Water Recovery Study for Pampa Pabellon Tailings Impoundment, Collahuasi, Chile

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ABSTRACT: A water recovery study has been completed for the Pampa de Pabellon tailings impoundment at Minera Doña Ines de Collahuasi, in the high Andes of northeastern Chile. The main objective of this study was to develop a water balance model, which could be used for prediction of future water losses under different tailings management scenarios. The study included (i) a detailed field investigation to determine *in-situ* properties of the Collahuasi tailings and (ii) calibration of an updated water balance model using water recovery data collected during the period July 2002 to February 2003. The field investigation indicated that the Collahuasi tailings are relatively fine-grained (55% average fines content) and do not show significant hydraulic segregation during placement. The initial void ratio of the Collahuasi tailings is about $e_0 = 1.3$ (± 0.1) and the final void ratio (after full consolidation) is approximately $e_f = 0.75$ (±0.05). The Collahuasi tailings typically maintain a high degree of saturation in the order of 80-90% with significant desaturation (down to 50%) only occurring in the near-surface layers (maximum ~0.3 m) during the warm summer months.

A simplified water recovery model was used to determine water losses as well as recoverable water quantities occurring from the active ("flooded") beaches during active discharge. With this approach the losses, which occur from inactive beaches (where no free water is available for recovery) need not be modeled (see Wels & Robertson, 2003). The total water losses during the 8-months monitoring period averaged 41,835 m^3/day or 70% of all process water discharged into the impoundment. This represents an average "make-up" water requirement of 0.605 m^3/t of ore processed. The average water recovery was 17,143 m^3/day (or 28.5% of all process water discharged with the tailings). The updated model was calibrated using the observed water losses and recovery rates. According to the model, entrainment losses represent the largest proportion of all losses (on average 74.7% of total water losses). Evaporation losses from active beaches represent the second largest component (on average 15.7% of total water losses). Water losses due to pond evaporation and rewetting represent a much smaller proportion of total water losses (5.4% and 4.2%, respectively). The modeling results suggest that there is only limited potential for improving water recovery rates due to the high initial entrainment losses of these fine-grained tailings.

1 INTRODUCTION

Compania Minera Dona Ines de Collahuasi ("Collahuasi") owns and operates a copper mine located in northeastern Chile, approximately 300 km east of Iquique. Collahuasi is currently planning the transfer of mining operations from the Rosario open pit mine to the Ujina open pit mine, with an associated increase in mill throughput from the current 60,000 tonnes per day (tpd) to 110,000 tpd. A significant portion of process water discharged into the tailings impoundment ("Tranque de Pampa Pabellon") is unavailable for reclaim, and is thus considered "lost" to the process water system. As a result, fresh water makeup is required from groundwater supply wells. At present, makeup water requirements of between 0.61 and 0.65 m^3/ton of ore milled are required to compensate for the process water losses in the tailings impoundment (AMEC, 2001). Current water use permits allow Collahuasi a maximum makeup water use of 0.72 m^3/tonne of ore milled at the increased mill throughput rate of 110,000 tpd.

As part of its expansion feasibility studies, Collahuasi carried out several water balance studies for its tailings impoundment to assess the adequacy of its future water supplies and to develop tailings management strategies to minimize water losses (AMEC, 2001; ARCADIS, 2002). However, these initial studies were limited by a general lack of tailings characterization required for model calibration.

In 2002, Robertson GeoConsultants Inc. was retained to carry out a detailed characterization and modeling study to update the earlier water balance studies. The primary objectives of this study were threefold: (i) determine the geotechnical and hydrological properties of the tailings, (ii) review and update the water balance model originally developed by AMEC and (iii) calibrate the updated water balance model using monthly records of tailings slurry discharge and water recovery for the period February 2002 to February 2003. This paper summarizes the key findings of this study.

2 TAILINGS CHARACTERISATION

2.1 *Methods*

The tailings characterization program included test pitting, sampling and testing of the tailings material (both *in-situ* and in the laboratory). The characterization program included three sampling campaigns during the winter months (May-July 2002) and one sampling campaign in the subsequent summer (January 2003). During the summer investigation tailings samples and *in-situ* measurements were taken at 11 locations (see Fig. 1). During the winter investigation, sampling and testing was carried out at six additional locations (Fig. 1).

