



South Africa's options for mine-impacted water re-use: A review

by T. Grewar¹

Synopsis

South Africa is a water-scarce country, rated as one of the 30 driest countries in the world. Worryingly, government expects water demand to outstrip supply as early as 2025. The South African government believes that substantial volumes of water can be made available through the re-use of treated mining-impacted water. Currently, however, large volumes of treated mining-impacted water are produced, often with no end use in mind other than discharge or disposal, when these treated effluents may have further uses in applications which are currently and unnecessarily using high-quality water. Treating the wastewaters to levels that meet 'fitness-for-use' guidelines for alternative applications such as agriculture, sanitation, or industrial processes will reduce the treatment cost burden compared to potable water production. The primary conclusion of this review is that the most suitable option for re-using treated mine-impacted water is in agriculture, for irrigation of crops (food, forage, or energy crops), which currently and unnecessarily makes use of the majority of South Africa's high-quality resources or potable water. Other findings include the realization that although guidelines and legislation for water re-use in South Africa exist and are readily available, they tend to be contradictory and confusing in many cases. It is imperative that these ambiguities and incongruities in the available guidelines and legislation for water re-use be clarified and updated swiftly.

Keywords

water re-use, mining-impacted water (MIW), agriculture, acid mine drainage (AMD).

Introduction

South Africa is a water-scarce country and is currently rated as one of the 30 driest countries in the world, with an average rainfall of 490 mm/a, approximately half of the global average. As an indicator of the degree of regional variability in South Africa's water supply, it has been shown that 70% of all runoff is from approximately 20% of the land area. Regardless of the water scarcity faced in South Africa, our water conservation track record is poor, with an average consumption of 280 L/d per person, almost 60% more than the global average of 175 L/d per person. Around 40% of this allocation is utilized in watering lawns and gardens (Zhuwakinyu, 2017).

The South African government predicts water demand to outstrip supply as early as 2025. On an international scale, the situation appears just as dire, with the United Nations High Level Panel on Water (HLPW) expecting

a 40% water shortfall by 2030, which may affect up to 1.8 billion people based on current water demand trajectories (Zhuwakinyu, 2017).

Currently, South Africa is experiencing the worst drought since 1904, which has triggered severe water shortages, negatively affecting agricultural output in all sectors (News24, 2016). The potential exists for nation-wide 'water-shedding' initiatives, similar to the electrical load-shedding programme initiated by Eskom, being implemented for homes and businesses in the near future if the situation continues to decline. Currently, water restrictions are in place country-wide with the Western Cape being the worst affected province. In 2016, eight of the nine provinces, with the exception of Gauteng, were declared drought disaster areas. The country's total water supply is currently estimated at 14.6 km³/a, of which surface water is the main source. The current demand is estimated to be between 15 km³/a and 16 km³/a, and it is expected that South Africa will experience a 17% water supply and demand gap by 2030 (Webb, 2015; News24, 2016; Zhuwakinyu, 2017).

The UN World Water Development Report (2017) argues that improved wastewater management could facilitate the achievement of the UN's 2030 Sustainable Development Goals (SDGs). SDG-6 specifically has a target to reduce the proportion of untreated wastewater by half by 2030. While sustainably increasing water recycling and safe re-use (WWAP, 2017). The report also suggests that wastewater which is traditionally discarded could be treated to provide a non-potable water resource for use in agriculture and energy production. According to the Water 2017 Report, more than 50 countries

¹ Biotechnology Division, Mintek South Africa.
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worldwide are already making use of treated wastewater for irrigation, accounting for approximately 10% of all irrigation water world-wide.

A number of proposals have been put forward by the South African government to increase water supply. These include; rainwater harvesting; desalination; increasing the yield from surface water; and promoting the use of groundwater on a larger scale (Webb, 2015). Currently, surface water comprises about 79% of the total water supply of the country while groundwater, mainly used in rural areas, comprises only about 14%, with the balance (7%) comprising re-used water. Government believes that substantial volumes of water can be made available through the increased re-use of return flows, especially in some coastal cities where potentially re-usable wastewater is currently discharged into the sea, as well as the re-use of treated acid mine drainage (AMD) in particular or mine-impacted water (MIW) in general (Webb, 2015).

In the context of this review, AMD is defined as an acidic effluent with high sulphate and metal concentrations emanating from abandoned or ownerless mines, and MIW is defined as any wastewater of varying pH that has in some way been affected by mining or a mining-related process, and hence can encompass AMD among other effluent types. For this reason, these two terms will be used interchangeably.

The goal of this review was to perform an overview of the literature to determine the current state of MIW re-use in South Africa and to provide a central resource of information regarding legislation, available guidelines, and potential options for re-using treated MIW.

Mining-impacted water in South Africa

The impacts of mining range from initial exploration through the life-cycle of the mine to beyond mine closure. Mining-impacted water disposal poses serious problems globally, and the quality of the impacted water depends greatly on the chemical and mineralogical characteristics of the orebody. Owing to its salinity, minewater generally cannot be discharged into river systems unless diluted with good quality water to reduce the salinity to within acceptable limits. For this reason, the Department of Water and Sanitation (DWS) is assessing the installation of desalination plants to treat MIW to levels that will enable safe discharge; however, the long-term view on MIW treatment includes desalination to potable standards to augment fresh water supply. A number of coal mines in Mpumalanga are already

treating minewater to potable standards, with the treatment costs estimated to be between R12 and R18 per cubic metre (Annandale *et al.*, 2007; Webb, 2015). The question, however, remains whether it is necessary to treat the minewater to potable levels, thereby incurring high treatment costs, when activities like irrigation of crops, flushing of toilets, and washing of clothes do not require potable water. Does it not make sense to reduce the treatment burden and subsequent cost by treating the water only to levels that are suitable for these or similar activities?

