Prediction of the environmental impact and sustainability of large scale irrigation with gypsiferous mine water on groundwater resources

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ABSTRACT

Irrigation of agricultural crops is one of the most cost effective options for the utilization of gypsiferous mine wastewater. In addition, it creates the opportunity to produce crops during the dry season. Gypsum is a slightly soluble salt and concentrating the gypsiferous soil solution through crop evapotranspiration precipitates gypsum in the soil profile, removing it from the water system and reducing the potential for groundwater pollution. In previous research, it was found that crops can be commercially produced under irrigation with gypsiferous mine water with no obvious impact on groundwater in the short-term (3 years). It was, however, recommended that monitoring should continue to confirm findings over a longer period and for different conditions. A research project was therefore initiated in 2001 to determine the impact of irrigation with several gypsiferous water/soil combinations on crop performance, soil properties and groundwater quality. Field trials were carried out in South Africa on three mines: Kleinkopjé and New Vaal Collieries (Anglo Coal), and at Syferfontein (Sasol). Different crop and pasture species grown on different soil types were centre pivot irrigated with different mine water qualities. Intensive monitoring systems were established in each irrigated field to determine the components of the soil water and salt balance. Boreholes were also installed to monitor groundwater level and quality. Field water and salt balance data were used for calibration and validation of the mechanistic, generic crop Soil Water Balance (SWB) model. The results of the field trials indicated that high crop and pasture yields can be obtained, provided land preparation, fertilization and irrigation water management are appropriate. The results of the soil water and salt balances indicated that considerable amounts of mine water can be used and considerable masses of salts can be removed from the water system through precipitation of gypsum in the soil profile. The groundwater impact *was limited based on borehole measurements, indicating the presence of a buffer zone between the cropped soil profile and groundwater, but this should be monitored over a longer period. With appropriate management, water and salt runoff, and under specific conditions, drainage and salt leaching can be intercepted, thereby minimizing unwanted impacts on groundwater. Thirty-year scenario simulations were run with SWB and the output of the model used as input into a groundwater model in order to predict the likely long-term effects of irrigation with gypsiferous mine water on groundwater for several case studies. The results of these simulations showed that while salts reached the groundwater, there was a drop in salt levels of the salt plume as it moved away from the irrigated area. This was due largely to dilution by rainwater infiltration and the dispersive characteristics of the aquifer. These results suggest that large-scale irrigation with gypsiferous water could be viable if irrigated fields are carefully sited and well managed. A site-specific approach is essential.*

KEY WORDS: irrigation, gypsiferous, wastewater, groundwater, simulations, SWB

INTRODUCTION

Mining in South Africa generates large volumes of mine wastewater which have the potential to adversely affect an already scarce water resource if not properly managed (Tanner et al., 1999). Disposal of mine wastewater is a world-wide problem occurring wherever operating coal- and gold mines, as well as closed underground and open-cast workings are found (Pulles et al., 1995). The type of wastewater emanating from mines depends largely on the chemical properties of the geological materials that come into contact with water (Thompson, 1980). The concentrations of salts and other constituents frequently render such waters unsuitable for direct discharge to the river systems except in periods of high rainfall when adequate dilution capacity is present and controlled release is permitted by the regulatory authorities (Pulles et al., 1996). In many cases the mine effluent is gypsiferous, meaning that it is dominated by calcium and sulphate ions. This occurs when acid mine drainage (AMD) is neutralized by naturally occurring calcite or dolomite, or by active liming, which may be required to correct pH and precipitate out metals (Van Staden, 1979).

The potential of gypsiferous mine water for use in crop irrigation was first evaluated in South Africa by Du Plessis (1983), using a steady state chemical equilibrium model (Oster and Rhoades, 1975) to predict the amount of salts leached, and which could potentially contaminate groundwater. Simulation results indicated that irrigating with gypsum rich water would result in lower soil and percolate salinity compared to a chloride rich water of otherwise similar ionic composition. This could be attributed to precipitation of gypsum in the soil. The increased sodium hazard caused by gypsum precipitation was not expected to seriously affect soil physical properties and crop yield using a typical mine water quality for irrigation (Du Plessis, 1983).

