Quantification of the impacts of coalmine water irrigation on the underlying aquifers

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Synopsis

It is predicted that vast volumes of affected mine water will be produced by mining activities in the Mpumalanga coalfields of South Africa. The potential environmental impact of this excess water is of great concern in a water-scarce country like South Africa.

Research over a period of more than 10 years has shown that this water can be used successfully for the irrigation of a range of crops (Annandale *et al*., 2002)[1]. There is, however, continuing concern from the local regulators regarding the long-term impact that large-scale mine water irrigation may have on groundwater quality and quantity.

Detailed research has been undertaken over the last three years to supplement the groundwater monitoring programme at five different pilot sites, on both virgin soils (greenfields) and in coalmining spoils. These sites range from sandy soils to very clayey soils. The research has included soil moisture measurements, collection of *in situ* soil moisture over time, long-term laboratory studies of the leaching and attenuation properties of different soils and the impact of irrigation on acid rock drainage processes, and in depth determination of the hydraulic properties of the subsurface at each of these sites, including falling head tests, pumping tests and point dilution tests. This has been supported by geochemical modelling of these processes to quantify the impacts.

The results indicate that many of the soils have considerable attenuation capacities and that in the period of irrigation, a large proportion of the salts have been contained in the upper portions of the unsaturated zones below each irrigation pivot. The volumes and quality of water leaching through to the aquifers have been quantified at each site. From this mixing ratios have been calculated in order to determine the effect of the irrigation water on the underlying aquifers.

Keywords: coalmines, irrigation, gypsiferous mine water.

Introduction

South Africa is a water-poor country. With increased industrialization and population growth, the demands on this resource are increasing. South Africa is the fourth largest producer of coal in the world, and the 224 million metric tons of coal produced per year directly supports employment for approximately 50 000 employees. Unfortunately, several water-related problems occur, largely associated with water quality deterioration related to acid generation due to pyrite oxidation as a result of mining.

Large volumes of mine water, affected by the phenomenon of acid mine drainage, are presently being produced as a result of mining activities in the Mpumalanga coalfields. When released into water environments, the high salinities of this water are responsible for unacceptable water quality degradation.

In a water-stressed country like South Africa, all water must be regarded as a potential resource. Irrigation provides a novel approach to the utilization and disposal of mine water, under the correct conditions as shown by Annandale *et al.* 2004[2], provided the environmental impact is not excessive. The current research investigates the impact of these activities on groundwater resources at five irrigation pivots (Figure 1) at collieries where mine water irrigation has been practised for periods ranging from several months to more than seven years.

The Mpumalanga coalfieds and associated mine water

Coal extraction has been ongoing at the Mpumalanga coalfields for more than 100 years and is generally mined by opencast or underground methods in South Africa (Grobbelaar, 2001)[3]. The depth of mining ranges from less than 10 m below surface to more than 100 m. The coal seams generally increase in depth to the south. (Mining methods are bord-and-pillar, stooping and opencast. Opencast mining has been introduced during the late seventies. Underground mining on the 2-Seam comprises in excess of 100 000 ha, while opencast mining is expected to eventually exceed 40 000 ha (Grobbelaar *et al*., 2002)[4]. All of this will eventually be filled with water.

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 Paper received Aug. 2008; revised paper received May 2009.