At each location, the tailings profile was logged and tailings from representative layers were taken for laboratory analyses. The depth and method of sampling varied, depending on the state of consolidation of the tailings. In beach areas with older, consolidated tailings a test pit was dug using shovels to a maximum depth of 1.0 m. Tailings samples were then taken from discrete intervals of the *in-situ* profile (typically from individual deposition layers) using a small trowel. In areas with freshly deposited, soft tailings, tailings samples were taken using a Shelby tube, which was manually pushed into the upper tailings profile (0-0.6 m).

All samples (typically ~1 kg) were placed into plastic bags, sealed, and labeled. Upon return to the field laboratory, a sub-sample was taken for determination of water content (the majority of samples were analysed within 48 hours). The remainder of the sample was shipped to a geotechnical laboratory (CESMEC, Santiago) for further testing.

The *in-situ* measurements carried out during the 2003 summer investigation included bulk density, gravimetric water content and field-saturated permeability. All other *in-situ* parameters of interest (dry density, void ratio, volumetric water content and degree of saturation) were back-calculated from these primary variables. The bulk density of consolidated tailings was determined using the standard sand cone method. The bulk density of freshly deposited (very soft to liquid) tailings was determined by carefully pushing a metal cylinder of known dimension (L = 0.18 m and Ø = 0.15 m) into the tailings, sliding a metal plate under the bottom and lifting the sample out of the tailings. The entire sample was

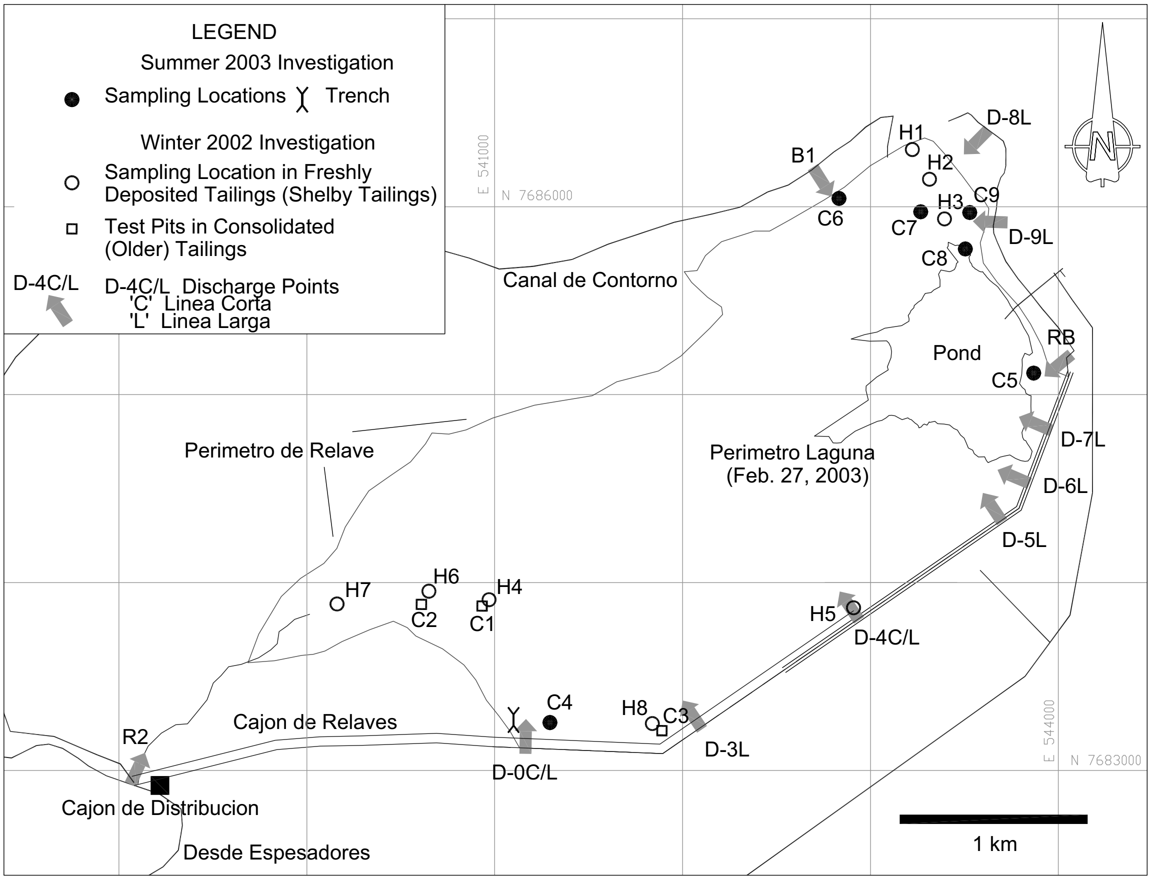

Figure 1. Location of tailings samples.

