Proceedings of Heap Leach Solutions, 2015
September 14-16, 2015, Reno, USA
Published by InfoMine, © 2015 InfoMine, ISBN: 978-0-9917905-8-6

Investigating Leaching Alternatives for Heterogeneous Heap Leach Pads

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Abstract

Heterogeneity of hydraulic properties that control flow of leachate through ore can vary across a heap leach pad at multiple scales. Small-scale heterogeneity can arise from differences in mineral type, grain size distribution, agglomeration schedules, irrigation leaks, and other effects that are confined to a localized area. Larger scale heterogeneity can be attributed to ore placement, traffic patterns, overburden compaction, and chemical weathering, all which occur over much broader regions. Large-scale heterogeneity gives rise to general structural features that can inhibit uniform wetting and metal liberation. In turn, this can result in significant losses in metal recovery.

To more fully understand large-scale heterogeneity, geophysical imaging has been conducted on several leach pads to assess internal structure in electrical properties. The variability in electrical properties can be used to infer heterogeneity of hydraulic properties due to the sensitivity of bulk electrical resistivity to the hydrologically based state variables of moisture content, ionic strength of pore water, and temperature. From the set of geophysical surveys, two generalized types of large-scale structural features have been identified and simulated in an unsaturated flow model. Simulations were then run to determine a leaching schedule or method that could help increase solution flow through lower permeable material. The simulations revealed that leaching schedules can be used to minimize the effect of structural geometry under certain conditions, although some geometries cannot be rectified from surface leaching alone and subsurface leaching through injection or rinsing is required to increase metal recovery.

Introduction

Ores stacked or dumped in a heap leach pile are heterogeneous in terms of hydraulic, geometallurgical, and geotechnical properties. Heterogeneity, defined as the spatial and temporal variability of a particular property (e.g., hydraulic conductivity), is introduced at all stages of the heap leach pile formation, and may arise from daily and seasonal environmental factors, engineering constraints, and metal production. Furthermore, heterogeneity may exist at multiple scales, such as differences in mineral type, grain size distribution, agglomeration schedules, irrigation leaks, and other localized effects. At a much broader scale, effects from traffic patterns, overburden compaction, and chemical weathering may affect flow of leachate through the ore and reduce extraction or the ability of the leach solution to effectively drain from the pile.

Measuring broad scale heterogeneity *in-situ* is difficult without the use of geophysical methods. Specifically, electrical resistivity can be used to understand important heap properties such as moisture content, inorganic mineral and solute concentrations, temperature, or the distribution of clayey material (Poisson et al., 2009; Rucker et al., 2009; Rucker 2010). When conducted in a time-lapse manner, changes in resistivity can be related to unique hydraulic parameter as all others will likely be static. The data plotted in Figure 1 is an example of monitoring surface irrigation of a heap leach pad with electrical resistivity. Snapshots of data were acquired every six hours during steady irrigation. The time series of plots represent snapshots of changes in electrical conductivity that directly correlates to changes in moisture content. The change was calculated from a baseline resistivity dataset prior to irrigation. From these data, it is clear that wetting below the upper lift is occurring preferentially on the left side while the subsurface moisture content on the right side is static. The figure highlights the role of broad scale heterogeneity of hydraulic properties and the ability of 1) raffinate to effectively wet up ore, and 2) pregnant leach solution (PLS) to drain out of the system.

In this work, we use geophysical data to investigate several different scenarios of heterogeneity that may manifest in heap leach piles. The heterogeneity in electrical properties is used to generalize heterogeneity in hydraulic properties, such as the values comprising constitutive relations that describe hydraulic conductivity, water potential pressure, and water content. Heterogeneous leach piles are then evaluated for their ability to transport solution and effectively drain during irrigation by modeling the leaching process with a numerical unsaturated flow model. The modeling also investigates leaching schedules through periodic application of leaching rates with resting periods. The results of the flow modeling with surface irrigation highlight issues surrounding low permeability and/or poorly draining ores and the eventual metal recovery from a leach pad. Lastly, a subsurface irrigation model is tested and demonstrates that raffinate can be injected and PLS recovered more quickly via injection wells.

Geophysical Surveys of Heaps

Assuming that the solid mineral grains comprising heap leach ore have relatively low electrical conductivity, the flow of electricity through a pile will be much like the flow of water. Thus larger, interconnected, water-filled pores provide a conductive medium for electrical current flow. Lower water content and/or reduced pore space interconnectivity will be more electrically resistive due to the more tortuous paths that the electrical current must take. Since the primary pathway for electrical current is through solution in the pore space, it is described as being electrolytic. Electrical conductivity of the solution is in turn directly correlated to the dissolved ion concentration. Hence, when the solution salinity is high, electrical conductivity increases (or resistivity decreases), and salinity is a major factor in determining the resistivity of the leach ore media (Ward and Fraser 1967).

