Comparative Life Cycle Assessment for Acid Mine Drainage Management Options in the Central Basin of the Witwatersrand Goldfields

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Abstract

Acid mine drainage (AMD) is a product of oxidation of disulfide minerals such as FeS2 in the presence of water and oxygen. The oxidation reaction is catalysed by *Acidithiobacillus sp*. The oxidation results in the formation of sulfuric acid that in turn causes the chemical of weathering of the surrounding rock. AMD management includes treatment or prevention of its formation. The management of AMD is site specific and any management option has to be fine-tuned to meet the volumes and the quality of the water to be treated. In this study life cycle assessment (LCA) was used to evaluate the environmental impacts associated with the prevention of AMD formation through the construction of a canal to prevent ingress of water into the mine voids. This is of importance to avoid burden-shifting in the management of AMD.

LCA is a robust and valuable tool to assess the true environmental impacts of processes in order to enable informed decision-making. The option of canal construction was compared to allowing water to ingress mine voids and subsequent formation of AMD. The functional unit for the research was the evaluation of the environmental impacts per removal (or prevention of the formation of) kilogram of acidity from AMD. The novel of this approach is to identify the environmental impacts.

This study has established that, allowing ingress affects the quality water resources that in turn affecting human health and ecosystem depletion. On the other hand, ingress control has the effects on resource depletion. The effects towards human health and ecosystem depletion due to allowing ingress was because of the formation of AMD. This results in the chemical weathering of the surrounding geology resulting in water containing potentially harmful elements and low pH. This makes the water not suitable for human consumption and causing drastic effects to the flora and fauna. Ingress control depletes natural resources due to the various raw materials that are required for construction of structures to prevent ingress control.

The role of LCA is not to give a directive, but rather to reveal trade-offs for proposed solutions and scenarios. In situations where natural resources are critical, it may be best to allow ingress and follow up with AMD remediation before it affect both ecosystems and human health. In cases where human health is critical, the option may be to implement ingress control.

Keywords: Acid Mine Drainage, Life Cycle Assessment, Functional Unit, Environmental Impacts

Introduction

AMD remains one of the biggest environmental challenges resulting from mining activities. It results from the oxidation of disulfide minerals, particularly pyrite in the presence of water and the reaction continues for as long as the conditions, particularly the availability of (oxygenated) water, remain favourable (e.g. Gray 1998; Blowes *et al*. 2003; Wolkersdorfer 2008; Nordstrom 2011). Ingress of water into the mines occurs through various pathways depending on the structural geology, mine design and surrounding geomorphology and hydrogeology. In active mining areas, the water is continuously pumped out to enable safe and efficient mining (McCarthy 2011), exposing disulphide minerals to oxidative weathering processes, allowing secondary acid-generating minerals to accumulate in the mine workings. In abandoned/disused mines, these secondary minerals are then dissolved, forming an acidic solution AMD reaction occurs, which fills the mine voids and may finally discharge into the surrounding environment, and contaminating fresh water systems (Younger 1997; McCarthy 2011). Most efforts to deal with AMD have focused on remediation and rehabilitation. Active and passive treatment methods have been developed and some are currently being implemented.

This study focused on alternative approach-ingress control–based on the assumption that identifying and sealing points of water ingress into mine voids decrease the volume of AMD generated, reducing the long term management costs. In this assessment, ingress is compared to a scenario that has not been explored and might be a good baseline for LCA comparison; this is the option to allow ingress followed with no subsequent remediation. Based on field observation and intuition, this should not even be an option but putting this option into the LCA analysis will offer a good baseline of comparison.

Life cycle assessment is a sustainability audit that determines the long-term environmental impact of any process (e.g. Curran, 2006; Lehtinen *et al*., 2011; Hegen *et al*., 2014). This is done by considering the environmental impact of producing the individual components that contribute to the process e.g. raw material, equipment, fuel/energy. The assessment can be applied to a whole system i.e. cradle to grave approach or limited to a designated part of the system by setting a system boundary.

