Approach for Assessing the Feasibility of Large-Scale Irrigation with Mining-Influenced Waters and Key Considerations for Implementation in the Witwatersrand Goldfields

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Abstract

An interdisciplinary study was conducted to investigate the agronomic, economic, and environmental aspects of regional-scale, long-term irrigation with mining-influenced waters in the Witwatersrand Goldfields and identify key considerations for locating and establishing such schemes, using the Eastern Basin (EB) of the goldfields as a case study. Modelling assessments indicated that irrigation with HDS-treated mine water can be productive, with <2% yield decline predicted, and profitable, with gross margin in excess of R20 000/ha for the selected cropping system. While irrigation with mine waters is expected to have some impacts on ground and surface water, groundwater modelling suggests that this practice can be sustained in the medium- to long-term with minimal environmental impacts. The key considerations for the successful implementation of large-scale mine water irrigation schemes were identified as water quality and balances, crop selection, total irrigation area, management of excess mine water, infrastructure, land availability and ownership, water costing, and the siting of irrigation schemes. The approach developed in this study can be codified into a framework for conducting feasibility assessments and providing guidance for the implementation of regional-scale mine water irrigation schemes.

Keywords: Irrigation, economics, hydrogeology, agriculture, modelling

Introduction

Mine water management is a major challenge in South Africa, particularly in the Witwatersrand Goldfields, where it is a taxpayer liability. In this region, the cessation of mining activities led to flooding of underground workings as pumping ceased. Due to the lack of mine closure regulations, many of these mines were abandoned without rehabilitation, and the management of mining-influenced water emanating from them became the state's responsibility.

Currently, up to 185 million litres per day (ML/day) of mining-influenced water are pumped and treated at three high-density sludge (HDS) plants commissioned in the Eastern, Central and Western Basins. Although HDS treatment is effective in reducing acidity and lowering the concentrations of some trace elements of concern, dissolved solute concentrations remain high. Given that the treated mine water is then released to nearby surface water courses, this results in an increased salt load to the Vaal River System (VRS), making this approach unsustainable in the long term. Therefore, long-term management strategies are sought.

Reverse Osmosis is the preferred technology for long-term management of the mining-influenced waters for regulatory compliance, as it produces potable water. However, this technology is expensive, energy-intensive and produces brine that needs to be managed. Irrigation has been proposed as a potentially cost-effective alternative option that can make productive use of these otherwise problematic waters. Additionally, having alternative irrigation water sources will improve agricultural productivity. This is especially important in catchments where irrigation has previously been curtailed, such as the VRS, and where water supply is often prioritised for other uses (DWS, 2016).

Previous studies have demonstrated successful irrigation with mine waters in the Coalfields, and the feasibility of irrigation as a mine water management strategy in the Witwatersrand Goldfields has been explored (Annandale *et al.* 2001, 2021; Jovanovic *et al.* 1998; Annandale *et al.* 2023). However, the implications of establishing large-scale mine water irrigation in the Witwatersrand goldfields are not well understood. This study aimed to assess the feasibility of regional-scale mine water irrigation in the Witwatersrand Goldfields of South Africa and identify key considerations for locating and establishing such schemes. Three key research components were identified as necessary to address these uncertainties, and these required an interdisciplinary approach. These components were agronomic, hydrogeological, and economic.

Assessment approach

An interdisciplinary study was conducted to investigate the agronomic, economic, and environmental aspects of long-term irrigation with mining-influenced waters from the Witwatersrand Goldfields, using the Eastern Basin as a model site. The research team consisted of agronomists, agricultural economists and hydrogeologists.

The agronomic component of the study aimed to demonstrate the productivity and evaluate the sustainability of mine water irrigation, and the main responsible team was the University of Pretoria, made up of agronomists. The hydrogeological component aimed to assess the impact of mine water irrigation on groundwater and receiving surface water bodies, providing an indication of potential environmental impacts. The team responsible for this component was Delta H, made up of hydrogeologists. The economic component aimed to investigate the economic aspects of mine water irrigation, providing an indication of costs and benefits. The main team responsible for this component was the Bureau for Food and Agricultural Policy (BFAP), composed of agricultural economists.

A phased approach was used to undertake the study, with outputs from the three teams at different phases used as inputs to subsequent phases in a feedback loop process, making the assessments iterative.

