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TECHNICAL ARTICLE

Irrigation Should be Explored as a Sustainable Management Solution to the Acid Mine Drainage Legacy of the Witwatersrand Goldfields

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Abstract
Mine closure in the Witwatersrand Goldfields of South Africa has resulted in an acid mine drainage (AMD) legacy that is difficult to manage and costly to address. As a short-term measure, three large high-density sludge (HDS) plants were erected that treat 185 megalitres of AMD per day (ML/day), at great cost to taxpayers. Longer-term solutions are sought, as the salt load to the Vaal River System is unacceptable. Long-term modelling was used to assess whether the untreated and HDS-treated AMD could be used for irrigation and to determine the scale of the potential opportunity. The Goldfields waters are not very acidic, and simulations indicate it should be feasible to utilise even the untreated water for irrigation, especially if growers commit to applying limestone to their fields. HDS treatment lowers the corrosivity and trace element concentrations, and because the water is gypsiferous, double cropping will precipitate more than a third of the salts in solution as gypsum in the soil profile, thereby reducing salt load to the water environment. The potential irrigated area depends on the cropping system; it is about 9000 ha for rotational cropping and 30,000 ha for supplemental maize irrigation. It is prudent to seriously consider irrigation as a potential long-term water management option for the Goldfields AMD.

Keywords Water quality · Crop production · Soil quality · Fitness-for-use

Introduction

Many deep underground mines in the Witwatersrand Goldfields of South Africa closed in the late 1990s and early 2000s. As a result, water began to accumulate in the mine workings and acid mine drainage (AMD) was generated (Coetzee et al. 2010). Often when mines close, active pumping and water treatment ceases, resulting in flooding and eventual decant with potentially serious downstream consequences. Such a decant risk was identified for all of the Witwatersrand Goldfields, which is divided into the Eastern, Central, and Western Basins. When mine water decanted from the Western Basin in 2002 and spilled into a nearby nature reserve, a sense of urgency was created, which culminated in a Report to the Inter-ministerial Committee on Acid Mine Drainage prepared by a team of experts (Coetzee et al. 2010).

One of the major concerns highlighted by the then Department of Water Affairs and Forestry (DWAF) regarding mine water from the Witwatersrand Goldfields was the salt load to Vaal River System. Previous studies conducted on behalf of the DWAF indicated that the AMD discharge was responsible for 13% of the total salt load in the Vaal Barrage (a point in the Vaal River downstream of most of the mining activity) and that the discharged AMD had the highest average salinity compared to the other contributors (DWAF (Department of Water Affairs and Forestry) 2009). This, together with the risk of flooding infrastructure, motivated the introduction of the so called "short-term solution", which involved the setting of conservative "Environmental Critical Levels," above which void water would not be allowed to rise in order to protect the environment and infrastructure. In addition, high density sludge (HDS) water treatment plants were built in the Eastern Basin (80 megalitres of AMD per day, ML/day), Central Basin (72 ML/day), and Western Basin (33 ML/day) (DWA (Department of Water Affairs) 2010) to neutralize these waters and reduce trace element concentrations. Figure 1 shows the location of the Witwatersrand Goldfields, the river system, the HDS

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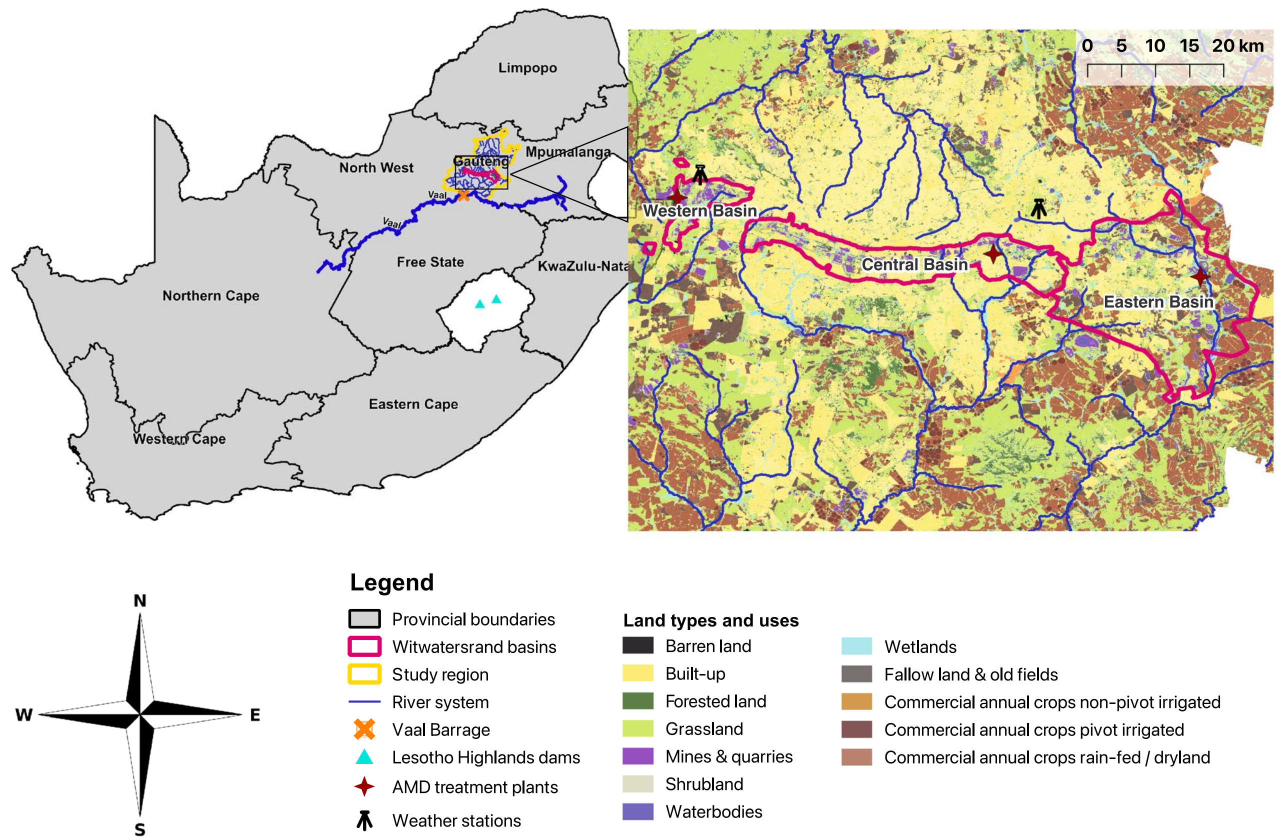

