IS IRRIGATION WITH COAL-MINE WATER SUSTAINABLE?

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ABSTRACT

The sustainability of irrigation with mine water was investigated on sites that offer a range of soils, crops, water qualities and weather conditions in the Republic of South Africa. Results indicate that neutralized acid mine drainage can be used successfully for irrigation of a large variety of crops. Gypsiferous waters do not seem to have any deleterious effects on the soil environment as gypsum precipitates in the soil and salt is removed from the water environment. Sodium rich mine waters are less suited to irrigation, as soil physical problems can arise that need to be managed, and there is limited opportunity for gypsum precipitation. Management of plant nutrition is important when irrigating with mine waters, and it is essential to take into account the ions that are being added with the water. Groundwater monitoring indicates that salt plumes below irrigated fields are probably attenuated by the vadoze zone, and also by rainfall recharge to the water table that dilutes salt concentrations still further. Interception of drainage from irrigation, however, is possible if sites are selected carefully. This is especially true when irrigating rehabilitated land overlying mine spoils, enabling the reuse and isolation of drainage waters. This study highlights that there are four considerations to managing irrigation with saline water, namely: the quality of the irrigation water; the hydrological setting of the irrigated area; the management of the leaching fraction, and the fate of the drainage water. When social aspects like job creation, especially after mine closure, are considered, we conclude that irrigation with certain mine waters, on carefully selected and managed sites, could be a cost effective component of a long-term mine and catchment water management strategy. However, it is crucial that mines institute long term monitoring strategies that involve other interest groups in the catchment, to ensure that any environmental impact remains acceptable.

1. IMPACTS OF MINING, MINE WATER MANAGEMENT AND IRRIGATION

South Africa's coal industry is the second biggest mining sector after gold. Mining impacts upon the natural water environment, and its effect may be manifest throughout the life cycle of the mine, and even long after mine closure. According to Younger et al. (2004), the potential impacts of mining on the water environment are a) disruption of hydrological pathways, b) seepage of contaminated leachate into aquifers, c) disposal of saline mine water into rivers, and d) depression of the water table around the dewatered zone.

The impacts of mining arising from the disruption of hydrological pathways, seepage of contaminated leachate into aquifers and depression of the water table tend to be relatively localised and limited compared to disposal of mine water (Younger et al., 2004). Disposal of mine water is a worldwide problem, occurring wherever operating mines, both underground and opencast workings are found (Pulles et al., 1995). The quality of the mine water depends largely on the chemical properties of the geological materials that come into contact with it (Thompson, 1980). Salts in solution usually cause such waters to be unsuited to direct discharge into river systems.

Management options for saline mine water in South Africa are discussed in detail by Pulles (2006) and are summarized as (1) pollution prevention at source, (2) reuse and recycling of water to minimize the volume of polluted water that could also be treated, (3) treatment of effluents should be implemented if the problem cannot be solved through prevention, reuse and recycling, and (4) discharge of treated effluent, which is considered the last resort. Pulles (2006) also reports the potential for utilizing gypsiferous mine-water for irrigation as a water reuse strategy, especially in the post-closure phase.

Coal-mines in South Africa have adopted these water management strategies; however, some have excessive volumes of water, and not all of it can easily be taken care of following these four hierarchical management options (Gunther, 2006). Treatment of these excessive volumes of mine waters will minimize pollution of water resources. However, this needs complex technologies with associated high costs to bring the water quality to a condition acceptable for release into natural watercourses. Interest has been growing in finding ways to limit the production of contaminated mine-water and to find more cost-effective treatment solutions.

In the early 80s, the potential to use gypsiferous mine-water for irrigation of field crops was first evaluated in South Africa by Du Plessis (1983), using the steady-state chemical equilibrium model of Oster & Rhoades, (1975). Du Plessis (1983) predicted the amount of salt that would leach, and could potentially contaminate groundwater, and found that irrigating with gypsum rich water would result in lower soil and percolate salinity compared to irrigation using 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 gypsiferous mine-water for irrigation (Du Plessis, 1983).