Site selection

Previous studies indicated that the Eastern Basin(EB) presented the greatest opportunity in the Goldfields for successful irrigation with mining-influenced waters. Of the three basins, the water quality in this Basin was most suitable for irrigation, and it has the greatest pumping and treatment capacity, up to 110 ML/day, compared to 70 ML/day in the Central Basin and 45 ML/day in the Western Basin (Annandale *et al.* 2023; TCTA 2017). Additionally, the treatment plant in this basin is in close proximity to prime agricultural land.

Delineation of "No-go" areas

"No-go" areas were identified as areas where irrigation return flows would be conveyed towards a river course within one year, as well as areas underlain by dolomite. These areas were delineated by the hydrogeologists by performing backward calculations of transport times to surface water drainage structures using a regional-scale single-layer numerical groundwater model. Delineation of the no-go areas also considered aquifer vulnerability, as prescribed by Parsons and Conrad (1998).

Cropping system selection

Cropping system selection required input from agronomists and entailed shortlisting more than 200 potential crops to 21 suitable for the Highveld, based on the agricultural economist's knowledge and experience. Thereafter, the shortlisted crops underwent an elimination process based on their risk profile, considering susceptibility to theft, fire, animal/bird damage, and damage due to production practices. All crops identified as high risk for these factors were eliminated, and the remaining crops were scored based on their socioeconomic inclusiveness and risk profile.

The factors contributing to socioeconomic inclusiveness were the labour multiplier and contribution to dietary diversity. The risk indicators remained the same. Scores of 1 to 3 were assigned to each indicator, with 3 indicating the highest positive score (e.g., low fire risk is assigned a score of 3, and a high contribution to dietary diversity is also assigned a score of 3). These scores were averaged to produce a combined score, and the crop ranking was assigned accordingly.

Following several iterations of the process and consultation with local farmers, maize (Zea mays), oats (Avena sativa), sweet sorghum (Sorghum bicolor), canola and soybean were selected for more detailed assessments. One objective was to maximise water use, which was addressed by selecting a double-cropping system with winter and summer crops.

Modelling scenarios

Two main scenarios were modelled, based on the area required to maximise the use of available water, either using summer or winter crop irrigation requirements to determine the total area. It was determined that a large cropping area would generally be required for the summer crop, as rainfall accounts for most of the crop's water requirements, with less irrigation needed. In contrast, irrigation requirements will increase in winter due to lower or no rainfall, requiring a smaller cropping area to utilise the available water. It was assumed that centre-pivot irrigation systems would be used.

Scenario 1, the Maximum Water Use scenario, aims to maximize water use by adding supplemental summer season irrigation, assuming that 6000 ha would be established based on summer crop requirements, while a smaller area of 2400 ha could be irrigated in winter with the available water. With this scenario, 3600 ha of monocropped maize is irrigated in summer, referred to as the "summer-only area", and 2400 ha is irrigated in both summer and winter, referred to as the "summer-winter" area. Scenario 2, the Minimum Water Use scenario, entails more intensive year-round irrigation and uses less water. This scenario assumes that 2400 ha, based on winter crop requirements, with the summer-irrigated area smaller than that required to maximise water use during the wet season. Although this scenario might have low irrigation system capital costs, it will require the management of excess mine waters in the summer season, and this may have indirect environmental impacts.

In addition to these cropping system scenarios, the potential spatial distribution of irrigation pivots (concentrated vs dispersed) was also simulated. It was expected that concentrated pivots would have a more pronounced environmental impact than the dispersed pivots. Furthermore, in the case where the minimum Area is established for irrigation, there would be some cost implications for the conveyance infrastructure as more extensive pipelines would be required if the pivots are dispersed than if they are concentrated. However, costs associated with conveyance infrastructure was not assessed in this study.

Siting of Irrigation Areas

The siting of irrigation areas was confined to a 30 km radius of the Eastern Basin treatment plant. The total available agricultural area within the region, the potential costs of establishing the infrastructure required to convey the mining-influenced water, potential receptors of return flows, and typical agricultural practices in the region were taken into account. The area required for the two scenarios, Maximum and Minimum Area, determined by the agronomists, was used as a spatial limit by the agricultural economists, who fit centre pivots within existing dryland fields using spatial and statistical algorithms, while excluding the "no-go" areas delineated by the hydrogeologists.

Agronomic modelling

The IrrigWQ Decision Support System (DSS), developed by du Plessis *et al.* (2023), was used to model long-term irrigation with mine water from this basin, providing yield, as well as solute and water balance predictions. IrrigWQ DSS is a site-specific, risk-based software tool for assessing irrigation water quality. The software uses a simplified version of the dynamic soil water balance (SWB) model to calculate soil-crop-water interactions and includes a simplified chemical equilibrium model to simulate precipitation reactions.