Fig. 1 Map of the Witwatersrand Goldfields showing the river system, the HDS plants and land types in the region

treatment plants, the Lesotho Highlands Dams, weather stations, and the land types in the region.

HDS is a relatively affordable water treatment option that addresses the acidity of water and reduces trace element levels. However, the salt load to the Vaal River System when this treated water is discharged is still unacceptable, and longer-term solutions are sought. Target salinities of 600 mg/L have proven difficult to meet, and if the area experiences low rainfall periods, the unsustainable release of expensive Lesotho Highlands water will be required to dilute the salinity (DWA (Department of Water Affairs) 2010; Rand Water Board 2021). This could lead to a surplus of water in the lower catchment, where it is not needed, and a deficit upstream (DWA (Department of Water Affairs) 2010).

Reverse osmosis (RO) was proposed as the preferred technology for the "long-term solution", as it is a proven technology that has been successfully demonstrated. In this way, the AMD would be used beneficially, and its salt load would not be discharged to the Vaal River. However, RO has high capital and running costs and is energy intensive. Due to the prevalence of abandoned and ownerless mines, this is a taxpayer liability, and so this option has been deemed unaffordable, and alternatives are sought. In the Witwatersrand Basins, the volume of AMD treated by HDS (185 ML/day) is relatively small compared to the volume (4000 ML/day) supplied by the local water utility, Rand Water (Rand Water Board 2021) to Gauteng, the province in which the Goldfields are located; therefore, treating this mine-affected water to potable standards with RO will not make a big contribution to the fresh water supply. Apart from the high cost of RO treatment, there may also be resistance to domestic consumption of purified mine-water.

However, as long as this water is not going to be used for domestic purposes, using the water for irrigation seems a reasonable strategy. Experience with commercial-scale irrigation in the Mpumalanga Coalfields of South Africa over a period of 20 years has demonstrated the feasibility of using gypsiferous mine waters for irrigation (Annandale et al. 2001, 2021; Jovanovic et al. 1998). Irrigation with these calcium- and sulphate-rich waters has also been shown to remove quite large fractions of the salt applied to fields from the water due to the precipitation of gypsum within the soil (Annandale et al. 1999, 2006; Jovanovic et al. 2002). The precipitation of gypsum in the soil profile is not deleterious, and the feasibility of using the Witwatersrand Basins water for irrigation to reduce salt load to the Vaal River is an attractive proposition (du Plessis 1983; Jovanovic et al.

2002; Toma et al. 1999). In addition to creating livelihoods, irrigation could be a cost-effective way to manage this relatively poor-quality water.

A number of concerns arose when irrigation with mine water was suggested as a potential long-term option to deal with the mine water from the Witwatersrand Goldfields. These were:

- Are these waters suitable for sustained irrigation and will the produce be safe to consume?
- What would be the environmental impact?
- Is sufficient irrigable land available in the built-up Witwatersrand region, and will it be possible to convey mine waters to them?
- Will farmers be willing to irrigate with these waters?
- What are the costs/benefits of this option, and
- Will irrigation with mine water be permitted?

This paper attempts to respond to these concerns, with some aspects covered in more detail than others.

Methods

Water Quality

Data for untreated and treated mine-influenced waters from the goldfields was supplied by the Department of Water and Sanitation (DWS) (Personal communication, Mr. Bashan Govender and Mr. Divan van Niekerk). This data was collated to determine the 95th percentile of constituent concentrations, and the 5^{th} percentile for pH, in order to provide a "worst-case" assessment of the suitability of these waters for irrigation. These water qualities are given in Table 1. Since the water quality data originates from random sampling events, the reported 95^{th} percentile values of the individual constituents of the AMD and HDS-treated water pairs do not always follow a logical pattern, and will for example, not necessarily exhibit a tight charge balance between anions and cations. The calcium values of the HDS-treated waters of the Eastern Basin are, for example, less than those of the AMD waters. However, the aim was to undertake an initial assessment, using conservative assumptions, of the potential of these waters for irrigation, so such discrepancies are unlikely to affect the conclusions drawn at the end of this study.