Minister Mokonyane reaffirmed the South African government's stance on water re-use and recycling while speaking at the launch of the United Nations World Water Development Report 2017 in March 2017. She stated that 'recycling water for industrial and agricultural purposes would go a long way towards ensuring the country's water security' (Zhuwakinyu, 2017). To help incentivize water re-use, the DWS announced in May 2016 that government would provide R600 million every year towards treating MIW, with the funds allocated directly by the National Treasury. Some of these funds will be recovered from users of the treated water (33%) while the balance of 67% will be recovered from the polluting mining operations through a proposed environmental levy (Zhuwakinyu, 2016).

Government's short-term intervention for MIW treatment in the Witwatersrand Basin in Gauteng have included the installation of three high-density sludge (HDS) treatment plants in Krugersdorp, Germiston, and the most recent commissioned in Springs during February 2017. These plants can treat 50 ML/d, 82 ML/d, and 110 ML/d of decant respectively, after which it is released into nearby water resources (Zhuwakinyu, 2017). The major problem with this solution, however, lies in the fact that water treated by HDS has sulphate levels that are well above those allowable for discharge, in addition to a number of issues surrounding storage and disposal of the sludge produced.

Current treatment technologies

Since this reviews' focus is not on MIW treatment technologies but rather on uses for the treated water, this section will merely highlight the more mainstream treatment options currently in use, along with some of the newer technologies that are becoming available. These include Mintek's passive biological sulphate reduction (BSR) process and SAVMIN™, both of which address salinity issues. These technologies are summarized in Table I.

Table I

Summary of available MIW treatment technologies

Technology	Treatment method	OPEX cost	Waste issues	Potable/non-potable
¹ Reverse osmosis (RO)	Membrane	High (R12-18/m ³)	Brines	Potable
² High-density sludge (HDS)	Precipitation	³ Low (R1-2/m ³)	Sludges	Non-potable/high-sulphate
⁴ Savmin™	Precipitation	Med/high (R10/m ³ for 2 g/L SO ₄)	Metal hydroxides, gypsum	⁵ Potable and non-potable
⁶ Passive biological sulphate reduction (BSR)	Biological dissimilatory sulphate reduction	⁷ Low/med (R3-5/m ³)	⁸ Sulphide	Non-potable/fit-for-use

¹Greenlee *et al.* (2009)

²Zhuwakinyu (2017)

³Van Zyl *et al.* (2001)

⁴Van Rooyen (2017)

⁵Potable water is possible depending on inlet feed composition

⁶Grewar (2017)

⁷Mintek (2018)

⁸Potential to include a polishing step where sulphide can be recovered as biosulphur (value-added product)

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Water re-use

The Department of Water and Sanitation is the custodian of South Africa's water resources and is responsible for ensuring that water resources remain fit for recognized uses and are maintained and protected (DWA, 1996).

Four broad categories of water use are recognized in the South African National Water Act (Act 36 of 1998), namely domestic, industrial, agricultural, and recreational use. These categories can each be subdivided into a number of subcategories, all of which may have vastly different water quality requirements. The minimum contaminant limits (MCLs) for a variety of constituents have been defined for the recognized water use categories in the South African Water Quality Guidelines (volumes 1 through 8) produced by the Department of Water Affairs and Forestry (1996). 'Water use' characterization involves investigating various characteristics of a specific water use (*i.e.* costs, socio-economic benefits, volume of use), which assists in determining the consequence thereof. In addition, various legislated guidelines are considered in conjunction with risk-based factors to determine the water quality required for a particular use. The water quality requirements for water use are usually determined on a site- or case-specific basis (DWA, 1996).

The traditional 'once-through' centralized water management system is being re-thought due to growing water scarcity owing to population growth, urbanization, and climate change. This has become a global problem that has triggered renewed interest in water recycling and re-use. An array of ecological and financial benefits can be generated by decentralized water re-use systems, in addition to the supplementing of existing stressed water supplies (Stoakley, 2013).

Water re-use philosophy

The National Water Resources Strategy (NWRS) first edition (2011) identified water re-use as one of a number of important strategies to balance water availability and requirements in the future. One of the commitments of the NWRS is, 'DWA [now the DWS], with sector partners will explore the use of new technologies for re-using waste water and for using treated mine water'. With the 2013 NWRS2 an annexure (D) was released specific to the national strategy for water re-use. It stated that water re-use can be classified as direct or indirect, planned or unplanned, on a large or a small scale irrespective of location. It may involve a variety of treatment options or none at all, with the reclaimed water being used for a number of activities, each with its own re-use strategy. There is, however, an associated risk that water re-use may be unplanned, unregulated, and/or result in unintended or undesirable consequences.

Water quality and security of supply, water treatment technology, cost relative to other water supply alternatives, social and cultural perceptions, and environmental considerations are the five key considerations that affect choices related to water re-use as an option for water supply augmentation (South Africa, 2013).

The inclusion of planned water reclamation, recycling, and re-use schemes in water resource systems reflects the increasing scarcity of water sources as a whole. Some of the categories of potential wastewater re-use are agricultural, landscape irrigation, industrial recycling and re-use (*i.e.*

cooling, washing), non-potable urban uses such as fire protection, air conditioning, sanitation (toilet flushing), and potable re-use.

Re-use and recycling within industrial processes is fast becoming the norm as regulations and laws regarding environmental protection and water security are becoming increasingly stringent. However, there are still large volumes of treated effluent being produced with no end use in mind other than discharge or disposal. These treated effluents could be re-purposed for other applications that are unnecessarily using high-quality water resources. By simply adopting the 'water quality cascade' approach (Stoakley, 2013), which refers to the linking of the quality of a wastewater source to an appropriate subsequent activity, all available water would be put to its most beneficial use even as the quality decreases after each re-use. For example, minewater may be suitable for a number of alternative applications (agriculture, sanitation, industry) provided that it is treated to acceptable levels for various contaminants. Advantages of this approach include the resultant capex and opex cost savings from a reduced treatment burden as well as the identification of an alternative water resource.