The use of gypsiferous mine wastewater for irrigating agricultural crops presents an opportunity to stabilize dry land crop production and enable dry season production, whilst at the same time providing a cost-effective method for minimizing excess mine drainage (Jovanovic et al., 2002). Comparisons of the capital costs of irrigation with alternative treatment options shows irrigation to be lower by an order of magnitude. Running costs are covered by the income generated from the sale of produce. By irrigating with gypsiferous wastewater, a large fraction of the salts can be removed from the water system through precipitation of gypsum in the soil profile, as the soil solution gets concentrated by root water uptake. This reduces the likelihood of off-site environmental pollution.

Reasonable estimates of volumes of mine water stored and generated are available for a number of active mines in the Central Witbank Coalfields (Mpumalanga Province, South

Africa). For instance, Kleinkopje Colliery (Witbank, Mpumalanga) currently has some 12 million m^3 of water stored underground, and it is estimated that the daily water make is in the order of 14 Mℓ d^{-1}. This is sufficient to sustain an irrigated system of some 500 to 700 ha (depending on the particular cropping system) (Jovanovic et al., 2002). Predictions of future water volumes and qualities that will decant from the closed collieries in the Mpumalanga Province have been made by Hodgson *et al*. (1999). For the Olifants Catchment, a volume of 170 Mℓ d^{-1} is suggested. Not all this water will report to the same locality, and several sub-areas where water will decant from the mines are envisaged. The expected discharge at each decanting position ranges between 12 – 40 Mℓ d^{-1}. These volumes of decant water have the potential support in excess of 6 000 ha of irrigation in the Olifants Catchment alone.

The use of gypsiferous mine water for irrigation has been investigated in quite some detail in South Africa. A wide range of crop and pasture species were screened for tolerance to irrigation with lime-treated AMD at Landau Colliery (Anglo Coal, Witbank, Mpumalanga Province) from 1993 to 1996 (Barnard et al., 1998; Jovanovic et al., 1998). Higher crop yields were obtained under irrigation with mine water compared to dry land production, without any foliar injury to the crop. Possible nutritional problems, for example deficiencies in K, Mg and NO_3, occurring due to Ca and SO_4 dominating the system, can be solved through fertilization. Soil salinity increased compared to the beginning of the trial, but the values of soil saturated electrical conductivity stabilised at a relatively low level around 200 mS m^{-1}, which is typical for a saturated gypsum solution. The commercial production of several centre pivot irrigated crops with gypsiferous mine water has also been tested in field trials at Kleinkopje Colliery (Anglo Coal, Witbank, Mpumalanga Province) since 1997 (Annandale et al., 2001; Jovanovic et al., 1998) and at Syferfontein (SASOL, Secunda, Mpumalanga Province) and New Vaal Colliery (Anglo Coal, Vereeninging, Gauteng Province) since 2001.

Data collected have been used to validate the Soil Water Balance (SWB) model (Annandale et al., 1999) which has been used for long-term predictions of the likely impact of irrigation with gypsiferous mine water on soil and groundwater resources. Crops like sugarbeans, wheat, maize, potatoes and pastures were very successfully produced under irrigation with gypsiferous mine water. Land preparation and fertilization management are critical for successful crop production, especially on rehabilitated soil. In the short to medium term (six years), irrigation with gypsiferous mine water proved to be sustainable with a negligible impact on the groundwater. The system is flexible and can be managed depending on the objectives that one wants to achieve, be it maximum crop production, water use, job creation, economic return or maximum gypsum precipitation and minimum salt leaching (Annandale et al., 2002).

The purpose of establishing several field trials in different regions was to assess the sustainability of irrigation with gypsiferous mine water under different environmental conditions, as well as to validate the SWB model for different climates, soils, cropping systems and water and salt balances. A detailed description of soil properties, water qualities and cropping systems at each mine are given by Jovanovic et al. (2002).