Modelling and Analysis

A site-specific, risk-based irrigation water quality Decision Support System (DSS) developed by du Plessis et al. (2017) was used to determine if there are cropping systems for which these waters may be deemed suitable for irrigation in the Goldfields region. The DSS can be downloaded free of charge from https://www.wateradmin.co.za/sawqi.html.

Model Description

The DSS is able to assess the implications of irrigating with a range of waters, including mining-influenced waters, on soil and crop resources, as well as on irrigation equipment. This is done through the assessment of suitability indicators, with each divided into one of four fitness-for-use (FFU) classes, which are colour coded to make the output intuitive,

Table 1 Worst-case water qualities used to assess suitability for irrigation for the EB (Eastern Basin), CB (Central Basin), and WB (Western Basin)

Constituent	EB AMD	EB HDS	CB AMD	CB HDS	WB AMD	WB HDS
pH	6.2	7.2	5.8	8.4	5.8	8.6
EC mS/m	300	260	490	403	350	385
Ca, mg/L	370	340	517	668	520	650
Mg, mg/L	120	95	251	178	130	90
Na, mg/L	200	206	207	192	110	170
SO_4, mg/L	1600	1660	3760	2710	2200	2400
Cl, mg/L	120	120	96	97	80	85
HCO_3, mg/L	0.1	166	0.1	0.1	0.1	50
SAR, $(mmol/L)^{1/2}$	2.3	2.6	1.9	1.7	1.1	1.6
Fe, mg/L	100	0.2	610	0.13	120	1.3
Mn, mg/L	0.4	0.1	25	1.5	30	3.1
Al, mg/L	ND	ND	144	0.05	ND	ND
Ni, mg/L	ND	ND	ND	0.02	3	0.05
B, mg/L	ND	ND	ND	ND	1.3	1.6
F, mg/L	ND	ND	ND	ND	1.3	1.4
U, µg/L	ND	ND	ND	5	86	29

AMD untreated water, *HDS* treated water, *ND* no data and are presented as being ideal, acceptable, tolerable or unacceptable.

The DSS operates at two tiers. Tier 1 simulations only require water quality data; conservative assumptions are made to assess water quality fitness-for-irrigation. The soil–crop–water interactions are calculated using an idealised soil profile with four layers and the assumption that crops withdraw 40% of the water they require from the top layer, with the percentage of water withdrawn by crops decreasing by 10% for each lower layer (Rhoades 1982, as quoted by Pratt and Suarez 1990). The levels of constituents in the irrigation water were used to calculate the steady state (or equilibrium) concentrations of soluble constituents in each layer. A conservative 10% leaching fraction was assumed for the profile, with immediate percolation and leaching of salts in solution when the profile exceeds field capacity.

Tier 2 allows the user to select site-specific conditions and assess how implementing certain management options, like different crop selections or leaching fractions, changes the fitness-for-irrigation of a given water. A simplified version of the dynamic soil water balance (SWB) model is used to perform the Tier 2 calculations (Annandale et al. 1999, 2001, 2011; Singels et al. 2010). This includes a simplified chemical equilibrium model that simulates gypsum solution and precipitation reactions (Robbins 1991). Simulations are run for a minimum of 10 years, but typically 45 year simulations are performed to better assess risk and sustainability using long-term data from an appropriate user selectable weather station in close proximity to the irrigated area. The model output presents water and salt balances of the user-selected crop or crops and assesses the suitability of the irrigation source for their production. A flow chart that indicates the difference between the Tier 1 and Tier 2 simulations is presented in Fig. 2.

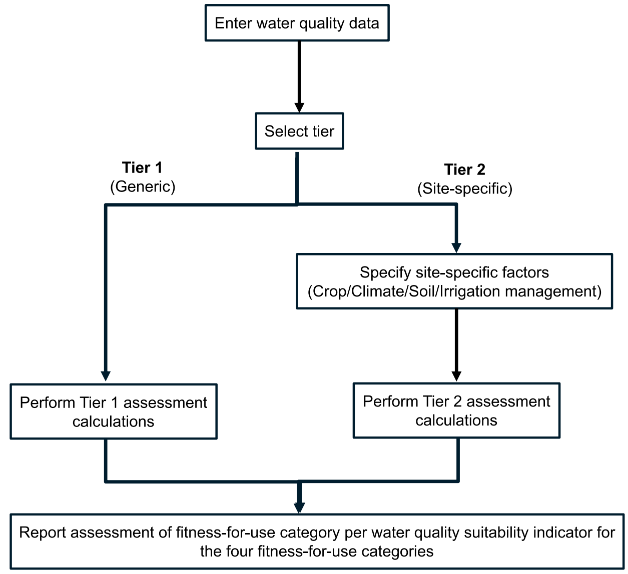

Fig. 2 Simplified schematic representation of Tier 1 and Tier 2 fitness-for-use simulations

Modelling Parameters

The DSS was used for several site-specific (Tier 2) 45-year simulations, using the worst-case water quality of the specific basins, both before and after treatment. A representative weather station with 50 years of daily temperatures and precipitation data close to each basin was selected. A summary of the weather data obtained from the selected weather stations is presented in Table 2.

