# High-Resolution Pit Water Quality Model for the Highway Reward Mine, Queensland, Australia

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## ABSTRACT

Field and laboratory data combined with computational modelling have been used to predict the pit water quality for the Highway Reward mine. Open pit mining of the Highway Reward copper-gold deposit has produced a final mining void with a diameter of 600 m and a depth of 280 m. This void will be left to fill with ground and surface water once pumping of pit water ceases. Several leaching tables were constructed to simulate weathering reactions and surface water run-off in the major pit wall units during a 200-day leaching experiment. To date, about three-quarters through the experiment, combined run-off from these cells has reached a pH <4, corresponding to actual present day pit water pH values and chemistries. While sulfide oxidation in the pitwalls leads to an acid, metal-rich leachate, bicarbonate-rich groundwater inflow during the dry season acts as a buffer. Acid generating salts appear to have only a small impact on the overall pit water chemistry. The kinetic test data have been combined with measured pit water chemistry data, measured surface and seasonal groundwater inflows, climatic data, and calculated pit lake surface area and volume to produce a high-resolution pit water quality model. This high-resolution pit water quality model will aid in the mine decommissioning process.

## INTRODUCTION

The mining of low-grade, large volume ore deposits will lead to an increasing number of open mining voids in the next 20 years (Stoddart, 1997). The range of realistic end-use options is limited for a specific mining void, thus many pits in Australia remain unfilled. Most of these voids flood once pumping is discontinued, and the water of the final mining void may interact with the local groundwater. In most of inland Australia, water supplies for human consumption and livestock use largely rely on groundwater resources. Hence, the prediction of final mining void hydrology and water quality is of growing importance as the mining industry increases open pit mining and more open pits undergo closure. Several physical and chemical processes thereby appear to determine the water quality of open pit lakes and surrounding aquifers. In particular, weathering reactions in pit walls and wastes draining into the pit have been identified as the key processes (Eary, 1998, 1999; Shevenell, 2000; Heikkinen *et al*, 2002). However, most studies lack the resolution to accurately predict the water quality in a developing open pit. Thus, this case study aims to predict the future pit and groundwater quality of an open pit environment using computational modelling in combination with detailed climatic, hydrological, hydrogeochemical, geochemical and mineralogical data.

## SITE DESCRIPTION

### Physiography

The Highway Reward copper-gold deposit is located at 20°22' S and 146°12' E, approximately 35 km southwest of Charters Towers, Queensland, Australia (Figure 1). The open pit is situated in a subtropical region with distinct dry and wet seasons. The average annual rainfall amounts to 650 mm and much of the precipitation occurs as high intensity rainfall events between November and April.

