Full-Scale Reducing and Alkalinity Producing System (RAPS) for the Passive Remediation of Polluted Mine Water from a Flooded Abandoned Underground Coal Mine, Carolina, South Africa

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Abstract

This paper documents the application of a reducing and alkalinity producing system (RAPS) named CaroRap implemented for coal mine water remediation in South Africa. RAPS combines the mechanisms of anaerobic treatment wetlands and anoxic limestone drains. These systems improve water quality by processes, amongst others, of calcite dissolution and sulfate reduction through sulfate-reducing bacteria (SRB). Results from the system, which became operational in January 2021, show an increase in pH from an average of 2.9 to that of 5.6 coupled with an increase by 35.8 mg/L in alkalinity.

Keywords: Reducing and Alkalinity Producing System, Sulfate-reducing Bacteria, Limestone, Alkalinity.

Introduction

For over 140 years, the mining industry has played a major role in the economic advancement of South Africa, making it the most industrialised country on the African continent (Minerals Council South Africa 2021). However, all this came at a cost as the environment is continuously being affected by polluted mine water. Mine influenced water, mainly Acid mine drainage (AMD), has turned out to be a grave environmental concern in the country, particularly for sustainability of the country's freshwater supply (McCarthy and Humphries 2013). Before the three statutes, i.e. National Water Act 36 of 1998 (NWA), the National Environmental Management Act 107 of 1998 (NEMA) and the Mineral and Petroleum Resources Development Act 28 of 2002 (MPRDA) were enacted, mining practices and their effects thereof on the immediate environment were not adequately regulated in South Africa (Humby 2013). As a consequence, mining companies disregarded environmentally friendly practices and found ways to circumvent environmental liabilities. This then resulted in mines being abandoned without appropriate rehabilitation and the South African government has since inherited environmental liabilities of most of the abandoned mine sites (Novhe *et al*. 2016). Presently, legislation and regulatory frameworks related to mine water management put pollution prevention as a priority, however, in cases where pollution is inevitable, treatment becomes a necessity. Therefore, the work conducted in this study contributes to the bigger basket of mine water management strategies, particularly the passive treatment technologies which have not been thoroughly studied or applied in South Africa.

Despite the quest for a just energy transition and the declining demand from its main export destinations, South Africa is still in the top ten class of large coal producers and exporters (Nicholas and Buckley 2019). In addition, coal plays an essential domestic role in the supply of energy as 93% of the country's electricity is produced by coal-fired stations (McCarthy and Humphries 2013). Mpumalanga Province is inundated with coal mines and produces over 80% of the country's coal. It is no surprise that this province is the 15th and 2nd largest emitter of carbon dioxide (CO_2) and sulfur dioxide (SO_2), respectively on a global scale (McCarthy and Humphries 2013; Evans 2019). Moreover, the most severe direct environmental concern is that of mine influenced water. Witkranz discharge site in Carolina is an ideal case in point. Acidic mine water with pH of 2.9 is constantly discharged into the environment, feeding a nearby stream, Boesmanspruit, which then confluences with other streams to feed into the Boesmanspruit Dam. Until 2012, this dam was used to supply the town of Carolina with portable water. Unfortunately, following a severe rainstorm event, the water quality in this dam rapidly deteriorated. There was a sudden drop in pH to 3.7 (from 7.4) and contaminants such as iron (Fe), aluminium (Al), manganese(Mn) and sulfate (SO4) were found in elevated levels, ultimately rendering the water toxic and unsuitable for human consumption and use (McCarthy and Humphries 2013). With the financial support of the Department of Mineral Resources and Energy (DMRE), the Council for Geoscience (CGS) stepped in and conducted pilot studies which ultimately led to the implementation of an up-scaled passive treatment system for AMD treatment at a legacy coal mining area, referred to as the Witkranz discharge site. The system, named CaroRap, comprises of a Reducing and Alkalinity Producing System (RAPS) that has been in operation from the 17th of January 2021 and has yielded desirable results.

Objectives

This study was undertaken with an aim to contribute to sustainable mine water management solutions in South Africa by focussing on exploration and, as far as possible, implementation of sustainable solutions to the remediation of mine water discharge. The remediation component is achieved by developing optimised passive treatment units for long-term remediation of polluted mine water, based on results, observations, and lessons learned from previous pilot scale studies that were carried out by CGS.