A virtual sprinkler irrigation system was selected to simulate the wetting of foliage to assess expected leaf scorching. Irrigations were triggered when the model detected a root zone deficit to field capacity in excess of 30 mm, with the irrigation amount calculated to leave 10 mm of 'room for rain'. Therefore, any leaching would occur due to the summer rainfall, and not through purposeful over-irrigation for salt management. Maize mono-cropping in summer, or a crop rotation of soybean in summer and a small grain, like wheat or stooling rye, in winter were selected as cropping systems worth investigating. Crop selection for irrigation with poor quality water is critical, as crops vary greatly in their tolerance to salinity and other constituents in irrigation waters. The salt thresholds above which yields decline (measured as the electrical conductivity of a saturated soil extract – EC_e), and the rate at which the yield declines once the threshold is exceeded for the selected crops, are presented in Table 3 (Maas and Hoffman 1977).

Results and Discussion

Are the Waters Suitable for Irrigation and Will the Produce be Safe to Consume?

The suitability of the waters for irrigation were assessed using 45-year DSS simulations, and the results are summarised below, first by considering possible effects on soil quality, then on crop yield, and finally the potential effects on irrigation infrastructure. The food safety of crops irrigated with mine waters is also discussed.

Potential Effects on Soil Quality: Root Zone Salinity

Except for untreated Central Basin water, which is more saline than the water from the other two basins, root zone salinity is predicted to lie squarely in the ideal or acceptable suitability categories (Fig. 3). Although these treated and untreated waters contain fair amounts of Na and Cl

Table 2 Weather data summary from representative weather stations used in the simulations

Basin	EB and CB	WB
Weather station (WS)	Germiston-Rand Airport	Krugersdorp-West
Weather station coordinates	26.15° S, 28.25° E	26.10° S, 27.75° E
Weather station elevation (m)	1660	1743
Minimum temperature (°C)	– 1.8	– 4.4
Maximum temperature (°C)	34	33
Mean annual precipitation (mm)	692	682

EB Eastern Basin, *CB* Central Basin, *WB* Western Basin

Table 3 Salinity response of selected crops (after Maas and Hoffman 1977)

Crop	Threshold EC_e (mS/m)	Slope (% yield decline per 100 mS/m above threshold)
Maize	170	12
Soybean	500	20
Wheat	600	7.1

and a high total salt concentration (EC), they are primarily gypsiferous waters from which gypsum precipitation can be expected when irrigating to achieve a low leaching fraction. Gypsum precipitation will lower effective root zone salinity, so the negative effect of the high salt concentrations will be less pronounced than when irrigating with non-gypsiferous waters of similar salinities. The diluting effect of the relatively high summer rainfall in this area (about 700 mm per annum) also contributes greatly to the less pronounced effect of irrigation water salinity than would perhaps be expected. This is more important when considering the potential effect of salinity on the yields of the selected crops.

Potential Effects on Soil Quality: Soil Permeability (Surface Infiltrability and Soil Hydraulic Conductivity)

Soil infiltrability and permeability fitness for use categories are described quantitatively, expressing the expected impact as "none" (ideal), "slight" (acceptable), "moderate" (tolerable) or "severe" (unacceptable). HDS treatment did not affect the assessment, and the Western and Central Basins fell into the ideal or acceptable classes. The Eastern Basin Water, with higher SAR and lower EC, fell into the ideal or acceptable categories 70% of the time, with the remainder of predictions lying within the tolerable classification. By adopting appropriate management practices, it should be possible to overcome any soil physical problems.

Potential Effects on Soil Quality: Trace Element Accumulation

Several trace element concentrations were reported as below detection limits (BDL). In such cases, the detection limit was taken to conservatively assess the waters for irrigation. Where such trace elements come up in DSS simulations as potentially problematic, more careful analyses with lower detection limits are indicated. Specifically, for these simulations, Se and Hg were highlighted as elements that needed to be more carefully analysed to ascertain if

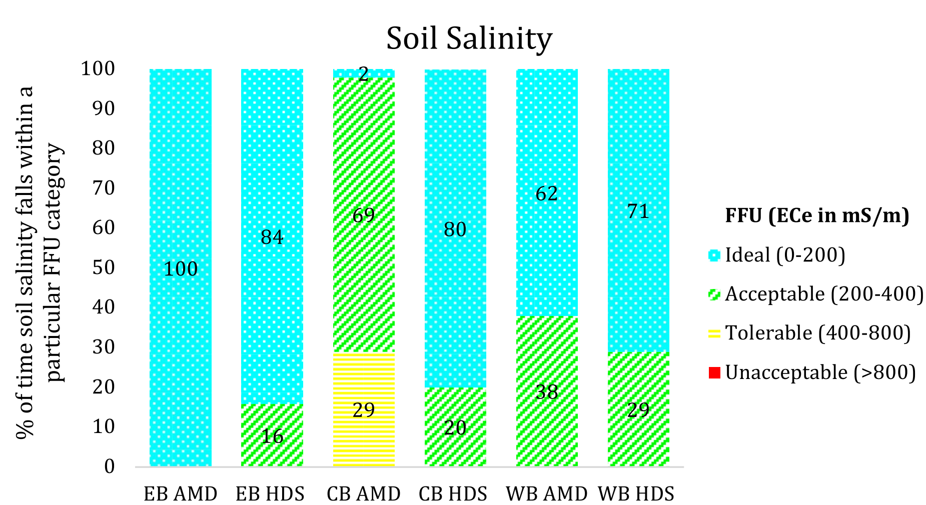

Fig. 3 Percentage of time (45 year simulation) that soil profile salinity falls within a particular fitness-for use (FFU) category. *EB* Eastern Basin, *CB* Central Basin, *WB* Western Basin, *AMD* untreated water, *HDS* treated water