As the impact of irrigation with gypsiferous water on crops and soils seems minimal and manageable, the focus of more recent investigations has turned to the impact on groundwater quality. Boreholes drilled at the different mines, either inside or in close proximity to the irrigated fields, have shown very little salt moving through the soil profile in the short term (2-6 years). However, there are justifiable concerns by regulating authorities that this practice, especially if allowed on a large scale, will merely be ‘buying time’, and could in fact turn a point source pollution problem into a more difficult to manage non-point source pollution problem. It is essential, therefore, to predict what the likely impact of large-scale irrigation could be on ground water resources.

The National Water Act (No. 36 of 1998) classifies irrigation, including irrigation with excess mine water, as a controlled activity that can only be practiced under license. Current concerns in the water-scarce Olifants River Catchment are that if all excess mine water is used for irrigation in future then the basic ecological and domestic needs of downstream water users may not be met. It is likely that a compromise will need to be agreed between all stakeholders that provides for these basic needs, but also allows for irrigation with mine waters as a cost effective way of providing food security and employment in the future as the region diversifies its economy away from coal mining.

FIELD WATER BALANCE

It is, of course, impossible to measure long term behaviour of a non-existing but proposed large-scale irrigation scheme. Models were therefore used to predict long-term environmental effects by simulating thirty years of irrigation with gypsiferous mine water. The long-term effect of irrigation with gypsiferous mine water on the soil was predicted with the Soil Water Balance (SWB) model (Annandale et al., 1999a). This is a daily time step, generic crop, irrigation scheduling model simulating the soil water and salt balance, as well as water stress- and soil salinity-affected crop growth. Water movement in the soil profile is simulated with a simple cascading model (Campbell and Diaz, 1988). Salt redistribution assumes complete mixing of irrigation and rainfall with the soil solution of the top soil layer, and similarly for the soil solution percolating to the next lower soil layer and so on. Precipitation and dissolution of gypsum and lime is determined using the approach of Robbins (1991). Potential evapotranspiration is calculated adopting the internationally standardized FAO (Food and Agriculture Organization of the United Nations, Rome, Italy) Penman-Monteith methodology (Allen et al., 1998). Long-term weather records for the simulations with SWB were generated using the CLIMGEN weather data generator of G.S. Campbell (Washington State University), which is a modified version of WGEN (Richardson and Wright, 1984). CLIMGEN has been assessed for South African conditions by Clemence (1997), who showed the estimates to be quite satisfactory.

Long-term simulations were carried out for lucerne (*Medicago sativa* cv. Pan 4860) - fescue (*Festuca arundinacea* cv. A.U. Triumph) perennial pasture, on a loamy sand Bainsvlei soil (Soil Classification Working Group, 1991) or Plinthic Ferralsol (FAO, 1998). Water qualities typical for Kleinkopje Colliery were used as input (Table 1). Generated weather data for Ogies (Lat. 26º13' S; Long. 28º72' E; Alt. 1571 m, average rainfall 738 mm), which is reasonably representative of climatic conditions in the Mpumalanga coalfields, were used (Annandale et al. 1999b). Irrigations with gypsum rich water (Table 1) were simulated to refill the soil profile on days when the calculated soil water deficit was > 20 mm (Annandale et al. 1999a). Simulated average irrigation was 1141 mm with 279 mm the average annual drainage. Simulations showed that roughly half the added salts would be leached under these circumstances. The simulated leachate qualities presented in Table 1 were used as inputs to the groundwater model.

Table 1. Input salt concentration of irrigation water and leachate concentration simulated by SWB.

Salt (mg ℓ^{-1})	**Ca**	**Mg**	**Na**	**K**	**Cl**	**SO_4**	**TDS**
Irrigation water	481	268	47	0	38	1 921	2 755
Average leachate concentration	470	1082	191	1	153	4 233	6 131

GROUNDWATER IMPACT OF LARGE-SCALE IRRIGATION

The model for simulating the transport of groundwater and solutes (salts and other pollutants) is based on the finite element method as described by Pinder and Gray (1977). The first step in constructing such a model is the subdivision of the area to be modelled into elements where the characteristics are similar. Subdivision of an area is typically influenced by the surface geometry, such as topography and streams. The hydraulic characteristics of the underlying aquifer, and the current groundwater quality distribution are also considered in each subdivision.