The aim of this re-use 'philosophy' would ultimately be to reduce potable water consumption and subsequently increase water conservation. The practice of using reclaimed wastewater is, however, not risk-free, hence proper planning and risk analysis are essential to mitigate the risks applicable to the re-use application identified.

Legislation regarding water re-use in South Africa

There are a number of South African Acts that are applicable when water is used and effluent is discharged. Although the Water Services Act (No. 108 of 1997) (WSA) and the National Water Act (Act 36 of 1998) (NWA) form the foundation for the legislative framework within the sector, other Acts which are also important include the Environment Conservation Act (Act 73 of 1989) (ECA) and the National Environment Management Act (Act 107 of 1998) (NEMA), where recent amendments would also be applicable. In some instances specific municipal bylaws may also be relevant (South Africa, 1989, 1997, 1998a, 1998b).

The NWA (Act 36 of 1998), however, is the primary legislation governing the use and discharge of 'wastewater'. The Act aims to ensure that the nation's water resources are protected and managed to reduce and prevent pollution and degradation of water resources. The Act also promotes the 'polluter pays' principle, and the stringent Wastewater Discharge Standards Guidelines proposed by the then Department of Water Affairs in 2010 will force industries to develop their own cleaner production systems. The Act requires that any person using wastewater for irrigation purposes, discharge, or disposal must register with the responsible authority as a registered water user and must ensure that the wastewater does not impact other water sources, property, or land and that the wastewater is not detrimental to the health of the public.

In South Africa, the WSA (Act 108 of 1997) relates more to the management of human drinking water and directs bulk water suppliers to the compulsory national standards in the form of SANS 241-1:2015. The SANS 241 standard is specifically designed with bulk water suppliers in mind and is

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aimed at safe water provision for domestic drinking use, and thus focuses on life-long safety for all types of users and aesthetic acceptability (South Africa, 1997).

Currently the re-use of effluent streams requires environmental authorization in terms of the NEMA (107:1998), and in some cases requires water use licences (WULs) in terms of the NWA (36:1998). Specifically, all new and existing mines are required, in terms of the NWA (36:1998), NEMA (107:1998), and the Mineral and Petroleum Resources Development Act (Act No. 28 of 2002) (MPRDA), to optimize water re-use and reclamation (DWA, 2013).

Other regulations relevant to the use of water for mining and related activities in South Africa, aimed at the protection of water resources, are published in terms of the NWA (36:1998) in the Government Notice 704 of 4 June 1999, known as GN704, which states that mines must collect, confine, and take reasonable measures to prevent water resource contamination as well as ensure that water used in any process at a mine or activity is recycled as far as practicable (Munnik and Pulles, 2009).

Although it is unfortunate that much of South Africa's water-quality woes stem from a lack of coordination in addressing the water contamination issue, this concern is expected to be addressed when the Mine Water Management Policy (MWMP) comes into effect. The draft proposal was approved by Cabinet in 2017 and later gazetted by the DWS in July 2017, allowing a 60-day period for public comment. The MWMP policy is aimed at (a) ensuring improved water quality management and reduction of water pollution, including through AMD treatment, (b) strengthening the protection of water resources from mine water contamination from short to long term, and (c) providing a basis for holding parties potentially liable for negative effects and damages through AMD-related pollution (DWS media statement, 14 July 2017; Zhuwakinyu, 2017).

Public perceptions relating to water re-use and recycling

Bruvold and Ward (1972) conducted one of the earliest studies on public perceptions of recycled water usage. They identified 'psychological repugnance', also known as the 'yuck factor', as the main reason for opposition to the use of treated water originating from municipal wastewater and

which will most likely also be applicable to the re-use of treated minewater. Several surveys completed more recently have revealed numerous additional factors that appear to influence the perceptions, acceptability, and overall successful implementation of recycled water regardless of the source within a community. Some of these factors include the sources of the water to be re-used, trust in and knowledge of the treatment processes producing the water for re-use, the specific activities related to water re-use, and the cost of water reuse (Bruvold and Ward, 1972; Stoakley, 2013).

Stoakley (2013) conducted surveys among South African university students to determine their perceptions around water re-use. The results showed a high degree of acceptability for non-potable uses such as watering gardens and toilet flushing, which increased with the premise that either the individual would personally not have access to clean water without re-use or it would benefit the environment. Reluctance appeared greater in the potable use category, with concerns surrounding health and safety being paramount.

Water re-use projects in the past have, however, shown that the level of community acceptance and perceptions around elements such as cost, risk, and necessity are vital indicators of a planned project's eventual success or failure (Stoakley, 2013). For these reasons, the benefits of proactively providing opportunities for public participation in the development process should be carefully considered and will far outweigh the perceived administrative burdens of such a task by ensuring a smoother, more successful implementation phase.

Fitness for use

The South African Water Quality Guidelines, volume 3 (DWA, 1996), sums up 'fitness for use' as a judgement of how suitable the quality of water is for its intended purpose or for protecting aquatic ecosystems. However, with modern technology water of nearly any quality can be produced for a specific purpose provided it can be treated to the required specifications. Therefore, how fit a particular water source is for use depends also on the design specifications for the process and how much the user is prepared to invest in treating the water to comply with these specifications. Hence, 'fitness for use' is largely defined by the use of water quality guidelines. Table II provides a summary of a number of different categories of water re-use.