Study Area

CaroRap system is located on farm Witkranz 53 IT, portion 11, approximately 10 km south of Carolina Town in Mpumalanga (Figure 1). The area forms part of the Ermelo coalfield and all coal seams in this area occur within the Vryheid Formation of the Ecca Group, Karoo Supergroup. This formation is characterized by sandstones with subordinate shales (Bell *et al*. 2002). Although information about the mining history of the area cannot be sourced at this stage, historical imagery as well as an old georeferenced mine plan show mining activities in a portion of land to the east of the discharge point. Both underground and open-cast mining methods seem to have been used in this area. There appears to have been some degree of rehabilitation and a pond was constructed at the discharge point. This is the pond which was later used as a "RAPS 1" unit. Notwithstanding the rehabilitation attempts, the adjacent environment has received noticeable pollution as the nearby Boesmanspruit which is fed by the discharged water has succumbed to a deterioration in water quality (McCarthy and Humphries 2013)

Methods

The selection of an appropriate treatment technique was, in the main, guided by site-specific conditions, chemistry of the water, the flow rate and locally available material. Passive treatment emerged as a winner because (1) it is relatively cheaper to implement in contrast to active treatment, (2) the area under study is in a remote location with adequate land space, (3) the flow rate (which is <50 L/s) can be managed by a passive system and (4) active treatment is generally applied at active mines while passive treatment is usually considered for abandoned or closed mines. The Witkranz discharge site is regarded as an abandoned site, therefore, the application of a passive treatment technique was befitting. Furthermore, previous pilot experiments by Novhe *et al*. (2016) highlighted the feasibility of passively treating the water discharging in the study area with a subsurface flow biogeochemical system containing compost and limestone. The baseline information

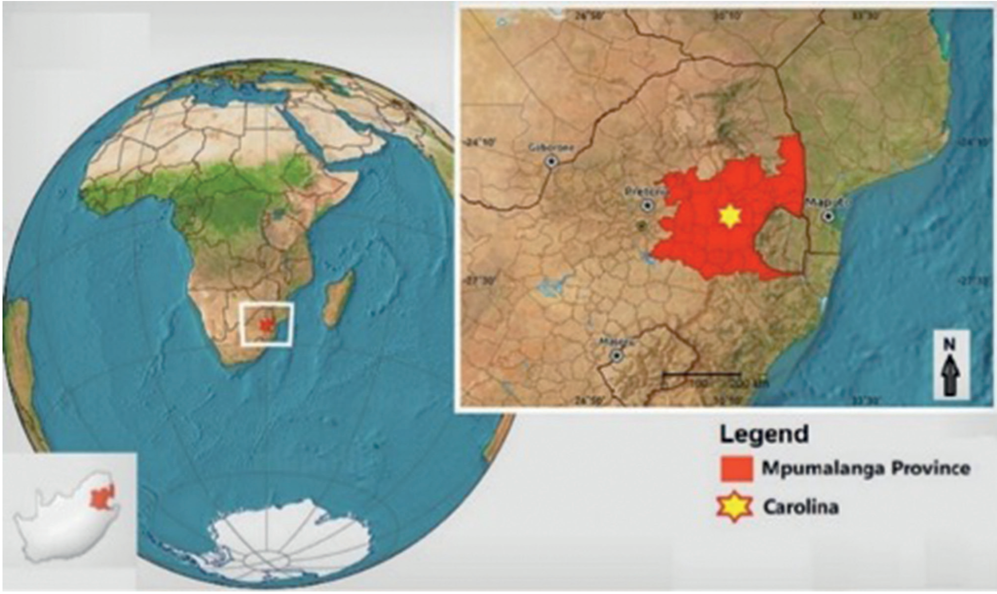


Figure 1 Map showing the location of Carolina, Mpumalanga Province (image: modified from Maphill 2011).

collected by the aforementioned authors is summarized in Table 1 below.

Further selection of the appropriate passive treatment technique was done in accordance with the flow chart compiled by Hedin *et al.* (1994). Other factors which were taken into consideration when selecting the suitable passive treatment technique are (1) potential applicability, effectiveness, and performance of the passive treatment in a South African context; (2) effectiveness and consumption rates of locally available reagents and, hence, the lifespan of the passive treatment system; (3) the feasibility and cost benefits of the implementation of the passive treatment system.