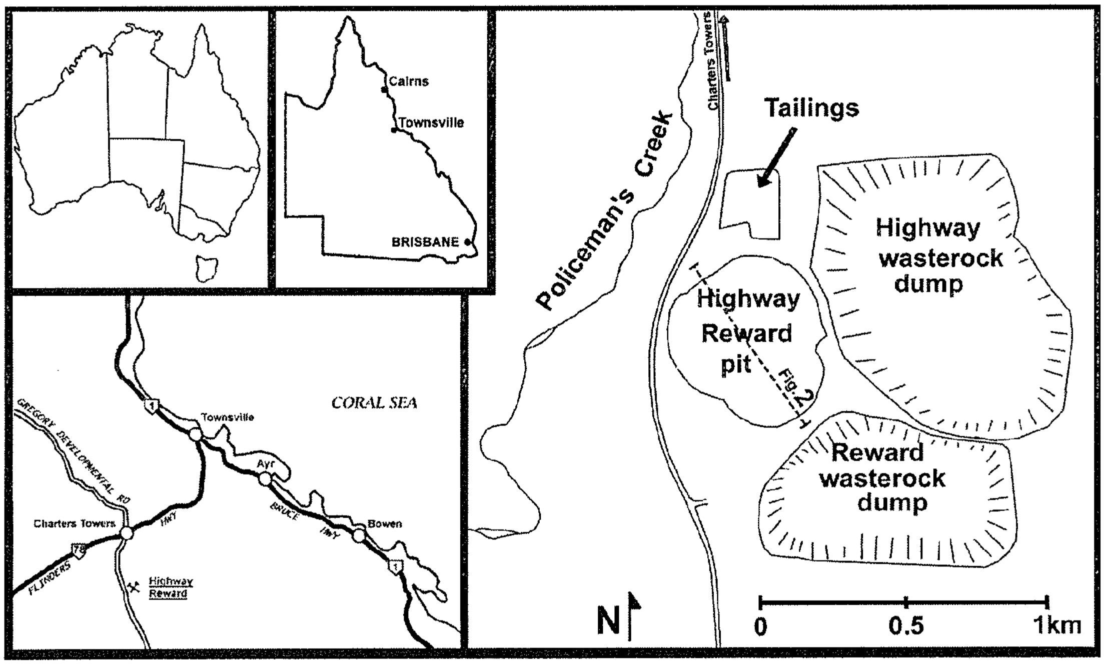

FIG 1 - Location of the Highway Reward pit.

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## Geology

The deposit is hosted by the late Cambrian Mount Windsor volcanics and is as such part of the late Cambrian – early Ordovician volcano-sedimentary Seventy Mile Range Group (Henderson, 1986). Together with the underlying Puddler Creek Formation and the overlying Trooper Creek Formation, the Seventy Mile Range Group forms a succession of andesitic pillow lavas, rhyolites, dacites and interbedded, epiclastic, deep-marine sediments (Henderson, 1986; Beams, Laurie and O'Neill, 1990). Copper and gold mineralisation occurs as discrete lenses within sub vertical massive sulfide lenses that are thought to be of submarine, exhalative origin (Henderson, 1986). Weathering of the orebody and the surrounding host rock is variable, ranging from 10 m to 70 m in the Highway section and to a depth of 120 m in the Reward section (Kevin Rosengren and Associates Pty Ltd, 1998). The deposit is partly overlain by 60 m thick Tertiary sediments, the Campaspe Beds (Figure 2). This regional cover sequence consists of coarse conglomerate, ferruginous clay and silt and is in places more than 100 m thick, filling palaeochannels and hosting numerous groundwater reservoirs (Pitt, 1988) that represent regionally significant ground water resources.

## Mining history

Mining of the deposit for gold commenced in 1979 as a small open cut operation, which produced 22 kg of gold until its closure in 1983. Cyanide leaching operations resulted in the presence of a small tailings dam on site. In the 1980s, extensive exploration located two separate massive sulfide Cu-Au orebodies at depth below the former workings. Subsequent development and mining of these resources resulted in the 150 m deep Reward pit and later in the intersecting 280 m deep Highway pit (Figure 1). Processing of the extracted ore was done off site, 100 km from the Highway Reward mine. The open cut mine ceased production in April 2002 and mining of the remaining resource below the open pit is now being completed by underground mining methods. Open pit and underground mining has resulted in the generation of large volumes of waste rock. Much of the waste rock is stored in two separate waste rock dumps (Figure 2). The older dump containing material from the Reward pit has been capped and revegetated. The younger dump contains waste rock from the Highway pit and is currently being rehabilitated. The final void has a diameter of 600 m, which will be left to fill with ground- and surface water once pumping ceases. During the 2000/2001 wet season, a major rock-slip occurred, destroying the haul road at the western section of the Highway pit. As a consequence, a second pit access was constructed by partly backfilling the remaining Reward pit with massive sulfide waste rock from the floor of the Highway void (Figure 1). Previous studies (GHD, 1999) concluded that partly backfilling the pit would have no detrimental impact on the water quality of the final pit lake; albeit it would take 83 years for the water level to reach equilibrium and to cover the backfilled waste rock completely.

## MATERIALS AND METHODS

### Pit wall surfaces

Weathering of wall rocks releases constituents to surface waters which ultimately influence the water quality in the final pit lake. Hence, it is necessary to accurately determine the relative surface area of each individual rock unit present in the pit walls. The relative abundance of the different rock units exposed along the pit wall was established using the geological mine plan in combination with TurboCAD Professional 5. In order to assess the run-off contribution from the different rock units to the final pit water composition, a detailed mineralogical and chemical classification of the various rock types was completed. Eighty-three core samples were obtained from drill holes which intersect the present pit wall. The samples were sighted for their texture, mineralogy, sulfide morphology and weathering status. In addition, ten 5 kg wall rock bulk samples were collected at representative sites along the haul road. Sample aliquots were milled in a chrome steel ring mill. Sample powders were dissolved in a hot $HF$-$HNO_3$-$HClO_4$ acid mixture, leached with HCl and analysed by inductively coupled plasma atomic emission spectrometry (ICP-AES) for Al, As, Ba, Ca, Cd, Cu, Fe, K, Mg, Mn, Na, Pb, S, Sb, Se, Si and Zn (Australian Laboratory Services, ALS, Brisbane). The mineralogy of the bulk samples was determined by X-ray diffraction (XRD) at the Advanced Analytical Centre (AAC), James Cook University (JCU), Cairns.

