Accounting for Complexity in Draindown Modeling for Heap Leach Closure

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Abstract

Active management of residual leach solutions, which no longer have commercial value, represents a significant financial liability for the closure of heap leach operations, and the duration of active management should be carefully planned both technically and financially. The state-of-practice in developing leachate management plans for closed facilities includes deterministic models such as the Heap Leach Draindown Estimator (HLDE) developed in the state of Nevada, USA. Such models rely on an approximation of the unit draindown rate using theoretical formulations of unsaturated flow, which is then extrapolated to a regular orthogonal geometry and a single defined date for cessation of irrigation. When adequate calibration data is available this method can yield satisfactory results; however, such calibration data is typically not available.

An improved method is proposed in this paper that takes into account the important variables that describe a heap leach pile such as geometry, material domains, and time. The method consists of a combination of numerical modeling of unsaturated flow and analytical modeling to predict the time required to achieve passive water management. To account for the non-linearity of draindown flow a unit draindown rate is determined for each domain through a rigorous finite element numerical modeling based on the physical and hydraulic properties of the leach material. This step can also account for different material types that may exist in the leach pile and create families of individual curves for each material. The geometry of the heap leach pile is taken into account by discretizing the pile into geometric domains, grouping areas of similar height.

The resulting draindown curves are then multiplied by the representative surface area to compute the expected volume of draindown from each of these domains. In the third step of the assessment, the individual draindown volumes are assembled in a time series honouring the actual schedule of when irrigation has been completed in the various regions of the facility leading up to the final closure date.

Various complexities can be added to the model to enable a complete water balance of the heap as well as integration with the site-wide closure water management plan. Some examples are recirculation to

some areas and not others, deployment of enhanced evaporation methods, treatment and discharge of draindown solutions, or reduction in infiltration by covering the heap or portions thereof.

An example of the method applied to a mine in Argentina is described in this paper, detailing the assumptions that were made with respect to the closure water balance and the functional parameters used for modeling the final draindown of the heap leach facility.

Introduction

Heap leaching is one of the lowest cost processing methods and is increasingly used in projects in all climates with large low-grade reserves. Heap leaching facilities vary widely in size and shape, and large solution inventories, often in the order of millions of cubic meters, must be managed in order to sustain economically viable operations.

Leaching of the ore is typically achieved in pre-determined leach cycles, where the leach solution is recirculated onto the heap continuously for a number of weeks or months. Once the metal concentration in the leach solution falls below an economic cut-off value, irrigation is moved onto a new leaching area and the process is repeated. The portion of the heap that is no longer to be irrigated transitions into the passive draindown phase.

Draindown is defined here as the period of time during which the flow rate is gradually reduced from the operational level to the residual steady-state value. Draindown is highly non-linear, with an initial quick reduction in flows rates, followed by a gradual slowing down. The example in Figure 1 illustrates the flux decay for unit surface columns (one square meter cross-section area).