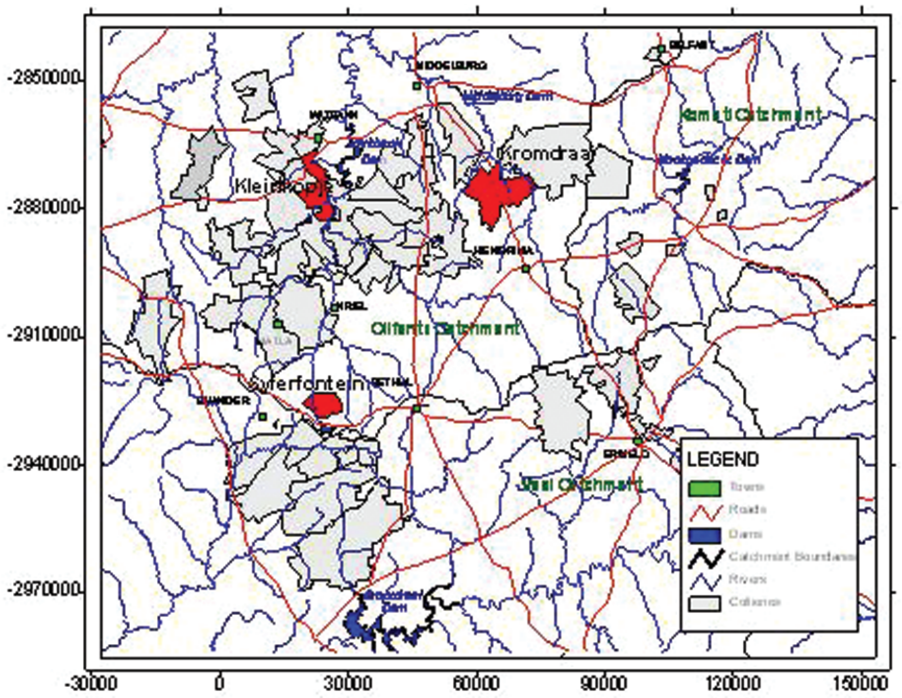

Figure 1—Collieries of Mpumalange, with positions of collieries in this study in red. The New Vaal Colliery, not indicated on this map, lies 130 km to the west of Syferfontein

Several sources of water influx are expected in South African collieries. In opencast areas, much of the influx is dependent on the state of post-mining rehabilitation, while in underground mining, factors such as the mining type, depth and degree of collapse and interconnectivity is important; all of this will determine the volume of water available. Projections for future volumes of water to decant from the mines have been made by Grobbelaar *et al.* (2002)[3]. In total, about 360 Mℓ/d will decant from all the mines in combination. These waters can be utilized as a resource for specific purposes, of which irrigation is one.

The phenomenon of acid mine drainage (AMD) is frequently associated with coalmining in South Africa. It occurs when sulphide minerals in rock are oxidized, usually as a result of exposure to moisture and oxygen. This results in the generation of sulphates, metals and acidity. Pyrite (FeS_2) is the most important sulphide found in South African coalmines. When exposed to water and oxygen, it can react to form sulphuric acid (H_2SO_4). The following oxidation and reduction reactions give the pyrite oxidation that leads to acid mine drainage.

$$FeS_2 + 7/2O_2 + H_2O => Fe^{2+} + 2SO_4^{2-} + 2H^+ \quad [1]$$

$$Fe^{2+} + 1/4O_2 + H^+ => Fe_3^+ + 1/2H_2O \quad [2]$$

$$Fe^{3+} + 3H_2O => Fe(OH)_3 + 3H^+ \quad [3]$$

$$FeS_2 + 14Fe^{3+} + 8H_2O => 15Fe^{2+} + 2SO_4^{2-} + 16H^+ (\text{Stumm and Morgan, } 1996)^5. \quad [4]$$

In the South African coalfields there are co-existing carbonates such as calcite and dolomite, which can neutralize the acidity generated (Usher, 2003)[6]. Alternatively, the acidity can be neutralized by lime addition, as occurs with acidic water pumped from the Kleinkopje Colliery workings.

From the overall reaction of calcite as buffering mineral, it is evident that calcium and sulphate will increase in concentration:

$$FeS_2 + 2CaCO_3 + 3,75\ O_2 + 1,5H_2O => Fe(OH)_3 + 2SO_4^{2-} + 2Ca^{2+} + 2CO_2 \quad [5]$$

This increase in Ca^{2+} and SO_4^{2-} can occur only up to a point, where the aqueous solubility of these ions becomes limited by the solubility of gypsum ($CaSO_4.2H_2O$). Using the PHREEQC geochemical model (Parkhurst and Appello, 1999)[7], the saturation state of the neutralized mine water used to irrigate at Kleinkopje's Pivot N.1's was determined (Figure 2). The results show that the gypsum approached saturation (SI=0) for most of the values. The implication of this is that when irrigation takes place, some evaporation, together with the selective uptake of essential nutrients, will result in gypsum precipitation.

Gypsum is a partially soluble salt. Concentrating the gypsiferous soil solution through crop evapotranspiration precipitates gypsum in the soil profile and therefore removes it from the water system (see Table I for irrigation water quality), reducing potential pollution (Annandale *et al.*, 2002)[1].

