# Using a risk based, site-specific Decision Support System to determine the suitability of mine water for irrigation

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## Abstract

Use of irrigation as a mine water management option often presents a cost-effective means of utilising poor quality mine-impacted waters that would otherwise need to be treated before release into surface water bodies. However, there are some waters that should not be considered for long-term irrigation, and site selection is critical. A newly developed risk based, site-specific irrigation water quality assessment tool defines key factors to consider when determining the viability and sustainability of irrigation with specific mine waters.

**Keywords:** Irrigation water quality, crop yield, crop quality, soil quality, Decision Support System

## Introduction

There is much interest in the beneficial use of mine water for agricultural irrigation. Irrigation is often a cost-effective means for operating mines to manage surplus water. Upon closure, irrigation may present a sustainable means for communities to diversify away from mining, by producing food and fibre sustainably, and creating employment. Large savings in water treatment costs are also likely to follow. However, not all mine waters are suitable for irrigation, and support is necessary to make informed decisions on suitability.

An irrigation water quality Decision Support System (DSS) has recently been developed (du Plessis et al 2017). Fitness-for-use of water is presented as being 'ideal', 'acceptable', 'tolerable' or 'unacceptable'. The DSS is novel in a number of ways. Firstly, it is risk based, enabling the user to assess the implications of irrigating with a range of waters, including mining impacted waters on soil and crop resources, as well as on irrigation equipment. Secondly, the guidelines are structured in three tiers. Tier 1 provides generalised, conservative estimates of the suitability of water for irrigation. If mine waters are shown to be ideal or acceptable at this level, there may be no need to treat water or to utilise it through irrigation, and release into surface water bodies will likely be permitted and desirable. As this is unlikely with most mine-impacted waters, Tier 2 supplies more site-specific guidelines, enabling the user to design a crop production system to best accommodate the specific water quality. If there are still concerns about the usability of water for irrigation, then a Tier 3 assessment is indicated. This will require detailed expert input to assess whether or not irrigation is at all feasible, and if concerns highlighted by the Tier 2 assessment can be mitigated. Finally, the DSS is electronic and user-friendly, with colour coding to make the suitability of waters for irrigation intuitive. Help files provide information regarding the current state of knowledge for suitability indicators, and describe the approach and calculating procedures used in the DSS.

## Methods

Water quality assessments at Tier 2 employ a scaled down version of the Soil Water Balance (SWB) crop growth and solute balance model (Annandale et al 2011), to dynamically simulate the interactions between irrigation water constituents and the soil-crop-atmosphere system. A simple cascading 11 layer soil water balance is used, with default parameters (field capacity, permanent wilting point, bulk density, and drainage characteristics) for predefined soil textures (clay, sandy loam, sand and coarse sand) populated in a database. A simple crop factor model is used (with many crop species parameters included in the database) to estimate water use, and a seasonal, root density-weighted profile salt content is estimated to predict yield reduction due to salinity using the Maas and Hoffmann (1977) approach. Soil profile chemical equilibrium reactions are modelled after Robbins (1991) in order to predict gypsum precipitation that reduces root zone salinity. Simulations are run over periods of 10 to 45 years in order to quantify the probability and severity of a specific effect occurring. Site-specificity is considered by means of populated databases that allow the user to select an appropriate weather station, soil texture, crop specie, irrigation management strategy, and irrigation system.

In this paper, the functionality of the DSS is demonstrated by simulating the effect on crop yield of 45 years of irrigation with five poor quality mine waters. The role of crop choice, climate and irrigation management on crop yield are also highlighted. In addition, nutrient supply to crops and trace element addition to the soil profile with irrigation water are demonstrated. Finally, the effect of mine impacted waters on corrosion and scaling of irrigation systems, and on soil physical properties are presented. Model predictions are discussed in the light of previous experience with irrigation using some of these waters.

## Water qualities

Much research on irrigation with mine waters has been carried out in South Africa. Du Plessis (1983) modelled the advantage of sulphate rich waters over chloride dominated waters, suggesting that irrigation with gypsiferous mine waters would be feasible. This was proved correct by Jovanovic et al (1998), who showed that irrigation of a wide range of crops was feasible using lime treated acid mine drainage (AMD). Annandale et al (1999 and 2002) investigated the long-term sustainability of irrigation with gypsiferous mine waters, and demonstrated that gypsum precipitation in the soil kept soil solution salinity levels relatively low, thereby facilitating sustainable crop production, without negative consequences for soil resources. Beletse worked with sodium bicarbonate rich water from a coal bed methane operation (Beletse et al 2008) and showed this particular mine water to be problematic for irrigation due to the high levels of salinity and sodium, with no opportunity to precipitate gypsum and reduce soil salinity. Beletse also considered sodium sulphate rich waters on heavy clay soils, and although pastures did grow with this water, the sustainability of the practice was questioned (Beletse 2008).