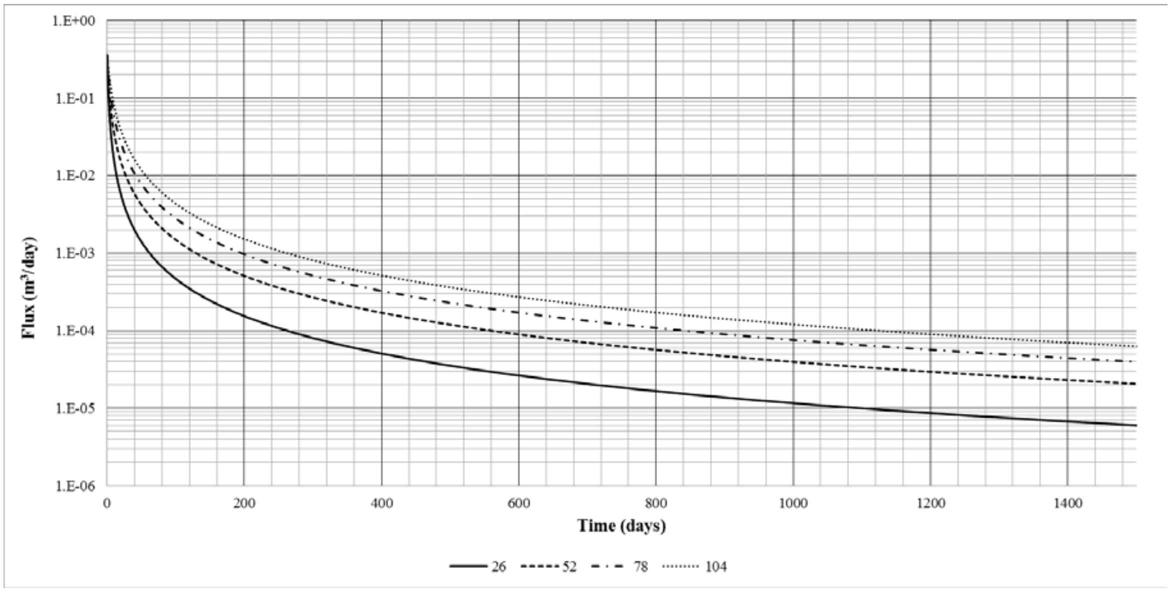

Figure 1: Example of unit draindown curves for various column heights (26 m, 52 m, 78 m, and 104 m)

The draindown of a heap as a whole can be described as a complex system of actively leached portions and portions of the heap in various degrees of draindown, more often than not including consecutive lifts irrigated several times before closure. It is therefore difficult to predict the fluxes of leach solution that will need to be managed in closure and post-closure periods, as well as the duration of such sustained fluxes.

Management of the leach solution inventory of a closed heap could be divided into distinct active and passive stages. During the active stage recirculating the solution to the heap may be necessary to prevent the existing ponds from overflowing while inventory reduction methods such as treatment-and-discharge or enhanced evaporation are implemented.

In the passive stage, recirculation is no longer necessary to prevent the ponds from overflowing. In some situations passive water management can only be achieved once the outflows from the leach pile, consisting of draindown and net percolation from precipitation, become less than the achievable evaporation flux from the surface of the water management ponds, i.e., the ponds will not overflow. Where excess storage capacity is available, temporary storage and subsequent evaporation may shorten the active management period.

Challenges of predicting draindown

When closure liabilities must be estimated significant costs (beyond already existing equipment and facilities) are associated with the duration of active water management (site presence, i.e. increased indirect costs) and the complexity of the water management system (necessity for water treatment, seasonal discharge, etc.). The draindown model is a tool that can provide the appropriate inputs in estimating these closure costs.

Accurately predicting final draindown of an entire heap is a process that must overcome challenges related to hydraulic properties of the heap material, geometry, heterogeneity of the heap leach ore, operational history of the heap, and the typical lack of adequate calibration data. The following subsections provide details on these parameters.

Throughout the entire life cycle of the heap leach pile, the flow regime within the heap is ideally unsaturated. Even during the active leaching period the irrigation rates are generally kept below values that would cause saturation of the heap material.

There are various practical reasons for this; for example, the need for air circulation for the lixiviation process to occur at reasonable efficiency, or slope stability limitations. It is therefore natural to approach the draindown as an unsaturated flow problem, where the moisture content of the pile changes continuously in time while it also varies spatially in the different regions of the heap.

The flow rates required to efficiently leach the metal from the ore are determined in the laboratory based on column experiments where flow rates and extraction coefficients are observed. These column studies are the basis for successful operations, but it was noted in various studies that column studies tend to drain faster than the full-scale heaps (Kappes, 2002; Muller and Newton, 2008).

To quantify the relationship between saturation levels and drainage quantities, the soil water characteristic curve (SWCC) is used. The SWCC, also referred to as the water retention curve, is a graphic expression of the relationship between the moisture content and the matric suction in a soil, and provides an indication of the manner in which a soil gains and releases the stored water.

