Predicting pit water quality for the Highway Reward mine, Queensland, Australia

Manfred Thienenkamp

School of Earth Sciences, James Cook University, PO Box 6811, Cairns, Qld 4870, Australia
e-mail address: Manfred.Thienenkamp@jcu.edu.au

Abstract

Open pit mining of the Highway Reward copper-gold deposit has produced a final mining void with a diameter of 600m and a depth of 280m, which will be left to fill with ground and rain water once pumping of pit water ceases. A detailed geological assessment of the pit walls indicated that the wall surface area consists of 13% sulfidic dacite, 32% sulfidic rhyolite, 12% sulfidic breccia, 10% metasediments, 12% alluvial sediments, and 17% massive sulfides (pyrite-chalcopyrite-sphalerite). The massive sulphide occurs partly as backfill in disused pit areas. Several leaching tables were constructed to simulate weathering reactions and surface water runoff in the major pit wall units during a 200-day leaching experiment. While sulphide oxidation in the pitwalls will produce acid metal rich leachate, bicarbonate rich groundwater inflow during the dry season acts as a weak buffer.

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 hydrological and geochemical pit water model. The hydrological model was run for 250 years and it is suggested that the pit lake will reach its equilibrium depth of ~100m in approximately 90 years from the start of filling. The geochemical model was run for 20 years and the results indicate that the pit lake will have a pH <4 and moderate but increasing metal concentrations. After 20 years the pit lake will start to flood the uncapped sulfide waste rock in the disused pit area. From then onwards, continuous wetting and drying of the waste rock along the water line and the dissolution of accumulated acid generating salts will cause decreasing pH and increased metal concentrations in the pit lake. This process will continue indefinitely as the pit lake will not be able to completely flood the sulfide waste rock.

1 Introduction

The possibility to economically mine low-grade, big 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 interacts with the local groundwater. In most of inland Australia, water for human consumption and livestock largely comes from 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 water quality of an open pit environment using computational modelling in combination with detailed climatic, hydrological, hydrogeochemical, geochemical and mineralogical data.

2 Physiography

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

3 Geology

The deposit is located in 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 et al. 1990).

The mineralisation occurs mainly in the form of almost vertical massive sulfide lenses and is thought to be of submarine, exhalative origin (Henderson 1986). Weathering of the orebody and the surrounding host rock is variable, ranging from 10m to 70m in the Highway section and to a depth of 120m in the Reward section (Kevin Rosengren & Associates Pty Ltd 1998).

In the east the deposit is partly overlain by 40m thick Tertiary sediments, the Campaspe beds. This regional cover sequence of coarse conglomerate, ferruginous clay and silt is in places more than 100m thick, filling palaeochannels and hosting numerous groundwater reservoirs (Pitt 1988).

4 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. Extensive exploration in the 1980's located two separate massive sulfide Cu-Au orebodies at depth below the former workings. Subsequent development and mining of these resources resulted in the 150m deep Reward pit and later in the intersecting 280m deep Highway pit. Processing of the extracted ore was done off site, 100km from the Highway Reward mine. Therefore, only remnants of a small and shallow cyanide tailings dam, which was operating from 1979 to 1983 exist on site.

Much of the waste rock is stored in two separate waste rock dumps. The older dump, containing material from the Reward pit, is capped and revegetated. The younger dump which, after cessation of open pit mining in April 2002, is now in the rehabilitation stage, contains waste rock from the Highway pit.

Mining by underground method still continuous at the site. The final void has a diameter of 600m and will be left to fill with groundwater 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 (Fig. 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.