Table II

Categories of potential re-use for treated AMD (adapted from DWA, 2013)

Category of re-use	Description of category
Urban use Unrestricted irrigation	Landscape irrigation of parks, playgrounds, school yards, golf courses, cemeteries, residential areas, green belts
Restricted irrigation	Irrigation of areas with infrequent and controlled access
Other uses	Fire protection, disaster preparedness, construction
Agricultural use Food crops	Irrigation for crops grown for human consumption
Non-food crops and crops consumed after processing	Irrigation for fodder, fibre, flowers, seeds, pastures, commercial nurseries, instant lawn
Other use Industrial re-use	Cooling system water, process water, toilets, laundries, air-conditioning, wash-down water
Residential re-use	Cleaning, laundries, toilets, air-conditioning
Potable re-use	Blending with municipal water supply, pipe-to-pipe supply

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Both locally and internationally, a number of limits and guidelines for different contaminants are available in the literature. However, many of these deviate significantly from one another in terms of approaches and methodologies used to arrive at the specified criteria. For this reason, the DWAF (now DWS) South African Water Quality Guidelines (SAWQG) volumes 1 to 8 (1996) were developed to provide a single set of guidelines and criteria for water quality and fitness for use that is appropriate for recognized water uses in a South African context.

Based on the definitions, concepts, and guidelines above, an assessment was performed in order to determine the most suitable uses for treated MIW. Using available data, which in some cases was limited, we directly compared the maximum contaminant limits (MCLs) of the more relevant elements in MIW for potentially feasible re-use activities, including crop irrigation (DWAF Volume 4; 1996), discharge to a sewer for sanitation (City of Johannesburg Metropolitan Municipality Water Services By-laws, 2008), discharge to a watercourse (South Africa, 1998b), and drinking water (SANS 241:2015). These are compared in Table III.

It should be noted here that although industrial re-use is an option and is being considered in some respects, it was not considered in this review to be a viable option. This was primarily due to the results from a study performed by the DWA (2013) that determined that although there are a large number of industries located within the Rand Water supply area affected by AMD decant, 67% of the industrial water demand is required by only three individual super-factories, all of which are distant from the AMD generation points and require very high-quality water (above potable water standards), which is not provided by neutralized or minimally treated AMD.

Interestingly, this direct comparison in Table III highlighted a number of incongruities in the available guidelines and legislation used to compare the MCLs:

- MCL levels for Ca and Mg have not been set for the select group of activities where re-use is possible, not even for human consumption
- SO₄ MCL levels are more stringent for discharge to a sewer than for human consumption, with none set at all for discharge to a watercourse
- MCL for SO₄ for irrigation is not set in any of the formal guidelines or legislation
- Allowable EC levels for irrigation differ in the NWA guidelines (South Africa, 2013) compared to the DWAF irrigation guidelines (1996)
- Fe MCL for discharge to a water resource is more stringent than that for human consumption, and the same applies in the case of Mn
- Allowable pH levels differ in the DWAF irrigation guidelines (1996) from those in the NWA guidelines (South Africa, 2013).

These incongruities and the absence of set limits in some cases within the available guidelines and legislation for water re-use pose a potential hindrance to the technology and R&D framework, which requires clear and unambiguous guidelines upon which new technology is designed and developed. These guidelines therefore need to be clarified and updated timeously so as to not adversely affect technology development in this sector.

The various options for treated MIW reuse are discussed in more detail below.

Domestic use

The success of the eMalahleni Water Reclamation Plant (EWRP) in Witbank has demonstrated the viability of using MIW treated to potable levels for residential human consumption. Potable water, however, comes at a hefty treatment price and depending on the treatment process, significant amounts of wastes (brines) are produced that present a costly disposal dilemma.

Table III

Comparison of the maximum contaminant limit (MCL) values for a variety of re-use activities with respect to primary MIW components

Contaminant	Maximum contaminant limits (MCLs) (mg/L)			
	⁹ Crop irrigation	¹⁰ Discharge – sewer	¹¹ Discharge – watercourse (general limits)	¹² Drinking Water
SO ₄	-	250	-	500
Cl ⁻	(a)700	1000	-	300
Mg	(b)-	-	-	-
Al	(c)20	-	-	0.3
Ca	-	-	-	-
Mn	(d)10	50	0.1	0.4
Fe	20	200	0.3	2
Na	(e)460	-	-	200
SAR (sodium adsorption ratio)	(f)15	-	-	-
EC (mS/m)	(g)540 (1 ¹³ 150–200)	500	<150	170
pH	6.5-8.4 (1 ¹³ 5.5–9.5)	-	5.5-9.5	5.0-9.7

Notes: (a) May exceed, depending on crop tolerance, target 100 mg/L; (b) Limits not set or not available; (c) May exceed, only acceptable over short term, target 5 mg/L; (d) May exceed, only acceptable over short term, target 0.02 mg/L; (e) May exceed, depending on crop tolerance, target 70 mg/L; (f) May exceed, some economically important crops can be irrigated without developing sodium toxicity, target 2.0 (g) May exceed, requires sound irrigation management, target 40 mS/m.

⁹DWAF 1996. South African Water Quality Guidelines for Agriculture: Irrigation (Volume 4)

¹⁰City of Johannesburg. 2008. Metropolitan Municipality Water Services By-laws

¹¹South Africa (2013)

¹²SANS 241:2015 Drinking water specification

¹³South African National Water Act (No. 36 of 1998)

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As mentioned previously, potable water is not necessary for a number of domestic activities. Hence MIW treated to the lowest requirements for such activities could provide significant savings in terms of treatment costs while simultaneously having a positive impact on the environment and our highly stressed water resources. This partial treatment should, however, not only focus on neutralization and the removal of metals, which in the past have been the primary focus of treatments options, but also on reducing the sulphate content as the salt load of the partially treated MIW would still present a contamination risk to resources via domestic sewerage systems.

Agriculture – crop irrigation

Agriculture accounts for around 70% of fresh water withdrawals from rivers, lakes, and aquifers worldwide with approximately 1000 L of water required to produce 1 kg of cereal grain, and 43 000 L to produce 1 kg of beef (Pimentel *et al.*, 2004; Webb, 2015).