The SWCC is normally determined experimentally, but theoretical methods were also developed to estimate it when experimental results are not available (van Genuchten, 1980; Brooks and Corey, 1964; Fredlund and Xing, 1994).

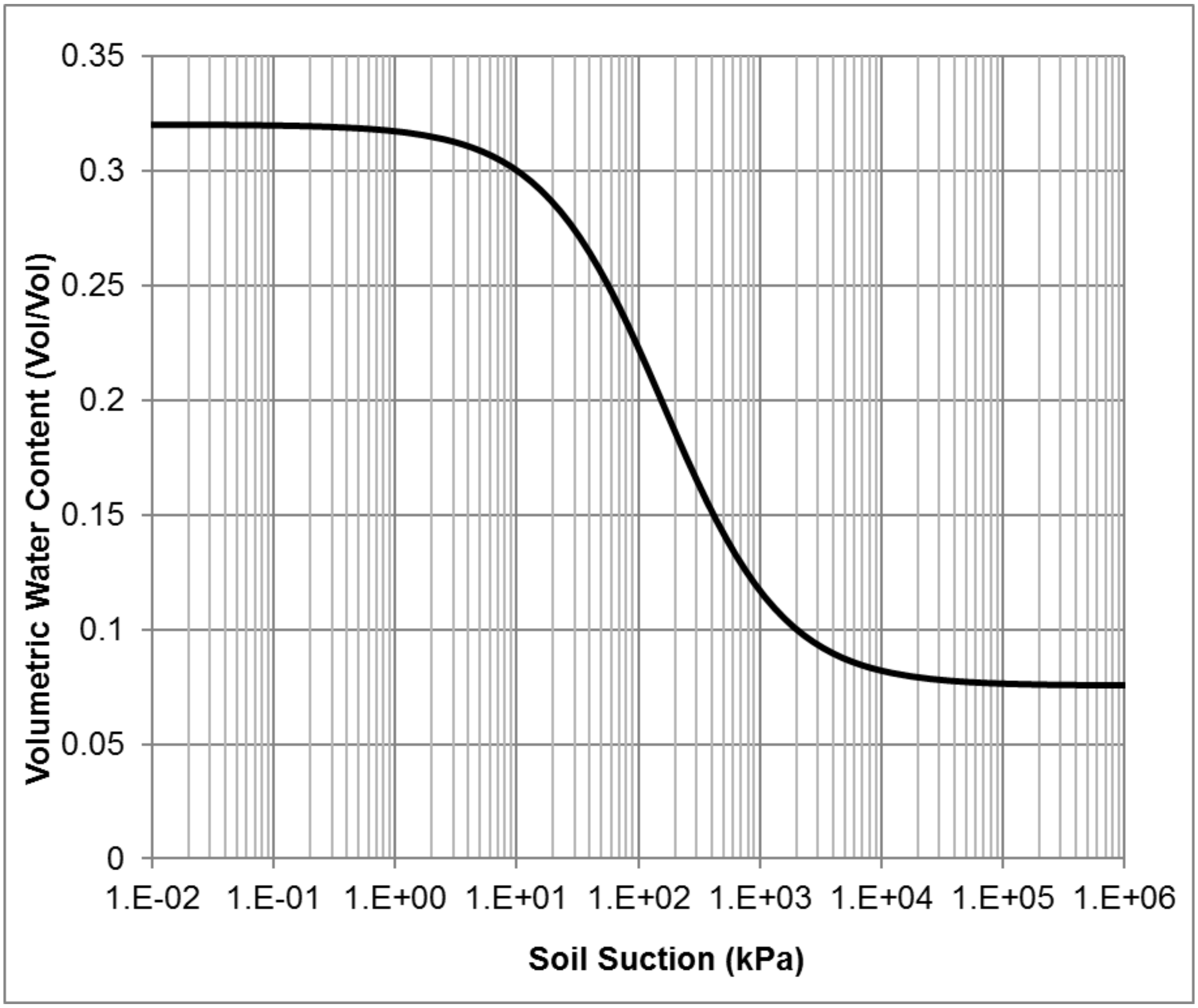

Figure 2: Example SWCC for heap leach materials

As suction increases, smaller and smaller pores become empty. Conversely, larger and larger suction is required to remove less and less water until a residual water content is reached where essentially no more water can be removed through normal natural processes. When irrigation of the heap leach pile occurs, the infiltrating water first fills the smaller pores (having a higher suction applied to them) and then gradually larger pores fill up as suction is reduced. Then, once irrigation is stopped and draindown begins, the largest pores start emptying water first, followed by successively smaller pores. The level of suction at which the largest pores begin to drain of water is called the air entry value (AEV).

Ideally a set of distinct SWCC curves would be determined to characterize the variations in the ore type (where required) and the various physical changes the ore goes through over the life of the heap (self-weight consolidation, decrepitation, pore clogging by mineral precipitation, etc.) (Greaser et al., 2019).

The pre-mining topography influences the shape and configuration of the heap. Some operations are located in areas where flat land is available for development, and therefore the shapes are regular. Other operations are located in difficult topography, where the constraints of the terrain will produce complicated shapes as the heap will be developed using the available footprint, as shown in Figure 3. This will yield highly variable overall 3-D shapes with sharply changing height, footprint. and slope angles (on the base liner).

Overlaying the 3-D shape, the internal geometry of the pile is an additional complicating factor, with the heaps typically built in successive lifts and commonly in successive phases adjacent to each other. The larger the heap, the more opportunities for the shape to become more complicated, as frequently the heap size is expanded beyond the original design to accommodate increased ore quantities.

Applying a unified draindown model to the entire heap would require a complex 3-D model domain of large dimensions and relatively small mesh size due to the non-linearity of the equations to be solved, making the model computationally excessively expensive.

