

Conceptual model for estimating water recovery in tailings impoundments

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ABSTRACT: In most semi-arid and arid regions water is a scarce commodity and “reclaim water” from the tailings impoundment is commonly used in the milling process to minimize water consumption. A comprehensive study has been initiated to study the influence of tailings management on water losses and water recovery for a very large tailings impoundment (52 km²) in the Atacama Desert in northern Chile. This paper develops the theoretical background and presents a novel approach for estimating water recovery. Water recovery is controlled by a complex interplay of various physical processes including tailings deposition and consolidation, evaporation, rewetting and seepage. The use of a deterministic water balance model, which accounts for all of these transient processes, was not feasible for this large tailings impoundment. Instead, a water recovery model was developed, which focuses only on water losses from the active tailings stream to estimate water recovery. The model assumes that only process water liberated during the initial settlement is available for water recovery. The major water losses in this model include (i) entrainment losses during initial settlement of the tailings, (ii) evaporation losses from flooded areas of the tailings beach and (iii) rewetting losses during discharge of fresh tailings onto older, desiccated tailings beaches. This water recovery model was applied to the Tranque de Talabre tailings impoundment to explain existing water losses and to predict water losses and recovery for alternative tailings discharge plans.

1 INTRODUCTION

Population growth and stricter environmental standards have resulted in greater control and regulation of the use of freshwater resources for industrial purposes. This development is forcing mining companies all over the world to reduce water consumption associated with their mining and processing operations, in particular in arid or semi-arid climates. The single largest water use at most metal mines occurs during the processing of ore (milling and floatation) and subsequent tailings discharge. Over the years, advances in mineral processing have significantly improved water recycling during the ore processing stages. In contrast, relatively little research has been carried out to minimize water losses, and maximize water recovery, associated with transport and final storage of tailings in tailings impoundments.

This paper describes a new conceptual model to explain existing water losses during tailings discharge and to evaluate the benefit of alternative discharge practices on water recovery. This model was first applied to “Tranque Talabre”, a very large (52 km²) tailings impoundment operated by CODELCO, Division Chuquicamata, a large copper mine operating in the northern, arid region of Chile. Table 1

provides summary statistics of this tailings operation, including current rates of water recovery. Statistics from other Chilean copper mines are shown for comparison.

2 CONCEPTS AND DEFINITIONS

In an arid climate, the only significant source of water entering the tailings impoundment is the process water discharged with the tailings slurry. Hence the rate of water recovery that can be achieved is strongly influenced by tailings deposition, a highly dynamic process, which varies in space and time. In the following, we will review some concepts of tailings deposition and beach formation for sub-aerial discharge, which are required for the analysis of water recovery. Other methods of tailings discharge such as “sub-aqueous discharge” into lakes/oceans or “dry” placement of dewatered tailings (“paste tailings”) are not discussed in this paper.

Figure 1 is a schematic representation of tailings deposition and the physical processes controlling water losses. In most impoundments, tailings are discharged from a series of spigots (or discharge points) strategically placed along the perimeter of

Table 1. Water recovery at selected copper mines in Chile.

Mine Site	Location	Tailings Production (tpd)	Solids Content of Slurry (wt %)	Water Recovery (%)	“Make-Up” Water Requirement (m ³ /t of ore)
Chuquicamata	Atacama Desert, northern Chile	161,000	54.9	20.0	0.636
Collahuasi	High Andes, northern Chile	66,500	52.1	29.7	0.579
Candelaria	Central region, Chile	70,000	52-54	57.7	0.400

the impoundment. Typically, any given discharge point is only used for a few weeks to months at a time. Those discharge points actively discharging tailings are referred to as active discharge points. Conversely, those discharge points temporarily not discharging tailings are referred to as inactive discharge points. During active discharge, an active (“wetted”) deposition area develops which typically has the shape of a fan. The areal extent of the active deposition area will grow over time as more and more tailings are discharged from the same discharge point and are deposited.

Because of evaporation and seepage, only those areas continuously receiving fresh tailings (will remain saturated at the surface (so-called “flooded areas”). When tailings are first discharged from a new discharge point, the flooded area may represent almost all of the active beach area. However, as the active (“wetted”) beach area grows and the surface gradients increase, the tailings stream tends to migrate. As a result the flooded area in a large, mature deposition area is typically significantly smaller than the total active deposition area of that active discharge point. These flooded areas may grow and shrink over time depending on discharge volume, solids content of the slurry and local microtopography created by tailings deposition. As will be shown later, a good estimation of the size of flooded areas is critical for estimating water losses.