### Mineral efflorescences

Secondary minerals were collected from pit walls and waste rocks along the haul road. Samples were generally scraped off with a knife into an airtight HDPE bag or polystyrene sample container. Other samples included pit wall rocks coated with secondary minerals. Samples were processed under an optical microscope whereby the secondary minerals were separated from their substrate. The efflorescences were identified using XRD at the JCU AAC.

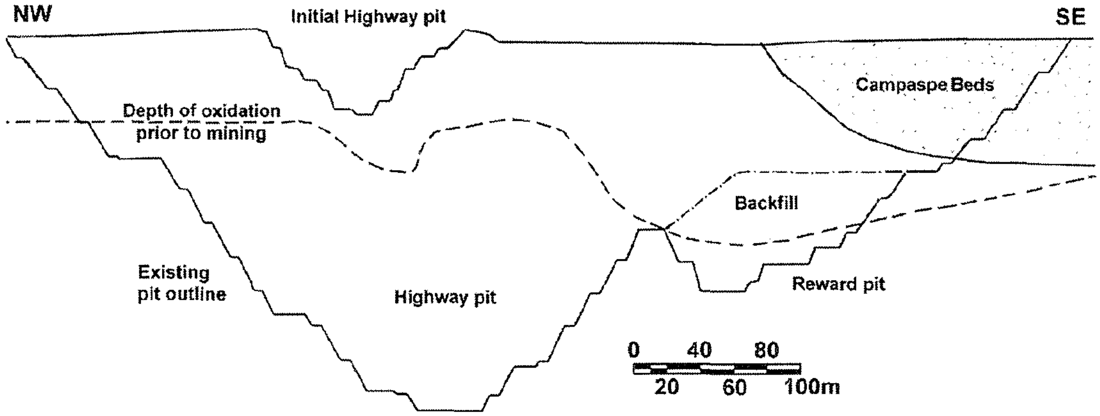


FIG 2 - Cross-section through the Highway Reward pit.

## Seasonal groundwater characteristics

Groundwater was sampled from nine different groundwater seeps flowing into the pit (April and November 2001). Flow rates were measured as volume/time at the discharge points. Measurements of temperature, pH and conductivity were conducted in the field using a Horiba U-10 water quality checker. Samples bottles for dissolved metals were filled, sealed with no headspace and kept on ice. Laboratory analysis was conducted within 24 hours of sample collection at the JCU Australian Centre for Tropical Freshwater Research (ACTFR), Townsville. Samples were analysed for Al, As, Ba, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, Pb, Sb, Se, $SiO_2$ and Zn as well as pH, conductivity, alkalinity, hardness, TDS, nitrogen, sulfate, chloride, bicarbonate and carbonate. Prior to analysis the water samples were filtered through 0.40 μm filter paper. The solids accumulating on the filter paper were investigated with a JEOL 6300 scanning electron microscope fitted with an energy dispersive X-ray microanalyser system (SEM-EDS) at JCU AAC, Cairns. SEM-EDS data were then compared with the output files from the geochemical simulation computer program PHREEQC 2.3.

## Wall rock leaching experiments

The leaching of pit wall rocks is the most influential factor determining pit water quality. Procedures simulating the leaching of pit walls must be practical and closely reassemble conditions in the field. Minewall stations as described by MEND (1995) are very maintenance intensive and prone to damage on site. Leaching columns as described by Pillard *et al* (1996) on the other hand do not physically nor chemically represent a pit wall surface.

