# Conceptual Project on Eliminating Acid Mine Drainage (AMD) by Directed Pumping

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## ABSTRACT

Acid mine drainage (AMD) poses a serious threat to water quality in the Witwatersrand region (South Africa), owing to extensive mine voids that have been abandoned, and subsequently flooded. In response to the severity of the situation, the South African government has undertaken construction of facilities to lower the water level to a safe depth (e.g. where no AMD decants into the surrounding surface- or groundwater) through pumping and treatment. It is proposed that the infrastructure that is currently being installed could better manage the problem by pumping from a greater depth than originally intended. It is hypothesised that the anoxic conditions at greater depth (ca. 2 km) will preclude the generation of AMD and hence reduce the need for treatment, while maintaining the desired water level below ground. The increased energy required for pumping from 2 km was calculated relative to the intended depth (just below the environmentally critical level). The expected energy increase was ≈10%, suggesting that it is feasible to use the existing/planned pumping infrastructure at greater depth. The effects of pH, temperature and initial availability of oxygen in reaction water on the formation rate of AMD from Witwatersrand coal waste rock have been quantified.

No statistically significant effects of initial oxygen availability, pH, or incubation temperature on the production of $SO_4^{2-}$ from coal mine waste rock were observed. In particular, decreased availability of $O_2$ in incubation water did not inhibit production of $SO_4^{2-}$. However, dissolved oxygen (DO) in many of the low DO treatment replicates increased, even though the incubation vessels were sealed, suggesting contamination.

The potential effects of pumping from depth on the aquifer were also investigated. In both cases, where oxygenated or low DO water was added to the surface and pumped from the bottom of an experimental column, the result was improved water quality with time (pH, EC, Fe, and $SO_4^{2-}$). However there is still considerable uncertainty as to whether this is a result of dilution without any formation of AMD or a result of dilution and no generation due to insufficient sulphide present to cause an ongoing reaction.

**Keywords:** Acid Mine Drainage (AMD), Acid Rock Drainage (ARD), Remediation, Pumping, Johannesburg.

## INTRODUCTION

Extensive gold mining activity around the Witwatersrand Basin (South Africa) has resulted in the formation of acid mine drainage (AMD). It is estimated that the potential AMD decant is in excess of 200 Ml/day, and contains high levels of sulphate and dissolved metals (McCarthy, 2011; Council for Geoscience *et al*., 2010). The South African government has awarded tenders to various industrial partners to mitigate the problem by pumping the water table down to just below the Environmentally Critical Level (ECL) by pumping from the ECL, and treating the resulting effluent using the High Density Sludge Process (HDSP) (Odendaal, 2013). This process is energy intensive, as it requires transport of large quantities of lime to the treatment site, pumping between tanks and treatment ponds, and disposal of the treatment residues. Pumping and treatment can only, however, be a temporary solution to the problem, as fresh AMD will continue to be generated in the mine voids for an indefinite length of time and will continue to require treatment.

In this work it was hypothesised that if water were to be pumped from a lower level, whilst holding the same ECL, acid might not be generated (following removal of the initial acid present in the void) as opposed to pumping from the ECL, where acid would continuously be generated by freshly aerated water. This hypothesis is based on the premise that at depth, oxygen is very limited in water. This effect can be observed in marine environments, where corrosion (due to oxidation) occurs in the surf zone, as well as in deep lakes, where the deep levels in the lake are anaerobic. This project sought to simulate anaerobic, subsurface conditions with a view to testing this hypothesis.

## LITERATURE

### Background

Acid mine drainage is generated in mine voids, primarily where pyrite-containing minerals are exposed to oxygenated water. The result is acidic water that is rich in sulphates and dissolved metals; in South Africa this frequently includes uranium (Cukrowska *et al*., 2008). Acid mine drainage poses a particular danger to the local environment of the Witwatersrand owing to the high number of abandoned mines and characteristics of the water table in this semi-arid region (Durand, 2012). Decant of AMD is a serious threat to the safety of communities and the environment of the Witwatersrand (Council for Geoscience *et al*., 2010).

