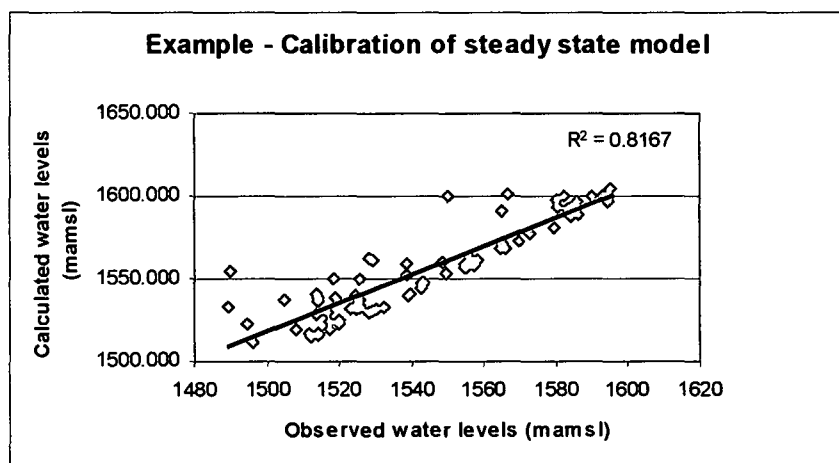


Figure 3-4 Example of the calibration of a steady state model by making use of the Bayesian interpolation technique.

3.6.6.1 Horizontal Flow Barriers

3.6.6.2 Definitions of terms used during the flow simulations

To avoid confusion, a few definitions are provided to distinguish and clearly explain the function of a horizontal flow barrier.

Modflow uses the term horizontal flow barrier to describe a vertical geological feature which retards or obstructs the normal horizontal groundwater flow.

- Horizontal flow barriers can be used for two similar functions by just varying a permeability factor. Horizontal flow barrier as defined by Modflow can function as the following:
 - The horizontal flow barrier can be used to simulate low-permeability geologic features, such as dykes vertical faults or slurry walls, that impede the horizontal flow of groundwater.
 - It can also be used to represent the coal barrier or unmined country rock between two mining areas if the coal barrier is too thin to be simulated in the model without severe refinement of the mesh. The coal barriers are areas left between the mined areas to support the roof of the mining area and to avoid seepage from one mine to the next. A minimum thickness of 30 m is normally required for the thickness of the coal barrier. The Horizontal flow barrier which will represent the coal barrier is referred to as an artificial coal barrier.

The above-mentioned definitions will be described in full detail in the next paragraph.

Horizontal flow barriers are geologic features which are approximated as a series of horizontal-flow barriers conceptually situated on the boundaries between pairs of adjacent cells in the finite-difference grid. Horizontal flow barriers are a very difficult feature to simulate in the model. Because of the block network a direction and impermeability value must be given to every cell where the dyke or sill is located. Because Modflow consists of a block network, the dykes are represented by a zig-zag pattern and not by a straight line as seen in nature. Thus care must be taken to assign the right permeability to the right block, otherwise an incorrect representation of the area might be simulated.

A value of $1\text{e-}9$ m/d was assigned to very thick and impermeable boundaries such as dykes (Dennis, 2002). The dykes at Rietspruit and Tavistock Colliery are approximately 5m thick. In case of a weathered dyke, a larger value for example $1\text{e-}4$ can be used to simulate flow through the permeable boundary.

The horizontal flow barrier can be used in a different way. A small value must be assigned to the unmined country rock to simulate low hydraulic conductivity of the feature. If the area of interest is for example, intermine flow area is 30 m thick and the matrix of the model area is for example 100×100 , the model will simulate wrong

answers because the block network will cause areas which are less than 100 m apart to collide. Horizontal flow barriers can thus be used to simulate the real situation. Flow barriers will be placed in the area where the blocks collide. A direction and a permeability (permeability of the unmined areas) will be assigned to the unmined country rock to represent the correct situation.

Horizontal Flow barriers in combination with unmined coal barrier refinement or both separately can be used to resolve the problem of thinner unmined coal barriers. An example of this type of application is illustrated in a later section (Section 3.15) to show the effect of both horizontal flow barriers and refinement and the difference in answers.

3.6.7 Horizontal Hydraulic Conductivity and Transmissivity:

Most aquifers are heterogeneous in terms of hydraulic properties. Field measurements indicate that hydraulic conductivity of aquifers consistently varies through space in an irregular manner (Bright *et al.*, 2002). Because of the high cost of subsurface measurements, detailed information on the spatial distribution of hydraulic conductivity is usually not available. It has therefore become common practice to assume that the hydraulic conductivity is a random space function that can be represented by a geostatistical model (Bright *et al.*, 2002).

A study was done in the Pittsburgh Coal Basin to predict conductance of coal unmined boundaries. The conductance of the coal unmined boundaries are normally expected to increase where unmined boundaries are thin, but there is still evidence that coal unmined boundaries may in some cases be sufficiently low in K to restrict seepage between mines, and in others to allow leakage to flow at a relatively high rate.

Relatively few data are available for horizontal K of coal unmined boundaries. The most relevant measurements appear to be based on field, rather than lab tests. Schubert (1980) compared lab to field measurements of overburden K for lithologies in Pennsylvania. He noted that field values were generally 4 to 6 orders of magnitude higher than for lab tests. He deduced that the aquifer tests were more representative of field behavior and represented dominantly fracture-enhanced permeability. He further concluded that the presence and properties of the fractures are likely to dominate the conductance behavior of most rocks in the coal measures.

The horizontal K of unmined coal and the unmined country rock are strongly influenced by fractures, joints and coal cleat, which are likely to be most continuous and pronounced where coal boundaries are thinnest.

PMWIN uses the horizontal hydraulic conductivity and layer thickness to calculate transmissivity. (Chiang and Kinzelbach, 1998).

3.6.8 Specific storage and Storage Coefficient

The specific storage of a saturated aquifer is the volume of water that a unit volume of aquifer releases from storage under a unit decline in hydraulic head, (Kruseman and de Ridder, 1994).

For transient flow simulations, Modflow requires dimensionless storage terms specified for each layer of the model.

- The specific storativity is defined as the volume of water that a unit column of aquifer releases from storage under a unit decline in hydraulic head.

The following storage coefficients were used for all three model simulations:

- Undisturbed areas - 0.0005
- Underground mining areas - 0.6 (Bord-and-pillar)
- Opencast pits - 0.25 (Rehabilitated)

3.6.9 Drains

During transient state the drain package of Modflow (McDonald and Harbaugh, 1988; Zhang, 2000) was used to simulate the interaction of rivers. The drain simulates a process of preventing the build-up of water in low-lying areas removing water from the aquifer at a rate proportional to the difference between the head in the aquifer and the elevation of a drain. When the hydraulic head is greater than the drain elevation, water flows into the drain and is removed from the groundwater system. Discharge to the drain is zero if the hydraulic head is lower than or equal to the median drain elevation. Recharge from the drain is always zero, regardless of the hydraulic head in the aquifer.

For all three models, drains were simulated on the rivers in the areas, to ensure any surfacing waters were recovered from the model domain. This is particularly important when decant occurs from opencast workings.

3.6.10 Recharge

The recharge package is designed to simulate already distributed recharge to the groundwater system.

The recharge rates for each area were calculated by making use of the average rainfall over the model area. Initially it was hoped to derive site-specific recharge values based on the water balances provided by the individual mines. Unfortunately the values obtained in this way were not regarded as sufficiently reliable and estimated regional values were obtained. The mine water balances provided are often static values and insufficient discrimination between different sources and types of water is provided to quantitatively derive values like recharge. In many cases the

water balances themselves are based on estimated values for recharge or water make and the other values are balanced with these. Recharge percentages of 3% was assigned to bord-and-pillar areas (Hodgson, 1999). For opencast pits the values used varied between 14% and 20% (Hodgson 2001). From the simulations in this research the sensitivity of recharge for the refilling times and timing of intermine flow is clear. More research on these topics throughout the Witbank Coalfield is required to allow closer approximation of the true situation.

3.7 ASSUMPTIONS AND LIMITATIONS

It is important to note that groundwater models are a representation of the real system. As such they have certain limitations and therefore assumptions have to be made when developing a model. The following assumptions were made:

- The rivers in the area were assumed to be drains.
- As there is no significant extraction of groundwater for irrigation or other users, no discharge was taken into account.
- Rainfall values and recharge percentages were taken from literature.
- Geological structures (faults, dykes etc.) where present, were taken into account.
- Only a basic calibration has been conducted

3.7.1 Sensitivity analysis

A sensitivity analysis is the process of varying model input parameters over a reasonable range and observing the relative change in model response. The purpose of the sensitivity analysis is to demonstrate the sensitivity of the model simulations to uncertainty in values of model input data. Sensitivity analyses are also beneficial in determining the direction of future data collection activities. Data for which the model is relatively sensitive would require future characterisation, as opposed to data for which the model is relatively insensitive. These data would not require further field characterisation.

A crude sensitivity analysis has been carried out on the calibrated model, to ascertain the influence of parameters on the model results.

Usually a sensitivity analysis indicates that the water levels in a model area are sensitive to both slight changes in hydraulic conductivity and recharge.

Sensitivity analyses were done on the three models to test the sensitivity of the models for above parameters mentioned. The results of the sensitivity analyses of the three models are described in detail in sections 3.9.3 and 3.11.2.7.

3.8 WATER BALANCE

There are situations in which it is useful to calculate flow terms for various sub-regions of the flow model. To facilitate such calculations, the computed flow terms for individual cells are referred to as cell-by-cell flow terms.

Water balances were calculated during the transient conditions of the flow model for specific areas for example, the opencast, underground areas as well as the intermine flow through the coal barriers.

Inflow: Groundwater recharge as a result of rainfall and constant heads which have been used to depict surface water features.

Outflow: Groundwater leaving the system through the defined flow boundaries of the model due to the gradient, and constant heads which have been used to depict surface water features.

3.9 KRIEL COLLIERY - TAVISTOCK COLLIERY FLOW MODEL SCENARIO

3.9.1 Conceptual Model

Intermine flow on the coal seam horizon could be possible at two localities. These are: (i) Possible interaction of water between Pit 6 and the Tavistock No. 4 Seam workings and (ii) Possible interaction of water between Pit 5 and the Matla No. 4 Seam workings which is located to the west of Kriel Colliery. The latter falls outside the study area and will not be discussed, since the distance between these areas is large enough to suggest that the interaction will be minor, based on current mine plans.

In both instances, flow from Kriel will only be possible after opencast mining has been completed, and the water levels in these pits have risen sufficiently.

The modelling area which consist of Tavistock and Kriel Colliery are located on the southern border of the Western Witbank Coalfield.

- Future intermine flow is suspected in the area between Kriel and Tavistock Colliery and thus a flow model was designed to calculate the amount of flow through the unmined boundary from Kriel to Tavistock Colliery as well as the time for the two opencast pits to fill up to decant level.
- In the southwestern part of Tavistock Colliery the Number 4 Seam is currently being mined. Mining at Kriel Opencast pits namely Pit 5 and Pit 6 is planned to start in 2004 and will be mined progressively over some 20 years (Hodgson, 2001).

In both pits the mining sequence is such that most of the pits will have to be dewatered during mining, because the coal floor dips towards the coal face.

Mining will start in 2004 in Pit 6 and in 2009 at Pit 5. Pit 5 is likely to cease in 2020 and in Pit 6 in 2024 (Hodgson, 2001).

Decanting elevations for each of the pits, i.e. 1566 for Pit 5 and 1561.5 for Pit 6, have been taken from the report by the Civil Engineering Department of Anglo American. See Figure 3-5 for the positions of the decant points at Kriel Colliery.

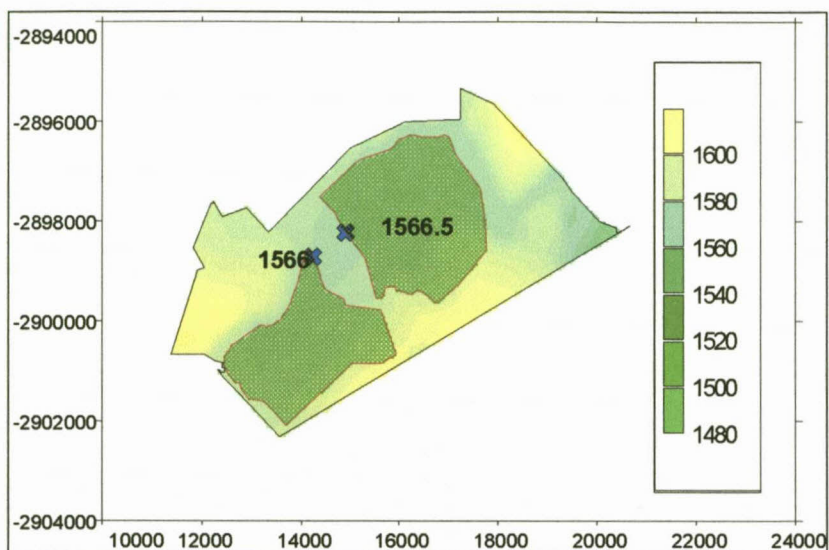


Figure 3-5 Positions of the decant point in the opencast areas

Hydraulic conductivities in the Kriel Colliery area range from 10^{-2} to 10^{-7} cm/sec. A hydraulic conductivity in the order of 10^{-7} ($0.000864\text{m}^3/\text{d}$) was reported for the 4 Seam by Hodgson and Grobbelaar (1998).

3.9.1.1 Stage curves

3.9.2 Stage curve calculations

Stage curves can be drawn to include the volumes in the opencast and underground areas at different elevations.

Stage curves were drawn for the two opencast pits at Kriel Colliery. Stage curves for the two pits are represented in

Figure 3-6 and

Figure 3-7. In

Figure 3-6 three points are demonstrated, namely A, B and C.

- A - the height of the mining area are extrapolated to 1568 m to include the decant position at 1566 mamsl.
- B - An assumption was made by Hodgson and Krantz (1998) that the spoil has a 25% void space. Hodgson said that it may be argued that some of the void space has already been taken up by moisture and that the effective capacity of the spoil should be reduced accordingly. Thus on the scale of the mining operations, this does not really make a difference. In the case of an underground area a void space is used in line with the coal extraction in the area.

- C - first the decant position is indicated and then the volume of water which can be expected at the elevation.

The capacities for the two opencast pits to hold water before they start to decant, were calculated by making use of WISH stage curves. Stage curves are able to calculate the volume vs. elevation for the opencast or underground area by making use of the floor contours of the area. A volume for the mining area is then plotted on the stage curves. Stage curves were plotted for Pits 5 and 6. The results from the stage curves can be seen in Table 3-1.

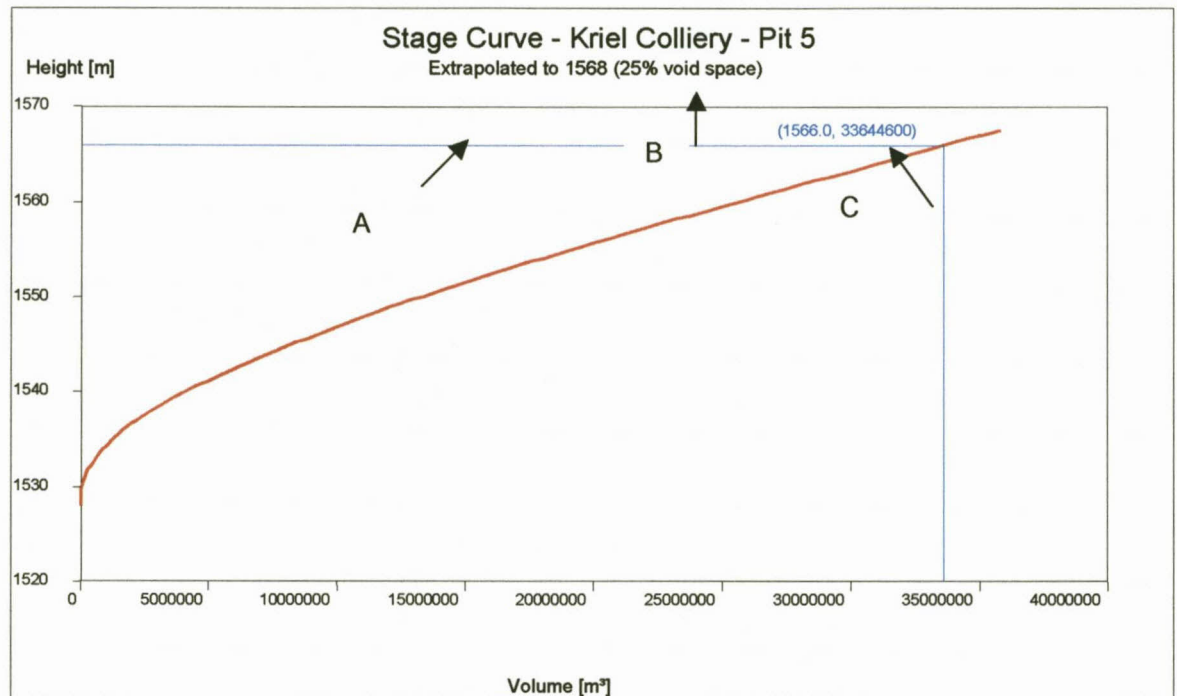


Figure 3-6 Stage curve for Pit 5 (future opencast) showing the position of the decant point as well as the volume of water at that specific point in the pit.

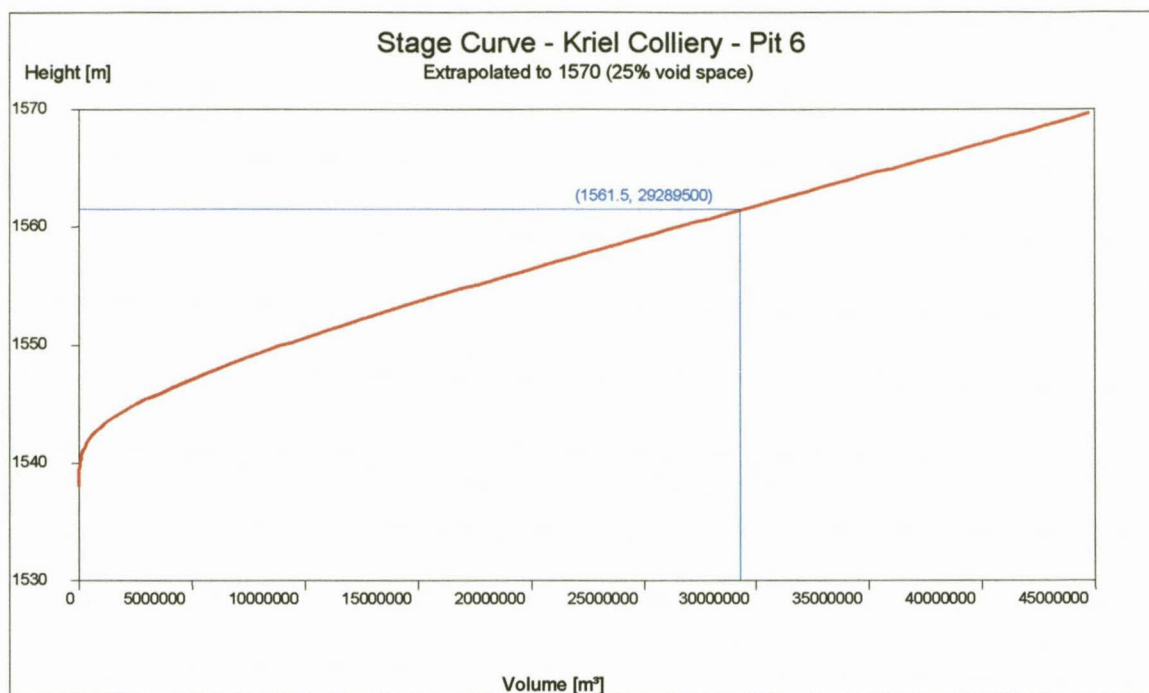


Figure 3-7 Stage curve for Pit 6 (future opencast) showing the position of the decant point as well as the volume of water at that specific point in the pit.

Table 3-1 Results from the stage curves from the two opencast pits.

Name of Pit	Decant elevation	Water in Pit (m ³)	Area (Ha)
Pit5	1566	33644600.0	537
Pit6	1561.5	29289500	757

From the stage curves can be seen that when Pit 6 is at decant level the pit can hold approximately 29.3 Mm³ of water. The holding capacity of Pit 5 is approximately 33.6 Mm³.

Empiric and analytical solutions were used to calculate the time for the opencast pits to fill to their decant levels. Based on an annual average rainfall of 700 mm (Hodgson, 2001) it was assumed that the recharge factor will not significantly change from during to after mining. Calculations showed that Pit 5 and 6 will take respectively between 44-45 years for pit 5 and 27-28 years for pit 6 to fill to their decant levels. Hodgson did the same calculations in 2001 and demonstrated that it would take 47 years for pit 5 and 23 years for pit 6 to fill. These calculations are thus in a close range to one another.

A flow model of the area was constructed.

By simulating the flow in the area using a model the following information should be available, namely:

- Areas where intermine flow is possible
- Flow volumes (volumes of water which flow through a unmined boundary from one colliery or from one mining area to another).
- Filling times of the mining areas

These results from the flow models can subsequently also be used for modelling of the chemistry of the area as will be discussed in the Chapter 4.

A post-mining simulation was done on the area. Thus a realistic situation was created to show what might happen in future (See Figure 3-8 for model extent).

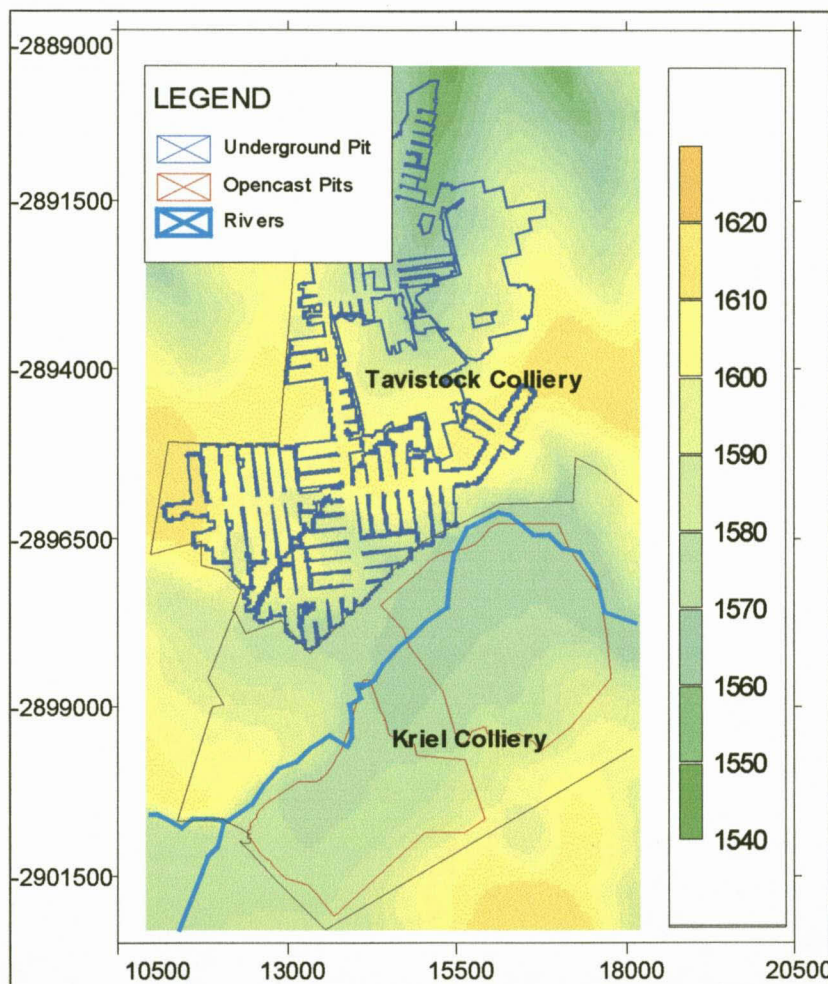


Figure 3-8 Extent of the Kriel Colliery - Tavistock Colliery flow model.

3.9.2.1 Discretisation

The mesh consisted of 320 x 190 cells in the x and y directions respectively. Figure 3-9 represent a schematic representation of the mesh size used in the flow models. Each of the cells is 50 x 50 m.

The coordinates for the modelled area are -2902500, 10500 (lower left corner) to -2886500, 20000 (upper right corner).

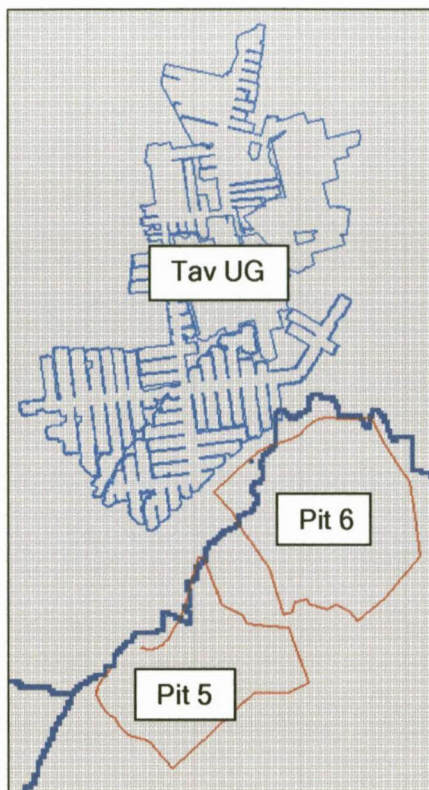


Figure 3-9 Spatial discretisation of the model system. Grid overlying the Kriel-Tavistock Flow model (Picture extracted from the flow model.)

3.9.2.2 Layers and layer construction

Both collieries have mined and intend to mine the No. 4 Seam, thus a one-layer model was constructed.

For the Kriel - Tavistock Flow Model the No. 4 Seam floor contours have been used for the bottom of the layer because mining exists on the 4 Seam horizon. The surface contours were used to simulate the top of the model area.

3.9.2.3 Initial hydraulic heads

In the case of the Kriel Tavistock model an average water level of 10 m below the surface was used to simulate the initial conditions during the steady state calibration of the model.

During transient state of the model, new water levels were created to simulate the water levels in the mining areas.

Both the opencast and underground areas were initially empty. Filling times were calculate for Pit 5 and Pit 6.

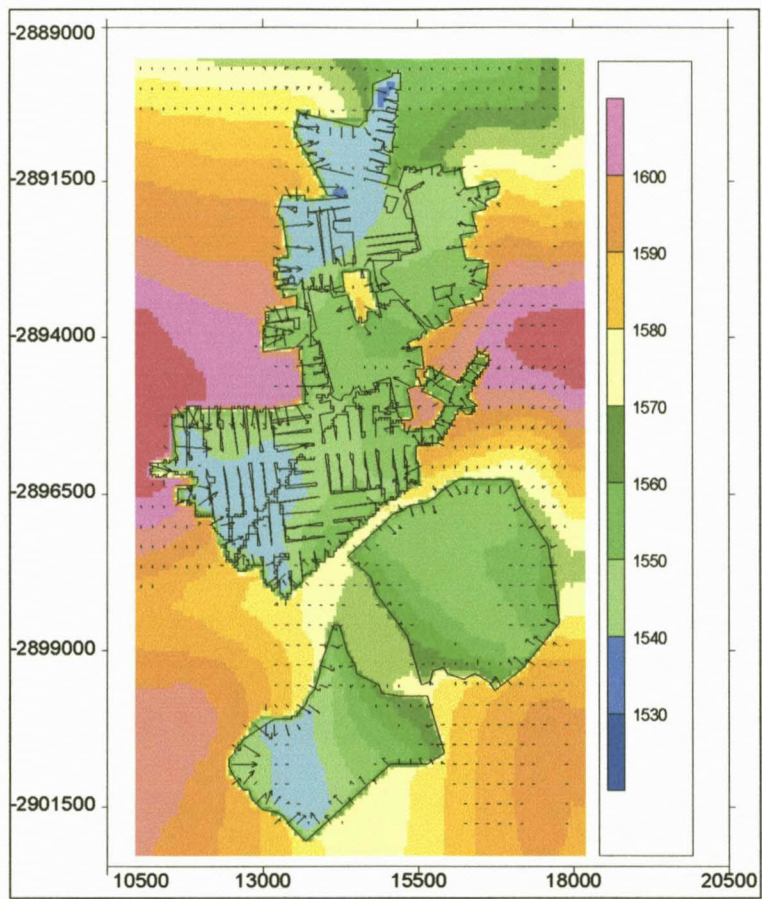


Figure 3-10 Initial water levels simulated in the flow model.

3.9.2.4 Horizontal Hydraulic Conductivity and Transmissivity

A hydraulic conductivity of 0.000864 m/d was taken from Hodgson and Grobbelaar (1998) to simulate the permeability of the coal layer. A hydraulic conductivity of 50 m/d was taken to simulate conditions in the opencast and underground areas.

3.9.3 Model results

After mining has stopped in the two opencast pits, the pits will start to fill up with water. To predict the filling times of the two opencast pits, a sensitivity analysis was done on the model.

Two parameters, namely conductivity and recharge percentages, were used to test the model sensitivity. Conductivities of 0.000864, 0.00864 and 0.8 were simulated against recharge percentages of 14 and 20%. See Table 3-2 for details on sensitivity analyses. See Figure 12 for a head versus time graph.

The recharge percentages of 14 and 20% are an indication of the rehabilitation state of the opencast area. Different recharge percentages were used to prove the point of the effect of better rehabilitation on the area.

From the model calculations it is clear that it will take approximately 27 and 44 years respectively for Pit 6 and 5 to fill to their decant levels if a recharge percentage of 20% was used. If a recharge percentage of 14% were used it will take respectively 39 and 63 years for the pits to fill to their decant levels. From the sensitivity analyses it can be concluded that it will take much longer for the opencast pits to fill if better rehabilitation techniques are used. It can safely be said that the pits will take between 27 and 63 years to reach their decant elevations (See Figure 3-12 to Figure 3-15 for filling times of respectively 14 and 20% recharge).

Because of the variation of the K-value on the coal seam, it was decided to test the effect of varying permeability of the coal barrier, to see how it will react on different K-values and what the influence are on filling times of the area. The models were run with two different conductivity values at different recharge values of respectively 14 and 20%.

For the two analyses, larger K-values were used. The first thought is that with a larger K-value the pits will fill up much quicker, but just the opposite is calculated by the model. This can be attributed to the fact that by increasing the K-value, the influx from the strata will increase. This will accelerate the inflow of water but it will also accelerate the rate of outflow. In this case, the groundwater is leaving the pit faster than it can flow in. It can thus be predicted that Pit 5 will take approximately between 44 and 70 years and Pit 6, 27 to 62 years to fill to their decant elevation for the different K-values. The importance of site-specific parameters is therefore very clear.

Table 3-2 Sensitivity analyses for Kriel - Tavistock flow model.

Pit	Hydraulic conductivity (m/d)	Recharge %	Time to decant (years)
Pit 5	0.000864	20%	44
Pit 6	0.000864	20%	27
Pit 5	0.000864	14%	63
Pit 6	0.000864	14%	39
Pit 5	0.00864	20%	46
Pit 6	0.00864	20%	31
Pit 5	0.00864	14%	67
Pit 6	0.00864	14%	55
Pit 5	0.864	20%	47
Pit 6	0.864	20%	34
Pit 5	0.864	14%	70
Pit 6	0.864	14%	62

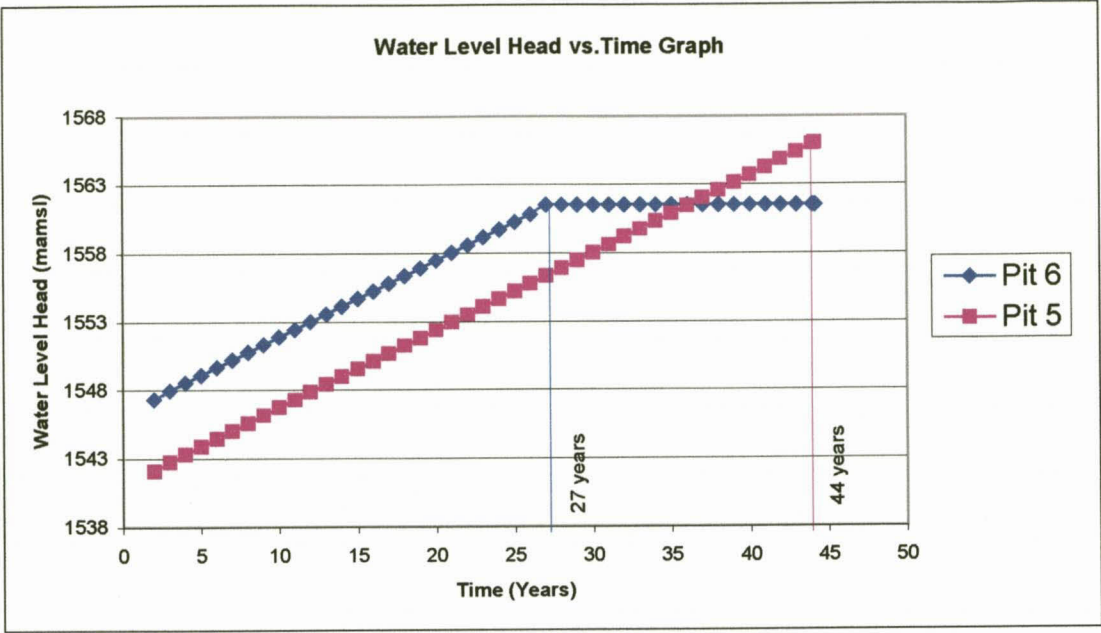


Figure 3-11 Water level heads vs. time for Pit 5 and Pit 6.

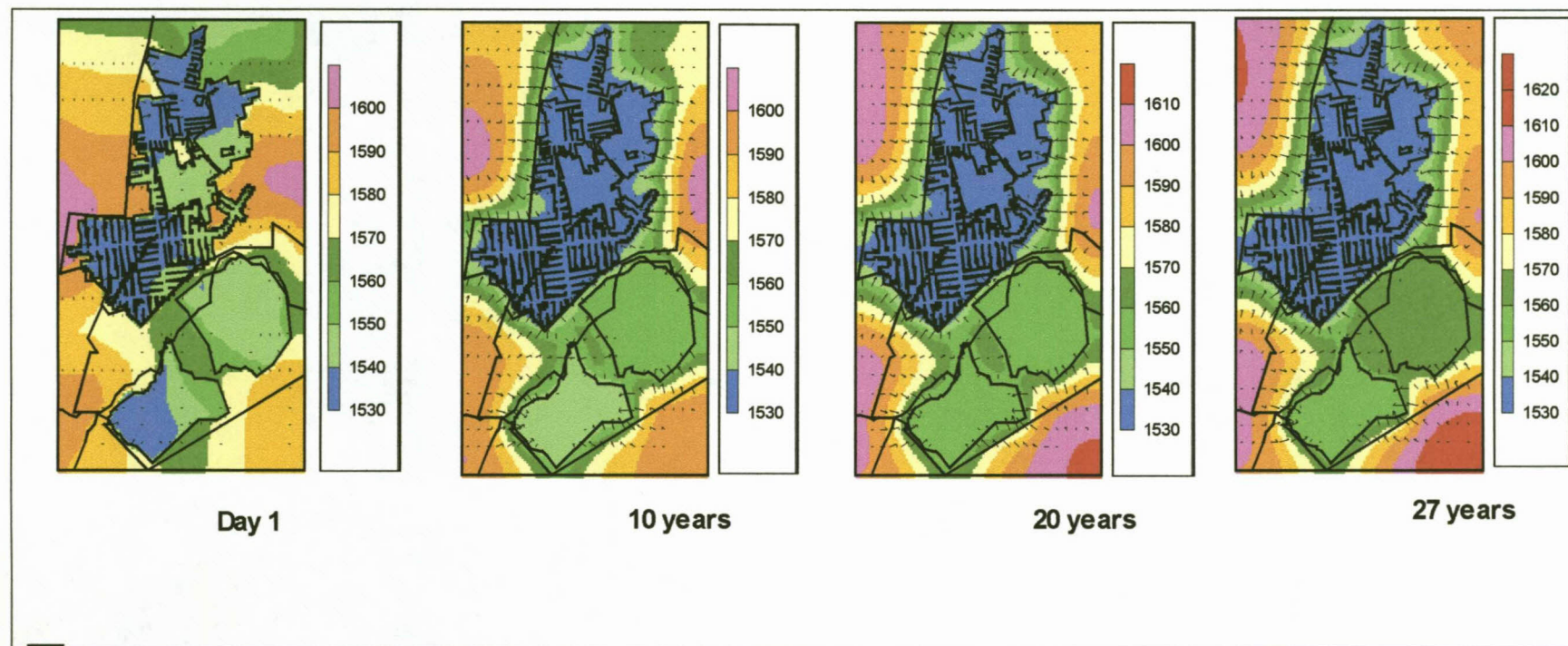


Figure 3-12 Sensitivity analyses on Kriel - Tavistock model - filling times using 20% recharge

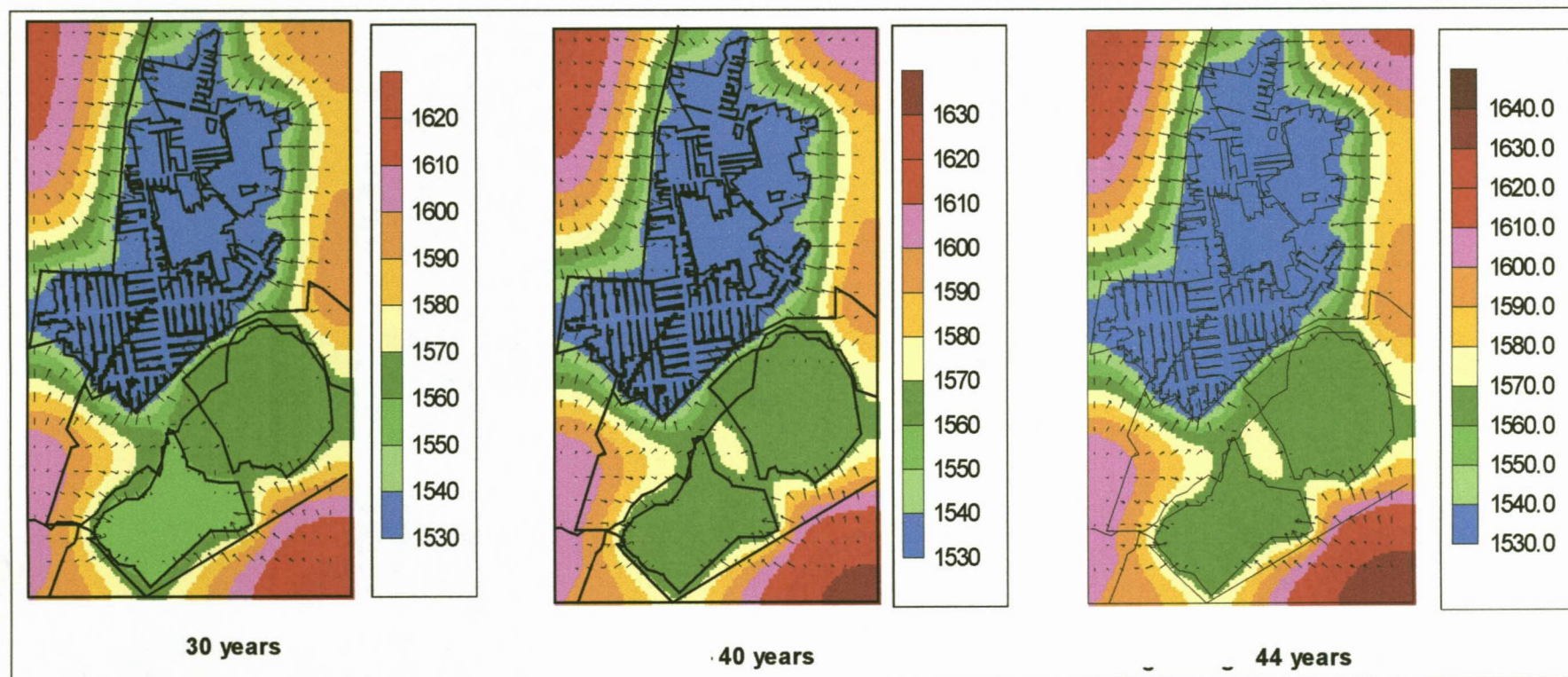


Figure 3-13 Sensitivity analyses on Kriel - Tavistock model - filling times using 20% recharge.

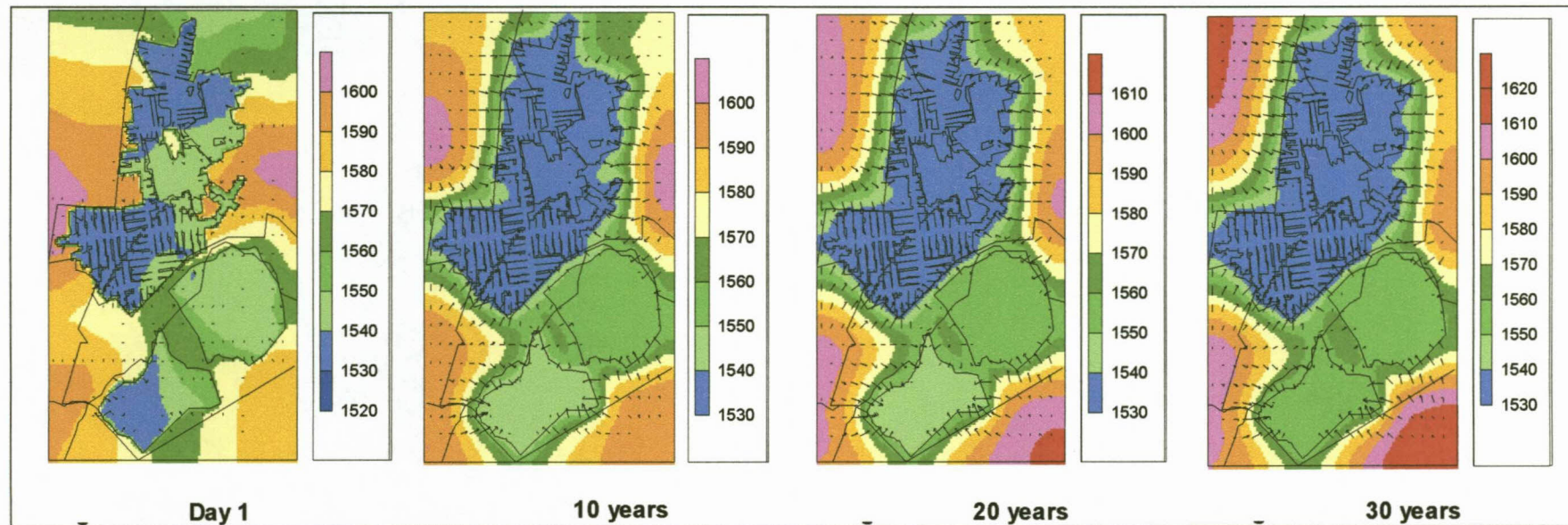


Figure 3-14 Sensitivity analyses on Kriel-Tavistock model - filling times using 14% recharge.

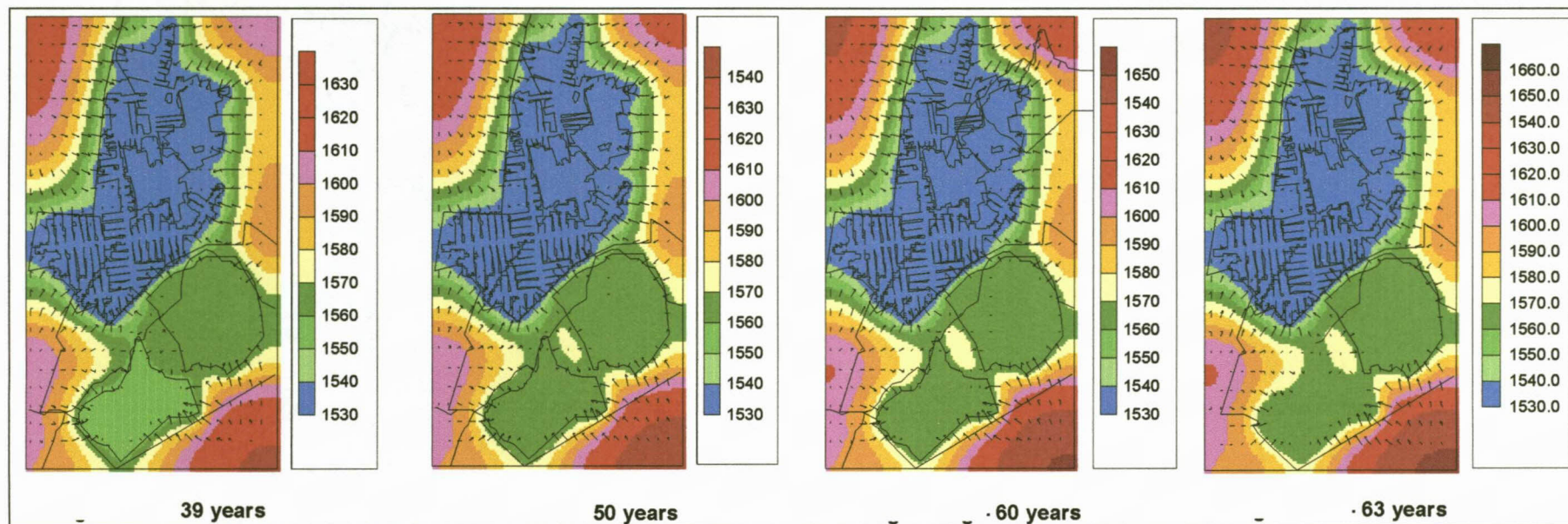


Figure 3-15 Sensitivity analyses on Kriel - Tavistock model - filling times using 14% recharge.

As Pit 6 starts to fill up, small amounts of water start to leak through the coal barrier from Kriel to Tavistock's underground area. The coal barrier in the area between the two collieries is approximately between 190 and 200m wide. A water budget was calculated during the course of the modelling simulation. The results from the water budget can be seen in Table 3-3.

For the calculations of the water budget the model area was subdivided into sub-regions. Three sub-regions were chosen and are as follows:

- Pit 6
- The unmined coal barrier between Kriel's Pit 6 and Tavistock's underground area
- Influx from the strata into Pit 5 and

The results of the water budget is calculated as follows: Water volumes for Pit 5 and 6 include the inflow from the strata into the pit. These volumes do not include the recharge percentage to the pits. The volumes of the intermine flow area are calculated as the flow from Kriel through the coal barrier to Tavistock's underground area.

Table 3-3 Results from the water budget report for the three sub-regions at Kriel-Tavistock model.

Years	5 years	10 years	20 years	30 years	40 years	50 years
Volumes	(m3/d)	(m3/d)	(m3/d)	(m3/d)	(m3/d)	(m3/d)
Pit 6	7.7	3.4	1.1	0.8	1.1	1.4
IMF	4.6	4.6	5.7	6.9	6.8	6.7
Pit 5	20.5	12.0	5.4	2.2	0.6	1.0

The decrease in the inflow volumes over time can be expected at Pit 6 for the first 27 to 30 years until the pit reaches its decant elevation. The decrease in the inflow volume is the result of the diminishing hydraulic gradient as the pit fills. Once the pit decants, an average decant volume of between 2800-2900 m³/d can be expected, based on the 20% recharge used on the opencast pits.

