An Automated Method for Assessment of Pit Lake Water Quality Risk using the Pit Quality Risk Assessment Protocol (PQRAP)

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Abstract
A pit lake water quality risk assessment tool was developed to characterise potential post-closure geochemical impacts from pit lakes. The risk is evaluated as a function of the pit water balance and geochemical criteria that are typically available at the pre-feasibility stage of mine development.

The water balance module includes all the major components of a pit water balance and calculates results using an analytical solution. Input uncertainty can be included in the GoldSim software used to develop the tool, which includes a Monte Carlo simulation option based on several stochastic distribution options.

A geochemical module evaluates parameters considered relevant to the potential for acidic, metalliferous or saline drainage and feeds into a risk assessment module, which scores geochemical results according to pre-defined risk criteria.

A Fuzzy Logic methodology is used to evaluate the risk criteria. A pre-defined risk matrix is used to convert risk criteria into combined risk scores. An automated decision tree is used to display key outputs for risk identification purposes.

The tool is applied in this paper using published data for the Rum Jungle minesite, south of Darwin in the Northern Territory of Australia to demonstrate the outputs that are generated.

Key Words: Acid Rock Drainage, Fuzzy logic, GoldSim.

Introduction
Mine pit lakes are currently generating interest at various levels, including government, industry and society at large. This is principally due to the potential for pit lakes to be long-term liabilities to mine owners, the state and potential receptors of mine water pollution. The work reported in this paper was largely driven by the release of the Guidelines for Preparing Mine Closure Plans, issued by the Department of Mines and Petroleum of Western Australia, June 2011, although the approach is universally applicable.

The evolution of pit water quality is driven by various physical and geochemical properties of the pit lake environment. Physical factors include lake morphology, limnology, rock morphology, climate, surface and groundwater hydrology, etc. and geochemical factors include pit wall and aquifer mineralogy and hydrochemistry of surface and groundwater sources. These factors contribute to a greater or lesser extent to pit water quality and pit water quality evolution.

To assess the likely water quality of a pit lake these aspects are typically assessed on an individual basis, using a checklist approach and / or a risk matrix that associates the risks with likelihood and consequence scores.

The approach presented in this paper endeavours to combine various physical, chemical and risk assessment components in an automated GoldSim-based (GoldSim, 2010) tool, referred to as the Pit

Quality Risk Assessment Protocol (PQRAP). The methodology used in the PQRAP uses analytical solutions, combining geochemistry with a pit water balance to calculate a risk score. The risk assessment methodology adopted is based on a multiple criteria assessment (MCA) approach using a variety of rating and weighting schemes to evaluate likely impacts on water quality. The risk score is calculated using a Fuzzy Logic approach (Tanaka, 1997 after Zadeh, 1965). Fuzzy logic is a superset of conventional (Boolean) logic that has been extended to handle the concept of partial truth; truth values between completely true and completely false (i.e. partial memberships of sets).

Along with the risk score, a flow chart / *decision tree* was developed (Figure 1) to identify the nature of pit lake water quality risks. This includes characteristics such as the probability of flooding of reactive pit wall materials (thereby limiting contact with oxygen) and different quantities that are useful to identify potential water quality related risks, including acidity, metal leaching, salinity and radiation.

Outputs from the PQRAP water balance and geochemical modules are included with the *decision tree* to assist in the interpretation and assessment of the results. Tick mark and cross indicators are tied to risk scores or calculated values to assist users in identifying the decision tree pathway.

As illustrated in Figure 1, relevant risk scores are inserted as larger yellow numbers and water balance and geochemical calculations are included as smaller green numbers. In this demonstration the scores are calculated using a 10 x 10 matrix, with a minimum score of 1 and the maximum score of 100, however, the scores the risk matrix generates can be tailored to a user’s needs.

In the operational version of the PQRAP, results are explained in text boxes when the mouse is hovered over them (demonstrated for soluble salts, in Figure 1) Some results are displayed as charts by pressing on a “button”. Explanations for individual outputs are omitted from the flow chart due to limited space, however, all are aimed at identifying pit lake water quality risk factors and their significance. Limnology is not included, as large amounts of data are required to provide useful information on pit lake stratification behaviour.