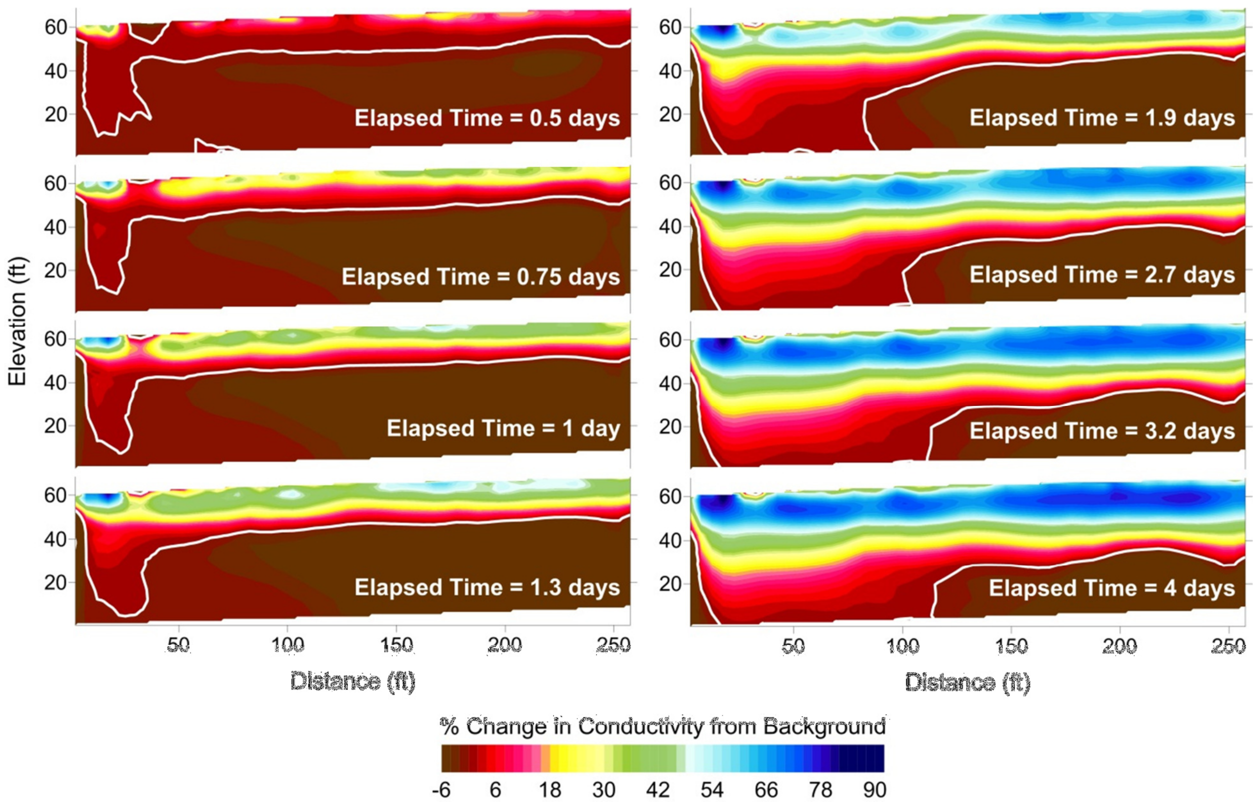

Figure 1. Electrical resistivity monitoring of surface leaching, showing electrical resistivity baseline and subsequent changes in resistivity over a four day period.

The flow of electricity, like water, occurs when a differential potential is applied across a medium. In electrical surveys, this is accomplished by placing current electrodes into the ground and the resistiveness of the medium is calculated by knowing the potential drop over a known distance. It has been observed in laboratory experiments that the resistance of a medium is proportional to the length over which the current is applied and inversely proportional to the area perpendicular to current flow.

There are many published studies using electrical resistivity geophysical methods to image engineered rock piles (Placencia-Gómez et al., 2010; Grangeia et al., 2011; Zarroca et al., 2015). While all these studies used geophysical imaging to solve different problems, they commonly highlighted the role of material to store solution with high total dissolved solids (TDS). In some cases, basic hydrogeological principles were used to infer preferential movement of the solution. Figure 2 is another set of examples of electrical resistivity, highlighting drainage through crushed copper ore. The resistivity data were collected using a Schlumberger array with the SuperSting R8 resistivity meter. Electrode separation was 3m in both examples and the data were processed with RES2DINV (Geotomo Software, http://www.geotomosoft.com). In Figure 2A, the upper lifts in the near surface are conductive. Along the bottom of the pile, however, variable resistivity can be seen, where low resistivity indicates higher moisture and high resistivity indicates low moisture. If the ore permeability is lower than the irrigation flux, excess solution storage will result. Excess storage may be occurring above the high resistivity, lower lifts (light blue) in the low resistivity (purple) areas.