Figure 1 also shows the potential pathways of water discharged with the tailings slurry. The key processes include surface runoff, evaporation and seepage. However, the magnitude of these processes varies depending on whether they occur on the flooded area, the active or inactive deposition areas or in the pond zone. Surface runoff predominantly occurs in the flooded area of the active deposition area where tailings are actively deposited. In arid regions, where surface run-on and precipitation are negligible, all surface runoff is supplied by process water, which is liberated from the tailings during the initial sedimentation and settlement. Surface runoff eventually reaches the recycle pond from where it can be pumped back to the mill for processing.

The three processes contributing to water losses in the active deposition areas are (i) beach seepage (or “rewetting”) into deeper, previously deposited tailings layers and ultimately into the foundation soils/bedrock, (ii) beach evaporation and (iii) water

entrainment in the pore spaces of the tailings. Because of flooded conditions (providing maximum downward gradient and an “infinite” supply of water), seepage rates within the flooded area are much higher than in other deposition areas, which are not flooded. For the same reason, evaporation will also be at a maximum (approaching potential evaporation) in the flooded areas. Entrainment losses depend mainly on the particle size of the tailings with fine clay tailings entraining much more water than freely draining coarse sand tailings. Water losses due to entrainment are expected to be relatively constant for tailings with a defined particle size distribution. Water losses due to seepage and evaporation will vary according to tailings discharge practices on the tailings dam.

As soon as active deposition ceases (or the flooded area shifts to a different portion of the active, wetted deposition area) the rate of downward seepage and the rate of (actual) evaporation decline towards much lower residual values. Numerical modeling indicates that the decline in seepage and evaporation occurs very quickly (within days) in coarse-grained tailings but can be much more gradual (within weeks) in the fine-grained tailings near the pond (RGC, 2003).

In the pond zone, the rate of seepage and evaporation remain nearly constant provided the pond level (hence the pond surface area) does not vary significantly. While the rate of pond evaporation is similar to that observed in the flooded areas, the rate of pond seepage tends to be much lower due to the preferential deposition of very fine tailings (slimes) in the pond zone with significantly lower permeability than the tailings deposited in the beach areas. Seepage losses from the pond may only constitute a significant factor in the water balance of a tailings impoundment if the pond water is contacting natural soils and/or bedrock with a high effective permeability).

A review of daily records of tailings discharge and water recovery for the Tranque de Talabre indicated significant short-term variations in water losses (RGC, 2003). Since the grain size distribution of the tailings is relatively constant, these variations are a reflection of the dynamic and highly transient nature of tailings deposition, which controls water losses. The two main factors believed to control the high variability in water losses relate to (i) the (nec-