Irrigated agriculture is the largest consumer of available water in South Africa. However, the abstraction rate related to irrigation has decreased dramatically from 80% of available water resources 45 years ago to around 63% currently (Zhuwakinyu, 2017). This downward trend has continued, with irrigators experiencing increasing pressure to reduce their water use. Since many irrigation schemes are situated at the lower end of drainage basins they often receive poor quality water due to the influence of upstream activities (DWAF: Volume 4, 1996).

Irrigators may experience a range of adverse effects as a result of variable water quality that may include reduced crop yield and quality, and soil degradation and damage to equipment from scaling or corrosion. These effects can be mitigated by switching to a more tolerant crop or simply changing the irrigation method (DWAF, 1996, vol.).

The South African government is planning a 33% increase in irrigated land by 2030 due to anticipated increasing demand from the agricultural sector. This is being driven by the National Development Plan (NDP), which has identified agriculture as a key element in food security, job creation, and social capital in rural communities as it has been recognized as having significant employment-creation potential due to the labour-intensive nature of the industry. Other factors such as climate change, drought, and population growth are also expected to contribute heavily to

the increased demand in this sector, which is expected to grow from 8.9 km³/a currently to 9.7 km³/a by 2035 (Webb, 2015; Zhuwakinyu, 2017).

The South African National Water Act (No. 36 of 1998), specifically the revision of general authorization in terms of Section 39 of the National Water Act (Act no. 36 of 1998), published under Government Notice 665 in Government Gazette 36820 dated 6 September 2013, classifies irrigation, specifically irrigation with biodegradable industrial wastewater and domestic wastewater, as a controlled activity in terms of Section 21 (e) that can be practiced only under license.

Biodegradable industrial wastewater is defined in the Act as wastewater that contains predominantly organic waste arising from industrial activities including, but not limited to, milk processing, abattoirs, manufacture of animal feed, and production of alcohol or alcoholic beverages in breweries, wineries, or malhouses. Although the Act specifies biodegradable wastewater, all wastewater regardless of source may be used for irrigation provided the water quality remains within the set guidelines. Permission is granted only if the location of the water use complies with the guidelines that aim at preventing pollution of other water sources such as aquifers, boreholes, watercourses, or wetlands. The Act also details precautionary practices to ensure that the water user follows acceptable construction, maintenance, and operational activities. In addition, sampling and monitoring is also required to be performed on a regular basis and the results reported to the relevant authority.

Wastewater limit values for a variety, albeit limited list, of contaminants are described in the Act (36:1998) for the irrigation of any land or property specific to areas of (a) up to 2000 m³, (b) up to 500 m³, and (c) up to 50 m³ with domestic or biodegradable waste water (Table IV).

This list is unfortunately far from comprehensive and does not cover contaminants such as metals and sulphates. However, guidelines for some of these are available in the South African Water Quality Guidelines - Volume 4: Agricultural Use: Irrigation (1996), produced by the DWAF (summarized in Table III), and these need to be used in conjunction with the Act to determine the quality of water required for irrigation purposes.

MIW re-use in irrigated agriculture

Pulles (2006) describes management options for saline MIW in South Africa as (1) pollution prevention at source, (2) re-

Table IV

Wastewater limit values for irrigation of any property or land up to 2000 m³ (adapted from South Africa, 2013)

Variables	Limits (<2000 m ³)	Limits (<500 m ³)	Limits (<50 m ³)
pH	5.5-9.5	6-9	6-9
Electrical conductivity (mS/m)	150	200	200
Suspended solids (mg/L)	25	-	-
Chloride as free Cl (mg/L)	0.25	-	-
Fluoride (mg/L)	1	-	-
COD (mg/L)	75	400	5000
Ammonia (ionized and un-ionized) as N (mg/L)	3	-	-
Nitrate, nitrite as N (mg/L)	15	-	-
Orthophosphate as P (mg/L)	10	-	-

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use and recycling of water to minimize the volume of polluted water that could also be treated, (3) treatment of effluents if the problem cannot be solved through prevention, re-use, and recycling, and (4) discharge of treated effluent, which is considered the last resort. In addition, he also mentions the potential for using gypsiferous or lime-treated minewater for agricultural irrigation as a re-use strategy, particularly post mine closure.

A number of opportunities are provided by using gypsiferous mine wastewater in irrigation, including the potential to enable dry season production as well as stabilizing dryland crop production. Simultaneously, it would provide a relatively cheap method of reducing the volumes of minewater decant being produced unchecked. By irrigating with gypsiferous wastewater, a large percentage of the salts present can be removed from the mine effluent through gypsum precipitation into the soil profile (Annandale *et al.*, 2007).

Several studies have been published around the treatment of MIW within the upper Olifants River catchment area which identified a number of advantages to irrigation with treated MIW. While the quantities, MIW treatment technologies, flow sheets, and the corresponding costs would have changed since these studies were done, it can be expected that the advantages identified would still be relevant today, and these are explored in more detail below.

Grobbelaar *et al.* (2004) reported estimates of the volumes of minewater stored and generated for various mines in the central Witbank coalfields in Mpumalanga. They state that after closure of the entire Mpumalanga coalfields, approximately 360 ML/d of mine-impacted water may be generated, while for the Olifants catchment area a volume of 170 ML/d was estimated. These enormous volumes, acting as an alternative water resource, could potentially support over 6 000 ha of irrigated land. On a more site-specific scale, the Kleinkopje Colliery in Witbank, which has an estimated daily water make of around 14 ML with a further 120 000 ML of water stored underground could, depending on the crop system chosen, sustain irrigation of 500–700 ha, alone.

In addition, van Zyl *et al.* (2001) reported that simply treating minewater decant to irrigation standards, rather than for urban or industrial applications, would reduce capital and running costs by 87% and 78%, respectively. Similarly, Annandale *et al.* (2007) compared the capital costs of several treatment options, and showed treatment for irrigation to be lower in cost by an order of magnitude. In addition, and of particular importance in the post-closure period of a mine, the income generated from the sale of the water could be offset against the running costs. Further benefits include job creation and protection of water resources, which are aligned to the government's NDP.