The potential use of mine water for agricultural crops was then tested in a series of field trials from 1993-2007 (Jovanovic et al., 1998; Annandale et al., 1999; Annandale et al., 2001; Annandale et al., 2002; Beletse, 2004; Annandale et al., 2006; Annandale et al., 2007; Beletse et al., 2008). The complexity of the studies required a multidisciplinary approach, including agronomists, soil scientists, hydrologists and engineers. The objective of this paper is, therefore, to present the results of these investigations, and to highlight successes and limitations with respect to environmental impact and sustainable use of such waters for irrigation of agricultural crops.

2. COMPOSITION OF COAL MINE WATER

Coal-mine water is usually saline, and typically dominated by calcium sulphate ($CaSO_4$), sodium sulphate (Na_2SO_4), magnesium sulphate ($MgSO_4$) or sodium bicarbonate ($NaHCO_3$). The compositions of saline mine waters tested for agricultural crop production in three provinces of South Africa (Annandale et al., 2007) are presented in Table 1. These water chemistries reflect typical coal-mine waters in South Africa. The Kromdraai water is a lime treated Acid Mine Drainage (AMD) and is dominated by large amounts of calcium (Ca) and sulphate (SO_4). Water qualities for Kleinkopjé (Major) and Kleinkopjé (Tweefontein) are dominated by Ca, magnesium (Mg) and SO_4. New Vaal water is a relatively good quality water not dominated by any particular salt. Syferfontein water is dominated by sodium (Na) and SO_4. Finally, water from the Waterberg area is rich in $NaHCO_3$.

Analyses (mg ℓ^{-1})	Mpumalanga Province				Free State Province	Limpopo Province
	Kromdraai	Kleinkopjé (Major)	Kleinkopjé (Tweefontein)	Syferfontein	New Vaal	Waterberg
Al	-	0.3	0.01	0.1	-	-
Ca	287	513	405	32	93	25.8
Mg	19	158	196	88	31	10
K	11	-	-	16	5	17
Na	6.5	51	47	796	132	2023
Fe	-	0.3	0.08	0.1	0.32	0.99
Mn	-	6	0.01	0.03	0.08	0.3
SO_4	998	2027	1464	1647	430	418
Cl	3	18	32	17.8	42	287
HCO_3	10	143	68	443	242	4712
TDS	1341	2917	2212	2435	1120	5125
pH	6	6.4	7.0	9.2	7.5	7.8
EC(mSm^{-1})	200	294	205	372	132	750

3. AVAILABILITY OF MINE WATER

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), which is one of the biggest Coalfields in the country. Grobbelaar et al. (2004) indicate that 360 Mℓ d^{-1} may be generated after closure of the entire Mpumalanga Coalfields. 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 decant position ranges between 12 and 40 Mℓ d^{-1}. These decant volumes have the potential to support in excess of 6 000 ha of irrigation in the Olifants Catchment alone. On a site-specific scale, Kleinkopjé Colliery (Witbank, Mpumalanga) for instance, has 12 x 10^6 Mℓ of water stored underground, and it is estimated from pumping and water level data that the daily water make is in the order of 14 Mℓ d^{-1} (Grobbelaar et al., 2004). This is sufficient to sustain an irrigated system of some 500 to 700 ha, depending on the particular cropping system chosen (Jovanovic et al., 2002). If the proposed Waterberg Coal Bed Methane (CBM) operation (Waterberg Coalfields, Limpopo Province) is found to be feasible and commissioned, a total volume of 2 million Mℓ of mine water will be generated per year, and this will continue for 30 years (Beletse et al., 2008).