Simplifications must therefore be made, in which the heap geometry is discretized as described in the following section, while unit draindown curves are applied to each sub-domain. The unit draindown curves are determined a priori based on the set of SWCC to be representative of the subdomains.

Figure 3: Example of heap leach pile in plan view.
Each colour represents a different operational phase

Another challenge in predicting the heap draindown is heterogeneity in the physical and hydraulic properties of the heap ore material. While the heap in general is thought of as a unified extraction unit, the geology of the orebody may yield leach ores with distinctly different properties. The primary source of heterogeneity in properties is often the mine plan, i.e., ore with distinct properties being stacked on the heap in various geometric configurations. Also, stacking plans with distinct construction phases being built over time may further increase heterogeneity.

Density of the heap material will normally increase with depth due to self-weight compaction, influencing hydraulic properties in a relatively consistent continuum. Layering during deposition will result in density gradients repeating at each layer, with a higher density trafficked layer near the surface, and with gradually increasing overall density increasing with depth.

Weathering characteristics of the various ore portions may also be different, resulting in changes in the properties after the material is placed on the heap. As these changes occur after placement, relatively similar initial properties may change over time, and become quite different by the time the heap is spent and final draindown can begin.

The history of heap operations will have a direct influence on the saturation state of the various regions at the end of operations. Application rates of the leach solution will also influence the saturation state of the heap at the end of operations. During normal operations, various areas of the heap are irrigated in a pre-determined sequence, resulting overall in zones that were irrigated for a long time in the past (sometimes years) compared to more recently irrigated sections.

Another challenge in heap leach draindown modeling is scarcity of suitable calibration data. Typically, reliable calibration datasets are limited or more often not available (the typical metallurgical estimates do not honor unsaturated flow principles – mass balance approach). Heap drainage values typically available are normally limited to a small subset of the site (but this is better than nothing).