- The volume of water that flows through the unmined coal barrier from Kriel to Tavistock's underground area increases over time. This can be attributed to the fact that the hydraulic pressure on the coal barrier increases as the pit fills to its decant elevation. An average flow through the coal barrier was calculated at 5.8 m³/d, by making use of the results from Table 3-3.

For Pit 5 the volume of inflow will decrease as the pit fills to its decant level.

Figure 3-16 was prepared to show the results from the water budget calculations.

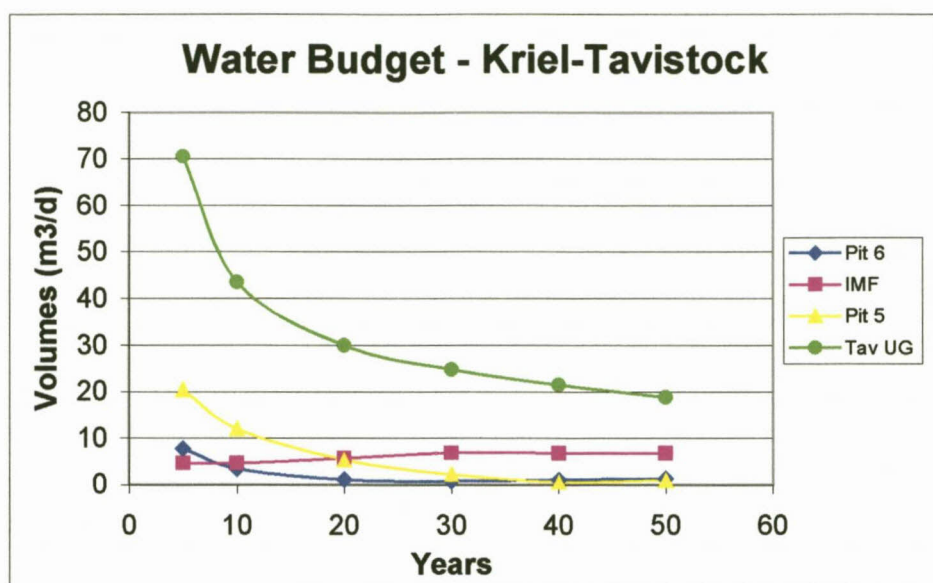


Figure 3-16 Graph showing the volumes of water that flows into the pits and through the IMF unmined boundary.

From the model it can be seen that the impact of intermine flow is minimal through the unmined coal barrier. From the water budget calculations it is clear that very little water is flowing through the coal barrier; this can be attributed to the fact that the barrier is 200 m wide as well as the low permeability of the strata. The small amounts of water which leaks through the coal barrier to the underground area are not problematic. The good quality water of Kriel Colliery will in fact enhance the quality of the underground area. The quality and the influence of intermine flow on the quality of opencast and underground areas will be discussed in Chapter 4.

3.9.3.1 Analytical and Stochastic calculations

By making use of Darcy's flow equation the flow through the coal barrier was calculated.

The coal barrier between Kriel and Tavistock Colliery was inspected and calculations were done to predict the amount of water seeping through the coal barrier.

Darcy's equation was used to calculate the flow by making use of the software "Decision Pro", which can stochastically generate different values.

The average flow (Q) through the coal barrier was calculated as $5.7 \text{ m}^3/\text{d}$ (See Table 3-4 for a complete summary of the analytical simulation). Flow will vary from a minimum of 2.11 up to maximum of $14.5 \text{ m}^3/\text{d}$. (See Figure 3-17 for graph of the frequency distribution of the coal barrier). The calculation of the flow through the coal barrier, by making use of Decision Pro, will be discussed and full interpretations of the graphs will be given in Section 3.12.

Table 3-4 Decision Pro simulation summary for the coal barrier between Kriel and Tavistock Collieries.

Simulation Summary	
Measure	Q
Observations	1,000
Mean	5.72296
Standard Deviation	1.7529
Posterior STD	0.05543
Variance	3.07266
Minimum	2.11858
5th Percentile	3.46252
Median	5.43874
95th Percentile	9.03066
Maximum	14.53921

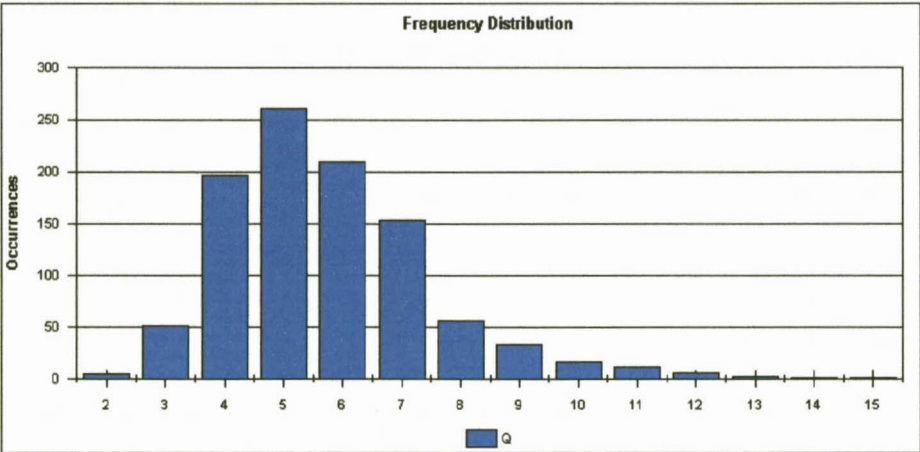


Figure 3-17 Graph showing the frequency distribution of flow through the unmined coal barrier.

From the calculations it is visible that the flow results of the model are in the same order as with the stochastic methods. Using stochastically generated values, a more realistic range of through flows can be given.

3.10 OVERALL CONCLUSIONS

The following conclusions can be drawn regarding the intermine flow taking place between Kriel and Tavistock Colliery. The two opencast pits, namely Pit 5 and 6, will take approximately 44 and 27 years respectively to reach their decant elevations. In this time small amounts of water will flow from Pit 6 to the underground area of Tavistock Colliery. From the water budget calculations an average flow was calculated over the coal barrier. A flow of $5.8 \text{ m}^3/\text{d}$ was calculated to flow through the barrier. Thus it can be concluded that intermine flow between these two collieries is minimal.

3.11 RIETSPRUIT COLLIERY - TAVISTOCK COLLIERY - TWEEFONTEIN COLLIERY FLOW MODEL

A typical scenario for intermine flow between different seams in underground mines and opencast on different seams is demonstrated in the Rietspruit-Tavistock-Tweefontein model. Figure 3-18 show a 3D visualization of the flow model.

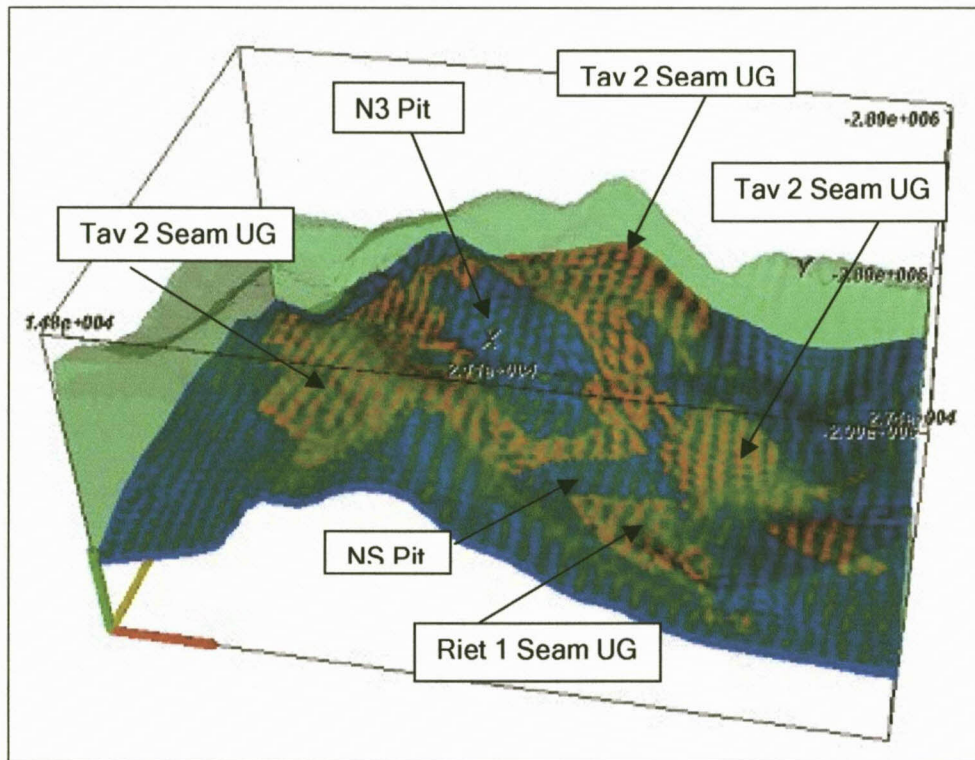


Figure 3-18 3D visualisation of the floor contours of the Rietspruit-Tavistock Tweefontein flow model.

Intermine flow can take place in several areas on the boundary between Rietspruit and its underground area, between Tavistock and Tweefontein Colliery as well as Rietspruit and Tavistock Colliery.

Two cross sections were prepared to give a north-west south-east section over the N3 and North-South opencast pit as well as a southwest-northeast section over the North-South Pit, Rietspruit underground and Tavistock underground area. The two sections are numbered respectively A and B (See Figure 3-19 for section lines).

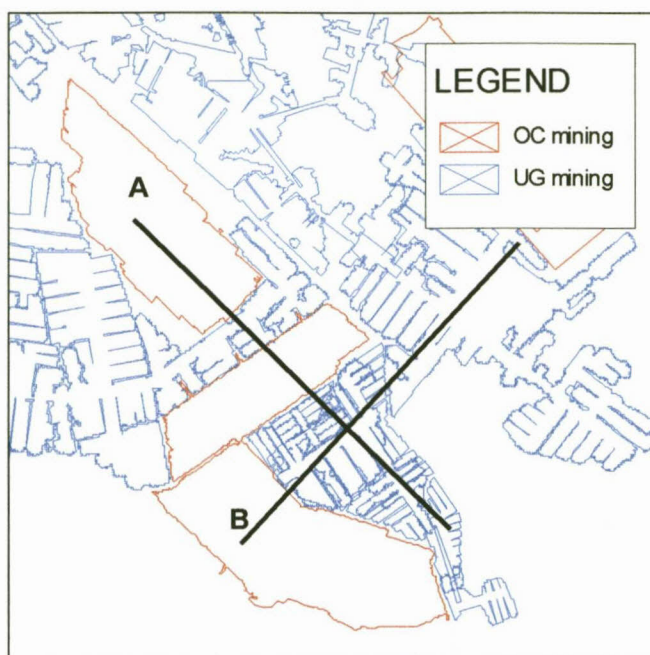


Figure 3-19 Locations of the cross section areas.

The two sections explain the type of mining in the areas, as well as mining heights and gradients of the areas. The sections can thus give a glimpse of current and future flow directions (See Figure 3-1 and Figure 3-20 for sections A and B).

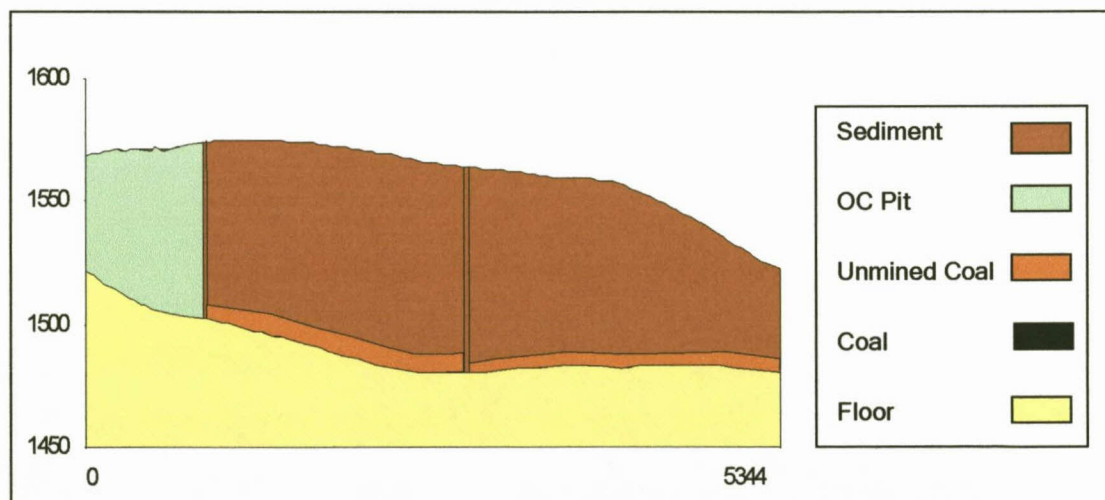


Figure 3-20 Cross section B. Southwest- Northeast cross section through the North-South Pit, Rietspruit 1 and 2 Seam underground and Tavistock 1 Seam underground. Cross section A can be seen in Figure 3-1.

Water in the mines will migrate along the floor of the coal seams and since the No. 2 Coal Seam is the dominant seam mined at Rietspruit, Tavistock and Tweefontein Collieries, water migration will at first be along this seam. The Rietspruit area is relatively flat and has an undulating gradient. Drainage of groundwater in the Rietspruit area takes place towards the south and the southeast (See Section B).

On a local scale, water will first accumulate in the opencast pits at Rietspruit Colliery. From there, it will migrate through the coal barriers to Tavistock- and Rietspruit underground workings.

The two opencast pits as well as the underground area at Rietspruit will decant with rising water levels. The North-South Pit will decant at a level of 1530 mamsl. The decant level the N3 Pit is towards the north, at the much higher level of 1559 mamsl. Rietspruit's underground area will decant at a level of 1521 into the Steenkool Spruit.

Opencast mining at the Tavistock North Pit areas will create linkages with the surface that did not previously exist. After opencast mining has been completed, the decanting of mine water will take place from the East Pit at an elevation of 1505.3 mamsl (Hodgson and de Necker, 2001).

Because of the flow of water to the north along the floor of the No. 2 Seam workings, water will start to dam against the coal barrier between Tavistock and Tweefontein Colliery which will sooner or later have an impact on Tweefontein Colliery's 2 Seam underground area.

The positions of the decant points in the study area can be seen in Figure 3-21.

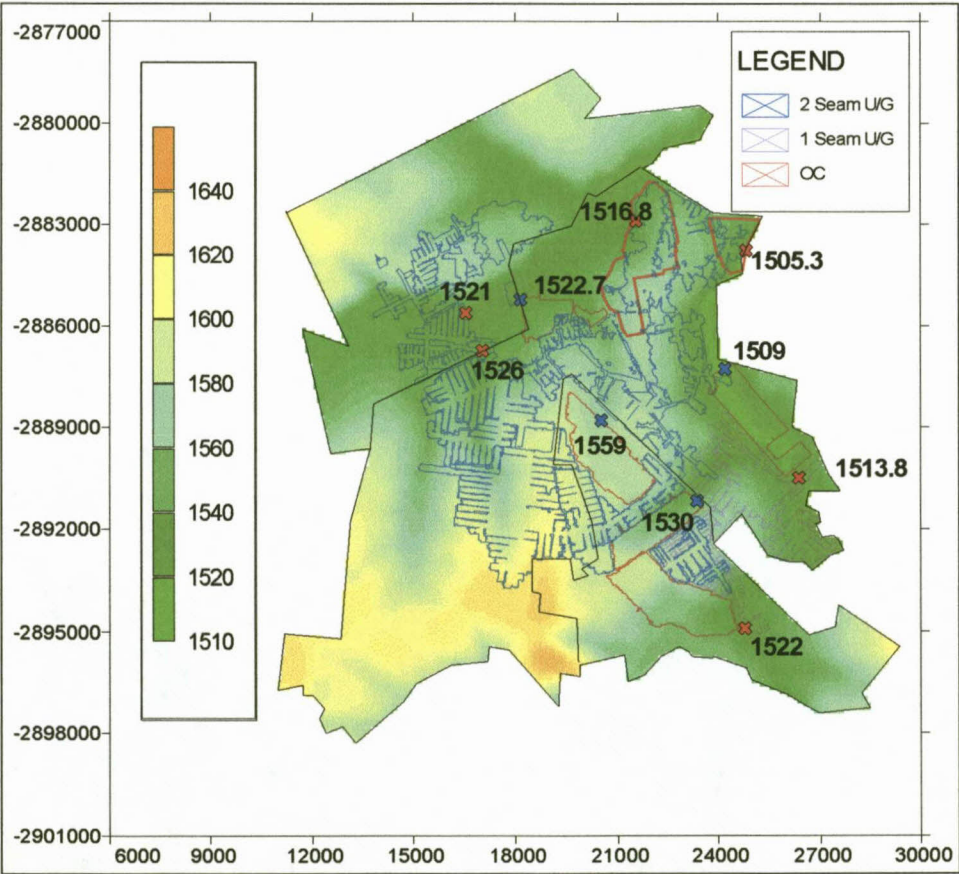


Figure 3-21 Decant positions Rietspruit, Tavistock and Tweefontein Collieries.

The floor contours indicate that water within the pits will predominantly accumulate in the northeastern part of the North-South Pit. The pits will fill up from here until decant levels are reached, as described earlier. At the N3 pit, water will first accumulate within the center of this pit.

For Tavistock Colliery the general water flow is towards the northwestern and southeastern parts of the colliery.

3.11.1 Stage curve calculations

Stage curves were drawn for the two opencast pits at Rietspruit Colliery. Stage curves for the void space in the two pits are represented in Figure 3-22 and

Figure 3-23.

By making use of current pit water levels received from Rietspruit Colliery, a calculation can be made of the projected amount of water currently present in the pit. With a water level elevation of 1500 in the N3 Pit, a volume of 34570 m³ was calculated. The capacity of the pit at decant elevation is approximately 47.3 Mm³.

See Figure 3-22 and Figure 3-23 for stage curves of Rietspruit's two opencast pits.

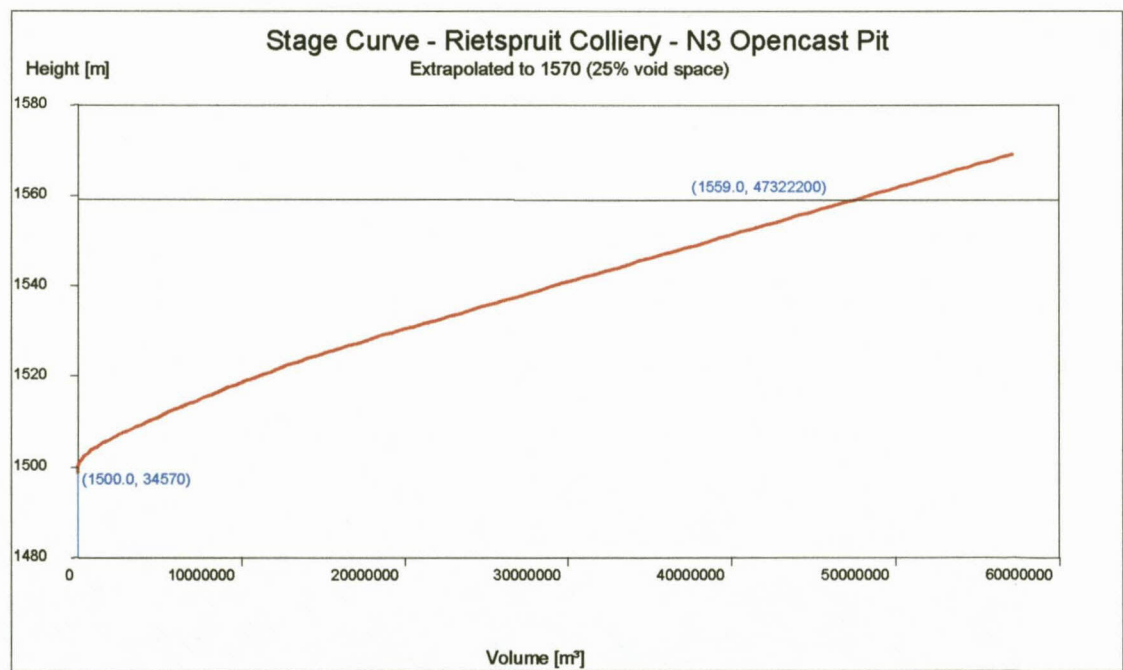


Figure 3-22 Rietspruit N3 Pit at current elevation of 1500 and decant elevation of 1559.

The current elevation at the North-South pit is at 1499 mamsl. A stage curve was also created to calculate the capacity of the pit. At the current water level of 1499 the pit

will hold 23.8 Mm³ of water and when the pit is completely filled up it will have a volume of 44.5 Mm³.

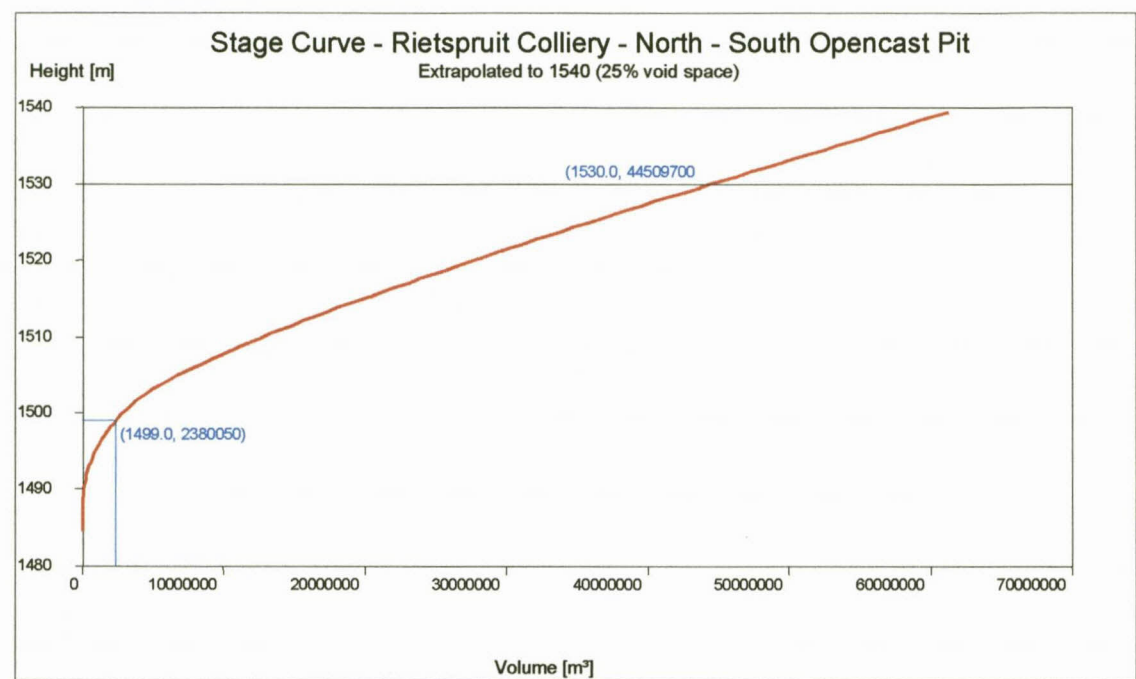


Figure 3-23 Rietspruit North-South Pit at current elevation of 1499 and decant elevation of 1530.

Results from the stage curve calculations of all the opencast and underground areas in the model area can be seen in Table 3-5.

Table 3-5 Positions of decant elevations and the volumes of water in the opencast and underground areas of the model area.

Name of Pit	Decant elevation	Water in Pit (m³)	Area (Ha)
N3 Pit	1559	47322200	381
North and South Pit	1530	44509700	707
Tavistock 2 Seam U/G	1526	75453200	2484
ATCOM O/C	1509	23672300	309
Tavistock 1 Seam U/G	1513.8	14089100	817
TwEEfontein 2 Seam U/G Pit	1521	22352200	6264

3.11.2 Model simulations

Intermine flow is suspected in a few areas in the Rietspruit-Tavistock-Tweefontein area. A flow model was constructed to simulate the groundwater flow in the area. It was decided to investigate a few unmined country rock or coal “barriers” in the area

to calculate the flow volumes through these barriers and to see if intermine flow plays a role in the filling times of pits (See Figure 3-24 for suspected intermine flow areas).

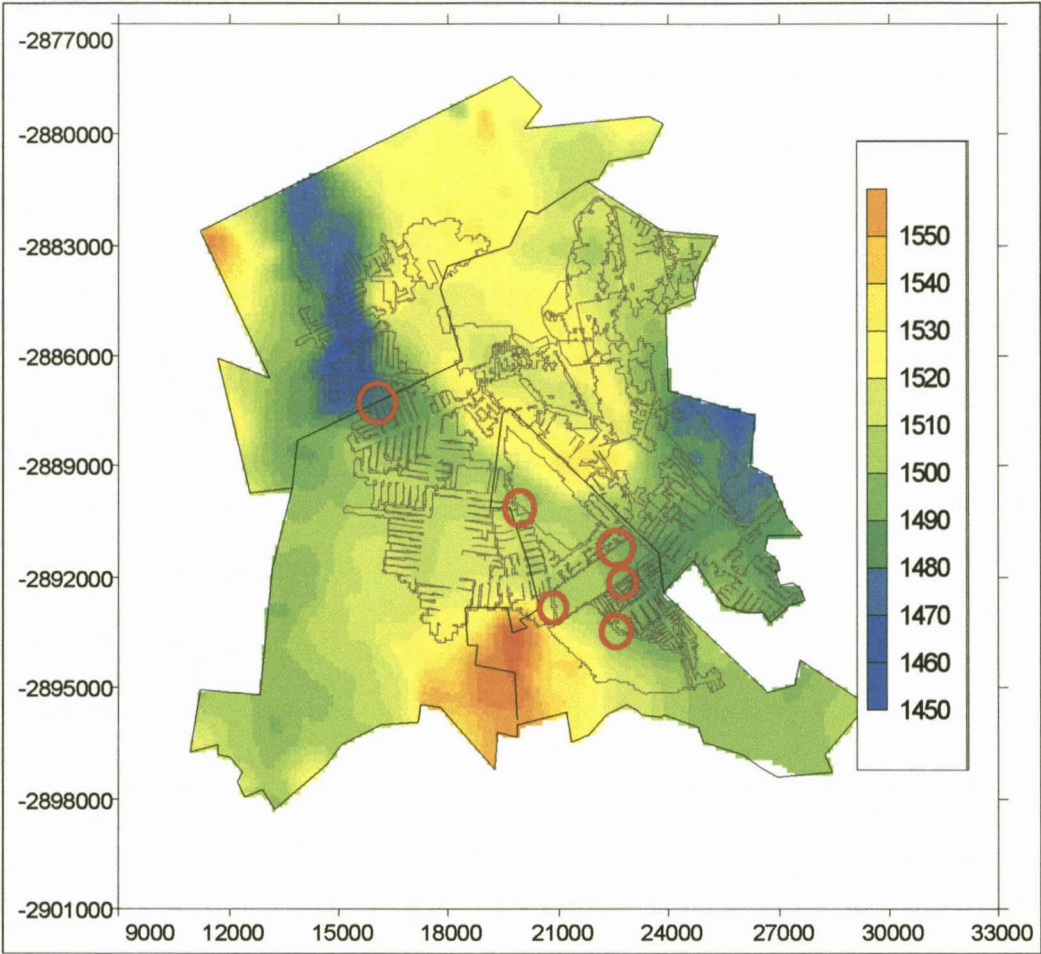


Figure 3-24 Suspected intermine flow area. The red circles are an indication of the areas where intermine flow is investigated.

3.11.2.1 Discretisation

The mesh constructed for the Rietspruit - Tavistock - Tweefontein flow model consisted of 182 x 226 cells in the x and y directions respectively. Each of the cells is 50 x 50 m (See Figure 3-25 for mesh of model).

The coordinates of the area are -2895340, 14420 (lower left corner) to -2886240, 27720 (upper right corner).

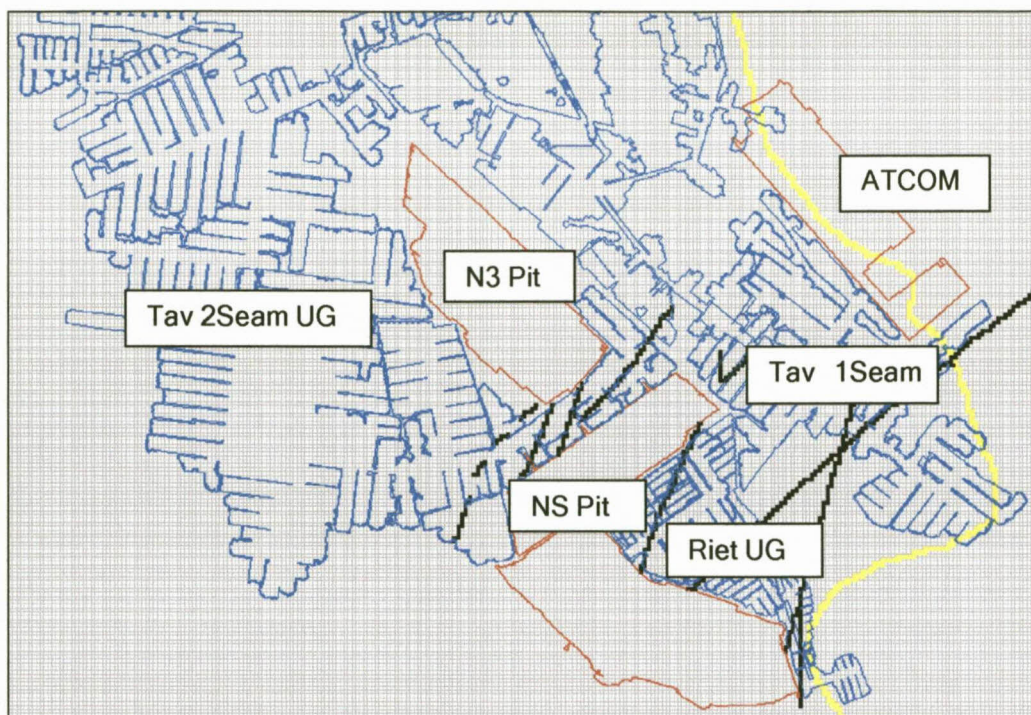


Figure 3-25 Spatial discretisation of the model system. Grid overlaying the Rietspruit - Tavistock - Tweefontein flow model.

3.11.2.2 Layers and layer construction

The model consists of two layers. For the flow model the 2 Seam floor contours have been used to simulate the bottom of the model, and the surface contours were used to simulate the top of the model. Mining heights of the underground mining areas were received from the Coaltech 2020 project (Jeffrey, 2002) (See Table 3-6 for mining heights in specific underground areas).

Table 3-6 Mining heights of the underground areas from (Jeffrey, 2002).

Area	Seam	Mining height
Tavistock	2	5.35
Rietspruit	1, 2	5.8
Tavistock	1	2.8
Tweefontein	2	5.35

3.11.2.3 Initial hydraulic heads

In the case of the Rietspruit-Tavistock-Tweefontein model, an average water level of 11 m below the surface was used to simulate the initial conditions during the steady state calibration of the model.

During the transient state of the model, new water levels were created to simulate the water levels in the mining areas.

Water levels received from Rietspruit Colliery were used to simulate the current water levels in the opencast pits. Water level of 1500 mamsl and 1499 mamsl respectively were used to simulate the average current water levels in the N3 and North-South pit (Coaltech 2020 project).

Rietspruit Colliery reported that the underground areas are currently empty. For Tavistock and Tweefontein the mines were simulated as empty (See Figure 3-26 for initial water levels used in the model area).

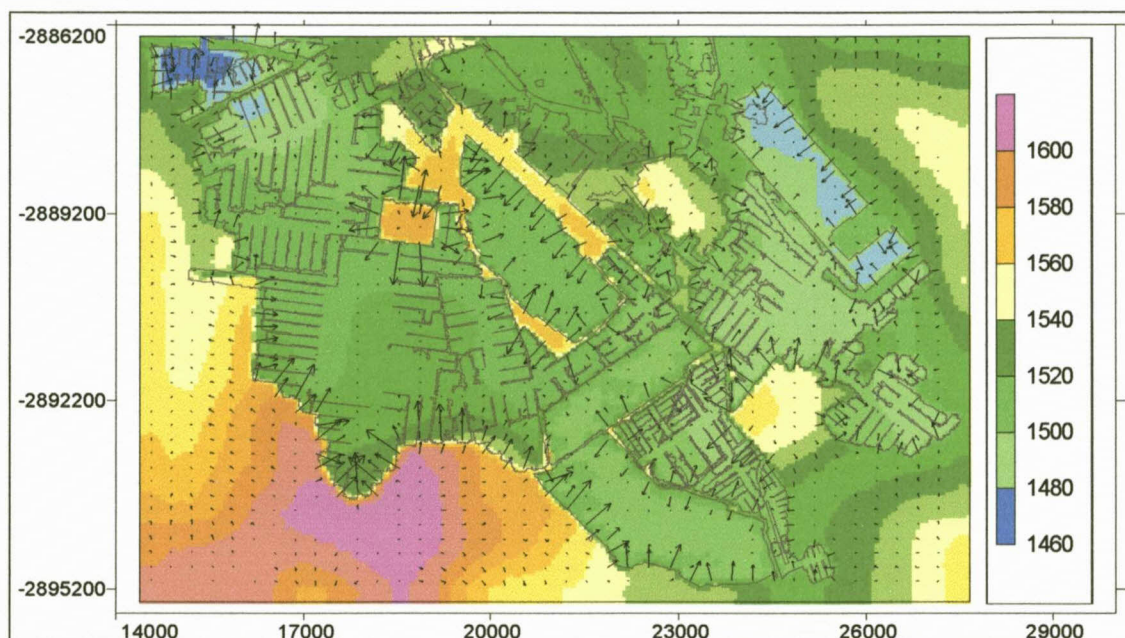


Figure 3-26 Initial water levels used in the flow simulation.

3.11.2.4 Horizontal Hydraulic Conductivity and Transmissivity

A hydraulic conductivity for the undisturbed coal has been measured at 0.1 m/d (Hodgson, 1995), and for the rest of the model area a hydraulic conductivity of 0.0015 was assigned (Hodgson and Krantz, 1998). A hydraulic conductivity of 50 m/d was taken for the opencast and underground areas.

3.11.2.5 Horizontal flow barrier

Horizontal flow barriers were used to simulate the dykes in the Rietspruit - Tavistock area. Note that the dykes in the opencast area were extracted with the coal and are not present the opencast areas. In some parts of the underground areas the dykes are left *in situ*, and were thus simulated in the model. Care must be taken to ensure that dykes that are already extracted are not left in place, and vice versa, otherwise the groundwater flow of the model will not correlate with the expected natural groundwater flow in the workings. Some of these dykes that were left *in situ* by the

mine, serve as impermeable obstacles that interfere with the natural groundwater flow occurring in the underground workings.

3.11.2.6 Rainfall

An average rainfall was taken over the model area. Rainfall data were available for only Tweefontein and Tavistock Collieries. The rainfall of the two areas are:

Tweefontein - 747.35 mm (Tweefontein EMPR, 1995)

Tavistock - 750 (Hodgson, 1995)

An average rainfall of 748.7 mm/a was used for the simulation of the model.

3.11.2.7 Model results

To establish intermine flow paths, particle tracking was done by making use of Modflow's tracking package PMPATH. PMPATH enables you to put a particle in any place in the model, and then the flow of that specific particle is shown over time. From the particle tracking it is visible that the North-South Pit is constantly losing water, and the long filling period might be attributed to this. A constant outflow is thus general (See Figure 3-27 to Figure 3-29 for the particle tracking of groundwater in three steps, namely in year 10, 50 and 100).

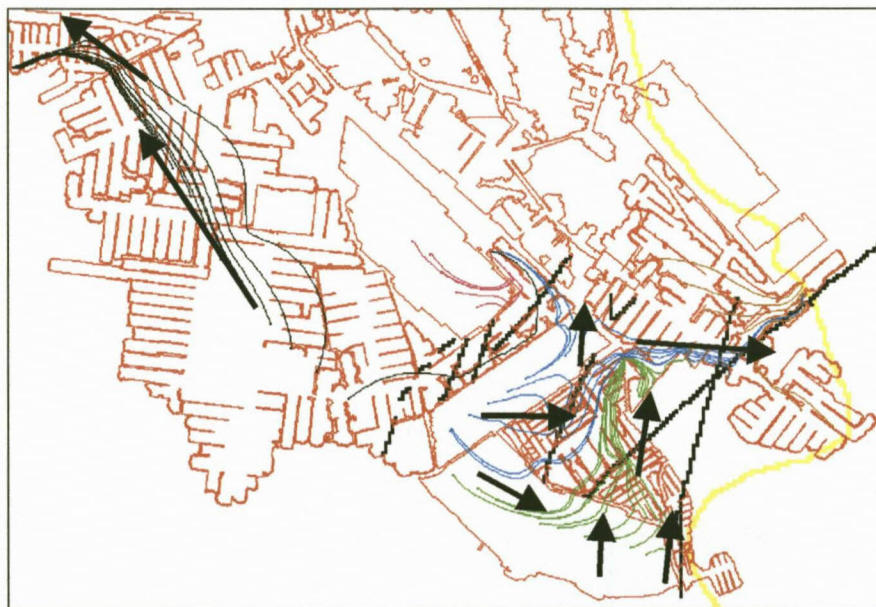


Figure 3-27 Particle tracking - 20 years.

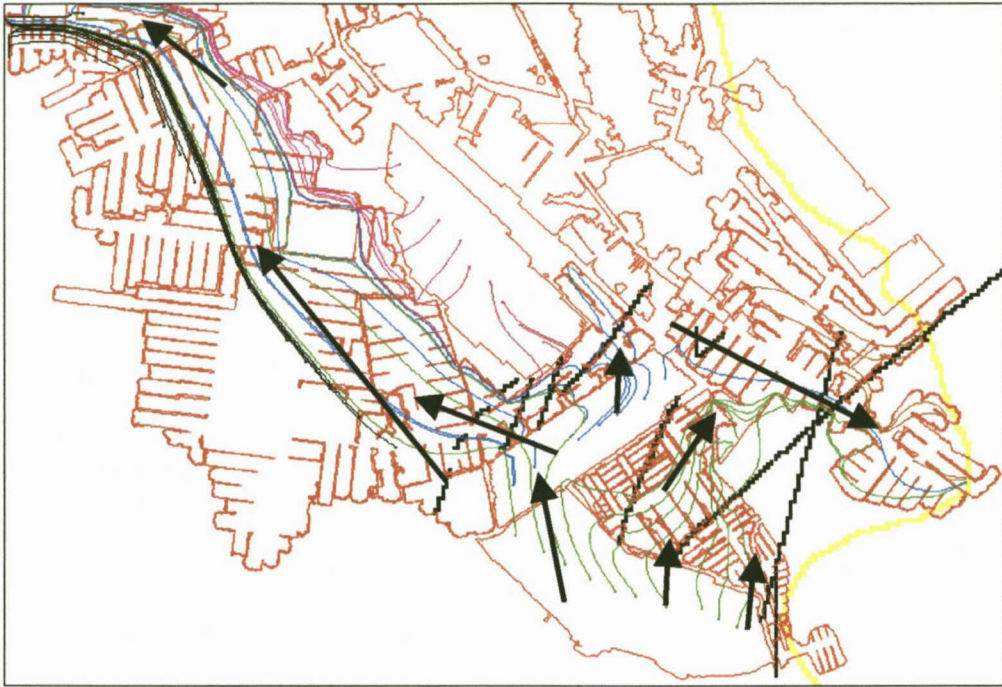


Figure 3-28 Particle tracking - 50 years.

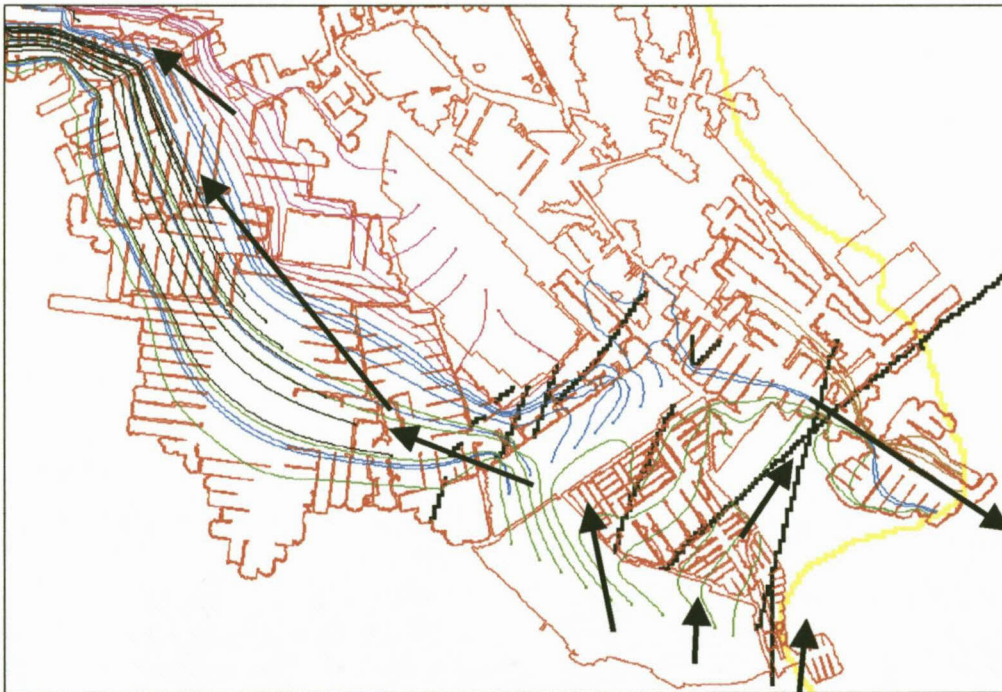


Figure 3-29 Particle tracking - 100 years.

Flow volumes through the different coal barriers were calculated. For the calculations of the water budget, the model area was subdivided into sub-regions.

Six sub-regions were chosen and their location can be seen in Figure 3-30. Figure 3-30 is just an illustration of the area where intermine flow is taking place. Intermine flow will normally take place in the area where the coal barrier is thin and also in areas where the greatest hydraulic gradient exists.

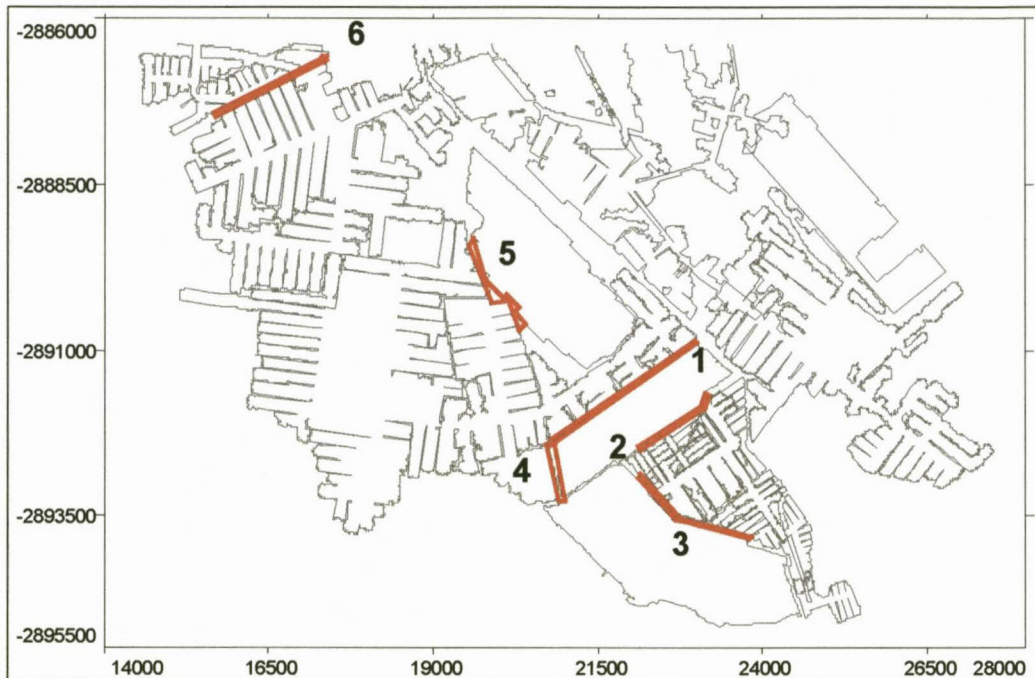


Figure 3-30 Positions of the intermine flow areas.

Water budgets were calculated for each of the coal barriers. Because of the uncertainty regarding true rebound times predicted by the model, only the water budget results for the first 40 years will be shown to give an indication of the amount of flow through the coal barriers. The results from the water budget for layer 1 and 2 can be seen in Table 3-7 and Table 3-8. Graphs were plotted to see the variation of volumes through the coal barriers over time. Flow in the first layer is much less than the flow in the second layer, because of the permeability of the coal layer. The permeability of 0.1 m/d was assigned to the coal layer (See Figure 3-31 and Figure 3-32 for graphs of the water budget of layer 1 and 2).

The volumes of mine water leaking through the coal barriers were measured in m^3/d .

Table 3-7 Results from the water budget report for layer 1.

ZONES	ZONE 1	ZONE 2	ZONE 3	ZONE 4	ZONE 5	ZONE 6
LAYER 1						
10	4	21	37	9	13	36
20	2	25	46	4	6	38
40	3	29	57	1	6	39
60	6	32	63	4	17	37
70	7	33	66	6	26	35

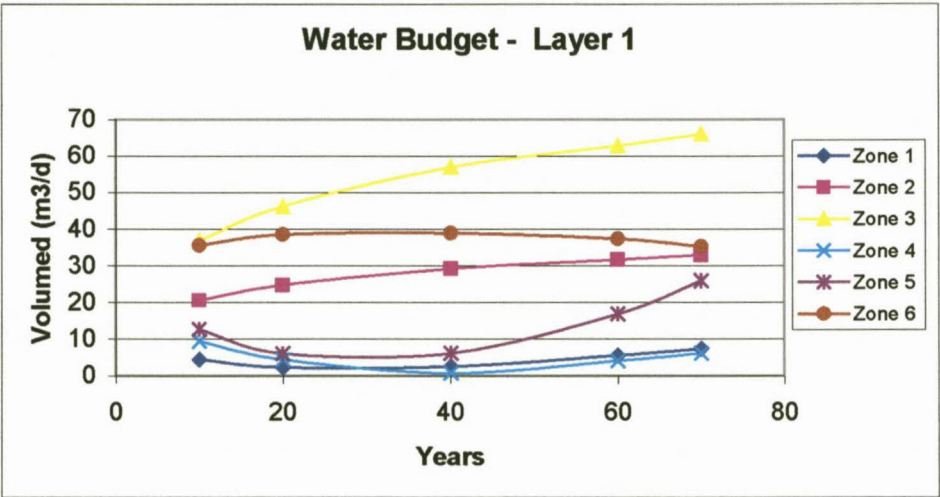


Figure 3-31 Water budget for layer 1.

Table 3-8 Results from the water budget report for layer 2.