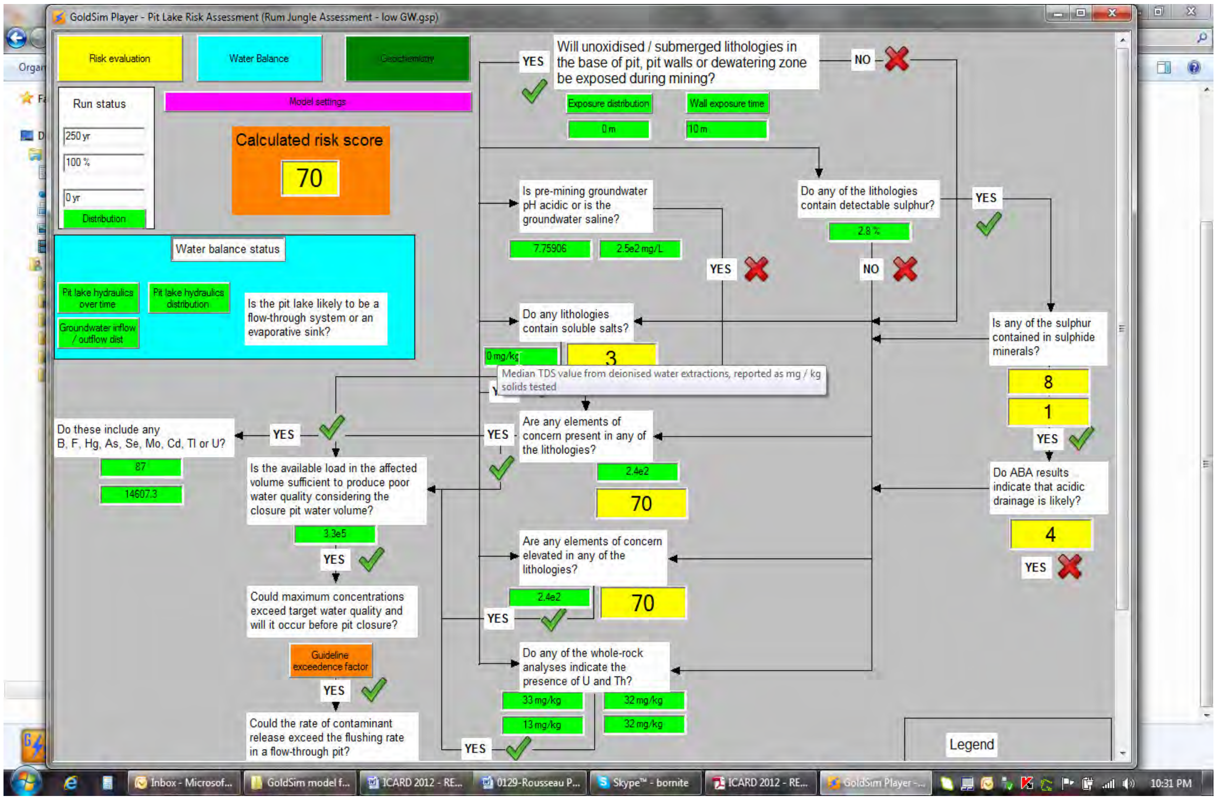

Figure 1. Flow chart output from the PQRAP tool for pit lake risk assessment, illustrating relevant risk scores and output values. Results descriptions are shown by hovering the mouse over them to minimise cluttering (as for Median TDS of water extracts).

Methodology

Risk identification and quantification

The PQRAP risk assessment tool follows an integrated approach to risk assessment by combining the water balance and geochemistry of wall rocks.

Risk factors that are specifically included in the assessment and which are used to calculate water quality impact likelihood scores are:

- Groundwater pH (to identify groundwater quality influence on pit water quality)
- Leachable salt concentrations from wall rock samples (to identify potential release of salinity)
- Total sulphur content (to quantify maximum Acid Potential (AP))
- Reduced sulphur content (to quantify actual AP)
- Organic carbon content (as an indicator of reducing conditions)
- Acid Neutralising Capacity (ANC) (to quantify Neutralising Potential (NP))
- Elemental concentrations, along with a generalisation of their mobility under acidic and neutral to alkaline conditions respectively.
- Concentration of uranium and thorium in wall rock (as a potential source of radioactivity).