Prediction of water movement across an area in question requires solution of several sets of equations. These are the interpolation of groundwater levels across the whole of the area using Bayesian interpolation, and the solution of the groundwater flow equation (a second order partial differential equation) for the whole of the area. This determines groundwater gradients, seepage velocity and the response of the aquifer due to external influences such as pumpage and recharge from irrigation and rainfall.

The governing equation may be written as:

$$T\left(\frac{\partial^2 h}{\partial x^2}\right) + T\left(\frac{\partial^2 h}{\partial y^2}\right) + T\left(\frac{\partial^2 h}{\partial z^2}\right) = S\frac{\partial h}{\partial t} - Q$$

where

S	=	Storage coefficient
$\frac{\partial h}{\partial t}$	=	Change in hydraulic head with time ($m\ d^{-1}$)
T	=	Transmissivity ($m^2\ d^{-1}$)
$\left(\frac{\partial^2 h}{\partial x^2}\right), \left(\frac{\partial^2 h}{\partial y^2}\right), \left(\frac{\partial^2 h}{\partial z^2}\right)$	=	Flux directions
Q	=	Abstraction/Recharge ($m^3\ d^{-1}$)

This equation describes the three-dimensional flow of groundwater through the substrata, calculating the water-table response. The equation may be solved analytically for simple problems, though for the pivot systems analysed in this study, piece-wise approximation of the equation is obtained through the finite element method, because of the complexity of the problem.

Once the water-level distribution is available over the whole of the area, seepage velocity and directions are calculated, using the following equation:

$$v = \frac{k\left(\frac{\partial h}{\partial l}\right)}{n}$$

where

v	=	Seepage velocity ($m\ d^{-1}$)
k	=	Hydraulic conductivity ($m\ d^{-1}$)
n	=	Effective porosity (%)
$\frac{\partial h}{\partial l}$	=	Groundwater gradient ($m\ m^{-1}$)

On the basis of the hydraulic gradients and flow velocities, movement of solutes through the aquifer may then be calculated. The mass transport equation in its one-dimensional form is:

$$D_x\left(\frac{\partial^2 c}{\partial x^2}\right) - V_x\left(\frac{\partial c}{\partial x}\right) = R\left(\frac{\partial c}{\partial t}\right)$$

where

D_x	=	Dispersion coefficient in the x-direction (m^2 d^{-1})
$\frac{\partial^2 c}{\partial x^2}$	=	Flux direction
V_x	=	Seepage velocity (m^{-1})
$\frac{\partial c}{\partial x}$	=	Change in concentration with distance
R	=	Retardation coefficient
$\frac{\partial c}{\partial t}$	=	Change in concentration with time (decay)

This equation may be expanded into two or three dimensions, depending on requirements. It is clear from the above that coupling of the mass transport equation with the flow equation becomes rather complex under real field conditions, because of the additional variables present. The dispersive properties of the soil and aquifer, degree of convection in these systems, as well as chemical reactions that take place must be known before the mass transport equation can be applied successfully.

Certain simplifying assumptions may be made with respect to this specific simulation without jeopardising the value of the model. An example of this is the vertical dimension in the equations may be eliminated. Most of the flow takes place within the weathered upper 10 – 15 m. Laterally, the aquifer extends over several kilometres, up to the nearest streams and beyond. The vertical dimension is therefore very small in comparison to the lateral dimensions. The time for the solute to travel vertically into the aquifer is therefore negligibly small in comparison to the time for the solute to disperse regionally. Elimination of the vertical dimension has little effect on the arrival time for the solute at some distant point relative to its source. Elimination of the vertical dimension from the simulation considerably reduces the complexity and computational effort. Another assumption is that for modelling purposes, chemical constituents may be grouped into various categories, depending on their reactivity, attenuation and decay properties.

Variables and constraints that affect the movement of solutes through an aquifer are typically:

- The transmissivity and hydraulic conductivity of the underlying strata.
- The storativity and effective porosity of the underlying strata.
- The hydraulic gradient, dispersion and convection characteristics of the aquifer.
- Boundaries such as dolerite dykes, catchment and surface.
- Other sources of water in the area such as streams, pans, dams and lakes.
- Sinks within the area where groundwater is abstracted or naturally emanates on surface in the form of streams or fountains.