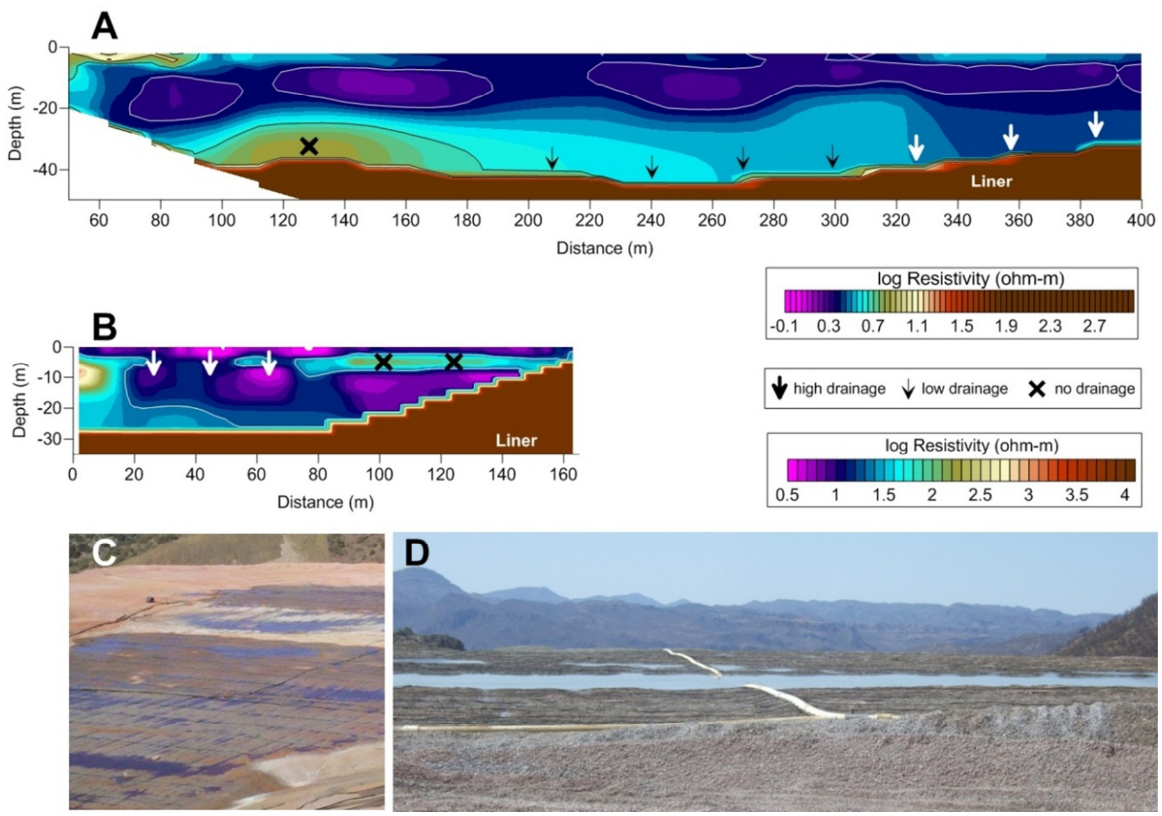

Figure 2. Profiles of electrical resistivity across heap leach pads, showing differential moisture conditions. A) variable deep moisture to the liner, B) variable shallow moisture, C and D) ponding due to low permeability surface conditions

Figure 2B shows a thin resistive layer near the surface (light blue marked by X) that may be inhibiting effective drainage. The resistive layer was most likely compacted during ore placement. Immediately above the compacted layer, the resistivity is very low and below the layer there are areas of high solution content indicating preferential flow. At the time of acquisition, excessive surface ponding of water was observed (Figures 2C and 2D).

Electrical Conduction in Porous Media

A decrease in resistivity due to electrically conductive porewater does not actually describe any effects of the ore itself, hence we need to remove the pore conduction effect of the conducting electrolyte if information about the heap leach materials are needed. Removing pore conduction effects is accomplished by normalizing the measured resistivity to the electrolyte resistivity, which is termed the formation factor, F_R

$$F_R = \frac{\rho_b}{\rho_w} \tag{1}$$

where ρ_b is the resistivity of the bulk sample and ρ_w is the resistivity of the fluid in the pore space. For copper heaps, where the salinity of raffinate and PLS is usually high, the formation factor has been observed to be approximately 1 to 30, with pore water resistivity on the order of 0.3 to 1 ohm-m. Archie (1942) proposed a power law between porosity and F_R (known hence forth as Archie's Law), which plots as a straight line with a negative slope on bi-logarithmic paper:

$$F_R = \phi^{-m} \tag{2}$$

The parameter m is obtained through regression analysis and is termed the cementation factor. The value of m generally lies between 1.3 to 3, with a generic value of 2 used most often. Trying to generalize Archie's Law to account for the non-zero offset observed when matching F_R to ϕ, Winsauer et al. (1953) added a multiplication factor, *a*, to Archie's Law:

$$F_R = a\phi^{-m} \text{ or } \quad \rho_{\mathrm{b}} = a\rho_w\phi^{-m} \tag{3}$$

which was found to vary between 0.6 and 1.3 for some sediments.

Equation 3 satisfies observations where the ore materials are completely saturated. In media with a substantial volume fraction of air, which is a non-conductor, the resistivity will be a function of the water saturation as well. Saturation, which varies between 0 and 1, describes the fraction of the pore space filled with water. Archie (1942) again showed an exponential relationship with the saturation and determined that the formation factor can be represented by:

$$F_R = S_w^{-n} \tag{4}$$

where S_w is the saturation and n is the saturation index. The combination of Eq. 4 with Eq. 3 results in a relationship that gives the specific electrical resistivity of a partially saturated material depending on PLS resistivity, hydraulic properties of saturation and porosity, and empirical fitting parameters:

$$\rho_{\mathrm{b}} = a\rho_w\phi^{-m}S_w^{-n} \tag{5}$$

Equation 5 assumes that the conduction mechanism is purely a pore space phenomena, i.e., neglecting surface conduction. Surface conduction is the flow of electricity along the surface of the mineral grains by the exchange of electrons (Ward and Fraser 1967). This is a galvanic conduction mechanism and is different from electrical flow through the saturating fluid. Surface conduction is an important mechanism in resistivity measurements when the material has a relatively high clay content. Barker and Worthington (1973) mention the importance of surface conduction mechanisms and suggested an equation based on a parallel resistor model:

$$\frac{1}{\rho_t} = \frac{1}{\rho_b} + \frac{1}{\rho_s} \tag{6}$$

where ρ_t is the measured resistivity of the host rock, ρ_b is the resistivity of the sand if it were not matrix conducting (Archie's component), and ρ_s is the resistivity of the conducting portion of the rock matrix. The volume fraction is often used in hydrogeology to obtain effective hydraulic conductivities, and depends on flow parallel or perpendicular to bedding planes.