The consequence scores are ranked based on the projected pit lake volume. Volume was chosen as the measure of consequence due to the higher implied cost of treating larger volumes and also the higher potential impact that may be caused through the presence or release of larger quantities of water, assuming the same water quality. This approach is considered justifiable in the absence of better measures of consequence, especially since environmental sensitivities, external to the pit, are not included at this stage.

To quantify overall risk, the inputs are configured to interact with a pre-defined risk matrix lookup table, including likelihood and consequence components in the matrix rows and columns respectively. Risk score values can be changed to alter the scores for specific combinations of likelihood and consequence, however, the default is the product of the likelihood and consequence scores. This flexibility allows for more or less weighting to be given to particular combinations of likelihood and consequence to "calibrate" or scale the risk scores against empirical data as development continues.

Both the likelihood and consequence risk scores are estimated on a continuous scale of 1 to 10 to assess the risk of impacts occurring, based on judgement by the developers.

A Fuzzy Logic methodology is used to calculate risk scores (Tanaka, 1997 after Zadeh, 1965), based on the authors' estimates for variable ranges and interactions between different variables. Fuzzy Logic is commonly used in engineering applications to control processes and machines and is thus a proven method for information management.

Where risks are considered to influence one another, calculation of risk scores is adjusted to reflect interactions or interdependencies. Examples include:

- Increasing ratios of ANC or NP relative to maximum acid potential (MPA) or AP result in lower risk scores than for acid risk associated with sulphide concentrations alone.
- Organic carbon is considered to be an indicator of possible sulphides in the PQRAP tool, since it is often an indicator of reducing environments. However, the use of organic carbon as an indicator of possible acidic drainage is eliminated from the evaluation if sulphur concentrations are known and included in the evaluation.

Water balance calculations

The water balance calculations for the PQRAP were calculated using a recursive loop method in GoldSim to balance surface water inflows and outflows with groundwater flow rates and evaporative losses. The calculations were based on the defined pit geometry.

The pit geometry was represented by an elliptical frustum (cut-off elliptical cone), which was considered to be the most likely simplified geometry for most hard rock pits. The pit dimensions are defined according to crest length and width and the basal length of the pit. The length to width ratio is assumed to be equal at the crest and the base. An equivalent circular radius, to calculate groundwater flows, is obtained from the surface area at the current pit lake elevation with the assumption that it is circular.

Surface water inflows were calculated using annual average values for precipitation and run-off coefficients. Mean annual evaporation was used to calculate evaporation rates. These aspects could be modelled more accurately using daily or seasonal data, however, this is not considered necessary for the general purpose risk assessment approach for which the PQRAP has been developed.

Quantities that are affected by the pit geometry, including groundwater inflow, evaporation and exposed pit wall area are calculated relative to the pit lake elevation for each time step. The pit lake elevation is calculated iteratively for each time step to balance the calculated pit lake volume with the groundwater inflow / outflow rate, using the pit lake elevation of the previous time step. This implies that time step length can affect the water balance significantly, depending mass fluxes, which should be considered by the user. The depth tolerance of the pit lake elevation calculations can be set in the water balance module to optimise calculation run times relative to precision.

Groundwater inflow rates to the pit (for pit lake elevations lower than the regional groundwater level) are calculated using the analytical solution of Marinelli and Niccolai (2000). Outflows from the pit wall could not be calculated using this approach, as the solution is not valid for water levels above the regional groundwater level. To circumvent this issue for flow-through pits, outflows through the pit walls are calculated using the Modified Dupuit equation (Singh and Reed 1988), with base of pit calculations still based on Marinelli and Niccolai (2000).

The pit lake evaporation rate is calculated from the pit lake surface area, as a function of the defined geometry and calculated water level, along with the A-pan evaporation rate for the site and the applicable A-pan correction factor for the region (or an estimate if not available). Allowance is also made for an adjustment for wind sheltering of the pit lake surface.