Taking into consideration all the aforementioned factors, RAPS was selected as the ideal passive treatment system for the site. A typical RAPS consists of a cell of vertical flow pond or a reducing alkalinity-producing system (RAPS) (as developed by Kepler and McCleary, 1994) and a settling pond. This kind combines the mechanisms of anaerobic treatment wetlands and anoxic limestone drains (ALDs) and has the potential to neutralize acid water and reduce sulfate while concomitantly precipitating elements such as Fe, Zn, As, and Al. For CaroRAP, RAPS system in pond 1 of the system, was constructed in an existing collection pond which required, *inter alia*, emptying of mine water, deepening by removing sediments, strengthening of the embankment walls, lining with a high density poly HDPE liner, construction of a berm and piping. Another pond, referred to as Pond 2, was proposed for a "RAPS 2" unit for further treatment of the water. However, this pond is currently being used as a receiving pond, accepting water from RAPS 1. The use of two RAPS systems in series is advantageous as it increases contaminant removal and further improves water quality. The ponds were designed to have an equal area of 900 m^3 (height = 1 m, length = 50 m and width = 18 m). Approximately 160 tons of limestone

***Table 1** Baseline information for Carolina mine impacted water.*

Flow (ℓ/min)	pH	EC (mS/m)	Dissolved oxygen (mg/ℓ)	Calculated acidity	Fe (mg/ℓ)	Al (mg/ℓ)	Mn (mg/ℓ)	Mg (mg/ℓ)	SO_4 (mg/ℓ)
34	2.9	254	5.20	967.77	331.56	40.62	20.3	61.25	2524.77

with $CaCO_3$ content of 85% was mixed with nearly 270 tons of spent mushroom compost (an organic carbon source) in RAPS 1.

This approach of mixing the limestone and manure was adopted from Younger *et al.* (2004). This method differs from the original RAPS design (depicted in Figure 2A) of Kepler and McCleary (1994), in which a distinct layer of limestone gravel underlies a layer of compost (as shown in Figure 2A). Mixing the two materials, as depicted in Figure 2B, reduces compaction and facilitates greater permeability of the substrate. A layer of water is maintained above the mixed limestone and manure substrate to encourage vertical downward flow. The calculated residence time is expected to be six days before the water is released from RAPS 1 unit. Depending on the efficiency of RAPS 1 with time, it will be decided whether to leave the second unit as an oxidation pond or to create a RAPS 2 with a similar design as RAPS 1. If RAPS 2 is considered, a relatively shallow and wide settling/oxidation pond is proposed for collection of treated water from the RAPS system. This pond will allow Fe, Al, Zn, and other precipitates to settle before the treated water is released to the receiving stream. The proposed settling pond ought to be sized to allow a primary retention time of approximately 12 h. Currently, RAPS 1 is operational and guidelines which were developed prior to the construction of the system are being used to continuously assess the efficacy of the system.

Results and Discussion

In four weeks of operation, the system (Figure 4), which is currently reliant on only RAPS 1 and an oxidation pond, has managed to raise the pH to an average of 5.6 from an average of 2.9 as shown in the left graph of Figure 5. There was also an increase in alkalinity in the ranges of about 35.8 mg/L. The increase in pH and alkalinity is attributed to bicarbonate ions released from the dissolution of limestone. In terms of metal and sulfate removal rates, the system managed to reduce total iron (Fe)