these were indeed, of any concern. Of course, the DSS can make no pronouncements on element concentrations that are not reported, making detailed analyses essential for such assessments. Trace element load was calculated by multiplying cumulative irrigation with the applicable trace element concentration, and assuming no leaching of these elements with limited mobility from the top 0.15 m soil surface layer (du Plessis et al. 2017). The time taken to reach internationally published soil threshold levels is then calculated, and the fitness-for-use class, assigned (NAS-NAE (National Academy of Sciences-National Academy of Engineering) 1973). Table 4 presents DSS output for the trace elements of potential concern, before and after water treatment.

On face value, the concentrations of several trace elements in untreated waters will accumulate to unacceptable levels within an unacceptably short period of time. Treatment clearly addresses any concerns around Fe in all three basins, as well as Ni in the Central and Western Basins. Mn is still assessed to be potentially unacceptable after treatment of the Central and Western Basins water.

In view of the fact that Fe, Al, and Mn are naturally abundant in many soils, it is debateable to what extent their concentrations pose a real problem as far as trace element accumulation is concerned (Sposito 2008). When applied to soils, the Fe, Mn, and Al in solution are rapidly converted to relatively insoluble forms. Their concentrations in the soil solution can be managed by liming the soil and maintaining a suitable redox potential, conditions in any event essential for successful irrigated crop production. The high Fe and Mn concentrations can, however, also present problems with deposits forming on produce irrigated with overhead application systems (an aspect that is not assessed by the DSS).

Uranium is obviously an element of concern to the public and the Western Basin waters should be more carefully analysed to ascertain if levels are indeed problematic. If they are, potential solutions should be sought.

Table 4 Number of years, estimated from annual average accumulation rates, to reach international soil threshold levels of selected trace elements of potential concern

Element	EB AMD	EB HDS	CB AMD	CB HDS	WB AMD	WB HDS
Al	-	-	5	1000	-	-
Fe	7	1000	1	1000	5	463
Mn	65	261	17	17	1	8
F	-	-	-	-	185	172
Ni	-	-	-	1000	8	482
U	-	-	-	260	14	42

Colours indicate fitness-for-use (FFU) classes [red = unacceptable (< 100 years), green = acceptable (150–200 years) and blue = ideal (> 200 years)]

EB Eastern Basin, *CB* Central Basin, *WB* Western Basin, *AMD* untreated water, *HDS* treated water, – no water quality data was available

Potential Root Zone Effects on Crop Yield

There appears to be no material concern about salinity effects on yields of maize, soybean, and wheat using the waters from the Eastern and Western Basins, whether treated or not (Fig. 4). The Central Basin has the poorest water quality and so in summer, substantial yield depression, relative to that expected under non-saline conditions, is expected for maize when irrigating with untreated Central Basin mine water. This is even more evident in winter, even for the more salt-tolerant soybean crop rotated with wheat. Although wheat is quite salt tolerant, moderate yield loss is also expected in winter, when there is little-to-no rainfall to dilute salinity in the root zone. If the water is treated, none of these crops should show any meaningful yield depression due to salinity.

Food Safety

Mine waters often contain high concentrations of trace elements that are considered potentially hazardous. Naturally, this raises concerns about the safety of consuming crops irrigated with these waters. From a food safety perspective, only a few of the elements typically found in mine waters have been listed as being of concern in international guidelines. These include As, Cd, Pb, and Hg (Codex Committee on Contaminants in Food (CCCF) 2019). No data was available for these elements for the goldfields waters, but in a study assessing the food safety of maize irrigated with similar circumneutral mine water from a colliery in Mpumalanga, Annandale et al. (2021) found that the concentration of potential elements of concern were an order or two of magnitude below thresholds set in published food safety guidelines. Although certain grain crops have been found to accumulate certain trace elements in their roots and shoots, typically only a small fraction of these elements are translocated to the grain (Ahmad et al. 2019; Farahat et al. 2017; Kama et al. 2023; Yang et al. 2022). It can, therefore, be expected that many crops irrigated with gypsiferous mine waters will be safe for consumption. However, it is important that the specific elements of potential concern listed, as well as others like uranium in the Western Basin, be further assessed, with detection limits assumed if water analyses indicate any elements to be below the method detection limits.

Potential Problems with Irrigation Equipment: Corrosion and Scaling

The DSS makes use of the Langelier saturation index (LI) to predict potential corrosion of irrigation pumps, conveyance structures, and irrigation systems for unsaturated waters, and potential scaling of such infrastructure for