With many AMD management solutions to choose from, it is important to have criteria on which to base decisions. In the past, the decisions were based on cost. However, it has since been acknowledged that solutions that are proposed to solve environmental challenges, do themselves lead to a form of environmental impacts such as depletion of natural resources, use of fossil fuels, taking up land space and producing waste.

Methods

In order to determine the holistic environmental impact of all proposed interventions, life cycle assessment (LCA) was performed.

Process descriptions

Two process were compared using a robust LCA to determine the environmental impacts with regard to AMD management in the Witwatersrand gold fields. This processes as shown in Figure 1 are:

i. Allowing water to ingress the mine voids resulting the formation of AMD and
ii. Prevention of ingress of water into the mine voids, thereby avoiding the formation of AMD.

Allowing ingress

This referrers to allowing surface water to flow naturally through the ingress point into the mine voids. It is assumed that for any given volume of water that enters the mine voids, an equivalent volume of AMD is generated. The chemistry of acid mine drainage used for the modelling exercise is given in the Table 1.

Ingress control

This refers to the construction of an ingress control structure. The LCA modeling is based on a site in the Witwatersrand Goldfields (Fig 2a), which was part of the Ingress Control project at the Council for Geoscience. The site was successfully constructed in 2017. The design and construction of the structure was based on the standard design (see Fig 2b).

With this approach, the site was prepared by clearing vegetation cover (see Fig 2), sealing the crack with concrete (or clay where applicable), and backfilling with soil. The top is sealed with alternating geotextile and HDPE layers. Finally, a layer of gravel is placed over the structure.

Life cycle assessment procedure

Life cycle assessment was performed using Simapro 8 software and the EcoInvent life cycle inventory database following the ISO 14040:2006 procedure. The LCA was used to evaluate the environmental impacts resulting from allowing ingress of surface water and eventually generating an equivalent amount

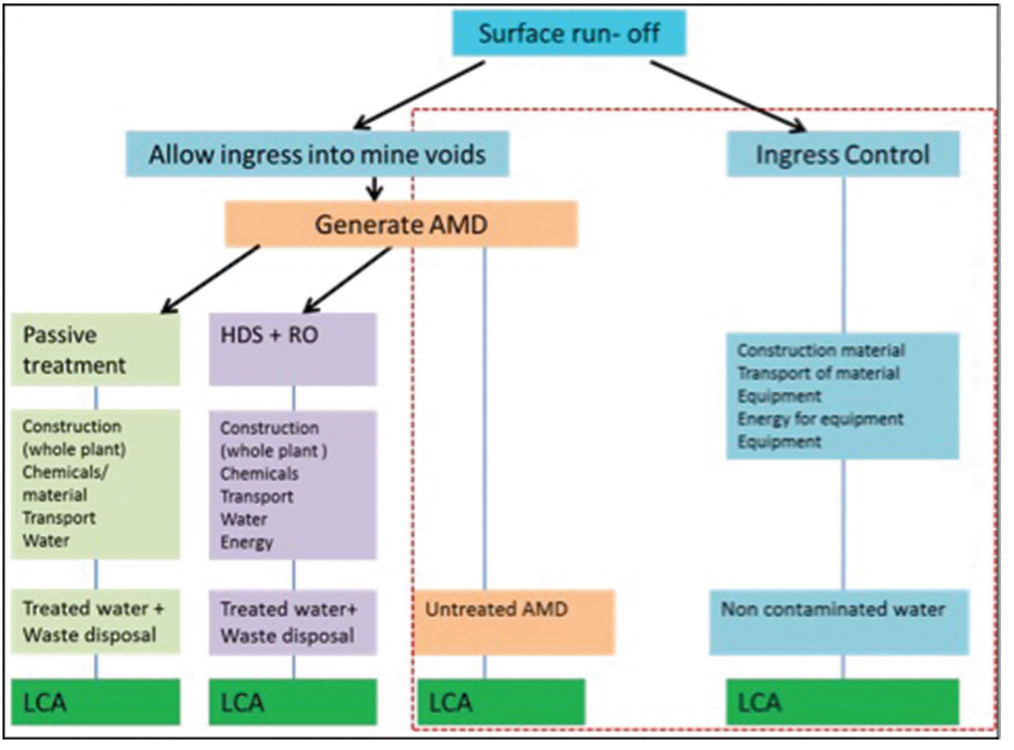

Figure 1 *Flow diagram illustrating the potential fate of water in ingress environment and steps leading to contributing to the LCA.*

