Irrigation with mine affected waters: A demonstration with untreated colliery water in South Africa

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Abstract

There is renewed interest in the use of mine water for irrigation as a means to reduce mine impacted water treatment costs and to create sustainable livelihoods as mines reach closure and communities need to diversify away from mining. Large volumes of mine waters are affected, and many mine waters are suitable for irrigation.

A 19 ha demonstration centre pivot has been erected on previously un-mined land in Middelburg, Mpumalanga, South Africa. Maize (summer) and stooling rye (winter) have been irrigated with an untreated, circum-neutral, calcium and magnesium sulphate dominated mine water since September 2017. Crops grew exceptionally well under irrigation with this particular mine water, far out producing rain fed crop production, and proving more profitable.

Currently, no off-site effect of irrigation have been detected, and grain produced is safe to consume. A newly developed irrigation water quality assessment tool indicates that Mn and B may be of some concern over time. We advocate regular testing for food or fodder safety, specifically for elements of potential concern, in order to assess if published soil thresholds are robust indicators of the suitability of poor quality waters for irrigation.

Keywords: Irrigation water quality, gypsum precipitation, mine closure, food safety, 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.

Site description

After a careful soil survey to select a site with irrigable soils, a 19 ha demonstration centre pivot has been erected on previously un-mined land in the Middelburg District of Mpumalanga, South Africa. This experimental site (25°48'25"S, 29°45'48"E, 1670 m.a.s.l.), has been planted to maize (summer) and stooling rye (winter), and has been irrigated with an untreated, slightly alkaline, calcium sulphate dominated coalmine water since September 2017. Soil water and salt balances were monitored in-field, as were potential off-site effects through surface and groundwater monitoring. The trial site, as well as the location of surface and groundwater monitoring stations is presented in Figure 1.

Agronomic practices

A local, large-scale, commercial farmer from the area, who leases the land from the mining house, is growing the crops for his own account. The centre pivot was erected by the colliery, which supplies mine water to the field under pressure. A white maize variety PHB 32B07BR was planted in early October 2017 at a seeding rate of 80 000 per hectare. Around the irrigated area, maize is also planted under rain-fed conditions at a lower seeding density of 50 000 per hectare. When this first irrigated maize crop was harvested in June 2018, stooling rye, a fodder crop was planted to demonstrate that irrigation could also be successful in winter. Due to logistical reasons, this crop was planted late and harvested early, to make way for the following maize crop. Ideally, from a water utilisation point of view, it is desirable to have a green transpiring canopy for as many months of the year as possible. Taking maize off early for silage, would enable the winter crop to be planted earlier, thereby maximising production. The winter crop in this trial will not be discussed in detail, but it was evident that this salt and cold tolerant crop could be successfully produced in the cooler winter months.

The maize was well fertilised (290 kg ha^{-1} nitrogen (N), 40 kg ha^{-1} phosphorus

Figure 1. A Google Earth image of the experimental site showing the location of the centre pivot (yellow circle), the monitoring boreholes (BH1 to BH4) surrounding the irrigated field, as well as piezometers (P1 to P3). The discard dump monitoring boreholes (DMBH8 to DMBH11), and Beestepan Dam, where surface water quality is monitored, are also indicated.

(P), 64 kg ha^{-1} potassium (K), and 10 kg ha^{-1} sulphur (S)), with nutrient supply depending on expected yields and soil analyses. Crop protection also received attention, with spray programmes followed to minimise disease and insect damage, and to control weeds. All input costs were recorded to estimate profitability at the end of the season.

Irrigation water quality

The mine water used was untreated, and pumped from one of the opencast voids to the field. The pH is circum-neutral (7.1), with an electrical conductivity (EC) of around 240 mS m^{-1}. The major cations were calcium (Ca) at 235 mg L^{-1}, magnesium (Mg) at 160 mg L^{-1} and sodium (Na) 70 mg L^{-1}. Major anions were bicarbonate (HCO_3) at 335 mg L^{-1}, chloride (Cl) at 10 mg L^{-1} and sulphate (SO_4) at 1130 mg L^{-1}. From a plant nutrient point of view, the water contained 3.5 mg L^{-1} nitrogen (N) and 35 mg L^{-1} potassium (K). Several trace elements were below detection limits and therefore not considered in this analysis. Trace elements that were present in measureable quantities were, in µg l^{-1}, aluminium (Al) 510, manganese (Mn) 390, iron (Fe) 110, zinc (Zn) 40, boron (B) 225, cobalt (Co) 3.2, vanadium (V) 7.5, and fluoride (F) 0.7.

This mine-impacted water was assessed using the Irrigation Water Quality DSS to identify options available to utilise this water and to alert the users to potential constituents of concern. No yield decline was simulated due to salinity for both maize and a cool season cereal, wheat (which would respond similarly to stooling rye), but wheat may be sensitive to boron according the the DSS.

Most trace elements will only reach soil thresholds after a millennium of irrigation, but Mn reaches its threshold in half a century.

