Quantification of the Impact of Irrigating with Coalmine Waters on the Underlying Aquifers

D. Vermeulen and B. Usher

Abstract It is predicted that vast volumes of impacted 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). 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 3 years to supplement the groundwater monitoring program at five different pilot sites, on both virgin soils (greenfields) and in coal mining 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 Coal mining · irrigation · gypsum-saturated · waters · attenuation capabilities

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1 Introduction

South Africa is a water-poor country. With increased industrialisation 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, largely associated with water quality deterioration due to pyrite oxidation, occur, as a result of mining.

Huge volumes of mine water, impacted on 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.

1.1 Objectives

In a water-stressed country like South Africa, all water must be regarded as a potential resource, and there is potentially a tremendous resource that can be utilised by activities such as irrigation, provided the environmental impact is not excessive. Irrigation provides for a novel approach to the utilisation and disposal of mine water, under the correct conditions. The significance of these findings lies in the versatility of this irrigation. Communities which often have very few other resources can utilise mine water to generate livelihoods. When one considers social aspects like job creation, especially after mine closure, it is clear that irrigation with certain mine waters, on carefully selected and managed sites, could form a sustainable, economically feasible and socially uplifting strategy in the developing world. This research investigated the impact of these activities on groundwater resources at five irrigation pivots at collieries across the coalfields of South Africa, where mine water irrigation has been done for periods ranging from several months to more than 7 years.

1.2 The Mpumalanga Coalfields and Associated Mine Water

Coal extraction has been ongoing at the Mpumalanga Coalfields for more than 100 years. Coal is generally mined by opencast- or underground methods in South Africa. (Grobbelaar 2001). 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 1970s. 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). 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.

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 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 eventually. This flow is referred to as intermine flow (Grobbelaar 2001). Projections for future volumes of water to decant from the mines have been made by Grobbelaar et al. (2002). In total, about 360 ml/day will decant from all the mines in combination.

1.3 Water Quality Impacts

Associated with coal mining in South Africa, the phenomenon of acid mine drainage (AMD) occurs. Acid mine drainage occurs when sulphide minerals in rock are oxidised, 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.

$$FeS_2 + 7/2\,O_2 + H_2O \Rightarrow Fe^{2+} + 2SO_4^{\ 2-} + 2H^+ \quad (1)$$

$$Fe^{2+} + 1/4O_2 + H+ \Rightarrow Fe^{3+} + 1/2\,H_2O \quad (2)$$

$$Fe^{3+} + 3H_2O \Rightarrow Fe(OH)_3 + 3H^+ \quad (3)$$

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

In the South African coalfields there are co-existing carbonates such as calcite and dolomite, which can neutralise the acidity generated (Usher 2003) Alternatively the acidity can be neutralised 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:

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

This increase in Ca^{2+} and $SO_4^{\ 2-}$ can only occur 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), the saturation state of the neutralised mine water used to irrigate at Kleinkopje's Pivot No1's was determined. 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 1 for irrigation water quality), reducing potential pollution (Annandale et al. 2002).

Table 1 Average water quality of the irrigation water at Kleinkopje 1

pH	EC	Ca	Mg	Na	K	Alkalinity	Cl	SO4	Fe	Mn	Al
	mS/m	mg/L	mg/L	mg/L	mg/L	As mg/L CaCO3	mg/L	mg/L	mg/L	mg/L	mg/L
6.21	344	578	242	52	12.9	34	12	2,550	3.1	10.3	0.01

1.4 Sustainability of Irrigation with Gypsiferous Mine Water

Annandale et al. (2002) did the initial work regarding 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
- The effects of gypsum precipitation and salt accumulation on soil characteristics and predict depths of salinisation of soil over time

The commercial production of several crops irrigated with gypsiferous mine water was tested in a field trial at Kleinkopjé 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 like 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 (3 years) with negligible impact on the soil salinity. Groundwater monitoring has been undertaken at these sites by Grobbelaar and Hodgson (1997–2001), Usher and Ellington (2002) and by Usher and Vermeulen (2003–2006). Observation of limited water quality impacts in the groundwater over time has prompted much of the research currently underway in the vadose zone below the root zone of each irrigated area.