The weathering and leaching behaviour of the pit wall rocks in the presented study were simulated using leaching tables. Ten leaching tables of the size 40 × 60 × 5 cm were constructed from high-density polyethene (HDPE). The bulk samples from representative sites along the haul road were screened, and rock sizes >3 cm ∅ were washed with deionized water to separate and retain the soluble mineral fraction prior to cutting the rock in half. The halves were then glued with their cut side onto the leaching tables, with the uncut sides representing the solid pit wall. The water used for cleaning the samples was evaporated, and the evaporate together with the finer rock material was evenly applied onto the pit wall samples present on the leaching tables. The leaching tables were placed undercover with temperatures and humidity being similar to the mine site. The rock surface on each table was determined and the rainfall in mm/day was recalculated into ml/day for each individual leaching table. Water to the ten leaching tables was applied with a spray gun in a manner which simulated rainfall at the mine site. The period from November 1998 to April 2000 served as a basis for the rainfall values. These data were chosen, as they closely resembled the long-term rainfall data for the Highway Reward site.

The duration of the 200-day accelerated kinetic experiment represents an actual time period of 1.5 years. This was achieved by drastically reducing the dry periods during which the oxidation is thought to be negligible (Fennemore, Neller and Davis, 1998). Run-off from the leaching tables was collected daily and measured for volume, pH and conductivity. Throughout the 200-day experiment, 12 leachate samples per table were collected and analysed by ICP-AES and inductively coupled plasma mass spectrometry (ICP-MS) for Al, As, Ba, Ca, Cd, Cu, Fe, K, Mg, Mn, Na, Pb, S, Sb, Se, Si and Zn at the JCU AAC, Townsville. In addition, two short-term leaching experiments were conducted on one of the most acidic leaching tables. The experiments simulated two major rainfall events of 44 mm and 139 mm per day over 160 and 480 minutes, respectively. The simulated rainfall was sprayed onto the tables in 16 and 48 regular 200 ml increments. Conductivity and pH of the run-off were measured and plotted onto charts to assess the influence of easily soluble acid generating salts (AGS) on the run-off quality.

## Modelling

Daily water volume and pit lake surface area in the void were calculated using the 1 m contour lines of the mine plan and long-term climate data in combination with TurboCAD Professional 5 and Excel spreadsheets. Volume calculations followed the general outline described by Tempel *et al* (2000).

$$\Delta S = P - E + R + GW_i - GW_o + SW_i - SW_o$$

where:

$\Delta S$ = change in the ground water storage in the pit lake

P = precipitation

E = evaporation

R = run-off from the pit walls

$GW_i$ = groundwater inflow

$SW_i$ = surface water inflow

The water balance in the pit was calculated on a daily basis utilising the 1998 - 2002 rainfall and evaporation records from the mine site. Groundwater inflow rates were assumed to remain constant at the measured levels. Once the height of groundwater inflow reached the pit-lake surface, groundwater inflow from this site was assumed not to add anymore to the overall pit-lake volume. The leachate contribution from the different wall rock units to the pit lake was calculated from the relative abundance of the wall rock units and the leachate compositions obtained from the leaching experiments.

Results of the mineralogical identifications, groundwater investigation, leaching experiments, evolving pit lake volume and lake surface, pit morphology and local meteorological records are used in combination with PHREEQC 2.3 and the hydrodynamics tool DYRESM-CAEDYM to model the complex physical, limnological and chemical development of the future Highway Reward pit lake. Final modelling results are outstanding as of November 2002.

## RESULTS AND DISCUSSION

## Pit walls

Rock units exposed along the pit walls consist of 13 per cent dacite, 32 per cent rhyolite, 12 per cent breccia, ten per cent metasediments, 12 per cent alluvial sediments, and 17 per cent massive sulfides (pyrite-chalcopyrite-sphalerite). The relatively high percentage of massive sulfides exposed in the pit wall is due the partial backfilling of the Reward pit with sulfidic waste rock. Furthermore, inspection of the 83 core samples showed that 72 samples (87 per cent) contain pyrite either as massive or disseminated pyrite grains in the rock mass. Only 11 samples (13 per cent) are free of pyrite and all but one of the pyrite free samples originate from the oxidised zone of the deposit.

The wall rocks, which were used to construct the leaching tables, contain major quartz, pyrite, biotite, albite and plagioclase. Minor components include chalcopyrite, gypsum and clinochlore. Excluding the massive sulfide unit, the samples have an average sulfur concentration of 2.4 wt per cent. Calcium concentrations are below 0.4 per cent in all but two samples highlighting the low acid neutralising potential (ANP) of the host rocks. Maximum concentrations for As (1050 ppm), Cd (87 ppm), Cu (2.71 wt per cent) and Zn (3.22 wt per cent) are reached in the massive sulfide samples.

