Incorporating Wall Rock Runoff into Pit Lake Water Quality Modeling in the Arid Western United States

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Abstract Constituent mass loading from pit wall runoff is increasingly incorporated into pit lake water quality models. In arid climates, pit wall runoff is a small portion of the pit lake water balance, but can be an important contributor to the chemical mass balance. Review of publicly available documents for recent pit lake models in the western United States demonstrates the importance of quantifying the effects of runoff coefficients, water quality, and pit geomorphology on wall runoff mass contributions to pit lakes.

Keywords pit wall runoff, pit lake chemistry

Introduction

Factors affecting the quantity and quality of pit wall runoff include climatic conditions and the geochemical and morphologic nature of the pit wall (Schafer and Eary 2009). Weathering results in accumulation of finer-grained materials on pit benches that may store more water than unweathered benches of competent crystalline rock, resulting in reduced runoff. Increased weathering of pit walls may also increase reactive surface area associated with finer materials, potentially decreasing pit wall runoff quality. Furthermore, the overall effect of pit wall runoff must be considered in the context of runoff interaction with groundwater quantity and quality. The influent runoff may have an ameliorating or degrading effect on pit lake water quality depending on the pit stratigraphy and groundwater quality.

Recently permitted open pit mines in the arid western United States have modeled pit wall runoff quantity and quality in several different ways. In some cases runoff has been considered negligible. Where pit wall runoff has been included in the pit lake model, the percentage of precipitation that is considered runoff varies from 20 to 100 %. Runoff water quality has been assigned based on wall washing, meteoric water mobility procedures (MWMP), synthetic precipitation leachate procedures (SPLP), humidity cell tests (HCT), as well as a combination of these analyses. While it was determined in one pit that 95 % of the pit lake mass came from groundwater, in another case pit wall runoff was determined to be the primary influence on pit lake water quality.

In this paper, fictional simplified pit lake models using total dissolved solids (TDS) to represent mass loading are used to explore the effects pit wall runoff in pit lake models. Consideration of assigned runoff quality, runoff coefficients, and pit morphology in a typical arid climate illustrate the potential effects of each parameter. The simulations demonstrate the importance of evaporative draw on groundwater, offsetting effect on the importance of pit wall runoff in arid climates. These simplified conceptual models can be used to assess the importance of runoff in predicting pit lake water quality before implementing an entire pit lake model.

Recent considerations of pit wall runoff in pit lake models

Recently, pit wall runoff has been incorporated in pit lake predictions at several mines in the arid western United States. However, each site has a different pit infilling period, runoff coefficient, and runoff was represented by a different analytical procedure at each pit. Pit infilling and runoff coefficients are directly, and complexly, related to the site geology, hydrology, pit shape, and material weathering (Schafer and Eary 2009, INAP 2012). These same four parameters, with the addition of available geochemical data, were often considered in selecting an analytical basis for assigning pit wall runoff quality. Considering the number of factors affecting pit wall runoff quantity and quality a wide variety of pit runoff modeling methods is expected; no single approach will be applicable to all pits.

Pit A is a backfilled pit in Nevada which would preclude the ≈ 16 ha pit lake predicted to form in the no action alternative. Approximately 30 % of the wall rock was predicted to be non-acid generating, with a substantial percentage having uncertain acid generation potential. Pit wall runoff was considered negligible to the overall pit lake water balance in this case based on hydrologic modeling (Table 1). While pit wall runoff was small, mass associated with the runoff was acknowledged to increase the pit lake mass load consistent with the overall conclusion that several constituents would exceed regulatory guidance.

Pit B, located in Arizona, is a ≈ 263 ha, ≈ 610 m deep, open pit mine. Non-ore materials were characterized as limited in sulfide and abundant in carbonates. 220 years after mining the pit was projected be a 90 % full, with a ≈ 335 m deep lake of generally good quality. Pit wall runoff volumes were simulated using a stochastic element varying between 20 % and 40 % of the total precipitation on the pit wall (Table 1) and accounted for approximately a quarter of the steady state water balance. Pit wall runoff quality was represented by SPLP data for non-acid generating rocks and a combination of HCT and SPLP data for acid generating rocks. Runoff was allocated to the exposed rock types based on surface area percentage. While the model predicted 95 % of the pit lake mass loading was derived from groundwater, key constituents As, Pb, Hg, Se, and Tl were derived largely from pit wall runoff in the simulations (Table 1).