2 Discussion and Results

2.1 Kleinkopje

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 of Syferfontein is also included.

Methodology

- 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 (Fig. 1).
- 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 Dept 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 meter 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.

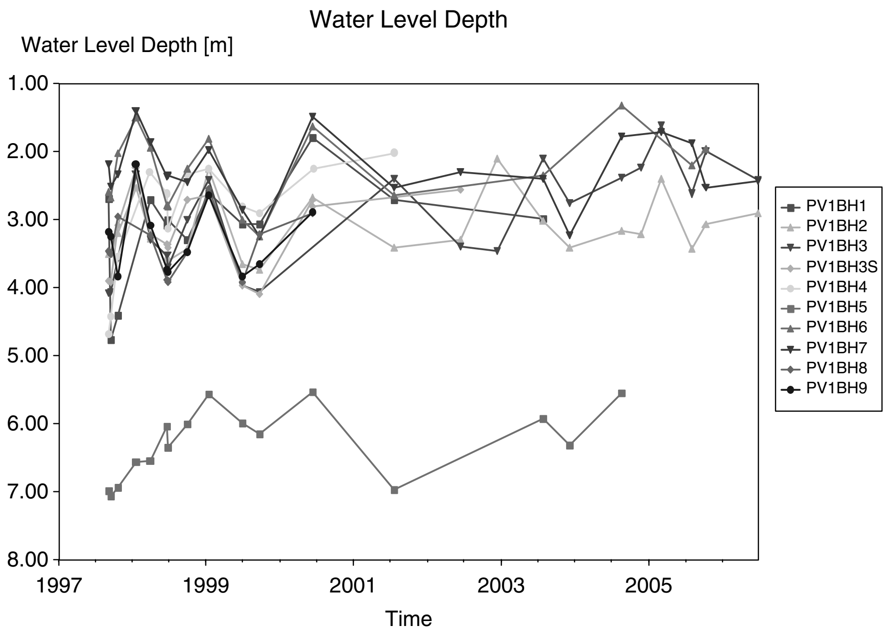


Fig. 1 Water levels at Pivot 1

- 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.

2.1.1 Results of Groundwater Monitoring

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 (Fig. 1). Of greater importance is the lack of increase in salinity, and more particularly sulphate (Fig. 2). 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 (Fig. 3) show a steady decrease in sulphate concentrations with depth. This suggests that the majority of salts are contained within the uppermost portions of the soil profile, above and in a clay layer present between 1 and 2.5 m. The percentage clay in this layer is 20% compared to about 5% in the soil above and below it. To verify this observation, leaching tests were done on representative samples obtained in the soil profiles. Background values outside the irrigation area are also compared with the values obtained inside the irrigation area (Fig. 4). In these tests, an excess of deionised