## Mineral efflorescences

Secondary minerals occurring on the pit walls include römerite ($Fe^{II}Fe^{III}_2$ $(SO_4)_4$ $14H_2O$), copiapite ($Fe^{II}Fe^{III}_4(SO_4)_6(OH)_2$ $20H_2O$), epsomite ($MgSO_4$ $7H_2O$), bianchite $(Zn,Fe)SO_4$ $6H_2O$), chalcanthite ($CuSO_4$ $5H_2O$), atacamite ($Cu_4Cl_2(OH)_6$), and gypsum ($CaSO_4$ $2H_2O$). Römerite and copiapite can be classified as acid generating salts (AGS) when dissolved in water. They cause low pH and high metal concentrations in the initial run-off with the onset of rainfall events (Bayless and Olyphant, 1993). Wetting and drying of the pit walls, oxidation of sulfides in the wallrock and acid weathering of gangue minerals produce acid run-off, which evaporates forming salt crusts.

## Groundwater

Groundwater, which enters the pit at a constant rate of 90 m$^3$/day, is sodium-chloride rich and has a pH ranging from 7.9 to 8.5 with the higher values occurring at the end of the dry season. Distinctly different TDS and hardness values as well as variable concentrations of Al, Ca, Cl, Fe, Na, Mg and Zn suggest that two different aquifers discharge into the pit. Groundwater entering at the northwestern wall of the pit has a lower conductivity and lower Ca, Cl and metal concentrations compared to the other groundwater samples. The lower elemental load suggests that groundwater seeping into the pit at the northwestern wall represents comparable young water. The seasonal Policeman's Creek could be the source of this particular seepage water.

At each groundwater seepage point, the physical and chemical parameters of the individual groundwaters remain constant during the dry and wet season (ie April and November 2001). Metal and metalloid concentrations, however, vary considerably, particularly Al, Fe, Mg, As and Se. Aluminium, Fe and Mg values are higher and As and Se values are consistently lower in the slightly higher pH groundwater collected in November 2001. Water accumulating at the pit floor has a pH ranging from 4.4 (April 2001) to 5.7 (November 2001). Water analyses revealed high concentrations of Al (2.5 - 8.1 mg/L), Cd (0.3 - 0.8 mg/L), Fe (12 - 101 mg/L), Mg (30 - 37 mg/L) and Zn (58 - 60 mg/L) with the higher values occurring in the lower pH water (April 2001). Arsenic and Se are more abundant in higher pH waters (pH 5.7), which is in agreement with their increased solubility at more alkaline conditions (Eary, 1999). The changes in pit floor water composition are thought to be due to a more alkaline groundwater dominated regime during the dry season (ie alkaline groundwater discharge >> acid run-off). Acid run-off water may dominate during the wet season (ie alkaline groundwater << acid run-off).

## Wall rock leaching experiment

The retention of some of the rainfall as porewater on the leaching tables resulted in the run-off volume from the tables being generally 120 ml less then the applied water volume. This implies that a corresponding daily rainfall of less than 2 mm does not produce any run-off, assuming a rainfall penetration depth of <3 cm into the wall rock and the application of water as intense rainfall events. In reality, the depth to which rainfall will penetrate the pit walls will vary considerably and rainfall events will be spread over 24 hours. Therefore, the volume of rainfall – needed to produce run-off – might be considerable higher in the open pit.

Preliminary data from the 200-day leaching experiment indicate that run-off from the pit walls will add acidic metalliferous leachate to the Highway Reward pit lake. Run-off water from the ten leaching tables have a pH value ranging from 3.2 to 8.5. Such a diversity in pH values is due to the different wall rock units present on the leaching tables. The abundance of pyrite in the wall rock and its oxidation contribute significant acidity. The chemistry of the run-off water appears to be controlled by pH, ranging from <100 µg/L Fe in the more alkaline water to 63 mg/L in the most acid water. Sulfate concentrations range from 15.7 mg/L in run-off water from pyrite-free leaching tables to 387 mg/L in run-off water from oxidised pyrite-rich material. Run-off from the massive sulfide leaching tables contains the highest heavy metal concentrations.