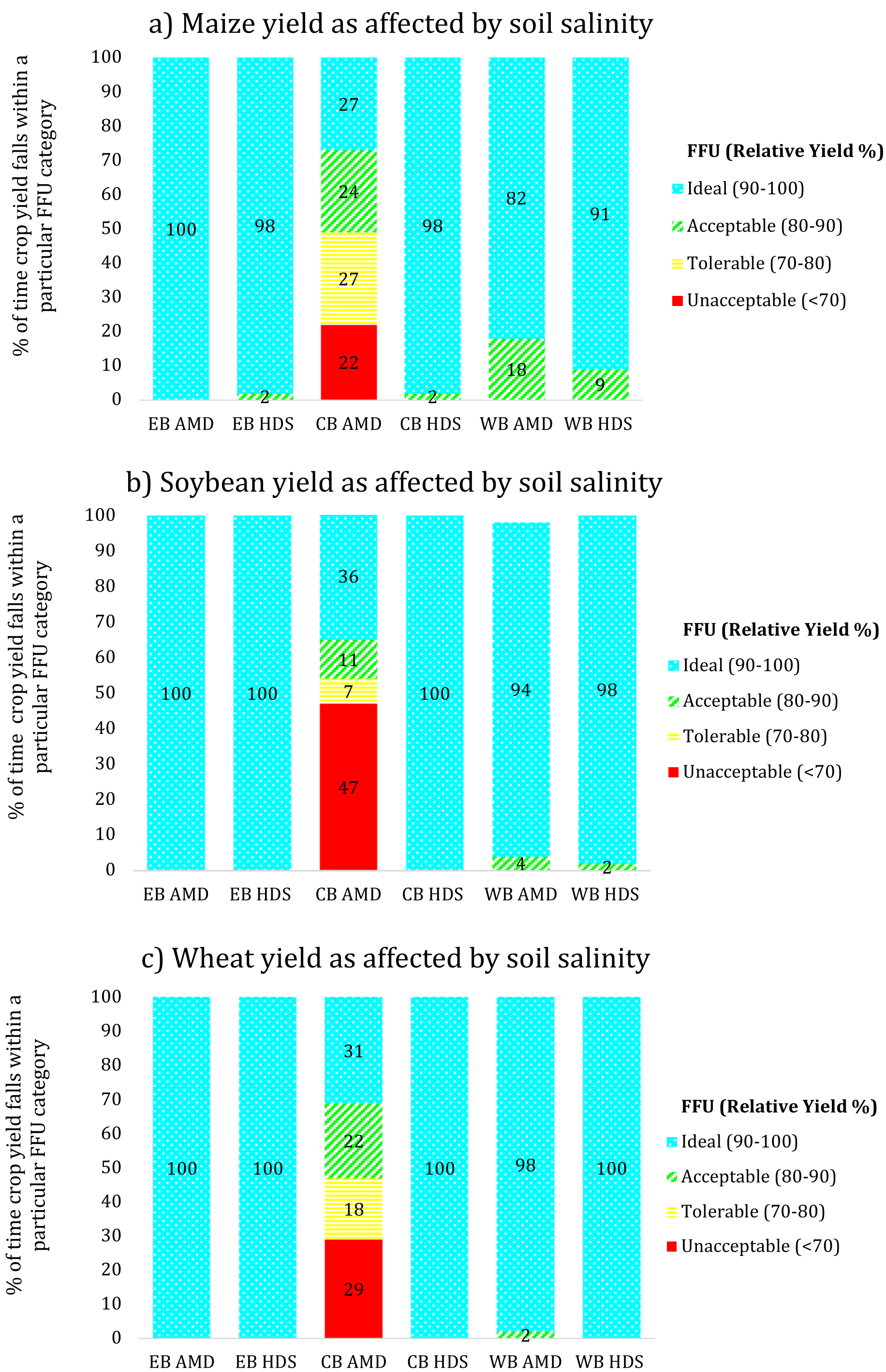

Fig. 4 Percentage of time **a** maize, **b** soybean and **c** wheat yield falls within a particular fitness-for use (FFU) relative yield category as affected by soil salinity. *EB* Eastern Basin, *CB* Central Basin, *WB* Western Basin, *AMD* untreated water, *HDS* treated water

oversaturated waters (Langelier 1936). All of the untreated waters are predicted to present an unacceptable level of corrosion, and this needs to be considered when selecting irrigation infrastructure materials if irrigation with untreated water is attempted. Treated Eastern Basin water is predicted to be ideal, treated Central Basin water presents a tolerable level of corrosiveness, and treated Western Basin water is predicted to cause scaling to a tolerable degree (Table 5). These potential problems need to be

Table 5 Corrosion or scaling potential of irrigation water as indicated by the Langelier index

Parameter	EB AMD	EB HDS	CB AMD	CB HDS	WB AMD	WB HDS
Langelier index (LI)	-3.9	0.24	-4.23	-1.51	-4.21	1.38
Corrosive or Scaling	Corrosive	Scaling	Corrosive	Corrosive	Corrosive	Scaling

Colours indicate fitness-for-use classes (FFU) [red = unacceptable (LI is > +2 or < −2), yellow = tolerable (LI is −1.0 to −2.0 or +1.0 to +2.0) and blue = ideal (LI is 0 to −0.5 or 0 to +0.5)]

EB Eastern Basin, *CB* Central Basin, *WB* Western Basin, *AMD* untreated water, *HDS* treated water further investigated and addressed during the planning of an irrigation scheme.

Potential Problems with Irrigation Equipment: Clogging of Micro-irrigation Emitters

Western Basin waters, whether treated or not, are predicted to present various challenges if used with drip irrigation. The Fe content of the untreated Eastern Basin water is expected to present clogging problems. Untreated Central Basin water has high levels of Fe and Mn that could cause problems with micro-irrigation systems; with treatment, the pH and to a lesser extent Mn would need to be considered (Table 6). These effects are of lesser or no importance if overhead sprinkler irrigation, rather than drip irrigation, is used.