Table 1 *Physicochemical parameters of the acid mine water used for LCA modelling.*

ORP	486.2	Ni	4.40
34	2.9	254	5.20
pH	3.36	K	1.56
EC (µS/cm)	7 679	Li	0.68
TDS (mg/L)	4 991	Sr	0.57
acidity calc (mg/L)	2 342.54	Cu	0.18
*SO_4^{2-}	6 686	Be	0.13
Mn	374.70	Rb	0.12
Ca	290.38	Se	0.089
Al	285.34	Cr	0.056
Mg	278.45	As	0.053
Na	53.26	U	0.04
Cl-	24	Cd	0.039
F-	14.94	Ba	0.021
Zn	13.17	Mo	0.0066
Co	9.32	Tl	0.0055
Fe	5.86	V	0.0029
NO_3^-	5.00	Ga	0.0022

*The concentrations of elements are given in mg/L.

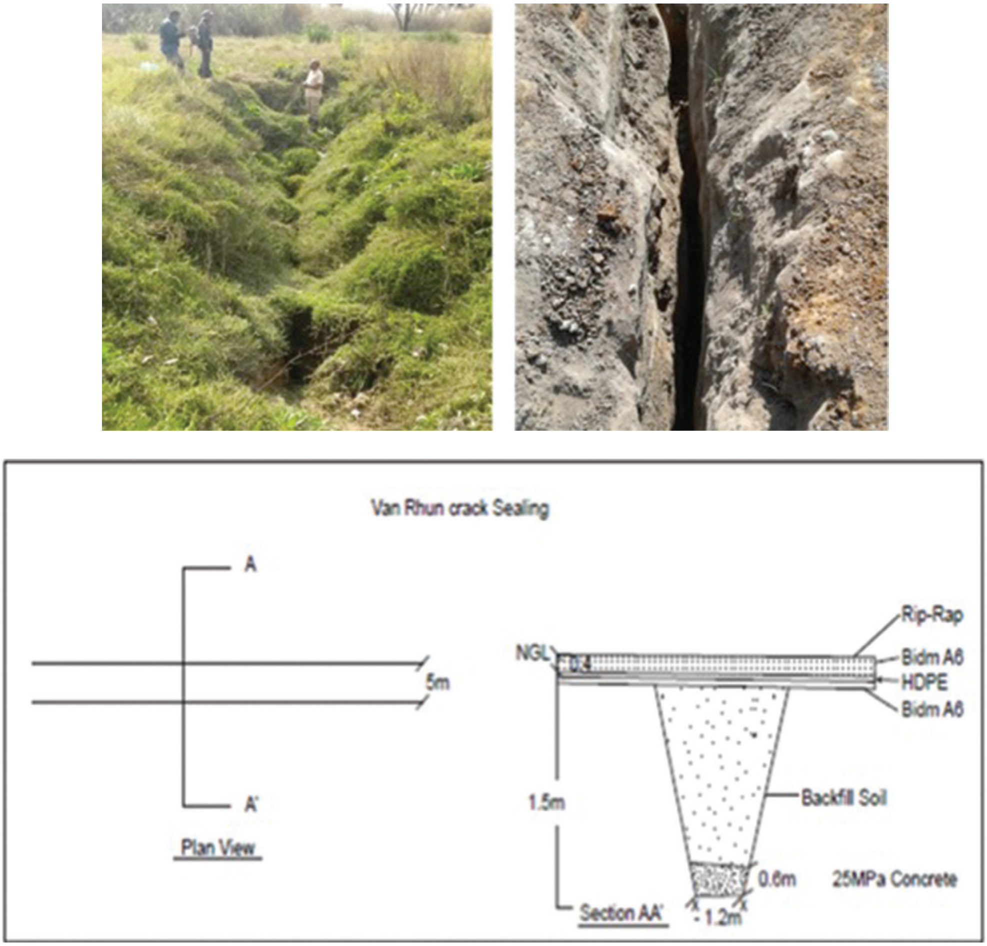

***Figure 2** Modderbee ingress point as seen in the field (Source: Tegegn and Coetzee 2017).*

of AMD and the impact resulting from preventing ingress by constructing an 'ingress control structure'.

System boundary

The system boundary defines the limits of the system being modelled. The system boundary was set at from the point of potential ingress to the point of release of the resulting water (from either scenario) into the environment.

The system included the raw material extraction, transport of the raw materials, and construction of the ingress control structure.

Functional unit

The functional unit, which is the unit of comparison/normalisation of the systems, was set to be 1 kg of acidity in the resulting water. Therefore, all the environmental impacts were normalised to 1 kg acidity for one year of activity. For every kg of acidity generated through allowing ingress, ingress control prevents a kg of