Worst-case water quality for the Eastern Basin mining-influenced waters was used as input to simulate irrigation over a 45-year period. An irrigation system efficiency of 80% was assumed. Irrigation was triggered when the model detected a root-zone deficit exceeding 20 mm relative to field capacity, with irrigation applied to field capacity. Therefore, any leaching would occur due to the summer rainfall, and not through purposeful over-irrigation for salt management. A representative weather station with 50 years of daily temperature and precipitation data, located close to the basin, was selected. A summary of the water quality data used in the agronomic modelling is presented in Table 1.

It was assumed that the trace elements present in the water would generally not be mobile and would therefore be less likely to migrate into groundwater than the major cations and anions presented in Table 1. The outputs from this exercise were used to determine the irrigation return flows and the concentrations of cations and anions expected to leach to groundwater. These were then used as inputs for the hydrogeological modelling.

Economic modelling

A whole-farm model was built in FINSIM to simulate the financial performance of an existing farm intensified with a mine-water-irrigated cropping system. A typical farm owned in the Eastern Basin was assumed to cultivate 450 ha of dryland cash crops (maize and soybean. The farm was then intensified by reallocating 120 ha to a mine-water-irrigated cropping system, with the remaining 330 ha allocated to dryland cash crops.

The model accounted for revenue, direct costs, overhead costs, assets/liabilities and asset replacement costs. Revenue was calculated using 2023 crop prices and yield estimates, which accounted for modelled reductions in yield due to salinity in the irrigation water. It was assumed that the farmer does not pay for the CAPEX investment in the water infrastructure required to convey water from the water treatment plant to the farm's point-of-supply, that farmers could access water on demand, and that no storage would be required.

Hydrogeological Modelling

A numerical finite-element 3D groundwater flow model was developed using the SPRING software code from Delta h Ingenieurgesellschaft mbH, Germany (König, 2011). Model simulations assumed no retardation due to sorption, cation exchange, or any microbiological degradation in the subsurface. The simulated plumes, therefore, represent a conservative worst-case scenario for pollutant transport.

No background concentrations were assumed in the model simulations to predict and visualise the net effect of the irrigation return flows on the ambient groundwater quality. The model was run with a weekly timestep over 50 years, and simulated return-flow concentration plumes were mapped across the study area. A unit (100%) source concentration (return-flow concentration) and drainage (return flow) were used as determined by the agronomic modelling.

Table 1 *Average quantities of major constituents in Eastern Basin (EB) mine water. Concentrations are in mg/L, acidity as mg/L CaCO3 eq., EC in mS/m and pH without units.*

pH	EC	Ca	Mg	K	Na	SO42-	Cl	TDS	Acidity
7.81	257	321	97	13	188	1254	110	2314	9

Results and discussion

Suitability of mine waters for sustained irrigation

The agronomic modelling provided outputs on site-specific effects of mine water on relative crop yield, which were also used as inputs for the economic modelling. It was predicted that the mine water would be suitable for sustained irrigation of all assessed cropping systems, with little to no yield reductions due to water quality, except for the maize in the maize-oats double-cropping system. However, the yield reductions were less than 2% compared with irrigation with good-quality water. Yield estimates provided by the agricultural economists, based on typical yields in the area, were 12 t/ha for good-quality water, 11.8 t/ha for maize irrigated with EB mine water, and 8.3 t/ha for dryland maize. The yield reductions were considered negligible, particularly compared with dryland maize, which is expected to yield substantially less.

Impact of mine water irrigation on groundwater and receiving surface water

The hydrogeological model used drainage volumes from the agronomic modelling as irrigation return flows recharging the aquifer, as well as the solutes predicted to leach from return flows, to predict return flow plume concentrations over time. Return flow plumes were modelled for 110 pivots in the Minimum Water Use Scenario (2400 ha) and 273 pivots in the Maximum Area Scenario (6000 ha). Table 2 presents an example of the output results showing plume concentrations for a single pivot and is not representative of the entire output data set. It should also be noted that the model simulations assume no retardation due to, e.g. sorption, cation exchange, or any microbiological degradation in the subsurface. The simulated plumes, therefore, represent a conservative worst-case scenario for pollutant transport.