ZONES	ZONE 1	ZONE 2	ZONE 3	ZONE 4	ZONE 5	ZONE 6
LAYER 2						
10	1117	80	168	67	44	246
20	595	96	213	31	22	272
40	333	113	265	4	21	278
60	706	123	293	20	57	267
70	932	128	309	31	86	253

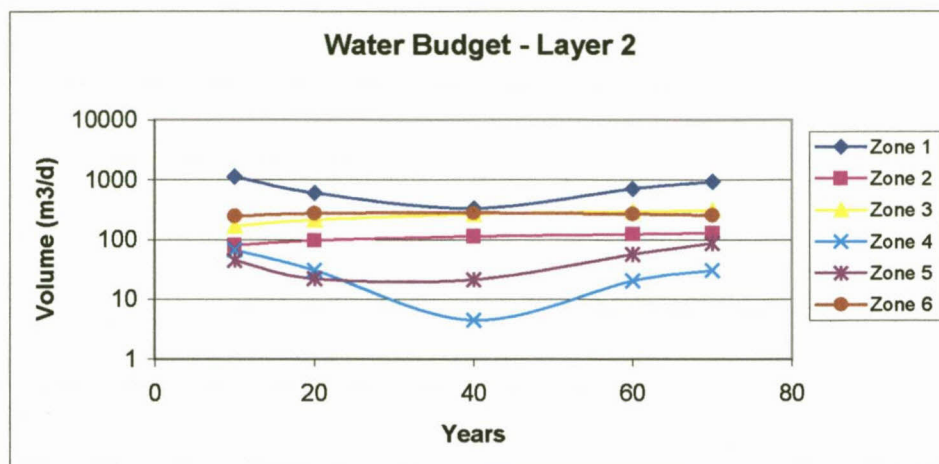


Figure 3-32 Water budget for layer 2.

An average volume per day was calculated over the first four zones to predict the amount of flow that the North-South Pit loses because of intermine flow for the first 70 years.

From the budget report and calculations it is visible that the North-South Pit loses approximately 1100 m³ of water per day through the four coal barriers.

From the flow volumes of layer 1 and 2 it can be concluded that Rietspruit Colliery is losing a huge amount of water through intermine flow to the Rietspruit and Tavistock underground areas. Figure 3-33 was compiled to show why intermine flow plays such a big role at Rietspruit Colliery. Mine plans received from Rietspruit and Tavistock Collieries show that in some places a minimum mine boundary exists between the workings. This impedes the simulation of the model and can thus influence the accuracy of the flow model in these parts. See Figure 3-33 for an illustration of the thickness of the coal barriers in the area around the North-South opencast pit. Arrows show some of the positions where a minimum coal barrier exist.

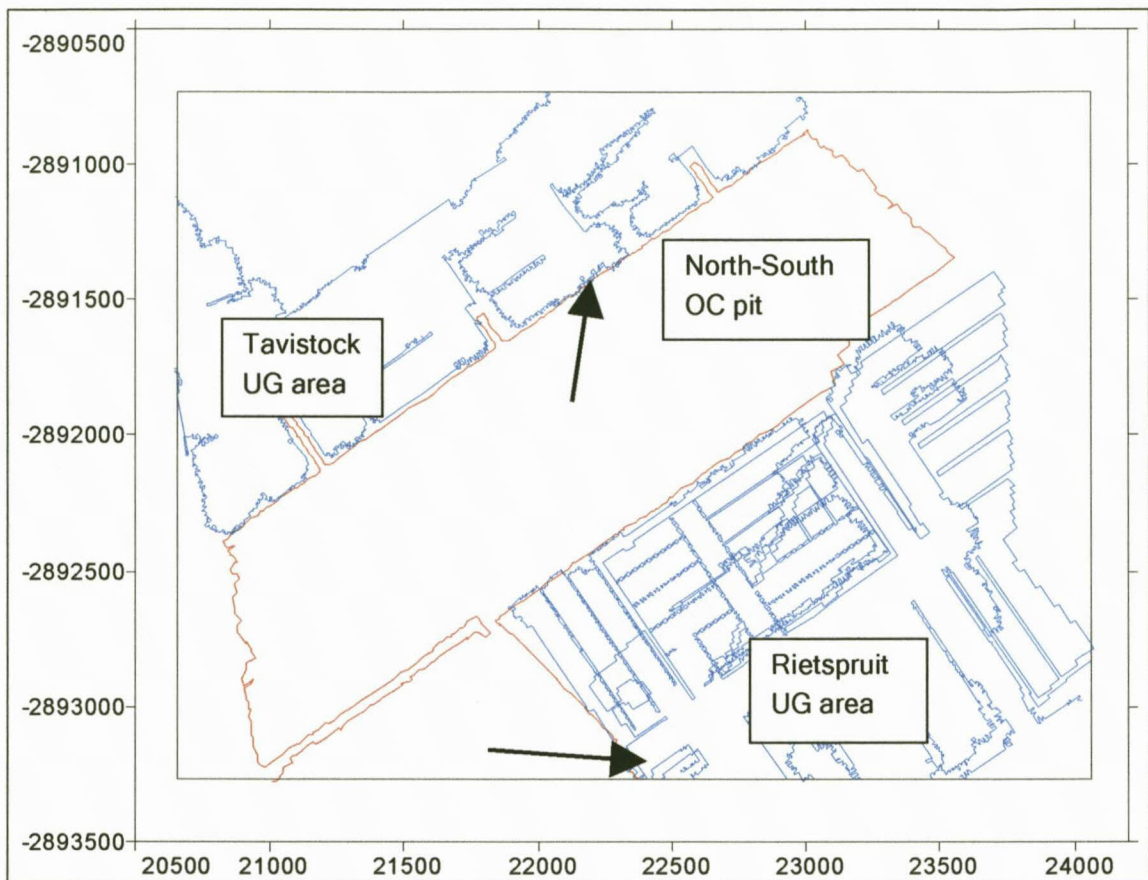


Figure 3-33 Coal barrier widths in the Rietspruit and Tavistock area.

Filling times were also calculated by making use of the flow model. The predicted filling times calculated by Modflow appear to be unrealistically long (See section 3.13.1), when compared with more simple volumetric refilling methods. The reasons for this lie in leakage from the pits and an over-estimation of flows by the models (See section 3.13.1). The opencast pits loses a huge amount of water through intermine flow, but filling times were still considered to be unrealistically long. An analytical model was used to predict the alternative filling times of the areas. For the analytical model the parameters depicted in Table 3-16 were used.

Table 3-9 Parameters used in analytical model.

Parameters	Values
Rainfall	748.7
NS-OC decant point	1530
NS-OC area (Ha)	706
NS decant point (mamsl)	1530
Volume at decant (MI)	44
Current WL (mamsl)	1499
K-value (m ³ /d)	0.1
Barrier Thickness (m)	30
Riet UG area(Ha)	429
Volume at decant (MI)	11

From the calculations of the analytical model the following filling times were predicted for the North-South opencast pit as well as for the Rietspruit underground area.

For the first 60 years water will flow from the North-South Pit to the underground area. It will take approximately 66 years for the underground area to fill up. After the underground area has been filled, the flow will rapidly decrease. The North-South Pit will take approximately 68.4 years to reach its decant elevation of 1530.

3.12 ANALYTICAL AND STOCHASTIC CALCULATIONS

The flow through the coal barrier for Zone 3 was tested by making use of analytical and stochastic methods to check the Modflow answers. Analytical methods, making use of Darcy's law, were used for the calculations. Parameters from the flow model for example, K-value, length, width as well as the head difference of coal barrier where intermine flow is present, were used to do the calculations.

A Log normal distribution were used during the stochastic calculations.

A frequency distribution (Figure 3-34) of the Q was plotted. From the graph it is visible that Q varies between 150 and 450 m³/d, but the flow will most likely be between 250 and 350 m³/d. The K-values were varied over a wide range. The K-values used in the calculation range between 0.03 and 0.26. The reason for the this is that information on K-values of coal barriers is very scarce, and thus a realistic range of answers can be calculated for different K-values (See Table 3-10 for a simulation summary of the flow calculations). A minimum flow of 123 and a maximum of 846 m³/d can be expected. A flow of 846 m³/d can be expected in areas where fractures are prominent, and this accelerates the flow through the coal barrier.

Table 3-10 Simulation summary of the flow through zone 3.

Simulation Summary	
Measure	Q
Observations	1,000
Mean	332.88309
Standard Deviation	102.04003
Posterior STD	3.22679
Variance	10,412.16793
Minimum	123.13536
5th Percentile	201.32068
Median	316.32914
95th Percentile	525.44027
Maximum	846.24789

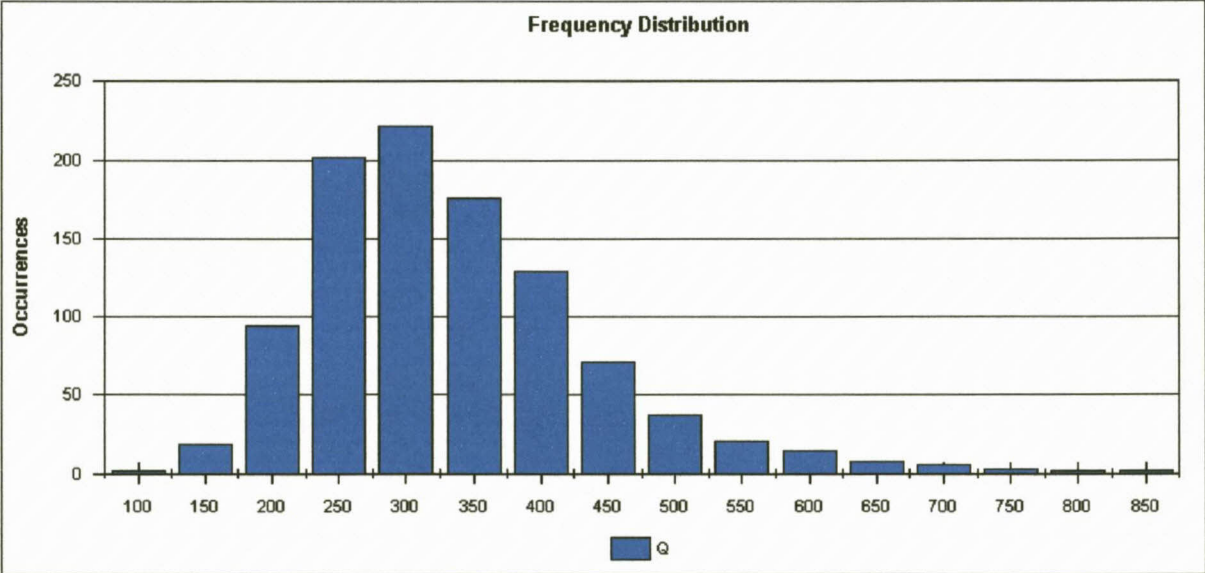


Figure 3-34 Frequency distribution graph of the flow through zone 3 by making use of analytical and stochastic methods.

From Figure 3-35 (cumulative distribution graph) the following it can be seen that a 50% probability, the flow will be less than 300 m³/d. There is a 20% chance of the flow being more than 400 m³/d. The expected range of flow is thus 250 - 400 m³/d.

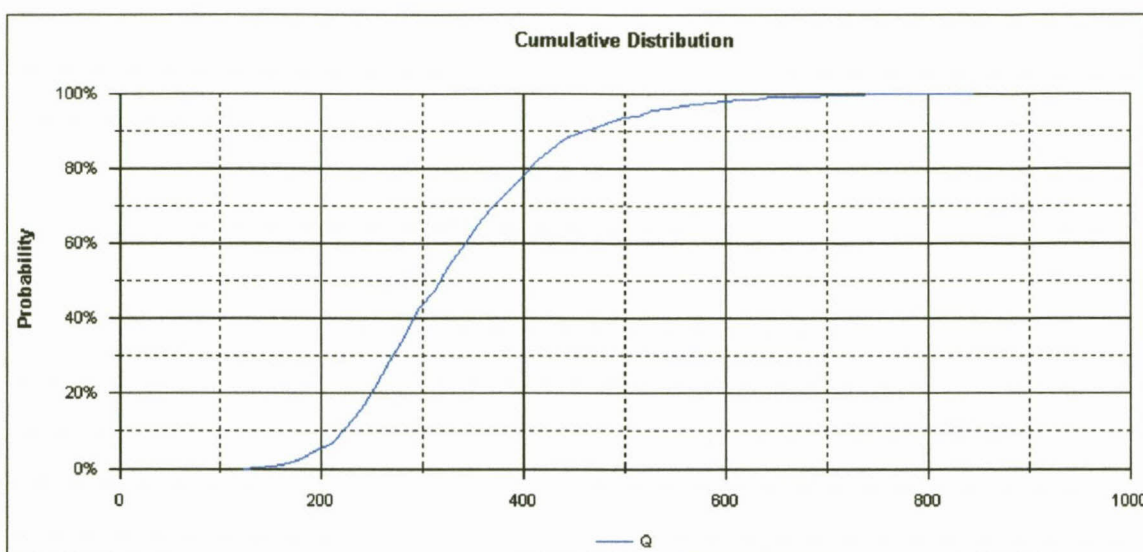


Figure 3-35 Cumulative distribution graph of the flow through zone 3.

It can be concluded that the answers from the Modflow simulations and the analytical methods are in a close range.

Modflow predicts a flow volume of $329 \text{ m}^3/\text{d}$ for zone 3, which is in the same order as the analytical methods, which predict a flow of $333 \text{ m}^3/\text{d}$. See Table 3-10 for flow predictions.

3.13 ISSUES OF CONCERN

During the simulation of the model, all the answers from Modflow were checked by analytical methods. All calculations were in the same order, except for the filling times of the model. Although much of the water from the opencast pits was lost through intermine flow, the opencasts pits still took an unrealistically long time to fill to their decant level. It was decided to investigate the situation to determine a reason for this discrepancy.

3.13.1 Investigation into discrepancy of refilling times

In the Rietspruit Tavistock area we are dealing with direct opencast - underground interaction because of intermine flow. The Rietspruit North-South opencast pit and Rietspruit underground workings are taken as an example to illustrate the difficulty of simulating an opencast and underground area next to each other.

The Modflow simulation was done with the intention of calculating the flow volumes and specifically the filling times of the specific areas. The filling times calculated by Modflow appear to be too long, and it was decided to determine any potential source of error using independent methods.

3.14 SIMULATION OF A OPENCAST AND UNDERGROUND AREAS IN MODFLOW

Two models were built so predict the filling times of opencast and underground areas. For the opencast and underground areas, the following models were used for the simulation:

- Opencast area - Modflow simulation
- Underground area - Modflow simulation as well as a box model simulation.

3.14.1 Opencast simulation

Kriel Pits 5 and 6 can be taken as a good example of modelling the flow and filling times of opencast pits. During the simulations of the opencast pits at Kriel Colliery the following was simulated. A 20 or 14% recharge was added to the area. K-values from literature are used. Calculations and predictions were made in the past by Hodgson, 1999 on the two opencast pits and during the calculations of the filling times, Modflow gave filling times in the same order.

A second scenario was created by making use of the Rietspruit North-South opencast pit. To illustrate the point, filling times were calculated for just the opencast pit and thus no influence of the underground mine right next to the pit was taken into account. A two-layer model was prepared to simulate the conditions and to predict the filling times of the opencast area. A recharge of 20% was applied to the opencast area. A horizontal K-value of 0.1 m/d was used and an S-value of 25%. See Table 3-11 for parameters used in the flow simulation.

Table 3-11 Parameters used in the model simulations.

North-South Opencast Pit	
Layers	2
K(horizontal)	0.1 m/d
Rainfall	750 mm/a
Recharge %	20%
Storativity	25%

A diagram was prepared to give an illustration of the way Modflow does the calculations (Figure 3-36).

The diagram illustrates a two-layer model of the North-South opencast pit. Horizontal K and rainfall are the two factors that have a prime influence on the filling times of the pit.

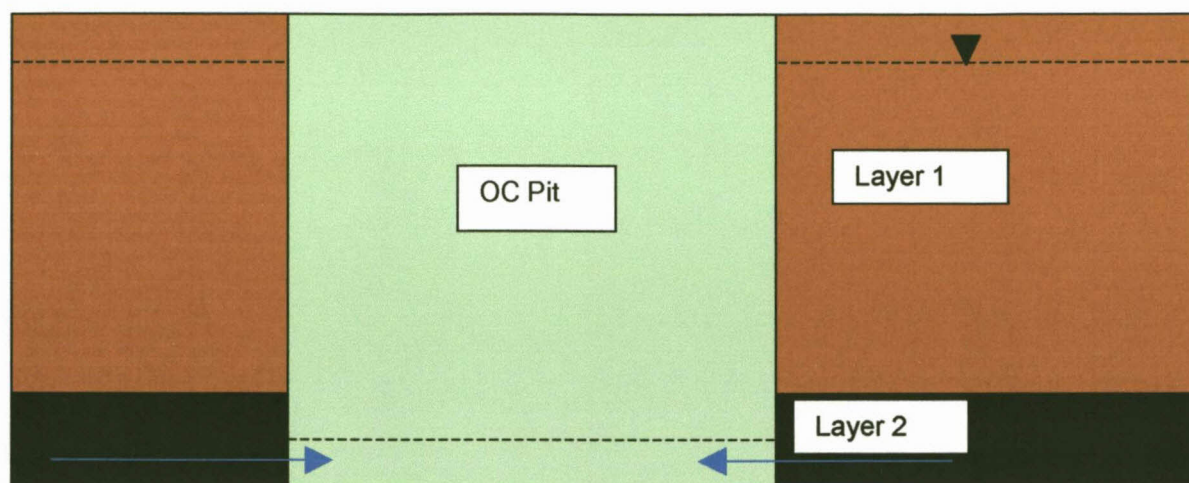


Figure 3-36 Representation of the Modflow calculations.

For the purpose of this section the existence of the underground lying to the right of the North-South Pit was ignored. A Modflow flow simulation was run to calculate the filling time of the pit. Results from the flow model indicate that the pit will take approximately 24 years to fill to its decant elevation of 1530 mamsl. An analytic method was then used to check the accuracy of the Modflow predictions. From the analytic method a filling time of 24.8 years was calculated.

Filling times were predicted by Hodgson *et al.* (1996) and Van Tonder (1997) for the North-South Pit. Filling times were calculated for just the opencast pit and a filling time of between 25 and 32 years was predicted, depending on the extent of the rehabilitation (Van Tonder, 1997). The filling times predicted are in a very close range. This validates the use of Modflow during the calculations of an opencast pit. Neither Hodgson nor Van Tonder's calculations included the influence of the underground area next to the opencast pit. If the intermine flow is taken into account, the simulation of refilling times is likely to change and the previous quoted times are probably erroneous.

Modflow is a saturated 3D model and thus can simulate the correct filling time of opencast pits.

3.14.2 Simulation of an underground area in Modflow

The North-South Pit and its neighboring underground area were chosen to investigate the discrepancy (See Figure 3-37 for the study area). A cross section was

drawn over the pit and workings to get a better idea of the surface and floor, and thus the water flow direction of the area (See Figure 3-38 for a cross section over area).

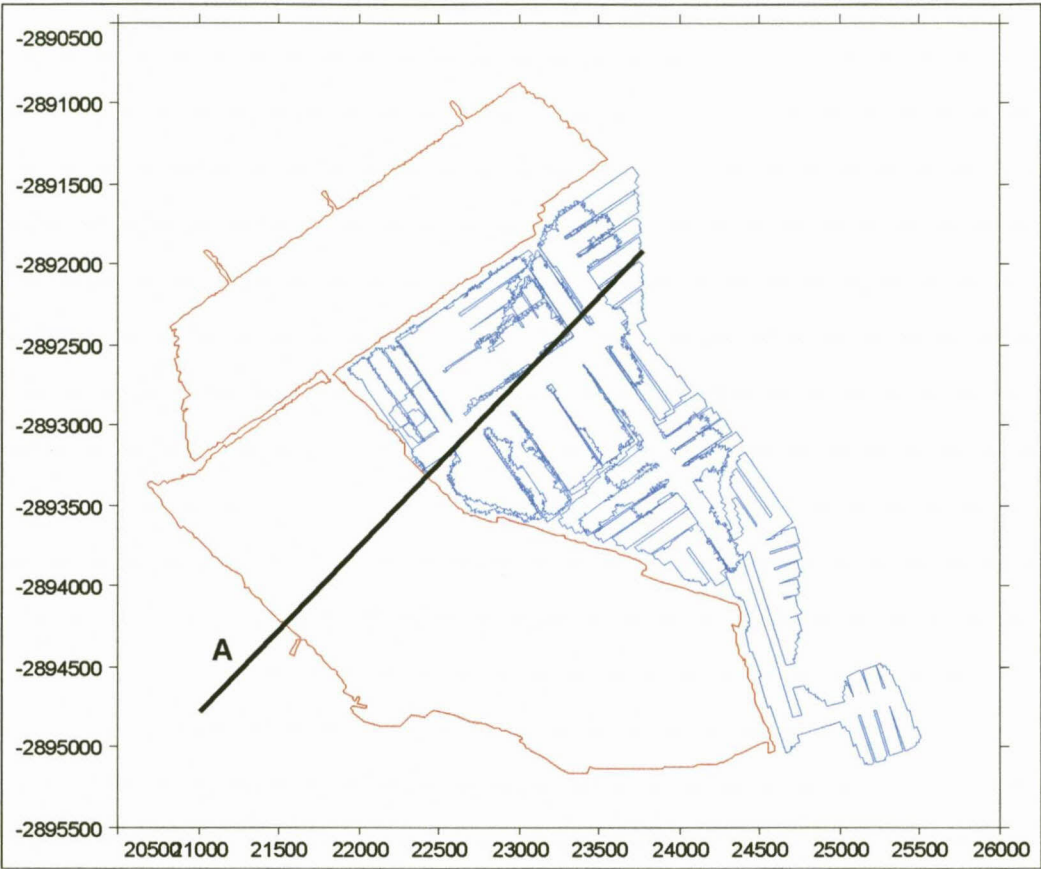


Figure 3-37 Opencast-underground interaction of Modflow

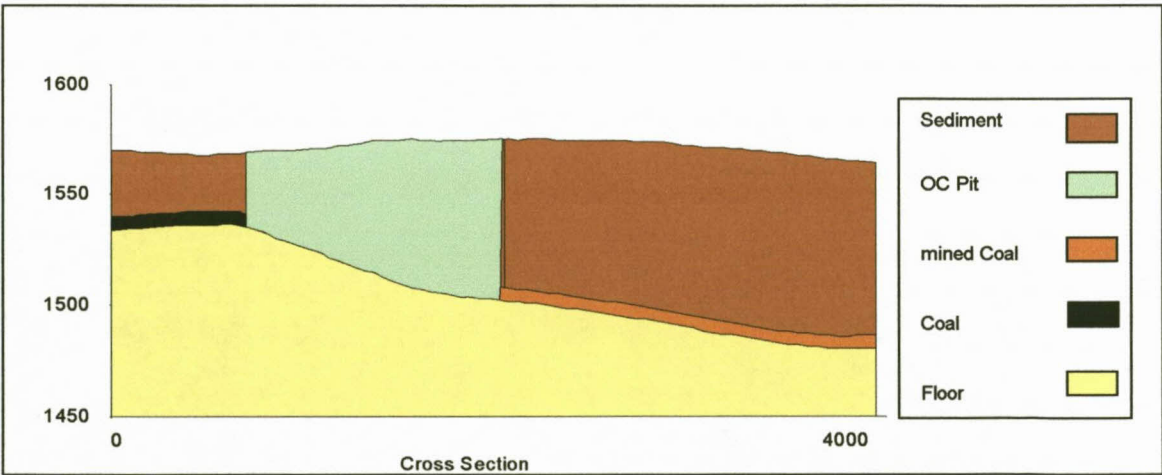


Figure 3-38 Cross section through the Rietspruit Area.

Two models were simulated for the prediction of the filling time of an underground area, namely a flow model by making use of Modflow, and an analytical box model.

This model illustrates the difficulties in calculating the filling times of underground areas. A Modflow model was built to simulate the filling times of the underground area. The model represents a homogeneous underground area. The underground mining area is 600 ha, and is 50 m below the water level. The excavation height of 3 m were used. The following parameters were used during the simulation of the flow model:

A K-value of 0.1 was used for the coal and a K of 50 for the mined-out underground area. S-values of 0.001 were used for the coal and 0.7 for the underground area. The K-vertical used for the simulation was 0.01 m/d. Secondly, an analytical box model was built to predict the filling time of the same underground area. Exactly the same parameters were used during the simulation of the box model (See Table 3-12 for the parameter specification of both models). Figure 3-39 gives an illustration of the two models.

Table 3-12 Specification of the parameters used for the underground area.

Parameters	Values(m/d)
K	0.1
S	0.001
K in Underground	50
S in Underground	0.7
K _(Vertical)	0.01

It was assumed that the underground mine contains no water at time = 0, i.e. unsaturated conditions exist in the mine. For this situation the following is true:

- Vertical influx (m^3/d)= Area*K_(vertical), because the gradient = 1
- Horizontal influx (m^3/d)=unsaturated horizontal through flow area*K_(horizontal) because the gradient = 1. At time = 0, the unsaturated through flow area is equal to 3m.

As the unsaturated thickness of the underground mine decreases with time (mine is filling up with water), the saturated horizontal inflow thickness increases (for this part the gradient is not equal to 1). A moving boundary condition thus exists. **It is important to note that Modflow cannot simulate a situation like this.**

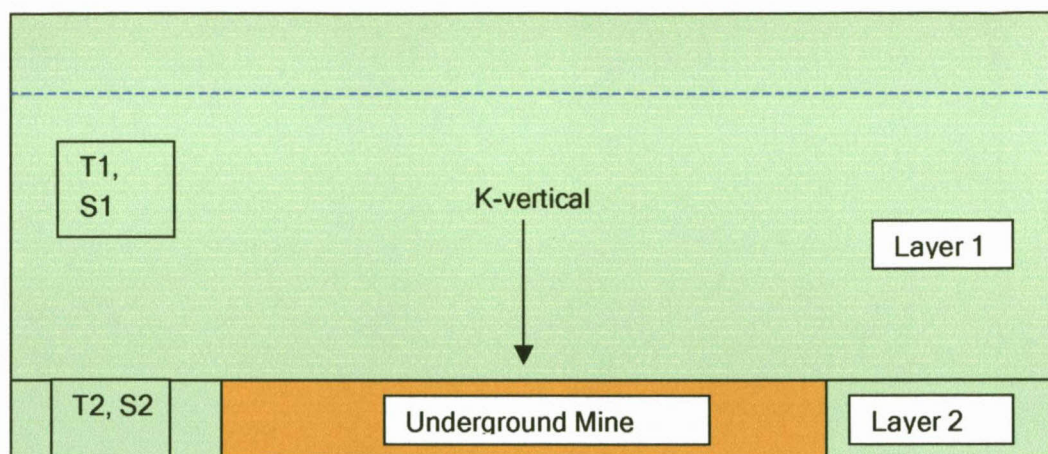


Figure 3-39 Underground flow model.

Two scenarios were run during the simulation to test the sensitivity as well as the accuracy of the two models. Two different K vertical values were used to test the models. From the results of the two models the results in Table 3-24 can be seen.

With a K vertical of 0.01 and 0.001, Modflow predicted filling times of respectively 110 and 1100 days.

The same K-values were used during the simulation of the analytical box model. A much longer time was predicted by the box model before the mine is full.

The reason for this is that, in Modflow the gradient is > 1 . Thus much more water is available. With the box model the gradient is 1.

It can thus be said with confidence that Modflow's calculation is erroneous during the filling time predictions of underground voids, which are overlain by saturated sediments. Modflow is thus over-estimating the flow to the underground in these situations.

Table 3-13 Results from the two scenarios.

Kv	Modflow Q (m ³ /d)	Real Q(m ³ /d)	Time to Fill the Mine (Modflow)- (d)	Real time(d)	
		Analytical Box model		Analytical Model	Box Model
0.01	97000	60000	110	210	
0.001	9700	6000	1100	2100	

Figure 3-40 was plotted to show the real filling time versus Modflow's filling time. It can be concluded that Modflow can make a significant error during the calculation of the filling times of the underground are. Modflow will fill the underground area faster than in real life, since inflows from the saturated rock overlying it can be estimated.

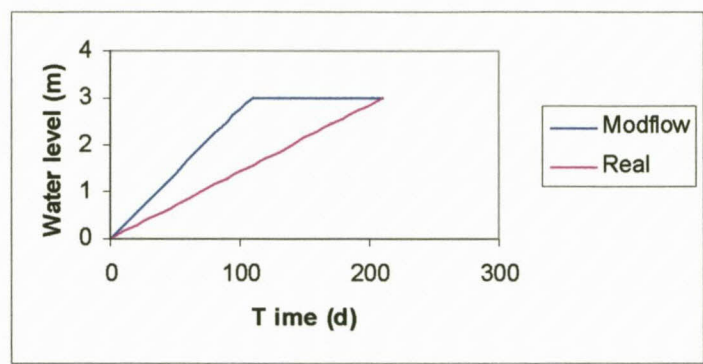


Figure 3-40 Graph showing the results from the real filling versus Modflow filling times.

In the case of the Rietspruit-Tavistock-Tweefontein Model, the very slow filling times calculated by Modflow of the opencast areas can thus be attributed to the fact that Modflow, which is a saturated model, cannot simulate an unsaturated situation. Modflow therefore can make significant errors in situations like these.

In the case of the N3 Pit at Rietspruit the filling times were checked by making use of the box model. The parameters depicted in Table 3-26 were used during the simulation.

Table 3-14 Parameters used in the box model simulations.

Parameters	Values
Rainfall	748.7
NS-OC decant point (mamsl)	1559
NS-OC area (Ha)	380
Volume at decant (MI)	47
Current WL (mamsl)	1510
K-value –Coal –Layer 2 (m3/d)	0.1
K-value – Layer 2 (m3/d)	0.0001
Barrier Thickness (m)	30
Tav UG area (Ha)	2547
Volume at decant (MI)	75

A leakage factor was also built into the model to predict the filling times with respect to different percentages.

As can be seen in Figure 3-27 to Figure 3-29, the perimeter through which the water can flow at the N3 Pit is very big. According to the parameters, the K of the coal is bigger than that of the strata above, and thus will let through water more easily. The leakage of the N3 Pit to the Tavistock underground area, which is attributed to the perimeter of the pit as well as the width of the barrier, will continue because of the size of the Tavistock underground area. Leakage will progress for a long time because of the continuous leak.

A sensitivity was done on the K-value, making use of a hydraulic conductivity of 0.0001, the water will still continue to flow to the underground area. Making use of the leakage factor, the filling time of the N3 Pit can be calculated as a percentage leakage. Making use of a 20% leakage factor, the pit will take approximately 130 years to fill. If 100% leakage is taking place, the pit will take approximately 210 years to fill to its decant elevation. This is in line with the results received from the flow model. Modflow predicted a filling time of 250 years for the pit to fill to decant elevation.

Thus if no additional flow is expected in or out of the pit, the pit will take approximately take 81.6 years with a recharge percentage of 20% to fill to its decant level. If a 15% recharge were applied the pit, the pit will take approximately 108 years to fill without any flow from the pit.

3.14.2.1 Conclusion

- Modflow is a saturated model, and during the simulation of an underground area, the situation changes from saturated to unsaturated.
- The situation is thus too complicated for Modflow or any other saturated flow model to simulate.
- Modflow is a very good model package to use, but it is very important to know the model package before embarking on modelling an area. Modflow is very accurate in predicting flow direction, flow volumes and filling times of opencast areas. But Modflow should be used with caution for predictions of filling times of underground areas. Modflow is not ideally suited to calculate filling times of opencast and underground areas next to each other. Modflow will always underestimate the filling times of the pit. In general an underground pit will take longer to fill than Modflow predicts.
- Whenever refilling times for underground models are simulated using saturated flow models, the answers should be checked for consistency using

volumetric/inflow calculations. This ensures that the model answers can be validated.

3.15 TESTING HORIZONTAL BARRIERS VERSUS MESH REFINEMENT

As already seen in this section, Modflow contains several functions to deal with problems such as thinner barriers. Two methods were tested for application in general, namely making use of the horizontal flow barrier (artificial flow barrier) or mesh refinement.

Firstly the horizontal flow barrier was implemented. The artificial barriers were placed in the areas between the two collieries to ensure that in the areas where intermine flow is taking place because of a bigger mesh, the horizontal flow barrier will mimic the unmined country rock barrier between the two areas. The K in line with the expected characteristic of the country rock was assigned to the horizontal flow barrier in the first and second layer. Figure 3-41 A show the area with a big mesh, as well as the position of the artificial barrier.

Secondly the refinement method was used. The rows and columns of the blocks in the area of interest were divided by two (See Figure 3-41 B for refined mesh).

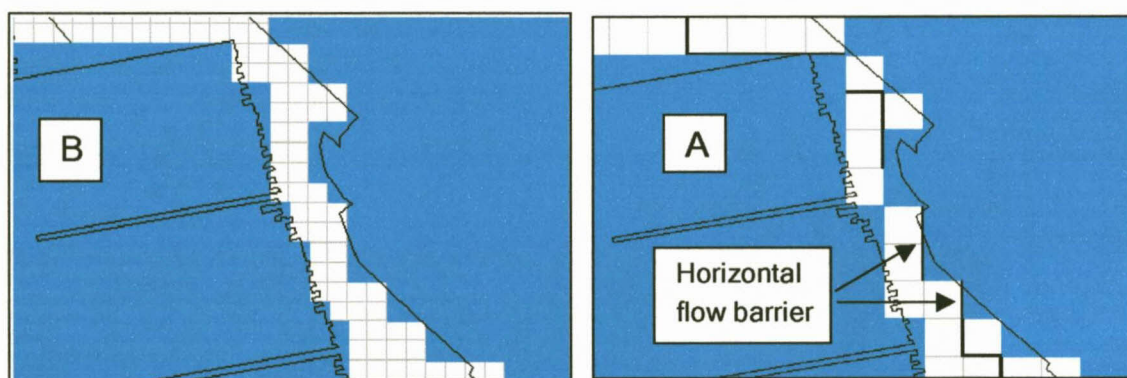


Figure 3-41 Testing of mesh size versus the artificial barrier.

The flow through the horizontal flow barrier as well as the refined mesh was calculated by making use of the water budget calculations of Modflow. The calculations of the two scenarios were in the same order. Figure 3-42 shows the refinement area, and Figure 3-43 the extent of the flow barrier. From the two graphs it is also visible that the heads in year ten are at almost exactly the same elevations.



Figure 3-42 Extent of model and as well as the position of refinement of the model.



Figure 3-43 Position of the horizontal flow barriers.

From the calculations it can be seen that the results from the two methods are in the same order. Thus both methods are very competent and can be used with confidence in any area where the coal barriers are thinner than the original mesh size of the model.

3.16 OVERALL CONCLUSION

Because of the existence of intermine flow in the location of the opencast and underground areas, particle tracking was done on the model to show the positions where intermine flow is possible. Water budget calculations were done on the coal barriers between the mined areas to see if the long filling times might be attributed to intermine flow through the barriers. From the water budget, it can be concluded that the pit is losing water through the four surrounding coal barriers. A volume of 1100 m³/d was calculated. A discrepancy in the calculations of filling times were investigated. Two models were simulated to test the filling times, namely a Modflow and a box model. From the results it can be seen that Modflow over-estimates the filling times of the pits if an unsaturated situation is present. In the case of a saturated conditions, Modflow will predict the correct filling times.

An analytical model was used to calculate the filling times of the North-South Pit as well as the Rietspruit underground area. From the calculations it is visible that the underground area will take approximately 66 years to fill and the opencast pit will take approximately 68 to fill to its decant elevation.

The box model was also used to predict the filling time of the N3 Pit. From the results of the box model it was predicted that the pit will take approximately 210 years to fill to its decant elevation of 1559. This is in the same order as predictions from the Modflow model, which predicted a filling time of approximately 250 years. The long filling time can be attributed to the fact that the perimeter of the pit is very big as well as an expected continuous leak to the Tavistock underground area.

3.17 GREENSIDE COLLIERY - KLEINKOPJE COLLIERY - WOLWEKRANS COLLIERY FLOW MODEL.

At SACE, opencast mining is currently proceeding into old mine workings, thus creating new decant points for the underground workings. Thus conduits between mine workings and the surface will become abundant.

For SACE to opencast into its old mine workings, dewatering of the underground area will be necessary. Because of the dewatering a hydraulic gradient will be created from Wolwekrans Colliery towards Kleinkopje Colliery. Figure 3-44 shows the current water bodies in the 2 Seam underground workings. Making use of surface contours and floor contours, a pressure difference of up to 25 m can be measured.

Under these circumstances, flux from Wolwekrans into Kleinkopje will be created. Grobbelaar *et al.* did a finite element model in 1998 on the coal barrier between Kleinkopje and Wolwekrans Collieries. A flux of 1,6ML/d was reported.

It is also suspected that an indirect connection exists between the water of the Wolwekrans 2 Seam workings and the Olifants River, seeing that the water levels at these facilities are at almost identical levels.

For the purpose of the study, the two major opencast pits at Kleinkopje were added together, because at the end the whole area of Block 2A and 4E will be mined, using opencast methods to mine onto the 2 Seam workings.

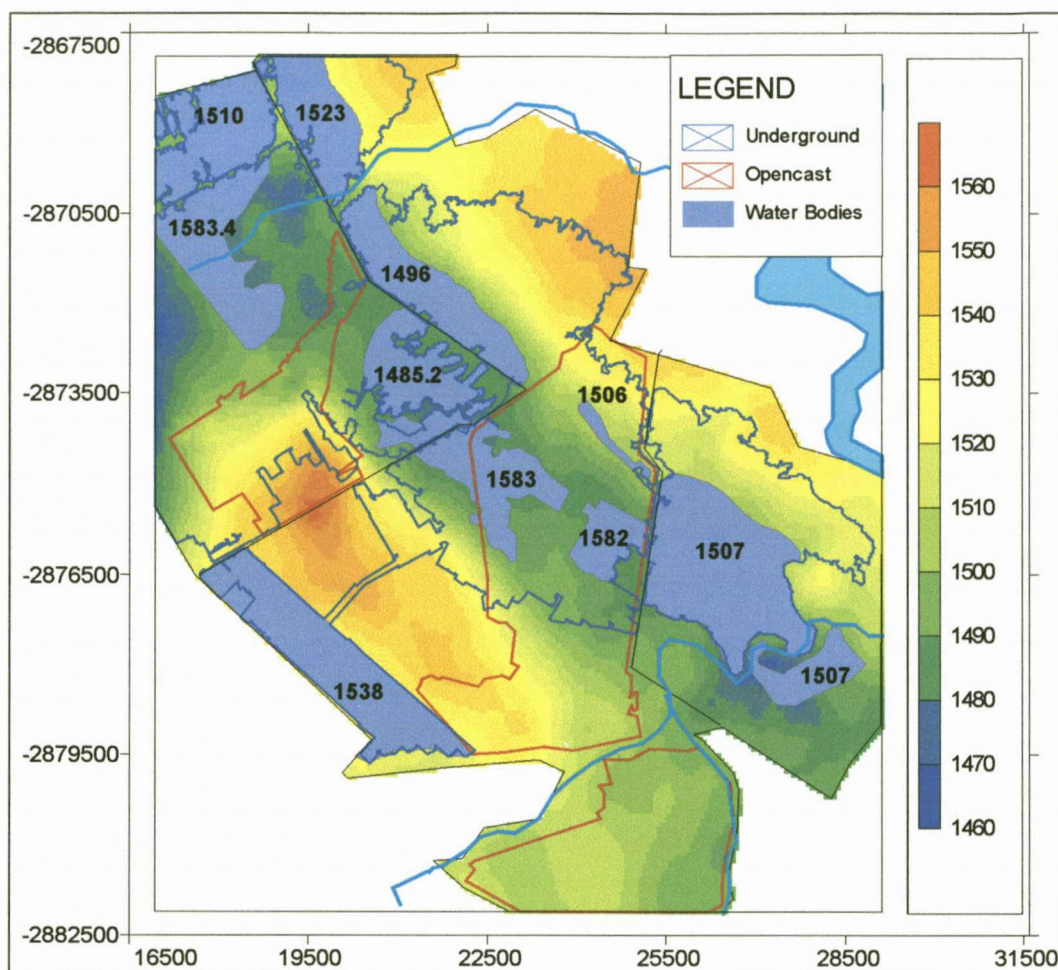


Figure 3-44 Positions of current water bodies on the 2 Seam floor contours of the model area.).

After mining has ceased at all three mines, the water levels in the area will rise to an equilibrium level. This level will be controlled by the lowest decanting point.

Positions of future decant point at the opencast and underground areas of the three collieries were traced by making use of WISH (See Figure 3-45 for the locations and elevations of the decant levels). It is postulated by Grobbelaar *et al.* (1998) that water will decant from two positions, one at Wolwekrans and one at Kleinkopje. Both of these are situated alongside the Olifants River at an elevation of approximately 1505 - 1506 mamsl, which is also the elevation of the Olifants River.

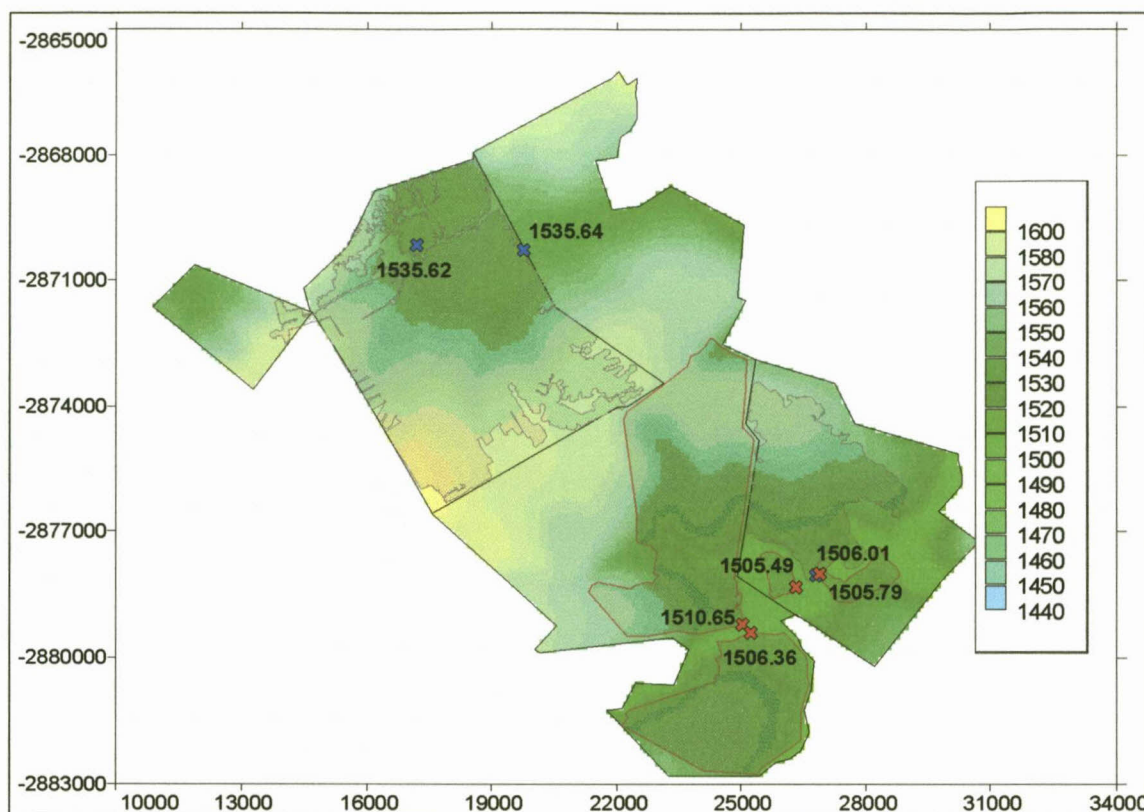


Figure 3-45 Locations of decant points in the model area.

3.17.1.1 Stage curves

Stage curves were calculated for Wolwekrans underground area, for Block 2A-4E opencast pit as well as for Block 5W.

From data received from Douglas Colliery it is clear that the Wolwekrans underground area is already or very close to the predicted decant level (information received from Douglas, 2002). From the stage curve it is clear that the underground can take approximately 48 Mm³ before the decant level is reached.

The predicted decant point for the Block 2A-4E is at 1510 mamsl. At this point the pit will have 59.6 Mm³ of water. Block 5W will also decant in the Olifants River at approximately 1506 mamsl. See Figure 3-46 to Figure 3-48 for stage curves and Table 3-15 for results from the stage curves.

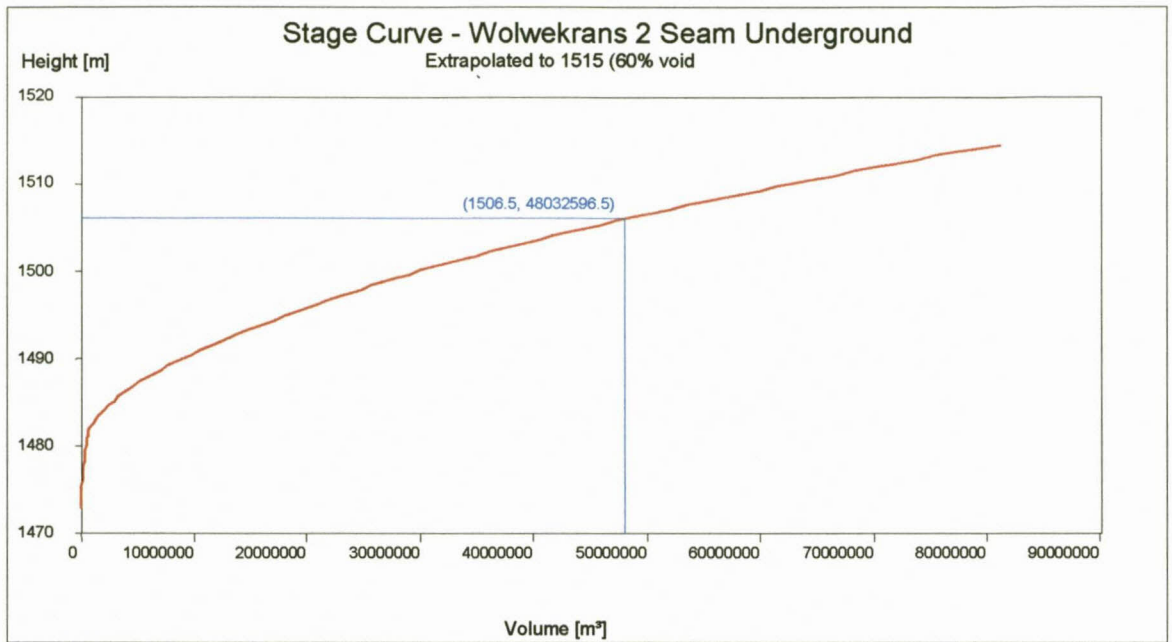


Figure 3-46 Stage curve for decant point at an elevation of 1506.5 mamsl.