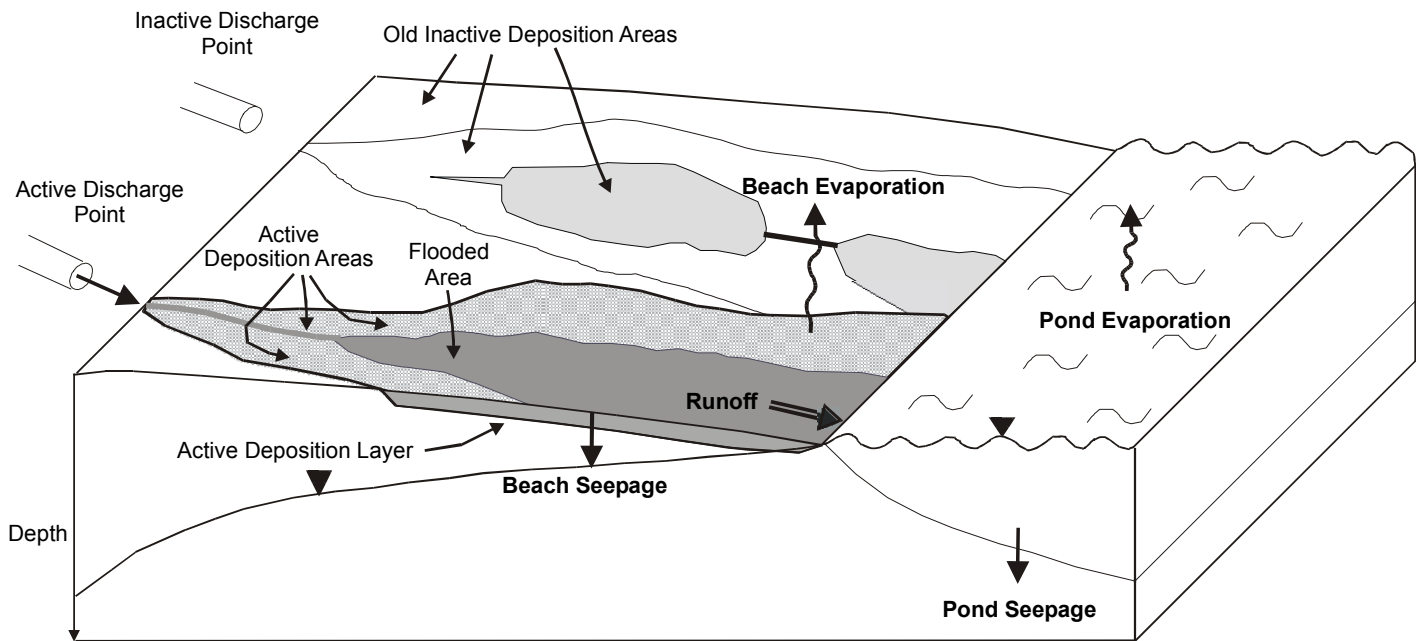


Figure 1. Schematic diagram of tailings deposition and associated water balance components.

essary) practice of switching discharge points and (ii) the naturally occurring shift of flooded areas within an active (wetted) deposition area.

Figure 2 illustrates the changes in seepage and evaporation losses expected to occur over time after start of tailings discharge in a new deposition area. Note that entrainment losses are believed to be relatively constant (for uniform tailings discharge) and are therefore not shown in Figure 2. Evaporation losses will gradually increase over time, simply because the flooded area grows in size (assuming evaporation rates remain constant). The factors controlling the development and maximum size of flooded areas are currently not very well understood and will require further work to define. However, there is evidence based largely on air photo interpretation, that the size of the flooded areas does not increase indefinitely with length of discharge, but instead approaches a certain maximum threshold (RGC, 2003).

Seepage losses show a more complicated trend with duration of discharge. Initially, seepage losses are high, because tailings are discharged onto older, desiccated tailings, which have undergone significant air-drying. Water infiltrates into the lower layers of older tailings due to pore suction and gravity-head driven seepage. Field experience indicates that these initial rewetting losses tend to consume all available free water over a period of 1-2 days with essentially no recovery during this initial wetting period (Rene Orellana, pers. Comm.). Once this initial moisture deficit is met and tailings have been re-saturated, rewetting losses drop off substantially.

The rate of seepage (or rewetting) losses increases again, however, if tailings are discharged for

an extended period of time, say greater than 1 month from the same discharge point. While the flooded areas, where active deposition of tailings occurs, approach a maximum size, there is a continuous increase in the size of the total (wetted) deposition area, as more and more tailings are deposited. Over time, the active tailings stream will occupy a smaller and smaller percentage of the total deposition area, i.e. the ratio of flooded area to wetted area will decrease. This natural shift of flooded areas across an active deposition fan will incur additional seepage losses because the freshly deposited tailings will desaturate (mainly due to evaporation) during the time between the deposition of successive lifts of tailings. When the active tailings stream returns to this area, the recently deposited tailings will be rewetted to saturation.

Note that the magnitude of the variable water losses illustrated in Figure 2 will vary depending on the tailings properties. For example, a shift from ac-

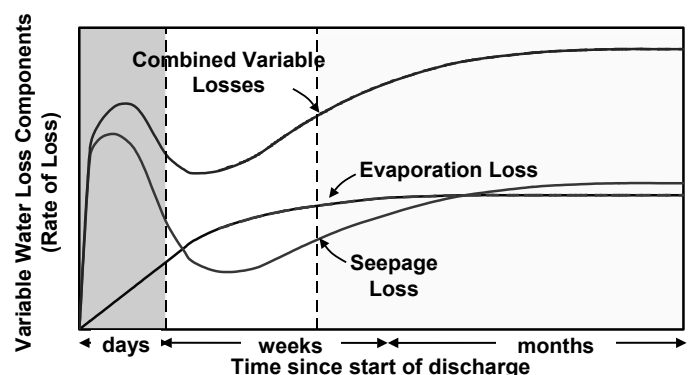


Figure 2. Schematic diagram illustrating changes in variable water loss components over time (entrainment losses not included).

tive deposition in the coarse beach area to a fines area near the pond is likely to reduce seepage losses but increase evaporation losses. Such a shift may either increase or decrease the total water losses, depending on whether the variable system losses were seepage-controlled or evaporation-controlled at the time.