The followed approach

The reality is that there really is no "best practice" for predicting heap leach draindown times, and such planning often relies solely on the experience of long-time operators and allowing for a wide margin of error.

A multitude of models are used to predict draindown time, ranging from simplified empirical methods to computational fluid dynamics integrating leach solution flow and metallurgical recovery. All these models are suitable to provide information for specific issues related to heap leach operations and closure.

A brief list would include the following methods:

- Simplified empirical methods, i.e. Heap Leach Draindown Estimator (HLDE) based on the implementation of the Brooks and Corey equation.
- Numerical models of saturated flow, i.e., conventional groundwater flow models.
- Numerical models of unsaturated flow, some of the most common codes used being HYDRUS, Seep/W and SVFlux.
- Computational fluid dynamics (CFD) modeling, typically used for recovery modeling, with a flow component; and
- Complex modeling environments including geochemical, metallurgical, and flow components such as Metsim and Goldsim.

Arguably multidimensional (geometry and heterogeneity) unsaturated flow numerical modeling is the superior approach. However, complicated models requiring days or weeks to run often far exceed the need for information. It is therefore important to keep in mind the "fit for purpose" approach, where simplified and cruder models could provide the information needed to make the required decisions.

Overall concept

Considering all the challenges presented in the sections above, SRK has developed an analytical model to predict the final draindown time of a heap leach pile. To overcome these challenges, the draindown analysis is conceptualized by breaking the heap into multiple smaller building blocks. Draindown analysis is conducted on each of these columns independently as if they have unit dimensions, and then the separate draindown curves are combined to yield a single composite curve, as shown schematically in Figure 4.

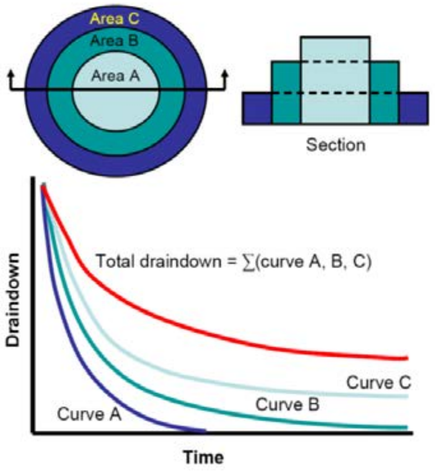

Figure 4: Conceptualized geometry used in draindown model

Each of these blocks represents a unique portion of the heap in the form of a column that extends from the base to the top of the heap, as illustrated in Figures 5 and 6. In this approach the dimensions (surface area and height), material properties, and draindown state (time passed since last production irrigation) of each column can be uniquely varied and the sequence in which they are summed up can be set based on an understanding of the construction and operating (i.e. irrigation) sequence. In essence, this approach presents a simplified three-dimensional representation of the problem.

Conceptually, the model manages leach solution inventory as if the heap consists of two sections: (1) passively draining phases; and (2) an active recirculation phase. This is a crucial feature of the model, as it allows recirculation to be included in the calculations while keeping track of real-time inventory on a daily time step. If recirculation is selected, the drained inventory from the passive phase is recirculated as part of the active phase, which means the passive phase reaches a drained state first.