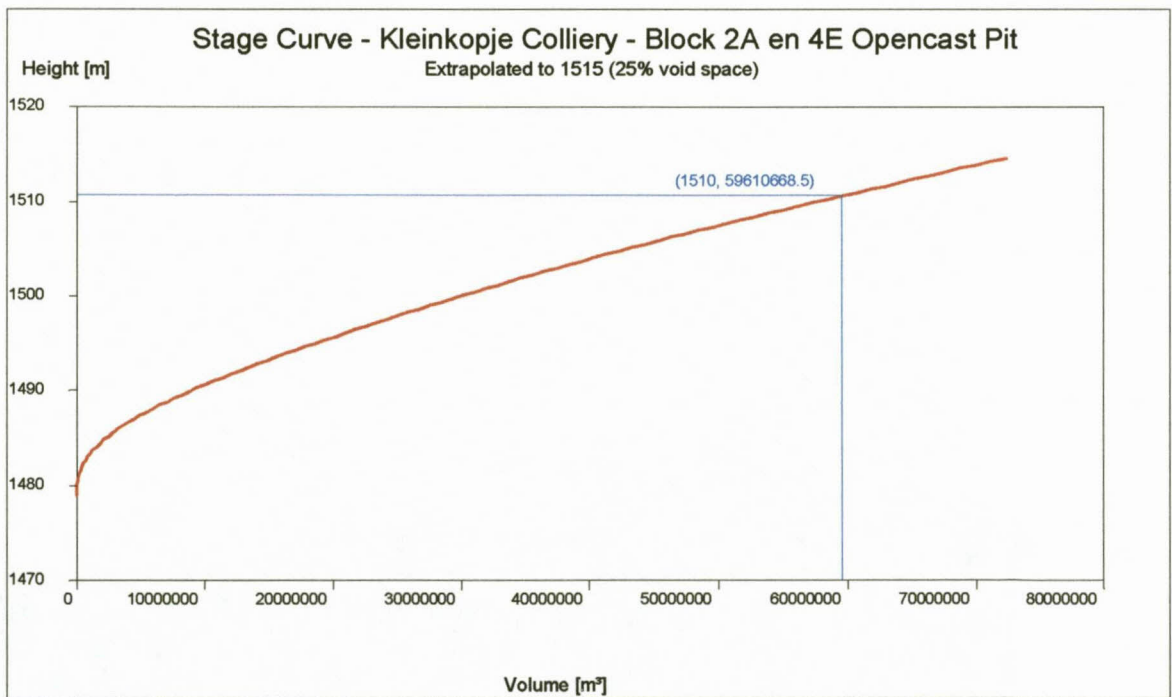


Figure 3-47 Stage curve for decant point at an elevation of 1510 mamsl.

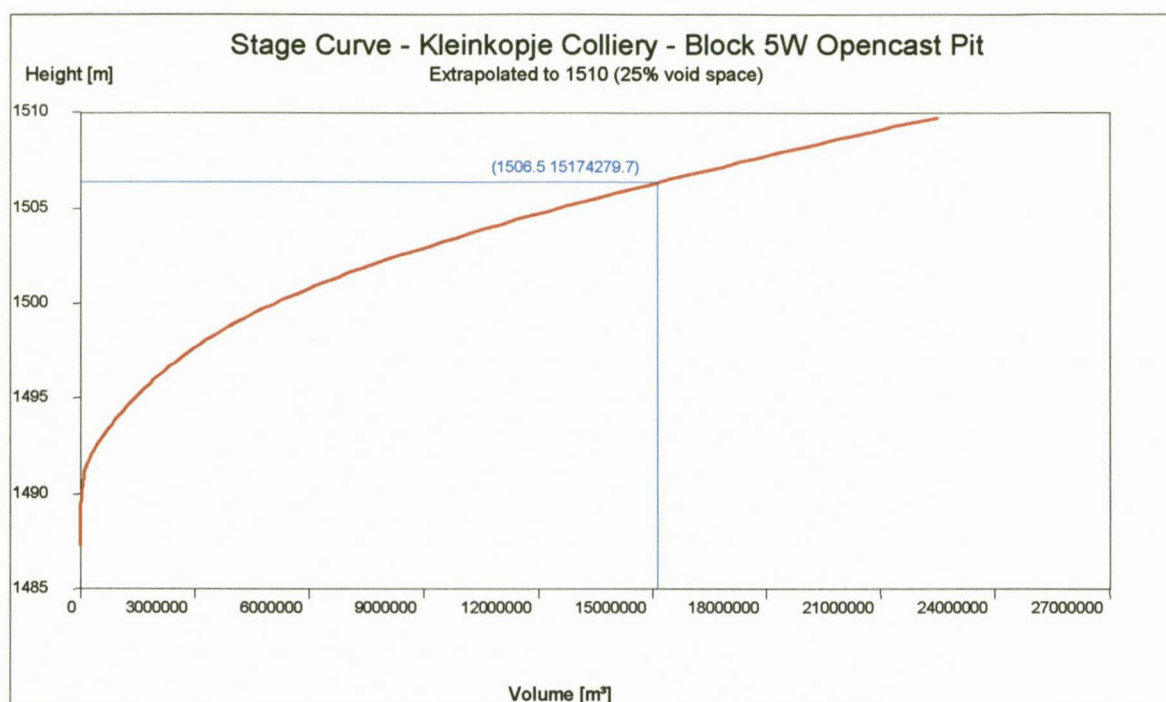


Figure 3-48 Stage curve for decant point for Pit 5W 1506.5

Table 3-15 Results from stage curve calculations. Decant points and the volume of water present at specific point.

Name of Pit	Decant point	Water in Pit (m ³)	Area (m ²)
Block 2A and 4E	1510	59610700	17168500
Block 5W	1506.5	15174300	9333000
Wolwekrans 2 S UG	1506.5	48032600	9717200

Making use of the stage curves and analytical calculations, filling times were calculated. Calculations showed that Block 2A-4E will take approximately 25 years to fill to their decant level and Block 5W 12 years.

3.17.2 Flow Model

The model area consisting of Greenside, Kleinkopje and Wolwekrans Collieries was simulated (See Figure 3-49 for the extent of the model area).

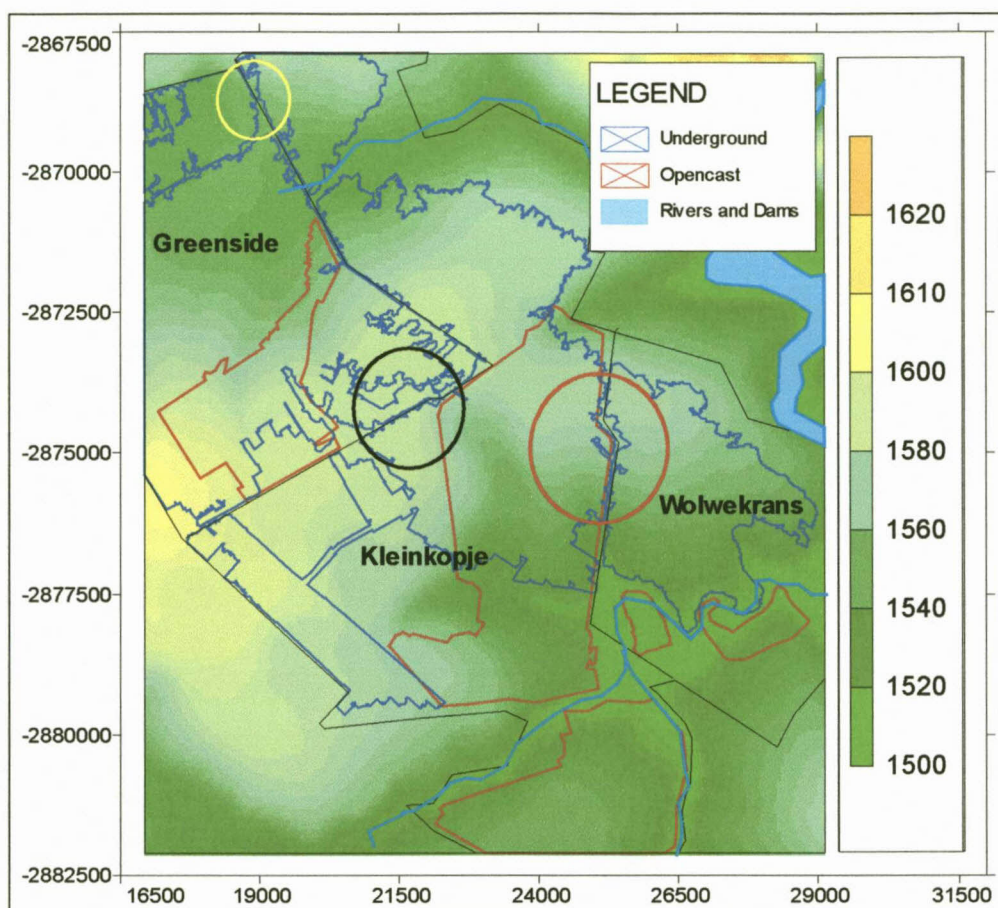


Figure 3-49 Extent of model. The positions of current and future intermine flow are shown by the coloured circles.

The red circles on the diagram highlight the area of interest, where intermine flow currently occurs. The black and yellow circles highlight the area of interest where future flow is possible. Figure 3-49 shows the positions of current and future intermine flow in the study area.

The red circle stipulates the coal barriers between Kleinkopje and Wolwekrans Colliery.

In this case, the unmined coal barrier varies considerably in thickness (Figure 3-49), ranging from approximately 30-600 m. The calculation of the seepage rate through the irregularly shaped boundary is complex. Modflow was used to do the calculations.

The thickness of the other two areas range between approximately 30-130 m and 45-300 m respectively.

A post-mining flow simulation was done on the area to calculate flow volumes as well as filling times over the coal barriers.

For the flow simulation, current water levels in the mine area were used, and for the rest the floor contours were used to simulate that the mines are empty after mining has stopped in the areas.

3.17.2.1 Discretisation

The mesh of the flow model consisted of 320 x 190 cells in the x and y directions respectively. Each of the cells is 50 x 50 m. Figure 3-50 is a schematic representation of the mesh used in the flow model.

The coordinates are -2902500, 10500 (lower left corner) to -2886500, 20000 (upper right corner).

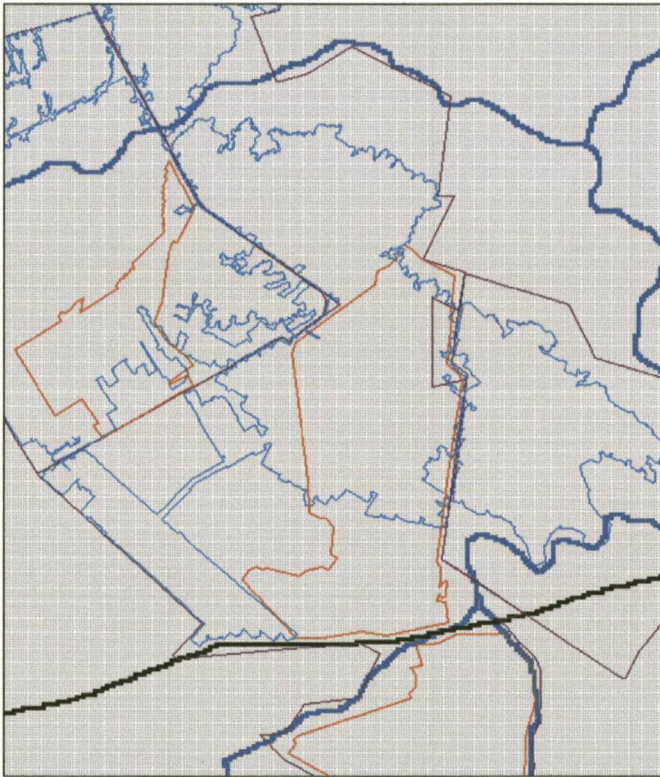


Figure 3-50 Spatial discretisation of the model system. Grid overlying the Rietspruit - Tavistock - Tweefontein flow model.

3.17.2.2 Layers and layer construction

The model consists of two layers. For the flow model the 2 Seam floor contours have been used to simulate the bottom of the model, and the surface contours were used to simulate the top of the model. Mining heights were used according to data received from the Coaltech 2020 project and Jeffrey (2002).

3.17.2.3 Initial hydraulic heads

In the case of the Greenside-Kleinkopje-Wolwekrans model, an average water level of 6m below the surface was used to simulate the initial conditions during the steady state calibration of the model.

During the transient state of the model, new water levels were created to simulate the water levels in the mining areas.

Water level data received from Douglas Colliery (Douglas 2002), show that the current water level in the Wolwekrans underground workings are at a water level of approximately 1506.5.

The latest water level data for SACE (Kleinkopje and Greenside Collieries) for the 2 Seam contours were used. See Figure 3-51 for water level elevations in the underground areas. The opencast areas at SACE were simulated as initially being empty.

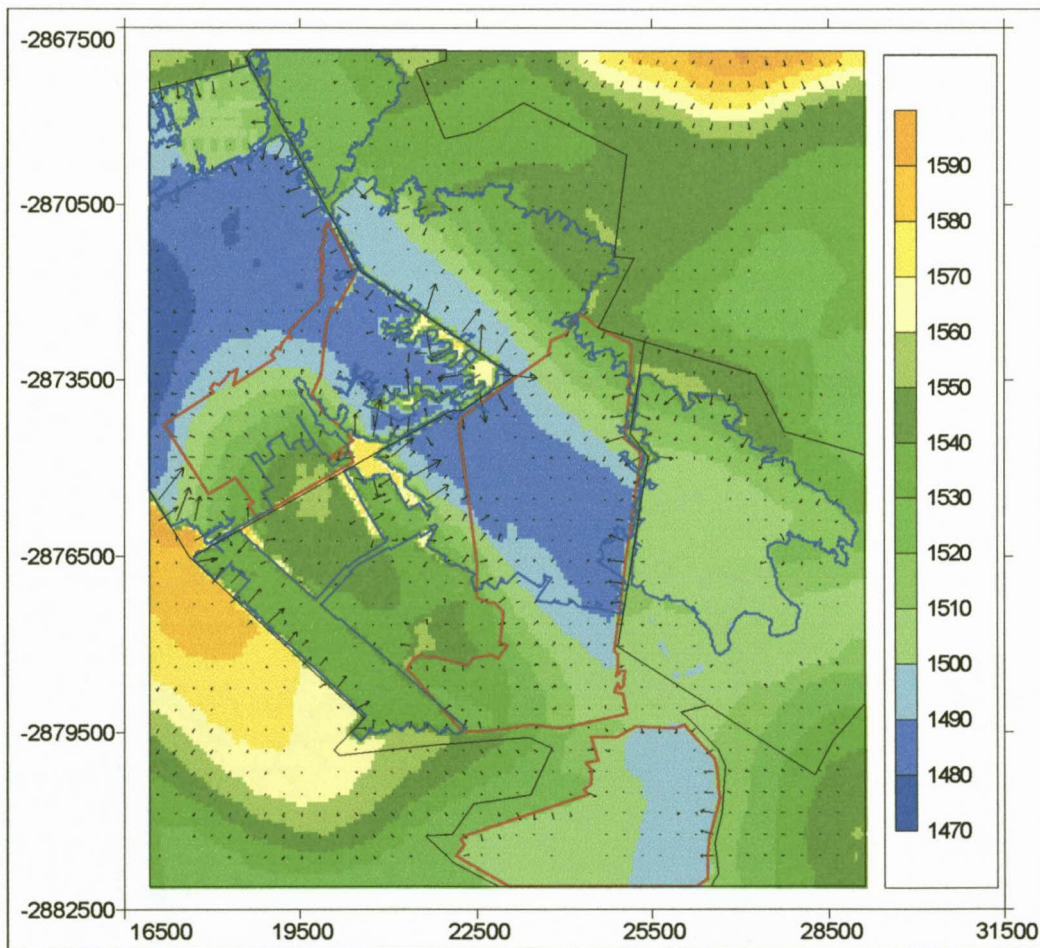


Figure 3-51 Initial water levels used in the flow simulation.

3.17.2.4 Horizontal Hydraulic Conductivity and Transmissivity

A hydraulic conductivity for the undisturbed coal has been taken as 0.154 m/d (Kleinkopje EMPR, 2001), calibrated to water levels. The K-values used are predicted by the packer test done in the Kleinkopje area. A hydraulic conductivity of 50 m/d was calculated for the opencast and underground areas.

3.17.2.5 Horizontal flow barriers

Horizontal flow barriers were used to simulated the Ogies Dyke, which runs through the southern part of the model area.

3.17.2.6 Rainfall

The rainfall data of two of the three areas were available. Thus an average rainfall was used to calculate the rainfall of the model areas.

- Greenside - 726 mm - Greenside EMPR, 1996 (Wates, Meiring and Barnard, 1996) ;
- Kleinkopje Colliery - 696 mm (Kleinkopje EMPR, 2001)

An average rainfall of 711 mm/a was used during the model simulations.

3.17.3 Model results

Soon after mining stopped in the two opencast pits, the pits will start to fill up with water. To predict the filling times of the two opencast pits a sensitivity analysis was done on the model.

Two parameters, namely conductivity and recharge percentages, were used to test the model sensitivity. A conductivity of 0.154 (EMPR 2001) was simulated against a recharge percentage of 14 and 20% (See Table 1 for details on sensitivity analyses and Figure 3-52 for head time graph). A conductivity of 0.5 was simulated versus a recharge of 20%.

Making use of a K-value of 0.154, it will take 20 and 32 years respectively for Block 5W and Block 2A-4E to fill to their decant levels if a recharge percentage of 20% is used and 29 and 46 years respectively if a recharge of 14% is used (See Figure 3-53 and Figure 3-54 for detail on the flow results).

During the simulation of filling times, making use of a K-value of 0.5, the filling times are in the same range. This can be attributed to the fact that water is leaving the area as fast as it will enter the pit, because of the higher conductivity of the sediment. It can safely be said that the pits will take between 20 to 50 years to reach their decant levels (See Table 3-16 for filling time predictions).

Table 3-16 Sensitivity analyses for Greenside - Kleinkopje - Wolwekrans flow model.

Pit	Hydraulic conductivity	Recharge %	Time to decant (years)
Block 2A	0.154	20%	32
Block 5W	0.154	20%	20
Block 2A	0.154	14%	46
Block 5W	0.154	14%	29
Block 2A	0.5	20%	33
Block 5W	0.5	20%	21

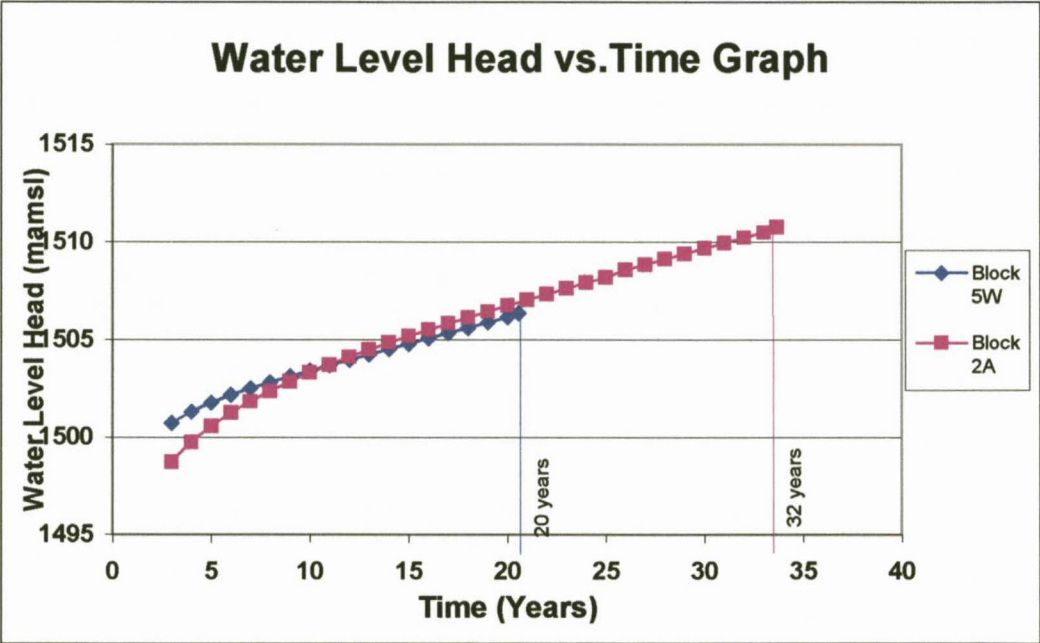


Figure 3-52 Water level heads versus time for Block 5W and Block 2A.

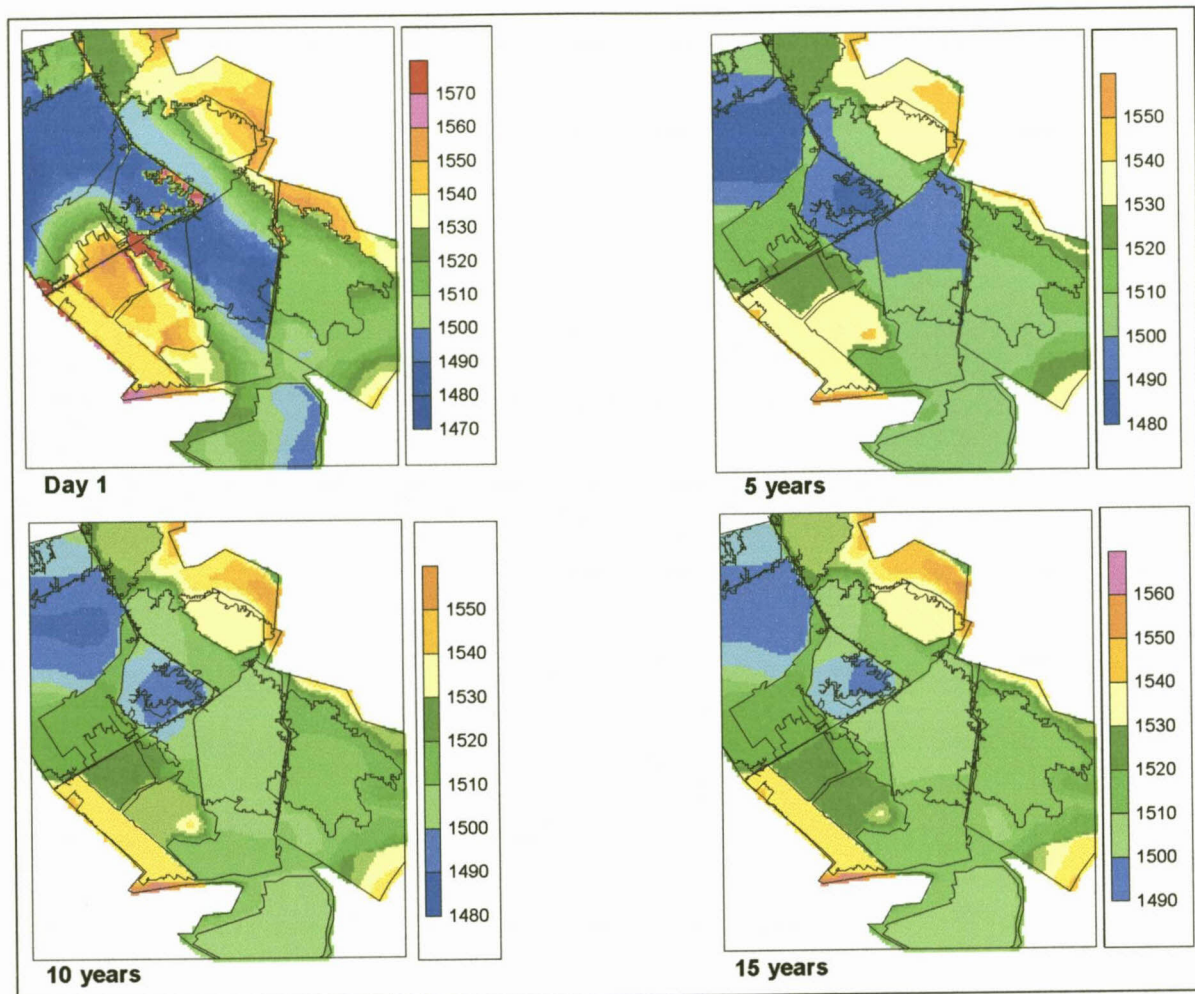


Figure 3-53 Results from the flow model simulation.

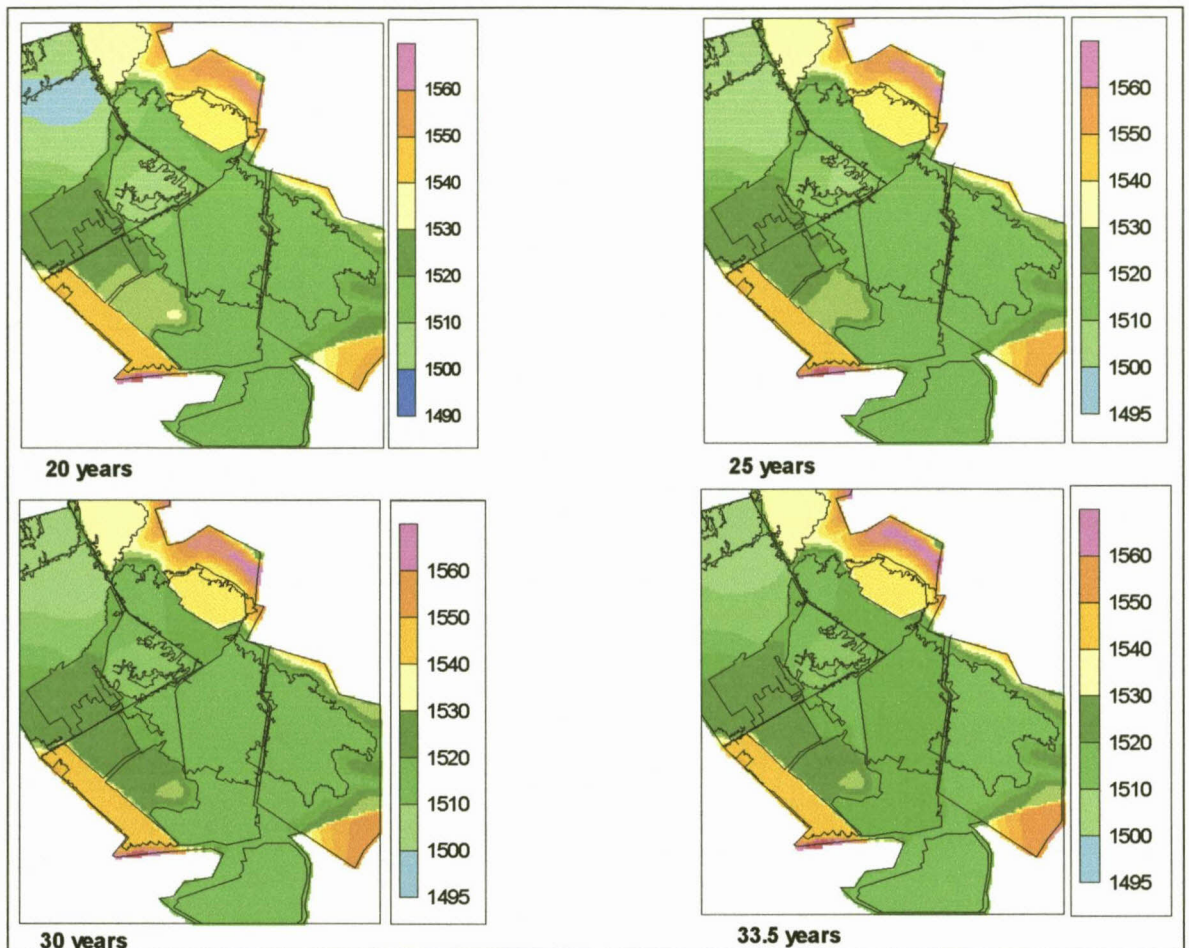


Figure 3-54 Results from the flow model simulation.

After the pumps have been stopped at SACE the opencast areas will start to fill. There is still a gradient between the Kleinkopje and Wolwekrans sections, thus a hydraulic flux from Wolwekrans toward Kleinkopje will still exist.

Three zones (coal barriers) were inspected during the modelling process for possible intermine flow and volumes. Making use of the water budget package, volumes were calculated over the coal barriers. The three zones can be defined as follows (See Figure 3-49 for positions of intermine flow (zones)):

- Zone 1 - unmined coal barrier between Kleinkopje and Wolwekrans Colliery (Red circle)
- Zone 2 - unmined coal barrier between Greenside and Kleinkopje (Blue circle)
- Zone 3 - unmined coal barrier between Kleinkopje and Greenside (Yellow circle)

An initial flux of 1.6 ML/d is calculated over the unmined coal barrier between the Kleinkopje and Wolwekrans sections for the first 4 years, because of the 25 m head between the two collieries. As Pit 2A-4E fills, the flux will progressively decrease and

thus the flow will progressively decrease over the coal barrier. After approximately 23 years, the flow will start to reverse and it will be from the Kleinkopje 2A-4E pit to Wolwekrans underground area. An increase in flow over the coal barrier from Kleinkopje to Wolwekrans will thus increase because of the rising water level in the opencast pit.

In Zone 2 a volume of approximately 1.45 ML/d was measured over the coal barrier between Greenside and Kleinkopje. The flux between the two areas is not big, but intermine flow is dominant because of the thin coal barrier between the two areas.

Flow in Zone 3 was measured at 1.15ML/d. A very small decrease in the flow volumes is measured over the boundary. This can be attributed to the fact that the flux between the two areas is and remains big.

See Table 3-17 and Figure 3-55 for the results over time for layer 1 and 2.

Table 3-17 Results form the water budget for layer 1 and 2.

YEARS	ZONE 1	ZONE 2	ZONE 3
3 years	1638	1452	1157
5 years	1198	1116	1179
10 years	674	943	1195
20 years	126	714	1093
25 years	97	625	1020
30 years	234	558	945
33 years	289	536	915

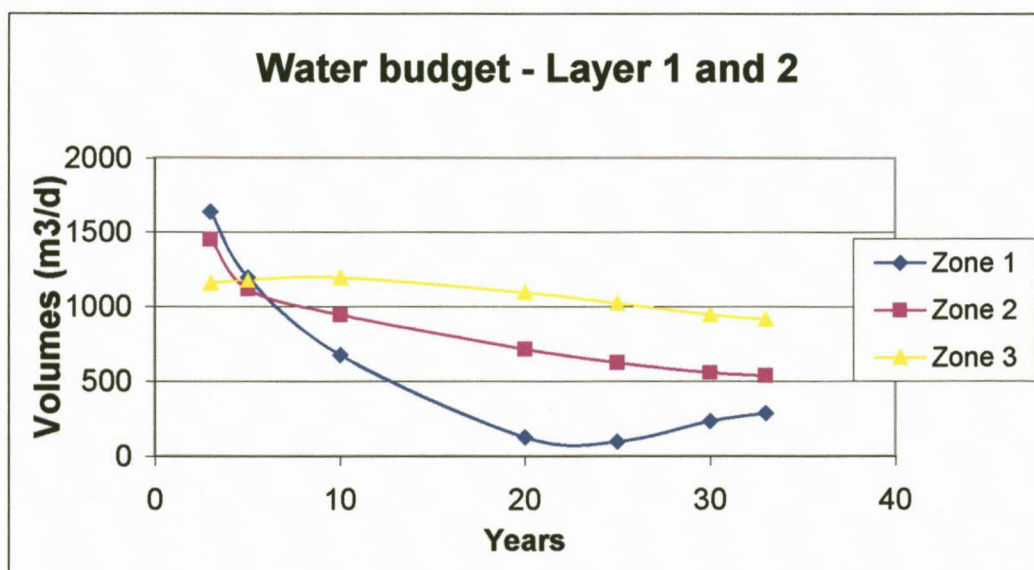


Figure 3-55 Flow volumes for layer 1 and 2 in the three areas.

3.18 OVERALL CONCLUSION

Block 5 W will take approximately 20 years and Block 2A-4E approximately 32 years to fill to their decant levels. A flux of 1.6 ML was measured over the coal barrier between the Kleinkopje and Wolwekrans Collieries. The flow will progressively decrease over time as the gradient diminishes.

A flux of 1.45 and 1.15 ML/d respectively was calculated over the coal barriers of zone 2 and 3.

Intermine flow plays a big role in the flooding of the mines.

3.19 SUMMARY OF THE THREE FLOW MODELS

See Table 3-18 for a summary of the flow models.

Table 3-18 Summary of the three models to show the results.

MODEL AREAS	K-values	Area (Ha)	Decant point	Decant vol	Filling time	Flow vol
	m/d	Ha	Mamsi	m3	years	m3/d
Kriel Tavistock Model						
Pit 6	0.000846	7569513	1561.5	29289500	27	
Pit 5	0.000846	5374012	1566	33644600	44	5.8
IMF barrier	0.000846					
Riet-Tav-Tweef Model						
North-South Pit	0.1	7069880	1530	44509677	68	
Rietspruit UG area	0.1	4048172		13350326	66	
N3 Pit	0.1	3804519	1559	47322207		
4 IMF barriers	0.1					1100
Greens-Kleink-Wolwek Model						
Block 5W	0.154	9332911	1506.36	15174280	20	
Block 2A-4E	0.154	17168527	1510.65	59610669	32	
Kleinkopje-Wolwekrans barrier	0.154					1600
Kleinkopje-Greenside barrier	0.154					1150
Greenside-Kleinkopje barrier	0.154					1450

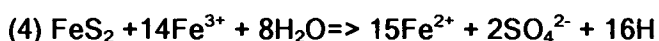
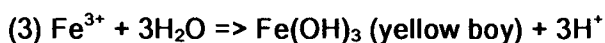
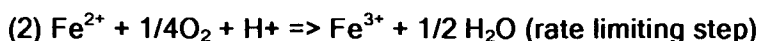
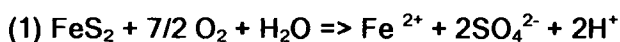
4 CHEMICAL REACTIONS WITHIN THE COAL MINES OF THE WESTERN WITBANK COALFIELD.

4.1 GROUNDWATER CHEMISTRY

Rock and coal within South African coal mines contain several mineral assemblages that are altered in the presence of water and oxygen. These alterations may take on either of two main forms, namely oxidation reactions and carbonate reactions.

In natural systems, the limiting factor for oxidation reactions is the availability of oxygen. Rainwater contains on average only 8 mg/L oxygen. When rainwater infiltrates into the earth's crust, this oxygen is available for reactions. Substances, which may be oxidised, are typically organic material within soil, sulphur-bearing minerals such as pyrite and other Fe^{2+} complexes. This oxidation process yields, at most, an equivalent amount of sulphate, namely 32 mg/L. In natural systems, the background concentration of sulphate therefore should never exceed the latter value, unless influenced from other sources.

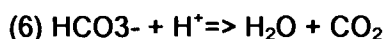
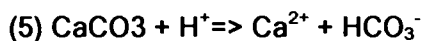
The evolution of coal mine waters can be explained by equation (1) below:



The reactions result in the sulphate associated with coal mines in South Africa. Where there is insufficient natural neutralisation of the generated acidity (denoted by the H^+) in the equations above, the pH of the water drops and secondary effects such as the mobilisation of metals occurs. Neutralisation occurs via various mechanisms:

- The natural alkalinity within the water
- Carbonate minerals such as calcite and dolomite
- Silicate weathering.

Neutralisation is the consumption of acidity in which hydrogen ions are consumed according to the following reactions:



These processes will all be dealt with at length further in this thesis, but it should be mentioned here that the natural alkalinity of the water would be the first buffering mechanism, followed by the carbonate minerals and finally the silicates. The rates at which neutralisation takes place decreases as we progress along the process with the water's alkalinity reacting immediately, the carbonate buffering reacting next and about 3 orders of magnitude faster than the pyrite reactions above. Finally the silicates react around two to three orders of magnitude more slowly than pyrite generation occurs, on a normalised surface area basis. Figure 4-1 indicates some of these principles.

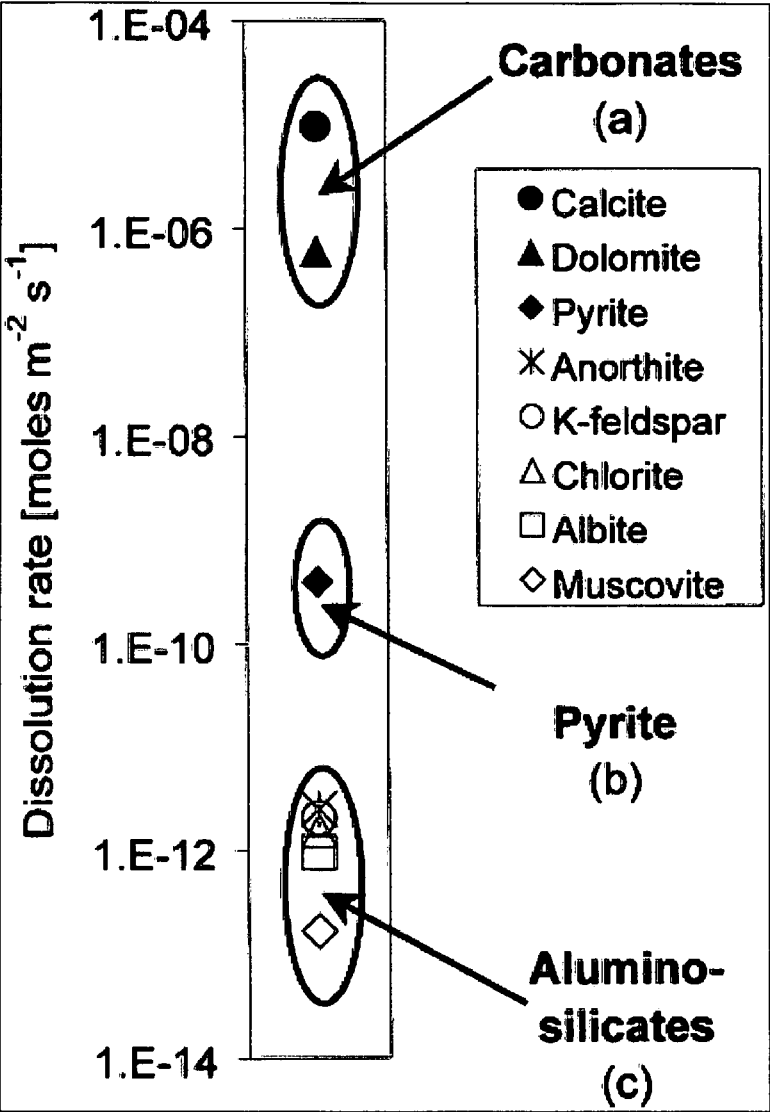


Figure 4-1 Normalised reaction rates for different minerals (after Banwart and Malmström, 2002).

4.1.1 The Chemistry of AMD

Acid mine drainage is a widespread phenomenon affecting the quality of water at many South African collieries (Usher *et al.*, 2001).

Acid mine drainage (AMD) occurs when freshly exposed sulphide bearing mineral ores are brought into contact with air and water, usually because of some disturbance to the geological environment, and this results in oxidising the sulphide sulphur to sulphuric acid.

Potential sources of acid mine drainage include surface runoff from opencast mining areas, runoff from residue dumps or ore stockpiles and drainage from underground workings (Pulles *et al.*, 1996). In South Africa the problem of AMD is the most severe in active mining areas where fresh material is constantly being exposed. The problem manifests itself with the formation of acidic water, which then requires the application of a pH-neutralisation program in order to prevent the circulation of a very corrosive type of water. The pH control program implies a chemical cost (usually lime), as well as a scaling or corrosion problem (cost) in the circulating pipework (Pulles *et al.*, 1996).

According to Pulles *et al.*, (1996), not all sulphide-bearing material will necessarily produce acid mine drainage when exposed to air and water, and the correct micro-environment must be present for the acid generation process to occur.

It is generally well established and accepted that the major factor contributing to the formation of acid mine drainage is the presence of the bacteria *Thiobacillus ferrooxidans* and *Thiobacillus thiooxidans* (Pulles *et al.*, 1996).

Bright orange coloured water and stained rocks are usually signs of acid mine drainage. The orange colour is characteristic of ferric hydroxide ($\text{Fe}(\text{OH})_3$) or better known as yellow boy, which will precipitate out of the water. $\text{Fe}(\text{OH})_3$ will precipitate as the acid mine drainage becomes neutralised. At low pH-values the metal ions remain soluble. When the pH rises, the iron oxidises and precipitates out. Depending on the conditions, the orange coloured precipitates may form inside the mine or several miles downstream. These precipitates can be harmful to aquatic life in several ways.

4.1.2 Stages in the development of AMD

AMD development is very complex and involves a combination of organic and sometimes inorganic processes and reactions.

For the production of AMD, where the pH of the system drops below 3, sulphide minerals must create an optimum micro-environment for rapid oxidation, and must continue to oxidise for a sufficiently long time to exhaust all of the neutralisation

potential of the rock. The amount of alkaline, often calcareous, material in the rock will rule the potential of the sulphide rock to generate acid.

During the exposure of sulphide rock to flowing water and oxygen, sulphide oxidation and acid generation will begin. The quantity of calcium-based carbonate present in the rock will immediately neutralise the small amount of acidity and maintain neutral to alkaline conditions in water passing over the rock (Broughton *et al.*, 1992). As acid generation continues the neutralising agent will be consumed or rendered ineffective in further neutralization. The pH of the water will decrease, which in turn enhances the conditions for further acid generation.

Over time the rate of acid generation will accelerate. A progressive decrease in the pH can thus be expected. This can be illustrated in a decreasing, step-like manner. See Figure 4-2 for details.

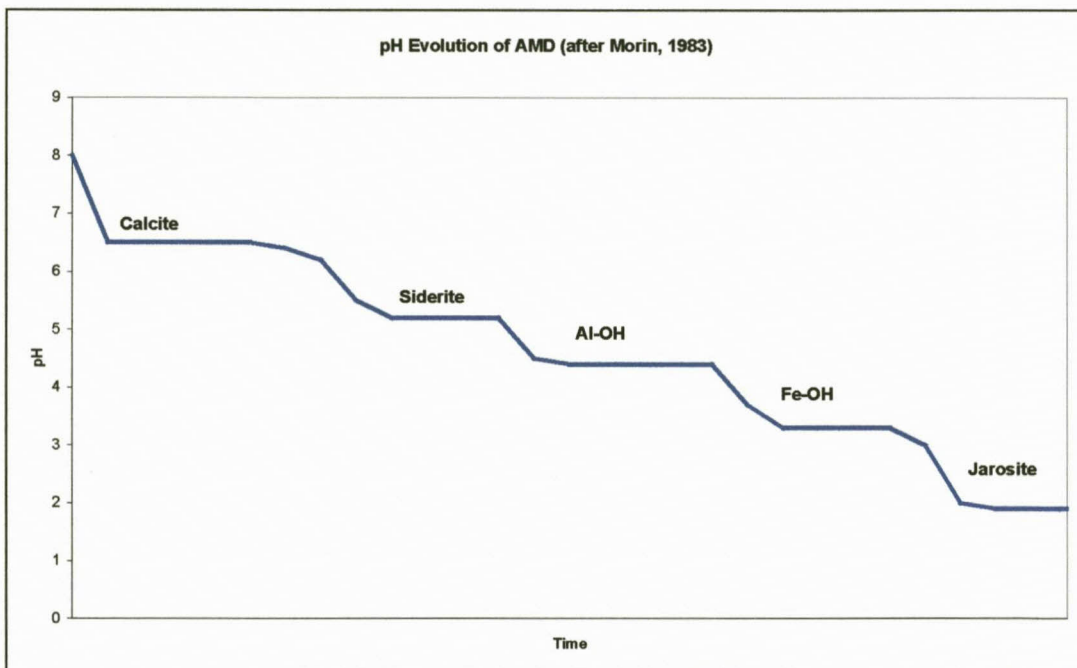


Figure 4-2. Stages in pH-evolution as a result of different buffering minerals (from Usher *et al.*, 2001).

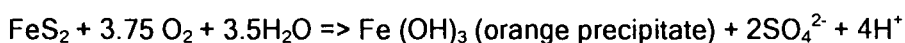
Each plateau of relatively steady pH represents the dissolution of a neutralising mineral that becomes soluble at that pH. If the rate of acid generation remains high enough to remove all of the neutralisation potential in the rock, the pH-values will drop below 3 and AMD will become severe. These various stages can last for weeks, months, or centuries until the sulphide minerals completely oxidise and the rock becomes inert, or until special waste management and AMD control actions are taken (Durkin and Herrmann, 1996, Usher *et al.*, 2001).

4.1.3 Reactions involved in AMD

Iron and sulphate-bearing water usually forms when rocks containing sulphide minerals (e.g. Pyrite, pyrrhotite etc.) are exposed to the atmosphere or an oxidising environment, and are subsequently leached by water.

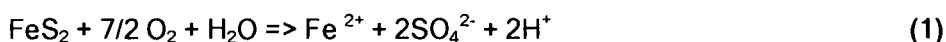
Pyrite (FeS_2) iron disulfide (commonly known as fool's gold), is one of the most important sulphides found in the waste rock of mines. When exposed to water and oxygen it can react to form sulphuric acid (H_2SO_4).

The production of acid via iron sulphide (e.g. pyrite) oxidation can be represented by the following reaction:



(Iron sulphide + Oxygen + Water = Ferric Hydroxide + Aqueous sulphuric acid)

The following detailed reactions demonstrate the key steps in the acid forming process:

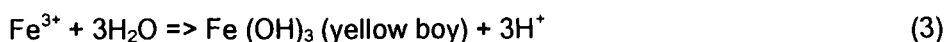


Acid is formed when sulphide minerals oxidise. Pyrite is the most abundant sulphide.

Reaction 1 shows the oxidation of the disulphide, releasing ferrous iron (Fe^{2+}) and two protons. The dissolved products, namely Fe^{2+} , 2SO_4^{2-} and 2H^+ represents an increase in the TDS and acidity of the water.



In Reaction 2 and 3 the ferrous iron is oxidised to ferric (Fe^{3+}) which hydrolyses to form ferric hydroxide (an insoluble compound at a pH greater than 3.5) and in the process three more protons are released.



Thus for every mole of pyrite, five protons are released. However, since one proton is consumed for the oxidation of ferrous to ferric, only four protons are actually produced (Evangelou, 1995).

Ferric Hydroxide will only precipitate from water at a pH above 3.3 as $\text{Fe}(\text{OH})_3$ after it has been sufficiently oxidised to facilitate the conversion of soluble ferrous iron to

soluble ferric iron. As can be seen from reaction (3), this process is a key acid producing stage. Once sulphides have been oxidised, it is extremely difficult to avoid ferric hydroxide precipitation.

Note: Reaction 1 represent chemical oxidation and occurs at pH > 5. It is a very slow reaction. Below a pH of 5 the rate increases enormously because of bacterial catalysis. At this stage reaction 2 is involved. These reaction rates are shown in Figure 4-3.

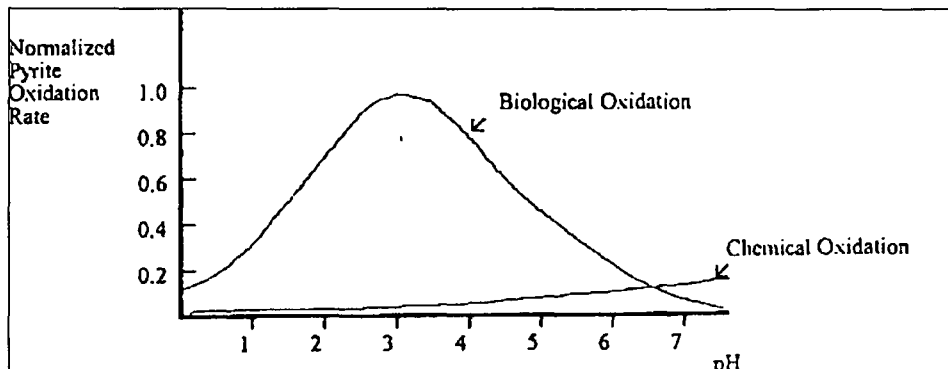
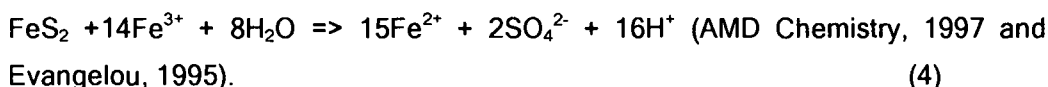


Figure 4-3 Chemical oxidation (from Scott, 1995).