The immediate geological region of the Witwatersrand is named the Witwatersrand Supergroup, and consists of sedimentary rock approximately 7500 m thick (Durand, 2012). The Witwatersrand groundwater table is mainly supplied by karst aquifers located in the adjacent Transvaal Supergroup. Water flows from these dolomite-rich aquifers into the Witwatersrand Supergroup, and many of the gold mines in the area are located below the water level of karst aquifers. Hence, millions of litres of water were pumped out daily during peak mining activity periods. Mining activity depressed the water table by as much as 3 km (Durand, 2012). Following cessation of mining activities and associated pumping, groundwater has ingressed into pyrite-rich mine voids left behind, and is currently discharging into rivers in the provinces of Gauteng and the North West.

Mine voids in the Witwatersrand region are classified into the western basin, central basin and eastern basin. The western basin alone has an estimated void volume of at least 45 Gl. Durand (2012) reports that decant of approximately 36 Ml of AMD per day was released from this basin into the Tweelopiesspruit river in Krugersdorp in 2010, although pumping undertaken at Rand Uranium has since reduced the decant considerably (Odendaal, 2013).

The severity of the AMD decant varies substantially with location. The water quality in the Witwatersrand Basin is seen to be most affected nearest mining operations, with some samples having pH < 2 and sulphate concentrations exceeding 7 000 mg/l in the worst cases (Cukrowska *et al.*, 2008). High concentrations of iron (up to 1 010 mg/l), as well as other metals including copper, nickel, cobalt and uranium were also reported.

In some cases, there are sufficient concentrations of uranium and other radioactive elements in mine decant and water bodies to pose serious risk to human health. For example, samples from some lakes near mining operations have been found to contain 14.8 mg/l of uranium, more than 1000× the safe limit for irrigation water of 10 µg/l (Durand, 2012).

## Mechanisms of AMD Generation

The mechanisms of AMD generation are extensively reported in literature. The principal process involved occurs when pyrite-containing rocks ($FeS_2$) are contacted by oxygenated water, where the overall reaction (Equation 1) occurs (Hallberg and Johnson, 2005):

$$FeS_2 + 15O_2 + 14H_2O \rightarrow 4Fe(OH)_3 + 18SO_4^{2-} + 16H^+ \qquad (1)$$

The above reaction occurs in multiple stages, and the primary oxidant is ferric iron instead of molecular oxygen – the attack of the ferric iron on the pyrite mineral occurs first, then the resulting ferrous iron is converted back to ferric iron by re-oxidation using oxygen dissolved in the mine water. Oxygenated water is therefore, essential for continuation of the cycle that produces acidity (Hallberg and Johnson, 2005). While this is a naturally occurring reaction, it is accelerated when large surface areas are exposed in mine voids and water and oxygen gain access to the minerals. While the reaction can occur in the absence of bacterial activity, micro-organisms such as *Acidithiobacillus ferrooxidans* can substantially increase the rate of generation (Akcil and Koldas, 2006). As a result of the low pH, metals leach out of the solid state further contaminating the water. In the Witwatersrand, the primary metals of concern are manganese, aluminium, iron, nickel, zinc, cobalt, copper, lead, radium, thorium, and uranium (Durand, 2012).

## Current Management Strategies

Three priority areas have been defined in the Witwatersrand (Council for Geoscience *et al.*, 2010):

- Prevent uncontrolled decant. This is to be accomplished by pumping water out of the voids to keep the water table below the ECL.
- Limit the ingress of water into the mineshafts. This is to be accomplished by sealing as many large openings as possible.
- Treat the water removed from the voids before being released to the environment. This could be through neutralisation with lime, passive remediation in limestone beds, bioremediation using aerobic wetlands, bioreactors and more (Hallberg and Johnson, 2005). In situ and passive methods are currently regarded as unfeasible for the Witwatersrand Basin due to the size and complexity of the voids as well the large decant rates expected. The expected cost of active treatment of the discharge is ZAR11 /$m^3$ (Council for Geoscience *et al.*, 2010); approximately USD1.1 /$m^3$.

In response to the AMD problem, these strategies are currently being implemented. The state-owned Trans-Caledon Tunnel Authority (TCTA) awarded a R319 million contract to Group Five Engineering in December 2012 (Odendaal, 2013) to construct pumping stations and HDSP treatment facilities for the central basin. In the western basin, upgrades are being carried out on the existing pumping and treatment facilities at Rand Uranium in order to expand capacity. Due to cost constraints, construction of pumping systems in the eastern basin has been postponed (Odendaal, 2013).