Sustainability of irrigation with gypsiferous mine water

Annandale *et al.* (2002)[1] did the initial work on irrigation with gypsiferous water in South Africa. Their research was to ascertain:

- Whether gypsiferous mine water can be used on a sustainable basis for irrigation of crops and/or amelioration of acidic soils

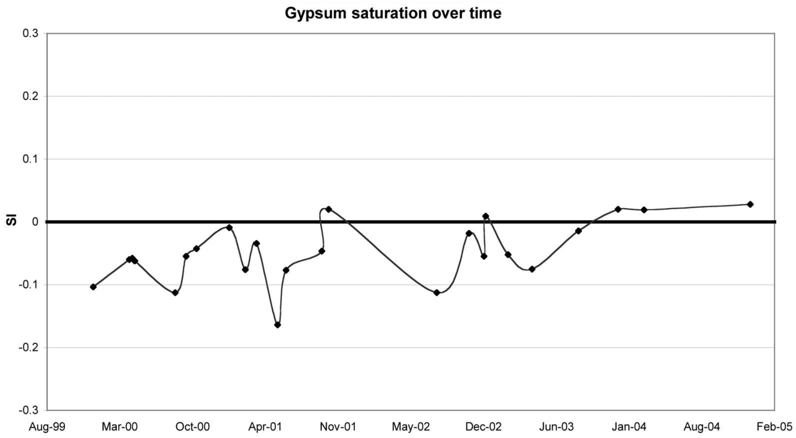

Figure 2_Gypsum saturation (SI) in neutralized mine water used to irrigate at Pivot 1

Table I

Average water quality of the irrigation water at Kleinkopje 1

pH	EC mS/m	Ca mg/ℓ	Mg mg/ℓ	Na mg/ℓ	K mg/ℓ	Alkalinity as mg/ℓ $CaCO_3$	Cl mg/ℓ	SO_4 mg/ℓ	Fe mg/ℓ	Mn mg/ℓ	Al mg/ℓ
6.21	344	578	242	52	12.9	34	12	2550	3.1	10.3	0.01

➤ The effects of gypsum precipitation and salt accumulation on soil characteristics and predict depths of salinization of soil over time.

The commercial production of several crops irrigated with gypsiferous mine water was tested in a field trial at Kleinkopje Colliery from 1997 to 2000, and also at the other pivots at Syferfontein, Optimum and New Vaal Collieries since 2000. From these trials, it was observed that no foliar injury was observed due to sprinkle irrigation with gypsiferous mine water, and that possible nutritional problems, such as deficiencies in K, Mg and NO_3, occurring due to Ca and SO_4 dominating the system, can be solved through fertilization. The soil salinity at Kleinkopje increased compared to the beginning of the trial, but the values of soil saturated electrical conductivity fluctuated around 200 mS/m, which is typical for a saturated gypsum solution. Crops such as sugarbeans, wheat and maize were found to be commercially viable. The finding from this research was that gypsiferous mine water for irrigation proved to be sustainable for crop production in the short term (three years) with negligible impact on the soil salinity.

Groundwater monitoring has been undertaken at these sites by Grobbelaar and Hodgson (1997–2001)[8] and by Usher *et al.* (2001–2005)[9,10]. Observation of limited water quality impacts in the groundwater over time has prompted much of the research at each irrigated area.

Results

Two collieries' results (Kleinkopje and Syferfontein) will be used to illustrate the results obtained.

Five irrigation pivots have been established as field tests, but this paper concentrates mainly on the observations from Pivot 1 at Kleinkopje Colliery, where the longest trials have been running (since 1997). Data from Syferfontein is also included to show an example with a different quality of mine water and different soil conditions.

Kleinkopje

Seven boreholes, of which farming activities later destroyed two, were drilled to monitor the influence of irrigation on the aquifer. These were constructed in such a way that no run-off from the irrigation enters the boreholes. Water levels are shallow, as expected from an irrigation area (Figure 3).

➤ These boreholes have been sampled quarterly since 1997 at the same depth with a Solinst specific-depth sampler. On each of these occasions, full chemical analyses of major ionic species and selected trace elements were done.

➤ In the more recent investigations, trenches were dug with an excavator until the water level of the water table aquifer at 3.5–4 m was reached. Samples were taken at various depths for soil characteristic analysis. Mineralogical determinations (XRD and XRF analyses using Norish and Hutton methods) were also done at the Geology Department of the Free State University.

➤ Three core boreholes were drilled within the pivot area: two inside the cultivated and irrigated portion and one outside for background values. The core samples were analysed at specific intervals for water-soluble constituents to determine the major cations and anions.