For the demonstration of the irrigation water quality DSS, three mine waters that we have experience with for irrigation were considered (lime treated AMD, sodium bicarbonate rich and sodium sulphate rich waters). In addition, a chloride rich water was "generated" by keeping the properties of our actual lime treated AMD water, except that sulphate and chloride concentrations on a mol charge basis were swopped, to see if the DSS would come to the same conclusions that du Plessis (1983) did. Finally, because we are currently interested in investigating whether it is feasible to directly apply AMD to heavily limed soil (to negate the need for a liming plant), we also considered an acidic water of pH 3. These waters' analyses are presented in Table 1.

## Relative crop yields

The DSS considers a relative crop yield above 90% to be ideal, between 80 and 90% is acceptable, between 70 and 80% is tolerable, and an unacceptable yield is below 70% of potential yield. Of course, in reality, this will depend on the grower and the profitability of producing a particular crop, but it is considered a useful guideline. Crops differ greatly in their sensitivity to or tolerance of salinity, but tend to show no yield penalty until a certain threshold salinity is exceeded, where after yield decline is linear, with the slope of this decline depending on the particular crop. The simulations presented are for a "Medium Sensitive" summer crop, maize, with a threshold saturation paste salinity of 170 mS/m and a 12% decrease in yield for each 100 mS/m increase in salinity, and two "Medium Tolerant" crops, soybeans, a summer crop with a threshold of 500 mS/m and slope of 20% and wheat, a winter crop with a threshold of 600 mS/m and slope of 7.1%.

*__Table 1__ Composition of mine waters evaluated with the DSS*

| | Lime treated AMD | Chloride rich water | Sodium bicarbonate rich water | Sodium sulphate rich water | AMD |
|---|---|---|---|---|---|
| **Major constituent** | | | | | |
| Calcium (mg/L) | 615 | 615 | 25 | 32 | 227 |
| Magnesium (mg/L) | 208 | 208 | 0 | 88 | 132 |
| Sodium (mg/L) | 10 | 10 | 2000 | 796 | 13 |
| Bicarbonate (mg/L) | 41 | 41 | 5000 | 450 | 0 |
| Chloride (mg/L) | 5 | 1500 | 375 | 18 | 3.5 |
| Sulphate (mg/L) | 2082 | 7 | 7 | 1647 | 2919 |
| pH | 5.7 | 5.7 | 7.5 | 8.9 | 3 |
| EC (mS/m) | 377 | 377 | 750 | 372 | 360 |
| TDS (mg/L) | 2961 | 2961 | 7407 | 3031 | 3295 |
| SAR (mol/L)0.5 | 0.1 | 0.1 | 111 | 16.5 | 0.2 |
| **Trace elements** | | | | | |
| Aluminium (mg/L) | 2 | | | | 158 |
| Iron (mg/L) | 31 | | | | 233 |
| Manganese (mg/L) | 28 | | | | 72 |
| Nutrients | | | | | |
| Nitrogen (mg/L) | 16 | | | | 19.5 |
| Phosphorus (mg/L) | 0.4 | | | | 0.5 |
| Potassium (mg/L) | 6 | | | | 7 |

Relative yields were simulated for 45 years of irrigation with five different water qualities using weather data from Loskop Dam, which is reasonably representative of the coal fields of Mpumalanga in South Africa. The long simulation period is used to estimate the risk of irrigation with these waters, so that relative yields can be presented as the fraction of time they fall in a particular fitness for use category. The irrigation management practice for these simulations was to apply 20 mm every time the soil profile had a deficit to field capacity of 25 mm, thereby leaving room for at least 5 mm of rain. Results are presented in Table 2.