With the formation of soluble ferric iron (Fe^{3+}) in the presence of fresh iron sulphide, further sulphide oxidation is accelerated, as represented in the following reaction:



Iron sulphides in material located below the water table will remain essentially stable, since the potential for oxidation is limited. The concentration of dissolved oxygen in natural waters is approximately 25,000 times lower than in the atmosphere [Evangelou, 1995].

However, where sulphuric materials are exposed to oxidising conditions (in air the iron sulphide will react and water can move the reaction products (e.g. iron and sulphate) into surface water and groundwater). As the acid water migrates, it further reacts with other minerals and dissolves a broader range of metals.

Therefore, pyrite continues to oxidise as long as ferric iron (Fe^{3+}) is generated. The conversion of ferrous to ferric as seen in Reaction 2 is also known as the rate-limiting step in the oxidation of pyrite (Singer and Stumm, 1970). However, since oxidation of

ferrous to ferric in the pH range of 3 is extremely slow (half-life in the order of 100 days), it appears that pyrite oxidation in this pH-range would be extremely slow, unless oxidation of ferrous at a low pH is catalysed by micro-organisms (Singer and Stumm, 1970). It turns out that in the pH-range of 2.5 - 3.5 (Jaynes *et al.*, 1984), the micro-organism, *T. ferrooxidans* can increase the rate of oxidation of ferrous iron to ferric iron by a factor of one million (Singer and Stumm, 1970; Backes *et al.*, 1986, Dugan, 1975, Azzie, 1999).

At low pH (<4.5) pyrite is oxidised by Fe^{3+} much more rapidly (Appelo and Postma, 1993) than by O_2 and more rapidly than dissolved Fe^{2+} is oxidised by O_2 to Fe^{3+} (Evangelou, 1995). This process rapidly consumes all Fe^{3+} and pyrite oxidation would cease unless Fe^{3+} is replenished by the process of oxidation of Fe^{2+} by oxygen (Appelo and Postma, 1993).

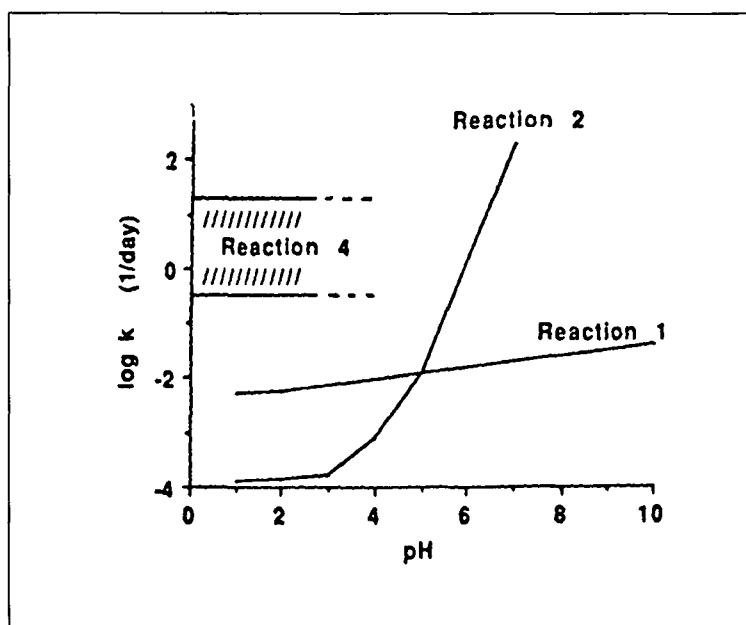
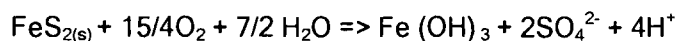


Figure 4-4. Comparison of rate constants as a function of pH for reactions 1, 2 and 4 (from Evangelou, 1995)

For this reason, *T. Ferrooxidans* is an acidophilic chemolithotrophic organism that is ubiquitous in geologic environments containing pyrite (Nordstrom, 1982). Thus, in the presence of *T. ferrooxidans* and under low pH conditions, pyrite oxidation can be described by Reaction 2 and 4. Reaction 3 taking place at pH values as low as 3, is a readily reversible dissolution/precipitation reaction that serves as a source as well as a sink of solution Fe^{3+} , and is a major step in the release of acid to the environment (Evangelou, 1995).

Acidity is caused by the liberation of hydrogen ions (H^+) in three of the four reaction steps.

The overall chemical reaction can be simplified to:



4.2 ACID-BASE ACCOUNTING (ABA)

Acid-base accounting (ABA) is a first order classification procedure whereby the acid-neutralising potential and acid-generating potential of rock samples are determined, and the difference, which is the net neutralising potential, is calculated, (Usher *et al*, 2001). The net neutralising potential, and/or the ratio of neutralising potential to acid-generation potential, is compared with a predetermined value, or set of values, to divide samples into categories that either require, or do not require, further determinative acid potential generation test work (Usher *et al.*, 2001).

Different methods can be used to conduct the ABA. These will generate different sets of sample data which can be evaluated. ABA indicates the overall balance of acidification potential (AP) and neutralisation potential (NP) (Schafer Laboratory, 1997).

Acid-base accounting is a screening process. There are a few limitations on ABA; it can't for example provide information on the speed with which acid is generated or neutralised. Because of these limitations, the test work procedures used in ABA are referred to as Static Procedures (Usher *et al*, 2001).

The potential for a given rock to generate and neutralise acid is determined by its mineralogical composition, namely the quantitative mineralogical composition, as well as the individual mineral grain size, shape, texture and spatial relationship with other mineral grains.

ABA is the most commonly used procedure for identifying potentially acid-forming materials at mine sites in Australia and Southeast Asia (Miller *et al.*, 1994), is typically considered state-of-the-art for overburden analysis (Hunter, 1997b) and is used in overburden in Canada, Australia and Russia (Evangelou and Zhang, 1995). It has a long and successful tradition in eastern US coal mining (Ziemkiewicz, 1997) and has been applied with some success to mine planning in the East, Midwest, and Western coalfields of the US (Perry, 1997).

ABA becomes a more powerful tool when used in conjunction with hydrologic data, mining and reclamation plans, mineralogy data etc. (Perry, 1997). A few primary advantages and disadvantages of the acid-base accounting method follow (From Usher *et al.*, 2001).

Primary advantages of the acid-base accounting method:

- Short turn-around time for sample processing
- Low cost
- Relatively simple analytical procedures
- Relatively simple interpretation of results (Hunter, 1997b; Evangelou and Zhang, 1995).

Primary disadvantages of acid-base accounting:

- It predicts maximum potential acidity and maximum neutralisation capability and implies a 1:1 acid to base reaction.
- The actual acid production and neutralisation release rates (Mills, 1998) cannot be predicted with this technique, nor can the completeness of the reaction be assessed.

4.3 CURRENT HYDROCHEMICAL CHARACTERISTICS OF THE WESTERN WITBANK CHEMISTRY

4.3.1 Tavistock Colliery

4.3.1.1 *Groundwater quality*

The groundwater quality results have indicated neutral, good quality water for most of Tavistock Colliery. The good quality of the water is attributed to the long period of dynamic flow through weathered sediments, which have washed away the leachable salts.

The positions of the samples were plotted and analyses by making use of the software package WISH. WISH enables one to plot available information on the chemistry of the area over time as well as making use of methods to classify the type of water.

Boreholes in old mine workings show contamination trends typical of the acid rock drainage. Groundwater in these locations have lower pH-values, relatively high TDS and sulphate concentrations, and occasional indications of heavy metal contamination.

Note that only boreholes which are of interest in the Tavistock area were plotted in the area. Figure 4-5 shows the positions of the sampling points as well as the current sulphate concentration of the monitoring points. Every monitoring point has a colour, for example, red, yellow or green. These colours give an indication of the quality of the water according to the SA drinking water standards, in this case sulphate. (Red - very high sulphate concentration >600mg/l, yellow - moderate to high with a sulphate concentration of between 400 and 600 mg/l, and green - low sulphate concentrations in the range of 0-400).

A lot of data are available on the chemistry of the area.

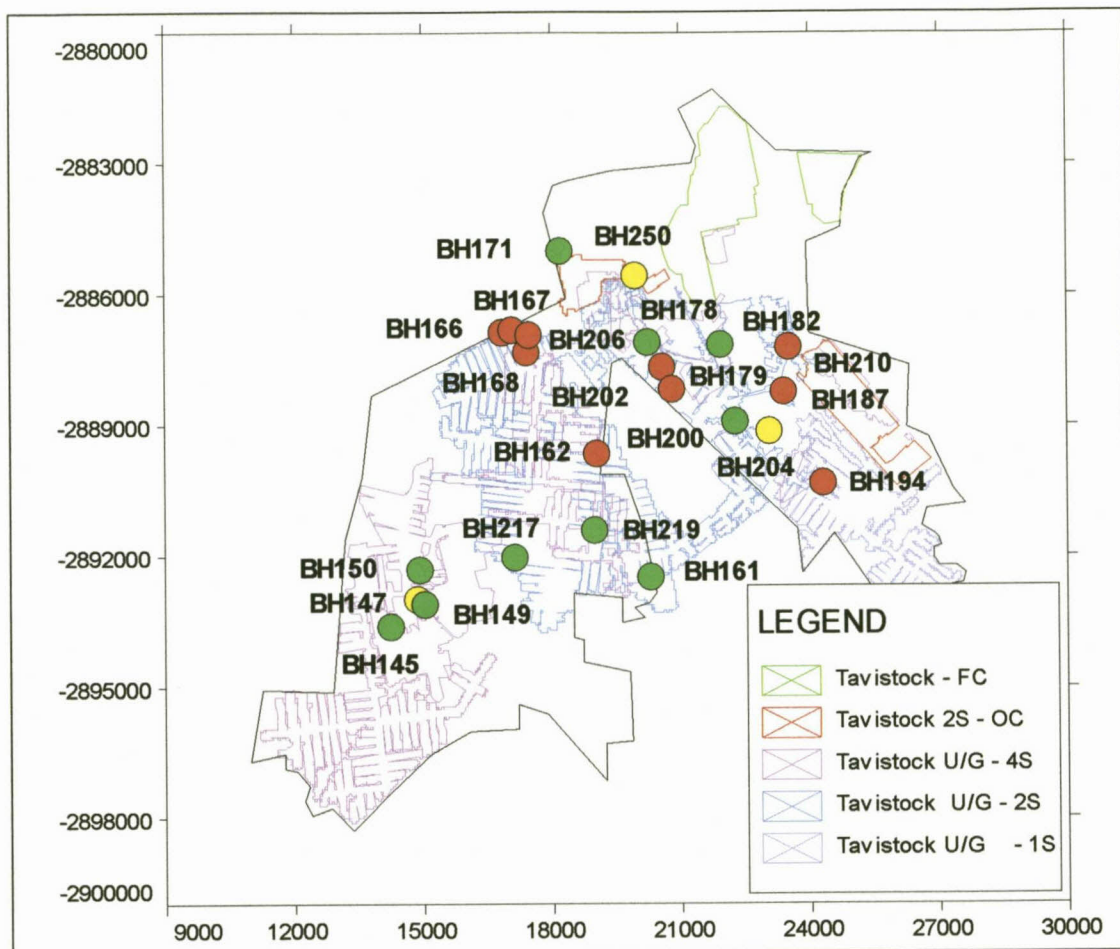


Figure 4-5 Borehole monitoring points at Tavistock Colliery (Red - very high (>600mg/l), yellow - moderate to high (400-600mg/l), and green - low (0-200mg/l)).

Sulphate values in excess of standards occur in several boreholes. Sulphate concentrations range from 16 to 2471 mg/l.

The pH of the boreholes ranges between 6 and 8, except for a few instances, namely Boreholes, 162, 187, 210 and 219, which range between 3.8 to 5.2. See Figure 4-6 of sulphate versus pH.

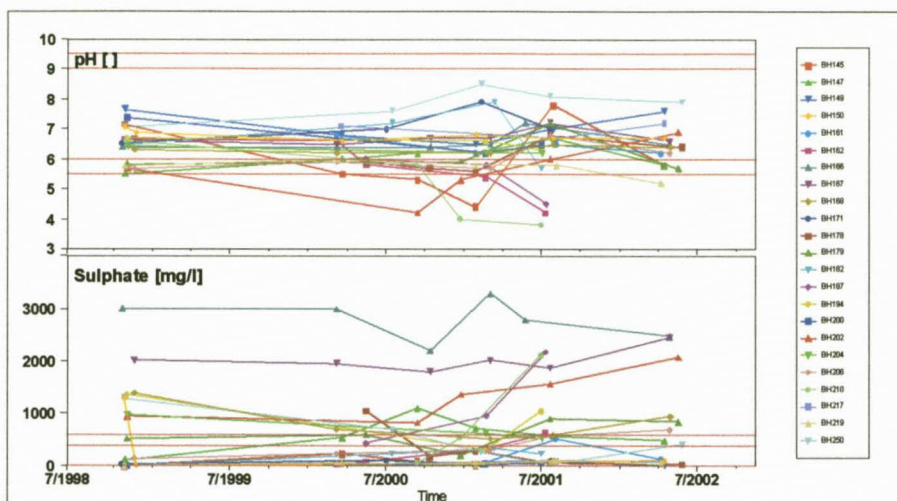


Figure 4-6 Line plots of the pH- and sulphate values for borehole water in the Tavistock area.

4.3.1.2 Stiff diagrams

A Stiff diagram was plotted to determine the major cations and anions present in the samples at Tavistock Colliery. By making use of Stiff diagrams, concentration dominance of the major cations and anions present in water samples can be seen. The diagram represents eight major ions, four cations and four anions. The cations, namely Na, K, Ca and Mg, are plotted to the left and anions, namely Cl, N, Alkalinity and SO₄, are plotted to the right. See Figure 4-7 for a representation of an example of a stiff diagram.

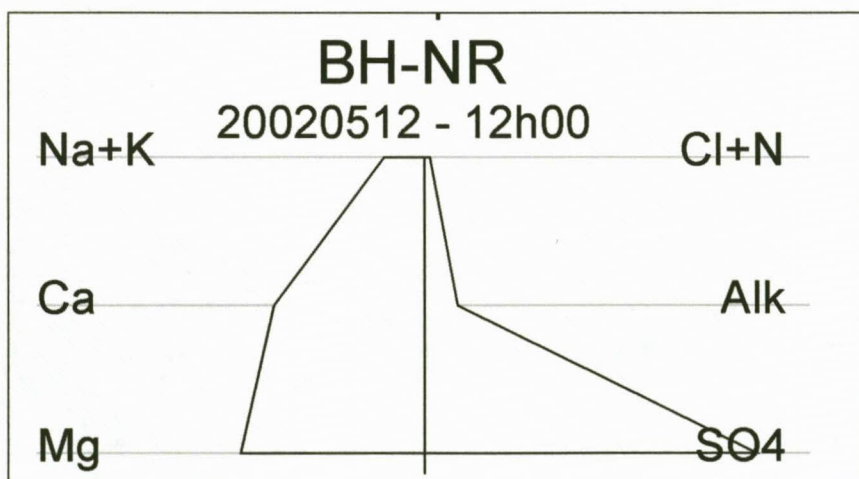


Figure 4-7 Representation of the Stiff diagram.

A Stiff diagram allows the identification of the major species as well as processes and gives a visual check on the ion balance.

Stiff diagrams were plotted for the sampling boreholes. See Figure 4-8 for Stiff diagrams for some of the boreholes. From Figure 4-8 it can be seen that Boreholes 166, 167 and 202, as well as 210 can be classified as boreholes with very high sulphate, calcium and magnesium concentrations.

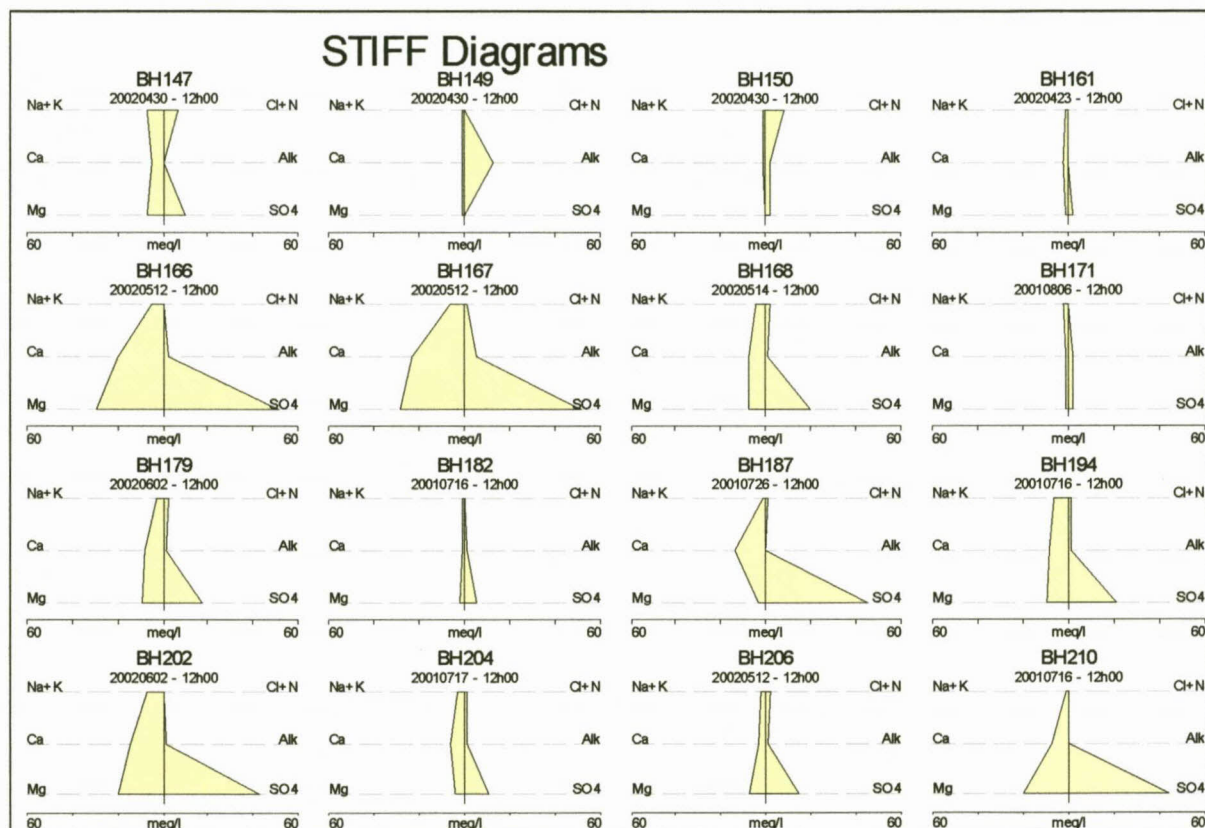


Figure 4-8 Stiff diagrams of borehole monitoring points at Tavistock Colliery.

Line plots were plotted to see if there is any correlation between the sulphate, calcium and magnesium concentrations of the area. It can be seen that boreholes 166 and 167 have very high concentrations of sulphate, and of both calcium and magnesium from the end of 1998 up till middle of 2002. The pH of above-mentioned borehole is still high and thus can be attributed to the fact that the calcium and magnesium carbonates are in excess. It is expected that dolomite and calcite will neutralise the pH of the pits, irrespective of the high sulphate concentration present. The calcite and dolomite cause a buffer effect (see section 4.1.1). These minerals will prevent the water from becoming acid as long as they exceed the acidification due to pyrite oxidation. When the concentration of calcium and magnesium decrease, acid generation will develop. See Figure 4-9 for the sulphate versus calcium and magnesium plot.

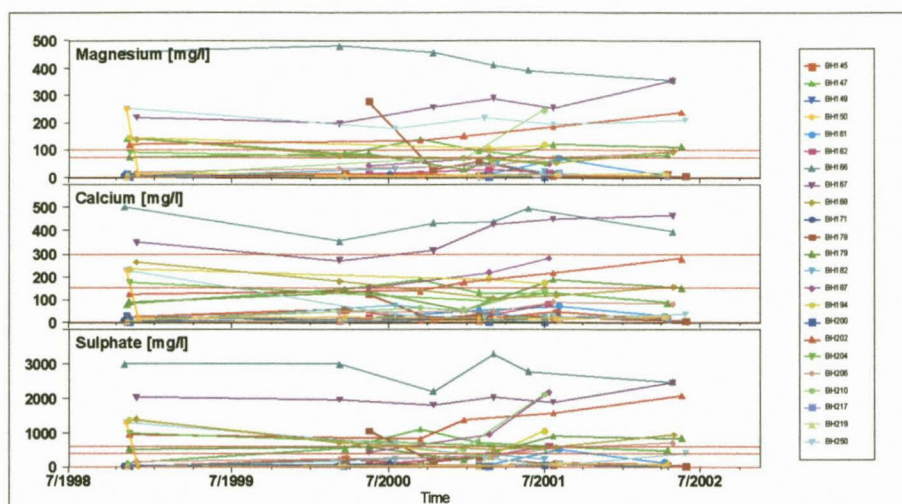


Figure 4-9 Line plots of the sulphate vs. calcium and magnesium values for borehole water in the Tavistock area.

4.3.1.3 Piper diagrams

The surface and groundwater chemistry in the study areas can also be shown by making use of specialised chemical plots.

Water can be classified by making use of Piper diagrams. In a Piper diagram the major cations (Ca, Mg, Na and K) and anions (Cl , SO_4 and $\text{HCO}_3 + \text{CO}_3$) are plotted as one point in a trilinear field. These two points are then extended into the main diamond shaped field of the Piper diagram to plot as one point. The water is classified depending on the position of this point.

A Piper diagram shows the water chemistries of boreholes located in the Tavistock area. See Figure 4-10 for Piper diagram.

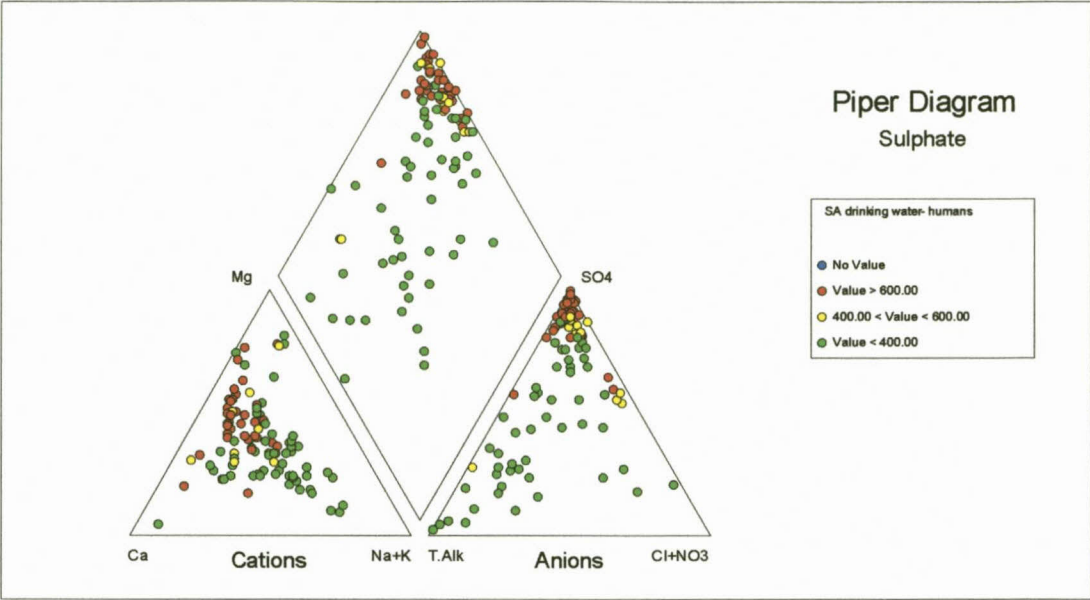


Figure 4-10. Piper diagram of the major elements from the boreholes at Tavistock Colliery.

Deviations from these areas imply that sulphate is a dominant source of degradation of the quality of the groundwater at Tavistock Colliery. Two strong trends of pollution are present. According to the Piper the water is of a sulphate-calcium-magnesium character.

4.3.1.4 Expand Durov diagram

This diagram shows similar ratio techniques to plot the concentrations of the major ions; however six triangular diagrams are used: Three for the anions and three for the cations. On each of the triangles the sum of the anions adds up to 50% and the ions are plotted in different combinations. The result is a plot with nine fields for classification. These fields give better splitting than the Piper diagram. The fields which are shown in can be described as follows.

Table 4-1 Classification of water by making use of the Expanded Durov diagram

1	2	3
Calcium bicarbonate	Bicarbonate Magnesium or (Calcium Magnesium)	Bicarbonate Sodium
4	5	6
Sulphate or (anions) and Calcium	No dominant cat or anions	Sulphate or (Anions) and Sodium
7	8	9
Chloride and Ca dominant	Chloride No Cations	Chloride and Sodium

1. HCO_3^- and Ca^{2+} water. This water type is often a recently recharged water or recharged water.
2. HCO_3^- and Mg^{2+} dominant of HCO_3^- and Ca^{2+} and Mg^{2+} important, indicates water often associated with dolomite or mafic igneous rocks.
3. HCO_3^- and Na^+ dominant of often indicates ion exchanged water.
4. SO_4^{2-} (or anions indiscriminate) and Ca^{2+} dominant, may be a recharge water in lavas or associated with gypsum deposits.
5. No dominant anions or cations, indicates water resulting from dissolution of mixing.
6. SO_4^{2-} (or anions indiscriminate) and Na^+ dominant, is a water type unless reverse ion exchange is taking place.
7. Cl^- and Ca^{2+} dominant is not a common water type unless reverse ion exchange is taking place.
8. Cl^- and no dominant cation suggests that reverse ion exchange is taking place.
9. Cl^- and Na^+ dominant frequently indicates and end point water in a water evolution sequence.

An Expanded Durov graph was plotted for the samples at Tavistock Colliery. The water chemistry of the sample at Tavistock Colliery is typical of mine water, especially the samples plotting in area 6. The samples that plot in the first row is representative of fresh water. See

Figure 4-11 for details.

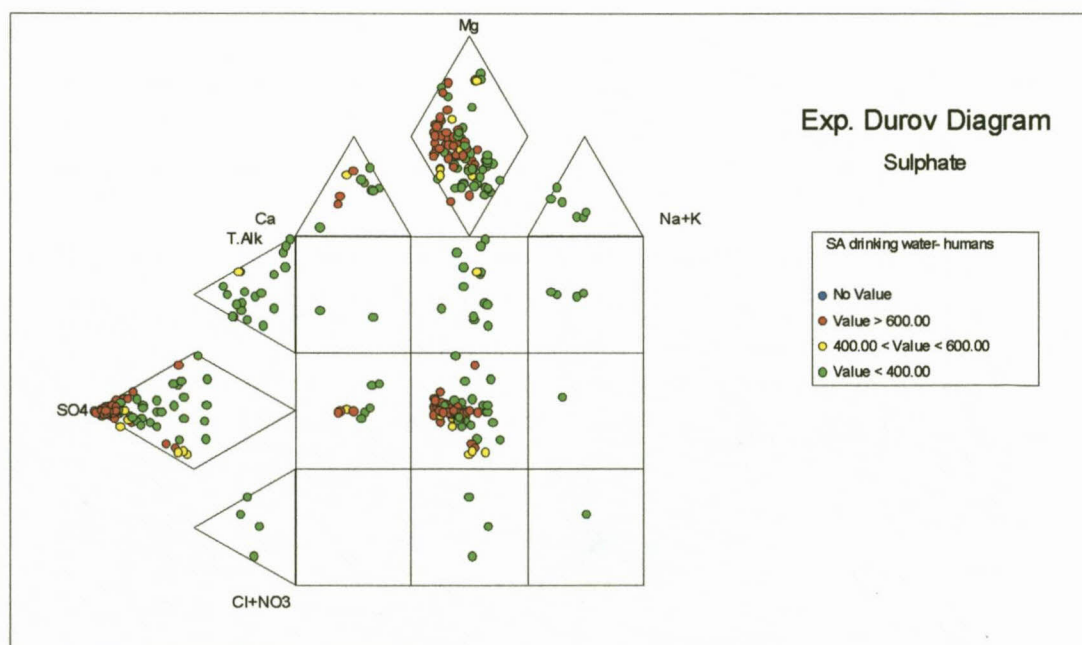


Figure 4-11 Expanded Durov shows the concentrations of the major ions in the borehole samples. Acid-Base Accounting

In general the water quality in underground workings is expected to be dictated by the pH-conditions. Coal samples have been obtained by Hodgson (1999) from Tavistock Colliery for acid-base determinations and leaching tests. The conclusions from these tests are (Hodgson, 1999):

- The initial pH-levels of the coal samples are high, ranging from 8,2 - 9,1. This suggests the presence of sodium carbonate that will initially counteract acidification during the flooding stage of the collieries.
- Significant quantities of calcium/magnesium carbonate are also present, which will act as a secondary neutralising agent once the sodium carbonate has been depleted.
- Overall, the acid potential of the coal exceeds its base potential in all the coal samples tested. All samples acidified in the laboratory during oxidation tests. Eventual acidification of unflooded underground areas is therefore inevitable.
- In the shorter term, i.e. while mining, acidification is possible in areas of dynamic water through flow.

After mining has ceased in the No. 4 Seam Underground, acid conditions will prevail because of the fact that the underground is leaching to the No. 2 Seam Underground. The through flow of water will leach the carbonate minerals from the coal. This will be followed by oxidation of the pyrite on the outside of the coal that is exposed and local acidification will take place. See Table 4-2 for expected water qualities in Tavistock's underground area.

Table 4-2. Typical expected water qualities for the underground workings at Tavistock.

pH		3,2
EC	mS/m	250 - 450
Ca	mg/L	100
Mg	mg/L	50
Na	mg/L	50
TAlk	mg/L	0
Cl	mg/L	20
SO4	mg/L	3500

It was suggested as a management option that the 4 seam underground area be sealed off to let the pit fill in order to prevent or decrease the drainage of acid mine water to the 2 Seam. The pipe option was also suggested to let the pit fill more

quickly (See Chapter 5). When flooded after mining, the acid conditions will revert to alkaline conditions, because of the liberation of remainder base potential from within the coal itself.

4.3.1.5 Conclusions

In terms of water quality of the mine during mining condition, this water is expected to be slightly acidic, at a pH of 6,5 with sulphate levels in the order of 2 400 mg/L (Hodgson, 1999).

Acid conditions are expected to occur in the medium term after closure on the No. 4 Seam horizon, because of the unflooded conditions and the presence of oxygen. Alkaline conditions are expected on the No. 2 Seam horizon, because of the flooded conditions. In the opencast pits, acid conditions will exist above the water level and alkaline conditions below the water table.

According to Hodgson (1999), water quality problems associated with mining at Tavistock Collieries will be minor for the immediate future, even up to the mine closure stage. He predicts that the filling up of the mines will take decades, and in that time, acid patches will develop in the opencast and in the No. 4 Seam workings.

4.4 RIETSPRUIT COLLIERY

4.4.1 Surface water quality

Figure 4-12 shows the positions of the surface monitoring points at Rietspruit Colliery. Sample positions show the current sulphate concentration of the monitoring points.

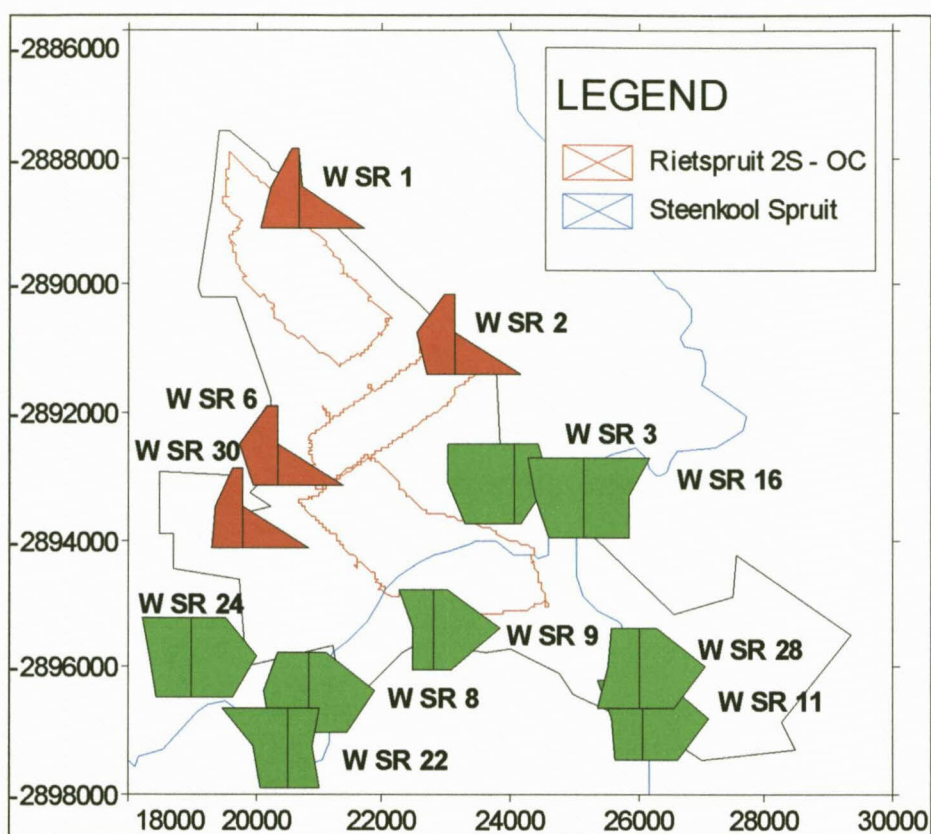


Figure 4-12 Positions of the surface monitoring points at Rietspruit Colliery. Sample positions show the current sulphate concentration of the monitoring points (Red - very high (>600mg/l), yellow - moderate to high (400-600mg/l), and green - low (0-200mg/l)).

The water quality of the samples in the vicinity and along the Steenkool Spruit is very good. According to the Stiff diagrams plotted in, it can be seen that samples taken along and near the Steenkool Spruit present higher relative concentrations of Cl and Alkalinity, while those nearer the pits have stronger sulphate character.

Currently the pH-levels of the samples range between 6.5 and 8.7, except for WSR3, which has a pH of 5.8. Sample WSR1 WSR2, WSR6 and WSR30, have very high sulphate concentrations, but for the rest of the samples, the sulphate concentration is not yet problematic. The high sulphate concentrations of samples WSR 1 and 2 can be attributed to the fact that these samples are located in the N3 and North-South opencast pits. See Figure 4-13 for graphs of pH and sulphate.

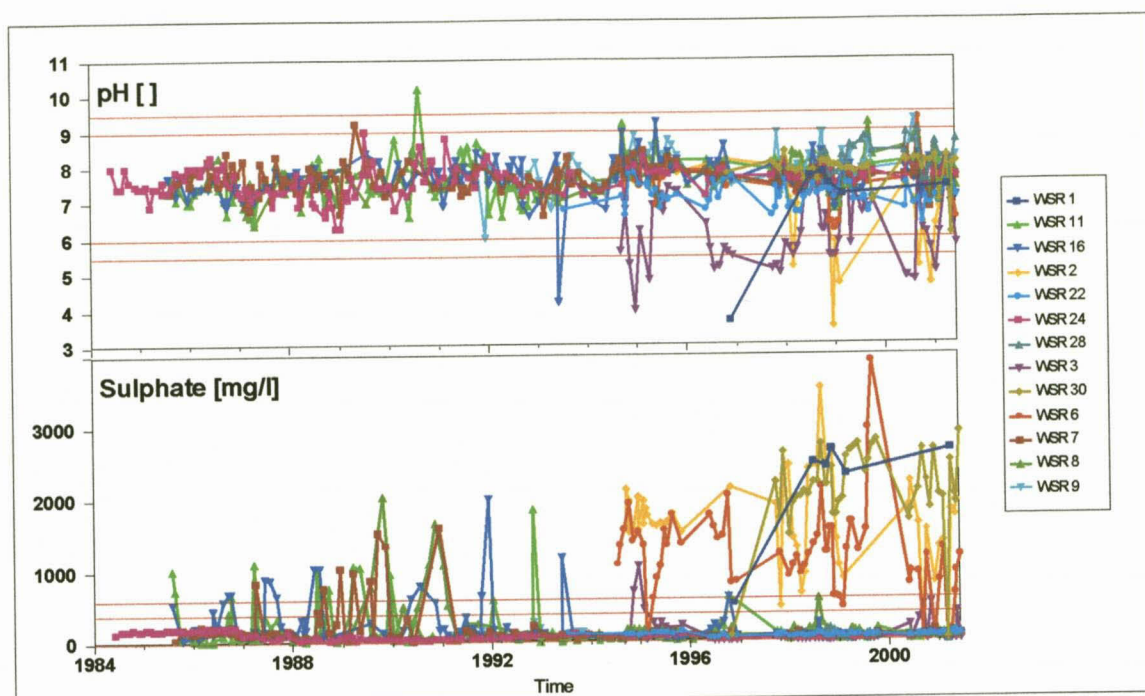


Figure 4-13 Line plots of the pH- and sulphate values of the surface monitoring points (1984 - 2000).

Two cations, namely calcium and magnesium, are dominant in most of the waters.

4.4.2 Groundwater and pit water quality

The positions of the borehole monitoring points are presented in Figure 4-14. Sample positions show the current sulphate concentration of the borehole monitoring points.

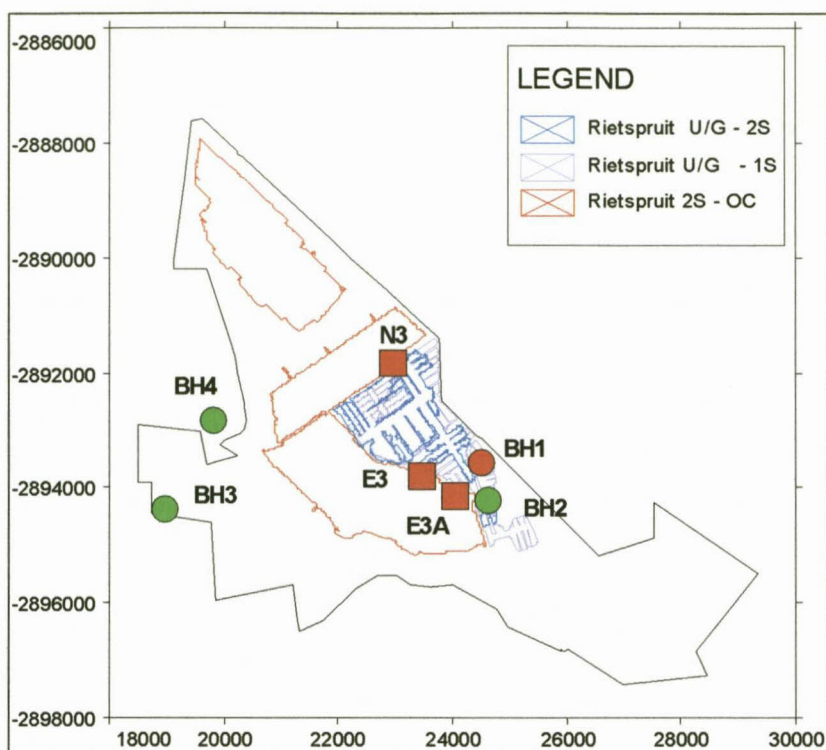


Figure 4-14 Positions of the borehole monitoring points at Rietspruit Colliery. Sample positions show the current sulphate concentration of the borehole monitoring points.

Dominant macro-elements are sulphate, calcium and magnesium. Figure 4-15 shows the graph for the pH- and sulphate concentrations of the four boreholes, as well as the measuring points for the opencast pits. The quality of the water in the boreholes around the pits is good. The pH for all the boreholes is neutral. The sulphate concentration of the boreholes is low, except for BH1. Borehole 1 shows a rapid increase in sulphate concentration at the beginning of 2000 and continues up till the present. Borehole 1 is located in the No. 2 Seam Underground. From information received from Rietspruit Colliery, it is clear that the underground workings at Rietspruit are relatively empty. The high sulphate concentration of Borehole 1 might be attributed to patches currently forming in the underground area because of intermine flow between the Rietspruit North-South Pit and its underground working. Ponds of water form in the low-lying area of the pit, where acid generation will start, because of the oxidation of pyrite and the presence of oxygen.

The monitoring points for the Rietspruit North-South opencast pit show excessive sulphate concentrations from 1994 to the present. It is known from literature that Rietspruit suffers from acid generation.

In the past, before the North and South Pits were linked, the decant level was at an elevation of 1524 mamsl, which is located to the far southern point of the South Pit. A huge amount of coal discard has been disposed of in this area and in a very unfavorable position, namely above the decant level and in the vicinity of the decant point. It was then decided to create another decant point as far away as possible from the present discard dumps. The decant point was established in the North Pit, with the current decant level at 1 530 mamsl. A dam wall was built at the decant point of the South Pit to reverse drainage to the North Pit (Van Tonder, 1997). Thus the high sulphate concentrations present in the North-South Pit can be attributed to presence of the discard dump in the pit.

The pH for these sampling points area is neutral. The pH of the waters range from 6.8 to 8.7 for the past few years. From this it is clear that sufficient base potential is currently available to neutralise acid that is being generated. The buffering of the water at this pH-level is usually due to the presence of calcium and magnesium carbonate within the rocks.

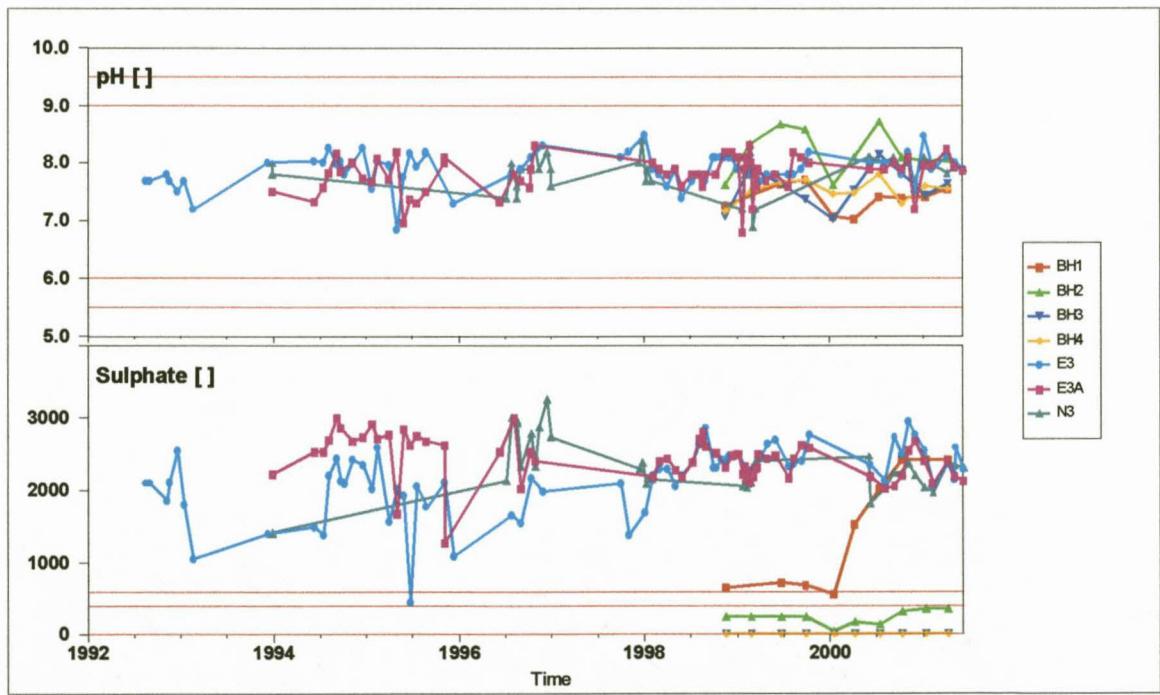


Figure 4-15 Line plots of the pH- and sulphate values for groundwater in the Rietspruit Colliery.

Figure 4-16 shows a graph of the calcium and magnesium versus the sulphate concentrations of the boreholes and monitoring points over time. Calcium and magnesium show a rapid increase in the beginning of 2000. Calcium and magnesium

carbonates can be classified as a permanent buffer agents (Hodgson, 1996). Acidification will normally occur at localities where the sulphate concentration significantly exceeds that of magnesium and calcium.

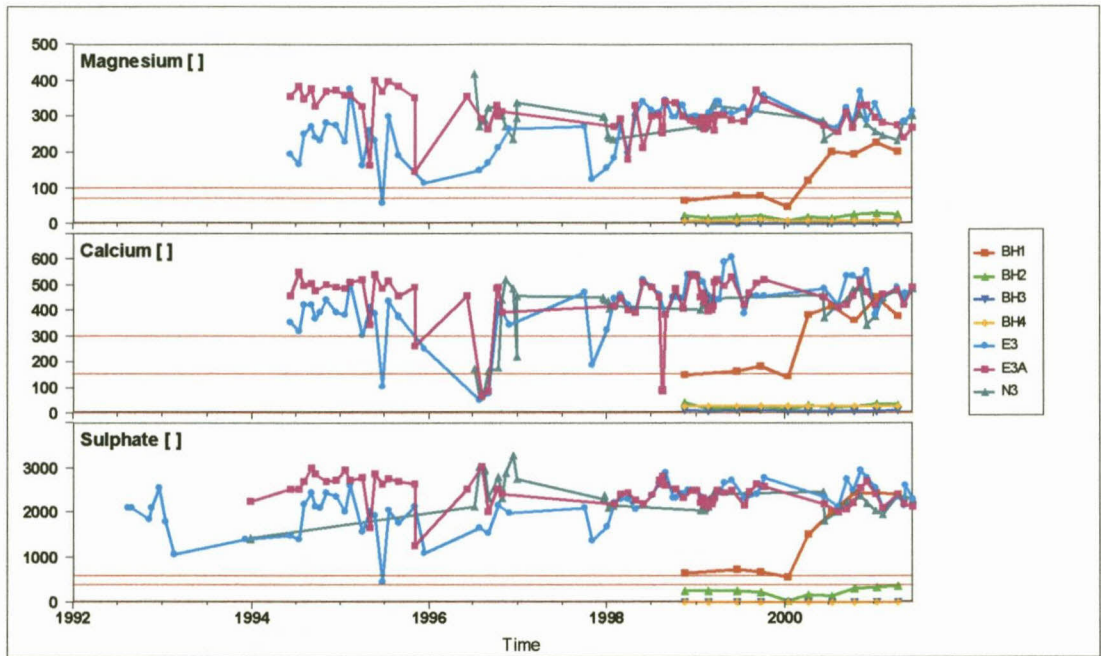


Figure 4-16 Line plots of the calcium and magnesium values.

From the Expanded Durov diagram in Figure 4-17, the following conclusions can be drawn. Boreholes 1, 2 and 3 are located in the first three blocks, which is an indication of fresh water. Borehole 1, as well as the three monitoring points located in the North-South opencast pit, are typical of mine water.