### Increasing Pumping Depth

Previous work has shown that by increasing the pumping depth (Figure 1), the energy requirements do not increase as much as might be expected, *e.g.* depending on the initial conditions, doubling the pumping flowrate may only result in a 10% increase in the energy requirement (Figure 2) (Janet et al. 201x). In this paper, we present results of experiments conducted to determine if it is in fact possible to prevent the formation of AMD by using this strategy.

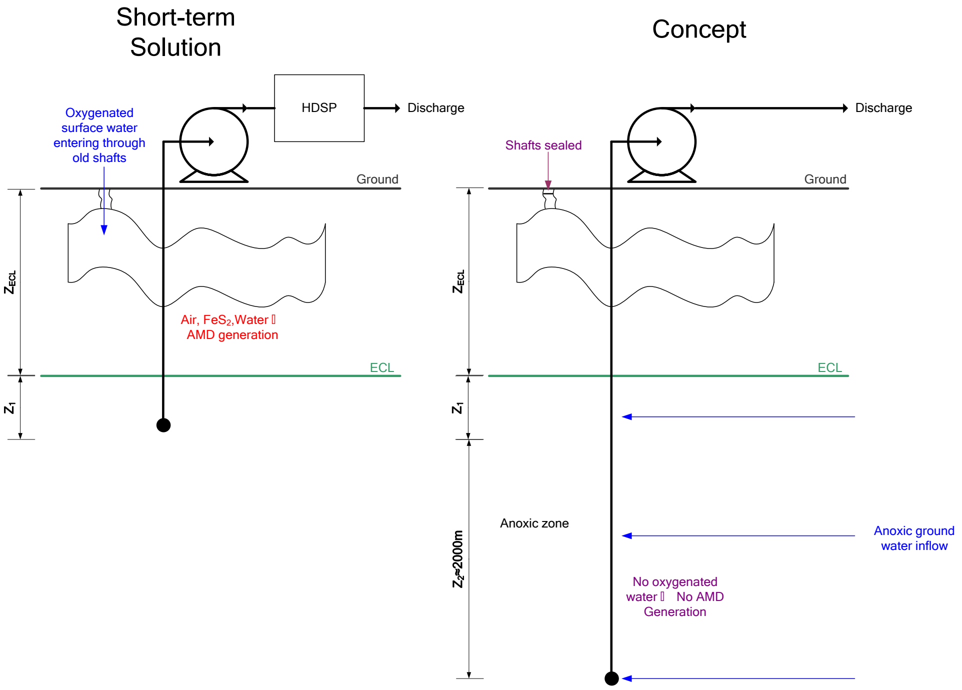

**Figure 1** Schematic comparison of current short term intervention plan (left) and the proposed concept of pumping from depth (right) From Janet *et al.*, 201x