It is clear that production of a medium sensitive maize crop is only feasible with the gypsiferous lime treated AMD water. Soybean is clearly a summer crop that can be produced with a wider range of poor qual-

*__Table 2__ Simulated % of time that yields of maize, soybean and wheat at Loskop would fall within specific fitness for use categories.*

| Fitness for Use | Relative crop yield | Lime treated AMD | | | Chloride rich water | | | Sodium bicarbonate rich water | | | Sodium sulphate rich water | | | AMD | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | % | Maize | Soybean | Wheat | Maize | Soybean | Wheat | Maize | Soybean | Wheat | Maize | Soybean | Wheat | Maize | Soybean | Wheat |
| Ideal | 90-100 | 91 | 100 | 100 | | 36 | 82 | | | 39 | | 91 | 100 | | | 27 |
| Acceptable | 80-90 | 9 | | | | 27 | 12 | | 9 | 24 | 9 | | | | | 30 |
| Tolerable | 70-80 | | | | | 9 | 6 | | 9 | 21 | 36 | 9 | | | | 24 |
| Unacceptable | <70 | | | | 100 | 27 | | 100 | 82 | 15 | 55 | | | 100 | 100 | 18 |

ity waters than maize, and wheat is able to be produced even with very poor quality waters. Clearly crop choice is one of the management practices available when assessing the feasibility of irrigating with a particular water quality. Directly irrigating with AMD does not look very promising, but initial pot trials undertaken at the University of Pretoria are encouraging when such waters are applied to highly buffered or limed soils.

The effect of location and irrigation management are illustrated in Table 3. Warmer, drier climates will be less suited to irrigation with saline waters than cooler wetter climates, where atmospheric evaporative demand is lower and a higher rainfall induced leaching environment is encountered. Simulations for Loskop are compared to those for Vaalharts, the biggest irrigation scheme in South Africa, which has a drier climate, with a far cooler winter. It is expected that maize will perform better in the more humid environment. In addition, two irrigation management strategies are compared. The "Deficit" irrigation strategy is designed to minimise leaching and use rainfall more efficiently. This is a wise strategy to follow when using good quality water, but irrigation is a salt concentrating practice, as crop roots extract water and exclude salts, and the higher the salinity, the greater the leaching requirement for sustainable irrigation. It is therefore not surprising that better yields are predicted for Vaalharts when effective leaching is increased from 5.7 to 7.5%.

## Plant nutrient supply through mine water irrigation

Some mine waters are quite high in essential plant macro-nutrients, like nitrogen, phosphorus and potassium. Irrigation with nutrient rich waters can be beneficial for crop production, as this may represent a saving in the cost of buying fertiliser and the expenses incurred in applying it. However, some crops may be negatively affected by high concentrations of nutrients, through excessive vegetative growth and lodging, delayed maturity and reduced crop quality. High nutrient levels may complicate fertiliser management and limit control over nitrate leaching and P wash off. The rationale adopted in the DSS is that the higher the nutrient content and the greater the supply of nutrients to the crop, the harder it becomes to manage crop nutrient requirements. However, crops vary greatly in their nutrient requirements, and pasture crops in particular, will not easily be adversely affected by high nutrient loads, so crop selection is once again important when irrigating with mine impacted waters. Table 4 illustrates the nutrient supply to soybean and wheat from our treated and untreated AMD waters.

***Table 3*** *Demonstration of the effect of location (climate) and irrigation management (deficit irrigation vs a salt leaching strategy) on water requirements, effective leaching and relative yield.*

| Fitness for Use | Relative crop yield (%) | Loskop Dam | | | | Vaalharts | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Deficit irrigation | | Leaching requirement | | Deficit irrigation | | Leaching requirement | |
| | | Maize | Wheat | Maize | Wheat | Maize | Wheat | Maize | Wheat |
| Ideal | 90-100 | | 100 | | 100 | | 100 | | 100 |
| Acceptable | 80-90 | 9 | | 9 | | | | | |
| Tolerable | 70-80 | 55 | | 45 | | 27 | | 36 | |
| Unacceptable | <70 | 36 | | 45 | | 73 | | 64 | |
| Irrigation | (mm) | 731 | 557 | 763 | 560 | 978 | 523 | 1003 | 527 |
| Effective Leaching | (%) | 8.9 | 1.1 | 11.1 | 2.2 | 5.7 | 1.7 | 7.5 | 2.9 |

*Simulations are for the sodium sulphate rich water on a maize-wheat rotation in the Loskop Dam area and at Vaalharts (drier region with cooler winters). The Deficit irrigation strategy is to irrigate with 15 mm whenever the deficit to field capacity reaches 20 mm, thereby leaving some room for rain. The leaching requirement strategy applies 15% more water than is required to return the profile to field capacity.*