4. IRRIGATION WITH LIME TREATED ACID MINE DRAINAGE (AMD)

The use of saline mine water for irrigation of agricultural crops has been tested for the last 20 years in South Africa in several phases. During the period between 1993 and 1996 a wide range of crop and pasture species were screened for tolerance to irrigation with lime-treated AMD at Landau Colliery (Witbank). Higher crop yields were obtained under sprinkler irrigation with treated mine-water compared to dryland production, without any foliar injury to the crop. Possible nutritional problems, for example deficiencies of potassium (K), Mg and nitrate (NO_3), occurring due to Ca and SO_4 dominating the system, can be solved through fertilisation. Soil salinity increased compared to the beginning of the trial, but the values of soil saturated electrical conductivity stabilised at relatively low levels, due to gypsum precipitation. The commercial production of several centre pivot irrigated crops with mine-water has also been tested in field trials at Kleinkopjé Colliery (Witbank) since 1997, at Syferfontein (Secunda), and New Vaal Colliery (Vereeniging) since 2001. The irrigation trial at Waterberg Coal Bed Methane pilot project (Lephalale) was carried out under drip and sprinkler irrigation systems between 2005 and 2006 (Beletse et al., 2008). A description of these irrigation trials with different irrigation water qualities, soils and weather conditions, follows.

5. IRRIGATION WITH $CASO_4$ AND $MGSO_4$ WATER

Crops like sugar-beans, wheat, maize and potatoes were very successfully produced under irrigation with $CaSO_4$ and $MgSO_4$ rich mine-water. Land preparation and fertilization management are, however, critical for successful crop production, especially on rehabilitated soil. In the short to medium term (eight years) irrigation with gypsiferous mine-water had a negligible impact on groundwater quality. 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. The major problem experienced was waterlogging due to poor site selection, especially during the summer months, when control over the soil water regime is difficult due to rainfall. The problem is not related to the chemistry of the water used for irrigation, as it was observed that crop performance was good in well-drained areas of the fields.

Clearly recognizable leaf symptoms associated with specific nutritional disorders were not observed. It therefore seems that one can produce crops using gypsiferous mine water without experiencing major plant nutritional problems, but it is essential to take into account what ions are being added to the soil in the irrigation water.

A seasonal fluctuation in soil salinity was observed due to rainfall in the summer season with dry winters. In the summer, low soil salinities were maintained because the salt load is lower (less irrigation) and the opportunity for flushing salts out of the root zone higher than in winter. Measurements taken between 1997 and 2007 showed that soil salinity increased from a low base and oscillated around 250 mS m^{-1}, as was modelled by Annandale et al. (1999) a decade earlier.

Gypsum precipitation was also shown to be taking place in the soil. The presence of gypsum did not create any physical and/or chemical property changes which could adversely affect crop production and soil management. Soils irrigated with such gypsiferous mine water might suffer from K or Mg deficiencies as Ca dominate the exchange complex. K and Mg levels on the adsorption complex of the soil should be monitored to prevent its deficiency and the application of potassium containing fertilizers is necessary on gypsiferous mine water irrigated soils. Such soils need to be managed and fertilized differently to those on which crops are produced under normal farming conditions. Crop production under irrigation with coal-mine water rich in Ca, Mg and SO_4 is therefore feasible, and sustainable if properly managed.

6. IRRIGATION WITH NA_2SO_4 WATER

Pasture production with Na_2SO_4 rich mine effluent is also feasible, at least in the short term (three years), but requires a well-drained profile and a large leaching fraction to prevent unsustainable build up of salt in the soil. Unfortunately, the waters do not present much of an opportunity for gypsum precipitation, which is able to drastically reduce the salt load of the receiving waters in the case of Ca and SO_4 rich mine waters. The application of $Ca(NO_3)_2$ as a nitrogen source to the crop adds Ca to the soil and removes some SO_4 from the water system by enhancing gypsum precipitation.

The effect of the Na_2SO_4 rich irrigation water on forage quality of the planted pastures (Fescue and Lucerne/alfalfa) was negligible for the growing period. However, Eragrostis and Kikuyu quality declined compared to fresh water irrigated pastures (Beletse, 2004). This could possibly be due to the uptake of considerable amounts of Na from the soil solution that may have inhibited the enzymatic processes of the plant.