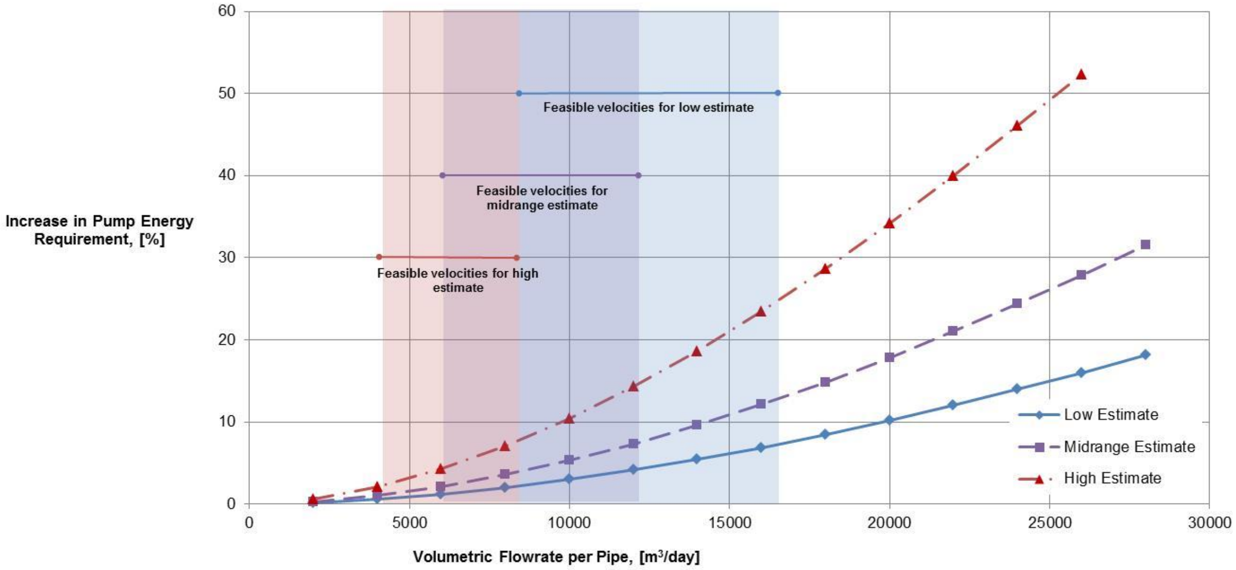

**Figure 2** Comparison of percentage increase in pumping energy when increasing pumping depth for three scenarios (low, mid and high estimates) (Janet *et al*., 201x)

## METHODOLOGY

Three PVC column reactors (6 m × 30 cm) were set up with pyrite-rich waste rock representative of an AMD-generating ore body (Figure 3), kindly provided by Optimum Coal. Each reactor had a solid casing installed in the centre, in which a peristaltic pump suction line could be inserted. The reactors had a cap at the surface to prevent air entering the system. Deoxygenated water was prepared by continuously bubbling nitrogen through a feed tank. Double head Watson and Marlow peristaltic pumps drew water from the base of each column whilst pumping deoxygenated water into the top of the column at the same flow rate of 31 ml/hour (equal to the net rainfall in the Witwatersrand). This equated to a 9 week hydraulic residence time.

The three columns were set up as follows:

- Column 1: Potable water added to surface, effluent (mimicking groundwater) removed from the base and DO, pH and $SO_4^{2-}$ measured. This investigated what would happen if the only source of water was percolation from the ground surface, mimicking the generation of AMD at the surface. The experiment was also designed to demonstrate potential remediation of AMD as the recharge passed through the aquifer.
- Column 2: De-oxygenated water added to the surface, effluent (groundwater) removed from the lowest level and DO, pH and $SO_4^{2-}$ measured. This experiment was designed to indicate whether AMD formed under anaerobic conditions.
- Column 3: De-oxygenated water added to different depths along the side of the central casing, effluent (groundwater) removed from the lowest level and DO, pH and $SO_4^{2-}$ measured. The column was initially filled with previously boiled water and purged with nitrogen prior to and during filling to minimise DO. This experiment sought to reproduce ingress of DO-poor water at different depths, as would be expected in an aquifer.

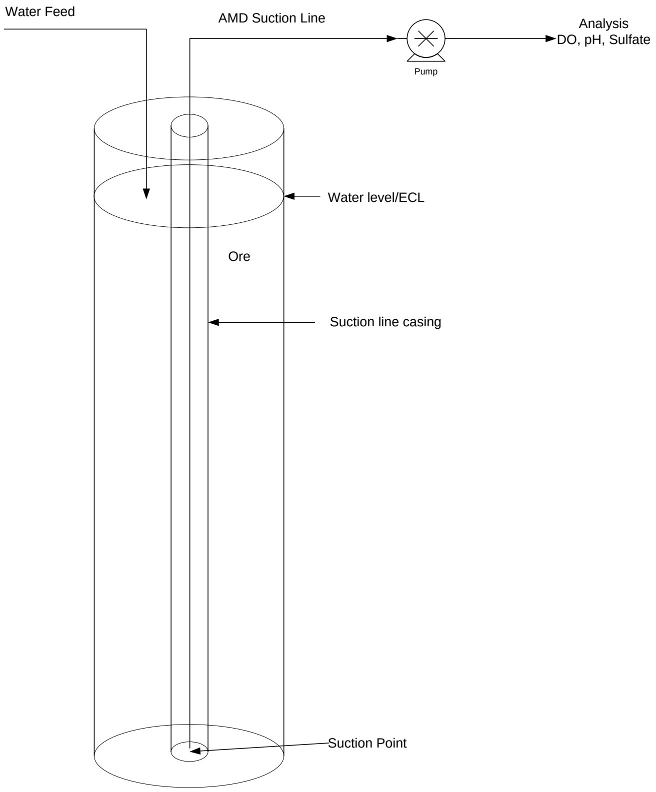

**Figure 3** Column reactor, showing feed ingress at the top and effluent removal via a casing in the centre of the column

Upon completion of the initial experiments, Columns 1 and 3 were purged with air whilst still full of water for a period of 30 min in an attempt to generate additional acid such that it could be assured that the results seen were not as a result of the rate of dilution being greater than the rate of acid generation.