Variability of different input values is accounted for using triangular stochastic distributions in GoldSim to define the probable range of values for most parameters. Inputs are based on measured values (if available) or estimated minimum, average and maximum values. By using Monte Carlo simulations, the probable ranges of different aspects of the pit mass balance are calculated. Along with the inflow and outflow rates from the pit, the following outputs are also calculated:

- Pit lake dimensions
- The pit lake elevation and rate of recovery after closure
- The radius of influence on the groundwater system

Inputs that are required by the PQRAP tool to calculate the water balance include the following:

- Pre-mining or regional average static water level
- Average hydraulic conductivity of the pit wall
- Pit catchment area
- Decant (overflow) elevation of the pit
- Elevation of the maximum pit depth
- Pit long-axis length at the pit rim (assuming a horizontal pit rim)
- Pit short-axis length at the pit rim (assuming a horizontal pit rim)
- Pit long-axis at the pit base
- Pit floor average vertical hydraulic conductivity
- Pit floor average horizontal hydraulic conductivity
- Mean annual precipitation
- Regional recharge as a proportion of Mean Annual Precipitation
- Mean annual evaporation
- A-Pan correction factor for the mine location
- A wind sheltering correction factor to reduce evaporation rates if the pit lake is expected to be sheltered by the pit walls. This is a user defined value with a default value of 1.

Geochemical calculations

The geochemical component of the PQRAP risk assessment tool is calculated using the whole rock chemistry of the pit walls as an indication of leaching potential, along with the chemistry of surface water, groundwater and rainfall inputs to the water and salt balance.

Leaching characteristics derived from kinetic testing or batch water extracts are only included in the PQRAP approach to evaluate the potential release of salinity and not to predict elemental leaching potential. The reason for this is that changes in pH and redox conditions cannot be accounted for using batch water leach extract data.

Geochemical leaching potential is thus calculated based on the available load. The available load is defined by the total elemental concentration in a volume of pit wall rock (calculated as the pit wall surface area multiplied by a probable reactive depth). The available load is divided by the pit lake volume to provide a maximum concentration, which triggers the first tier of risk scores. In addition to this simplistic batch approach, a simplified kinetic approach is included. The kinetic approach is similar to the batch approach, but assumes that all the sulphur in the pit wall rock is present as pyrite and that it would be released at a rate proportional to the reactive surface area and the intrinsic oxidation rate; the rates of reaction of all elements are subsequently scaled to the calculated pyrite oxidation rate.

The reactive surface area is calculated by assuming that the calculated pit wall rock volume contains cubic blocks of a given size. Under field conditions these blocks would represent jointing, stress fracturing or any other structural features that provide pathways for entry of oxygen and water into the exposed pit wall. The intrinsic oxidation rate is multiplied by this calculated surface area to derive the reacted load over a period of time.

Although the geochemical calculations are not accurate, they provide a useful and rapid estimation of probable worst case pit lake water quality evolution and a means to evaluate the likely worst-case ARD related water quality. This excludes consideration of mineral solubility boundaries, which may be relevant.

Calculated “kinetic concentrations” from the geochemical module, although not speciated, allow comparison of maximum potential concentrations to pre-defined water quality guideline values. The comparison of water quality guidelines is integrated with the risk scoring process according to the ratio of the concentration relative to the guideline. Risk scores are allocated according to the toxicity and geochemical mobility of the elements concerned. Toxicity is based on the minimum guideline value and mobility classifications are based on known geochemical behaviour under acidic and neutral to alkaline conditions (see Table 1). Higher risk scores are generated for elements with high mobility and high toxicity and lower scores for low mobility and low toxicity.

Table 1. Toxicity / mobility classifications for different elements in the PQRAP.

Hi toxicity					
Hi mobility		Medium mobility		Low mobility	
Acid	Neutral / Alkaline	Acid	Neutral / Alkaline	Acid	Neutral / Alkaline
Cu		Pb	Cu		Pb
Zn			Zn		
Cd	Cd				
Sb	Sb				
Hg	Hg				
Tl	Tl				
Cr	Cr				
Medium toxicity					
Hi mobility		Medium mobility		Low mobility	
Acid	Neutral / Alkaline	Acid	Neutral / Alkaline	Acid	Neutral / Alkaline
B	B				
F	F				
As	As				
Se	Se				
U	U				
Ni			Ni		
Al	Al				
Mo	Mo				
		V	V		
		Co			Co

Required data inputs for a complete calculation of the geochemical component of the PQRAP tool include the following:

- Average elevation where the transition from weathered rock to fresh rock occurs in the pit wall.
- Elevation tolerance that is used to calculate the pit wall surface area interactions as a function of pit lake depth.
- Average depth of influence of oxygen and water, which may result in sulphide oxidation and weathering of other minerals.
- Average rock density.
- Average element concentrations for unweathered pit wall rock and for the total exposed pit wall geological profile.
- Average solute concentrations in groundwater, surface water and rain water inflows to the pit.
- Average total sulphur concentration.
- Proportion of total sulphur present as sulphide sulphur (from sulphur speciation analyses).
- Mean measured sulphide mineral concentration (as sulphur).
- Average Groundwater pH.
- Organic carbon concentration.
- Neutralisation Potential (either as $CaCO_3$ or as H_2SO_4 to comply with current Australian conventions).
- Neutralisation potential in unweathered material only.
- Water extract total dissolved solids (TDS) concentrations.
- Average Groundwater TDS.
- Sulphide oxidation rates.
- Specific surface area (per unit of mass).