While the time trends of water losses shown in Figure 2 are qualitative, they provide first clues on how to best manage tailings discharge. In general, both very short (days) and very long (months) periods of discharge from a single discharge point should be avoided. The best management practice is likely that of a regular rotation of discharge points to avoid the development of very large active deposition areas.

3 INFLUENCE OF TAILINGS DEPOSITION ON WATER LOSSES

Figure 3 illustrates the three major steps in tailings deposition and the resulting changes in the solid, liquid (water), and air phase. Phase diagrams are shown for coarse tailings (predominantly deposited on the beach area) and for fine tailings (predominantly deposited near the recycle pond). Note that these phase diagrams are drawn to scale using recent results of field and laboratory testing of tailings from the Tranque de Talabre (RGC, 2003).

The void ratio of the tailings slurry discharged into the Tranque de Talabre has a void ratio of about 2.0, i.e. about 2/3 of the volumetric discharge is water and only 1/3 is solids. During the initial stage of settlement, the tailings “settle out” and any excess process water “bleeds” to the surface. The time required for settlement varies from less than an hour for coarse-grained tailings to 1-2 days for the fine-grained tailings. Some of the free water will evaporate or seep into the deeper tailings profile. However, the majority of this water will flow as surface runoff into the pond.

Note that the volume of process water liberated during settlement varies significantly with grading of the tailings. Figure 3 indicates that about 50% of the process water is initially released during settlement of the coarse tailings compared to only 25% during settlement of the finer tailings, owing to their lower compressibility. By definition, tailings settlement occurs only in flooded areas of the active beach.

Once settlement is completed and all free water has run off, the tailings begin to consolidate due to the increased effective stresses imposed by drainage and air-drying. This process is defined as initial consolidation (also referred to as “Stage 1 Evaporation”) and may require a few days (for coarse-grained tailings) to several weeks (fine-grained tailings). Most of the water released during this initial

consolidation is consumed by evaporation or seepage with very little, if any, surface runoff to the pond. In other words, this stage of tailings deposition contributes predominantly to water losses with little opportunity for water recovery. The process of initial consolidation is characteristically observed in active deposition areas, which have just been deposited (but are no longer flooded).

The final stage of tailings deposition is that of desaturation of the tailings (also referred to as “Stage 2 Evaporation”). During this phase, evaporation and drainage result in desaturation of the previously deposited tailings. The distinction between initial consolidation and desaturation is defined by the state at which the pore pressure in the tailings is zero. When negative pore pressures (suction) develop in the pore water, water is drained from the large pores resulting in desaturation. Desaturation assists in consolidating the tailings (in particular for fine-grained tailings) as a consequence of the compressive stresses induced in the grain skeleton of the soil by the tension in the pore water. A freshly deposited tailings layer may undergo several wetting-drying cycles (saturation and desaturation cycles) before it reaches its fully consolidated state.

4 WATER RECOVERY MODEL

The above discussion illustrates that the development of a water balance for a tailings impoundment is a difficult task, if all the actual physical processes influencing water movement are to be considered. Perhaps the most difficult aspect is the continual change in the depositional pattern, forever changing the magnitude of the variable water losses (seepage and evaporation) in space and time. Due to this complexity, a three-dimensional deterministic model with a rigorous simulation of the various physical processes is typically not feasible. Instead, a water balance spreadsheet model was developed to predict water losses and water recovery.

The water recovery model presented here is a simplified version of a water balance model, which had been developed by AMEC and RGC for the Collahuasi tailings impoundment (AMEC, 2001). The model presented here only considers water losses occurring in the area actively receiving tailings discharge. While this model is more simplistic in its formulation it provides, we believe, a better representation of the physical processes contributing to water losses. Due to its simplicity it is also more easily used for modeling transient changes in water losses.