The effect of Na_2SO_4 rich mine water on the soil chemical properties was also evaluated. Salts accumulated at 0.4-0.6 m depths, which indicate leaching from the soil surface. An increase in salt was generally observed during the growing period, and fluctuated with rainfall and dry spells. EC_e of the soil decreased after heavy rainfall, and average EC_e was not above the threshold level that could restrict crop growth for Fescue. A high exchangeable sodium percentage (ESP) was observed in the upper few centimetres of the soil and fluctuated during the growing period. Measurement of the hydraulic conductivity of the soil is recommended to monitor the effect of the water on the infiltration rate of the soil, as high Na levels are likely to cause deflocculation or dispersion of clay particles (Beletse, 2004).

7. IRRIGATION WITH $NAHCO_3$ WATER

The highly concentrated $NaHCO_3$ water from the deep aquifer of the Waterberg is of very poor quality for irrigation. Salt tolerant crops such as barley, Italian ryegrass, cotton and Bermuda grass, however, can be grown with very skilful irrigation and crop management. Crop production under sprinkler irrigation clearly showed that barley, Italian ryegrass and Bermuda grass were able to grow without leaf burn and toxicity problems. However, cotton foliage was scorched due to the high levels of Na in the irrigation water. It is recommended that with water of this quality, irrigation systems that apply water directly to the soil surface would be preferable. This is especially prudent if one also considers the likely mechanical impact of sprinkler irrigation on surface crusting and on salt accumulation.

The effect of $NaHCO_3$ rich water on soil chemical and physical properties was also evaluated. EC_e reached a maximum around 800 mS m^{-1} in the winter season, which could limit yields even of salt tolerant crops. In the summer experiment, however, the accumulation of salts in the root zone was far lower than the threshold tolerance level due to the high summer rainfall. The high sodium adsorption ratio of the irrigation water increased ESP values in the soil and led to severe clay dispersion in the winter season. The application of gypsum and organic matter to the soil, however, minimized the negative effects of the irrigation water on infiltration. The high irrigation frequency was also essential to keep the salinity stress as low as possible by keeping the soil wet and the soil solution as dilute as possible.

Special attention should be given to potassium and nitrogen fertilization for crops irrigated with such waters, as the recommended high irrigation frequency and leaching fraction can leach these nutrients below the root zone.

8. MODELLING

Knowledge of the chemical composition of a coal-mine water is necessary, but not on its own sufficient to evaluate its suitability for irrigation. Other factors such as climate, soil properties, drainage condition and irrigation method should also be considered when making this evaluation. To consider site-specific irrigation water quality effects on crop production and soil quality, the Soil Water Balance (SWB) model was developed (Annandale et al., 1999). SWB is a generic crop growth, soil water and salt balance model that has been used to estimate the long-term impact of several coal-mine water qualities on a number of soils and crops, under different climatic conditions for various irrigation management scenarios (Annandale et al., 2007).

Annandale et al. (1999), used SWB to predict the soil water and salt balance of lime treated acid mine water irrigated crops. The predictions of crop growth, soil water content and soil solution EC_e for single season simulations gave good agreement with observed data. Annandale et al. (2001) also used SWB to predict the long-term affect of gypsiferous mine water on crop production and soil chemical properties. Similarly, the model was also used to determine the long-term impact of $NaHCO_3$ and Na_2SO_4 rich mine water on crop production and soil properties (Beletse et al., 2008; Beletse, 2004).