The transmissivity and hydraulic conductivity of the underlying strata will influence the movement of solutes. While no pumping tests have been performed at the pivot sites, the borehole logs indicate low-yielding characteristics for the aquifer. Records show that the average blowout yield is in the order of 0.5 l s^{-1}, which translates into a hydraulic conductivity of 0.2–0.01 m d^{-1}, with an average value of 0.1 m d^{-1}.

The movement of solutes will also be influenced by the storativity and effective porosity of the underlying strata. The storage coefficient of aquifers in the Witbank/Highveld Coalfields has been determined using pumping test methods, and an average value of 10^{-3} can be assumed for the fractured aquifer. The reason for this relatively low storativity value lies in the fact that only a small proportion of the pores and fractures in the fresh aquifer partake in water flow. In the upper, weathered aquifer the effective porosity is an order of magnitude higher, and a value of 10^{-2} can be achieved. This higher value is due to the fact that almost all the calcium that normally binds the sedimentary grains together has been leached from this horizon. Water can therefore permeate through the weathered matrix.

As the regional water-table gradient, dispersion and convection characteristics of the aquifer will also directly influence the movement of solutes, measurement of static water levels in the monitoring boreholes is necessary for the determination of the regional water-table gradient. Since the regional water-table gradient within the area is controlled by the surface topography, the latter may be used as a controlling factor in a Bayesian estimation model to infer groundwater levels in areas where monitoring boreholes are not available. This provides a well-defined distribution of water tables, which, in turn, is essential for calculating groundwater flow directions and velocities.

Groundwater boundaries exist in various forms in nature and have to be accounted for in models. Typical boundaries are dolerite dykes and sills, which may act as impermeable barriers in the transverse direction or as conductive zones along intrusive contacts. Close to the surface, dolerite weathers and water permeates easily through it. Other boundaries are, for instance, catchment boundaries, where a change in the direction of the water-table gradient may occur. Surface boundaries, above which the groundwater level cannot rise without decanting, should also be considered. Boundaries of these types can be accommodated in flow and mass transport models, with the prerequisite that knowledge about these boundaries must be available for the areas in question.

Points where water is taken from the system, such as boreholes, drains or fountains, are referred to as sinks. The finite element model to be used in this exercise can accommodate sinks at any position in the model, and the effect of water abstraction or water loss at these points can be simulated. This facility may be used to predict the response of a solute plume during groundwater abstraction. Currently, there are no users of groundwater in the areas that could impact on the movement of solutes through the aquifer.

One of the sub-areas where water will decant from the underground collieries is west of the town of Witbank. It is anticipated that 20 Ml/d will be available at this point.

By way of demonstrating the potential impact that irrigating with such a large volume of water will have on the geohydrology of the area, 16 pivots (40 ha each) (Figure 1) have been accommodated in a finite element model for the area. The idea is that irrigation will tap water from the mines underlying the pivots. In some instances, liming of the mine water would be required to raise the pH of the water to acceptable levels.

Input data used in these particular simulations are summarised as follows:

Quality of deep drainage	6 000 mg/l TDS; 4 000 mg/l SO_4
Attenuation	zero
Aquifer transmissivity	10 m^2 d^{-1}
Storage coefficient for the weathered strata	0.20
Recharge from rainfall (outside irrigated area)	3%
Annual rainfall	740 mm
Simulation time	Steady state

Surface contours are shown in Figure 1 and the simulated steady state sulphate plume for the specific pivot arrangement in Figure 2. Units on the X and Y axes of these maps are in metres.