Currently, mine land post mine closure is rehabilitated, but usually not to the advantage of the local communities. Mines in South Africa tend to be located in water-scarce areas, and use of the land for agricultural purposes would require fresh water to be provided from further afield, which is not economically viable. However, as explained above, the treatment of MIW provides a water source on site or nearby, which then allows agriculture on the mine land to become a realistic opportunity for the surrounding community on a year-round basis (Jovanovich *et al.*, 2002).

In summary, it is clear that using treated MIW for crop irrigation confers a number of notable advantages, including the facts that (a) MIW requires a low level of treatment prior to re-use in irrigation, resulting in substantial treatment cost savings, (b) large portions of irrigated land are located near MIW sources, which would limit the collection and distribution costs if MIW was utilized, (c) the treatment and re-use of MIW could operate as a single financial initiative, with income from the MIW-irrigated crops funding the MIW treatment and/or creating jobs and food security for the local community, (d) treatment and re-use of MIW in crop irrigation would relieve the environmental and health liabilities of the mines producing the MIW, while simultaneously stimulating agriculture in the vicinity, and (e) would make more high-quality or potable water available for more pressing needs (van Zyl *et al.*, 2001).

The potential for linking mining with agriculture has been recognized by some in the industry, although it will need widespread adoption to make a significant impact on the *status quo*. A recent article in Mining Weekly Online (14 September 2016) quoted Exxaro CEO Mxolisi Mgojo as saying that 'I really think the land around our coal mines should be developed into agricultural hubs'. The same article reports that Sibanye Gold is rolling out a modern approach to ensure community development in the areas in which it operates, with the aim to leave an agricultural economy in its place when operations cease in 30–40 years' time. It was reported that 640 people are already employed and the community has been benefitting from the sale of produce to the Spar retail group.

Local case studies

Over the last 30 years various studies have been performed in South Africa on the potential of using minewater for irrigation, with varying levels of success (du Plessis, 1983, Jovanovic *et al.*, 1998; Annandale *et al.*, 1999, 2001, 2002, 2006, 2007, 2009; Pretorius *et al.*, 1999; Jovanovich *et al.*, 2002, 2004; van der Laan *et al.*, 2014). A few examples are discussed below.

In 1983 Du Plessis (1983) was the first to investigate the use of gypsiferous minewater for irrigation purposes. He found that lower soil and percolate salinity was achieved by irrigating with gypsum-rich water instead of chloride-rich water of similar composition and attributed this to the precipitation of gypsum in the soil. Furthermore, the increase in sodium caused by gypsum precipitation did not significantly affect the physical properties of the soil or crop yield.

Lime-treated MIW has been used successfully in the irrigation of crops at the Landau Colliery Kromdraai Opencast Section (Witbank, Mpumalanga). A field screening trial of 20 agronomic and pasture crops, including maize, soybean, rye, wheat, lucerne, and kikuyu was investigated for irrigation by lime-treated MIW on a sandy acidic soil. The results indicated that considerable yield increases of irrigated crops could be realized compared with rain-fed cropping, provided that irrigation and fertilization practices were managed correctly (Jovanovic *et al.*, 1998).

In 1997–1998, Annandale *et al.* (2001) undertook a field trial at Kleinkopje Colliery in Witbank (Mpumalanga) to determine the effect of using gypsiferous minewater for

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irrigation of crops of sugar bean and wheat on rehabilitated opencast mine land. They found considerable increases in yields of sugar beans and wheat under irrigation with gypsiferous minewater compared with rain-fed cropping. Specifically, yields of sugar beans on virgin land were higher compared to those on the rehabilitated land. They attributed this to a number of reasons, including late planting date, soil compaction, low soil pH, and nutrient deficiencies, and not necessarily the quality of the irrigation water. Excellent wheat yields were obtained on both virgin and rehabilitated land, which was attributed to the fact that wheat is more tolerant to salinity than beans. In addition, no symptoms of foliar injury due to overhead irrigation with gypsiferous water were observed.

Annandale *et al.* (2007, 2009) carried out a long-term study at three mines, namely Kleinkopjé Colliery near Witbank, New Vaal Colliery near Vereeniging, and Syferfontein near Secunda. The average water qualities used are summarized in Table V. All sites were centre-pivot irrigated with gypsiferous minewater, and some had begun irrigation with minewater as far back as 1997. They found that the maize yield from irrigation with minewater was lower than dryland-produced crops, particularly on rehabilitated land, but attributed this to the poor drainage of the site and the rapid rise in the electrical conductivity (EC) observed over the irrigation period. However, wheat yield was unaffected by similar water quality. They also determined that potatoes were successfully produced using gypsiferous minewater, and that pasture crops like lucerne and fescue were unaffected by irrigation with Na₂SO₄-rich minewater at Syferfontein. No symptoms of foliar injury due to centre-pivot sprinkler irrigation with gypsiferous minewater were observed for all crops. They did, however, note that potassium (K) uptake was suppressed by the presence of high calcium (Ca) and magnesium (Mg) in the water, and suggested that this could be corrected by regular application of K-containing fertilizer and following proper irrigation management. Some crop failures were noted but these were attributed to poor site selection, resulting in waterlogging of crops, rather than the water quality.