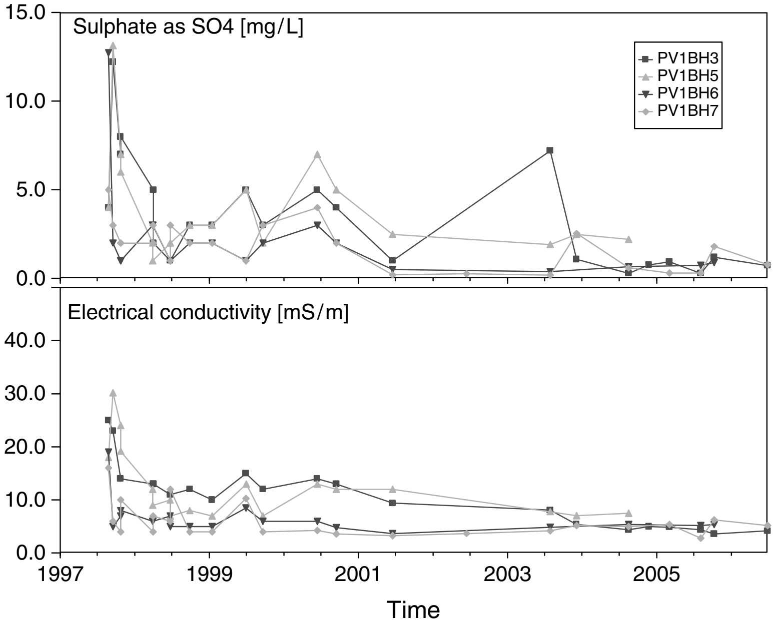


Fig. 2 EC and sulphate concentrations in monitoring boreholes at Pivot 1

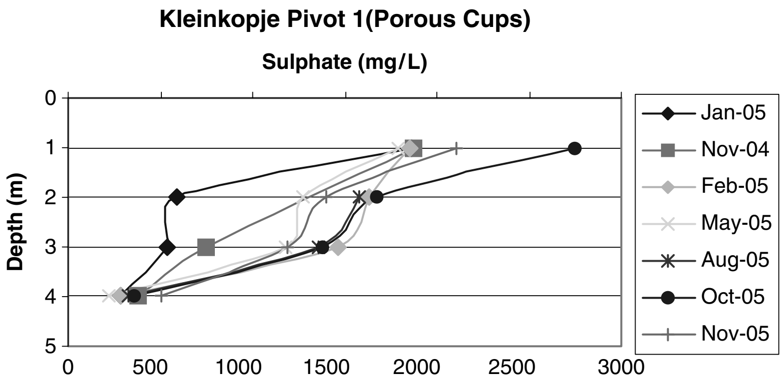
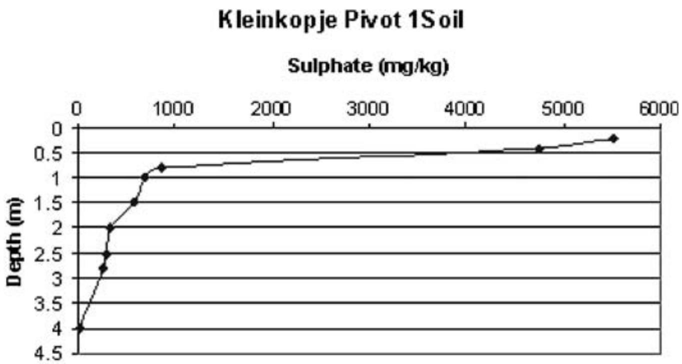


Fig. 3 Sulphate concentrations with depth in the porous cups



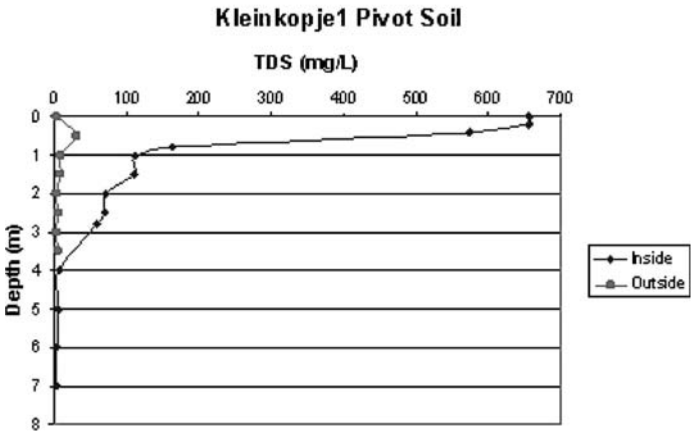


Fig. 4 Sulphate concentrations liberated from the soil with depth (above) and TDS-values of the soil profile inside and outside the pivot area (below)

water was added to each soil sample and the liberated ions in the supernatant analysed. 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. Figure 4 also indicates that most of the salts are present in the first metre of soil, above the layer with increased clay 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 mobilised through the soil profile and into the aquifer. The soil composition and associated sorption and hydraulic properties may be informative. The typical composition determined by standard soil composition tests shows a marked increase in clay content below the depth of 1 m. This is confirmed by XRD, which indicates >40% quartz, 2–10% clay, and 2–10% hematite. No gypsum could be detected in the soils.