Environmental Impact—The Fate of Solutes

The trace elements in these mine waters are generally not very mobile in soils, and therefore not of great concern, provided the soil accumulation thresholds are acceptable, as already discussed. The key environmental concern with mine water irrigation in the Goldfields is the salinization of the ground and surface water. Irrigation is a consumptive use of water, and with calcium- and sulphate-dominated mine waters, there is an opportunity to precipitate a large amount of gypsum in the soil profile, as root water uptake concentrates the soil solution. These precipitating salts are thus removed from the water system (du Plessis 1983). Should irrigation cease, these salts will be very slowly remobilised (over centuries to millennia, according to other similar simulations) and should therefore be of no concern. Gypsum is widely used in agriculture as a soil ameliorant and has been found to improve chemical and physical properties of acidic and sodic soils (Chen and Dick 2011; Ilyas et al. 1993; Toma et al. 1999). Gypsum precipitation is not harmful to the soil, and the capacity for such precipitation is not limited. Table 7 shows the predicted seasonal salt balances for the two cropping systems selected. The potential for gypsum precipitation varies depending on the cropping system and water composition. Gypsum precipitation is predicted to be greater when irrigating soybean and wheat in a double cropping system than when irrigating summer maize as a monocrop in the wet season. This is due to differences in the volumes of irrigation water applied, as well as in the amount of salts leached. The double cropping system requires more than 700 mm of irrigation, almost three times that required by the single cropping system (less than 250 mm), because the double cropping system also has a crop growing in the dry winter months, with little or no rainfall to supplement the irrigation or to leach salts. For a soybean-wheat rotation, it is predicted that between just over 30% and just under 60% of the salts applied to the fields through irrigation with Goldfields mine water will precipitate in the soil profile. For a single cropping system, such as maize, grown in the wet summer months, less than 10% of the salts are expected to precipitate when irrigating with Eastern Basin water, while 30–40% of the salts are expected to precipitate when irrigating with Western Basin water. In the case of the Central Basin for mono-cropped maize, just over 15% of the salt is expected to precipitate with untreated water and about 30% is expected to precipitate with treated water. It should be recalled that the above assessments were derived using the 95th percentile highest concentrations of the available

Table 6 Potential of an irrigation water constituent to cause clogging of drippers

Constituent	EB AMD	EB HDS	CB AMD	CB HDS	WB AMD	WB HDS
pH	6.2	7.2	5.8	8.4	5.8	8.6
Mn (mg/L)	0.4	0.1	1.5	1.5	30	3.1
Fe (mg/L)	100	0.2	610	0.1	120	1.3

Colours indicate fitness-for-use (FFU) classes [red = unacceptable (pH is > 8, Mn and Fe are > 1.5 mg/L), yellow = tolerable (pH is 7.5–8, Mn and Fe are 0.5–1.5 mg/L), green = acceptable (pH is 7–7.5, Mn is 0.1–0.5 mg/L and Fe is 0.2–0.5 mg/L) and blue = ideal (pH is < 7, Mn is < 0.1 mg/L and Fe is < 0.2 mg/L)]

EB Eastern Basin, *CB* Central Basin, *WB* Western Basin, *AMD* untreated water, *HDS* treated water

Table 7 Annual salt balance of soils irrigated with untreated and treated mine waters for different cropping systems

Water	Salts added		Gypsum precipitated				Salt leached	
	(t/ha)		(t/ha)		(% of salt added)		(t/ha)	
	Maize	Soy–wheat	Maize	Soy–wheat	Maize	Soy–wheat	Maize	Soy–wheat
EB AMD	5.3	18	0.5	8	9	42	4.8	11
EB HDS	5.7	20	0.3	7	5	35	5.0	12
CB AMD	11.0	37	1.9	12	17	32	8.9	25
CB HDS	8.5	30	2.8	15	33	51	5.8	14
WB AMD	7.4	25	2.3	13	31	51	5.2	12
WB HDS	8.3	28	3.3	16	40	58	5.0	12

EB Eastern Basin, *CB* Central Basin, *WB* Western Basin, *AMD* untreated water, *HDS* treated water

water analyses, so the crop yield response may in practice be better than predicted (actual salinity will be better than those assumed) and gypsum precipitation may be somewhat less (actual sulphate and calcium concentrations may be less than assumed).

Salts not precipitating must be leached from the root zone for irrigation to be sustainable and this leaching of salts from irrigated fields will likely be greatly aided by rainfall (Annandale et al. 2006). The ultimate fate of these salts will depend heavily on the irrigated field's position in the hydrologic landscape, but lags between irrigation application and the surfacing of salts in water bodies are likely to take decades or even longer (Annandale et al. 2006). As part of planning such an irrigation project, a geohydrological modelling exercise will be useful to site irrigated fields appropriately. It may also be possible to site fields so as to be able to intercept percolation for possible re-use or treatment, but the salt load in this water will be considerably less than that applied to fields through irrigation.