Table V

Average irrigation water qualities at the different mines (adapted from Annandale *et al.*, 2007, 2009)

Analyte	Analyses (mg/L)			
	Kleinkopjé (Major)	Kleinkopjé (Tweefontein)	Syferfontein	New Vaal
Al	0.3	0.01	0.1	-
Ca	513	405	32	93
Mg	158	196	88	31
K	-	-	16	5
Na	51	47	796	132
Fe	0.3	0.08	0.1	0.32
Mn	6	0.01	0.03	0.08
SO ₄	2027	1464	1647	430
Cl ⁻	18	32	17.8	42
TDS	2917	2212	2435	1120
pH	6.4	7.0	9.2	7.5
EC (mS/m)	294	205	372	132

In general, crop production under irrigation with minewater rich in Ca and sulphate was found to be feasible and sustainable, if properly managed. The same team also investigated the sustainability of irrigation with gypsiferous coalfield minewater on a commercial scale and found that crops like sugar beans, wheat, maize, potatoes, and pastures were very successfully produced with no significant impact on the soil or surface and groundwater resources being observed, at least in the short to medium term (eight years).

In 2014, van der Laan *et al.* reported on the potential for goldfield minewater from the Witwatersrand area to be used as an alternative irrigation water resource. The minewater was either pre-neutralized, as was the case for prior studies performed on coalfield minewater described above, or raw minewater was applied to soils or mine tailings that had been preconditioned with slaked lime or limestone. The preconditioning of the soils was expected to facilitate *in situ* neutralization and sequestration of many of the contaminants present in the raw minewater. The results illustrated that goldfield minewater could be used as a cost-effective solution for the irrigation of salt-tolerant crops on agricultural land or vegetation on mine tailings. The researchers calculated that 60% of the salts from the neutralized minewater would be retained within the soil profile, compared to 75–90% salt removal achieved from the raw water when irrigating pretreated mine tailings or clay soils.

The work described above is significant as it highlights the potential for the use of coal or gold minewater to be used for the production of various types of crops ranging from food for human consumption to forage and pasture crops for livestock consumption and even for energy crops for biofuel production. This is where the re-use strategy for MIW within agriculture specifically fits within the framework of the Water-Energy-Food (WEF) nexus, which is rapidly becoming a strategic area of importance, globally.

Sanitation

About 40% of the water consumed by South African households is used to flush toilets, and about 60% of the total water and sanitation costs are used to fund the treatment of this contaminated wastewater. On average, 200 g/d of human waste per person is flushed down the toilet, while 6–9 L of drinking quality water is used for each flush (Webb, 2015). Potable water is, however, not necessary for sanitation purposes and this represents a major mismanagement of our limited water resources.

Unfortunately in South Africa, unlike other countries such as Japan and Australia, dual reticulation systems which allow for the use of treated wastewater for sanitation are rare. These would be required in order to make use of wastewater for sanitation purposes in residential homes. The lack of these dual reticulation systems therefore currently prevents the use of wastewater for any purpose, be it sanitation or otherwise, in the majority of residential homes in South Africa. However, Dr Jo Burgess from the WRC (26 May 2016) explained in a personal communication that wastewater re-use may be permitted in a commercial building such as a business or separate ablution facilities as in schools or camping grounds, provided adequate signage is put up to alert users to the fact that wastewater is in use for sanitation

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and should not be consumed. The wastewater would also need to meet various limits for discharge to the sewer system in order to prevent scaling of the pipelines and not overburden the treatment facilities.

The sanitation system would also need to be situated nearby a decant point or MIW source in order to make logical and economic sense, since transporting 'dirty' water large distances is not economically viable. These limitations unfortunately reduce the volume of treated MIW that could be feasibly utilized, thereby making the overall impact of sanitation as an alternative activity for MIW re-use somewhat insignificant under the current circumstances. Going forward, however, re-use of MIW in sanitation should be revisited once legislation is amended and infrastructure improved to allow for this option to be more widely utilized.

Industrial re-use/recycling

Although the re-use of MIW in industry was not considered during this comparative study, the option is still available and was therefore included in the overall review discussion surrounding options for MIW re-use.

Significant amounts of water are used (both consumed and non-consumed) in almost all aspects of mining, although the most intensive areas of water use are for cooling of drilling machinery, dust suppression, and minerals processing. However, these are case-specific and can vary greatly depending on factors such as water chemistry, climate, water availability, mine management and practices, geology, ore mineralogy, and the commodity being mined. Generally, lower grade ores require more water for processing. This water is abstracted either directly (from boreholes, dams, streams, or rivers) or indirectly (via a water services provider) from water resources (surface water and groundwater). Due to water scarcity becoming more widespread, governments around the world are becoming increasingly aware of the importance of safeguarding water resources, which is forcing mining companies to revisit their processes with a view of reducing their water footprint.

Many mining companies are investing heavily in new water infrastructure and management systems to re-use/recycle water as well as improving metal recovery processes and treating effluent prior to discharge. Over 90% of minewater can be re-used if treatments such as reverse osmosis and microfiltration are employed. An often-overlooked aspect of mining is that potable water is often not

required for the majority of processes, especially mineral processing and cooling, where some mining operations are making use of treated residential waste/sewage in an effort to reduce their water footprint. With proper water management procedures in place, the mining industry would be able to save up to 40% of its fresh water intake. However, it is recognized that an acceptable water quality is not the only consideration when determining the re-use of MIW (treated or otherwise). The primary concern is the removal of salts from the system so that there would be no need to use dilution water on eventual discharge (DWA, 2013; Toledano and Roorda, 2014).

Four different categories are defined in the DWAF Volume 3: Industrial Use (1996) for industrial processes according to the purity of water required, and these are summarized in Table VI.

From the DWA (2013) report, it was concluded that only Category 4 industrial processes might be capable of using neutralized MIW, and the options for this are limited. Raw MIW cannot be considered for any of the industrial use categories listed in Table VI. Desalinated MIW, if treated to a high enough standard to be considered domestic quality, will be suitable for Category 3 processes while Categories 1 and 2 require a higher water quality than domestic (potable) water. The extra costs associated with attaining the higher quality water required for Categories 1, 2, and 3 will outweigh the benefits of supplying users in these categories, in which case only select Category 4 users could benefit depending on their proximity to an AMD decant point.

A few case studies of water re-use strategies by various mines are discussed in more detail below.