acidity from being generated. Ingress of water on site was measured during different times of the year. In January 2016, the area was flooded and no measurement could be taken. In May 2016, the ingress of water was measured to be 6 L/s and in August the same year the area was dry. For this LCA, a flow rate of 6 L/s was used. Based on the chemistry of the water, a kg of acidity is equivalent to 16 L of AMD.

Materials and transport

There is no material required for allowing ingress. For ingress control, the clay is found on site, the geotextile and HPDE are sourced from a local supplier within 100 km radius from site.

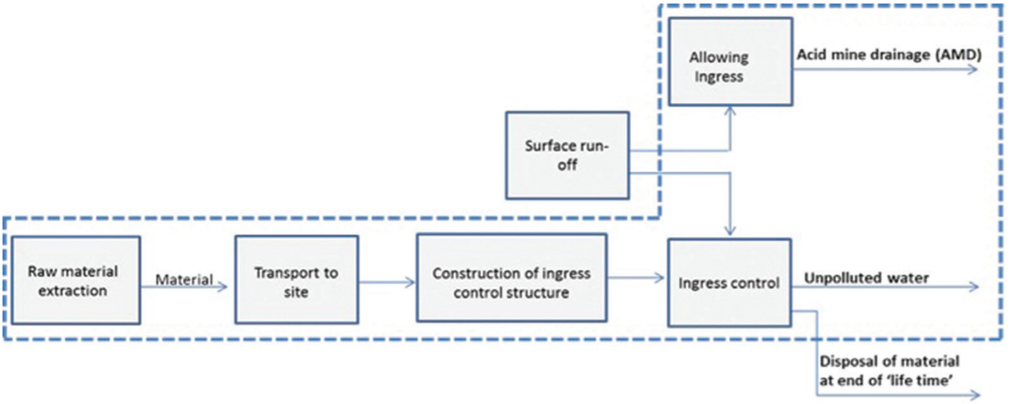

Figure 3 *System boundary for LCA on allowing ingress and ingress control.*

Operation and maintenance

There is no maintenance required for allowing ingress. The ingress control structure requires no maintenance during its prescribed lifespan.

Environmental impact assessment

The environmental impacts that were assessed during this LCA study were: damage to human health, damage to ecosystems and damage to resources.

Results and discussion

The biggest impact of allowing ingress is the generation of acid mine drainage. The acid mine drainage has a negative impact on human health and ecosystems. The natural resources required to generate AMD besides the water itself are negligible as shown in Fig 4(a), while ingress control impacts all three environmental impacts as shown in Fig 4(b).