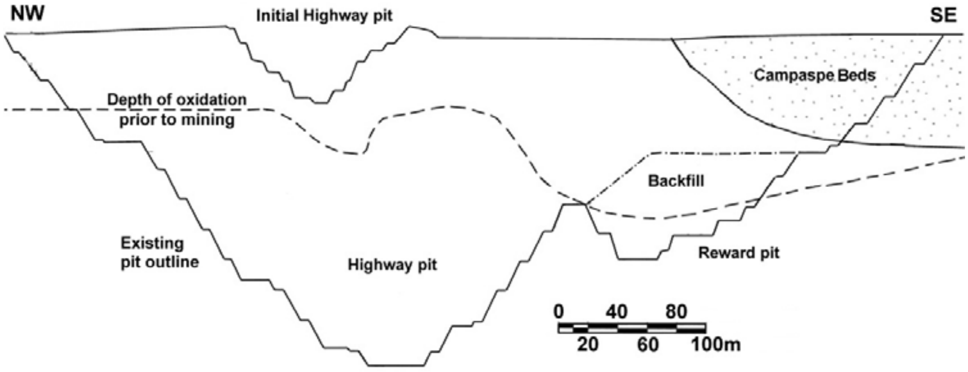

Fig. 1 Cross section through the Highway Reward pit (no vertical exaggeration)

5 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 runoff 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, and inspected for their texture, mineralogy, sulfide morphology and weathering status. In addition, ten 5kg wall-rock bulk samples were collected at representative sites along the haul road. Sample aliquots were milled in a chrome steel ring mill. The samples were submitted to Australian Laboratory Services in Brisbane. 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.

The mineralogy of the bulk samples was determined by X-ray diffraction (XRD, Siemens D5005, from 1° to 60°) at the Advanced Analytical Centre (AAC), James Cook University (JCU), Cairns.

Mineral efflorescences

Secondary minerals were collected from pitwalls 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 secondary mineral coated rock fragments. Samples were processed under an optical microscope, separating the primary rock material from the secondary mineral sample. The efflorescences were analysed by XRD at the JCU AAC.

5.3 Seasonal groundwater characteristics

Groundwater was sampled in April and November 2001 from 9 different groundwater seeps flowing into the pit. Flow rates were measured at the discharge points. Measurements of temperature, pH and conductivity were conducted in the field using a Horiba U-10 water quality checker. Sample 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, sulphate, chloride, bicarbonate and carbonate.

Prior to analysis, the water samples were filtered through 0.40μm filter paper. The solids accumulating on the filter paper were investigated with a JEOL 6300 scanning electron microscope by energy dispersive X-ray microanalyser system (SEM-EDS) at the JCU AAC, Cairns. SEM-EDS data were then compared with the output files from the geochemical simulation computer program PHREEQC 2.8.

5.4 Wall-rock leaching experiments

The weathering and leaching behaviour of the pit wall-rocks were simulated using artificial pit wall sections. These were created from the bulk samples for a 200-day kinetic experiment. Ten leaching tables of the size 40x60x5cm were constructed from high-density polyethene (HDPE). The bulk samples were screened, and rock sizes >3cm ∅ 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, representing part of 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 solid pit wall samples present on the leaching tables. 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 that 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 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 et al. 1998). Runoff 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.

5.5 Modelling

Daily water volume and pit lake surface area in the void were calculated using the 1m 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).

Water balance in the pit was calculated on a daily basis for 250 years, utilising the 1998-2002 rainfall and evaporation records from the mine site. Groundwater inflow rates were assumed to remain constant at the measured levels. The rainfall model included different scenarios incorporating an increase in rainfall by up to 30%. Once the height of groundwater inflow reached the pit-lake surface, groundwater inflow from this site was assumed not to add further to the overall pit-lake volume. This assumption was considered reasonable, as overall groundwater inflow rates were low and therefore insignificant in the overall water balance.

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 groundwater investigation, leaching experiments, evolving pit lake volume and lake surface, local meteorological records and evaporation rates were combined with PHREEQC 2.8 to model the chemical development of the Highway Reward pit lake for the first 20 years of filling.