Sample DO, EC and pH values were measured using a handheld Consort C5010 multiprobe, which was calibrated prior to each use. Iron and sulphate were measured using a Merck Pharo 300 spectroquant, using test kit 1.14671.0002 for iron and test kit 1.14791.0001 for sulphate. Samples were prepared and analysed according to the manufacturer's directions. Measurements inside the columns (temperature and pH) were taken using a Hydrolab MS5 EC-pH probe.

## RESULTS AND DISCUSSION

### Comparison of Column 1 (oxygenated feed) with Column 3 (de-oxygenated water feed)

The change in pH of the columns' effluent is shown in Figure 4. Acid was rapidly generated in both columns and the pH gradually rose thereafter. The low DO column (Column 3) had a slightly higher pH than Column 1 after 5 weeks.

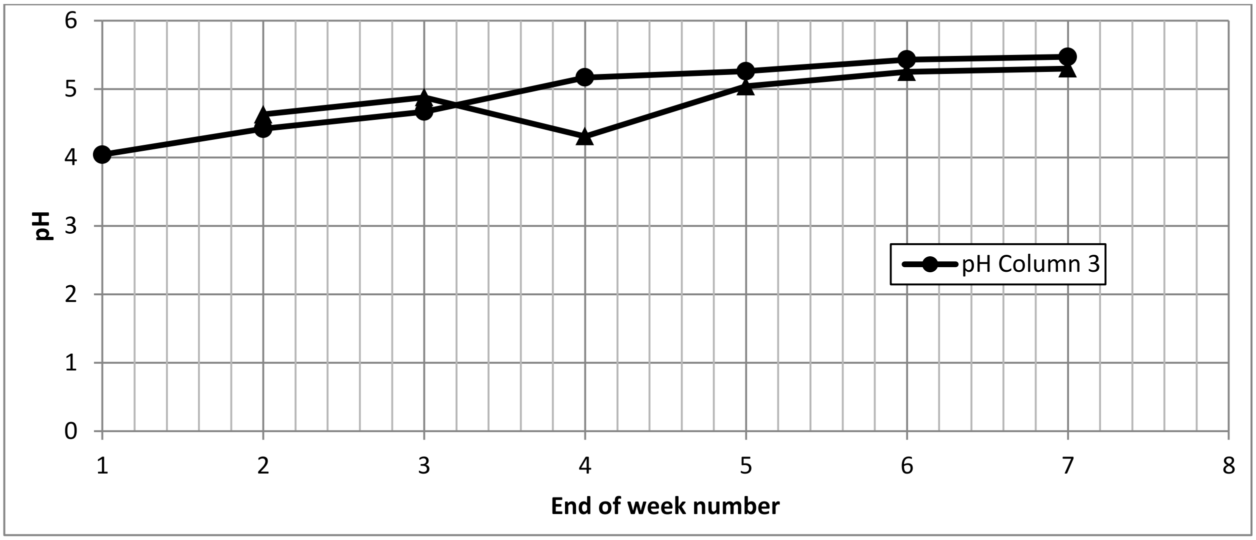

**Figure 4** The pH in both columns over time

The DO concentrations in columns 1 and 3 are presented in Figure 5. The values were erratic, although there seemed to be a decrease in DO with time, suggesting that available oxygen was utilised as the reactions proceeded. However, the DO probe was adversely affected by low pH and high sulphate values; these data are not reliable.