Allowing ingress impacts on ecosystem occurs when AMD contaminates soil and water bodies on which ecosystems rely. Impact on human health occurs when humans come in contact with AMD, e.g. swimming in affected water bodies, and when they ingest through drinking water or eating crop exposed to AMD. The contamination of soil and water bodies is due to the potentially toxic elements such as As, Pb, U and Cr in AMD as well low pH that is characteristic of AMD.

Human health impacts due to the prevention of ingress of water into the mine voids Figure 4b is predominantly due to transportation of material to site. The manufacturing of polyethylene have the second highest on human health. Concrete has the least effect on human health, this effect results from the manufacturing of the concrete. For ecosystems, transport has the highest impact, followed by concrete and lastly, gravel. The production of polyethylene has the highest impact on natural resources, transport also contributes a substantially.

Transporting the raw materials and HDPE has more environmental impacts as compared to the impacts associated with concrete and gravel. This is because of the use of fossil fuel thereby depleting the natural resource. The burning of these fossil fuels during the transportation of raw materials and making of HDPE produce greenhouse gases such as CO_2 and methane. On the hand the making HDPE requires the mining of fossil fuels such as petroleum products. Gravel has the least impact to the environment because it was collected from site.it

Environmental impacts comparison

The difference in impact between allowing ingress and ingress control is significantly large and explicitly allocated as shown in Figure 5.

Allowing ingress has a significantly higher impact on both human health and ecosystems and a minor impact on resources as compared to ingress control. On the other hand, ingress control has significantly higher impact on resources. It also has an impact on health and ecosystems.

The higher impacts towards human health and ecosystem depletion due to allowing ingress is because of the formation of AMD. This results in the chemical weathering of