Case Study – Rum Jungle Mine Whites Open Cut

The Rum Jungle Mine is a legacy site located approximately 70km SSE of Darwin, Northern Territory, Australia. The site is managed by the Office of the Supervising Scientist of the Northern Territory and has been the location for several ARD related scientific studies, some still planned and ongoing. The Whites Open Cut is the largest of the mined out pits at the site. Although the pit has been a site for tailings disposal and subject to various mitigation actions, the assessment carried out by the PQRAP tool is to identify inherent risk prior to mining and thus ignores these aspects. Typically these aspects would be pre-evaluated in a modern mining context.

Rum Jungle was selected as a case study for this paper, as it has generated an adequate quantity of suitable data, which is available in the public domain. Data was collected from various sources, including mainly Robertson Geoconsultants (2010) and Robertson Geoconsultants (2011) as well as measurements on generally available mapping information. Further data was obtained from official sources such as the Australian Bureau of Meteorology for the town of Bachelor, 7km NNW from the Rum Jungle site and other minor sources. The PQRAP risk assessment tool was populated with the data obtained from these sources and run for a period of 250 years at a 0.025 year time step (approximately weekly time steps) for 100 realisations, using the Monte Carlo simulation option.

Two options were run to compare scenarios where the upstream catchment was either routed into or through the Whites Open Cut. Selected results for the two options, illustrating a single Monte Carlo realisation of the water balance calculation, are provided in Figure 2 below. It is notable that no groundwater outflow is predicted, as the regional groundwater table is within 1m of the surface according to the field data that was used, which is within the model tolerance limits. Groundwater outflows would be represented by a negative groundwater flow rate if present.

To illustrate some of the outputs that are generated by the PQRAP relating to geochemical evolution (assuming surface water is diverted around the pit), calculated decant (surface overflow) loads from the pit and calculated pit lake concentrations over time are presented in Figure 2 and Figure 3 respectively.

According to Figure 2 potential outflows from the pit only start to be relevant after 20 years, as the pit lake is filling during this time. Pit lake concentrations, calculated from defined weathering rates and water fluxes are presented in Figure 3. A slow increase in concentration is probably related to evaporative concentration in the pit, as the water balance at Rum Jungle is negative, although wetter than most of Australia. The results also show variability in the behaviour of different elements, which is primarily associated with mixing of different solute sources. This can be deduced from the fact that leached geochemical loads are based on batch calculations, which are scaled against sulphur and do not include speciation.

By combining physical observations on the pit wall and the water balance, additional parameters can be calculated. An example is presented in Figure 4 as the height of the exposed fresh (unweathered) rock in the pit wall above the pit lake water level. Another feature is that the parameters that are calculated in GoldSim using the Monte Carlo simulation option can individually be displayed as probability histories, as for Figure 4, thus providing an indication of result uncertainty.