The water recovery model can be written as follows:

$$\text{Water Recovery} = Q_D - L_{Total} \quad (1)$$

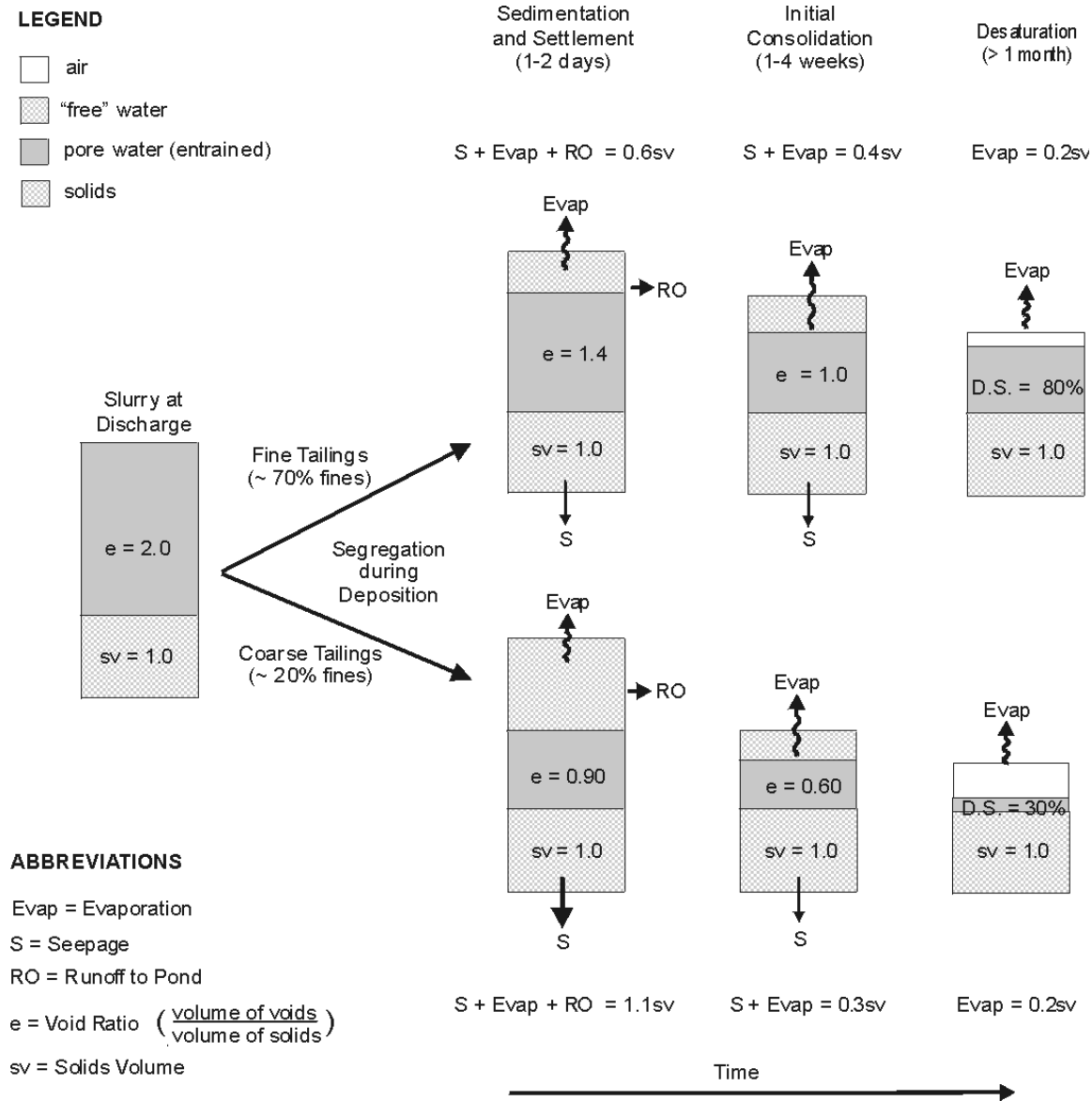


Figure 3. Changes in the water phase during and following tailings deposition.

where Q_D is the total discharge of process water; and L_{Total} is the total water losses. Q_D is determined using the following formula:

$$Q_D = \text{tonnes of tailings discharged} * (1/C_p - 1) \quad (2)$$

where C_p is defined as the slurry density in % solids by weight.

The total water losses (L_{Total}) consist of four components (see earlier discussion):

$$L_{Total} = L_{ENT} + L_{EVAP} + L_{REW} + L_{POND} \quad (3)$$

where L_{ENT} = entrainment losses occurring during initial settlement; L_{EVAP} = evaporation losses occurring from the flooded areas of the active beach; L_{REW} = rewetting losses occurring on the flooded areas of the active beach; and L_{POND} = evaporation and seepage losses occurring in the reclaim pond ("aguas claras").