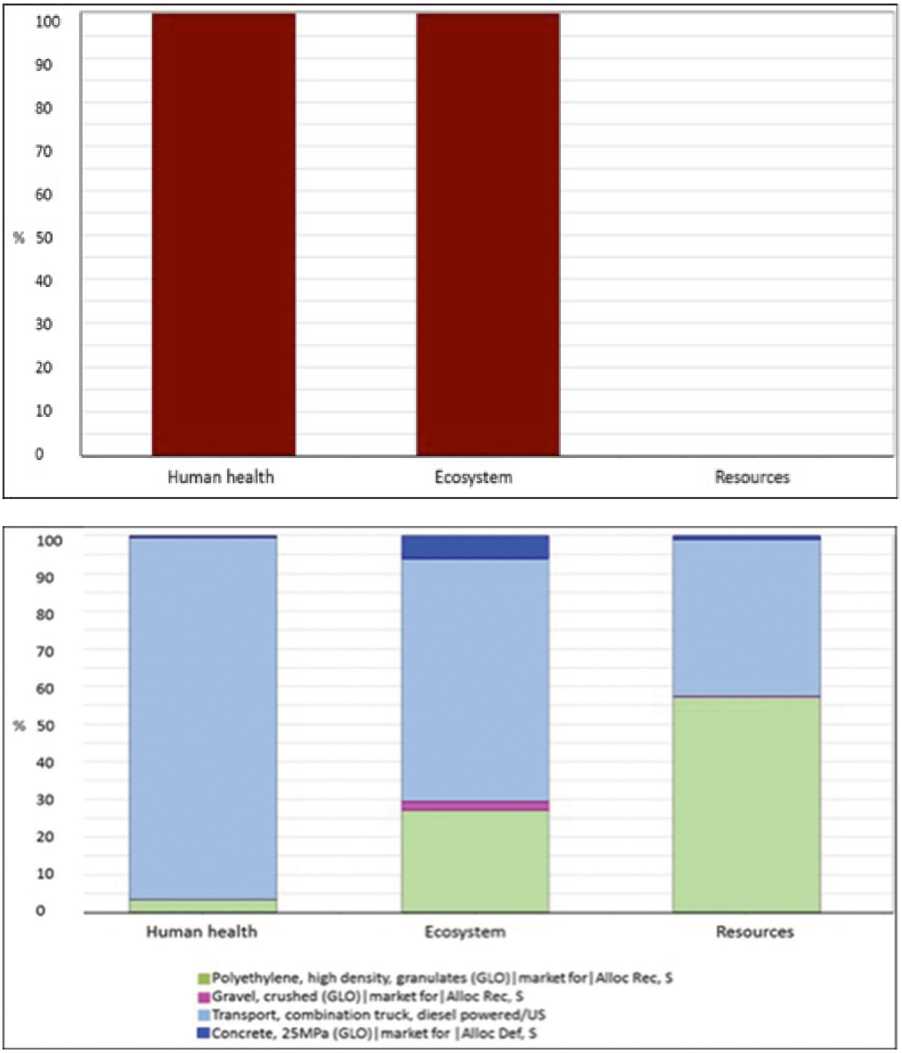

***Figure 4** Environmental impacts associated with allowing ingress (a) and prevention of ingress (b) on surface water and subsequent formation of AMD.*

the surrounding geology resulting in water containing potentially harmful elements and low pH. This makes the water not suitable for human consumption and causing drastic effects to the flora and fauna. Ingress control depletes the resources as shown in Figure 5. This is due to the various raw materials that are required to prevent ingress control. This raw materials are made from the resources that found in the environment.

Conclusions

According to this life cycle assessment, allowing ingress has substantial negative effects on two of the three assessment criteria; human health and ecosystem depletion. Alternatively, ingress control has a greater effect on resource depletion. This information enables decision makers to select a solution based on their preference and needs. In situations where natural resources are critical, it may be best to allow ingress and follow up with AMD remediation before it affect both ecosystems and human health. In cases where human health is critical, the option may be to implement ingress control. LCA is a valuable tool to assess the true environmental impacts of processes in order to enable wise

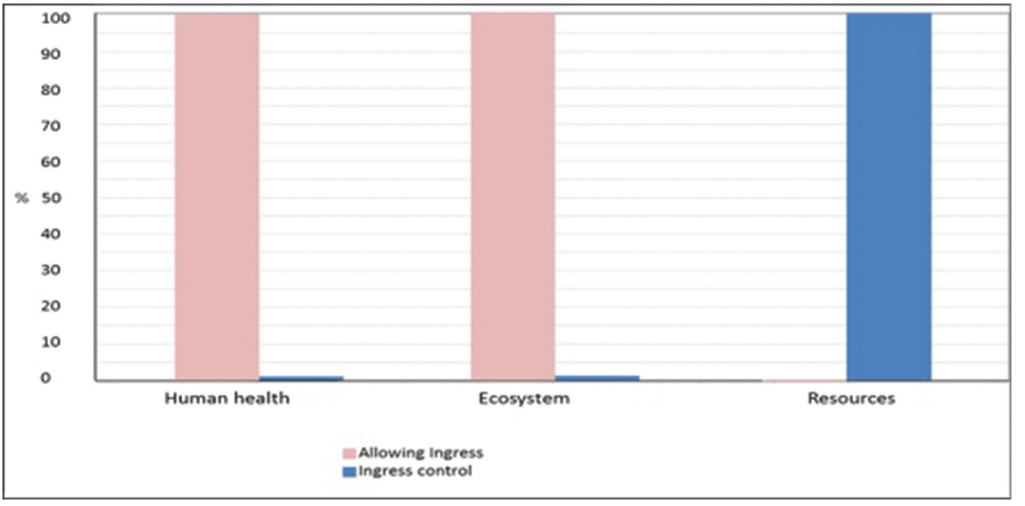

Figure 5 *The comparison of the environmental impacts due to the prevention of ingress and allowing ingress.*

decision making. The role of LCA is not to give a directive, rather, to reveal trade-offs for proposed solutions and scenarios.

Recommendations

It is recommended that LCA be continuously used in other projects to ensure that solutions proposed to stakeholders have been evaluated for environmental impact.

Acknowledgements

Our sincere appreciation goes to the management of Council for Geoscience for the support of the study and the Department of Mineral Resources and Energy for funding of the Mine Water Management project that allowed this study to be undertaken.

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