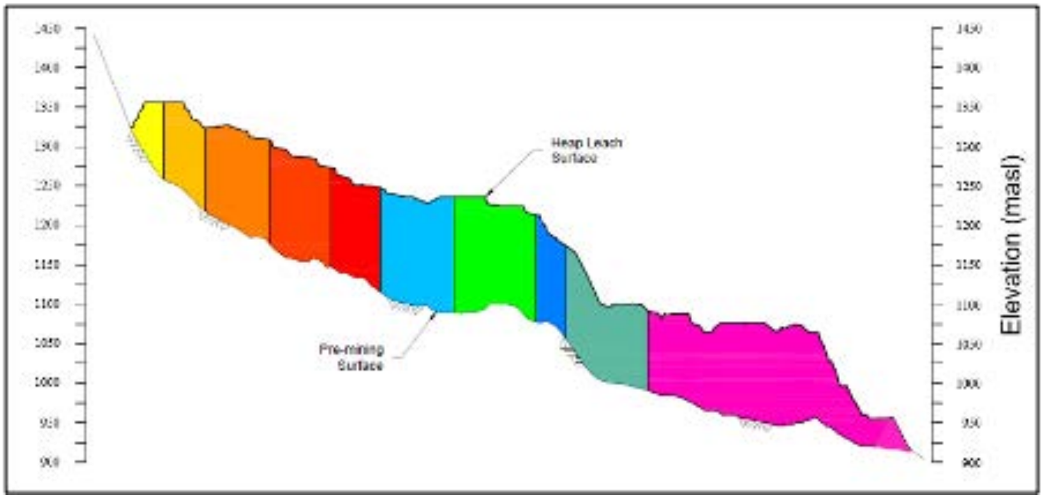

Figure 5: Elevation profile through an example valley-fill type heap leach facility

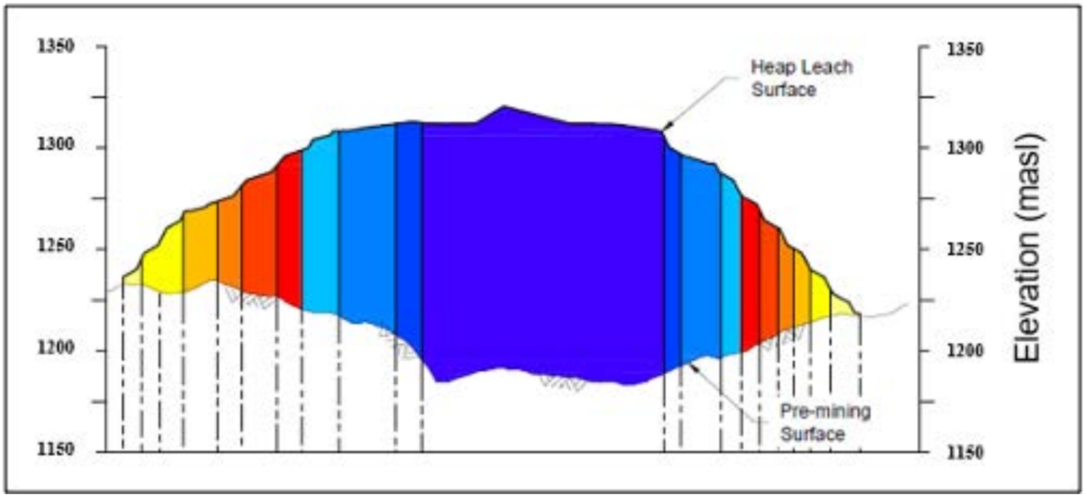

Figure 6: Cross-section of an example heap leach facility showing column discretization by height

The drainable inventory is calculated as the difference between the volume of water at the initial time in the model and the residual water expected to never drain. This takes into account the time passed since the last day of irrigation for each cell and computes the water content based on the draindown curves previously modeled. The inventory of leach solution is calculated on the initial model date based on the moisture content within each phase, which is a function of the time passed since the last irrigation of each particular phase was completed.

The chosen computation platform is Microsoft Excel, building on the wide distribution of, and familiarity with, the software. The choice was guided by the desire to create a tool that could be widely used by the site personnel of SRK's client corporations. The model includes four interconnected functional modules: draindown, inventory, recirculation, and evaporation. The computed water balance includes a series of intermediate terms dealing with assumed pond storage capacity.

Typical model inputs

Draindown curves

At its core, the model is based on the fact that assuming soil properties are homogeneous, the height of the column will cause large differences in draindown flux from different areas of the pile. The draindown curves were therefore created for the unit surface area, which is then multiplied by the footprint of each column, phase by phase. This was done to avoid the need to create a large matrix of curves for each height for each surface area, and to facilitate updating the model in the future when more refined heap leach configurations become available.