The entrainment losses are estimated using the following equation:

$$\text{Entrainment Losses} = e_o * (\text{tonnes of tailings})/G_s \quad (4)$$

where e_o = void ratio after completion of initial settlement; and G_s = specific gravity of tailings solids.

The evaporation losses from the flooded areas are estimated using the following equation:

$$\text{Evaporation Losses} = PE * f_{pan} * \text{Flooded Area} \quad (5)$$

where PE = pan evaporation; and f_{pan} = pan factor.

Rewetting losses can be subdivided into two components:

- Initial rewetting losses which occur during placement of the first initial layer onto a previously inactive deposition area; and
- Repeated wetting losses which occur during continuous discharge of tailings onto the same active beach area.

Initial rewetting losses are defined as:

$$\text{Initial Re-wetting Loss} = \text{DRW} * (1 - S_{dry}) * e_f / (1 + e_f) * \text{active tailings beach area} \quad (6)$$

where S_{dry} = average degree of saturation of inactive tailings beach prior to re-wetting; DRW = average

effective depth of rewetting; and e_f = final void ratio (after completion of Stage 1 and Stage 2 evaporation).

Repeated wetting losses can be expected to occur when the active, wetted area grows larger than the flooded area sustained by the slurry discharge, and the flooded area begins to shift across the large fan area. This repeated wetting loss is estimated as follows:

$$\text{Repeated Wetting Loss} = MD * \text{flooded area} \quad (7)$$

where MD = moisture deficit. The moisture deficit is a function of the time the recently deposited tailings have been exposed to air-drying thus resulting in a moisture deficit. The moisture deficit function is site-specific and may be developed by numerical modeling of evaporative drying of representative tailings profiles and/or repeated in-situ measurements of density and moisture content at representative locations.

Visual observations suggest that the flooded areas, where tailings are deposited, shift continually across the active beach area. The time available for evaporation between the deposition of successive layers on the same portion of the active beach area (required for estimating MD) is defined as the average "return time" (T_{Ret}) that will pass before the tailings slurry returns to the same location. This average return time can be estimated as follows:

$$\text{Return Time} = (R_f - 1) * T_{Dep} \quad (8)$$

where R_f = ratio of active beach to flooded area; and T_{Dep} = average time required for deposition of a single layer.

The average time required for deposition of a single layer is a function of the rate of solids discharge, the thickness of the individual tailings layer, and the in-situ dry density:

$$T_{Dep} = D_{layer} * \text{flooded area} * \delta_d / Q_d \quad (9)$$

where D_{layer} = thickness of individual tailings layer;

and δ_d = dry bulk density.

The evaporation losses from the recycle pond are estimated as follows:

$$\text{Pond Evaporation} = PE * f_{pan} * \text{Pond Area} \quad (10)$$

The seepage losses from the recycle pond are estimated as follows:

$$\text{Pond Seepage} = K_{pond} * i * \text{Pond Area} \quad (11)$$

where K_{pond} = vertical hydraulic conductivity of the tailings underlying the recycle pond; and i = hydraulic gradient at the recycle pond.

5 APPLICATION OF THE WATER RECOVERY MODEL

The water recovery model was applied to the Tranque de Talabre in order to estimate the magnitude and relative importance of entrainment losses, evaporation losses and rewetting losses. The water recovery model was calibrated using the model input parameters summarized in Table 2. The model input parameters are based on a detailed tailings characterization study and numerical modeling carried out for the Tranque de Talabre (see RGC, 2003 for more details).

Figure 4 summarizes the computed water balance for the 16-month observation period from October 2000 to January 2002. Note that entrainment and evaporation losses were estimated with the water recovery model (using the model input parameters shown in Table 2), whereas rewetting losses were assumed to equal all residual losses. The observed rate of water recovery during the 16-month observation period averaged about 290 L/s or 20% of the water discharged with the slurry into the impoundment. At an average milling rate of about 161,000 tpd, this water recovery amounted to about 0.156 m³/tonne of ore milled.

Table 2. Summary of Input Parameters for Water Recovery Model (RGC, 2003).