Availability of Irrigable Land, Conveyance of Waters, and Willingness of Farmers to Irrigate with Mine Water

Dryland farming is a risky business in South Africa, and profit margins are currently under pressure. It is expected from our experience with growers utilising mine water in the Mpumalanga Coalfields that commercial farmers would welcome the availability of mine water for irrigation, as long as there is surety of supply at low cost, reasonable crop yields are attainable, and their soils and ground and surface water resources will not be unacceptably affected. Irrigation should reduce their production risk substantially. The capital costs for irrigated farming are high but will be much less than alternative water treatment capital costs. Running costs for seasonal production are also high, but these can be borne by the growers who will be able to productively utilise these waters. In their study on irrigation with mine water from the coalfields, Annandale et al. (2021) predicted that a positive return on investment of at least R2.88 net present value (NPV) per m^3 of applied irrigation water can be realized for monocrop maize, and R2.22 NPV/m^3 for a maize-soybean-oats double cropping system, even when irrigating with water of very poor quality (an EC of 650 mS/m). The NPV increases significantly if the water is of similar quality to that in the Goldfields (EC of 350 mS/m). An NPV of R8.69/m^3 was predicted for monocrop maize and an NPV of R4.05/m^3 for a maize-soybean-oats double cropping system. This was compared to the expected cost of R26 per m^3 for water treatment to potable standards using HDS and reverse osmosis treatment (Annandale et al. 2021).

In addition, increased production will create much needed employment. Organised agriculture should be approached to gauge the interest of their members in such water sources. Table 8 indicates the predicted cropping system dependent areas required to use the mine waters emanating from the three basins.

There has been concern expressed over the availability of irrigable land near the mine water sources. A report by van der Laan et al. (2014) indicates that land is available, especially if the water is piped out of heavily built-up areas. If the water is conveyed to regions of lower elevation, it can be supplied to farmers under pressure, which will greatly reduce electricity costs to pump the water, making the irrigation option even more financially feasible and sustainable for growers. If the water is allowed to decant naturally, rather than being pumped from specific locations in close proximity to the treatment plants, this may result in several smaller streams of water that may be easier to use for irrigation, but detailed studies will be required to determine the opportunities and risks of this option.

Economic and Regulatory Aspects of Mine Water Irrigation

The Goldfields waters are not very acidic, and it appears feasible to utilise them untreated, except perhaps for the Central Basin, especially if growers commit to applying limestone to their fields. The HDS-treated waters are more suitable for irrigation than the untreated waters, but it is uncertain whether growers will be able to bear these pre-treatment costs, should this be required.

The cost to the taxpayer of the irrigation option will depend on whether water is pumped or allowed to decant, as well as the cost of any necessary conveyance infrastructure. In addition, the cost of current pre-treatment with the

Table 8 Long-term modelled seasonal irrigation water requirements and calculated irrigated areas required for two cropping systems in the three basins

Mine water	Eastern Basin		Central Basin		Western Basin	
	80 ML/day		72 ML/day		33 ML/day	
Cropping system	Maize	Soy–wheat	Maize	Soy–wheat	Maize	Soy–wheat
Irrigation (mm)	221	767	222	771	244	831
Area (ha)	13200	3800	11800	3400	4900	1500

Unlimited storage capacity for water during the periods in which no irrigation occurred was assumed

HDS process will remain if irrigation with untreated water is deemed undesirable. There will also be the cost of intercepting and treating the water percolating below the root-zone, if this is required.

Because there are so many potential irrigation options available, and their economic analyses are scale and cropping system dependent, detailed economic analyses of any specific proposed irrigation schemes would be essential. However, if the irrigated crop production system is set up to deliver yields close to those obtained with good quality water, an income should be generated from the mine water, instead of a treatment cost. The economic activity and job creation associated with the irrigation option will also be of great benefit to the country.

As far as regulatory requirements for mine water irrigation are concerned, Pocock and Coetzee (2021) indicate that although it is possible with the current regulatory framework to obtain approval to irrigate with mine water, the process is complex and cumbersome. To facilitate and streamline such approval processes, they have developed guidelines to assist both applicants and regulators (Pocock and Coetzee 2021).

Conclusions

With careful planning, irrigation with mine-influenced waters is an option worthy of serious consideration in the Goldfields of South Africa. The potential for job creation and productive use of these waters certainly make this an attractive option. Since these waters are gypsiferous in nature, irrigating a double cropping system with the worst-case water qualities assumed in this study presents the opportunity to precipitate, on average, at least a third of the salts in solution as gypsum in the soil profile, thereby reducing the salt load to ground and surface waters. It appears worthwhile, therefore, to attempt to address any potential concerns with using irrigation to manage these waters.

It is also clear that there are many technical considerations that require attention when setting up a mine water irrigation scheme. To assist with this process, Heuer et al. (2021) developed guidelines for site selection, evaluation of water quality, and selection of cropping systems as well as the identification of potential constituents of concern, with recommendations for the establishment of monitoring requirements and thresholds for action.

Regulatory guidelines are also available to assist with the establishment of such irrigation schemes (Pocock and Coetzee 2021). It will be essential to intensively monitor and control such large scale mine water irrigation schemes, both to ensure that off-site impacts are acceptable and that such schemes are not used as disposal mechanisms for surplus mine waters, particularly during times of excessive rainfall. Assessments made here rely on the accuracy of the water quality data supplied. It is imperative that decisions are made based on reliable data.

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Data availability This is a modelling study, and all the input data required to run the simulations discussed in this paper are given (water qualities, cropping systems, irrigation strategy, local weather stations in close proximity to water sources). In addition, a link is given to download the DSS free of charge, so any interested reader can recreate the output data generated by the DSS.

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