Located in Nevada, Pit C was incrementally expanded by ≈ 85 ha to reach ≈ 526 ha and 488 m deep. Pit geology was dominated by volcanics and alluvium. Pit wall runoff was based on the final four weeks of HCT, or MWMP when HCT was not available (Table 1). The HCT and MWMP results were scaled to adjust for field conditions. Pit C lake water quality was predicted to be circum-neutral to alkaline with As, F, and TDS in excess of regulatory reference values after 200 years of infilling, corresponding to a 335 m deep lake with a surface area of ≈ 158 ha. The pit wall runoff was ≈ 2 % of the overall pit lake influent through 200 years.

Pit D, located in Nevada, is a ≈ 295 ha, ≈ 762 m deep, open pit mine. Pit D lithologies include non-acid generating quartz apatite porphyry as well as quartz porphyry, rhyolite, and Ordovician sedimentary rock types which are subdivided based on acid generation potential. ≈ 15 % of the exposed pit surface was classified acid generating material. The pit was projected to be a little over half full after 200 years, with a ≈ 259 m deep lake. Pit D lake water quality was projected to be circum-neutral with few exceedances of Nevada standards. Pit D lake modeling water balance was taken directly from a hydrologic model which included pit wall runoff. Based on time step volumes, pit area, and precipitation rates, runoff was approximately 50 % of pit wall rainfall. Pit wall runoff loading was based on average HCT efflu-

Pit	Precipitation cm/a	Evaporation cm/a	Infilling Duration	Runoff Coefficient	Analytical Basis
A	29.2	115.6	Backfilled/220	negligible	None
B	43.4	181.6	215	0.2-0.4	HCT/SPLP
C	17.0	118.1	200	≈0.2	HCT(4wks)/MWMP
D	23.1	95.3	>600	≈0.5	HCT (ave)

***Table 1** Pit Lake water quality models mentioning pit wall runoff; meteorology, infilling period, and analytical basis of runoff water quality.*

ent concentrations scaled by half an order of magnitude to account for differences in grain size (Table 1). All HCTs ran in excess of 50 weeks. Mass loading was weighted to the exposure of each lithology. While no comparison of mass loading sources was presented, pit wall runoff accounted for 62 % of inflow in early time and 48 % at year 200.

Simplified Pit Wall Runoff Models Method

Simplified models based on TDS were used to evaluate the influence of pit wall runoff on pit lake water quality, and did not include equilibrium chemistry and mass loading from inundated pit walls. Terminal pit lakes forming in two different shaped pits were considered, each pit was 457 m deep, with planar areas of ≈ 202 ha, and ≈ 405 ha at the ground surface (fig.1). Each pit has a specific volume ("V" in m^3) and lake area ("LA" in m^2) as a function of stage ("S" in m) based on the pit geometry.

Time-stage relationships (fig. 2), which would normally be provided by a groundwater model, were calculated as an exponential function of the pit geometry provided stage. Time functions were altered to allow for different infilling periods and equilibrium stages. At equilibrium stage, the stage, volume, and lake area were held constant as time proceeded.

Based on the changes in stage (ΔS), pit lake volume (ΔV), lake area (ΔLA), as well as the assigned precipitation and evaporation rates, water volumes attributed to evaporation (E), direct precipitation (P_d), indirect precipitation (P_i), and groundwater inflow (GW_in) were calculated for each new time step as described below.

$$E = \Delta LA \times E_\mathrm{rate} \times \Delta T \tag{1}$$

$$P_\mathrm{d} = \Delta LA \times P_\mathrm{rate} \times \Delta T \tag{2}$$

$$P_\mathrm{i} = LA_\mathrm{max} - (\Delta LA) \times (P_\mathrm{rate} \times \Delta T) - P_\mathrm{d} \tag{3}$$

Where:

E_rate = Evaporation rate
P_rate = Precipitation rate
LA_max = maximum planar pit surface area
ΔT = elapsed time (years)

The change in pit lake volume (ΔV) can be described by the following volumetric water balance:

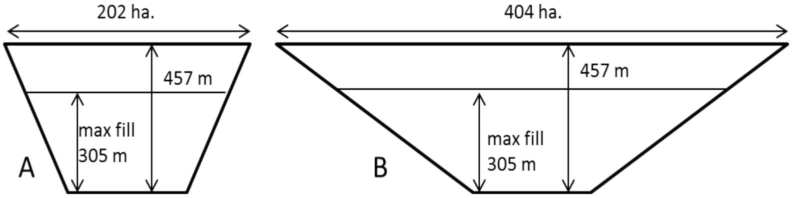

Fig. 1 *Conceptual pits A) 202 ha pit and B) 404 ha, each pit was allowed to fill to a maximum of 305 m during simulations.*

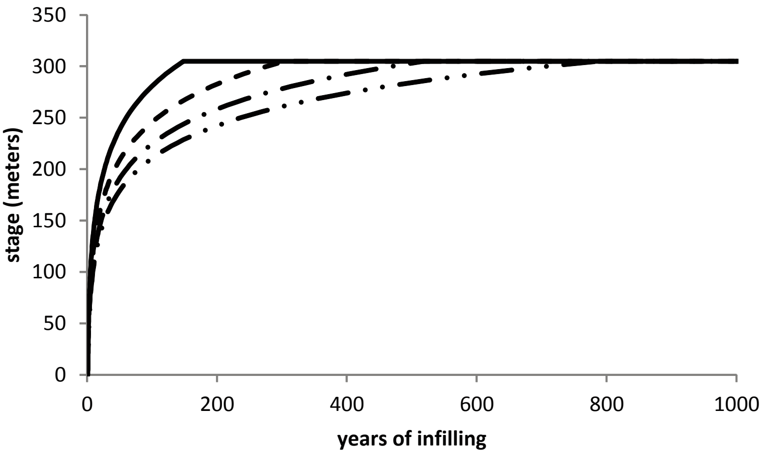

Fig. 2 *Time – stage relationship at 202 ha pit, 457 m deep, filling to 305 m deep over ≈150(—), ≈300(- - -), ≈ 500(–·–), and ≈800(–··–) year periods.*

$$\Delta V = GW_{\mathrm{in}} - E + P_{\mathrm{i}} + P_{\mathrm{d}} \quad (4)$$

Based on the relation above, time step groundwater inflow volume can be calculated as follows:

$$GW_{\mathrm{in}} = \Delta V + E - P_{\mathrm{i}} - P_{\mathrm{d}} \quad (5)$$

In the simplified pit lake models direct precipitation was assumed to have no dissolved mass. Pit wall runoff was calculated from the indirect precipitation rates as described above and assigned a runoff coefficient, thus limiting the amount of indirect precipitation entering the pit to 20 %, 50 %, or 80 %, of the total indirect precipitation. In all cases the evaporation was set to 1.2 m per year and precipitation rates were set to 0.3 m per year to reflect the precipitation and evaporation rates in the arid western United States (Table 1).

Groundwater quality was consistently assigned a concentration of 100 mg/L TDS. Runoff water quality was assigned TDS concentrations of 100, 300, and 500 mg/L, depending on the simulation. At each time step the respective water quality was applied to the runoff volume and the groundwater inflow volume to determine the mass added to the pit lake during the time step. Additional mass from each water source was incrementally summed and cumulated and the cumulative total divided by pit lake water volume to represent pit lake water quality.

Simplified Pit Wall Runoff Models Results

Simplified pit lake model results reveal that infilling time has minimal importance on groundwater quality; however, only cases where groundwater is equivalent to, or better than, runoff quality were considered. The effects of runoff coefficient, runoff water quality, and pit geometry produced significant changes in water balance which drive pit lake quality. The results presented here reflect the overall mass load delivered to the pit lake in TDS, no mass has been removed from the simulated pit lake solution via the precipitation of solids that would decreased the dissolved mass in a real pit lake. Therefore, the concentration increases shown here are generally over represented.