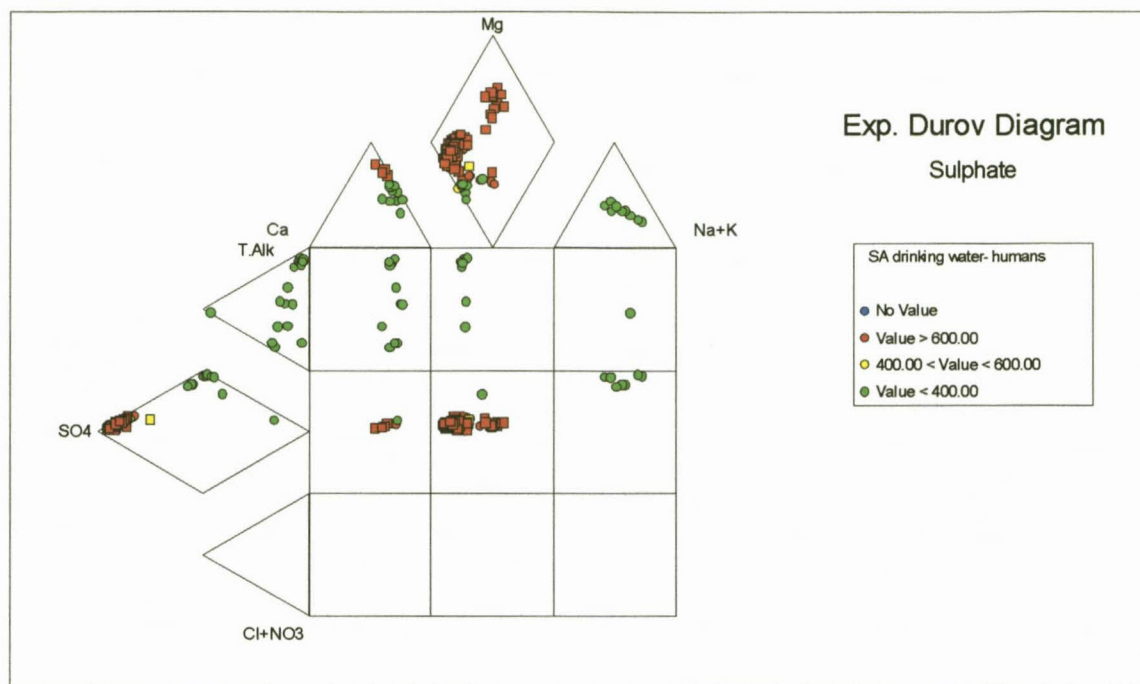


Figure 4-17 Expanded Durov diagram for Rietspruit Colliery.

4.4.2.1 Acid-Base Accounting

In 1996 representative rock samples of the complete geological succession at Rietspruit were tested for the geochemical characteristics.

Acid-base determinations on the spoil at Rietspruit Colliery have indicated that the acid and base potential of the rocks left behind within the opencast pits, are just about equal and that the pits will generally remain alkaline on condition that coal discards are not disposed of above decant levels in the pits. Projected sulphate concentrations range from 1 600 - 2 400 for in-pit water, at a pH of 6,5 (Hodgson, 1996).

4.4.2.2 Conclusions

The coal discards which have been disposed of in the South Pit have a very negative influence on the chemistry of the pit. This will mobilise heavy metals as well as high sulphate concentrations from the discard and spoil.

Currently, sufficient base potential is available to neutralise acid which is generated.

In the long term when the neutralizing potential is depleted the pH will drop drastically. The addition of fly ash to the pit can be introduced as a management option to improve the quality of the pit. This will be covered in detail in Chapter 5.

4.5 KLEINKOPJE COLLIERY

4.5.1 Surface water quality

The locations of the monitoring points in the Kleinkopje area are shown in Figure 4-18. The monitoring points show the sulphate concentration of the specific monitoring points in the area.

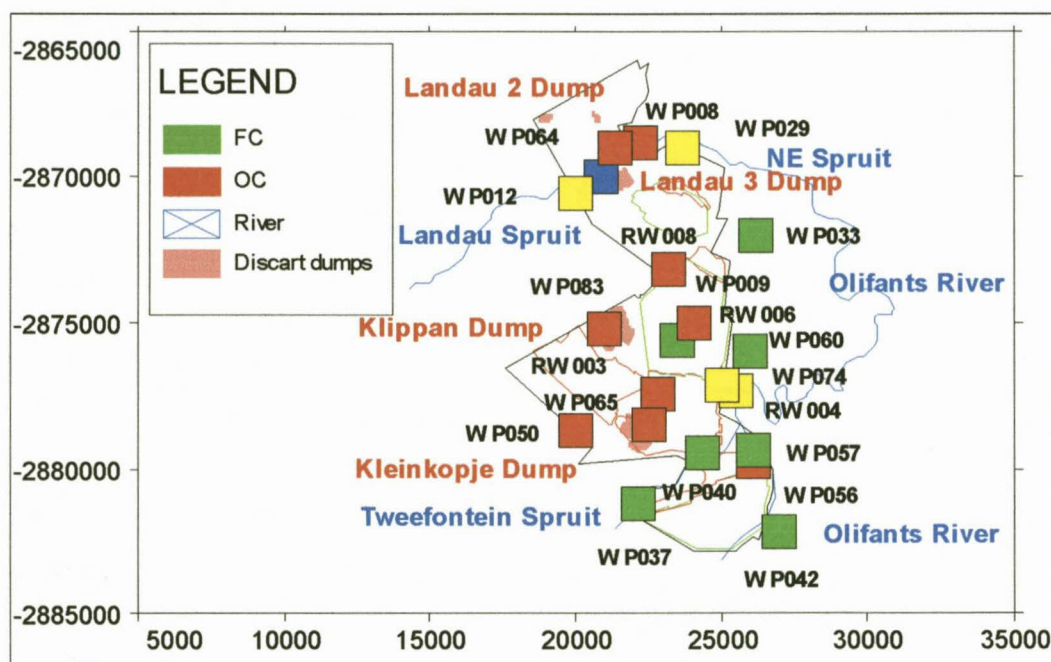


Figure 4-18 Surface water-sampling positions. The monitoring points are indicated as squares. Sample positions show the current sulphate concentration of the monitoring points (Yellow - moderate to high (400-600mg/l), and green - low (0-200mg/l)).

Studies conducted by Wates, Meiring and Barnard in 1990 to 1991 showed that the water quality in the Olifants River Catchment deteriorated as the surface streams traverse the coal mining area of the basin (Kleinkopje EMPR, 2001).

The impact of coal mining is that the total dissolved salts increase from 270-mg/l to 790 mg/l with calcium and magnesium as the dominant cationic species, increasing from 33% to 42%, and with sulphate becoming the dominant anionic species, increasing from 6% to 39 %. Point sources of heavy metals in excess of acceptable levels were traced to power stations and acid drainage streams associated with mining activity (Kleinkopje EMPR, 2001).

The Landau Spruit entering the property has an average sulphate concentration of 1600 mg/l. However, the average sulphate concentration at the point where the stream leaves the property is 515 mg/l. The decrease in concentration can be attributed to sulphate-reducing bacteria in the wetlands and a dilution effect from urban catchments feeding the Landau Spruit (Kleinkopje EMPR, 2001). Two discard dumps, namely Landau 1 and 2 are lying respectively to the north and south of the spruit, and will also contribute to the quality of the spruit. The Northeast Spruit is relatively unaffected. The maximum sulphate concentration occurred when opencast mining was at a peak in the area (2580 mg/l) (Kleinkopje EMPR, 2001). The average sulphate concentrations where the Olifants River enters and leaves the property are 326 mg/l and 121 mg/l respectively.

The Klippan and Kleinkopje discard dump contribute to some of the high sulphate concentrations in the central parts of the colliery. Two monitoring points, namely WP064 and WP083 are affected directly by later discard dumps.

Stiff diagrams were plotted in Figure 4-19 to determine the major cations and anions present in the specific monitoring points in the area. From the Stiff diagrams it can be seen that sulphate is the dominant anion, and calcium and magnesium are the dominant cations.

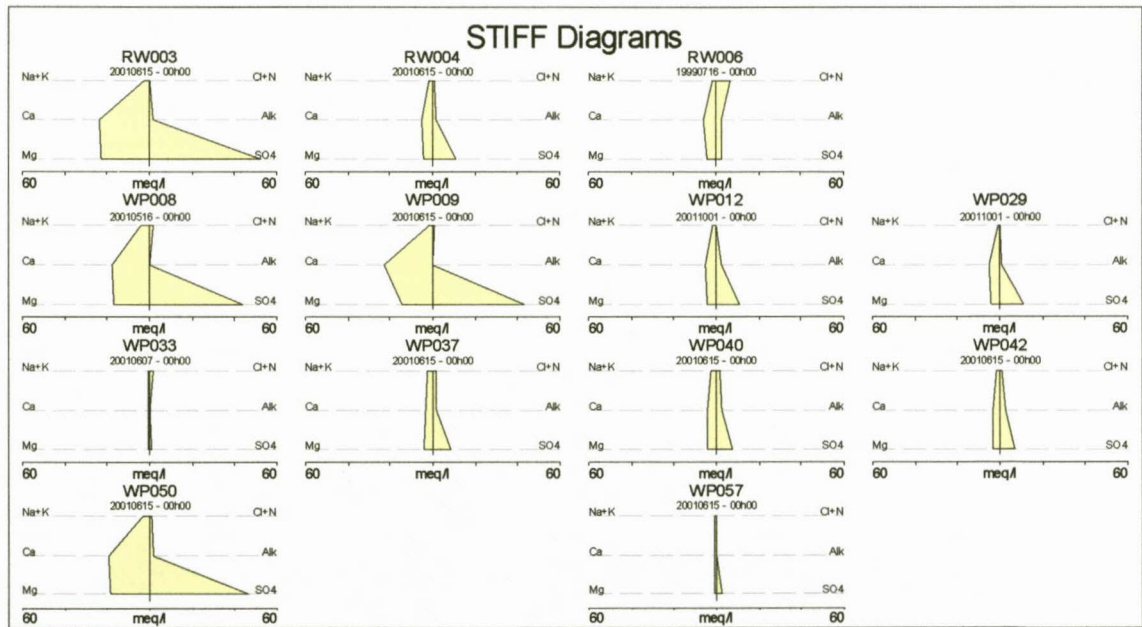


Figure 4-19 Stiff diagrams of the surface monitoring points at Kleinkopje Colliery.

A pH, sulphate graph was plotted for a more detailed description, and can be seen in Figure 4-20. Data range over a period from 1990 to 2002 for sulphate.

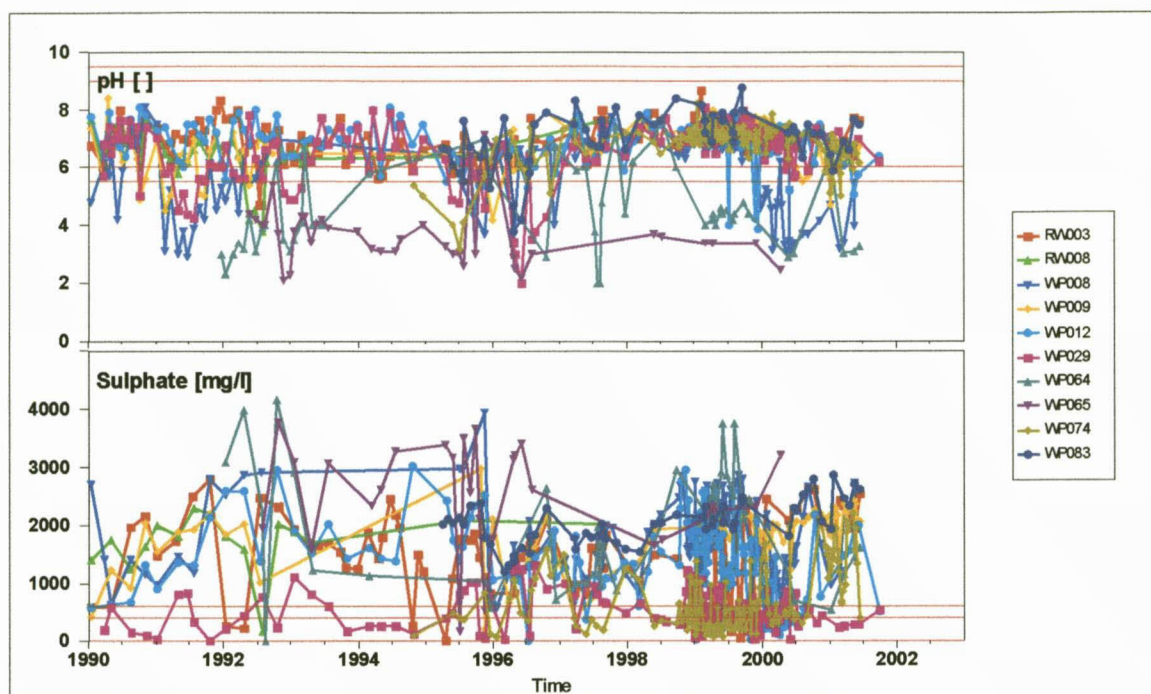


Figure 4-20 Line plots of the pH- and sulphate values for groundwater in the Kleinkopje Colliery.

4.5.2 Groundwater quality

Groundwater is sampled at various times from the known monitoring boreholes. Groundwater samples are taken on a regular base in boreholes KKW11, KKW13, KKW14, KKW40, KKW41, KKW42, KKW43 and KKW44 and are shown in Figure 4-21. The monitoring boreholes show the sulphate concentration of the specific monitoring points.

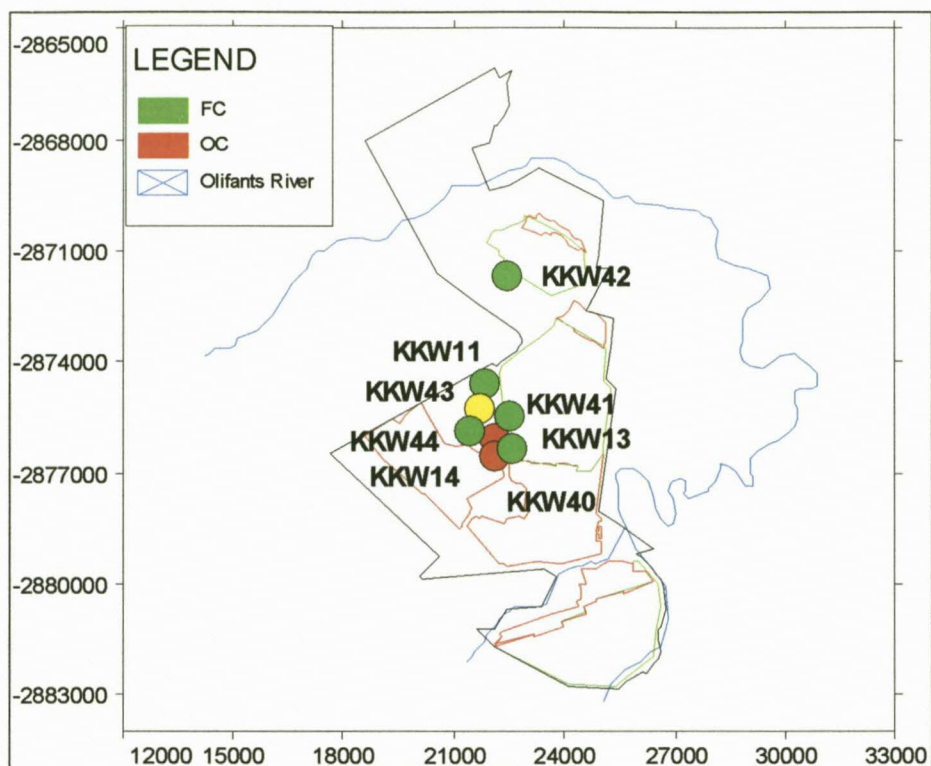


Figure 4-21 Groundwater sampling positions. The sampling points are indicated by circles. Sample positions show the current sulphate concentration of the monitoring points. (Red - very high (>600mg/l), yellow - moderate to high (400-600mg/l), and green - low (0-200mg/l))

The groundwater quality represented by the samples taken from these boreholes is relatively good except for three boreholes, namely KKW13, KKW14, and KKW43, where high sulphate concentrations are measured. The pH of all the above-mentioned boreholes is moderate to low.

Figure 4-22 and Figure 4-23 give an indication of the pH-sulphate as well as the dominant ion concentrations of the boreholes over a time period.

From Figure 4-22 it can be seen that there is a correlation between the sulphate and pH of the KKW013, KKW014 and KKW043. The higher the sulphate the lower the pH. The correlation is also visible with calcium and magnesium for the three boreholes.

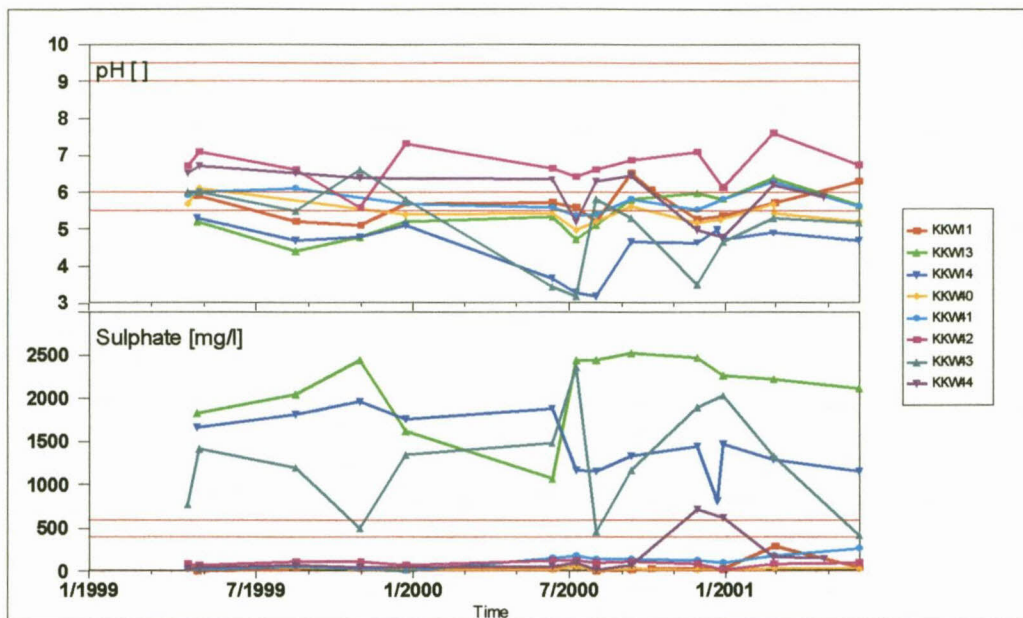


Figure 4-22 Line plots of the pH- and sulphate values for groundwater in the Kleinkopje Colliery (1984 - 2000).

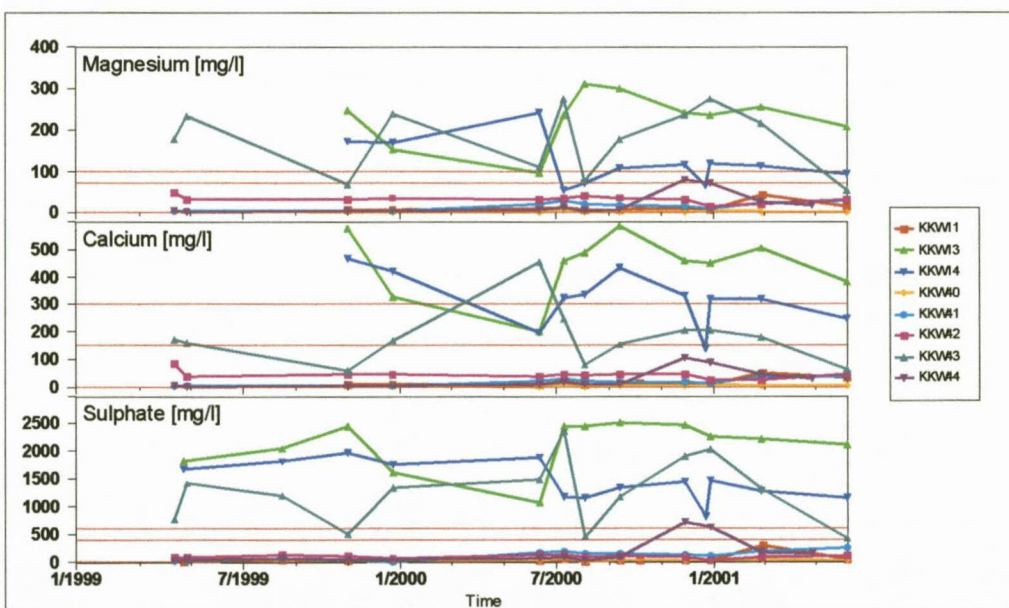


Figure 4-23 Line plots of the calcium and magnesium and sulphate values.

The Piper diagram showed in Figure 4-24 indicates the sulphate enrichment and the calcium tending nature of the water.

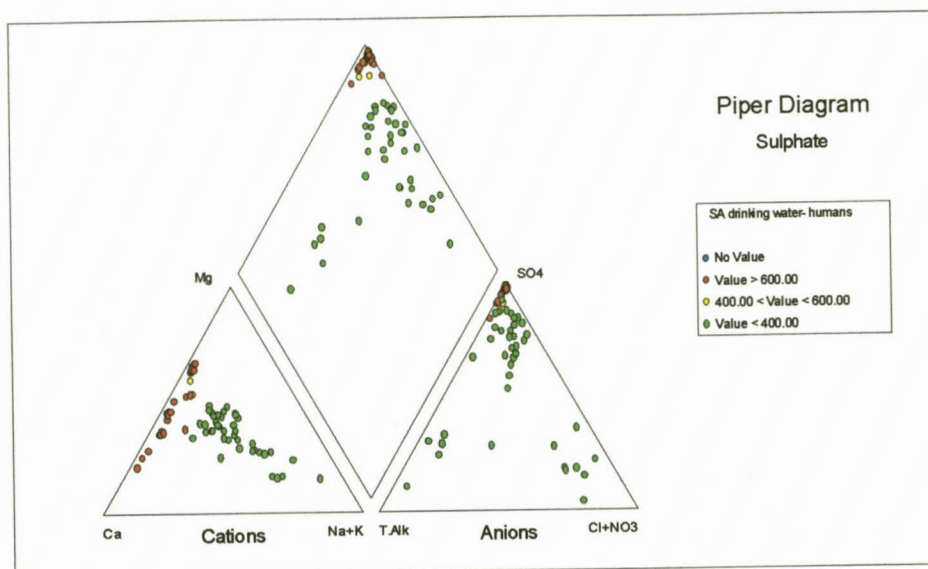


Figure 4-24 Piper diagram of the major elements at the borehole positions indicated at Kleinkopje Colliery.

4.5.3 Conclusions

The quality of the surface waters are good, with low to moderate sulphate concentrations except for the monitoring point located in or close to the discard dumps. The water quality of the underground areas are relatively good with neutral pH levels. Exceptions occur where high sulphate waters associated with the mining areas is very evident.

4.6 KRIEL COLLIERY

4.6.1 Surface water quality

Water samples for surface water quality determination were taken at pans, dams and at the Riet Spruit. Figure 4-25 shows the positions of the surface monitoring points in the vicinity of Pit 5 and 6.

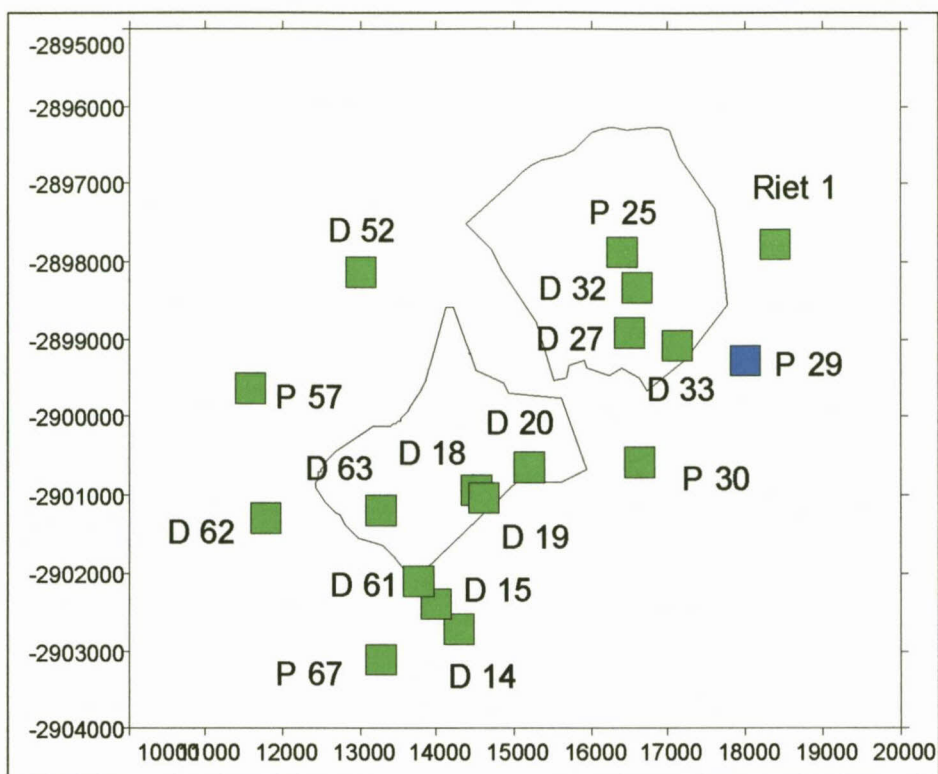


Figure 4-25 Positions of the surface monitoring points in the vicinity of Pit 5 and 6 in the Kriel Colliery area.

From the results the following conclusions can be drawn:

The surface water is of good quality and unpolluted, except for a few instances but which is located near the Kriel underground area south of the opencast pits and thus not included in the study area.

The pH in the area ranges from 5.8 to 8. The sulphate concentrations are very low, ranging from 2 to 220.

4.6.2 Groundwater quality

The positions of the borehole monitoring points can be seen in Figure 4-26.

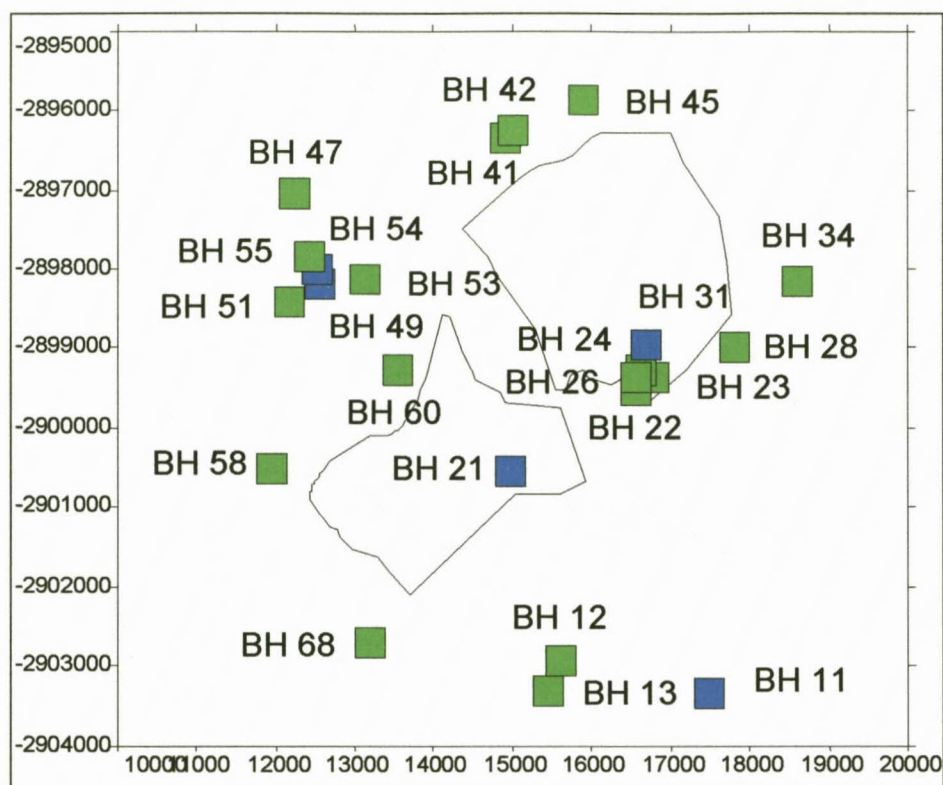


Figure 4-26 Positions of the borehole monitoring points in the vicinity of Pit 5 and 6.

Groundwater qualities within the vicinity of Pit 5 and 6 are of good quality and unpolluted in general. The pH in the boreholes ranges from 6.2 to 7.4. The sulphate concentrations are very low. The good quality of the area can be attributed to the fact that very little mining has been done in the area.

Mining of the two opencast pits has not yet started. Mining in Pit 6 are to be stated in 2004 and in 2009 for Pit 5, (Hodgson, 2001). When future opencast pits start mining, the quality of the water might deteriorate. Mining will cease respectively in 2024 and 2019.

The salinity levels of the two opencast pits will vary greatly depending on whether dynamic or stagnant conditions exist (Hodgson, 1998, Hodgson 2001). According to Hodgson, 1998. water will have to be pumped from the pits during the mining process, because of the slope of the floor, thus dynamic conditions will exist in the pits. Depending on the flow dynamics the sulphate levels are expected to be in the range of 660 - 1320 mg/l.

4.6.3 Acid-base accounting for Kriel Pits 5 and 6

In 1998 forty-one rock samples were collected from six cored boreholes at Pits 5 and 6, (Hodgson, et al., 1998). Two of these boreholes are located on the northwestern boundary of the area, one in the box cut area and the other two southeast of the pits.

These boreholes penetrated the total geological succession down to the floor of the No. 4 Seam. Through field investigation, the cores were subdivided into identifiable lithological units. Each of these units was crushed and pulverized, followed by acid-base testing, (Hodgson, et al., 1998)

From acid-base accounting done by Hodgson and Grobbelaar in 1998 for Pit 5 and 6, it was concluded that the composite pit water will have a pH level of 6.5. Results showed that the initial pH of the pit water could be as high as 8.5, but through oxidation of pyrite, the pH will drop to the buffering level of the calcium/magnesium carbonate in the spoil.

4.6.4 Conclusions

- Groundwater quality is good and unpolluted in general. The good quality are attributed to the fact that mining hasn't yet started in opencast pits. During the mining at the opencast pits, sulphate concentrations of 660 - 1320 mg/l are expected depending on the flow dynamics.
- Occasional higher concentrations of heavy metals such as copper and zinc can be attributed to the pumping installations in boreholes and not to natural causes.

4.7 DETERMINATION OF THE HYDROCHEMICAL IMPACT OF INTERMINE FLOW

In this chapter two methods will be used to calculate in pit water chemistry, namely,

- Mass Transport modelling- movement of solutes through groundwater and,
- Phreeqc calculations- calculation of aqueous geochemistry.

These two methods will be discussed in full detail in the next two sections

4.7.1 Mass Transport Calculations using MT3D

Modflow's flow models were used to calculate the mass transport of the area. The mass transport module with PMWIN MT3D (Chiang and Kinzelbach, 1998) was used for these calculations.

4.7.1.1 *Introduction to mass Transport modelling*

A transport model simulates the movement of a solute as it moves with the groundwater through the subsurface. Due to sorption processes, the movement of a solute can be retarded relative to the bulk movement of the groundwater. Dispersion and degradation processes can serve to reduce solute concentrations.

Fate and transport models require the development of a calibrated groundwater flow model or, at a minimum, an accurate determination of the velocity and direction of groundwater flow that has been based on field data. The model simulates the movement of contaminants by advection and diffusion, the spread and dilution of contaminants by dispersion, the removal or release of contaminants by sorption or desorption of contaminants onto or from subsurface sediment or rock, or chemical alteration of the contaminant by chemical reactions which may or may not be controlled by biological processes (biodegradation). In addition to a thorough hydrogeological investigation, the simulation of fate and transport processes requires a complete characterisation of the horizontal and vertical distribution of average linear velocity (direction and magnitude) determined by a calibrated groundwater flow model or through accurate determination of direction and rate of groundwater flow from field data.

The outputs from the model simulations are the contaminant concentrations that are in equilibrium with the groundwater flow system and the geochemical conditions defined for the modeled area. As with groundwater flow models, fate and transport models should be calibrated and verified by adjusting values of the different

hydrogeologic or geochemical conditions to reduce any disparity between the model simulations and field data. This process may result in a re-evaluation of the model used for simulating groundwater flow if adjustment of values of geochemical data do not result in an acceptable model simulation. Predictive simulations may be made with a fate and transport model to predict the expected concentrations of contaminants in groundwater as a result of implementation of a remedial action. Monitoring of hydraulic heads and groundwater chemistry will be required to support predictive simulations (Dennis, 2000).

4.7.1.2 Solute Transport Basic Concepts

Solutes, or chemical contaminants, are transported by moving groundwater. This process is called advection and is the dominant transport mechanism. In groundwater models, this process is simulated by particle tracking.

Groundwater flow paths are not uniform, however. The twisting of the flowpaths through the pores around soil particles causes dispersion of the solute. Dispersion is also caused by variations in groundwater velocities within the flow-paths. (See Figure 4-27 for representation of the flow-path during dispersion)

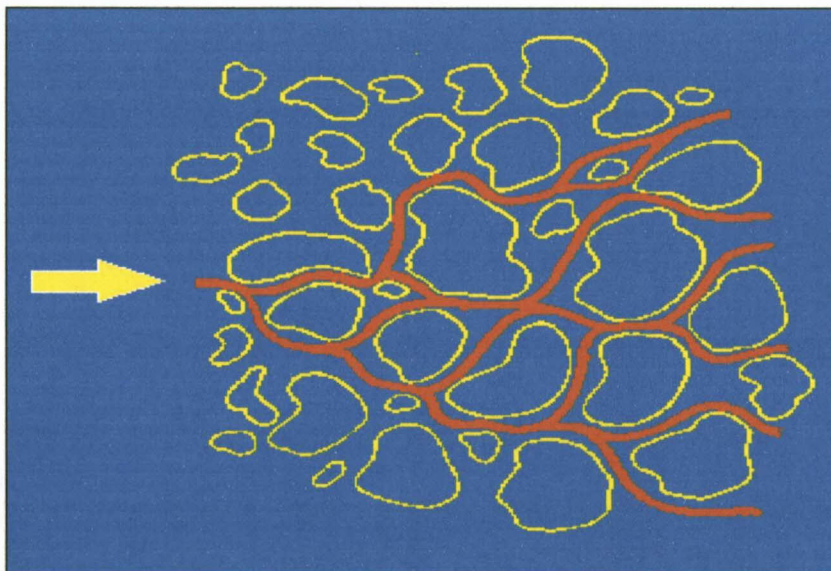


Figure 4-27 Dispersion of water through along its flow path.

Diffusion is the movement of solute from areas of high solute concentration to areas of low solute concentration (Figure 4-28). It is typically a very minor transport mechanism and is usually ignored. It can be a factor in effective reaction or retardation rates. The following figure illustrates the effects of these processes on the

concentration of a solute with distance from a constant solute source. With advection only (no dispersion or diffusion) the solute concentration versus distance is represented by the advection line. Solute concentration would remain equal to the source concentration until reaching the plume boundary at which point the solute concentration would immediately drop to zero or background. With advection and diffusion, as represented by the diffusion line, there would be a small transition zone from source concentration to zero or background. When dispersion is included, the transition zone becomes much larger (Dennis,2000)

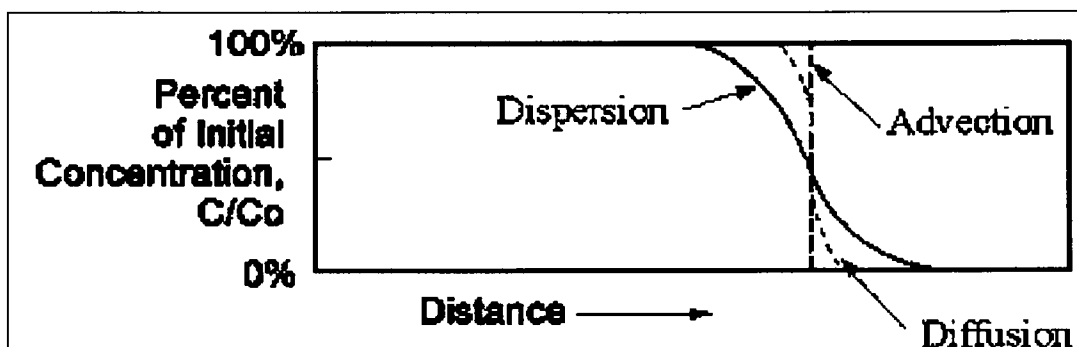


Figure 4-28 Diffusion particles from a high concentration to a low concentration in the ground.

4.7.2 Geochemical modeling using PHREEQC

Phreeqc (Parkhurst, 1995) is a computer program written in C programming language that is design to perform a wide variety of aqueous geochemistry calculations. Phreeqc is based on an ion-associated aqueous model and has capabilities for (1) speciation and saturation index calculations, (2) reactions-path and advective-transport calculations involving specified irreversible reactions, mixing of solutions, mineral and gas equilibria, surface-complexation reactions, and ion-exchange reactions, and (3) inverse modeling, which finds sets of mineral and gas mole transfers that account for composition differences between waters, within specified compositional uncertainties.

Phreeqc is capable of simulating a wide range of geochemical reactions including mixing of waters, addition of net irreversible reactions to solution, dissolving and precipitating phases to achieve equilibrium with the aqueous phase and effects of changing temperature. Concentrations of elements, molalities and activities of aqueous species, pH, pe, saturation indices, and mole transfers of phases to achieve equilibrium can be calculated as a function of specified reversible and irreversible geochemical reactions, provided sufficient thermodynamic data are available.

4.7.2.1 Phreeqc calculations

Phreeqc calculations were done by making use of water quality data available in the study areas. A representative solution (sample or combination of samples) of the area was taken to do the calculations. Specification calculations were performed on each solution.

The following calculations were done on the samples:

- Selection and input of the solutions and interpretation of the results (Saturation Index and distribution of species).
- Adjustment of individual element concentrations to achieve charge balance or equilibrium with a pure phase.
- Then the resulting speciated solutions were used in subsequent reactions for example mixing.

4.7.2.2 Solution selection

The solutions are compiled by making use of the boreholes or sampling positions preferably in the pit or underground areas.

Representative samples of the opencast and underground areas were taken to do the calculations. The initial solutions used in the calculations represent the chemical composition of these real samples.

4.7.2.3 Saturation index

For each of the three samples mentioned, the saturation index of the solutions were calculated.

The saturation index can be defined as follow: See equation for detail.

$$SI = \text{Log} \left[\frac{IAP}{K_{sp}} \right]$$

Where:

IAP = Ion activity product $[A]^a [B]^b$ calculated from the measured concentrations.

K_{sp} = the solubility product of the solid species $[A_xB_y]$. Obtained from theoretical values, read from tables or calculated from thermodynamic data.

As a general rule the SI can be used as follows: If:

SI < 0 - the groundwater is undersaturated in $[A_xB_y]$ and dissolution will occur.

SI = 0 - the water is in equilibrium with the solid

SI > 0 - the water is supersaturated with the solid components and precipitation should result.

4.7.2.4 Equilibrium phase

Equilibrium phase is used to define the amount of an assemblage of pure phase that can react reversible with the aqueous phase. Pure phases included fixed composition minerals for example, calcite, dolomite, and gypsum and gases with fixed partial pressures. If pure phase are brought into contact with an aqueous solution, each phase will dissolve or precipitate to achieve equilibrium or will dissolve completely.

4.7.2.5 Mixing

Mixing is used if two of more aqueous solutions are to be mixed together. The mixing occurs as part of the reaction calculations. In mixing, each solution is multiplied by its mixing fraction and a new solution is calculated by summing over all of the fraction solutions.

Mixing fractions as calculated by the Modflow numerical modeling simulations (Section 4.8.2 and 4.9.2) were used.

By making use of Modflow's intermine flow volume predictions between collieries, mixing of colliery water can be simulated. In this case a percentage of water from the intermine flow causing colliery will be mixed with the receiving colliery to show the result of the mixing of different colliery waters.

4.8 EVALUATING THE HYDROCHEMICAL IMPACT OF FLOW BETWEEN KRIEL AND TAVISTOCK

4.8.1 Kriel and Tavistocks Phreeqc calculations

Representative samples of Kriel's opencast pits and Tavistocks underground area were taken to do the Phreeqc calculations. Kriel's chemical composition is defined as Kriel OC and Tavistocks chemical composition is represented by BH 301. The chemical composition of the two areas was taken from borehole information available on the areas. The chemical composition of the two solutions can be seen in Table 4-3.

4.8.1.1 Kriel opencast pit sample

The initial solution was compiled by making use of the following boreholes in the area, namely, boreholes, 21-24, 26 and 31, which is located in the opencast pits. Because mining will first start in 2004 at Pit 6 the pit chemistry is not yet available predictions were made by Hodgson,2001. This report expectst an initial pH of 6.5 for Pit 5 and 6. The sulphate levels are expected to be in the range of 660 - 1320 mg/l, (Hodgson 2001). For the rest of the parameters, average concentrations were used. See Table 4-3 for the initial concentration of pit water at Kriel Colliery.

Table 4-3 Chemical composition of Kriel's OC solution.

Kriel OC	Temp	Units	pH	S(6) *	Cl	Na	Ca	K	Mg	C(4) *	Fe	Al
	25	(mg/l)	6.5	660	20	29	155	18	74	180	1	0.1

S(6) - Sulphate

C(4) - Alkalinity

The results from the saturation index can be seen in Table 4-4.

Table 4-4 Results from the saturation indices of the initial solution for Kriel's opencast pit.

Solutions		Distribution of species(mg/l)			Saturation Indices			
	pH	SO4	Ca	Mg	Calcite	Dolomite	Gibbsite	Gypsum
Kriel OC	6.50	660	155	74	-0.94	-1.86	2.36	-0.74

Calcite - (CaCO_3)

Dolomite - ($\text{CaMg}(\text{CO}_3)_2$)

Gibbsite - ($\text{Al}(\text{OH})_3$)

Gypsum - ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$)

In case of Kriels opencast pit sample, the calcite, dolomite, and gypsum are unsaturated. Gibbsite and goethite are oversaturated and should precipitate.

Evaluation done by Usher et.al, 2001, by making use of Phreeqc shows that the iron species are often oversaturated. Williams and Smith (2000) reported that it is not clear if this is due to the inability of geochemical speciation models to accurately handle these values, or iron species due to the slow kinetics of formation or due to real supersaturation.

4.8.1.2 Kriel OC in equilibrium with dolomite

Kriels opencast pit sample was put into equilibrium with dolomite, the following can be expected of the quality of the solution. Calcite and gypsum are still unsaturated but closer to saturation.

During the equilibrium phase CO_2 (g) in corporation with dolomite or calcite were used to equilibrate the solution. If a pH of a solution is held constant with buffer reactions, and it is permitted to equilibrate with gaseous carbon dioxide, the total hydrated and unhydrated CO_2 in solution is independent of pH, while the bicarbonate and carbonate concentrations increase with pH in accordance with the pK values. These equilibria are influenced by temperature and salt concentration (ionic strength).

HCO_3^- dominates in water at pH 6.35 and below, while above pH 10.33, CO_3^{2-} is quantatively significant. Between pH 6.35 and 10.35, HCO_3^- predominates. Most natural waters fall into the pH range of 5.5 to 8.5, (Azzie, 1999).

The next step allows the water to react with excess dolomite. The results can be seen in Table 4-5. The calcium and magnesium show an increase because dolomite major releases these ions on dissolution.

Table 4-5 Results from the saturation indices of the equilibrated solution.

Solutions		Distribution of species			Saturation Indices			
Kriel OC	pH	SO4	Ca	Mg	Calcite	Dolomite	Gibbsite	Gypsum
Equilibrium (dolomite)	7.16	660.76	168.75	81.46	-0.0117	0.00	1.87	-0.72

4.8.1.3 Borehole 301 - Tavistock underground

A second solution was compiled by making use of the latest chemical data available on borehole 301, which are located in Tavistock's underground area. See Table 4-6 for initial concentrations of Borehole 301.

Table 4-6 Chemical composition of BH301.

SOLUTION	Temp	Units	pH	S(6) *	Cl	Na	Ca	K	Mg	C(4) *	Fe	Al
BH 301	25	(mg/l)	6.8	2046	42	96	567	7	168	278	3	0.5

The results from the saturation index can be seen in Table 4-7.

Table 4-7 Results from the saturation indices of the initial solution of BH 301.

Solutions		Distribution of species			Saturation Indices			
	pH	SO4	Ca	Mg	Calcite	Dolomite	Gibbsite	Gypsum
BH 301	6.80	2046.36	547	168	-0.18	-0.56	2.89	-0.02

From the results it can be seen that the solution from BH 301 is unsaturated in calcite, dolomite Gibbsite is oversaturated while Gypsum is at equilibrium with this water. This indicates the important sulphate limiting effect gypsum has on the waters in the Witbank Coalfield.

4.8.1.4 BH 301 in Equilibrium with Dolomite

It was decided to equilibrate solution from BH 301 with dolomite. With dolomite in equilibrium BH 301 are oversaturated in calcite and unsaturated in gypsum. And increase in the initial pH is visible. Very high calcium and magnesium concentrations are present. Excess dolomite was added to the solution. The pH dropped a bit, but a further increase in the calcium are visible. See Table 4-8 for details.

Table 4-8 Results from the saturation indices of the equilibrated solution.

Solutions		Distribution of species			Saturation Indices			
BH 301	pH	SO4	Ca	Mg	Calcite	Dolomite	Gibbsite	Gypsum
Equilibrium (dolomite)	7.01	2046.36	571.4	168.64	0.10	0.00	2.71	-0.02

4.8.2 Mixing of solutions

Mixing of waters from different areas is a common process in nature. In the case of Kriel Tavistock, 3 waters will be mixed. The three solutions can be defined as follow:

- Kriel OC - intermine flow with flow from Kriels Pit 6 to Tavistocks Underground area.
- BH 301- composition of Tavistocks Underground pit water
- Aquifer solution - inflows from the side(horizontal hydraulics) and top (vertical hydraulics and recharge) of Tavistocks underground area.

An average concentration was given for the solution to describe the chemistry of the unmined coal by making use of chemical data available

Table 4-9 Chemical composition of IMF solution.

Aquifer solution	Temp	units	pH	SO4	Cl	Na	Ca	K	Mg	C(4)	Fe	Al
Inflow	25	mg/l	7	115	24	65	20	5	10	184.8	0	0.36

Table 4-10 is an introduction to the calculations of the mixing fractions used in the Phreeqc calculations. The water levels at the specific year were obtained from the results of Modflow's water levels. The water levels were then used to calculate the volume of water present in Tavistock's underground area at that specific year by making use of Wish stage curves. The intermine flow (from Kriel OC) volumes, is the volume of water which moves through the coal barrier from Kriel to Tavistocks underground. The horizontal inflow, gained from Modflow's water budget report, is the volume of groundwater which flows form the side into the underground areas (aquifer solution). The recharge was also gained from the water budget report for the underground area. See Table 4-10 for detail over years.

Table 4-10 Introduction to the calculations of the mixing ratios.

Years	Volumes	WL	IMF volume (m ³ /d)	Aquifer solution (m ³ /d)	sum(IMF+Aq sol) (m3/d)	Inflow p/a	Recharge
10	434032239.80	1538.50	4.59	43.47	48.06	17541.90	1900
20	441540188.50	1539.10	5.80	29.91	35.71	13034.15	1900
30	458558205.40	1540.46	6.87	24.77	31.64	11548.60	1900
40	460810590.00	1540.64	6.79	21.45	28.24	10307.60	1900
50	465065094.20	1540.98	6.69	18.82	25.51	9311.15	1900
60	472322777.90	1541.56	6.55	17.35	23.90	8723.50	1900
70	479455329.10	1542.13	6.38	16.11	22.49	8208.85	1900

Mixing ratios for the three solutions were calculated by making use of Table 4-11. The ratios varies from year to year. See Table 4-11 for mixing ratios.