9. POSSIBLE IMPACT OF MINE WATER IRRIGATION ON WATER RESOURCES

Once the research results had shown that the impact of irrigating crops and soils with gypsiferous mine water was both minimal and manageable, the focus of the research shifted to evaluate the possible impact of irrigation on groundwater quality. Boreholes drilled inside or in close proximity to irrigated fields have shown very little salt moving through the soil profile in the short term (2-8 years). According to Vermeulen et al. (2008), the salts are attenuated by different mechanisms between the soil surface and the shallow aquifers, often by clay layers. This monitoring is on a localised scale and cannot be extrapolated to unequivocally determine larger-scale irrigation impacts. Thus, Annandale et al. (2006) investigated the impact of large-scale irrigation with gypsiferous mine water on groundwater resources in South Africa. Results of their study suggested that irrigating large areas with gypsum-rich coal-mine water could be feasible and sustainable if careful attention is paid to the specificity of each situation. They concluded that irrigation with gypsiferous mine water, if properly managed, could seriously be considered as part of the solution towards the challenge of managing the considerable volumes of coal-mine water available during mining and post closure. Annandale et al. (2007) also reported 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. Percolation from irrigation in excess of what the underlying aquifers can transmit from the site, will lead to rising water tables, and over time, water logging and salinization of the root zone. This would necessitate the installation of expensive drainage systems and appropriate disposal of the drainage waters, or ultimately, result in the failure of the irrigation scheme.

10. CONCLUSIONS AND RECOMMENDATIONS

Research conducted over two decades, has indicated that neutralized AMD can be used with great success for the irrigation of a large variety of crops. Because of the gypsiferous nature of these waters, gypsum is precipitated in the soil and salt is therefore removed from the water environment. These waters also do not seem to have major deleterious effects on the soil environment. However, sodium rich mine waters are less suited to irrigation, as soil physical problems can arise and need to be managed. Plant nutritional management is important when irrigating with mine waters, and it is essential to take into account all the ions that are being added with the water. Salt plumes below irrigated fields can be attenuated by the unsaturated zone between the base of the root zone and top of the water table, and rainfall may dilute salt concentrations still further. Interception of drainage from irrigated fields is possible if sites are selected carefully. This is especially true when irrigating over rehabilitated mine spoils, enabling the reuse and isolation of drainage waters. We argue that there are four components to managing irrigation with saline water, namely: The quality of the irrigation water; the hydrological setting of the irrigated area; management of the leaching fraction; and fate of the drainage water. Normally, water quality and hydrological setting are fixed for a given irrigated area, and these constrain the management of leaching and, therefore, the fate of drainage water. In the case of mine water irrigation, this is not necessarily so. We can decide to irrigate with certain mine waters and not with others. We can, for example, neutralize otherwise toxic AMD and use the treated water to irrigate crops for economic gain. Our hydrological setting is also somewhat flexible, especially as we are dealing with relatively small areas, often less than 1000 ha per mine. We can choose, for example, if we are to irrigate over spoil or not, and can select the site carefully so that percolation can be intercepted, reused and isolated. Isolated water can be stored on site, or considered for controlled release or further treatment. Finally, once the water quality and hydrological setting are fixed, an appropriate irrigation management programme can be recommended. When social aspects like job creation, especially after mine closure, are considered, we conclude that irrigation with certain mine waters, on carefully selected and managed sites, could provide a sustainable long-term solution to dealing with excess mine-water after closure, and supporting water management strategies, in mining impacted catchments. However, it is crucial that long term monitoring strategies around such irrigation areas be put in place to provide early warning for unforeseen events from mine water use. This will allow implementation of adaptive management strategies to ensure that any environmental impact remains acceptable.

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12. REFERENCES

Annandale, J.G., Jovanovic, N.Z., Benade, N. and Tanner, P.D. (1999) "Modelling the long-term effect of irrigation with gypsiferous water on soil and water resources." Agric. Ecosys. and the Environ, 76, 109-119.

Annandale, J.G., Jovanovic, N.Z., Claassens, A.S., Benadé, N., Lorentz, S.A., Johnston MA, Tanner P.D., Aken M.E. and Hodgson, F.D.I. (2001) "The influence of irrigation with gypsiferous mine water on soil properties and drainage water." Water Research Commission Report No. K5/858, Pretoria, South Africa.