To use these relations, the moisture content or ionic strength are calculated from the field-measured resistivity. Eq. 6 is inverted to obtain the dependent variables of saturation and concentration from the single independent variable of resistivity. The measured resistivity is only one variable and many pieces of information are needed to form a quantitative expression that is useful for hydrologic interpretation. The inversion then is non-unique as many combinations of these parameters can give the same resistivity value. Direct hydrologic modeling, in-situ measurements, or a combination of the two could provide the additional information needed to ensure uniqueness. With the hydrologic modeling, estimates are made as to the location and extent to which the PLS has drained through the ore. The PLS content is converted to a resistivity distribution using the relationships formulated above. In essence, the resistivity data provides constraints to help focus the hydrologic modeling results to obtain more realistic distributions of water content and concentrations of various solutes in the PLS.

Hydrogeological Models

Unsaturated flow modeling was conducted using the numerical code, HYDRUS (Šimůnek, et al., 2012). The purpose of the modeling was 1) to understand the ability of different material structures, as observed from the geophysical data, to drain effectively and 2) to predict the amount of increased storage for ores that do not drain. HYDRUS solves the Richards equation for saturated-unsaturated water flow and the convection-dispersion equation for heat and solute transport. The flow equation can incorporate a sink term to account for water uptake by plant roots. The heat transport equation considers transport due to heat conduction and convection with flowing water (Šimůnek et al., 2012). We limited the investigation in this work to modeling the flow of solution through leach ore; several others have used HYDRUS to solve solution flow problems through heaps (e.g., Cariaga et al., 2015; McCaffery et al., 2014). References to the modeling equations and assumptions can be found in these sources.

Surface Irrigation

The first set of models was conducted in order to understand drainage through and storage in a homogeneous heap for comparison to results from heterogeneous heaps. A homogeneous heap was modelled using a one-dimensional geometry with steady infiltration at the surface and free drainage at the bottom using parameters consistent with Webb et al. (2008). Infiltration was set at 0.147 m/d (6 L/m^2/day or 0.0025 gpd/ft^2) for the first 90 days and shut off for the second 90-day period. The simulated heap height was 30 m and we simulated a well- and moderately-draining heap according to the Van Genuchten hydraulic properties in Table 1 (Figure 3A and 3B shows the shapes of the constitutive relations for the four types of ore materials in Table 1). A well-draining material is characterized by a high saturated hydraulic conductivity (K_s) and a low storage potential as represented by a high water release value (α).

Table 1: Ore material hydraulic properties used for modeling heaps

Soil Type	K_s (m/d)	n	α (m^{-1})	θ_r	θ_s
Well Draining	24.3	1.22	54	0.04	0.27
Moderately Draining	2.6	1.23	2.8	0.02	0.30
Poorly Draining	0.023	1.3	0.05	0.05	0.273
Compacted	0.000023	1.3	0.05	0.05	0.273

When infiltrating from the surface, the wetting front takes time to reach the bottom of the heap depending on the ratio of the change in hydraulic conductivity before and after wetting to the change in moisture. After turning off the surface source, the solution will redistribute through the ore and come to equilibrium. If the solution content is greater than the ore's water holding capacity, drainage of PLS will occur as effluent. The infiltration and drainage flux can be mapped through time to understand the speed of the wetting front and the amount of solution recovered from the bottom of the heap. Figure 4 shows the results of these data for a well- and a moderately-draining ore, both with an initial water content of 0.07. The cumulative flux is the height of water in meters and the volume can be computed by multiplying by the planar surface area through which the solution flows. For the well-draining ore, the PLS wetting front reaches the bottom of the heap in about 41 days versus 58 days for the moderately draining ore. After turning off the surface irrigation, the ore immediately begins to drain, but at a slower rate than during infiltration (as indicated by the slope of the flux curve). After 90 days of drainage, an excess of 3.07 m is observed for the well-draining ore and 4.56 m is observed for the moderately-draining ore, thus the moderately-draining ore stores an extra 1.5 m of solution. Absent from these homogeneous models are the poorly draining and compacted ore. The compacted ore is similar to the poorly-draining ore, except with a significantly lower saturated hydraulic conductivity. Since the saturated hydraulic conductivity for these soils is less than the irrigation rate, ponding would immediately start and percolation would be limited.