Table 4-11 Mixing ratios.

Years	Mixing fraction (Kriel-OC)	Mixing fraction-Aquifer inflow	Mine fraction (BH 301)
	Kriel OC (IMF)	Aquifer solution	BH301
10	0.00004	0.01634	0.98362
20	0.00005	0.01595	0.98400
30	0.00005	0.01532	0.98462
40	0.00005	0.01522	0.98473
50	0.00005	0.01506	0.98489
60	0.00005	0.01482	0.98513
70	0.00005	0.01459	0.98536

These mixing fractions were used to calculate the dilution of sulphate over years. At first the initial concentrations of Solution 1, 2 and 3 were added together. From the

mixing of the three solutions, a new solution were created. This new solution which is which is now the new water quality of Tavistocks underground area will then every time reacts with the intermine flow volumes from Kriel and the inflows from the side and top. Thus every time water is added and every time a new solution will be created. This will cause sulphate to dilute, and thus improve the quality of the water in the underground area over decades.

From Table 4-12 it is clear that the concentration of the calcium and magnesium are decreasing during mixing. During the process, calcium and magnesium causes a buffer effect, which result in stabilisation of the pH as well as a decrease in the Sulphate concentration. The sulphate concentration will thus drop because of the addition of better quality water to the system.

See Table 4-12 and Figure 4-29 for improvement of the quality of Tavistock's underground area.

Table 4-12 Chemistry of the mixed waters.

Years	Mixing	Distribution of species			
		pH	SO4	Ca	Mg
10	MIX 1	6.80	2014.94	1119.67	331.89
20	MIX 2	6.80	1984.49	1102.36	326.89
30	MIX 3	6.80	1955.77	1086.01	322.18
40	MIX 4	6.80	1927.72	1070.06	317.57
50	MIX 5	6.80	1900.34	1054.50	313.09
60	MIX 6	6.80	1873.82	1039.43	308.73
70	MIX 7	6.80	1848.08	1024.85	304.51

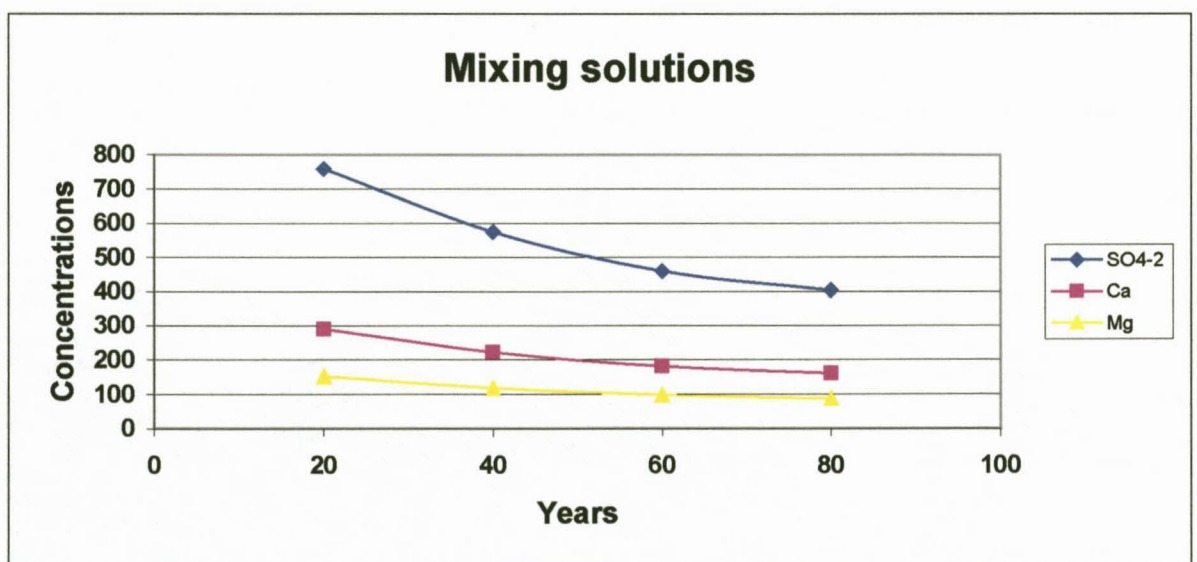


Figure 4-29 Concentrations of the mixing solutions.

4.8.3 Kriel-Tavistock mass transport calculations

Mass transport was done on the Kriel-Tavistock model area. The specific scenario was done to ascertain what the influence of the intermine flow from Kriel Colliery will be on the chemistry of Tavistock's underground area. The original flow model was used and modified to do a mass transport simulation. The initial sulphate concentrations used in the calculations of Phreeqc were assigned to the areas as described in the preceding section. The reasons for the calculation of the mass transport of the area are:

- To see the dilution effect over time in the mined areas.
- To compare the two methods used for chemical evaluation.
- To compare Phreeqc and mass transport in terms of providing realistic answers.

The two methods used have a slight difference in results. This can be ascribed to the fact that Phreeqc gives only one concentration for the whole area, whereas mass transport gives a range of concentrations in the pit. See Figure 4-30 and Figure 4-31 for the dilution process over 70 years.

Table 4-13 Mass Transport Sulphate concentrations.

Years	SO4-2 Concentrations		
	Pit 6	Tav - UG	Pit 5
10	560 - 460	2000 - 1950	595 - 480
20	495 - 320	1965 - 1865	540 - 330
30	415 - 230	1930 - 1766	490 - 275
40	370 - 150	1885 - 1679	445 - 195
50	320 - 120	1860 - 1580	405 - 145
60	280 - 90	1825 - 1500	370 - 105
70	240 - 55	1790 - 1450	335 - 75

Both these methods have benefits and disadvantages but based on this case study, mass transport calculations appears to hold several advantages. The most important of these is that a more realistic distribution of concentrations over a mined area can be obtained to give areas of higher and lower concentrations as is found in reality.

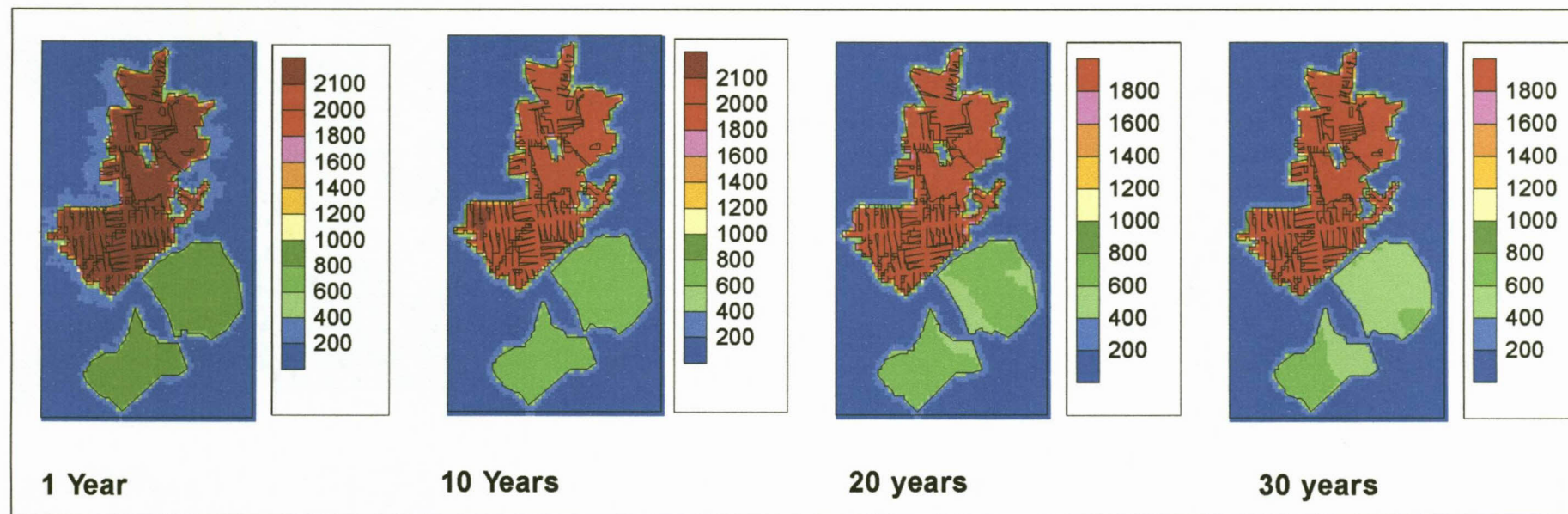


Figure 4-30 Dilution of the pits and underground area by making use of Modflows chemical package.

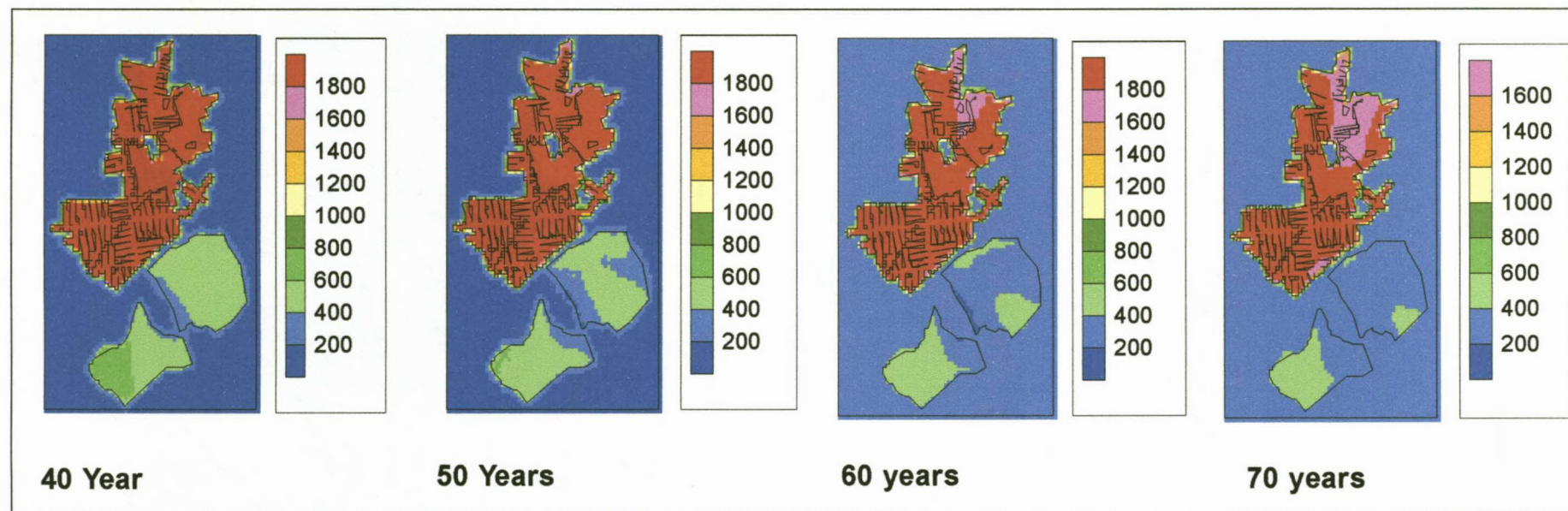


Figure 4-31 Dilution of the pits and underground area by making use of Modflows mass transport package.

Table 4-16 Results from the saturation indices of solution Rietspruit NS at equilibrium with dolomite and calcite.

Solutions		Distribution of species			Saturation Indices			
Rietspruit NS	pH	SO4	Ca	Mg	Calcite	Dolomite	Gibbsite	Gypsum
Equilibrium Dolomite	7.81	2403.43	433.72	274.63	-0.067	0.000	1.219	-0.101
Equilibrium Calcite	7.86	2403.43	403.76	293.23	0.000	0.193	1.171	-0.133

4.9.1.3 Rietspruit underground area solution

A second solution was prepared by making use of the latest chemical data available on Borehole 1, located in the Rietspruit's underground area. The composition of Rietspruits underground area can be seen in Table 4-17.

Table 4-17 Chemical composition of Rietspruits underground area.

SOLUTION	Temp	Units	pH	SO4	Cl	Na	Ca	K	Mg	C(4)	Fe
Rietspruit U/G	25	mg/l	7.50	1132.02	20	150	212	20	110	89	0.3

From the results of the initial solution it can be seen that calcite, dolomite and gibbsite are oversaturated and should precipitate. Gypsum is unsaturated (Table 4-18).

Table 4-18 Results from the saturation indices of the initial solution.

Solutions		Distribution of species			Saturation Indices			
	pH	SO4	Ca	Mg	Calcite	Dolomite	Gibbsite	Gypsum
Rietspruit U/G	7.50	1132.02	212	110	0.201	0.448	0.542	-0.512

4.9.1.4 Rietspruit underground solution in equilibrium with Calcite and dolomite

In the first step dolomite was used to equilibrate the solution. Calcite and gypsum are both now unsaturated and an increase in the pH is evident. The results can be seen below:

Table 4-19 Results from the saturation indices of Rietspruits underground area solution at equilibrium with dolomite and calcite.

Solutions		Distribution of species			Saturation Indices			
Rietspruit U/G	pH	SO4	Ca	Mg	Calcite	Dolomite	Gibbsite	Gypsum
Equilibrium (dolomite)	7.96	1132.02	193.82	97.9	-0.019	0.000	0.093	-0.533

4.9.2 Mixing of solutions

The solutions were mixed as in the previous section to see if there is any improvement in the chemistry of the Rietspruit underground area over time. The third solution was compiled by making use of boreholes which is located in the unmined

4.9 EVALUATING THE HYDROCHEMICAL IMPACT OF FLOW BETWEEN RIETSPRUIT AND TAVISTOCK PHREEQC CALCULATIONS

4.9.1 Rietspruit and Tavistock Phreeqc calculations

As in the case of Kriel-Tavistock, two solutions where intermine flow occurs were selected for the calculations, namely Rietspruit's NS opencast pit and it's underground area.

4.9.1.1 *Rietspruit's NS opencast pit solution*

The first solution was prepared by making use of the chemical data available in the North-South opencast area. Monitoring point E3A was used for the calculations. See Table 4-14 for composition of the North-South Pit.

Table 4-14 Chemical composition of the Rietspruit NS Pit

SOLUTION	Temp	Units	pH	SO4	Cl	Na	Ca	K	Mg	C(4)	Al
Rietspruit NS	25	mg/l	8	2403.43	23	115	464	13	296	215	0.2

The results from the saturation index can be seen in Table 4-15.

Table 4-15 Results from the saturation indices of the initial solution.

Solution	Distribution of species				Saturation Indices			
	pH	SO4	Ca	Mg	Calcite	Dolomite	Gibbsite	Gypsum
Rietspruit NS	7.80	2403.43	464	296	0.860	1.854	1.229	-0.089

Calcite, dolomite and gibbsite are oversaturated. Gypsum is very close to saturation, depending on the specific thermodynamic constant selected.

4.9.1.2 *Precipitation of Dolomite and Calcite from Rietspruit NS solution*

The initial solution was again used and oversaturated carbonates allowed to precipitate. From the results the following can be seen in Table 4-16. After the equilibration of the solution with dolomite calcite and gypsum are now unsaturated, since calcium is removed from solution. Gibbsite stays oversaturated. A decrease in the calcium and magnesium are present. Equilibration of the initial solution with calcite (Table 4-16) showed that the pH increased from 7.8 - 7.86, while dolomite and gibbsite are oversaturated. Gypsum stays unsaturated.

areas around the underground area. See Table 4-20 for composition of (Rietspruit gw).

Table 4-20 Chemical composition of Rietspruit gw.

SOLUTION	Temp	Units	pH	SO4	Cl	Na	Ca	K	Mg	C(4)	Al	Fe
Rietspruit gw	25	mg/l	7	5.3	5	3.4	6.7	1	2.5	32	0.1	0.27

Mixing fractions used in the Phreeqc calculations were calculated as previously described.From Table 4-21 it is clear that the concentrations decrease during mixing. See Table 4-21 as well as Figure 4-32 and Figure 4-33 for results and graphs from the mixing of waters.

Table 4-21 Results from the mixing of colliery waters.

Years	Mixing	pH	SO4	Ca	Mg
20	MIX 1	7.35	758.93	289.40	151.74
40	MIX 2	7.25	574.51	222.59	118.10
60	MIX 3	7.17	459.13	180.90	97.38
80	MIX 4	7.12	403.53	160.70	87.06

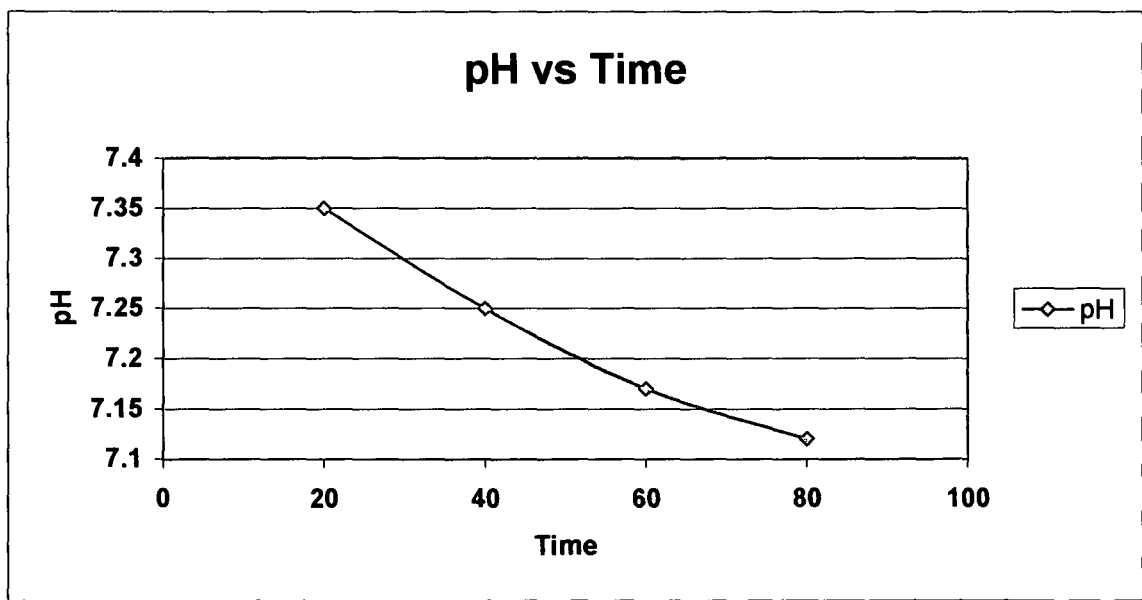


Figure 4-32 Results from the mixing of solutions - pH versus time graph.

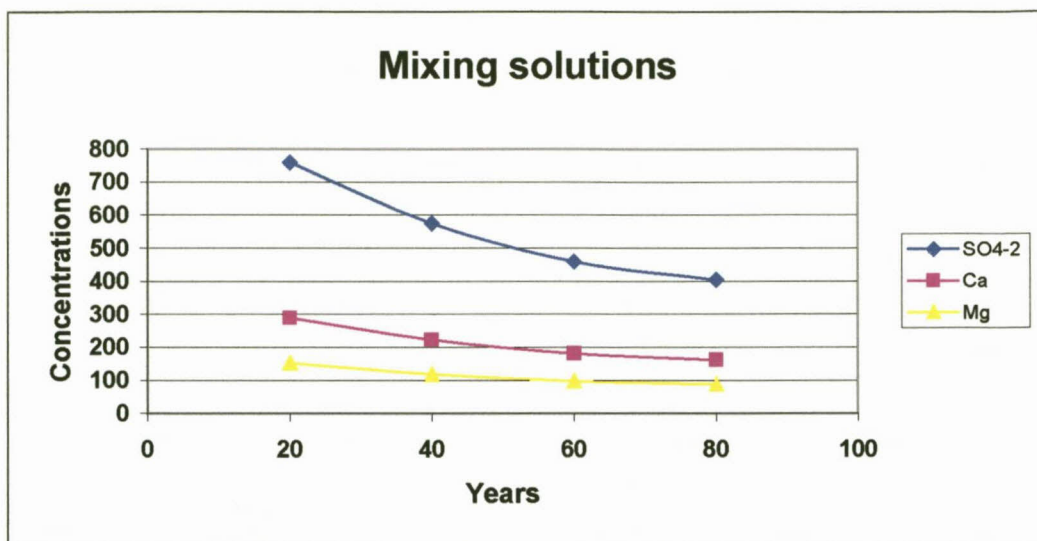


Figure 4-33 Results from the mixing of solutions - mixing concentrations versus time.

4.10 THE NATURE OF RIETSPRUIT COLLIERY WATER BASED ON SATURATION STATE

Phreeqc analyses were done on samples from Rietspruit Colliery. 1073 samples were used for the calculations. Different calculations were done to see how the waters might react in future.

The saturation indices were calculated for all these samples. The saturation indices for calcite, dolomite and gibbsite were used to plot versus the pH of the samples in the area. From Figure 4-34 it can be seen that the saturation index for the samples occur in the pH occur over a wide range. Most of the samples are in equilibrium with dolomite and calcite in the pH range between 7 and 8. Gibbsite is dominantly oversaturated between a pH of 6 and 9 except for 2 samples which are unsaturated at a pH of between 3 and 4 as well as 5 samples at a pH of between 8 and 9. Gibbsite, and the carbonates are often alluded to for their buffering roles at different pH values. From this assessment it can be seen that the carbonates are very active in determining pH buffer levels at values ranging from around 6.6 to just above 8 at this colliery. This is significantly different to values quoted by researchers such as Hodgson and Krantz, 1998. Reasons for this could lie in factors such as partial pressure of CO₂ for example. Usher et al, 2001 discuss the influence that these partial pressures can have on the buffering pH level of carbonates.

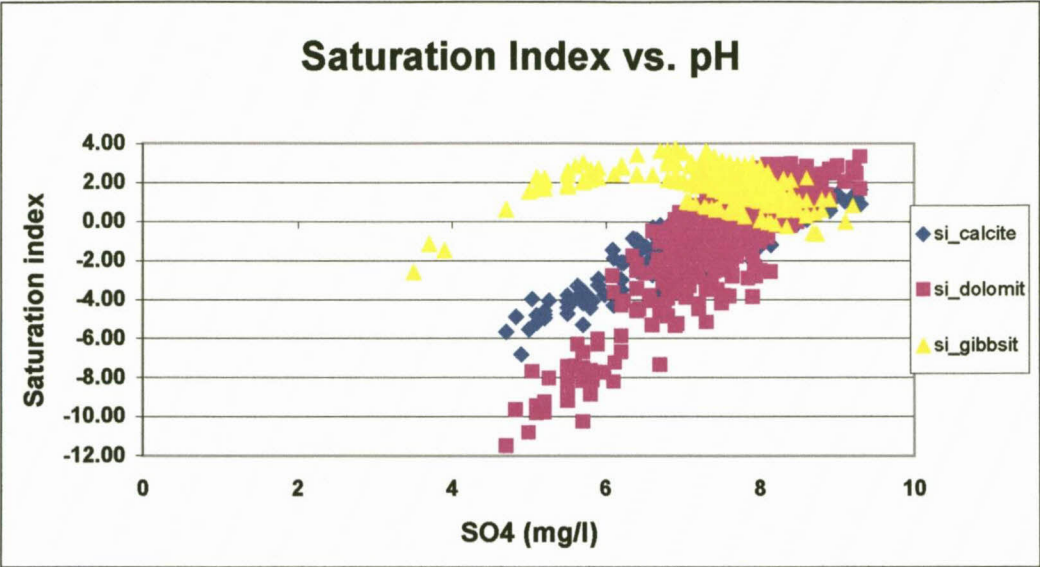


Figure 4-34 Saturation index of Calcite, dolomite and gibbsite versus pH.

The saturation index of gypsum was plotted versus the sulphate concentrations of the area. Almost all the samples are unsaturated except for a few samples. 50 % of the samples are under-saturated at a sulphate concentration below 1000mg/l and 50% have a much higher sulphate concentration. A few suspected values are also present and can be ignored. See figure Figure 4-35 for graph.

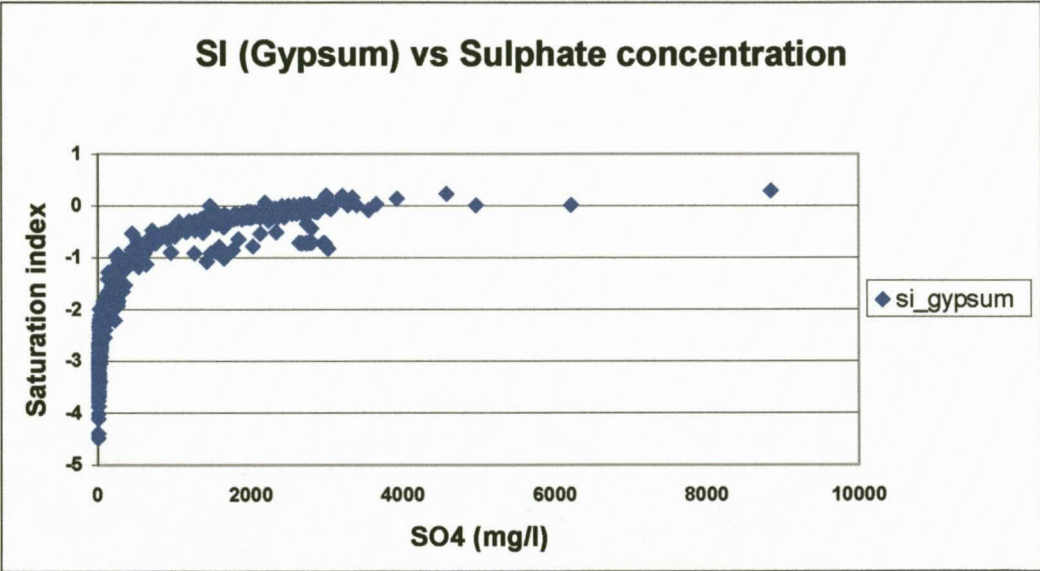


Figure 4-35 The saturation index of gypsum versus sulphate.

From this figure it is clear that gypsum saturation provides some upper limit to sulphate concentrations. and that except in extraordinary circumstances sulphate values will be constrained to a range of below 3000-3500 mg/l by this phenomenon.

4.11 KLEINKOPJE CALCULATIONS

An analyses was done on 738 samples located in the Kleinkopje area. Saturation indices of calcite, dolomite, gibbsite and goethite were plotted versus the pH in Figure 4-36. The following can be concluded from the assessment. Gibbsite and goethite are mostly oversaturated and range between a pH of 5 and 8. Goethite is only unsaturated between a pH of 2 and 4. Calcite and dolomite are mostly unsaturated in the range between a pH of 2 and 6. From this assessment it can be seen that the carbonates at Kleinkopje Colliery are very active at pH buffer levels with values ranging from around 6.8 to 8.

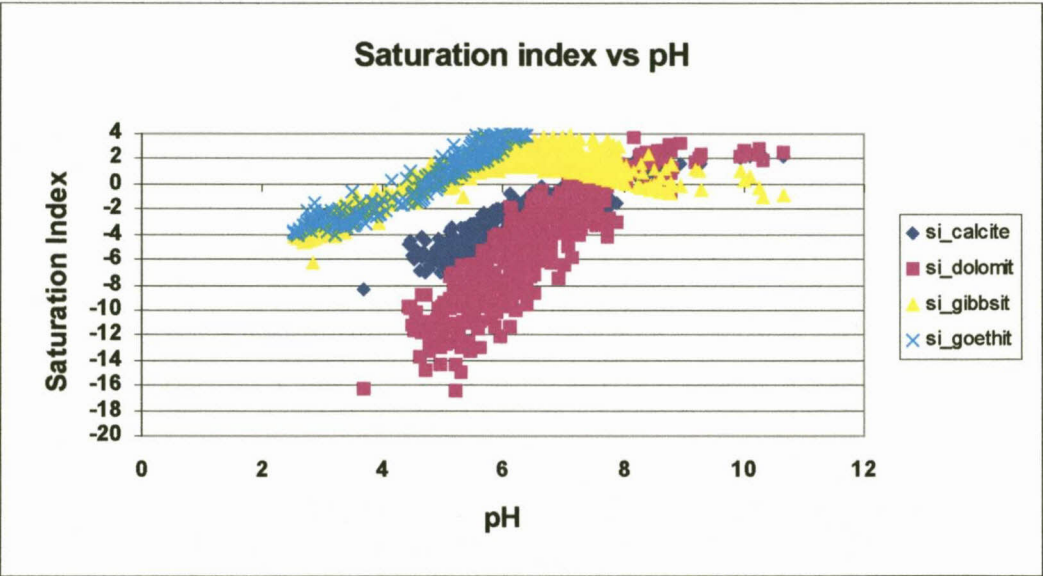


Figure 4-36 Saturation index of Calcite, dolomite and gibbsite versus pH.

The saturation of gypsum was plotted versus the sulphate concentration in Figure 4-37. Most of the samples are undersaturated or nearing saturation as the concentration increases up to value of around 3000 mg/l.

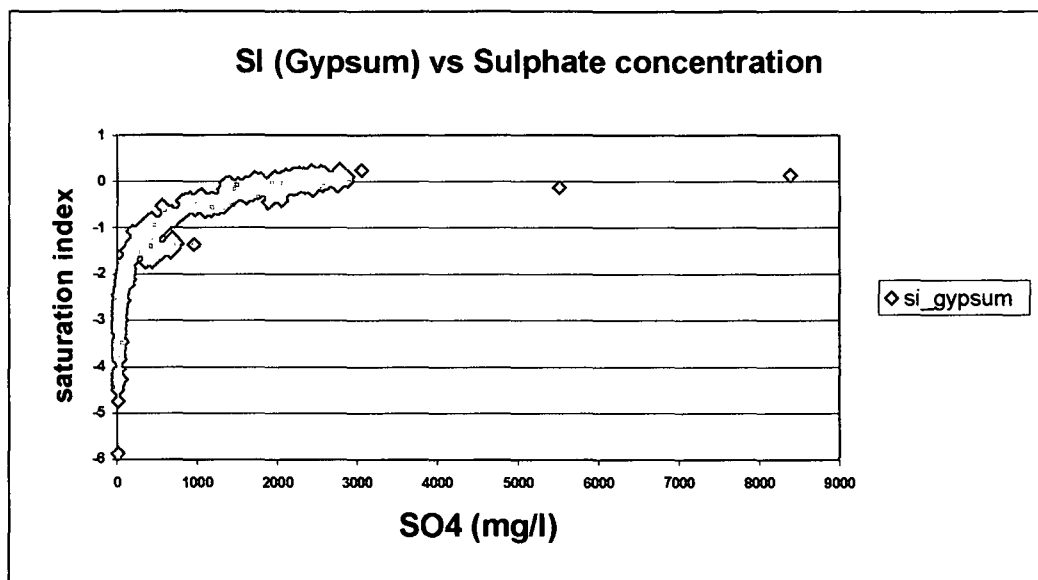


Figure 4-37 The saturation index of gypsum versus sulphate.

4.12 OVERALL CONCLUSION

At Tavisock Colliery acid conditions are expected on the No. 4 seam horizon because of the throughflow as well as the flow to the 2 seam underground areas. The quality of the water in the 2 seam will be better as the 2 seam fill to decant level.

Surface and groundwater quality at Kleinkopje Colliery is good in general except for the monitoring points located in and close to the Kleinkopje and Klippan discard dumps.

Kriel has never had a history of acid water generation, and the quality of Pit 5 and 6 will improve over time as the pits start to fill up.

Because of the discard spoiled in the southern part of the North-South opencast pit at Rietspruit Colliery the quality of the pit will be influenced. Currently high sulphate values are measured in the North-south pit, but because of the buffer reaction which is caused by the carbonate minerals in the strata, the pH of the pit is still neutral. Acid conditions can be expected in future if the base potential is used up. Water from the North-South pit which is flowing to the underground workings at Rietspruit will have a negative affect on the chemistry of the underground. Acid patches are also forming in the Rietspruit underground area.

Mass transport calculations were done on the Kriel Tavistock model to predict the influence of intermine flow on the future chemistry in this area. Although small amounts of water are flowing through the coal barrier between Kriel and Tavistock

Colliery, it has a positive influence on the chemistry. The quality of the underground area improved. Mass transport give a range of concentrations all over the pit. This gives a representation of the real life situation with varying concentrations in different parts of a Pit or underground area. The quality of the underground area after 70 years ranges between 1790 to 1450 mg/l sulphate.

Phreeqc calculations were also done on the area. Mixing of three solutions were done to predict the future chemistry of the underground area at Tavistock Colliery. The same parameters were used during the calculations as during the mass transport calculations. Phreeqc gives an average sulphate concentration for the whole pit and was calculated as 1848 mg/l sulphate.

From the Phreeqc calculations done in the Rietspruit area, it can be concluded that mixing of waters will have a positive effect on the chemistry of the area.

The determination of saturation indices against pH and sulphate for over 2000 samples have shown that dolomite and/or calcite are the active buffers in most neutral to alkaline waters. Gypsum precipitation also seems to have a limiting effect on sulphate values where calcium still occurs in the system.

The flow models discussed in Chapter 3, were used to gauge the impact of implementing different management options for specific areas in the study area.

5.1 KRIEL-TAVISTOCK MANAGEMENT OPTIONS

Predictions from the flow models suggest that Pit 5 and Pit 6 will take 44 and 27 years respectively to decant. During the filling times small volumes of water start to flow through the barrier between Pit 6 and Tavistock Colliery. The current situation at Tavistock Colliery is that the No. 2 and 4 Seam workings are connected to each other by shafts and boreholes.

Two management options were tested for implementation at the Kriel- Tavistock area:

- Placing of hydraulic seals in the areas where the No.4 Seam underground workings are connected with No. 2 Seam workings. This will stop or prevent the water from flowing directly into the No. 2 Seam workings.
- Filling times of the underground area can be accelerated by constructing a pipeline from Kriel's Pit 6 to the underground workings of Tavistock. The pipeline from Pit 6 to the underground workings will be implemented after 27 years when Pit 6 reaches its decant elevation. The implementation of the pipelines will prevent the opencast pit from decanting on surface and at the same time accelerate the filling of Tavistock's underground workings. This management option will also slow and decrease acid generation in the underground workings, because currently acid patches are developing in the 4 Seam workings, due to aerobic conditions.

5.2 SEALING OF UNDERGROUND AREA

Numerous conduits normally exist between mining operation and the surface. Two areas are identified where the 4 Seam workings are connected with the 2 Seam. Figure 5-1 shows the locations of the conduits.

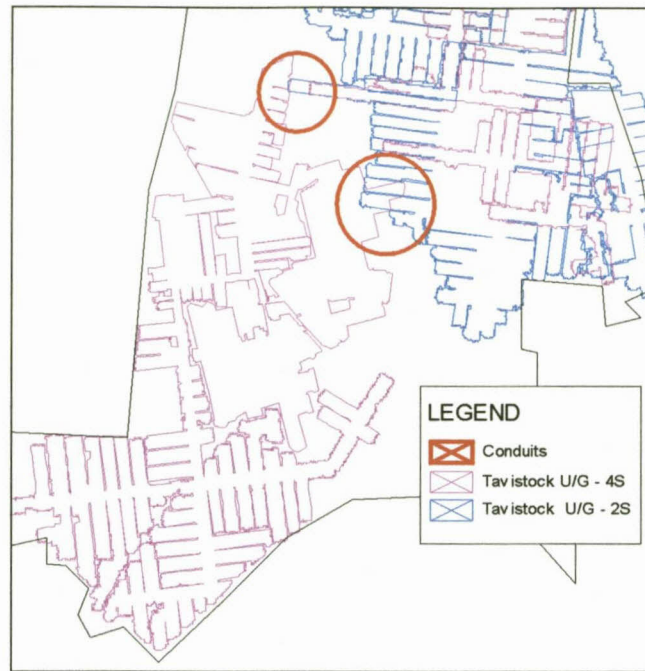


Figure 5-1 Red circles indicate the positions where the 4 Seam underground area is connected with the 2 Seam workings at Tavistock Colliery.

5.2.1 Hydraulic Mine Seals

Currently, most underground mine seals are hydraulic mine seals, although surface access seals are still used in “no water, no head” situations for economic reasons. Hydraulic mine seals are installed in entries (drifts, slopes, shafts, and adjacent strata) where significant hydrostatic pressure will be exerted on the seals. The primary functions of the seals is to eliminate potential access to the abandoned mine works following closure, to minimise AMD production by limiting infiltration of air and water into the deep mine, and to minimise AMD production by limiting infiltration of water and maximise inundation.

The primary goal in the design and installation of hydraulic mine seals is to construct a mine seal system that serves as a structural bulkhead and acts as a water tight dam capable of withstanding the maximum hydrostatic head that may develop as a result of the flooding of the mine complex.

A secondary consideration in the design and siting of hydraulic mine seals is the hydrologic performance of the seal. The adjacent stratum has natural joints, bedding planes, and subsidence cracks (from mining) that may serve to transmit significant water around the mine seal area. Thus, while the structural design will specify a minimum required thickness necessary to safely impound the water at design heads

and pressures, the potential for water to migrate around the mine seal through adjacent strata must be compensated for in the design. See Figure 5-2 for an example of a hydraulic seals which can be implemented at the site.

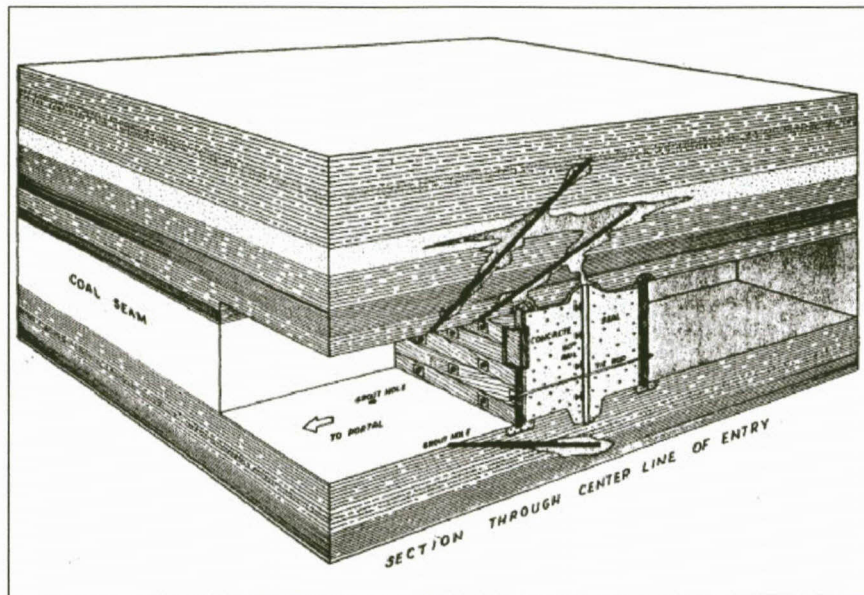


Figure 5-2 An example of a deep mine hydraulic seal or underground barrier dam (Skousen et al., 1998).

5.2.1.1 Current quality predictions of the 2 and 4 Seam workings

Seeing that the No. 2 and 4 Seams are interconnected and that the decant elevation of the 2 Seam workings is at 1520 mamsl, the final water level in the 4 Seam workings will also be at 1520 mamsl. Only small portions of the No. 4 Seam workings will thus be flooded at this elevation. Acidification of the No. 4 Seam workings is therefore inevitable.

5.2.1.2 Implementation of hydraulic mine seals

The Number 4 Seam is currently empty because of the through flow to the lower lying 2 Seam. Acid patches are forming in the low lying areas because of the presence of oxygen. Implementing hydraulic seals in the areas where the workings are connected will give the No. 4 Seam time to fill up. Filling up of the workings means that the quality of the mine water will improve over time as the workings start to fill up.

As will be discussed in section 5.3, the mine will take approximately 70 years to fill to its decant elevation of 1554 mamsl. Figure 5-3 illustrates the filling time of the underground area.

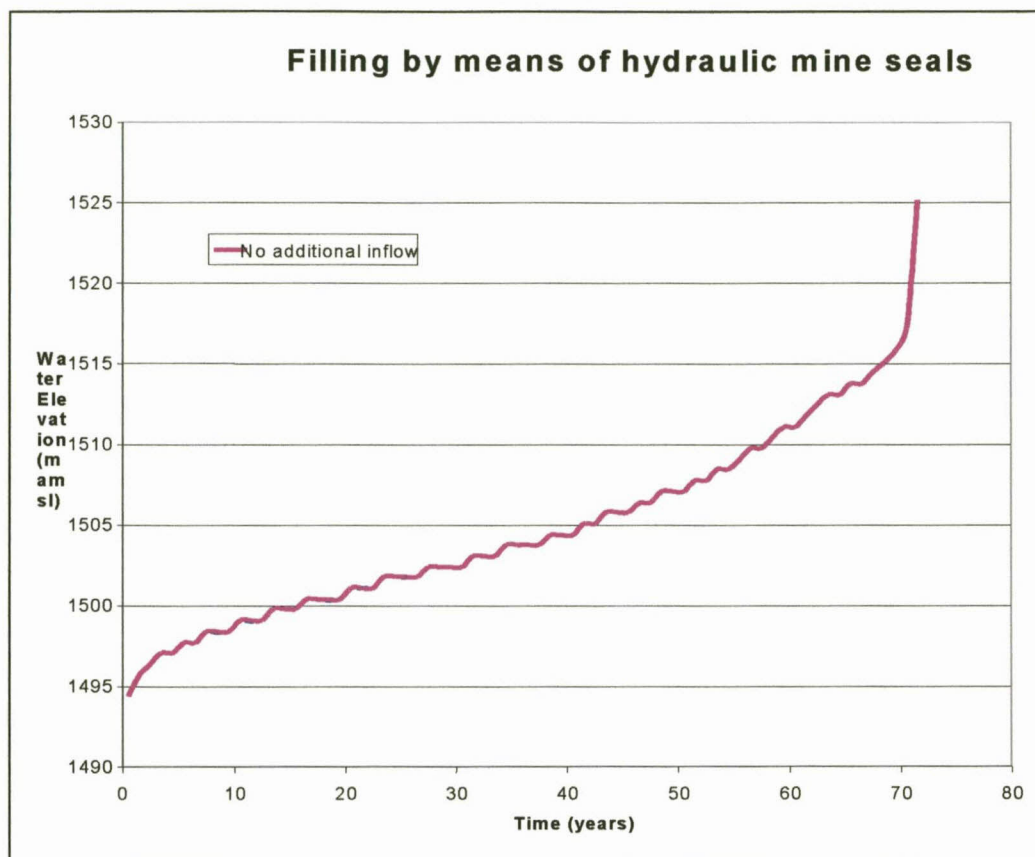


Figure 5-3 Filling times of the Tavistock 4 Seam underground area.

5.3 EVALUATING THE EFFECT OF INCREASING THE INTERMINE FLOW ON REFILLING TIMES AT TAVISTOCK 4 SEAM UNDERGROUND.

In Chapter 3 the intermine flow between Kriel's Pit 6 and Tavistock were modelled. This simulation showed that there is a small rate of flow from Kriel to Tavistock and that the opencast pit will take approximately 27 years to reach the decant elevation.

Once this pit start to decant, several potential problems exist. These include where to dispose of the water in such a way that the environmental consequences are minimised. One possible solution that would be beneficial to both Kriel and Tavistock would be piping this water from Kriel directly into Tavistock's 4 Seam workings. See Figure 5-4 for an illustration of the projection of the pipeline from Kriel Pit 6 to Tavistock's underground workings.

The pipeline will be constructed from the top of Pit 6 to the bottom of the underground area. Flow can be regulated by the installation of a sluice system, or valve, which can control the flow.

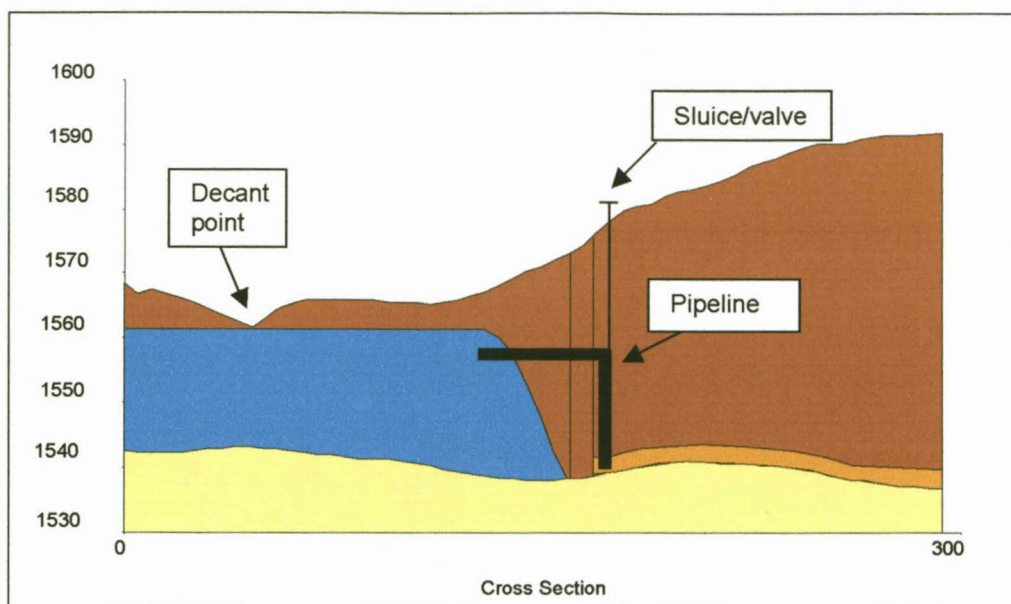


Figure 5-4 Implementation of the pipeline between Kriel and Tavistock Colliery.

An assessment was made using the stage curve from the 4 Seam workings, and the expected inflow volumes as derived from the model. Using a method of storage refilling, an assessment of the impact of the increased influx on the time to inundation can be made. See Figure 5-5 for a stage curve of the 4 Seam underground workings at Tavistock Colliery.

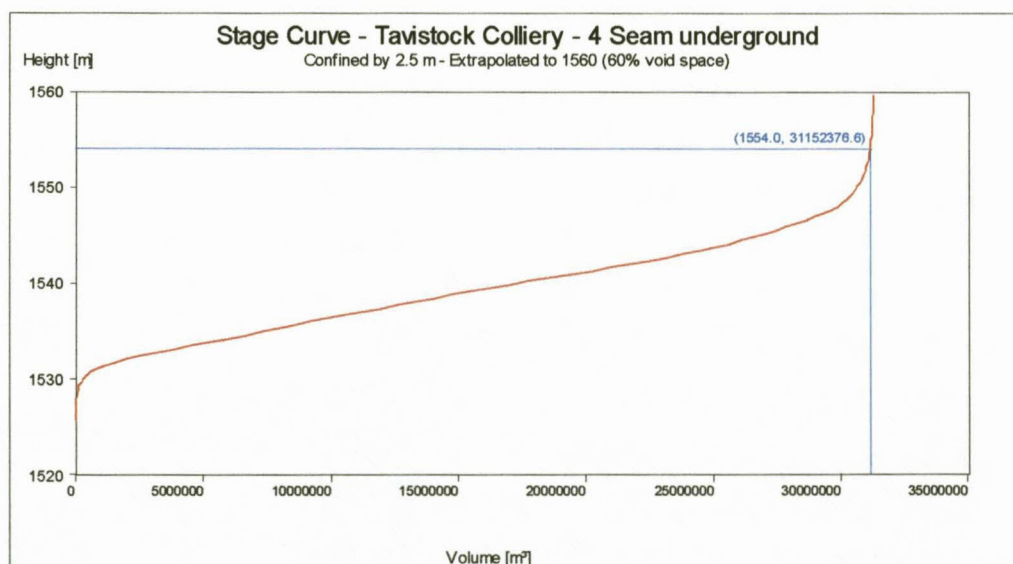


Figure 5-5 Stage curve for the Tavistock 4 Seam workings

These calculations indicate that, if the 4 Seam workings can be isolated from the 2 Seam workings below, natural influx from recharge and intermine flow will take

approximately 70 years to fill these workings. If the option is exercised of piping the excess Kriel water into these workings, it is clear that the area will be filled within thirteen years after this increased influx has started. This result is a far more rapid inundation of these potentially acid-generation workings and could provide excellent control over the long-term water quality. Figure 5-6 represents the filling times of the underground area.