Annandale, J.G., Jovanovic, N.Z., Tanner, P.D., Benade, N. and Du Plessis, H.M. (2002) "The sustainability of irrigation with gypsiferous mine-water and implications for the mining industry in South Africa." Mine Water and the Environ, 21, 81-90.

Annandale, J.G., Jovanovic, N.Z., Hodgson, F.D.I., Usher, B., Aken, M.E., Van Der Westhuizen, A.M., Bristow, K.L. and Steyn, J.M. (2006) Prediction of the environmental impact and sustainability of large-scale irrigation with gypsiferous mine-water on groundwater resources. Water SA, 32 (1), 21-28.

Annandale, J.G., Beletse, Y.G., De Jager, P.C., Jovanovic, N.Z., Steyn, J.M., Benadé, N., Lorentz, S.A., Hodgson, F.D.I., Usher, B., Vermeulen, P.D. and Aken, M.E. (2007) "Predicting the environmental impact and sustainability of irrigation with coal-mine water." Water Research Commission Report No. 1149/01/07, Pretoria, South Africa.

Beletse, Y.G. (2004) "Modelling the soil water and salt balance of planted pastures irrigated with sodium sulphate rich mine effluent." MSc dissertation, Dept. of Plant Production & Soil Science, University of Pretoria.

Beletse Y.G., J.G., Annandale, J.M. Steyn, I. Hall and Aken, M.E. (2008) "Can crops be irrigated with sodium bicarbonate rich CBM deep aquifer water? I. Theoretical and field evaluation." J. Ecolog. Eng, 33, 26-36

Du Plessis, H.M. (1983) "Using lime treated acid mine water for irrigation." Wat. Sci. Techl, 15, 145-154.

Grobbelaar, R., Usher, B., Cruywagen, L.M., DE Necker, E. and Hodgson, F.D.I. (2004) "Long-term impact of intermine flow from collieries in the Mpumalanga area." Water Research Commission Report No. 1056/1/04, Pretoria, South Africa.

Gunther, P. (2006) "Emalahleni mine water reclamation project. In: WISA, mine water division (ed.). Mine water drainage-South African perspective, 19-20 October 2006." Water Institute southern Africa, Johannesburg, South Africa.

Jovanovic, N.Z., Barnard, R.O., Rethman, N.F.G. and Annandale, J.G. (1998) "Crops can be irrigated with lime-treated acid mine drainage." Water SA, 24(2), 113-122.

Jovanovic, N.Z., J.G., Annandale, A.M. van der Westhuizen and Steyn, J.M. (2002) "Monitoring the soil water and salt balance under irrigation with gypsiferous mine wastewater." Surface Mining 2002-Modern Development for the New Millennium. ISBN 1-919783-40-7, South African Institute of Mining and Metallurgy.

Oster J.D. and Rhoades, J.D. (1975) "Calculated drainage water composition and salt burdens resulting from irrigation with river waters in the Western United States." J. Environ. Qual. 4, 73-79.

Pulles, W. (2006) "Management options for mine water drainage in South Africa." In: WISA, mine water division (ed.). Mine water drainage-South African perspective,19-20 October 2006. Water Institute southern Africa, Johannesburg,

South Africa.
Pulles, W., Howie, D., Otto, D. and Easton, J. (1995) “A manual on mine water treatment and management in South Africa.” Water Research Commission Report No. TT 80/96, Pretoria, South Africa.
Thompson, J.G. (1980) “Acid mine waters in South Africa and their amelioration.” Water S, 6, 130-134.
Vermeulen, P.D., Usher B.H. and G.J. Van Tonder (2008) “Determining of the impact of coal mine water irrigation on groundwater resources.” Water Research Commission Report No. 1507/1/08, Pretoria, South Africa.
Younger, P.L. and Wolkersdorfer, C. (2004) “Mining impacts on the fresh water environments: Technical and managerial guidelines for catchment scale management.” Mine Water and the Environ, 23, S2-S80.