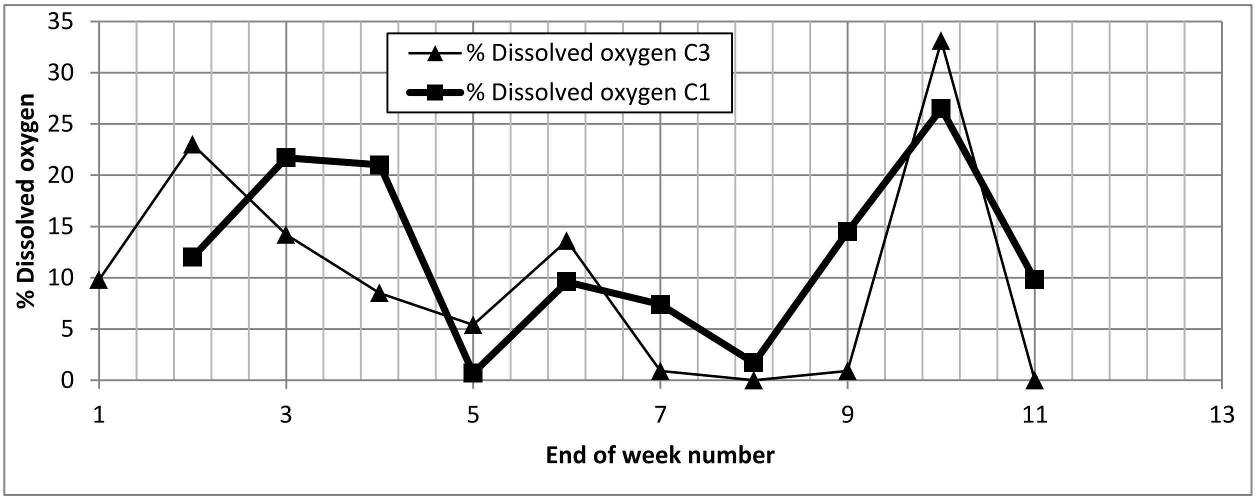

**Figure 5** Dissolved oxygen in Columns 1 and 3, showing erratic nature of the data.

Both sulphate and iron concentrations in Column 1 rose rapidly and then decreased (Figure 6). The sulphate values fluctuated substantially throughout the experiment. It is believed that this is a result of the type of analysis used. It is understood that the BaCl test would give significantly more accurate results, and this is recommended for future work. The iron was shown to decrease.

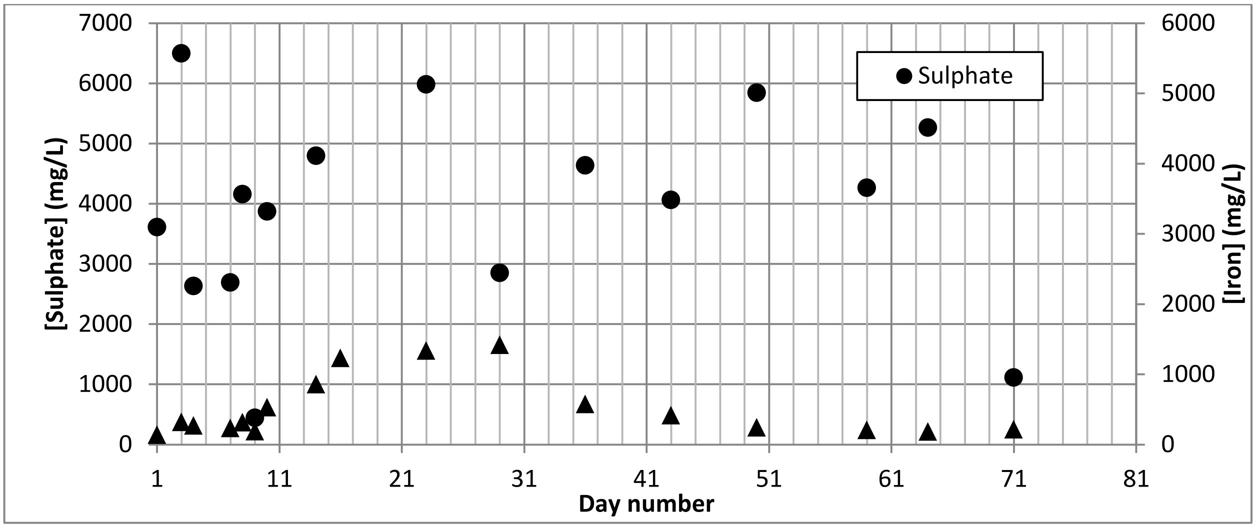

**Figure 6** Variation of sulphate and iron in Column 1

The change in sulphate and iron in Column 3 is shown in Figure 7. Similarly to Column 1, concentrations rose rapidly within the first day and subsequently decreased. The two columns reached similar initial values and both showed a decreasing trend with time. The variation of the sulphate concentrations is once again observed.