Increasing runoff percentage, not surprisingly, increased the pit lake TDS. In the case of a 202 ha, 457 m deep pit, filling to an equilibrium stage of 305 m deep over ≈ 150 years, with a runoff quality of 500 mg/L and groundwater quality of 100 mg/L the effects of runoff coefficient were visible (fig. 3). However, over the 1000 year simulation, groundwater accounted for 69–76 % of the influent volume and runoff only accounted for 2 – 10 %. In this case, where runoff water quality was substantially worse than groundwater quality, runoff accounted for 14–41 % of the pit lake mass load at 1000 years. There would be no runoff coefficient effect on pit lake water quality if runoff water quality was equal to groundwater quality. Where runoff water quality is better than groundwater quality increasing the runoff coefficient would have an ameliorating effect on pit lake water quality, decreasing pit lake concentrations with increasing runoff coefficient.

Pit lake water quality was also affected by runoff quality. For the same pit as discussed above, with runoff held to 50 % of pit wall precipitation, the effect of runoff qualities ranging from 100 mg/L to 500 mg/L were noticeable over a 1000 year simulation (fig. 4). In all three simulations presented in Fig. 3, groundwater accounted for 72 % of the influent volume, while runoff accounted for 6 %. Mass associated with groundwater accounted for 71 – 92 % of the pit lake mass and runoff accounted for 8–29 % of the mass in the pit lake over the 1000 year period depending on runoff quality.

Simulations performed for two different pit shapes, both (472 m) deep and both filling to 305 m deep produced disparate results. One pit had a surface expression of 202 ha, while the other had a larger catchment area of 404 ha (fig. 1). In both cases (fig. 5) runoff quality was 500 mg/L; however, the larger pit resulted in increased runoff, thus increasing the

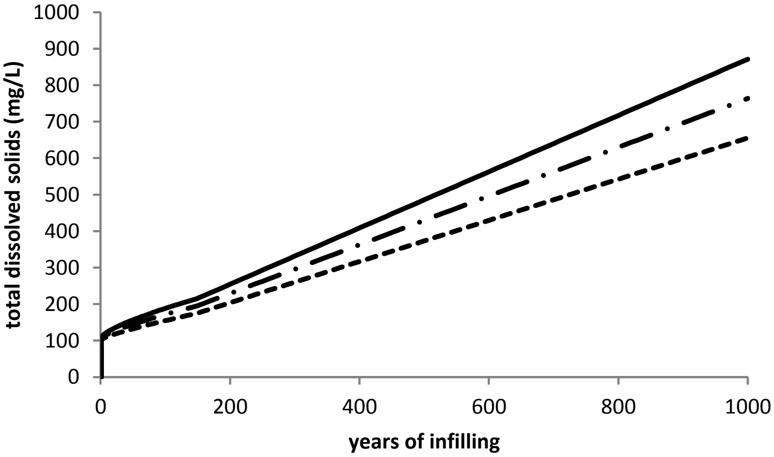

Fig. 3 Pit lake TDS concentration (mg/L) as a function of time for a 202 ha pit with a runoff quality of 500 mg/L at 20 % (- - -), 50 % (– · –), and 80 % (—) runoff, reaching equilibrium stage at 150 yrs.

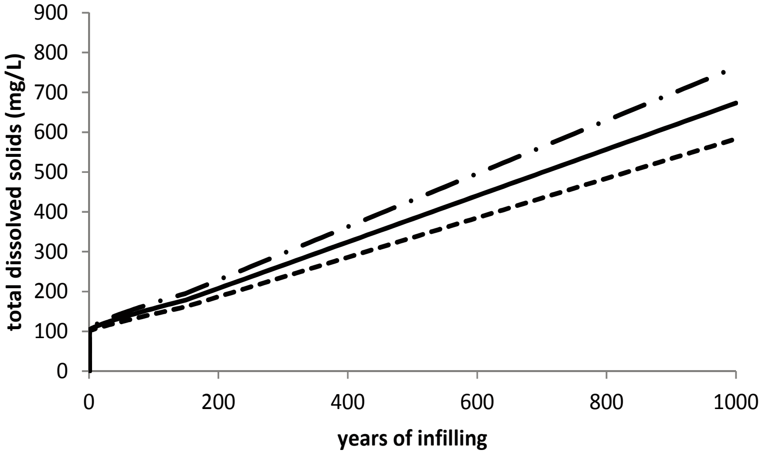

Fig. 4 Pit lake TDS concentration (mg/L) as a function of time, reaching equilibrium stage at 150 yrs, for 202 ha pit at 50 % runoff with a runoff quality of 100 (- - -), 300 (—), and 500 (– · –) mg/L.