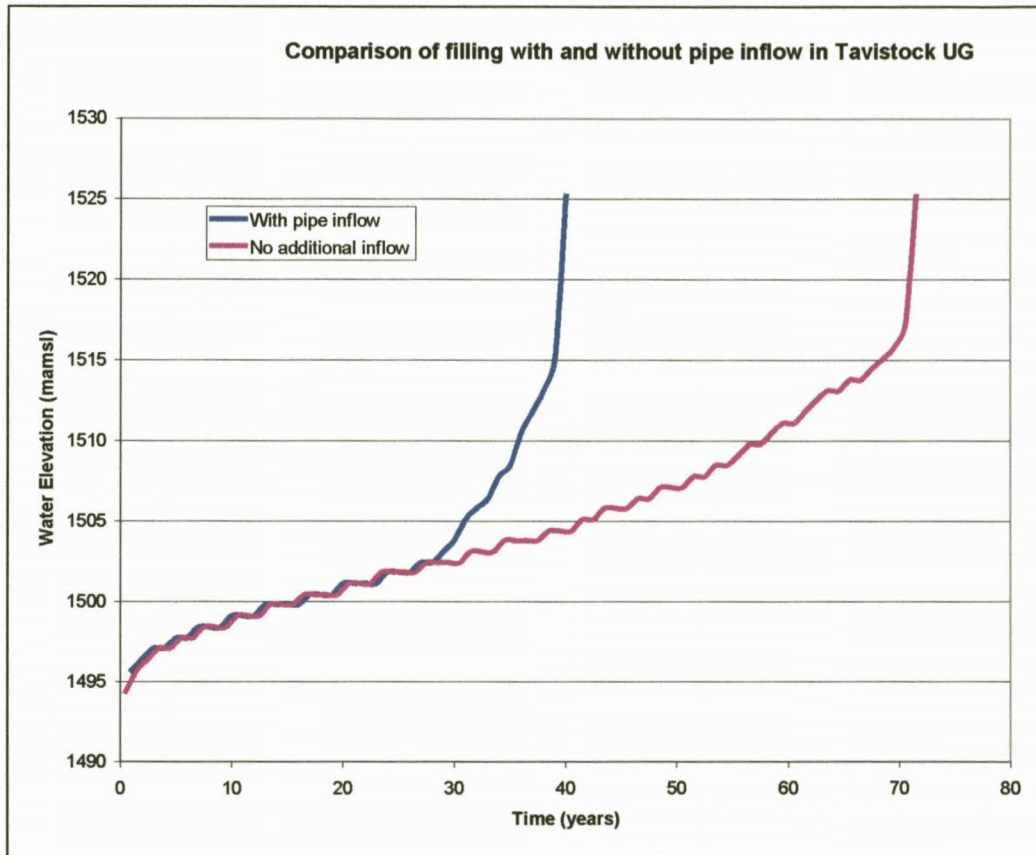


Figure 5-6 Filling times of the Tavistock No. 4 Seam underground area.

5.3.1 Implication of the flooding process at Tavistock Colliery

Making use of the pipeline from Kriel's Pit 6 to the underground area, the underground area will be flooded in approximately 38 years. The flooding of the mine will thus have a good influence on the chemistry of the area, by reducing the time that AMD reactions occur and by diluting the water in the underground workings.

5.3.2 Additional benefits

- Dilution of huge quantities of water in the No. 4 Seam workings
- An additional source of alkalinity if the projected water quality from Kriel, based on ABA (Chapter 4, section 4.6.3), decants from Pit 6 of alkalinity,

- Kriel will get rid of the excess decant water without having a negative influence on the environment.

For such a system to work, negotiation between the mines and also the regulators, most notably the DWA&F, will be required.

5.3.3 Lime treatment on Tavistock's underground area

If the underground area at Tavistock is not sealed off, acid patches will form because of available oxygen. Lime treatment can be used as a treatment option to render the acid conditions that form in the pit over time.

Phreeqc was used to measure quality improvement of the pit if lime is added to the acid water present in the pit.

5.3.4 Treatment of polluted mine water

Limestone (CaCO_3) has been used for decades to raise pH and precipitate metals in AMD. It has the lowest material cost and is the safest, easiest way to handle the AMD chemicals, and produces the most compact and easy way to handle sludge material. Unfortunately, its successful application has been limited because of its low solubility especially in cold weather, its tendency to develop an external coating, or armor, of ferric hydroxide when added to AMD, and its inability to raise pH to sufficient levels for Mn removal. In cases where the pH is low and mineral acidity is also relatively low (low metal concentrations), finely-ground limestone may be dumped in streams directly, or the limestone may be ground by water-powered rotating drums and metered into the stream. Limestone has also been used to treat AMD in anaerobic (anoxic limestone drains) and aerobic environments (open limestone channels) (Skousen *et al.*, 1998).

According to Bosman (1983) the "best available means of treatment" in South Africa is to confine to the neutralisation of acid mine water with lime and the removal of the resultant precipitate from the water by sedimentation. Where neutralisation and precipitation take place *in situ*, as a result of the presence of alkaline minerals in the mine, the effluent seldom contains much suspended matter and is usually discharged as such.

Apart from iron and aluminium being precipitated from solution as hydroxides, some calcium sulphate is removed from solution when the water contains so much sulphate that the solubility of this salt is exceeded during lime neutralisation. However, the solubility of calcium sulphate in water is in excess of 2000 mg/l (Bosman, 1983). In

addition treated effluents often contain appreciable amounts of magnesium and sodium sulphate as well as calcium, magnesium and sodium chlorides.

5.3.4.1 Lime treatment

Lime may be bought in a variety of forms, depending on the quantities required and local availability. Commercial, hydrated lime (Ca(OH)_2) is expensive and will only be used where small quantities are required. Usually, it is bought in the pebble form called quicklime (CaO). Calcium carbonate (CaCO_3) is available in both powder and stone forms. Limestone is not as reactive and requires longer residence times than the other forms. However, the application of limestone in anoxic beds for passive neutralisation of acid mine drainage is increasing (Pulles *et al.*, 1996).

Although lime is the cheapest of the neutralisation chemicals, this advantage is often negated by poor management underground. In this case, the aim of neutralisation is to raise the feed pH to a level at which the chosen flocculant operates optimally. The pH is often measured too close to the dosing point, with the result that the lime has either not mixed completely, or has not reacted completely. The measured pH is then observed as being too low and additional, unnecessary lime is dosed upstream. Factors such as insufficient mixing due to lime's low solubility, poor baffle and launder design, compound this problem. The problems of insufficient reaction time and mixing are however still applicable to automatic control systems. Such a system is further disadvantaged, by the hostile conditions encountered underground. Humidity and lack of maintenance of the pH probe are the major problems, which have too often resulted in failure of the control system and subsequent abandonment (Pulles *et al.*, 1996).

5.3.5 Limestone addition to Tavistock's underground area

A Solution from Tavistocks underground area was used to illustrate the expected water quality for Tavistock's No. 4 Seam workings. See Table 5-1 for the composition of the acid solution.

100 mg calcitic lime (CaCO_3) was added to the acid solution to determine what the difference in pH was and if lime addition is an effective treatment for acid entities.

Table 5-1 Chemical composition of Tavistock's No. 4 Seam underground area.

SOLUTION	Temp	Units	pH	S(6)	Cl	Na	Ca	K	Mg	C(4)
Tav u/g	25	mg/l	3.2	3500	20	50	100	10	50	0

The results from the lime treatment are represented in Table 5-2. The pH shows an enormous improvement from 3.2 to 7.79. Thus the water can be altered from an acid entity to an alkaline entity. The sharp increase in the calcium concentration is because of the excess CaCO_3 added to the solution. No real improvement in sulphate concentration is yielded for these example, since the sulphate was already at gypsum saturation levels before the neutraliser was added. Where sulphate levels are lower, the addition of calcium-based neutralisers can also cause reduction of sulphate through precipitation.

Table 5-2 Results from the addition of lime to the initial solution.

Solution	pH	Ca	Mg
Tav u/g Initial solution	3.20	1005	50
Tav u/g Final solution	7.79	342.14	100.37

From the results it is clear that lime can be seen as a good treatment option, if it can be administered effectively and at a low enough cost.

5.3.6 Treatment Costs

Although chemical addition appears to be a solution, the costs of chemical treatment can be excessive. In South Africa published costs are limited.

Skousen (1998) (Table 5-3) gives the following guideline costs for the addition of different treatment chemicals.

Table 5-3 Chemical compounds used in AMD treatment (from Skousen, 1998)

Common Name	Chemical Name	Formula	Conversion Factor ¹	Neutralization Efficiency ²	1996 Cost ³ \$ per ton or gal. Bulk <Bulk	
Limestone	Calcium Carbonate	CaCO_3	1.00	50%	\$10	\$15
Hydrated Lime	Calcium hydroxide	Ca(OH)_2	0.74	95%	\$60	\$100
Pebble Quicklime	Calcium oxide	CaO	0.56	90%	\$80	\$240
Soda Ash	Sodium Carbonate	Na_2CO_3	1.06	60%	\$200	\$320
Caustic Soda (solid)	Sodium hydroxide	NaOH	0.80	100%	\$680	\$880
20% Liquid Caustic	Sodium hydroxide	NaOH	784	100%	\$0.46	\$0.60
50% Liquid Caustic	Sodium hydroxide	NaOH	256	100%	\$1.10	\$1.25
Ammonia	Anhydrous Ammonia	NH_3	0.34	100%	\$300	\$680

The conversion factor may be multiplied by the estimated tons of acid/year to get tons of chemical needed for neutralisation per year. For liquid caustic, the conversion factor gives gallons needed for neutralisation. Neutralisation efficiency estimates the relative effectiveness of the chemical in neutralising AMD acidity. For example, if 100 tons of acid/year was the volume of acid to be neutralised, then it can be estimated that 78 tons of hydrated lime would be needed to neutralise the acidity in the water ($100(0.74)/0.95$). The price of chemical depends on the quantity being delivered. Bulk means delivery of chemical in a large truck, whereas <Bulk means purchased in small quantities.

From this table it is clear that if significant volumes of water are to be chemically treated costs, in the long term will be a serious consideration. Appropriate water management to optimise water qualities and minimise treated volumes is therefore vital.

5.3.7 Implication of flushing at Kriel's opencast pit

Flushing implies the introduction of clean water into opencast pits or portions of opencast pits, to regulate the water quality within the spoil.

Natural flushing has been ongoing for up to 15 years at operational and closed collieries. An example of the positive effect that flushing has on the in-pit water quality can be seen in the predictions made of Kriel's chemistry by making use of mass transport modelling.

The following conclusions can be drawn in terms of flushing of the opencast pits at Kriel Colliery:

The improvement of the quality of the water in the opencast pits is the direct result of water being recharged from surface, adding clean water on top of polluted pit water. Some stratification of water will thus occur and if the option of piping the decant is taken, then the cleaner water is likely to flow to Tavistock, with mixing reduced. This does, however, imply that the effective recharge and therefore mixing at Kriel will be reduced. The water quality in the pit will therefore not improve much over time. In real terms, this is not significantly different to the decant scenario, and the slightly smaller water quality deterioration will be worthwhile in terms of the mutual benefits to both collieries.

Flushing will in general reduce the concentrations in the pit water, but sulphate concentrations can still be above acceptable limits. Figure 5-7 shows a hypothetical situation where complete mixing of recharge is assumed; this is analogous to the mixing discussed by Grobbelaar *et al.*, (2001) and Hodgson and Krantz (1998).

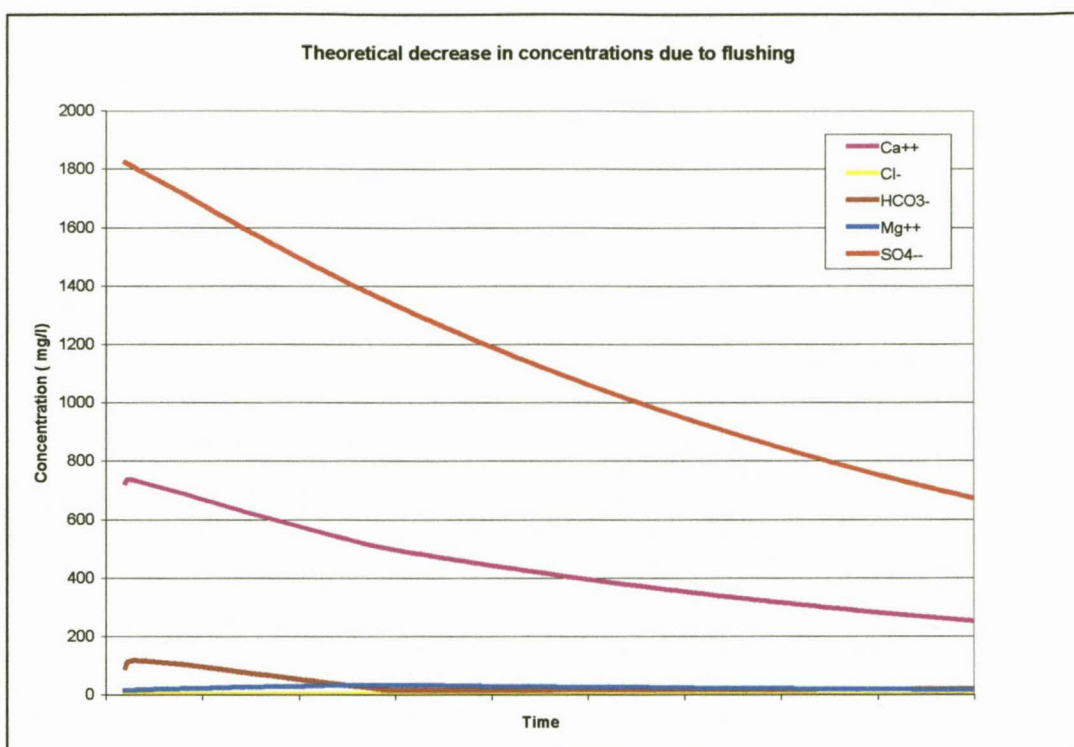


Figure 5-7 Example of a mine being flushed by complete mixing of recharge.

For the current opencast mines, some degree of flushing will always be part and parcel of the water management strategy (Hodgson and Krantz, 1998).

5.4 RIETSPRUIT-TAVISTOCK-TWEEFONTEIN MANAGEMENT OPTIONS

The original flow model was used to consider management implementations. Two management options were tested for implementation:

- Building of walls in the areas where intermine flow is taking place to prevent the water in the opencast pits from flowing to the Rietspruit underground workings. This will accelerate the filling of the opencast pit.
- Application of ash to the Rietspruit opencast.
- Implication of coal barriers in the Tweefontein area.

5.4.1 Coal barriers in general

Coal barriers provide local and regional mechanical stability to underground collieries (Rangasamy *et al.*, 2001).

It must be emphasized that the mechanical stability of the barrier pillar must first be established before attempting to design a barrier pillar for water management. As will be shown later, charts can be used to determine either the minimum barrier pillar

width, maximum pumping rate required to manage or reduce the risk of sudden inrushes of water into the mine.

Flooding of mines is currently a very important issue, thus mining techniques must be improved to help improve quality of the mines and accelerate filling of mines. To ensure the faster filling of mines, thicker barriers must be left to prevent the mine from losing water through the coal barriers.

Restrictions can be placed on either the minimum required barrier pillar widths, maximum allowed reservoir water head, or the rate of compartment and/or roadway dewatering, depending on mining depth below surface and the geotechnical environment within which flow occurs.

5.4.1.1 Mechanisms for water flow.

The porosity and hence the intrinsic permeability of the rock mass in and around barrier pillars is extremely low. Water ingress is dominated by flow along rock mass discontinuities such as bedding planes, joints, stress fractures, faults, dykes and cleats. The flow path from a water-bearing area to a dry area is thus dependent on the location persistence and hydraulic condition of these discontinuities. The hydraulic conductivity of discontinuities is assumed to obey Darcy's Law for laminar flow. The path and rate of water flow from barrier pillar bound reservoirs will thus vary considerably from mine to mine.

5.4.1.2 Classification of flow regimes

Water flow through and around coal barrier pillars can be classified according to the rock type hosting the discontinuities that allow water leakage. Discharge of water onto the dry side of a barrier pillar from a flooded or partially flooded area will normally be a combination of water seeping from the roof, coal or floor. The geohydrological conditions of the immediate roof, coal and floor will determine the type of flow regime pertinent to a particular mine. The bulk of local underground collieries can be classified into the seven flow regimes. As an illustration only one regime was chosen, which fits the general descriptions of the coal barriers in the study area. Figure 5-8 gives a description of one of the flow regimes. Hydraulic design charts can be used to classify the barriers. The hydraulic chart can be seen in Figure 5-9.

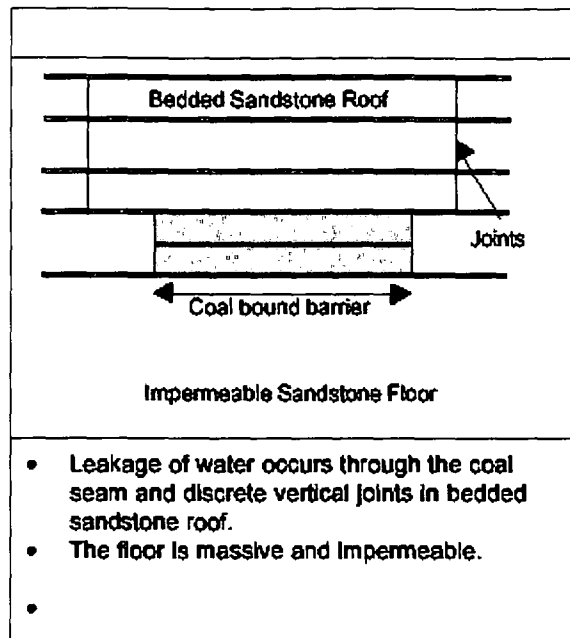


Figure 5-8 Example of the flow regime which can be used in the study area (from Rangasamy *et al.*, 2001).

The chart can be interpreted as follows:

If the workings are 75 m below the surface and the approximate time to knee depth ponding is between 10 and 20 hours (High flow regime), and if the water head that needs to be withstood is 15 m above the seam floor of the compartment, then a barrier pillar width of approximately 15 m is required (See Figure 5-9).

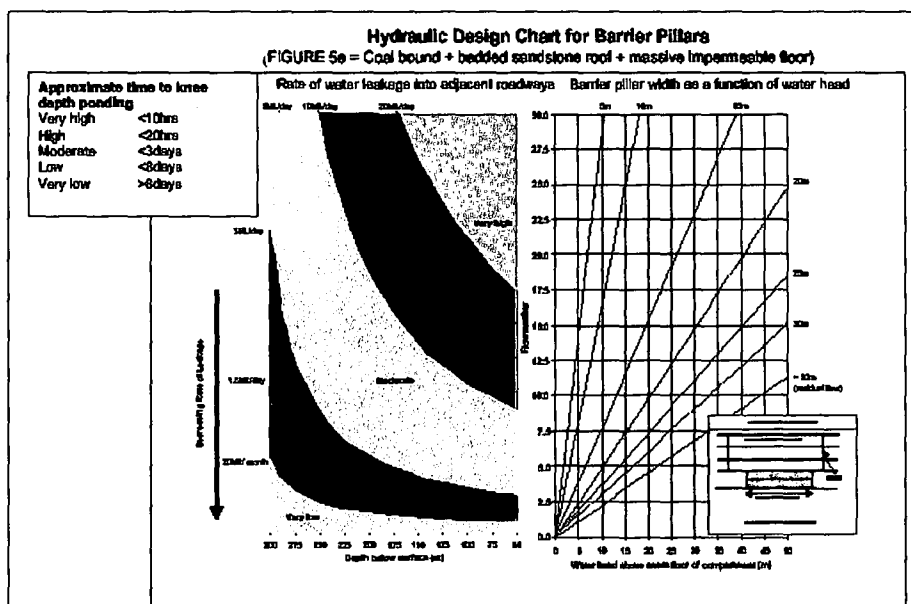


Figure 5-9 Hydraulic design chart for barrier pillars (from Rangasamy *et al.*, 2001).

5.5 FLOW BARRIERS AS A MANAGEMENT OPTION (RIETSPRUIT AS EXAMPLE)

The coal barrier between the pit and the underground working is transmissive enough to allow significant volumes of water to flow through, as seen in Chapter 3. The leakage occurs through fractures in the first layer and through the coal in the second layer. As already seen in chapter 3, the North-South Pit will take longer to fill to the decant elevation because of the constant leakage to the underground area. The proposed intermine flow minimisation strategy involves placing of hydraulic seals in the areas where intermine flow is dominant to prevent the water from flowing from the opencast pit to the underground workings.

The hydraulic seals were built into the Rietspruit-Tavistock-Tweefontein flow model. A ten-year simulation was done to see if these seals will have a positive effect on the water flow, and if it is viable to use hydraulic seals as a management option. By making use of the horizontal flow barrier package of Modflow (which will represent the hydraulic seals), hydraulic seal walls were placed in the path where intermine flow is present. A very small K-value was assigned to the walls, to ensure that it will serve as an impermeable boundary.

Three model simulations were done, for successive 10-year periods. After 10 years particle tracking was done on the area to track the flow paths of the water. The hydraulic seals were shifted as the flow shifts to try to block off the flow. From the particle tracking results it is visible that hydraulic seals are not an option, because if the water is blocked, it will find another way around the seal. The only way to stop the flow from the opencast pit to the workings is to build hydraulic seals along the entire length of the coal barrier, and with the high cost associated with the building of these seals, it definitely cannot be considered as a practical management option. See Figure 5-10 A-C for the three model simulations as well as the changing path of the water as the barriers were moved.

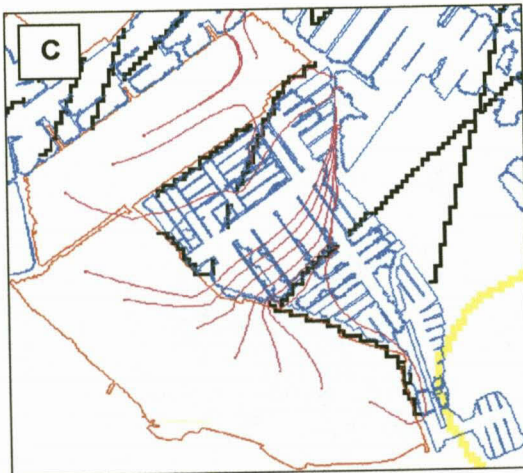
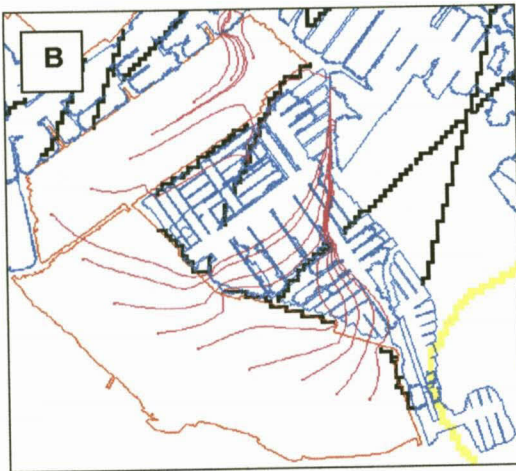
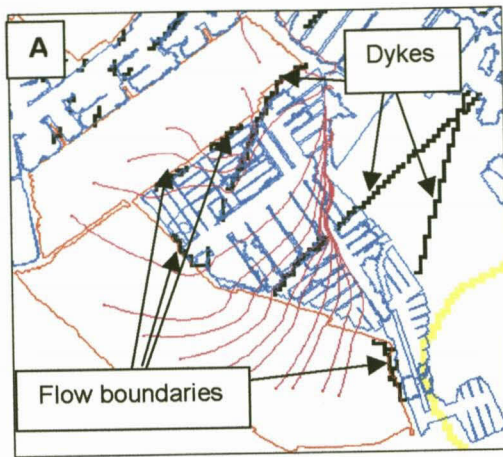


Figure 5-10 Flow path of water by making use of Impermeable barriers.

5.5.1 Possible application of fly ash to the Rietspruit Opencast area

Fly ash is a waste product from coal combustion that contains a significant alkalinity. Research by van den Berg *et al.* (2001) into the viability of fly ash as neutraliser in South African mines, has shown that the alkalinity of the ash is high but that it can be leached fairly rapidly. The heavy metal content of these ashes is also high and consequently if the ash is disposed of in an environment which eventually acidifies, severe environmental problems can occur.

The disposal of coal discard in the southern part of the North-South Pit at Rietspruit Colliery, discussed in Chapter 4 section 4.4.2, was used to gauge the impact of implementing fly ash to the opencast pit. 60 Mt of coal discard has been disposed of into this opencast pit (van den Berg *et al.*, 2001). The application of Matla fly ash (van den Berg *et al.*, 2001) on top of the spoil and discard, i.e. above the decant level of the South Pit has been previously recommended. Under these conditions the heavy metals from the fly ash will not be mobilised by water under alkaline conditions. This will prevent the potential problems outlined above.

The placement of fly ash as a cover over the discards and spoils can be used as a management option. The following can be expected during the application of fly ash to the discard:

- It will decrease the ingress of water and air into the discards. This will reduce the oxidation rate of the pyrite.
- It will provide a constant source of alkaline water to the underlying discard and spoil.

The leaching of fly ash's alkalinity can be restricted. The following factors can influence the leaching of the alkalinity.

- Leaching will only occur during periods of excess water in the fly ash. The field capacity of the fly ash was calculated in the order of 10%. If the field capacity of the fly ash exceeds 10%, the water will percolate downwards. From experimentations at Kendal it was found that water is in excess in the first 2 m of the ash for approximately nine months of the year with an average moisture content of 20%. Under the right conditions, significant moisture movement through the ash is thus possible. For ideal conditions and to ensure maximum penetration, the ash should be covered by a layer of water. Rietspruit is known for its undulating surface topography, and maximum penetration is therefore not possible.

The sediments underneath the ash cover will retain some of the water with raised alkalinity. This process will increase the base potential of the upper portions of the spoil. Limiting the activity of *Thiobacillus ferrooxidans* (which causes AMD) in the horizon. Hydroxide, carbonate or bicarbonate present in water will ensure alkalinity. If these three anions react with soil constituents, they will reduce the alkalinity of the water. This may limit the depth to which the additional alkalinity is carried into the spoil, where additional neutralising potential may be required. Thus the depth of affectivity of the cover of fly ash as well as the influence on the spoil water chemistry cannot be predicted.

A study was done by Carlson *et al.* (2001) to examine the laboratory characteristics of fly ash and native soil materials to demonstrate their potential use in landfills, lagoon liner, and final vegetative cover application. Following the evaluation of the geotechnical and engineering aspects, the flyash/soil was subjected to leaching and the chemical characteristics of the leachate were determined through laboratory analyses.

The 25/75 and 30/70 Fly ash/Soil mixture displayed engineering characteristics which indicate good potential for use in landfill liner applications (Carlson *et al.*, 2001). If fly ash is to be applied, an upper cover consisting of a mixture of ash and soils in the ratios given will provide an additional safeguard against system failure.

A soil/ash mixture therefore appears to be a possible solution to discards placed into pits. If these areas are covered with such a mixture and placed in the deepest part of the pit, inundation by water and the alkalinity effect should provide a solution to the heightened potential acidity from such areas.

5.5.2 Implementation of a seal in the 2 Seam workings at Tweefontein Colliery

The implementation of a hydraulic seal on the 2 Seam horizon at Tweefontein Colliery was investigated. See Figure 5-11 (red circle) for the position of the area.

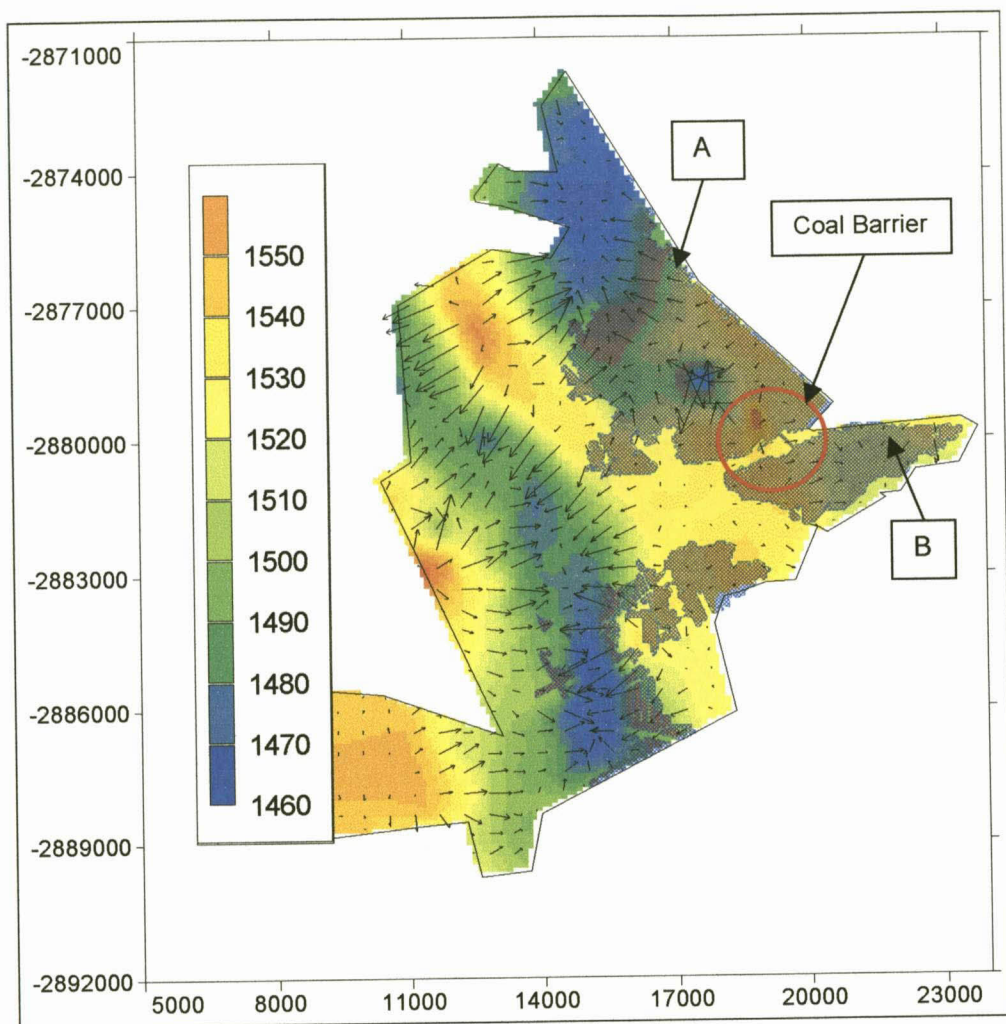


Figure 5-11 Application of coal barriers in the Tweefontein 2 Seam area.

Stage curves were plotted for area A and B to predict the volume present in the pit as well as the filling times of the underground areas (Figure 5-11). (See Figure 5-12 and Figure 5-13 for the stage curves).

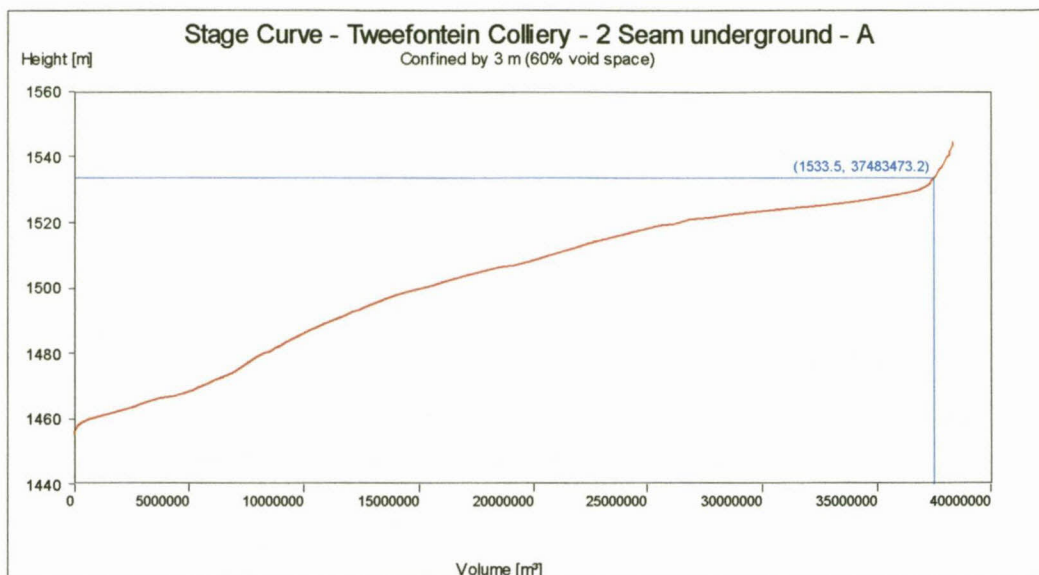


Figure 5-12 Stage curve for the Tweefontein 2 Seam workings - Area A

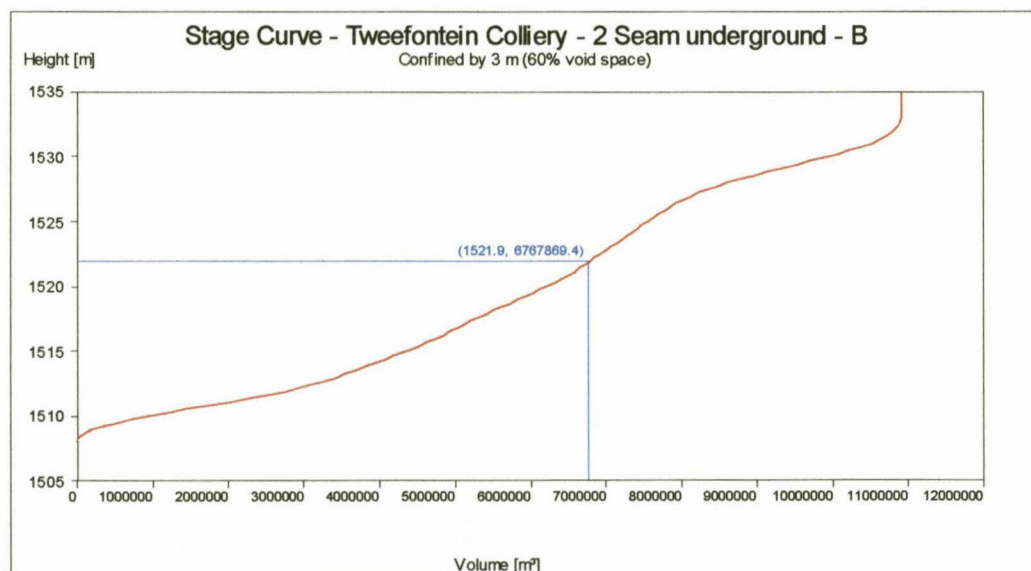


Figure 5-13 Stage curve for the Tweefontein 2 Seam workings - Area B

Making use of analytical methods, the filling times for the two underground areas were predicted. Area A will take approximately 78 years to fill and Area B 50 years. The filling time for area A and B as a unit is predicted as 71 years.

A hydraulic seal should be placed in the right area between the two areas, so that if Area B is full, the water will flow over the seal to Area A. This will accelerate the filling time of Area A by approximately 10 years. The overall filling time and therefore aerated portion of the mine, is thus minimised.

6 CONCLUSIONS

The following conclusions can be drawn from the research in this investigation:

- The paleogeologic conditions of coal deposition and formation provide several keys to understanding current phenomena. These include pH- Eh conditions, the occurrence of paleodrainage channels, variable aquifer parameters in current mines and the co-existence of pyrite and carbonates currently observed.
- Numerical models such as Modflow can be fruitfully used to understand the hydrologic interactions that occur in typical intermine flow areas.
- Comparison between numerical models and analytical or empiric approaches often provide the same broad answers. Numerical models allow the evaluation of conditions over time and can resolve complex situations, which other methods are often incapable of handling.
- Although these models are often the best tools to accommodate all the possible influences, in certain instances the values must be used with circumspection. In this thesis a specific example is shown where numerical models used in groundwater will not be able to simulate the situation correctly, due to the unsaturated/saturated moving boundary encountered in nature.
- Modflow is a very good model package to use and is very accurate in predicting flow direction, flow volumes and filling times of opencast areas. Modflow should be used with caution for predictions of filling times of underground areas. Refilling times for underground models using saturated flow models should be checked for consistency using volumetric/inflow calculations.
- Comparison of mass transport approaches and mixing cell approaches using a geochemical model provide similar results. In this specific instance the mass transport approach proves more insightful, due to the spatial variation in concentration change.
- Mass transport or mixing cell approaches are often insufficient to explain future chemical evolutions, and methods of combining reactions with progressive flows must be employed.
- Using Phreeqc to evaluate almost 2000 samples at two collieries, it is clear that sulphate concentrations are often limited by the saturation of gypsum. Wherever sufficient calcium is present in the water, gypsum precipitation will prevent sulphate from reaching very high levels. An upper limit of around 3000 mg/l is suggested by these evaluations.

The following conclusions can be drawn regarding the quantification of intermine flow in the Western Witbank Coalfield:

- As Pit 6 at Kriel starts to fill up, small amounts of water start to leak through the unmined coal barrier between Kriel and Tavistock. An average volume of 5.8 m³/d is expected to flow through the unmined coal barrier. Thus the influence of intermine flow from Kriel to Tavistock Colliery is minimal. The small amounts of water leaking through the unmined coal barrier to the underground area are not considered problematic. The good quality water of Kriel Colliery will in fact enhance the quality of the underground area.
- When Pit 6 reaches decant, an average decant volume of between 2800-2900 m³/d can be expected, based on the 20% recharge used for the opencast pits.
- Pit 5 and 6 will take approximately 44 and 27 years respectively to fill to their decant levels.
- From the water budget report of the Rietspruit-Tavistock-Tweefontein model it is visible that the North-South Pit loses approximately 2000 m³ of water per day through intermine flow. The pit loses water to the Rietspruit underground area as well as to Tavistock underground areas.
- Despite this loss of water, refilling times determined by numerical modelling were vastly different to values obtained previously with other methods.
- A comparison of a numerical models and analytical box models was done. Results from the flow model for the North-South Pit indicate that the pit will take approximately 24 years to fill. The box model predicted a filling time of 24.8 years. Modflow is a saturated 3D model and thus can simulate the correct filling time of opencast pits.
- For the prediction of the filling times of the underground area unsaturated conditions exist. A moving boundary condition exists. Modflow cannot simulate a situation like this. Modflow is thus over-estimates the flow to the underground.
- In the case of the N3 Pit, the filling times of Modflow and the box model are in the same range; Modflow predicted a filling time of 250 versus a filling time of 210 for the box model. The long filling time can be attributed to the fact that the N3 Pit will lose water continuously over a large perimeter.
- An initial flux of 1.6 ML/d (ranging between 0.3 and 1.6 ML/d) was calculated over the unmined coal barrier between the Kleinkopje and Wolwekrans section. A volume of approximately 1.45 ML/d was calculated over the unmined coal barrier between Greenside and Kleinkopje, and a flow of 1.15ML/d over the Kleinkopje Greenside unmined coal barrier.
- Filling times predicted for Block 5W and Block 2A are 20 and 32 years respectively (based on a recharge of 20%).

In terms of water quality in the study area the following conclusions can be drawn:

- The water quality of Tavistock Colliery is expected to be slightly acidic, at a pH of 6,5 with sulphate levels in the order of 2 400 mg/L (Hodgson, 1999). Acid conditions are expected to occur in the medium term after closure on the No. 4 Seam horizon, because of the unflooded conditions and the presence of oxygen. Alkaline conditions are expected on the No. 2 Seam horizon because of the flooded conditions. In the opencast pits, acid conditions will exist above the water level and alkaline conditions below the water table.
- The coal discards which have been disposed of in the South Pit at Rietspruit Colliery will cause acid generation. Currently, sufficient base potential is available to neutralise the acid generated.
- The groundwater qualities within the vicinity of Pit 5 and 6 are expected to be good in general.

From the results of the mixing of waters the following can be concluded:

- In the case of Kriel-Tavistock the sulphate concentration of the Tavistock underground area drops because of the addition of better quality water from Kriel to the system.
- In the case of mixing waters in the Rietspruit area the concentrations decrease during mixing. Acid generation can thus be expected over time, because of the presence of oxygen.

A few management options were tested for application in the study area:

- Placing of hydraulic seals at the two areas in Tavistock's No. 2 and 4 Seam underground workings are where these are connected. Sealing off the underground area will cause the workings to fill in approximately 70 years. Currently acid generation has started in the low lying areas of the underground because of the presence of oxygen. By sealing off the 4 Seam workings from the 2 seam workings, the quality of the underground area can be enhanced.
- The option of constructing a pipeline from Kriel to Tavistock Colliery after Kriel's Pit 6 decant is considered a viable option. By constructing the pipeline Kriel will get rid of the excess decant water without having a negative influence on the environment. This will result in the underground at Tavistock filling up in a shorter time. Current filling predictions with the pipeline is approximately 40 years.
- Placing of hydraulic seals in the unmined coal barriers at Rietspruit Colliery was investigated to prevent water in the opencast pit from flowing into the underground workings. From the results of particle tracking it is visible that the water will choose another flow path. Thus implementation won't be successful.

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- Because of the discard dump located in the southern part of the North-South Pit, the application of fly ash can be considered. A fly ash/soil mixture will decrease the ingress of water and air into the discards. This will reduce the oxidation rate of the pyrite. It will also provide a constant source of alkaline water to the underlying discard and spoil.

6.1 RECOMMENDATIONS

- As was seen from the sensitivity analyses done in the flow model, K-values of the coal and coal barriers play a very big role in the simulation of flow models. K-values of coal and coal barriers are very scarce and site-specific values at the intermine flow areas are strongly recommended.
- During the model simulations the initial heads of the underground and opencast area were mostly simulated as empty because little data are available on the current water levels in the pits and workings. The availability of water level data plays a very important role in the accuracy of the flow model, and in particular filling times of the areas. More regular sampling of boreholes is also recommended.
- Water balances should be done in a more dynamic manner, clearly identifying the source of water. This is in line with Pulles *et al.* (2001), who suggest that the water balances currently reported by the mines are poor.
- Intermine solutions to water management should be explored. The Kriel/Tavistock option discussed in this thesis is an example of where a mutually beneficial solution can be obtained
- Future mines should consider the water management implications of mining in the planning stages. This will avoid situations where only the minimum coal is left unmined or where areas where influxes are great can be avoided.

Opsomming

Die geometrie van mynbou areas in the Westelike Witbank Steenkoolvelde dui daarop dat intermyn vloei plaasvind. Intermyn vloei areas in die Witbank Steenkoolveld is reeds deur Grobbelaar (2001) geïdentifiseer.

Die doel van die navorsing is om intermyn vloei areas te identifiseer, kwantifiseer en die impak evaluasie van grondwater asook oppervlak water gehalte in die Witbank Steenkoolvelde te ondersoek. Die studie is deel van breër navorsing en is geborg deur COALTECH 2020. Die doel van die projek is om bestuursopsies te identifiseer om optimale water kwaliteit en kwantiteit in Suid Afrika se Steenkoolvelde te bevorder. Fokus is geplaas op die Westelike Witbank Steenkoolvelde. Die doel was om intermyn vloei te kwantifiseer in die studie area, asook te bepaal wat die impak van verskillende bestuursopsies is. Navorsing wys dat die paleo geologiese toestand gedurende die afsettings proses van steenkool 'n groot rol gespeel het in die huidige hidrochemie en hidrogeologiese verskynsels.

Numeriese vloei Modelle asook analitiese en empiriese metodes is gebruik om vloei rigtings, vloei volumes en opvultye te bepaal. Navorsing bewys dat numeriese model pakette, byvoorbeeld Modflow, gebruik kan word om hidrologiese interaksies wat in intermyn vloei areas te identifiseer. Vergelyking tussen die twee benaderings gee soortgelyke resultate, maar numeriese Modelle laat die evaluasie van veranderende kondisies en die oplos van komplekse situasies meer bevredigend toe. Sekere gedeeltes in die tesis beklemtoon resultate wat behoedsaam gebruik moet word.

A spesifieke voorbeeld wat in ondergrondse myne voorkom en wat oordek word deur versadigde media a.g.v. bewegende grens toestande, kan veroorsaak dat die model 'n fout begaan. Opvultye vir ondergrondse werke, veral die versadigde vloei Modelle, moet eers getoets word vir akkuraatheid deur gebruik te maak van volumetriese/invloei berekening. Massa Vervoer benaderings asook vermenging van water deur gebruik te maak van geochemiese Modelle is vergelyk. Massa vervoer gee 'n beter benadering a.g.v. die ruimtelike variasie in die sulfaat konsentrasies. Phreeqc is gebruik om ongeveer 2000 water monsters by twee mynbou areas te toets. Daar word gevind dat die sulfaat konsentrasies min is by gips versadiging. 'n Boonste limiet van ongeveer 3000mg/l is voorgestel deur gebruik te maak van laasgenoemde evaluasie. Intermyn vloei oor die ongemynde steenkoolgrense varieer baie. Vloei volumes varieer van meer as 1.5 Ml/d by Kleimkopje/Wolwekrans en Greenside/Kleimkopje tot minder as 10-3m/d by Kriel/Tavistock. Evaluasie van die situasie rondom Rietspruit Put wys dat a.g.v. die groot omtrek van die put asook die dikte van die ongemynde grens, groot hoeveelhede vloei verwag kan word na die nabyliggende ondergrondse werke.

Die lekkasie gee aanleiding tot baie lang opvultye van meer as 200 jaar vir die N3 Put. 'n Evaluasie van bestuursopsies is gemaak en by Kriel is die opsie van 'n pyp om die

voervloei volume na die ondergrondse werke van Tavistock te laat vloei voorgesel. Onder die ander opsies wat ondersoek is, is daar geillustreer dat ondeurlaatbare grense nie effektief sal wees om vloei van Rietsoruit na die nabyliggende ondergrondse werke te keer nie. Aanbevelings vir verdere navorsing sluit in meer gedetailleerde waterbalanse van die mynbou areas, omgewingspesifiede ondersoeke in terme van akwifere parameters, effektiewe hervulling en gelokaliseerde intermyn bestuursplanne.

8 REFERENCES

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