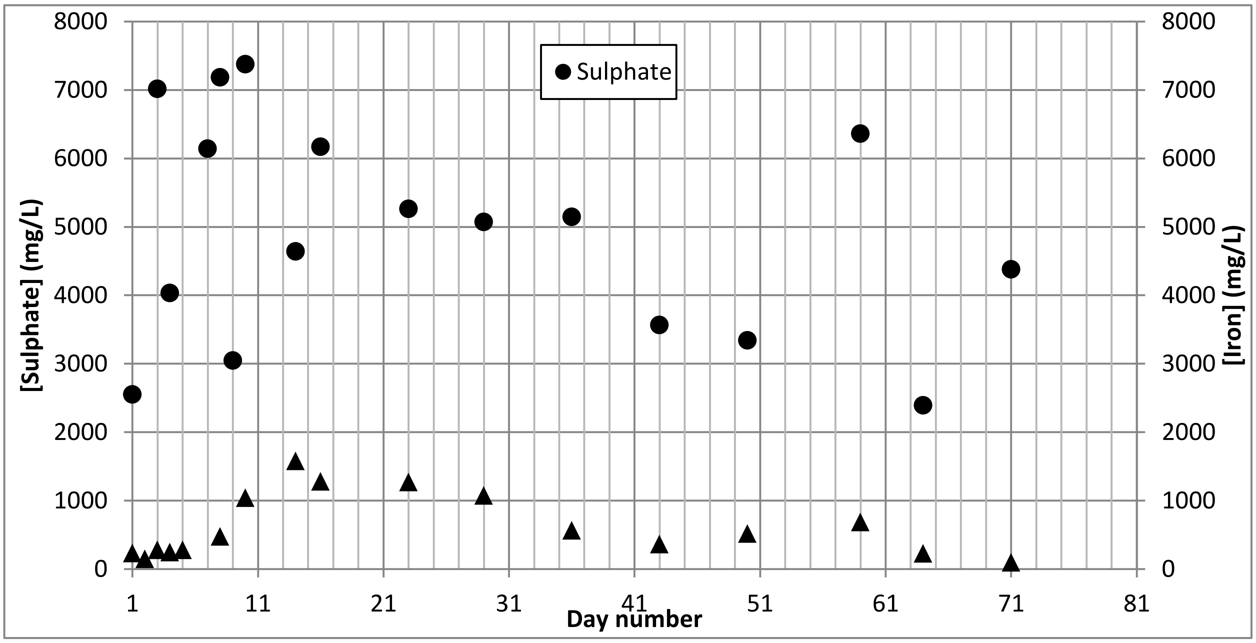

**Figure 7** Variation of sulphate and iron in Column 3

Figure 8 illustrates the results when we inserted a Hydrolab MS5 autoprobe onto Columns 1 and 3. The Hydrolab MS5 auto probe, able to measure and record pH, EC and temperature was initially placed in Column 3 from 28 March 2014 to 16 April 2014 and then transferred to Column 1 from 16 April to 23 April. Whilst the probe did not record the beginning of the experiment in Column 1, the data recorded clearly showed an increase in pH, and a decrease in EC (Figure 8), and in Figure 9 the data are presented for Column 3. The rise in pH is particularly evident in the low DO experiment where the pH increased by 1.5 and EC decreased by approximately 25% .