➤ Porous cups were installed in the core boreholes at metre intervals, and bedded in silica flower. The holes were backfilled with material originating from the hole. Each layer between the porous cups was sealed with a thin layer of cement.

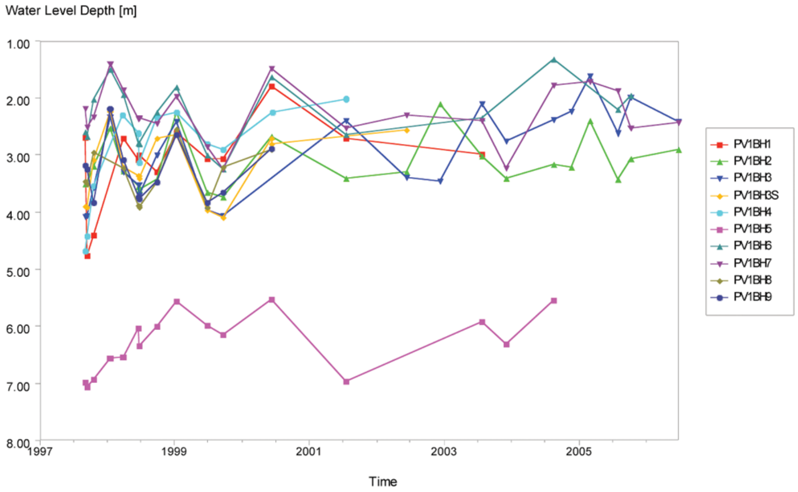

Figure 3—Water levels at Pivot 1

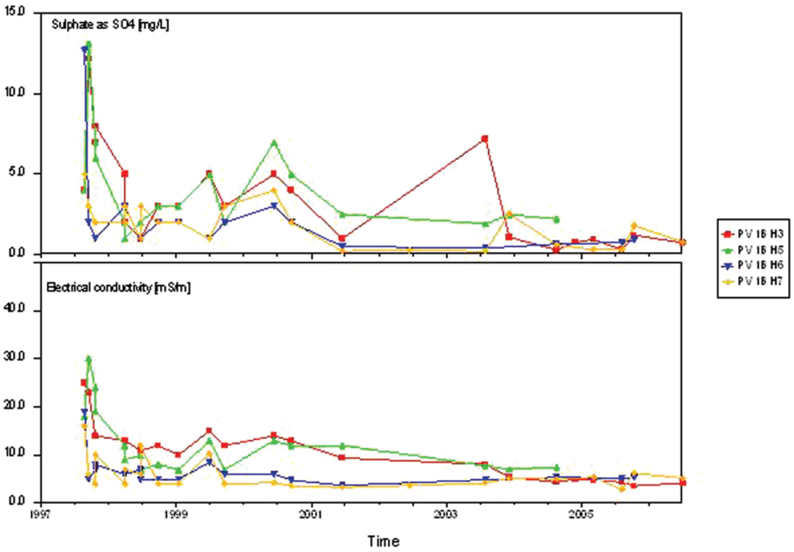

Figure 4-EC and sulphate concentrations in monitoring boreholes at Pivot 1

➤ Tensiometers were installed next to the porous cups to determine the moisture content of the unsaturated zone at each depth. From this, the migration of salt between the root zone and aquifer was monitored over time.

Results of the field investigations

Groundwater monitoring results since 1997, when irrigation started, have shown that the impact on the underlying aquifer is not significant. Water levels have not risen to any degree, although some seasonal variation, consistent with the Karoo sediments in the area, occurs (Figure 3). Of greater importance is the lack of increase in salinity, and more particularly sulphate (Figure 4). It is clear from this data series that, as yet, irrigation activities have very little discernible influence on the underlying aquifer's water quality.

The data from the porous cups' monitoring provide some insight into the reasons for this apparent lack of salinity increase in the aquifer. The data show a steady decrease in sulphate concentrations with depth in the pore water (Figure 5). This suggests that the majority of salts are contained within the uppermost portions of the soil profile, above the clay layer (See Table II), and in the clay layer.

To verify this observation, leaching tests were done on representative samples obtained in the soil profiles (Figure 6). Background values outside the irrigation area are also compared with the values obtained inside the irrigation area (Figure 6). In these tests, an excess of deionized water was added to each soil sample and the liberated ions in the supernatant analysed. Figure 7 illustrates the build-up of all salts in the soils above and within the clayey layers, and that a limited proportion of the associated salts move through into the groundwater. The results of the soil tests suggest that the porous cup results are consistent with the trapped pore water, and adsorbed/precipitated ions at each of these levels. Figures 5, 6 and 7 also indicate that most of the salts are present in the first metre of soil, above the layer with increased clay content (Table II).