2.2 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 $Na\text{-}SO_4$ character. This would be expected to be more "mobile" irrigation water. However, this pivot is underlain by a heavy clay soil. For the first meter in depth the clay percentage is 63%, and for 1–4.5 m it varies between 40% and 31%. The results again indicate that only the very shallow soils and soil water show elevated salinity or sulphate (Figure 5). 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.

3 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). An example of Kleinkopje is illustrated in Fig. 6 and the results of the different sites are summarised in Table 2.

To calculate the salts retained in the soil, the following calculations was made:

Bulk density (obtained from Lorentz et al. 2001). * ***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 following results were obtained per hectare of irrigation (Table 3):

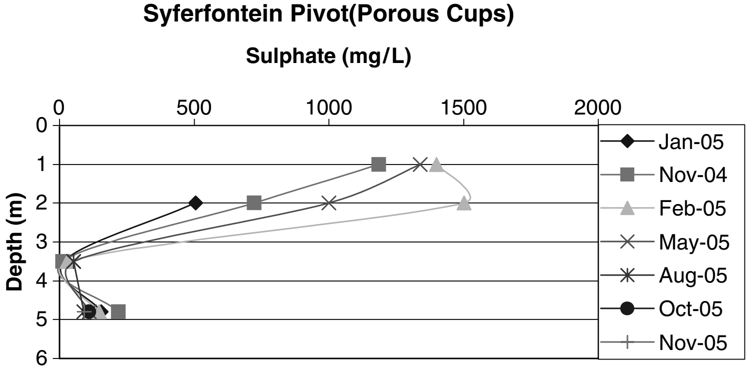


Fig. 5 Sulphate concentrations with depth in the porous cups

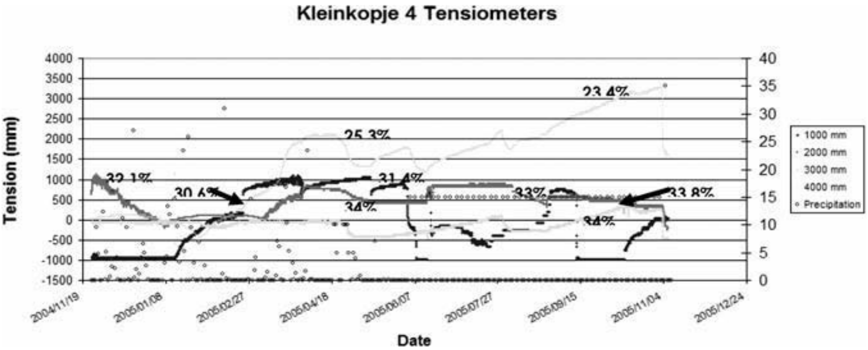


Fig. 6 Tensiometer data for Kleinkopje with estimated volumetric water content

Table 2 Tensiometer data at Irrigation sites

Depth	1,000 mm	2,000 mm	3,000 mm	4,000 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 3 Salt balance calculation at the irrigation sites.

Site	% Total sulphate applied through irrigation retained in vadoze zone	% 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	21-38
Kleinkopje 2	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

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.

4 Conclusion

The results to date 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 coal mining 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 the development of accurate conceptual models of the interaction between irrigation and the underlying soils and aquifers. A general model for irrigation sites indicates the following:

1. 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.
2. 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.
3. 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 with respect to gypsum above 1 m, implicating gypsum precipitation. Deeper down the soil water is unsaturated with regard to 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 most of these salts occur in the soil water (about 60% 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 a result low concentrations are detected through borehole sampling.

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