In order to establish the overall chemical composition of the future pit lake water, the run-off waters from all individual leaching tables were combined, producing a pH value of 3.8. Bearing in mind that groundwater inflow was not considered, this is close to pH 4.5 measured in surface ponds on the pit floor in April 2001. Thus, backfilling parts of the pit with acid generating rock will have a profound impact on the water quality of a future pit lake.

Three distinct types of run-off waters have been recognised which are generated by particular wall rock units (Table 1).

**TABLE 1**

*Characteristics of run-off waters and related rocktypes.*

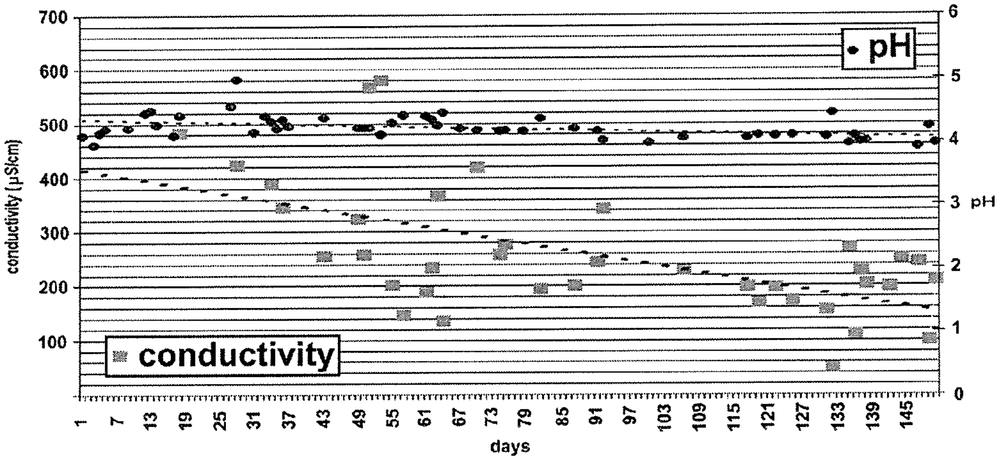
| Run-off category | pH and conductivity | Wall rock units producing run-off water |
|---|---|---|
| A | pH 3.5 - 4.8<br>cond. 100 - 400 µS/cm | Pyrite rich mixed breccias<br>Pyrite rich rhyolites |
| B | pH 6 - 8.5<br>cond. <100 µS/cm | Strongly weathered rhyolites at the southern end of the pit<br>Sheared sediments<br>Brecciated dacites<br>Sand sized volcanoclastics |
| C | pH <4<br>cond. >800 µS/cm | Massive sulfide from the lower pit<br>Backfilled waste rock |

The two rock units generating category 'A' waters are located in the median reaches of the pit wall, whereas the four rock units producing category 'B' run-off are located in the upper, median and lower reaches. The rock units causing the most acid category 'C' waters originally only occurred at lower levels of the pit, however, due to backfilling of the Reward pit they are now present at higher levels. The temporal development of pH and conductivity in the run-off waters is shown in Figure 3. Category 'A' run-off waters display slightly decreasing acid pH and strongly decreasing conductivity values. Category 'B' waters show stable near neutral pH and falling conductivity values. Category 'C' waters develop to more acid pH and increasing conductivity values.

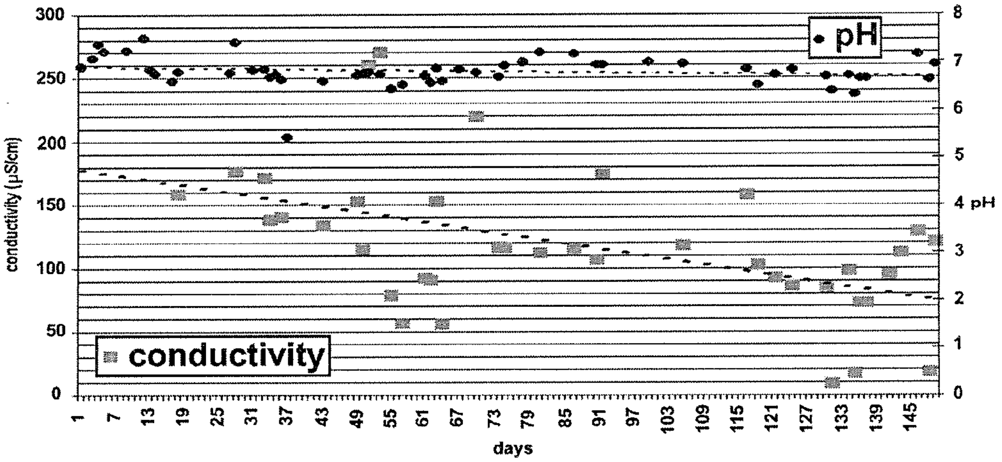
The experiment demonstrated that the two most acid generating rocks of category 'C' would determine the pH of the open pit lake despite the fact that they only account for 17 per cent of the total pit wall surface area. Category 'B' rock units produce slightly alkaline run-off waters, in two out of four cases. Nevertheless, the buffering capacities of the waters are too low to compensate for the acidity generated by the rocks of category 'C'.