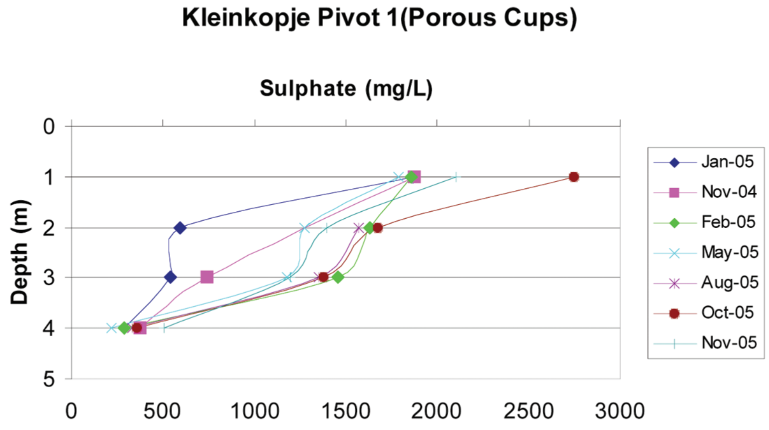

Figure 5—Sulphate concentrations with depth in the porous cups

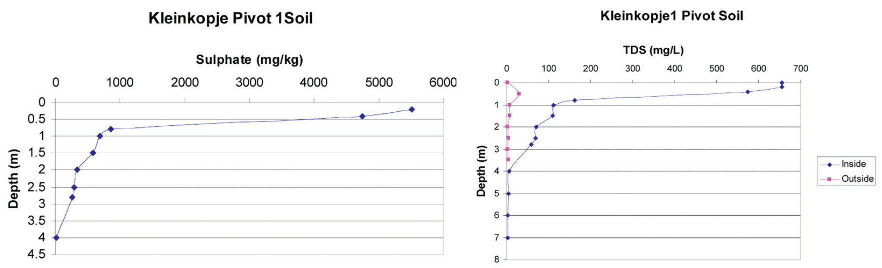

Figure 6—Sulphate concentrations liberated from the soil with depth and TDS-values of the soil profile inside and outside the pivot area

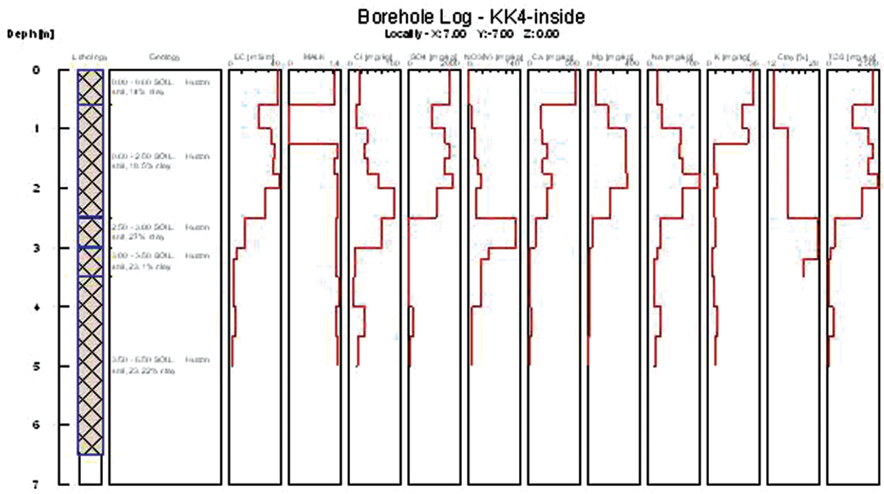

Figure 7—Soil leaching analyses with depth within Kleinkopje Pivot 4

Table II

Soil composition (particle size grading) at Kleinkopje Pivot 1

Depth (m)	Sand	Coarse silt	Fine silt	Clay
0–0.4	79.19	5.18	9.34	4.67
0.4–0.8	78.39	9.74	4.62	4.62
0.8–1.0	73.74	10.30	13.93	0.00
1.0–2.5	61.11	16.46	9.29	18.58
2.5–2.8	66.33	15.37	9.24	9.24