Local examples of water re-use in the mining industry

In South Africa, the Witbank coalfields, located in the eMalahleni Municipality, contain many mines, some of which are closed or abandoned and contain significant volumes of polluted groundwater which contaminates groundwater and surface water sources. The eMalahleni Municipality is struggling to meet the water demand of its burgeoning population and was coping with this by removing 60% more than it was licensed to (75 ML/d) from the Witbank Dam by abstracting approximately 120 ML/d, with predictions of this increasing to 180 ML/d by 2030 (ICMM, 2012). In 2007, Anglo American's AngloCoal division partnered with BHP Billiton and the eMalahleni Local Municipality in an effort to

Table VI

Categories of processes that have been defined according to required water quality (DWAF, 1996, Vol. 3)

Category 1	Processes that require a high-quality water with relatively tight to stringent specification of limits for most or all of the relevant water quality constituents. Standard or specialized technology is essential to provide water conforming to the required quality specifications. Consequently, costs of in-house treatment to provide such water are a major consideration in the economics of the process.
Category 2	Processes that require water of a quality intermediate between the high quality required for Category 1 processes and domestic water quality (Category 3 processes). Specifications for some water quality constituents are somewhat tighter or more stringent than for domestic water quality. Standard technology is usually sufficient to reach the required water quality criteria. Cost for such additional water treatment begins to be significant in the economics of the process.
Category 3	Processes for which domestic water quality is the baseline minimum standard. Water of this quality may be used in the process without further treatment, or minimum treatment using low to standard technology may be necessary to reach the specifications laid down for a desired water quality. Costs for further in-house treatment are not significant in the economics of the process.
Category 4	Processes that within certain limitations can use water of more or less any quality without creating any problems. No additional treatment is usually required and there is therefore no further cost.

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overcome the problems of AMD pollution and water scarcity in the city. They built the flagship eMalahleni Water Reclamation Project (EWRP), mentioned previously in this review, which utilizes treatment technologies including ultrafiltration and reverse osmosis, at a cost of US\$100 million. The EWRP produces potable water from the mine effluent and currently supplies around 12% of eMalahleni's water. Pipelines were constructed from the participating mines (Kleinkopje, Greenside Colliery, and South Witbank Colliery) to a central water storage facility, a water treatment plant, and two reservoirs. Part of the plant is financed by the selling of potable water back to the municipality at the operating costs (Toledano and Roorda, 2014).

Anglo Platinum's Modikwa Mine, located in the mineral-rich Bushveld Complex region in South Africa, originally extracted all its process water from the Olifants River, much to the ire of the Kruger National Park and surrounding communities. In an effort to reduce its overall water usage and the subsequent costs involved in transportation and handling, the mine installed two separate dewatering plants, including high-rate clarifiers and a filter press, on the north and south shafts. The plants recover over 98% of the process water, and the clarified water is stored for re-use during mining operations (Talbot and Talbot, 2012).

Discharge to water resources

The National Water Act (Act 36 of 1998) also governs the discharge of domestic and industrial wastewater to a water resource through a pipe, canal, sewer, or other conduit. The user must register as a water user with the relevant authority. The Act provides a list of wastewater limit values that must be adhered to during discharge. These limits are compared, among others, to the limits set by the City of Johannesburg (2008) bylaws for discharge to sewers in Table III.

The Act governs the discharge of up to 2 000 m³ of wastewater on any given day provided that the discharged water complies with the general wastewater limit values set out in Table III, does not alter the natural ambient water temperature of the receiving water resource by more than 2 or 3°C, depending on the water source as listed in the Act, and is not a complex industrial wastewater.

Similarly to irrigation with wastewater, the Act details precautionary practices in addition to the requirements for sampling and monitoring on a regular basis and the reporting of results to the relevant authority.

Conclusions and recommendations

The re-use of treated mine-impacted water is not currently a priority in South Africa. Although the discharge of effluent to water resources should be the option of last resort, it is often the first choice of many in the mining industry and industry as a whole due to its simplicity and low cost. Unfortunately, the discharge option in many instances requires the use of high-quality water to dilute the treated effluent to within allowable discharge limits for TDS in particular (600 mg/L) and salinity in general. In addition, many activities are using high-quality or potable water unnecessarily (*e.g.* sanitation, crop irrigation).

Throughout this report, various options for re-using treated MIW were investigated. The primary conclusion of

this review is that the most suitable option for re-using treated mine-impacted water is in agriculture, namely irrigation of crops (food, forage, or energy crops), which currently and unnecessarily makes use of the majority of South Africa's high-quality resources or potable water. This is due to a number of facts.

- ▶ Using MIW for irrigation would make substantial volumes of high-quality or potable water, that was previously reserved for irrigation, available for more pressing needs (*e.g.* drinking water).
- ▶ Treating minewater decant to irrigation levels, rather than for urban/industrial use, would lead to a 87% and 78% reduction in capital and running costs, respectively.
- ▶ Irrigated farm areas are often located near MIW sources, limiting the need for collection and distribution of treated MIW for crop production.
- ▶ The treatment and use of the MIW could operate as a single financial initiative, with income from the MIW-irrigated crops (energy/forage/food crops) funding the MIW treatment and/or creating jobs and providing food/energy security for the local community.
- ▶ This option would relieve the environmental and health liabilities of the mines producing the MIW, while stimulating agriculture in the vicinity.
- ▶ This option fits well within the WEF nexus, which is becoming increasingly prominent on the international agenda that continues to focus on collaborative initiatives on solving the numerous limitations surrounding water, energy, and food provision to a growing global population.

Another important finding of this review includes the realization that although guidelines and legislation relating to water re-use in South Africa exist and are readily accessible, they tend to be contradictory and confusing in many cases, which will have the unintended consequence of negatively affecting technology development in the sector. For this reason, it is imperative that these ambiguities and incongruities within the available guidelines and legislation for water re-use be clarified and updated swiftly.

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