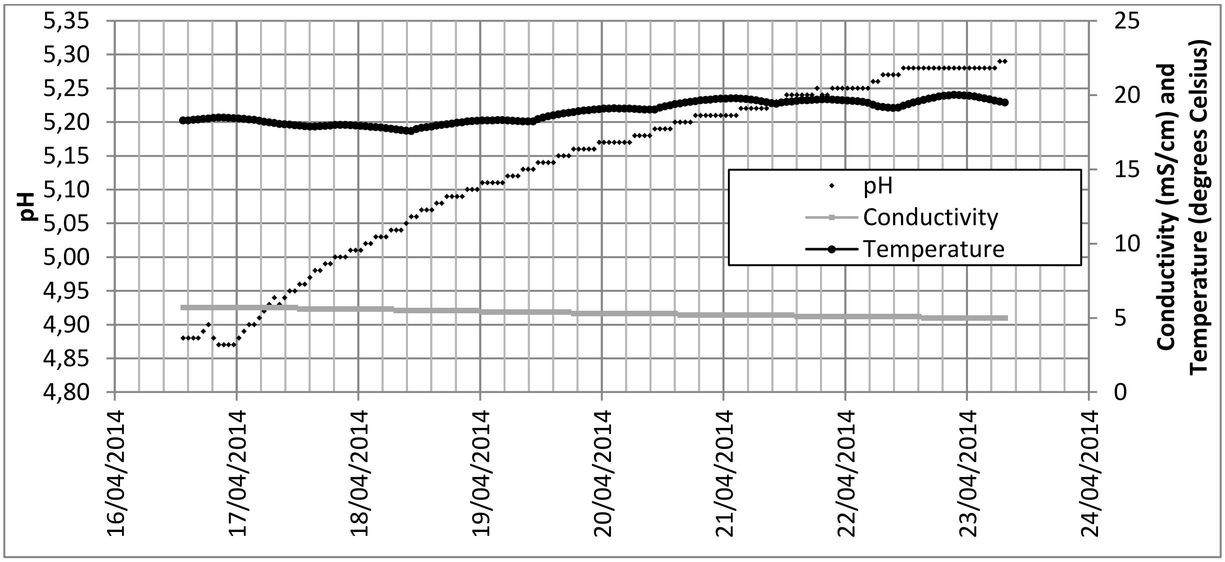

**Figure 8** Temperature, pH, and EC profiles within Column 1

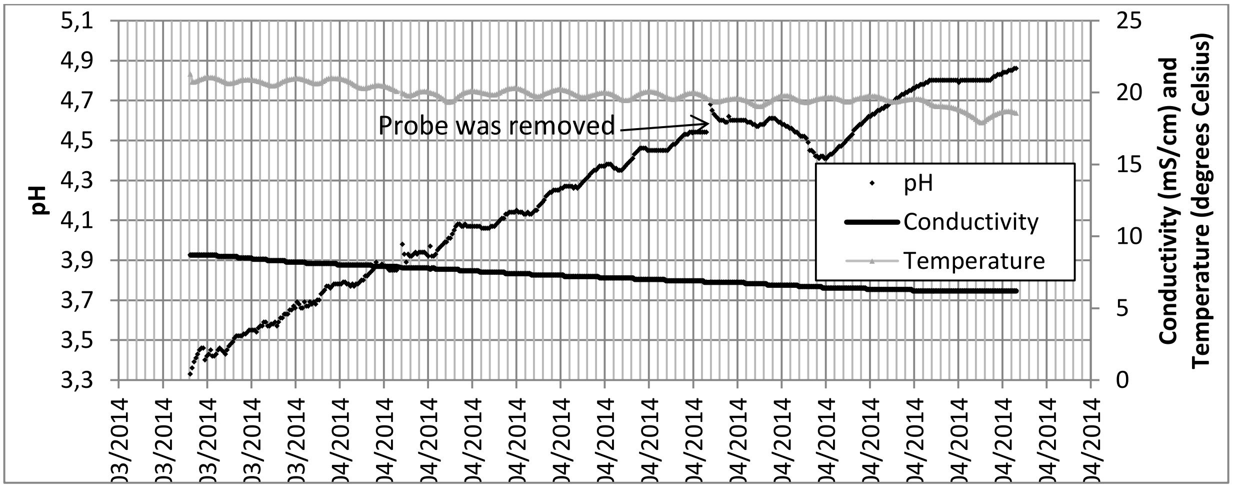

**Figure 9** Temperature, pH, and EC profiles within Column 3.

The long-term measurements obtained from use of the Hydrolab probe indicated that by pumping from the bottom of the column, water quality improved and that improvement occurred regardless of the oxygen content of the feed.

## CONCLUSION

It has been shown that the energy to pump water from 2 km below surface is not substantially different from removing water from just below the ECL. It has further been demonstrated that acid is rapidly generated by waste rock. With time, all water quality parameters improved significantly by pumping water from the base of the columns where AMD was unable to form. It was not possible to conclude whether this improvement in quality was a result of dilution due to depletion of the mineral or if AMD was no longer being generated due to the establishment of anaerobic conditions. Future work to assess this will proceed.

## ACKNOWLEDGEMENTS

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