Environmental impact monitoring

A pair of boreholes, one deep (B1) and one shallow (B2) is located on the eastern side of the field and another pair, also one deep (B3) and one shallow (B4), are located on the western side of the field (Figure 1). The shallow boreholes (2 and 4 referred to as Shallow Upstream and Shallow Downstream, respectively) are about 10 m deep and the deep boreholes (1 and 3 referred to as Deep Upstream and Deep Downstream, respectively) are around 30 m deep. These boreholes are sampled and analyzed by the colliery every quarter.

Measured EC and SO_4 of the downstream boreholes were quite high even before any irrigation had taken place (irrigation commenced in September 2017), thus indicating that these solute signatures are determined by an external salt source. The chemical signatures of these downstream boreholes also indicate that these waters are NaCl dominated and not Ca/Mg sulphate dominated, as is the case for the irrigation water. The most likely explanation for these observed elevated salt levels prior to irrigation is that they can be attributed to runoff from the discard dump that is located adjacent to these boreholes. Four additional boreholes have recently been drilled around the discard dump to enable groundwater monitoring closer to the discard dumps, thereby reducing uncertainty around the effect of irrigation on groundwater resources. These boreholes are marked DMBH in Figure 1. It appears that irrigation water currently has a minimal effect on groundwater, as it is not clearly accumulating SO_4 (Figure 2).

Beestepan Dam (Figure 1) was identified as a monitoring point where one could potentially observe any effect of irrigation on downstream surface water bodies. Sulphate was the selected constituent to flag such effect, and the decision taken was that if a 20% increase above the original (before irrigation) concentration, attributable to irrigation is observed, all irrigation should be stopped immediately. This, however, is somewhat complicated by the fact that a discard dump in close proximity to the field will also affect the water quality in this dam. The average sulphate concentration in Beestepan Dam for the three years prior to the commencement of irrigation (October 2014 to August 2017) was 535 mg L^{-1}. The threshold for action is therefore 642 mg L^{-1}. Average sulphate concentration in the first irrigation season stood at 309 mg L^{-1}, and is currently around 400 mg L^{-1}. This is affected by rain, with declining values in the rainy season, and increases observed in the dry season or in drought years.

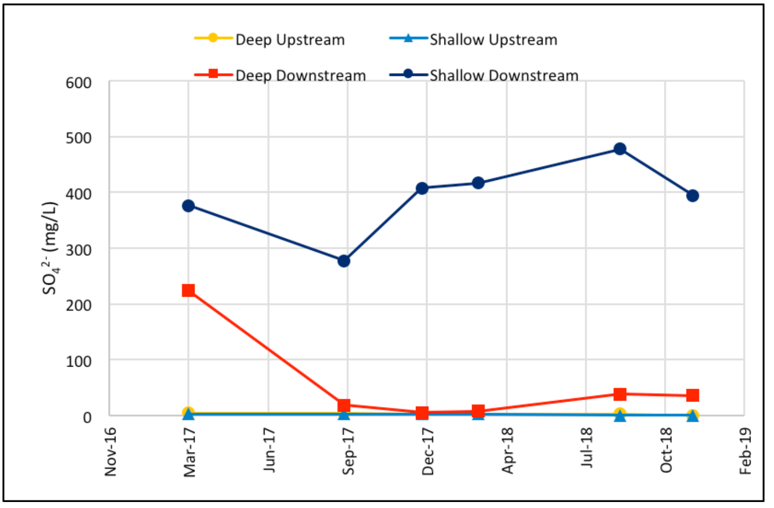

Figure 2. Sulphate concentrations in monitoring boreholes surrounding the field.

Field salt and water balance

Over the three cropping seasons (18 months), around 900 mm of irrigation has been applied to the field. This roughly adds up to the addition of 2.1 t ha^{-1} Ca, 1.4 t ha^{-1} Mg and just over 10 t ha^{-1} sulphate. In addition, 340 t ha^{-1} K and 2 t ha^{-1} B was added through the irrigation water. It is clear that the irrigator needs to take into account what is being added with the irrigation water and adjust fertilisation programmes accordingly. In addition, it would be prudent to take regular soil samples to identify any nutrient imbalances that may develop.

The DSS simulated over 45 years that around 1000 mm of irrigation would be applied per year on average. This would add 886 t ha^{-1} salt, of which 324 t ha^{-1} is leached, and 175 t ha^{-1} is predicted to precipitate as gypsum, about 20% of the salt added. It appears that Ca limits gypsum precipitation so there may be opportunities with the fertilisation programme to increase precipitation, which does the soil no harm, but keeps solutes out of water bodies. The balance (387 t ha^{-1}) is stored in the soil profile.