Table III

Soil composition (particle size grading) at Syferfontein

Depth (m)	Sand	Coarse silt	Fine silt	Clay
0–0.8	28.04	8.99	0.10	63.46
0.8-	na	na	na	na
1.44-	44.19	16.27	0.40	40.70
2.44-	62.11	8.42	0.40	31.58
3.5-	67.71	10.02	0.30	26.04
4.65-	82.50	10.00	0.40	10.00

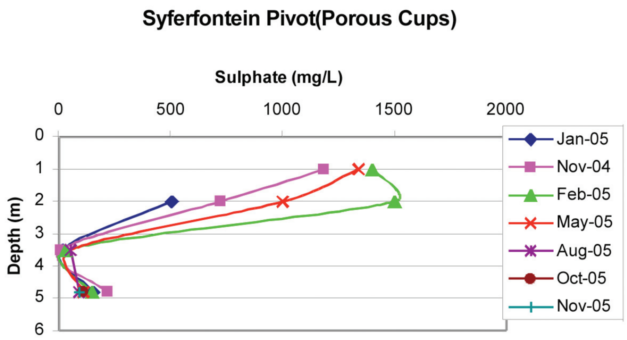

Figure 8—Sulphate concentrations with depth in the porous cups

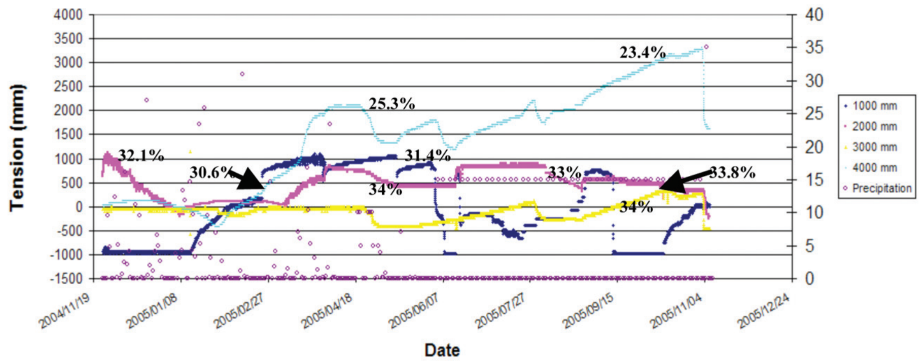

Figure 9—Tensiometer data for Kleinkopje with estimated volumetric water content

One of the implications of this would be that there are hydraulic and attenuation factors preventing the salts in the mine water used for irrigation from being mobilized through the soil profile and into the aquifer. The soil composition and associated sorption and hydraulic properties may be informative. The typical particle size distribution determined by standard soil grading tests is provided in Table II. This shows a marked increase in clay content below the depth of 1m. This is confirmed by XRD, which indicates > 40% quartz, 2–10% clay, and 2–10% haematite. No gypsum could be detected in the soils.

Syferfontein

In contrast, the results of another pivot site can be considered. The Syferfontein Colliery lies further south, and the irrigation water is less gypsiferous and has a stronger Na-SO_4 character. This would be expected to be more 'mobile' irrigation water. However, this pivot is underlain by a heavy clay soil (Table III). The results again indicate that only the very shallow soils and soil water show elevated salinity or sulphate (Figure 8). The result is that groundwater-monitoring systems around this pivot have also not shown any significant changes in water quality in the period 1999–2004.

Quantification of the salt

In order to determine the hydraulic behaviour, salt balances and attenuation, and the movement of the salts at the various irrigation sites, tensiometer experiments have been performed on site. Moisture potentials were calculated from the tensiometer data using a method determined by Hutson (1983)[11]. An example of Kleinkopje is illustrated in Figure 9 and the results of the different sites are summarized in Table IV.

Table IV

Estimated moisture content vs. depth at each site

Depth	1000 mm	2000 mm	3000 mm	4000 mm
Kleinkopje 1	0.32	0.373	0.34	0.34
Kleinkopje 2	0.358	0.339	0.34	0.28
Syferfontein	0.384	0.35	0.274	0.262

Table V

Salt balance calculations at the irrigation sites

Site	% Total sulphate applied through irrigation retained in vadose zone	% of total sulphate applied through irrigation in soil water	% of salts retained that are in soil water	Sulphate in soil (ton/ha)	Sulphate in soil water (ton/ha)
Kleinkopje 1	67%	25–38	37–56	56	21–28
Kleinkopje 4	77%	49–57	63–74	48	32–35
Syferfontein	82%	21–36	25–44	42	13
New Vaal	85%	30–38	35–45	18	7