Parameter	Symbol	Model Input
Pan Evaporation	PE	Monthly Average PE in Calama (mean annual average = 11.9 mm/day)
Pan factor	f_{pan}	0.7
Flooded Area	$A_{flooded}$	0.1ha per L/s of slurry discharge
Average effective depth of rewetting	D_{RW}	0.15m
Thickness of individual tailings layer	D_{layer}	0.15m
Void Ratio of Tailings after Completion of Initial Settlement	e_0	1.12
Final void ratio of Tailings (after completion of Stage 1 and Stage 2 consolidation)	e_f	0.79
Specific Gravity of Tailings Solids	G_s	2.65
Dry bulk density of deposited tailings	δ_d	1.5 t/m ³
Average degree of saturation of inactive tailings beach prior to re-wetting	S_{dry}	50%
Average time required for deposition of a single layer	T_{Dep}	3.1 days
Ratio of active beach to flooded area	R_f	Variable
Return Time	T_{ret}	Variable
Moisture deficit	MD	Variable
Surface Area of Recycle Pond(s)	A_{pond}	35 ha
Vertical Permeability of Slimes underlying pond	K_{pond}	1*10 ⁻⁹ m/s

According to the water recovery model, the highest water losses are due to entrainment during initial deposition, accounting for 765 L/s or 52% of all water discharged with the slurry. Evaporation losses and rewetting losses from the flooded beaches account for an additional 217 L/s (15%) and 169 L/s (11%), respectively. Evaporation from the recycle pond(s) is estimated to represent only a minor component (34 L/s or 2%) of the water balance. Estimated seepage losses from the recycle pond are negligible (<1 L/s) and are not shown in Figure 4.

Figure 5 shows the estimated monthly time trends of entrainment losses, evaporation losses from flooded areas and pond evaporation using the model input parameters shown in Table 2. Again, seepage losses from the recycle pond were negligible and are therefore not shown. The solid circles show the monthly rewetting losses, which represent the (monthly) residual losses not accounted for by entrainment and evaporation.

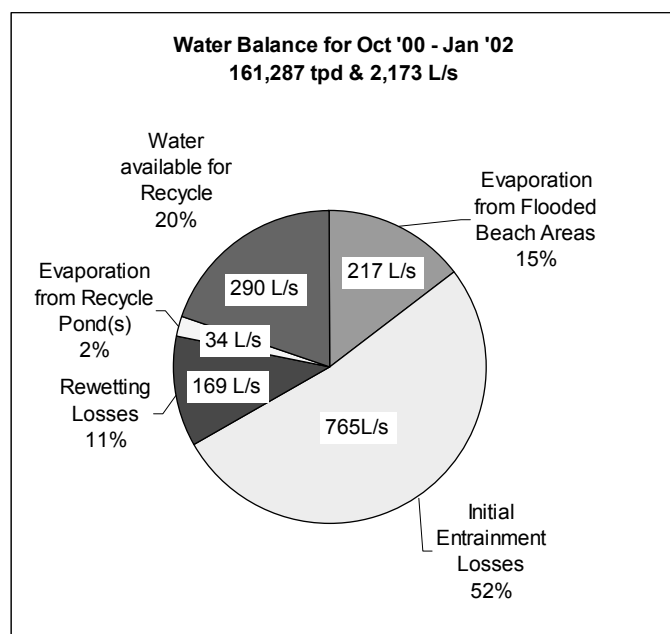


Figure 4. Water balance for Tranque de Talabre.

Monthly entrainment losses are relatively constant except for December 2001 and January 2002, when tailings production decreased significantly. Evaporation losses are generally higher in the summer months and lower in the winter months, due to the seasonal variation in potential evaporation. Significant changes to the size of the flooded areas (assumed proportional to the discharge rate) and thus evaporation losses occurred only in December 2001 and January 2002.

The estimated rewetting losses were of similar magnitude as the evaporation losses, but did not show a clear seasonal pattern (Figure 5). This is consistent with our conceptual model, which assumes that rewetting losses are predominantly controlled by discharge practices. Daily rewetting losses aver-

aged about 169 L/s over the entire observation period. However, the monthly rewetting losses varied significantly, ranging from essentially no rewetting losses for November 2001 to a high of 250 L/s in January 2002. The near-zero rewetting losses for November 2001 were likely caused by the development of an erosion channel in the coarser beach area during this time, which resulted in deposition of tailings primarily near the recycle pond where rewetting losses are very small.

6 CONCLUSIONS

A water recovery model has been developed which focuses only on the active tailings stream to estimate water losses and water recovery. The model assumes that all water stored in the tailings after initial deposition is eventually lost to evaporation or seepage and will not be available for recovery. Only process water liberated during the initial settlement and not consumed by evaporation and/or rewetting during flow towards the recycle pond is available for recovery.