The DSS also predicts that soil saturated paste electrical conductivity (ECe), a measure of salinity, will increase upon commencement of irrigation, but will soon stabilise around a level below 200 mS m^{-1}, a clear sign that gypsum is precipitating and excess salts are leaching, thereby preventing the profile from becoming too saline for the production of most crops. This is depicted in Figure 3, where 45 years of maize wheat production is simulated. The salinity threshold levels for maize, wheat and soybeans (Maas and Hoffman, 1977), are also indicated in this figure. It is clear that maize may not be the best crop choice for summer production, especially if water quality deteriorates, but soybean should do well in summer, and cool season cereal crops like wheat, should show no yield decrease due to salinity.

Crop yield and profitability of production

The summer rainfall region of South Africa often experiences mid-summer droughts that can drastically reduce dryland yields. The advantage of having irrigation available, even with relatively poor quality mine water, is evident in Table 1. Yields more than doubled under irrigation compared to rainfed production, and although input costs of irrigated systems are higher, it appears that in most years, production under irrigation will be more stable and profitable than traditional dryland farming, even if the grower has to pay for pumping costs.

Food safety

Although mine waters contain a range of metals including iron, aluminium, and manganese, the main elements of concern

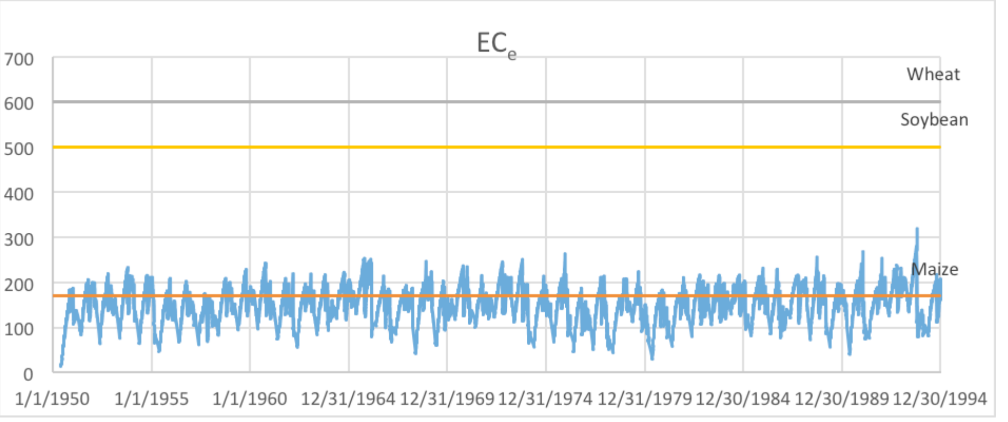

Figure 3. *Soil profile salinity (ECe in mS m-1) predicted by the DSS for 45 years of irrigation of a maize-wheat rotation with the water quality used in this demonstration. Salinity thresholds for three crops are also indicated.*

Table 1 *Maize yields and profitability in 2017/18 and 2018/19. Typical exchange rate 14 South African Rand (R) to 1 US$*

Season	2017/18		2018/19	
Field	Irrigated	Dryland	Irrigated	Dryland
Yield (t/ha)	13	5,4	14,7	5,6
Cost (R/ha)	17859	15980	17092	14586
Cost (R/t)	1374	2959	1163	2605
Avg SAFEX Price (R/t) (May - July)	2070		2998	
Earnings (R/ha)	26910	11178	44071	16789
Profit/Loss (R/ha) (excl pumping costs)	9051	-4802	26979	2203
Profit/Loss (R/ha) (incl pumping costs of R5000/ha)	4051	-	21979	-

Table 2 *International grain food safety thresholds for human consumption adapted from Codex Alimentarius Commission 2011, 2013, South African Department of Health 2016. The measured values for the 2017/18 season are also presented.*

	China	EU/SA	Ireland	Irrigated	Dryland
			mg/kg		
As	0.5	-	-	0.003	0.004
Cd	0.1	0.1	0.1	<0.001	<0.001
Cr	1	-	-	0.002	0.002
Pb	0.2	0.2	0.1	0.006	0.005
Hg	0.02	-	-	<0.001	<0.001

were identified as arsenic (As), cadmium (Cd), chromium (Cr), lead (Pb) and mercury (Hg). International guidelines for these elements are presented in Table 2, together with the levels measured in the grain from the 2017/18 season.

It is clear that the grain produced is safe for human consumption and levels of constituents of concern are at least an order of magnitude lower than the recommended safety thresholds. At the time of writing, the analyses for the second maize season were not yet available, but are also likely to be of no concern.

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. It is clear from this study, that it is possible to profitably utilise some mine affected waters. This has important implications for sustainable mine closure, and diversification of communities away from mining post closure. Currently, no off-site effects of irrigation have been detected, and grain produced is safe to consume. We advocate that food and forage safety be assessed when using mine waters for irrigation, in order to ascertain if trace element thresholds commonly published in irrigation water quality guidelines are robust. This is especially important for elements that are naturally abundant in soil, and many mine waters, like Fe, Al and Mn, and are likely to become unavailable for plant uptake over time.

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