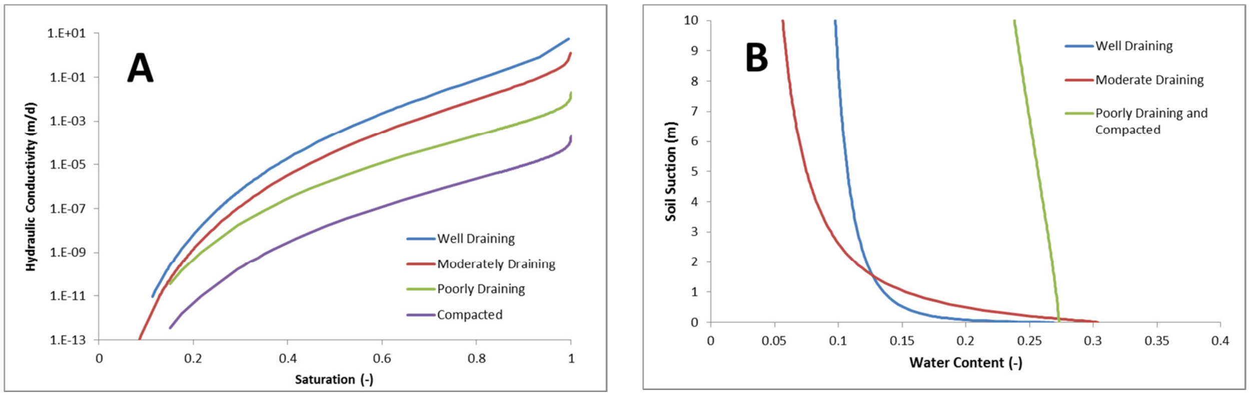

Figure 3. Soil Properties for different ore types used in the unsaturated flow model. A) hydraulic conductivity functions; B) soil characteristic functions

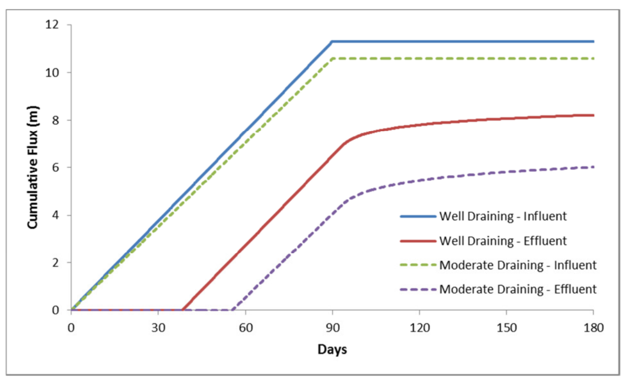

Figure 4. Cumulative flux from the top and bottom of a homogeneous heap

A heterogeneous heap was simulated with a thin, poorly-draining layer in the middle of a normally well-draining heap (Figure 5A). This model is similar to the geophysical example shown in Figure 2B. The height of the poorly-draining layer was 5m at 10 to 15m below the pad surface. An irrigation flux of 0.147 m/d (6 L/m^2/day or 0.0025 gpd/ft^2) was applied at the surface for 90 days with an initial pressure head condition of -100 m. The solid lines in Figure 5B show the predicted raffinate and PLS flux into the top and out of the bottom of the heap. The slope of the flux is only slightly lower than that of the homogeneous heap comprising moderately draining ore, suggesting that a small poorly draining layer has minimal effects on the total movement of solution through the heap. However, the solid lines showing solution pressure head in Figure 5C indicates excessive internal saturation. Since the hydraulic conductivity of the low-permeability layer is lower than the irrigation flux, the solution saturation occurs above the layer (perched water table) regardless of depth or thickness of the poorly draining layer. For this instance, saturation reaches the surface starting on day 22 with resultant ponding and potentially geotechnical instability in actual field conditions.

A second model was then run to estimate the maximum allowable irrigation rate that could be applied to avoid saturating the upper material by changing the upper boundary condition to a minimal suction head value near 0 m. The new boundary condition allows us to back calculate a flux that would keep the entire heap unsaturated. The slope of the dotted low flux data in Figures 5B shows that the surface irrigation rate could not exceed 0.018 m/d (0.7 L/m^2/day or 0.0003 gpd/ft^2) in order to keep from saturating the material and that breakthrough of the pregnant leach solution from the bottom of the heap would occur in about 210 days. The unsaturated conditions are verified in Figure 5C.

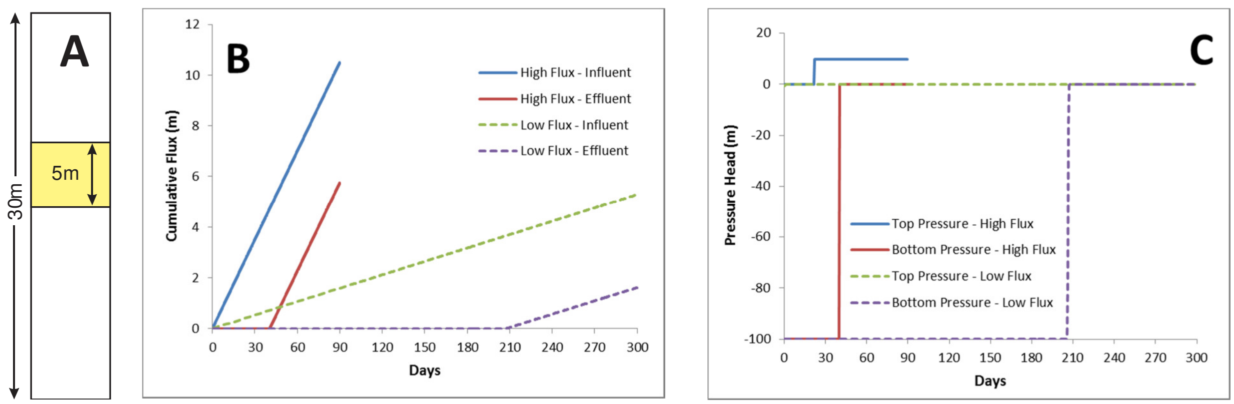

Figure 5. Output data from a heterogeneous heap with steady flow. A) Heap geometry; B) Cumulative flux for high and low irrigation rates with a poorly draining layer; C) pressure heads for high and low flux with a poorly draining layer.