6 Results and discussion

6.1 Pit wall geology, mineralogy and geochemistry

Rock units exposed along the pit walls consist initially of 13% sulfidic dacite, 32% sulfidic rhyolite, 12% sulfidic breccia, 10% metasediments, 12% alluvial sediments, and 17% massive sulfides (pyrite-chalcopyrite-sphalerite). As the open pit fills with water the individual proportions of exposed pit wall areas change, submerging massive sulfide rocks at the pit floor, but increasing the relative presence of the backfilled waste rock. Furthermore, inspection of the 83 core samples showed that 72 samples (87%) contain pyrite either as massive or disseminated pyrite grains in the rock mass. Only 11 samples (13%) 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 sulphide unit, the samples have an average sulphur concentration of 2.4 wt%. Calcium concentrations are below 0.4% in all but two samples, highlighting the low acid neutralising potential (ANP) of the host rock. Maximum concentrations for As (1050ppm), Cd (87ppm), Cu (2.71wt%) and Zn (3.22wt%) are reached in the massive sulfide samples.

6.2 Mineral efflorescences

The secondary minerals occurring on the pit walls were identified as 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, copiapite and bianchite can be classified as acid generating salts when dissolved in water. They cause low pH and high metal concentrations in the initial runoff with the onset of rainfall events (Bayless and Olyphant 1993). Wetting and drying of the pit walls, oxidation of sulfides in the wall-rock and acid weathering of gangue minerals produce acid runoff, which evaporates forming salt crusts.

6.3 Seasonal groundwater characteristics

Groundwater entering the pit is sodium-chloride rich and has a pH between 7.9 and 8.5 with the higher values occurring at the end of the dry season. Distinctly different results in TDS and hardness values in November as well as concentrations of Al, Ca, Cl, Fe, Na, Mg and Zn suggest that two different aquifers discharge into the pit. Groundwater entering at the north-western side of the pit has a lower conductivity and lower concentrations of Ca, Cl and most of the metals compared to the other ground water samples. Therefore, groundwater at the north-western side of the pit represents comparatively young water. The bed of a nearby creek could be the source of this particular seepage water.

At each groundwater seepage point the physical and major chemical parameters of the groundwater were very similar in April and November 2001. Metal and metalloid concentrations, however, varied considerably, particularly

Al, Fe, Mg, As and Se. Aluminium, Fe and Mg values were higher and As and Se values were consistently lower in the slightly higher pH groundwater collected in November 2001.

Water accumulating at the pit floor had a pH ranging from 4.4 in April 2001 to 5.7 in 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 collected in April 2001. Arsenic and Se are more abundant in higher pH waters (pH 5.7), which is in agreement with their increased solubility under 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 (i.e. alkaline groundwater discharge >> acid runoff). Acid runoff water may dominate during the wet season (i.e. alkaline groundwater << acid runoff).

6.4 Wall-rock leaching experiment

Results from the 200-day leaching experiment indicate that runoff from the pitwalls will add significant acidity to the Highway Reward pit lake. Runoff water from the ten leaching tables had pH values ranging from 3.2 to 8.5. Such a diversity in pH values is due to the different mineralogical units present on the leaching tables. The abundance of pyrite in the wall-rock and its oxidation contribute significant acidity. The chemistry of the runoff 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 ranged from 15.7 mg/l in runoff water from pyrite-free leaching tables to 387 mg/l runoff water from oxidised pyrite rich material. Runoff water from the pyrite rich leaching tables contained the highest heavy metal concentrations.

Three distinct types of runoff waters have been recognised. These are generated by particular wall-rock units (Table 1). The four rock units producing category "B" runoff are located in the upper, median and lower reaches of the pit wall, whereas the two rock units generating category "A" waters are located in the median reaches. The rock units causing the most acid category "C" waters originally only occurred at lower levels of the pit; however, due to back filling of waste rock, they are now present at higher levels.