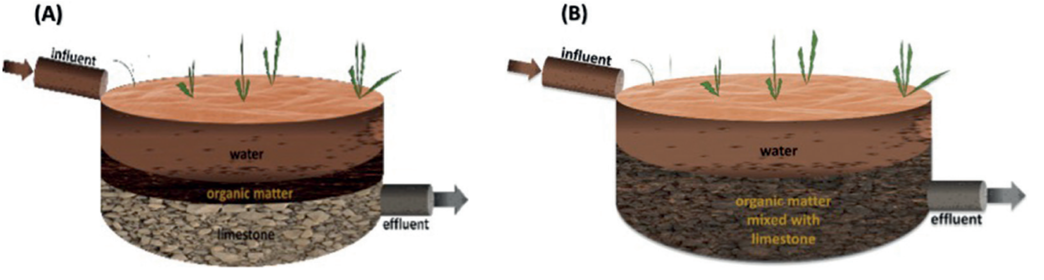
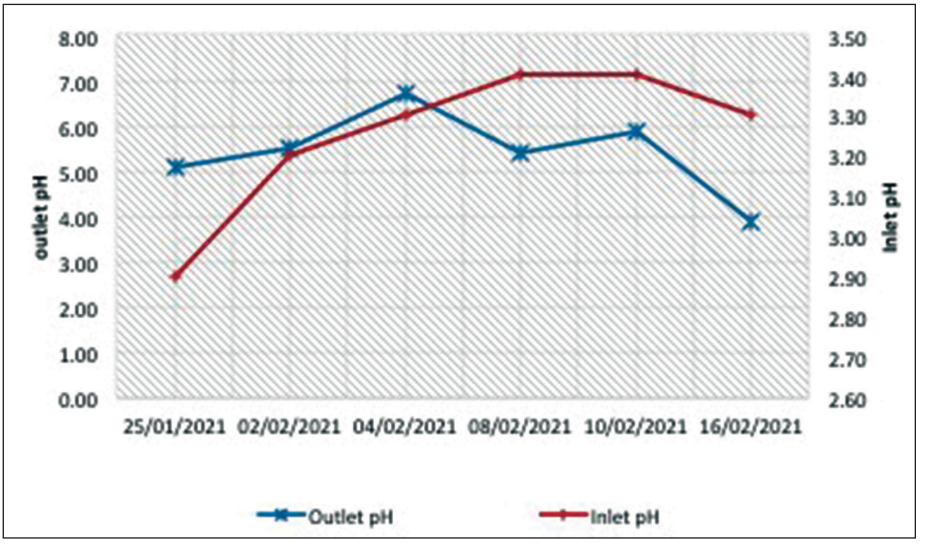


Figure 2 A typical diagrammatic representation of a RAPS setup (A) and a modified setup (B) currently used to treat mine water from the Witkranz discharge site.

Figure 3 Refurbishment of the first pond (RAPS 1) (left) and compost mixed with limestone in RAPS 1 (right).

Figure 4 An overview of RAPS 1 showing channeled inlet water, ponded mine water under treatment and a berm in the center (for increasing retention time).

by 92% and Al by 58.8%. The graph on the righthand side of Figure 5 shows a substantial decrease in Fe content in the system. On the other hand, the system managed minimal removal rates in terms of Mn and SO4 (shown on the right graph of Figure 6), which were reduced by 22.8% and 19%, respectively. The minimal removal of Mn as shown on the left graph of Figure 6, is attributed to the presence of Fe in the system which tends to compete for oxygen consumption. There was an increase in the Ca^{2+} concentration in the system as a result of calcite dissolution. This rise, from the average of about 38.8 mg/L to 108.5 mg/L, was expected as Ca^{2+} ions are released into the solution when limestone reacts with mine water.



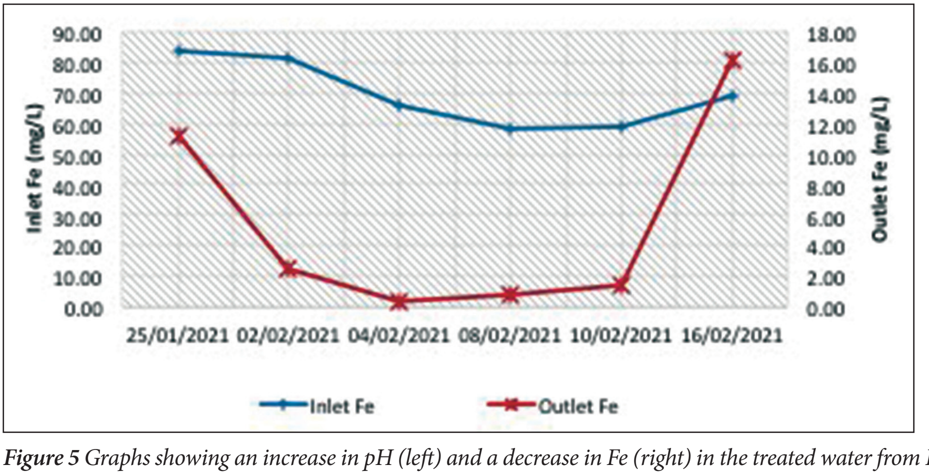


Figure 5 Graphs showing an increase in pH (left) and a decrease in Fe (right) in the treated water from RAPS 1.