The temporal variation of pH and conductivity also indicates that weathering of sulfides and gangue minerals on the leaching tables controls the chemistry of run-off waters. Category 'A' run-off displays stable slight acid pH values but a decreasing conductivity over time. This indicates that weathering reactions are slow. Run-off waters produced by category 'B' wall rocks have stable neutral to alkaline pH values and low conductivities. These rocks contain negligible, disseminated amounts of sulfides and therefore weathering is slow with only little contribution to the bulk run-off chemistry. Category 'C' run-off waters on the other hand display falling acid pH and rising conductivity values indicating that sulfide weathering and associated metal release are still accelerating.

Category "A" runoff waters



Category "B" runoff waters



Category "C" runoff waters

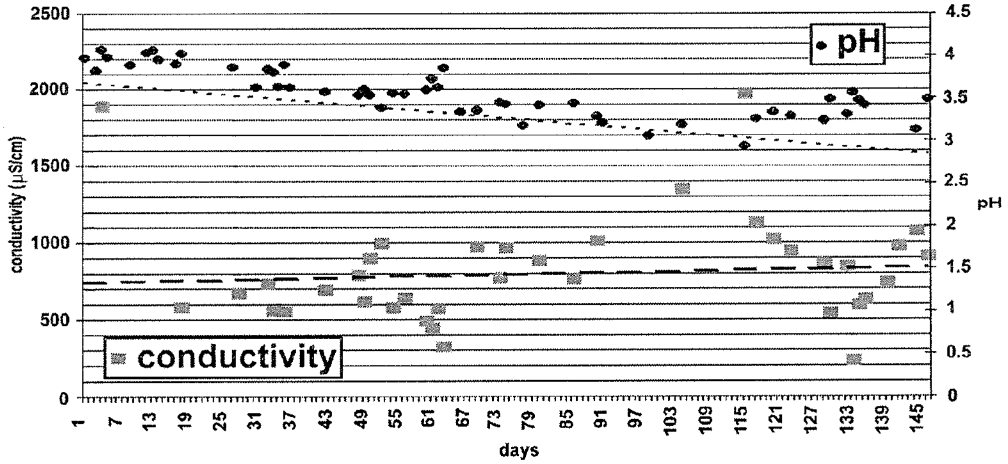


FIG 3 - Conductivity and pH values of category A, B and C run-off waters as measured during the 200-day kinetic leaching experiment.

The short-term leaching experiments (160 minutes, 480 minutes) indicate stable but low pH values and decreasing conductivities (695 µS/cm > 420 µS/cm, 1680 µS/cm > 176 µS/cm respectively) during simulated major rainfall events (Figure 4). The frequently reported drop in pH during the onset of rainfall events (Younger, 2000; Alpers *et al*, 1994) caused by the re-dissolution of acid generating salts (AGS) was not observed. This suggests that AGS contribute only minor acidity to the run-off at Highway-Reward and that the acid production occurs predominantly through oxidation and dissolution of primary sulfide minerals. Evidence for this is found in the 480 minute leaching experiment whereby 15 minute pauses in the watering routine led to increasing conductivity and decreasing pH values (Figure 4; 2400 - 3000 ml, 4600 - 4800 ml). During these pauses, the wetted sulfidic material had enough time to oxidise and to produce temporarily higher conductivity and lower pH run-off waters.