The same models were run for a lift of compacted ore with hydraulic properties shown in Table 1. Both a steady low flux at the surface and a constant suction head near 0m was used to establish acceptable irrigation rates to minimize ponding. However, since the lift has such low hydraulic conductivity, no solution could penetrate the ore within a reasonable period of time (300 days) for either boundary condition. Any irrigation rate eventually created a perched water table within the upper material and the compacted lift remained mostly dry at its initial condition. Figure 6A shows the water content distribution for a model of compacted ore. For these results, the lower lift was assumed to have been partially leached prior to stacking the compacted lift and any new ore was placed above the compacted lift. Figure 6B shows the conversion of water content from the HYDRUS model to effective saturation using the saturated (θ_s) and residual (θ_r) water content values as end points of 0 to 1 (Table 1). Finally, the saturation was converted to an electrical resistivity value (Figure 6C) using parameters in Table 2 for completing Equation 5. The only significant difference among the ore types, besides the saturation, was the resistivity of the pore water. It was assumed the new ore was being leached with high acid (conductivity of 30 mS/cm and 6 g/L free acid) and the partially leached ore was effectively devoid of acid (conductivity of 18 mS/cm and >1 g/L acid). The resistivity distribution of Figure 6C demonstrates how a geophysical survey from the surface could identify issues associated with drainage by identifying dry compacted layers.

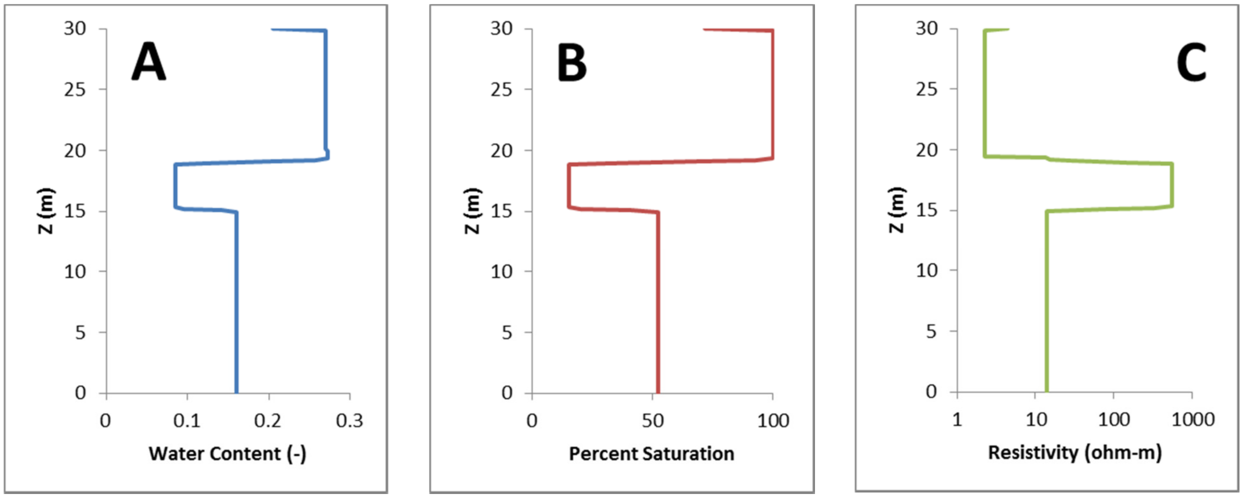

Figure 6. Model results from a heap with a lift of compacted ore. A) water content from Hydrus; B) conversion of water content to percent saturation using Table 1; C) conversion of saturation to electrical resistivity using Equation 5 and parameters in Table 2.

Table 2: Soil electrical properties used for modeling different ore types

Soil Type	ρ_w (ohm-m)	A	M	n
New Ore	0.33	0.6	2	2
Compacted Lift	2	0.6	2	2
Partially Leached Ore	0.55	0.6	2	2

The next flow modeling case examined a 30 m heap that was constructed with the bottom half comprising poorly-draining ore and the top half comprising well-draining ore (Figure 7A). The hydrogeological model is represented geophysically in the left hand side of Figure 2A. This is a realistic scenario for many mines as different phases of the mine plan may exploit argillaceous or low competent ore or the construction methods may change (e.g., Rucker, 2015). Again, an irrigation rate of 0.147 m/d (6 L/m^2/day or 0.0025 gpd/ft^2) would have saturated the upper portion of the pad within 27 days, due to the low hydraulic conductivity of the lower layer. Therefore, a model was run to determine the highest achievable irrigation rate without saturating the ore with a constant suction head boundary condition near zero. Figure 7B compares the model results (the 15m layer) to the case of the individual 5m lift of Figure 5B. The irrigation rate is nearly identical, but the drainage occurs slightly faster from the 15m layer. This is due to the slightly higher hydraulic conductivity at a higher suction for the poorly-draining ore relative to the well-draining ore.