Considering the conservative (no retardation or transformation; i.e., worst-case) scenario, it was predicted that irrigation with EB mine water would increase groundwater solute concentrations over time. Plumes were also predicted to migrate up to 1km from the source; however, source concentrations that migrated that far were generally low and similar to those presented in Table 2 as source plume concentrations after 10 years. It was predicted that plumes of concentrated pivots would generally migrate further and increase in concentration faster than those of dispersed pivots, due to the convergence of plumes from nearby pivots.

It is predicted that, in all scenarios, return flow plumes will begin reaching surface water courses after 10 years of irrigation. However, this will occur within less than 5% of the plumes. After 50 years of irrigation, the proportion of plumes that reach surface water courses increases up to 43% in the Maximum Mine Water Use scenario and up to 65% in the Minimum Mine Water Use scenario when pivots are sited in a concentrated configuration.

Assuming a worst-case scenario where the receiving water body has no assimilative capacity and return flow fluxes to the surface

***Table 2** Modelled return flow plume concentrations (in mg/L) at the source after 10 and 50 years of irrigation for the most conservative scenario.*

Solute	Plume concentration at the source after 10 years	Plume concentration at the source after 50 years
Calcium as Ca	34–68	270–304
Chloride as Cl	31–63	250–282
Potassium as K	4–7	30–33
Magnesium as Mg	32–64	255–287
Sodium as Na	52–105	420–472
Sulphate as SO4	238–476	1904–2142
Total solutes	391–783	3130–3521

water bodies are similar to return flow fluxes to the saturated zone, the amount of solutes expected to migrate to surface water courses was estimated using the proportion of plumes expected to reach surface water after 50 years of irrigation. It was predicted that the Maximum Mine Water Use scenario would contribute an estimated 80 t/day of solutes to surface water courses, and irrigating 2400 ha would contribute an estimated 33 t/day, which is substantially less than the estimated 254 t/day currently being discharged with HDS-treated water.

Location and distribution of irrigated areas were identified as key factors in ensuring the sustainability of this practice and ensuring impacts remain acceptable.

Economic aspects of mine water irrigation

The economic assessments provided outputs on the profitability and cost of establishing an irrigation system at the farm level. The economic assessments indicated that irrigation with Eastern Basin mine water is economically viable and can be profitable, with an average gross margin in excess of R20 000/ha predicted for the maize-oats cropping system over the 8-year modelling period (Table 3). The Maximum Mine Water Use scenario was predicted to be less profitable than the Minimum Mine Water Use scenario due to a smaller area being planted in winter, resulting in insufficient additional income to cover the extra cost of repaying the irrigation investment. The cost of irrigation water that farmers pay is expected to play a significant role in determining its feasibility for crop production.

Conclusion

This interdisciplinary study successfully developed an approach that provided insights into the agronomic, economic, and environmental aspects of large-scale, long-term irrigation with mining-influenced waters and identified key factors to consider when implementing such schemes.

In the Eastern Basin, the mine water is expected to be suitable for sustained irrigation, provided water quality does not deteriorate over time and a suitable cropping system is selected. Some environmental impacts, particularly the transport of solutes to ground and surface water, are expected. However, it is important to determine whether these impacts are acceptable, which will depend on the type of water use (e.g., drinking, agricultural, industrial) and the baseline conditions before irrigation commences, which will require site-specific assessments. The magnitude and extent of the impacts were found to be strongly influenced by the distribution of pivots and the total irrigated area, both of which are influenced by water use. Mine water irrigation is expected to be profitable; however, its economic sustainability depends on water cost management, optimised cropping strategies, and long-term investment perspectives

The key factors to be considered for the large-scale establishment of mine water irrigation schemes were water quality and use, crop selection, total irrigation area, management of excess mine water, infrastructure, land availability and ownership, water costing, and the siting of irrigation schemes. It is evident that the successful roll-out of mine water irrigation at a regional scale requires careful planning based on in-depth, site-specific assessments, as well as adaptive management. This study developed an approach to assess the feasibility of large-scale mine water irrigation and to identify key considerations for implementing such schemes, which can be developed into a mine water irrigation feasibility assessment and implementation framework.

Table 3 *Predicted 8-year gross margins of dryland and mine water irrigated crops in rands per hectare (R/ha).*

System		2023	2024	2025	2026	2027	2028	2029	2030
Maize	Dryland	12500	13800	11600	13200	12400	12600	11900	12500
Soybeans		14500	10000	9400	9200	9400	9600	10500	10700
Maize	Irrigated	12700	16000	11500	13600	12300	12400	11300	12000
Oats		10500	12400	8700	10200	9200	9000	8000	8300

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