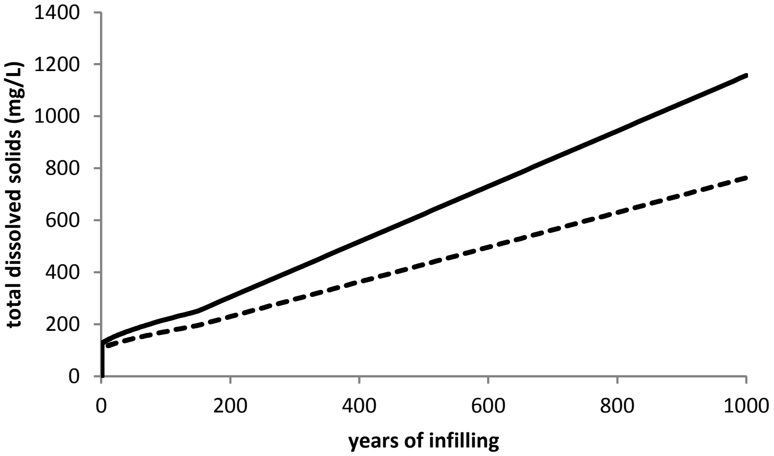

Fig. 5 Pit lake total dissolved solid concentration (mg/L) as a function of time for a 457 m deep, filling to 305 m deep over ≈150 years, groundwater quality of 100 mg/L at 50 % runoff with a runoff quality of 500 mg/L and pit acreages of 202 ha (- - -) and 404 ha (—) respectively.

runoff mass load to the pit. Runoff accounted for 11 % of the influent volume, and 44 % of the mass in the larger pit. Groundwater accounted for 67 % of the influent volume and 56 % of the mass. In the smaller pit, runoff accounted for 6 % of the volume and 30 % of the mass, while groundwater was 72 % of the influent volume. Unlike the previously discussed examples, these two examples have different infilling functions and there is a substantial difference in volume in between these two simulations.

Conclusions

Several expected results related to water balance and water quality are demonstrated through simplified pit lake water quality models that include runoff. The simplified models show the effects of pit morphology and runoff coefficient on runoff quantity and water balance. Runoff water quantity is typically small in arid climates, offset in water balance by the ever-present evaporative draw on groundwater. Evaporative consumption of pit lake water keeps groundwater inputs high, even at equilibrium stage, unless the pit lake is small in comparison to the pit. Despite the potentially small water quantities associated with runoff, it can load significant mass to the pit lake when runoff quality is poor in comparison to groundwater quality.

In some recent pit lake models runoff coefficients were assigned a value based on professional judgment with no references, despite demonstrating a potentially substantial effect on pit lake water quality. Runoff coefficients are dependent on precipitation rate and duration (on an individual storm basis), whether it falls as rain or snow, pit bench width, hydrologic characteristics of the rock, pit aspect, and evaporation/sublimation (Prohaska and Dragišić 1991). One component of the water balance that was not considered in recent pit lake models, or this effort, is the interflow derived from pit wall precipitation. Empirical runoff coefficient data from existing pits, or as a pit develops, could be useful in further defining the complex parameter of runoff coefficients and interflow.

Runoff water quality is typically assigned a constant value for each lithology based on an analytical procedure, as seen in recent pit lake models. In general MWMP, SPLP, and wall washing stations on loose walls are likely to have higher TDS than average or late term HCT results. Of the recent cases, results from the HCT are more likely to capture the acidity and metals generated through the oxidation of sulfide bearing rocks. The use of net acid generation test results on acid generating materials to capture the behavior of acid generating lithologies could also be useful in assigning pit wall runoff quality. However, pit wall runoff concentrations may not be constant. As pit walls weather, reactive surface area is likely to increase, thus increasing mass loading to runoff. Acid generating rocks are more likely to disaggregate, resulting in increased surface area subject to oxidation over time. In this regard, a model that considers runoff quality on a kinetic and mass-balanced basis (instead of a constant concentration basis) might be an improvement to the state of the art. In many cases, the pit wall could be considered miniature waste dumps spread across the benches of the pit.

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