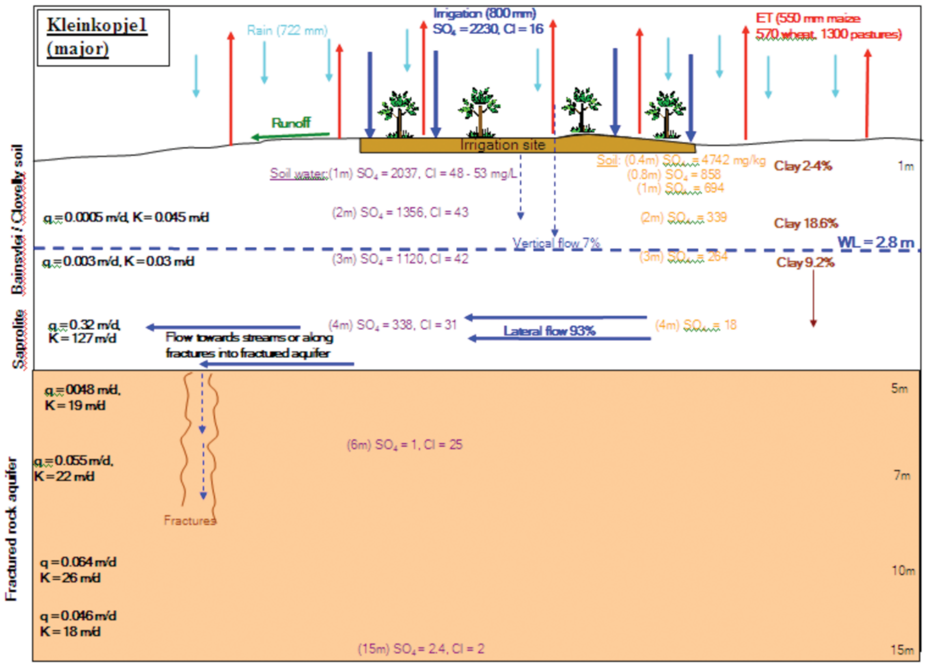

Figure 10—Detailed model of Kleinkopje

- ➤ *To calculate the salts retained in the soil, the following calculation was made*—Bulk density (obtained from Lorentz *et al*., 2001)[12].*thickness of the layer * sulphate concentration in the soil
- ➤ *To calculate the percentage salts retained in the soil*—Sulphate retained/total sulphate applied over the period of irrigation
- ➤ *To calculate the sulphate retained in the soil water*—Sulphate concentration in soil water*thickness of layer*moisture content at that depth

From these calculations, the distribution of salts per hectare of irrigation was determined, as reflected in Table V.

Because the calculations are so sensitive to the input parameters, they cannot be regarded as exact figures, but rather in a range of ± 10% accuracy.

The Kleinkopje Pivot 1 site can be used as illustration to show all the inputs and concepts related to these calculations. This is shown by Figure 10.

Spoils irrigation

Laboratory and field studies, together with geochemical models, were carried out to determine the behaviour of the spoils under various irrigation conditions. The cumulative understanding from the collective use of these techniques allowed the construction of feasible conceptual reaction models to predict the expected outcomes from the different applications of mine water irrigation.

The tests and models indicate the great importance of the reactive nature of the spoils on which irrigation will occur. The potential for acid generation is a very important indicator of where to apply mine water irrigation, while it is also clear that in high sulphide areas, the irrigation will enhance reactions and therefore lead to more rapid acidification and a higher salt load generation.

The reuse of irrigation in certain systems has both advantages and disadvantages. The advantage of a 'closed' or semi-closed loop means that the salt is not released into the environment. Secondary minerals solubility constraints will limit the possible upper values. It is therefore clear that the nature of the recirculating water is important. Where the mine water used for irrigation is largely gypsyferous, the recirculation scenario is feasible under the correct conditions (e.g. impermeable floor rocks). Where this water contains many other elements, such as the sodium bicarbonate waters at Syferfontein, the solubility limits become far higher due to the increase in ionic strength of the percolating water. Under these conditions, concentrations will continue rising to very high levels. This continuous rise is confirmed not only by theoretical considerations and geochemical models, but also by observations from laboratory tests. The nature of the spoils of irrigation water quality will determine the soluble concentrations of different elements.