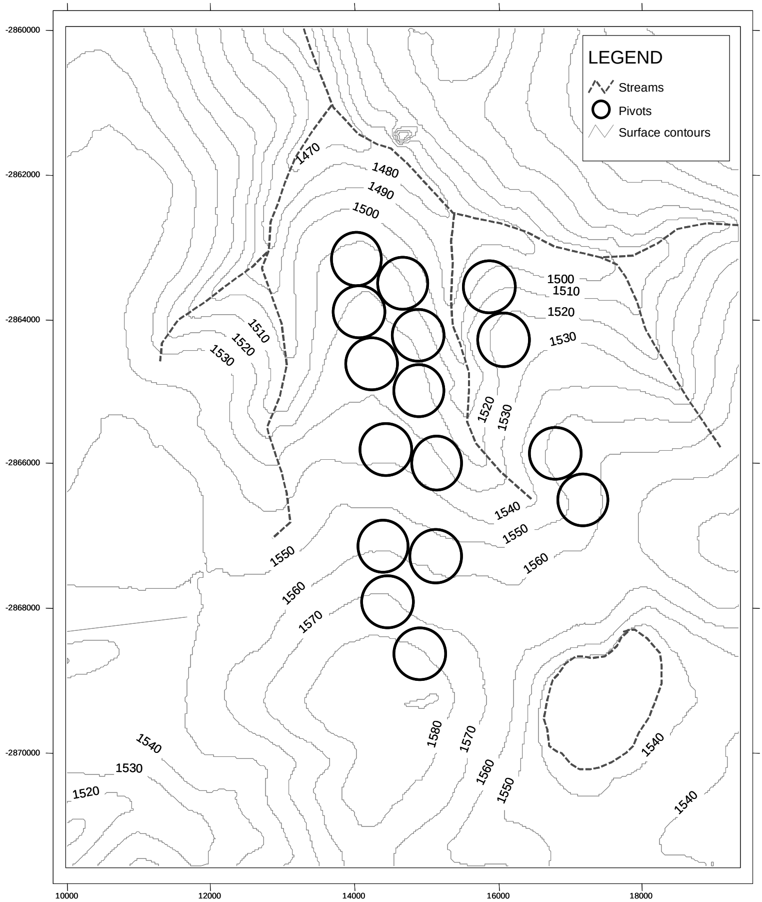

Figure 1. Pivot arrangement and surface contours for the area that has been modelled.

Figure 2. Simulated sulphate concentrations as percentages of the original sulphate concentrations at the pivots.

As seen in Figure 1, groundwater (and associated salts) fed by deep drainage from the pivots will dominantly migrate to the north, exiting in the streams that flow to the north. Salts carried with the water from the pivots should mainly be limited to the weathered strata. In instances where the deep drainage from irrigation passes into deeper layers, this will flow back into the mines that underlie the pivots. In most field situations bivalent ions migrate more slowly than monovalent ions, and significant retardation of the salt migration could be expected. The data in Figure 2 for sulphate demonstrates the worst-case scenario, without retardation. The simulations also showed that groundwater is intercepted at a rate of just over 2Ml d^{-1} by the streams in the north, and that salt accumulation in the groundwaters in the south and southwest is limited through dilution by rainfall.

It is important to note that 2Ml d^{-1} is the maximum volume of deep drainage water that could flow through this specific aquifer for the indicated pivot configuration. The SWB simulations, however, showed that the deep drainage from the irrigated sites was in the order of 4.9 Ml d^{-1}. This would result in areas becoming waterlogged and the irrigation scheme would fail in the long term. A potential solution to this problem would be to rearrange the pivots in a longer N-S transect, if suitable soils were available, to increase the area to the east and west through which the excess recharge could be transmitted. Another solution would be to reduce the recharge emanating from the field by increasing the irrigated area and reducing the irrigation application on an aerial basis. First indications from the modelling exercise are that such an irrigation configuration could be viable because of the limited aerial extent of the sulphate plume and the interception of the plume that is possible in the streams.

CONCLUSIONS

Results of this study suggest that irrigating large areas with gypsum rich waste-water could be feasible and sustainable if careful attention is paid to the specificity of each situation. It is also clear, however, that large errors can be made in designing such irrigation schemes if the amount of deep drainage leaving the root zone, the storage capacity between the base of the root zone and the underlying aquifer systems, and the hydraulic characteristics of the aquifers are not properly matched. Irrigation in excess of what the landscape can cope with will lead to rising water tables and in time water logging and salinisation of the rootzone, and ultimately failure of the irrigation scheme. In order to improve on the analyses and results presented in this paper it is essential that soil water balance and groundwater models are coupled in a way that includes the feedback needed between them to more accurately describe the system we are trying to manage.

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