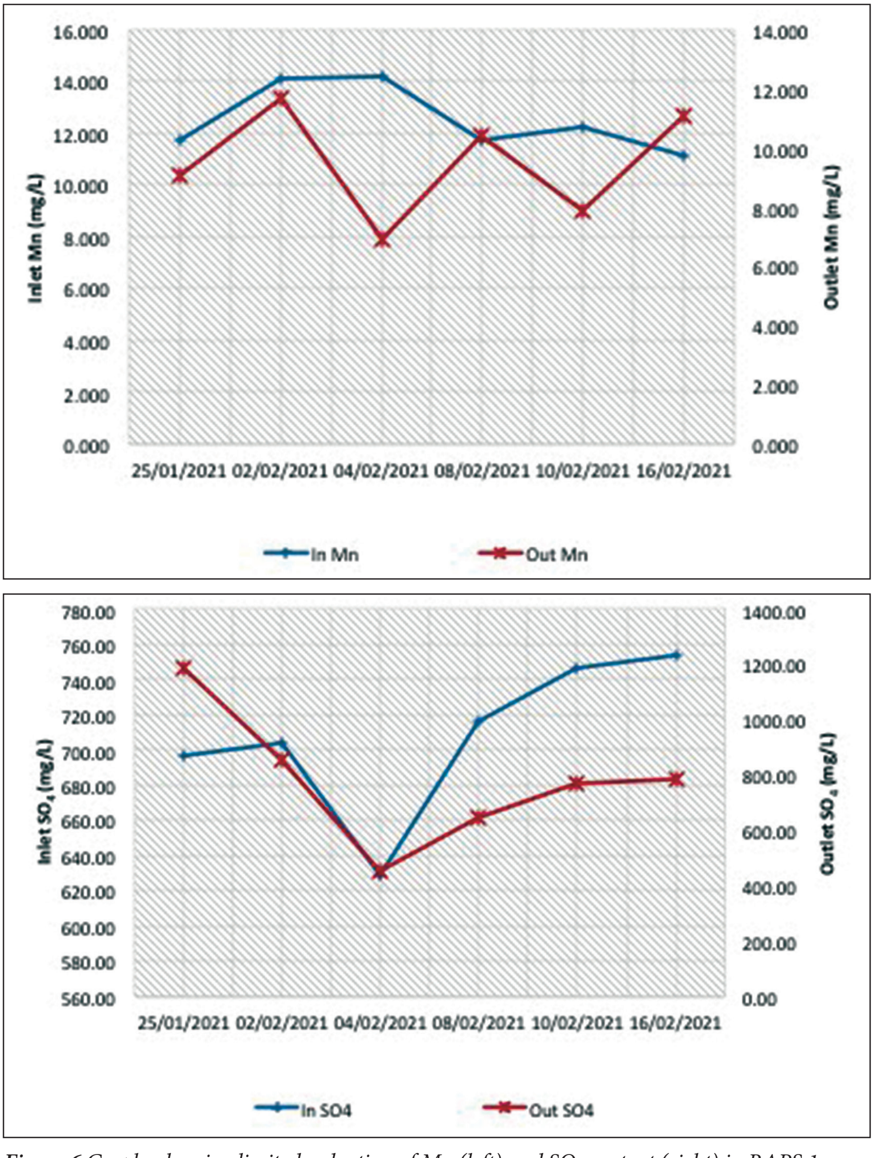


***Figure 6** Graphs showing limited reduction of Mn (left) and SO_4 content (right) in RAPS 1.*

Conclusion

Although the CaroRAP system was recently implemented and is currently reliant on one RAPS unit, results indicate that the discharged water is being successfully neutralised. There are limitations with regards to adequate removal of Mn and SO_4 and measures for optimisation of such will be explored further. SO_4 reduction is dependent on microbial activities, as such, factors such as a suitable organic substrate, pH and contact time, to name a few, will be looked into in the quest to improve the efficiency of the system. Although not currently in the plan, Mn removal can be optimised by incorporating a Mn removal bed in the system. Metals precipitating as sulfides, oxides or hydroxides in the aerobic units, tend to accumulate in passive treatment units, presenting an opportune situation for the recovery of valuable products that can compensate for remediation costs. The efficiency of the system was affected by heavy rains. Passive treatment systems typically tend to underperform in high flow conditions. Going forward, the CaroRAP system will be monitored continuously to observe its efficiency and identify methods for optimisation in differing seasons. A better understanding of the interaction of surface water and groundwater in the area will also be sought in order to gain a pertinent knowledge of the overall hydrological and hydrogeological dynamics. Moreover, the environmental impact of the system will be studied and documented.

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