The draindown unit curves can be created using various methods. Unsaturated flow modeling using Hydrus or Seep/W would yield the most accurate unit draindown curves, although spreadsheet models solving the Brooks and Corey equation could result in satisfactory curves.

Climate parameters

Precipitation and potential evaporation values can be included in the model, to allow quantification of the soil-atmosphere interaction and the long-term moisture regime in the heap. Site precipitation data is highly desirable, but synthetic precipitation data obtained through reanalysis methods are also routinely used by SRK. Potential evaporation (PE) values are typically computed based on a range of models, with the most common being the FAO model based on the Penman-Monteith equations (FAO, 1998) and Priestly-Taylor model (Priestly and Taylor, 1972). A simple snow sublimation routine can also be included if appropriate.

Operational history

Operational history of a heap is captured in the model by the final irrigation schedule input, meaning the last complete cycle of irrigation for each of the zones in the heap. The idea is that the final irrigation schedule allows quantification of the time elapsed since the last active irrigation on any particular location on the heap. This will in turn allow the model to find the corresponding moisture content in that location and thus compute the inventory for the initial and each subsequent time step. The fundamental assumption is that the model time starts once the final irrigation is complete and continues until the outflow from the heap diminishes to a pre-determined value, allowing long-term passive water management.

Ore volume isopach

Based on drawings (as built or design schematics) and ore deposition schedules, an isopach is produced for the heap in an effort to obtain the characteristic footprint of the number of lifts placed within each phase. The isopach is developed into a matrix of reference values for each height and for each zone within the heap, which is then multiplied by the unit draindown flux to compute the overall flux for any particular time step.

Model results example

The heart of the model is the water balance sheet. On this sheet the inflow and outflow terms are brought together and the water balance for each time step is computed. The water management methods, such as treat and discharge or enhanced evaporation, are accounted for in the water balance.

Pinpointing the date of transition from active to passive water management is a trial-and-error process. Although a goal seek function is available to direct the search, due to the many assumptions one must consider in such a complex system a multi-variable chart was found to be most useful. Although some parameters cannot be plotted against a native scale, i.e., volumes and fluxes cannot be plotted on the same scale, the changes of the parameter values against time and against each other are the meaningful outcome.

An example of a modelled draindown scenario is shown in Figure 7. This is a fictitious scenario in which active water management is required for the first seven years, with the first four years of continuous recirculation followed by three years of seasonal recirculation. The available pond capacity increases as new ponds become available, although the pond volume (red curve) is shown to be well below the existing capacity.