### Modelling

Physical modelling of the pit lake focused on the relation between the regional Campaspe Beds and water levels in the pit. The Campaspe Beds are the host of several aquifers in the region. Contact of pit lake water with the Campaspe Beds could cause significant degradation of these aquifers. The results of the water level modelling showed that water in the pit would reach its final depth of around 100 m in approximately 100 years. Thus water of the open pit will not reach a level where it could flow out into the surrounding Campaspe Beds.

## CONCLUSIONS

The final mining void of the Highway Reward copper-gold deposit will be left to fill with ground and surface water. A detailed mineralogical and geochemical study of the pit walls combined with hydrological and hydrochemical data and kinetic laboratory experiments has revealed that the pit water quality will be influenced by:

1. oxidation of massive sulfides exposed in the pit walls and waste rock backfill;
2. inflow of groundwater; and
3. to a lesser extend dissolution of AGS during rainfall events.

The water at the base of the pit is a mixture of groundwater and run-off from the pit walls. Lower pH values of the pit water have been detected during the wet season corresponding to active acid generation in the exposed sulfidic wall rocks and to a much lesser extend dissolution of mineral efflorescences. A higher pH of the pit water has been detected during the dry season, which is possibly caused by a dominating inflow of higher pH groundwater. Mineralogical investigations of the pit wall material and kinetic data from leaching experiments indicate that the final pit lake will have an acid character and be rich in dissolved metals. The short-term leaching experiments showed that AGS even so being present do not dominate the run-off chemistry. Physical modelling of the future pit lake showed that waters will be contained in the open void and will not interact with the surrounding unconfined aquifer. The pending modelling stage will give a more accurate prediction of the pit lake's final chemical properties as well as its development over time.

## ACKNOWLEDGEMENTS

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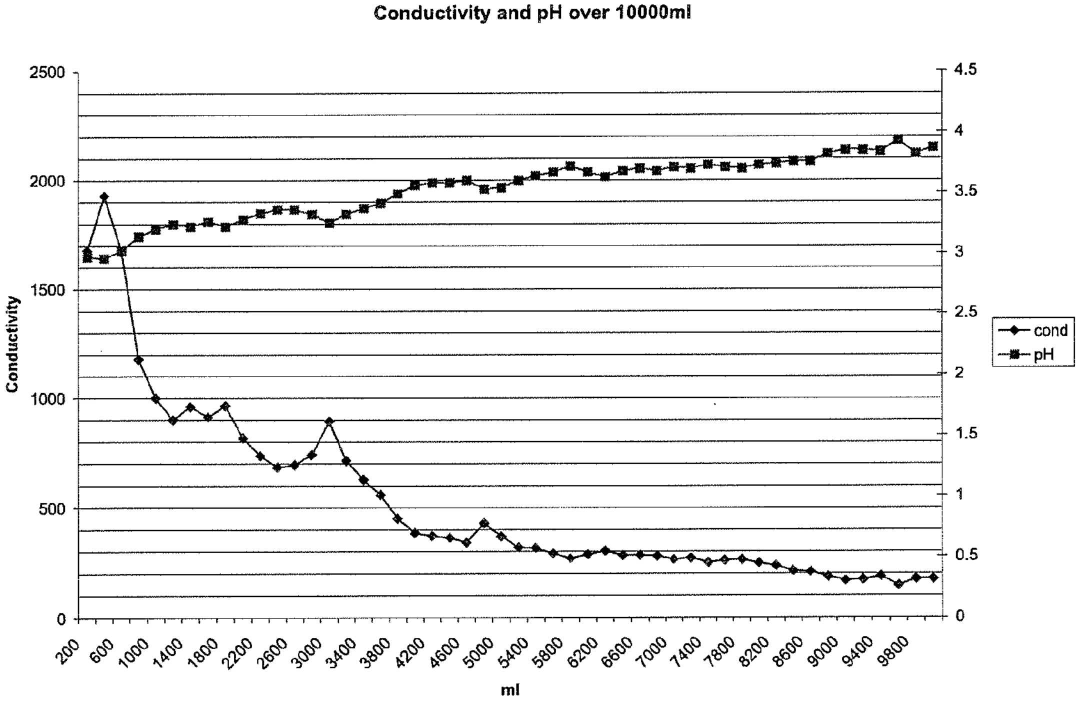

FIG 4 - Conductivity and pH values of leachates as measured in the 10 000 ml short-term dissolution experiment.

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