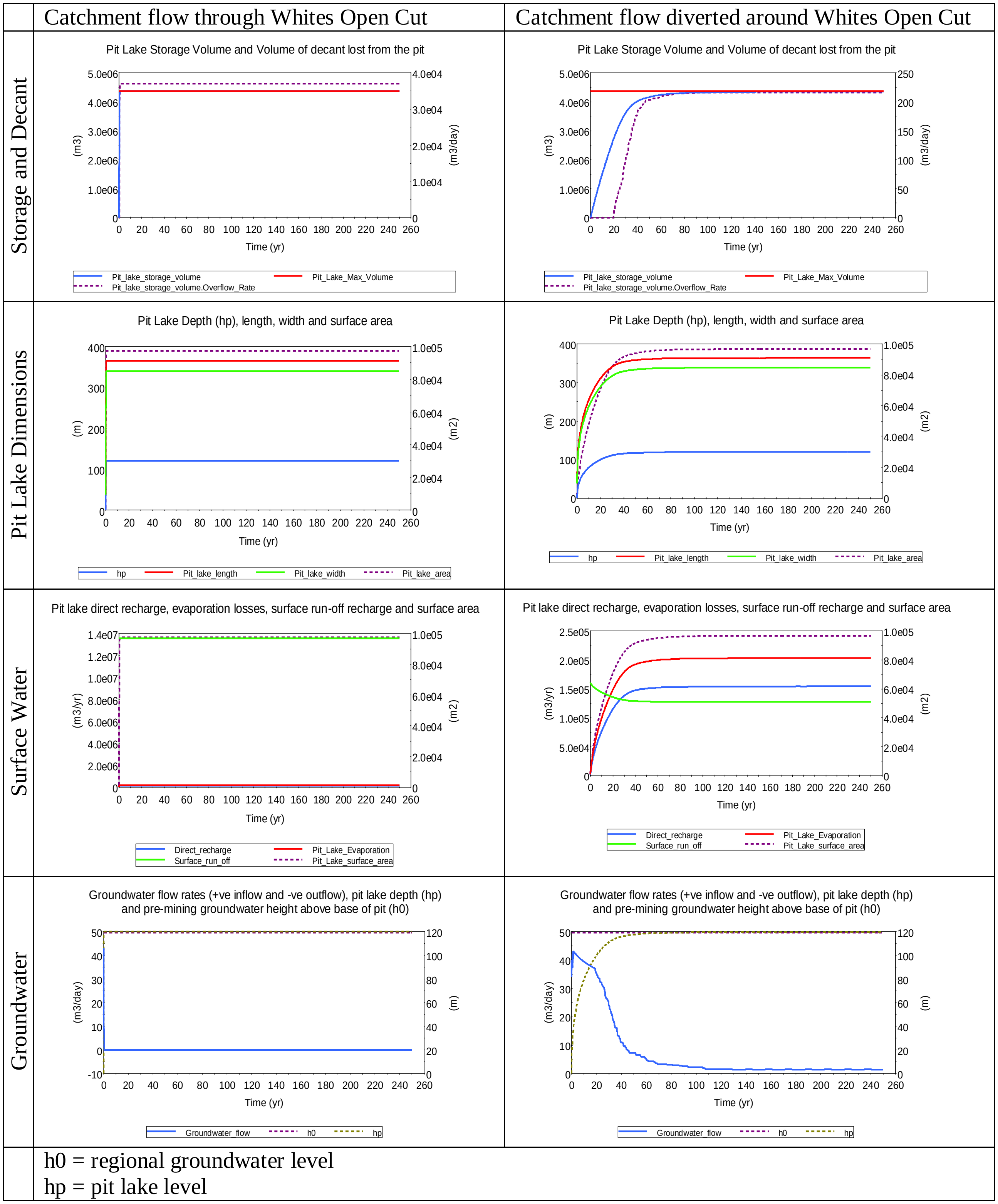

Figure 2. Selected water balance outputs from the PQRAP.