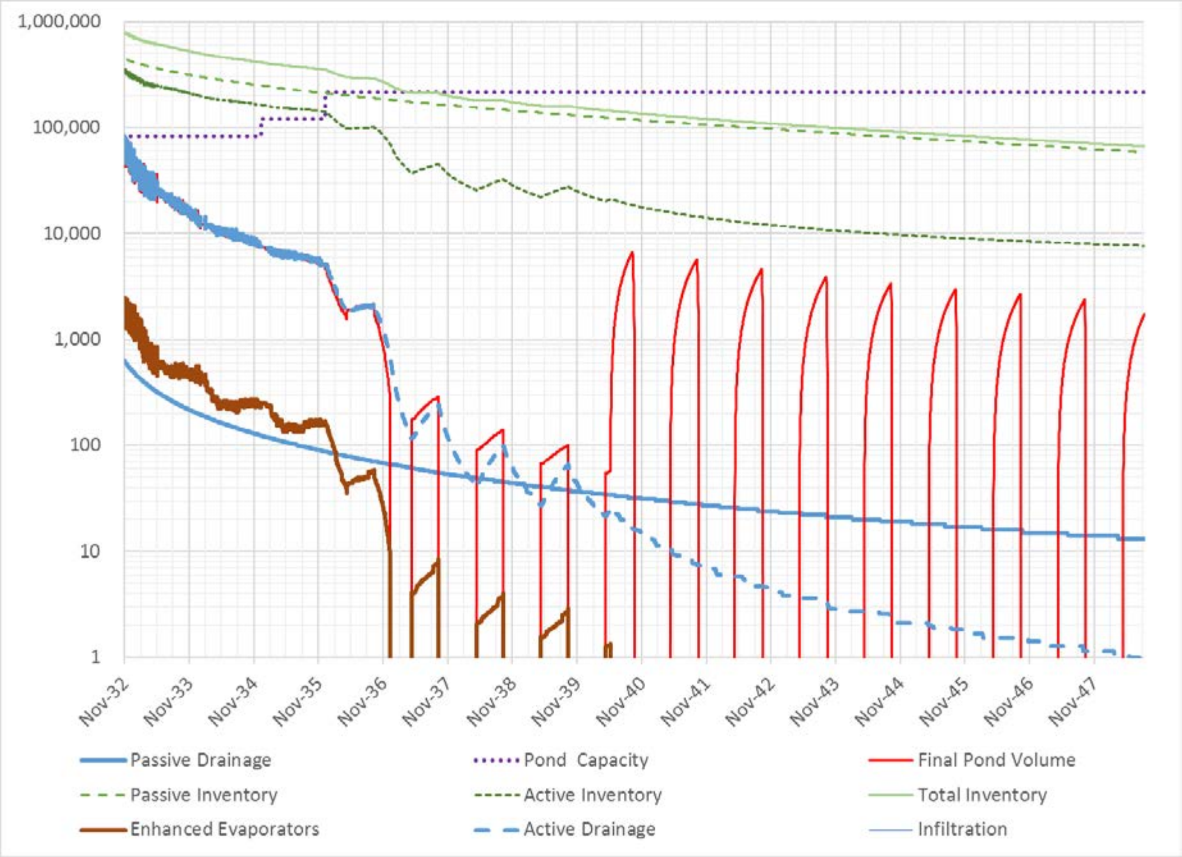

Figure 7: Example of draindown model results

Discussion and conclusion

The model can be implemented for any climate, from cold arid to wet moist, with the appropriate surface water management assumptions being included in the inputs. This flexibility is allowed by the fact that run-off and net percolation are dealt with as separate independent terms in the water balance. This fact is also one of the limitations of the model, where the direct effect of precipitation on the moisture content of the heap cannot be assessed.

During implementation of the model for a mine in South America it was noted that discretization of the entire heap into phases as defined by the mine plan, as opposed to distinct irrigation grid rotations, can result in overestimation of drainable inventory. Optimizing discretization within the limitations of the Excel file size could improve the accuracy of the predicted draindown flux and in turn the necessity of excess pond capacity.

When considering a facility covered with a geomembrane, the draindown problem becomes simplified since net percolation is nil. The passive draindown concept still applies, with all other challenges discussed above still present. However, as shown in the previous sections, the model is suitable to predict draindown for such facilities.

The analytical model presented here can also be used to predict draindown from other mine waste facilities such as tailings deposits and waste rock dumps. Material heterogeneity is present in these other waste materials, although differences in particle size distribution and SWCC of tailings may range on a narrower scale. Geometry, the same as for heap leach facilities, is dictated by the original topography. The notable difference is the relatively uniform moisture content the tailings typically present at the end of active deposition. The time scale for tailings draindown is also expected to exceed the time scale of heap leach draindown by a wide margin, possibly orders of magnitude, while waste rock draindown is likely to be similar.

The appeal of this modeling approach resides primarily in its simplicity, as it leverages user familiarity with the Excel platform and computing a series of building blocks. No computational fudge factors such as constants or internal adjustment factors are used. The internal structure of the model is fully transparent to allow easy review and query of assumptions, although the large number of computations and referencing loops requires a thorough understanding of the working principles.

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