As a last trial for surface irrigation using both 5m lift and 15m layer cases, a rinse-rest model was conducted by incorporating resting periods into the irrigation schedule, similar to the work by Silver (2013). For the heap with a 5 m layer of poorly draining ore, an initial 21 day wetup period was followed by 10 days of rest before another 5 days of irrigation. The schedule of 5 days on + 10 days off was continued for 300 days with results shown in Figure 8A. The pulsed flow was compared to the steady-state irrigation rate that prevented saturation (dotted lines of Figure 5B). The results show that the pulsed scheduling allows a higher average flux through the surface (0.03 m^2/day, 1 l/m^2/hr, or 0.0005 gpm/ft^2) compared to 0.018 m^2/day (0.7 l/m^2/hr or 0.0003 gpm/ft^2) while maintaining a steady PLS effluent rate. The arrival of the wetting front at the bottom of the heap also occurs faster with the pulsed flow irrigation scheme. There are, however, periods of hydraulic head build up on the low permeable layer, creating a perched water layer of about 2m. The perched layer drained within a day of irrigation being turned off. As for the thicker 15m poorly draining layer, a different schedule was created to maintain the same level of safety as the 5m lift. Figure 8B shows the results for pulsed flow, where a 5 day on + 50 day off schedule was needed to sufficiently drain the solution for 2m perched water layer thickness. The average rate for the pulsed surface irrigation is much lower than the steady irrigation (0.01 m^2/day compared to 0.018 m^2/day (0.4 vs 0.8 l/m^2/day or 0.0008 vs 0.0016 gpd/ft^2), demonstrating that there is no advantage in devising a tailored irrigation schedule for thick poorly draining ore.

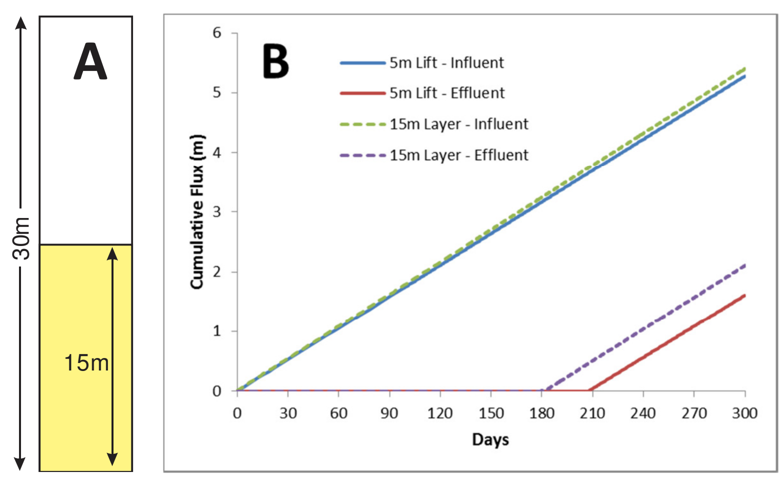

Figure 7. Output data from a heterogeneous heap with steady flow. A) Heap geometry; B) Cumulative flux for 5m and 15m layers

Subsurface Irrigation

As shown by the above examples, overcoming drainage issues of excess storage, low surface irrigation rates, and long PLS arrival times can be difficult via surface leaching alone. Moreover, layers with low hydraulic conductivity may impede metal recovery from within and below the layer. A remedy may be to direct the solution to specific areas deeper in a using subsurface irrigation through injection or rinse wells. The number of wells needed depends on the desired solution coverage which is controlled by the specific hydraulic properties of the ore, as well as available flow rate and pressures in the line feeding the wells. In several examples (Seal et al., 2012; Rucker, 2014; 2015), wells were spaced 25 m to 35 m apart and operated independently or simultaneously in a group with flow rates upwards of 11,000 m^3/d.

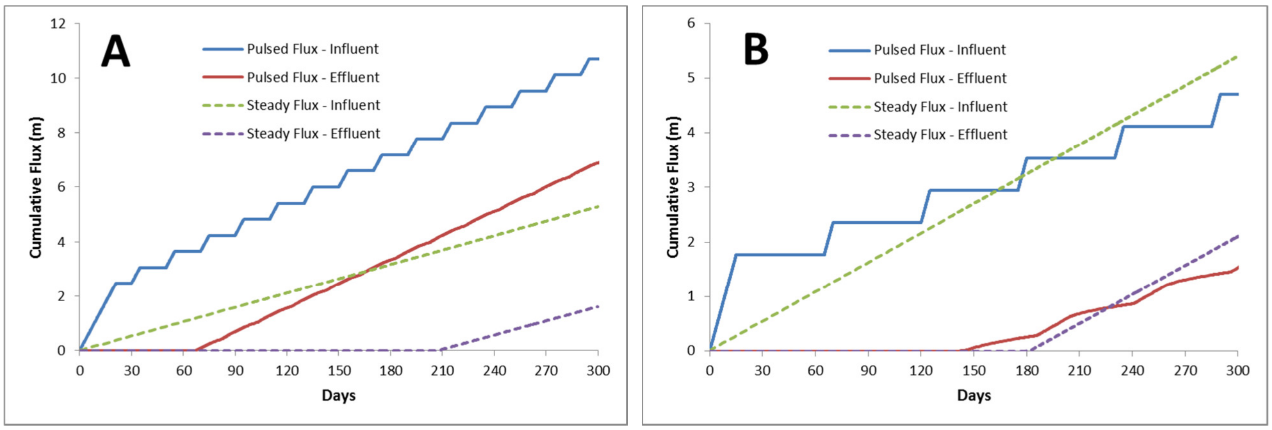

Figure 8. Cumulative flux from pulsed and steady flow in a heterogeneous heap with A) 5m poorly draining layer; B) 15m poorly draining layer

An example of subsurface irrigation flow modeling is presented in Figure 9, where a two-dimensional axisymmetric flow model was constructed with moderately draining ore. A single 5m lift of poorly draining ore was placed in the center of the leach pad, similar to the geometry shown in Figure 5A. The axisymmetric model is a simplified three dimensional model in a cylindrical coordinate system that assumes the properties are equivalent for all angles α (Figure 9A). The model was initiated with a fairly wet ore with draindown for 180 days to establish a new initial condition for injection. For the remaining 90 days, injection occurred below the low permeable lift over a screened interval of 3 m. For this model, it was further assumed that the wells were gravity fed solution from the top of the well and maintained a minimal pressure head value of 0.01m (i.e., just above saturation).