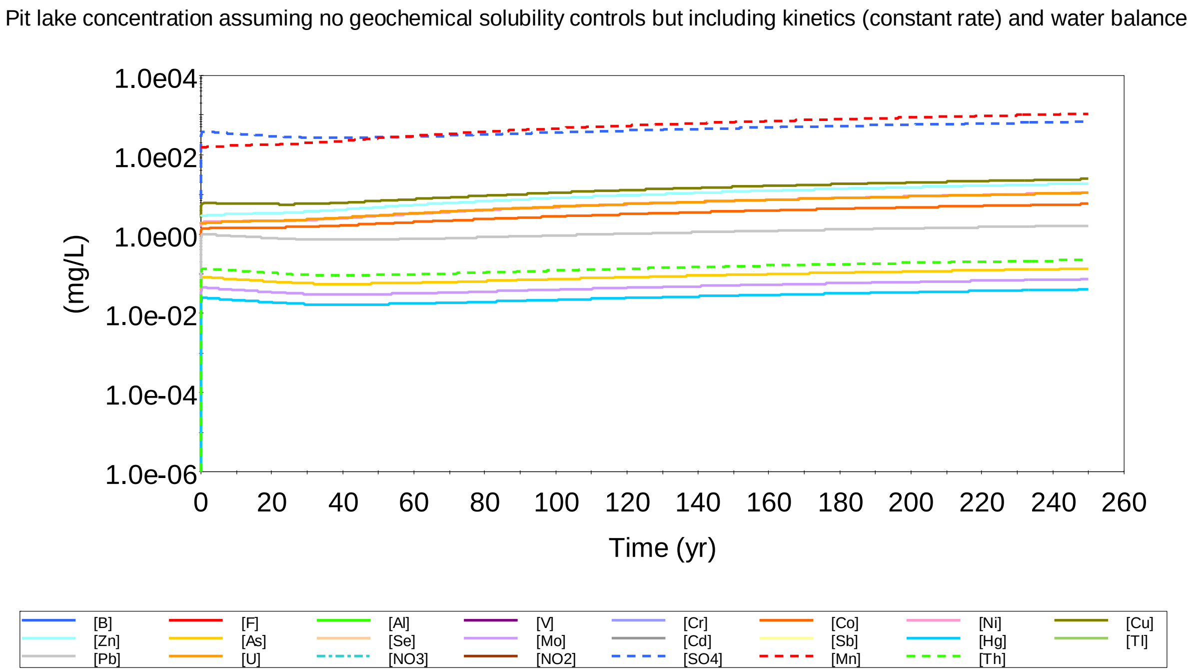

Figure 3. Un-speciated pit lake element concentrations according to calculated surface area, pyrite kinetic rates and pit lake volume.

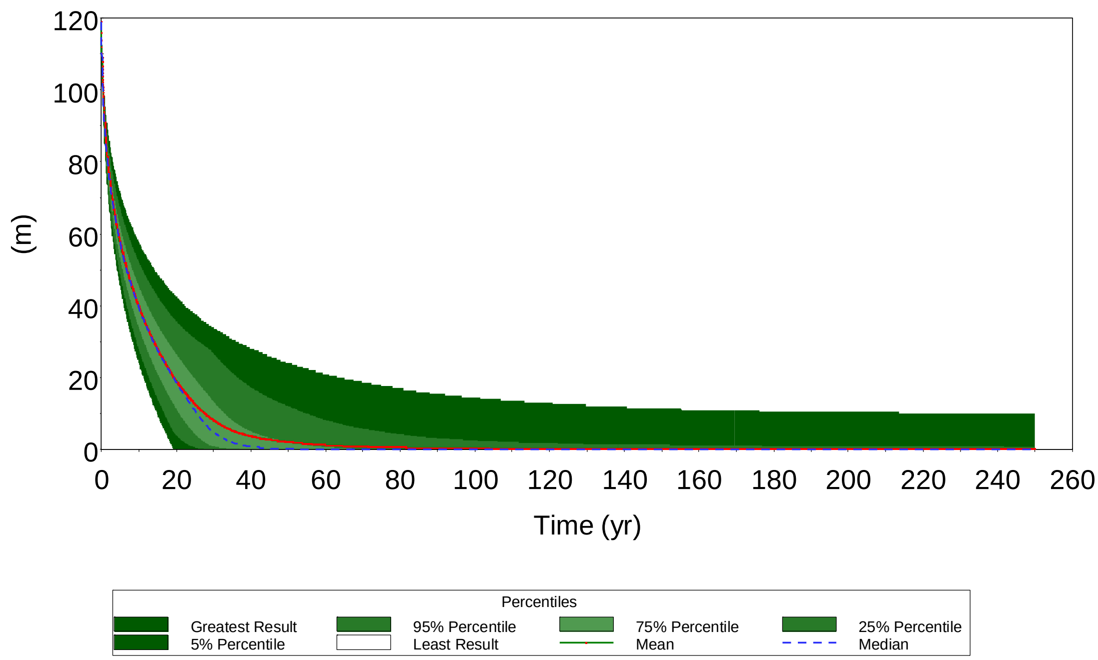

Figure 4. Height of exposed fresh wall rock above the pit lake, indicating the potential for un-oxidised material to be exposed above the pit lake (reported as a probability history).

Being able to calculate derived parameters such as exposed wall rock probabilistically provides a powerful means of generating additional information for characterising a site, as long as the site conceptual model is applicable and error margins do not exceed relevant boundary values.