The water recovery model requires a total of 16 input parameters, including geotechnical / hydrological tailings properties, climate parameters and parameters related to tailings deposition including the size of the active deposition area, the extent of flooding and individual layer thickness. A combination of field/laboratory testing, air photo interpretation and soil atmosphere modeling is required to parameterize the model.

The model was applied to the Tranque de Talabre tailings impoundment to evaluate the magnitude of various water loss components under current discharge conditions. The model suggests that ~52% of all process water discharged into the impoundment is lost to entrainment during initial deposition. This water loss is primarily a function of the tailings properties (in particular grading) and can not be reduced by altering the current tailings discharge scheme. Evaporation losses and rewetting losses from the flooded beaches account for an additional 15% and 11%, respectively. Those losses could potentially be reduced by devising discharge practices which lead to a reduction in the aerial extent of flooded beaches.

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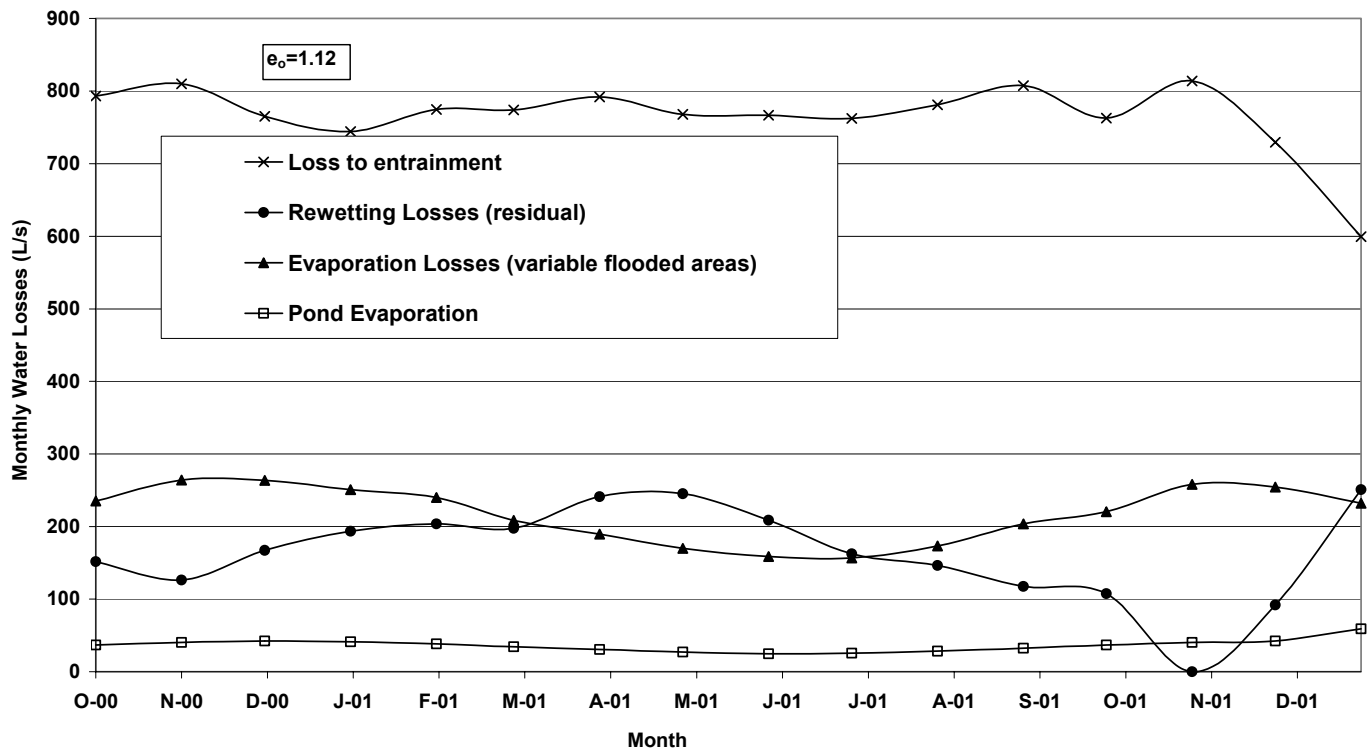


Figure 5. Simulated entrainment, evaporation and rewetting losses using the water recovery model.

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