Table 1. Different runoff categories and associated rock types from 200 day leaching experiment

runoff category	pH & conductivity	Wall-rock units producing runoff water
A	pH 3.5-4.8 cond. 100-400mS/cm	pyrite rich mixed breccias pyrite rich rhyolites
B	pH 6-8.5 cond. <100mS/cm	strongly weathered rhyolites at the southern end of the pit sheared sediments brecciated dacites sand sized volcanoclastics
C	pH <4 cond. >800mS/cm	massive sulfide from the lower pit backfilled waste rock

The retention of some of the rainfall as pore water on the leaching tables resulted in the runoff water volume from the tables being generally 120ml less then the applied water volume. This implies that a corresponding daily rainfall of less than 2mm does not produce any runoff, assuming a rainfall penetration depth of <3cm 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 runoff might be considerable higher in the case of the open pit.

Category "A" runoff waters display slightly decreasing acid pH and strongly decreasing conductivity. Category "B" waters show stable near neutral pH and falling conductivity values. Category "C" waters develop to more acid pH and increasing conductivity values.

Backfilling parts of the pit with acid generating rock will have a profound impact on the water quality of a future pit lake. In order to establish the overall chemical composition of the future pit lake water, the runoff 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 ponds on the pit floor in April 2001.

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% of the total pit wall surface area. Category "B" rock units produce slightly alkaline runoff waters, in two out of four cases. Nevertheless, the buffering capacities of the waters are too low to compensate for the acid generation of category "C" waters.

The development of pH and conductivity indicates that weathering of sulfides and gangue minerals on the leaching tables play an important role in runoff formation. Category "A" runoff displays stable slightly acid pH values, but a decreasing conductivity over time indicates that weathering reactions are slow. Runoff produced by category "B" wall-rocks produce stable neutral to alkaline pH values and low conductivities. These rocks contain negligible and very disseminated amounts of sulfides and therefore weathering is slow, with only little contribution to the bulk runoff chemistry. Category "C" runoff on the other hand displays falling acid pH and rising conductivity values, indicating that sulphide weathering is still accelerating and a likely source for metal and metalloids in the runoff water.

6.5 Modelling

The results of the hydrologic modelling suggest that the pit lake will fill to a depth of approximately 100m within 90 years from the start of flooding and will, even under the modelled increased rainfall conditions, not be able to cover the entire backfill. Metal concentrations in the lake water are predicted to increase by approximately 100%. However, for the modelled time period, concentrations for most metals will remain below the ANZECC and ARMCANZ (2000) water quality guidelines for livestock consumption. However, the chemistry of the pit lake was modelled for only 20 years. At the end of the 20 year modelling period the lake is predicted to get into contact with the sulfide waste rock of the access ramp, and water quality will most likely deteriorate. Deterioration will be due to continual wetting and drying of the waste rock along the waterline and the predicted, by then advanced, oxidation of the uncapped sulfide rock. This advanced oxidation would lead to the generation and accumulation of acid generating salts in the waste rock. These salts will be easily dissolved upon flooding – lowering the pH of the pit lake water and increasing metal concentrations. Further, the flooding of the lower slopes of the access ramp will change the natural angle of repose (Bryant 1991) of the dumped waste rock material and might therefore result in the partial slumping of the access ramp into the pit lake, further releasing accumulated soluble acid generating salts into the open pit water body

7 Conclusion

The final mining void of the Highway Reward copper-gold deposit will be left to fill with groundwater and surface water upon mine closure. 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 controlled by (a): sulfide oxidation in the pit walls; (b): dissolution of acid generating salts during rainfall events; (c): groundwater inflow and chemistry.

The water at the base of the pit is a mixture of groundwater and runoff 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 dissolution of mineral efflorescences. A higher pH of the pit water during the dry season is possibly caused by a dominating inflow of higher pH groundwater during this time.

Mineralogical investigations of the pit wall material, kinetic data from ten leaching experiments, and geochemical modelling with PHREEQC indicate that the pit lake will have an acid character and be initially only moderately rich in dissolved metals. The acid generating salts on the pit walls may be an important contributor to this acidity as they dissolve in the rising pit lake water. As the pit lake reaches the height of the backfill, fluctuations in water table and eventual saturation of the sulfidic waste rock will lead to an increase in pit lake metal concentrations and lowering of the lake pH.

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