Figure 9B shows the water content distribution after 90 days of subsurface irrigation. Immediately near the well, the water content of the formation indicates saturated conditions. However, the increase in water content above background levels is distributed laterally at least 5 m suggesting for this scenario the well field could be designed on 10 m centers. Figure 9C shows the cumulative volume of raffinate into the heap and volume of PLS to the drainage layer as effluent. A significant aspect to these simulations is that the time of solution arrival has been reduced significantly compared to surface irrigation. The 11-day arrival for subsurface irrigation is much faster than any surface irrigation models with similar ore.

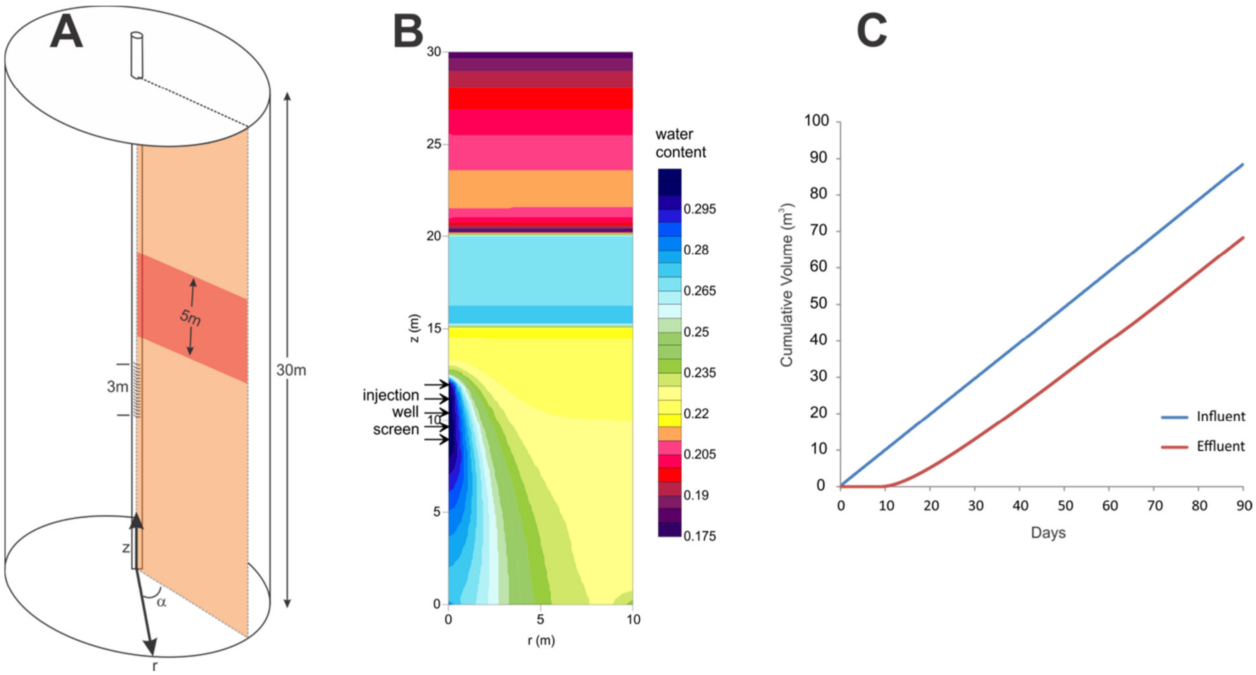

Figure 9. Subsurface irrigation model example: A) two dimensional axisymmetric model geometry with 5m poorly draining lift; B) water content distribution after 90 days of rinsing; C) cumulative volume into and out of the heap.

Conclusion

Unsaturated flow models incorporating surface irrigation were conducted on homogeneous and heterogeneous heap realizations to understand flow and drainage though ore with different levels of permeability and storage. Imposed heterogeneities were derived from geophysical imaging across typical leach pads and included a single mid-level layer and the bottom half of the leach pad, both comprising low permeable, poorly draining ore. The homogeneous models provide background for comparing the effects from PLS arrival and retention during irrigation. The heterogeneous models showed how a layer, regardless of thickness, can impede flow and create in-heap saturated conditions if the ore hydraulic conductivity is less than the applied irrigation rate. Conditions were then tested to understand whether tailored irrigation schedules with periodic resting periods could overcome the difficulties associated with low hydraulic conductivity values. Appropriate schedules can be devised, but their success depends on the length of time allowed for draindown, or the 'off' time.

Lastly, a model was developed to show how subsurface irrigation by injecting or rinsing could benefit the leaching operation by applying solution below lower permeable regions. The model showed that gravity injection of raffinate deeper within the heap allowed for faster PLS recovery and more effective rinsing at depth. Practically, subsurface irrigation has already been applied at a number of heap leach facilities. The method has also been adapted for poorly draining or compacted ore by applying sufficient pressure to mechanically alter the hydraulic properties and increase drainage.

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