Where mine water of relatively consistent quality is used, the changes in longer-term quality will be far less dramatic. The system reaches an equilibrium state and can continue in this state for long periods. The nature of the mine water is important in terms of the alkalinity, acidity and total ionic strength. The former two parameters will play a role in determining the depletion of the neutralization capacity of the rock, which in turn will determine the relative reactivity and generated salts. Where mine water containing some alkalinity is used, this will decrease the salt loads in the long term, provided that the alkalinity is mostly associated with calcium-containing carbonates. Where this is not the case, the ionic strength effects of the co-existing dominant cation will result in the benefits of added alkalinity being offset and concentrations rising steadily in the longer term.

Assessment of the salt load addition from spoils irrigation shows that there will be benefits to irrigation on spoils in the short to medium term, particularly if gypsum-rich water is used.

Conclusion and recommendations

The results point to several potentially significant findings for the wider application of mine water irrigation. Where the soils are richer in clay content, there is a significant attenuation of salts in the shallower zones. While the attenuation capacity of clays is a well-established concept, the long-term viability of irrigating with water influenced by coalmining is not widely accepted by regulators in South Africa. The groundwater monitoring results indicate that this attenuation makes mine water irrigation a viable option in the short to medium term where gypsum-saturated waters are used, as analysis of the water in the aquifers below show limited increase in degradation in quality, except in sandy soils.

Analysis of the tensiometer data over time, continued groundwater and soil water monitoring, and detailed analysis of the soil characteristics as far as hydraulic and mass transport properties at each site, allowed for the development of conceptual models of the interaction between irrigation and the underlying soils and aquifers. A general model for irrigation sites indicates the following:

- Tensiometer data indicates that the soil throughout the profile is high in moisture content, with the exception of the top 0.5–1 m. On average the moisture content is above 30%. The tensiometer data also indicates that the deeper layers dry out during winter.
- The clay rich layers play an important role in the moisture content, with a build-up of moisture above these layers. This indicates that clay does play a role in the vertical flux. Although this is a well-known fact, it is very important as the clay layers therefore have an influence on the salt distribution through the soil profiles.
- Data from soil analysis with depth through the profile indicates that most of the salt is contained in the top 2 m of the profile. Chemical modelling of the soil water indicates saturation of the water by gypsum above one metre, implicating gypsum precipitation. Deeper down the soil water is unsaturated by gypsum. Approximately 80% of the salts applied over the years of irrigation are retained. Data from soil water analysis obtained of the porous cup sampling indicates that a lot of these salts occur in the soil water (about 30% of the total salts applied), and that the balance precipitates in the soil or gets adsorbed. This implies that over the short to medium term the irrigation with coal mine water does not influence the aquifers to a great degree. Dissolved salts leach to the aquifers at a very low rate and are diluted at such a fast rate because of lateral groundwater flux, as determined by point-dilution tests; the q-values obtained are illustrated in Figure 10. As a result, low concentrations are detected through borehole sampling.

Based on the research completed, the following can be recommended for mine water irrigation, as part of holistic management of mine water:

- It is recommended that mine water irrigation be strongly considered as part of the suite of mine water management options by the mining industry and by regulators.
- Irrigation with mine water must be implemented such that the environmental impacts are minimized. Based on the expected slow salinity build-up observed at the different sites, it is recommended that irrigation be done on an alternating basis (i.e. alternating between two pivots over time), if site criteria selection has been adhered to (Vermeulen *et al.*, 2008), and that mine water irrigation should not be done for periods exceeding 10 years in any particular area. A non-negotiable prerequisite is that appropriate monitoring be put in place at such a site. These boreholes must be constructed in such a way that they monitor all the different flow zones and aquifers at these sites.

- ➤ To determine the impact of the viability of irrigation with coal mine water in the long term, it is suggested that monitoring continues at the various test sites. Monitoring should be done as described in the guidelines outlined in this project.
- ➤ Water to be used for irrigation must be gypsyferous, low in sodium and non-acidic.
- ➤ Preference should be given to irrigation on small areas of spoils rather than on unimpacted undisturbed soil.
- ➤ Spoils to be used for irrigation should preferably be non-acid generating.

Acknowledgements

This study was sponsored by the Water Research Commission and Coaltech 2020. The funding for the research and co-operation of all the mines in the area is gratefully acknowledged. This study would not have been possible without the full co-operation of the collieries and their controlling companies. This is gratefully acknowledged.

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