In Table 2 the probable values for the average ABA characteristics of the pit walls are presented numerically. These values are calculated by the PQRAP according to the range of measured Neutralising Potential (NP) vs. Acid Potential (AP) (calculated from total sulphur concentrations) for different outcrops in the pit wall and are indicative of acidification risk.

Table 2. Distribution of calculated average wall rock NPR (NP/AP) ratio.

Mean	**Std Dev**	**Min**	**5%**	**25%**	**50%**	**75%**	**95%**	**Max**
124	15	92	100	112	123	135	150	165

The risk scores generated by the PQRAP for Whites Open Cut, according to the risk module, are summarised in Table 3 and the decision tree flow chart for the flooded scenario was previously provided in Figure 1. The risk scores that are calculated provide a rapid assessment method to identify probable causes of poor water quality and also provide a mechanism for comparative ranking of risk.

The risk score may vary over time, depending on the values of individual components at a particular time, of the water storage volume and leached loads for instance. However, in the case of the Rum Jungle assessment the overall Risk Score remains 70 throughout the run period.

Table 3. Summary of risk scores generated by the PQRAP output for the flooded pit scenario.

Risk element	**Risk score**	**Description**
Groundwater pH	14	Evaluates whether groundwater pH is acidic, as this would influence pit lake water quality over the long term.
Organic carbon	7	Organic carbon is used as an indicator of reducing conditions and thus the potential for sulphide minerals (only used if no sulphur / sulphide concentrations are provided.
ABA risk	28	Calculates a risk score based on the reduced sulphur or sulphide mineral concentration and the ratio of NP to AP.
Sulphide sulphur	56	Calculates a risk score based on sulphide sulphur concentration alone, ignoring NP.
Element enrichment	70	Calculates a risk score based on the risk of acidification, toxicity and likely mobility of elements, depending on whether pH is likely to be acidic or neutral to alkaline.
Pit water concentration	70	Calculates a risk score based on the risk of acidification, toxicity and likely mobility of elements, depending on whether pH is likely to be acidic or neutral to alkaline.
Salinity risk	63	A risk score that is calculated taking into account salinity contributed by potential sulphide oxidation, leachable salinity in wall rock material or from groundwater ingress.
Radiation risk	56	A risk score indicating the potential for radioactivity to be present, calculated uranium and thorium concentrations in wall rock and assuming a nuclear decay chain in equilibrium.
Overall Risk	70	Classifies risk according to the highest risk score from all included components.

The risk scores that are produced in **Table 3** indicate that acidification is unlikely to occur in the Whites Open Cut, but that there is a high risk of metal leaching and salinity and a significant potential for radiation. The accuracy of this assessment cannot be directly compared with site measurements at this stage due to historic in-pit tailings disposal and limited historic monitoring data, however, the findings are in general agreement with known site issues. Since sulphides are known to be present at Rum Jungle, the assessment of ARD potential also needs to consider armouring and availability of AP and NP, although the acidification risk score indicates that sufficient NP is available on site if acidity is generated.

Conclusion

The PQRAP risk assessment tool provides a mechanism to integrate water balance and geochemical information early in a project's life with very limited information. It also uses a Fuzzy Logic approach to quantify interactions between different influences on pit water quality and includes a mechanism to apply pre-defined criteria to calculate risk scores automatically based on a user-defined risk matrix.

Useful outputs include a simplified water balance and an approximation of anticipated leaching characteristics, based on expected sulphide oxidation rates.

At this stage, the approach is considered to be useful for a preliminary assessment of site characteristics for an open pit that may affect the environmental risk associated with pit lake water quality. This depends on the user understanding the limitations of the assumptions that are used, however, as they are highly simplified for the geochemical component in particular.

Although the PQRAP has shortcomings in its current form, it provides a demonstration of how an integrated approach to pit lake water quality risk assessment may be achieved in principle. It also provides a means to integrate specialist knowledge in such assessments. This principle is also applicable to environmental systems in general, as individual system components often do not act in isolation as environmental hazards.

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Acronyms

ABA	Acid Base Accounting
ANC	Acid Neutralising Capacity
AP	Acid Potential
ARD	Acid Rock Drainage
KCB	Klohn Crippen Berger
MPA	Maximum Potential Acidity (Australian usage for AP)
NP	Neutralisation Potential
NPR	Net Potential Ratio
PQRAP	Pit Quality Risk Assessment Protocol
TDS	Total Dissolved Solids