*Table 4 Simulated plant nutrient (nitrogen) supply to a wheat-soybean rotation irrigated with lime treated AMD and AMD for Loskop weather data with irrigation leaving 5 mm room for rain once deficit to field capacity reaches 25 mm.*

| Fitness for Use | Contribution to crop N removal | Lime treated AMD | | | | AMD | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Soybean | | Wheat | | Soybean | | Wheat | |
| | | Time (%) | Applied (kg/ha) | Time (%) | Applied (kg/ha) | Time (%) | Applied (kg/ha) | Time (%) | Applied (kg/ha) |
| Ideal | 0-10% | | | | | | | | |
| Acceptable | 10-30% | 53 | 102 | | | 7 | 107 | | |
| Tolerable | 30-50% | 47 | 130 | 100 | 88 | 91 | 141 | 55 | 103 |
| Unacceptable | >50% | | | | | 2 | 191 | 45 | 114 |

## Trace element accumulation in soil

A concern often raised with the use of mine water for irrigation is the fate of trace elements in the water. Especially with circum-neutral waters this is usually not of great concern, but with lower pH waters this should certainly not be ignored. The DSS calculates how many years it will take to reach protective threshold soil values in the top 150 mm of the soil profile. Aluminium, iron and manganese are identified as the elements most likely to be flagged by regulators. However, the fact that they are found in abundance in natural soils raises the question whether or not these guidelines should be relaxed somewhat. To ascertain the real risk of detrimental food or forage safety due to trace element accumulation, more research needs to be done.

## Corrosion and scaling of irrigation equipment and effect of mine water on soil physical properties

The DSS uses the Langelier Index to estimate corrosion or scaling of irrigation equipment. This may not be the best index for sulphate rich waters, as it was developed for carbonate rich waters. However, it can be seen in Table 6 that the sodium bicarbonate and sodium sulphate rich waters are predicted to be scaling, with the other waters indicated to be corrosive, especially the AMD. In addition, the DSS also predicts the effect of water quality on infiltration and hydraulic conductivity. Sodium is particularly problematic, but the negative effect is somewhat counteracted by high salinity levels.

***Table 5*** *Predicted effect of irrigation with different mine affected waters on corrosion (negative Langelier Index) or scaling (positive Langelier Index) of irrigation equipment, and the % of time soil physical properties will fall in specific fitness for use categories.*

| Parameter | Fitness for Use | Lime treated AMD | Chloride rich water | Sodium bicarbonate rich water | Sodium sulphate rich water | AMD |
|---|---|---|---|---|---|---|
| Corrosion (-) Scaling (+) Langelier Index | Ideal | | | | | |
| | Acceptable | | | 0.84 | | |
| | Tolerable | -1.62 | -1.61 | | 1.34 | |
| | Unacceptable | | | | | -6 |
| Surface Infiltration (% of time) | Ideal | 92 | 92 | 92 | 92 | 92 |
| | Acceptable | 8 | 8 | 8 | 8 | 8 |
| | Tolerable | | | | | |
| | Unacceptable | | | | | |
| Soil Hydraulic Conductivity (% of time) | Ideal | 100 | 89 | 42 | 78 | 98 |
| | Acceptable | | | 28 | 2 | |
| | Tolerable | | | 17 | | |
| | Unacceptable | | 11 | 13 | 20 | 2 |

## Conclusions

Not all mine waters are suitable for irrigation. However, the user-friendly DSS is able to assess site-specific factors that influence the suitability of mine waters for irrigation, and present the risk taken in using such waters, as far as crop yield and quality, soil factors and irrigation equipment is concerned. In some cases, a more detailed Tier 3 assessment is required, to ascertain if negative Tier 2 assessment issues, like for trace element loading in the simulations presented here, can be mitigated. This may require expert input by crop or soil scientists. The DSS will assist regulating authorities to make decisions on permitting mine water irrigation, and in consideration of mine closure options.

Future research should focus on the assessment of food and forage safety when using mine waters for irrigation, and improvements to algorithms for scaling and corrosion using gypsiferous waters. In addition, the need to discriminate against waters high in trace elements that are abundant in soils should be considered. Finally, an effort should be made to improve and expand parameters used in the model, especially for effects like scorching of foliage with low pH waters.

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