then placed in a plastic bag and the total weight determined upon return to the laboratory. All *in-situ* measurements (and sampling) were carried out on freshly exposed tailings in order to minimize air-drying of the tailings.

The *in-situ* field-saturated permeability of the tailings was determined using a Guelph permeameter (Soil Moisture Equipment Corp., 1986). The Guelph permeameter allows the measurement of the steady-state infiltration rate required to maintain a constant depth of water in an uncased, cylindrical auger hole that terminates above the water table (Reynolds, 1993).

Table 1 summarizes the parameters determined in the laboratory and the test procedures followed. The particle size distribution (PSD), Atterberg limits (and USCS soil classification), solids density and gravimetric water contents of the tailings samples were determined in CESMEC's Santiago laboratory using standard testing procedures. The initial void ratio (e_i) was determined using an undrained settlement test. For this test, a known mass of dry tailings (1.5 kg) was mixed with decanted slurry water (1446ml) to reconstitute the solids content of the tailings slurry (Cp = 51%). This slurry was placed in a graduated cylinder and allowed to settle for a period of 7 days. The progress of settlement was recorded by measuring the height of the settled solids over time. Knowing the total amount of solids and the volume (based on height) the void ratio of the settled tailings mass was computed.

The saturated hydraulic conductivity was determined on five representative tailings samples covering the range of grading (and fines content) encountered during sampling. The hydraulic conductivity was determined in a flexible wall permeameter. The permeameter tests were carried out at a confining pressure of ~20 kPa (representing lithostatic pressure at a depth of about 1m) using tailings samples which had been remolded to the *in-situ* density and moisture conditions measured in the field.

2.2 *Results*

Table 2 provides summary statistics of the intrinsic material properties (PSD, Gs, Atterberg limits) of the Collahuasi tailings. The majority of tailings sampled in the Collahuasi tailings impoundment are fine-grained tailings (fines content >50%) representing either a silt (ML) or a lean clay (CL). The fines content of the tailings typically ranged from 40% to 70%, with lower fines contents encountered close to the discharge points and higher fines contents observed at greater distance from the discharge point. The relatively fine grind of the tailings prevents significant hydraulic segregation and the development of a coarse beach area near the discharge point, as commonly observed in other tailings impoundments.

The *in-situ* parameters (density, void ratio, degree of saturation etc) determined in the field varied significantly depending primarily on the time available for consolidation and evaporative drying prior to sampling. Figure 2 shows the void ratio determined on near-surface samples from various sites as a function of time since cessation of tailings deposition. The void ratios measured in near-surface samples during the winter 2002 investigation showed a consistent decrease with time since last discharge, approximating a logarithmic relationship (solid line). In contrast, the void ratios determined during the summer 2003 field investigation showed very little relationship with time since discharge, suggesting that the final void ratio is reached within a few days (dashed line). The rate of consolidation can be expected to be generally higher during the summer months compared to the winter months, primarily as a result of higher rates of evaporative drying. During the winter months actual rates of evaporation are greatly diminished, not only because of reduced rates of solar radiation, but also because of freezing of the tailings surface. Much of the available solar energy available during the day is expended to thaw the near-surface tailings.

The degree of saturation of the Collahuasi tailings typically varied from ~80% to near full saturation (100%) and showed no significant correlation with fines content (RGC, 2003). The only tailings sample with a significantly lower degree of saturation (57%) was observed in the top 0.15m of a test pit excavated in a 3-month old beach with large desiccation cracks. This sample probably represents the maximum extent of air-drying that Collahuasi tailings may experience during the summer months. Yet even in this desiccated tailings profile, the degree of saturation at greater depth (>0.3m) was ~90% illustrating the limited extent of air-drying in these fine

Table 1. Summary of lab testing procedures.

Parameter	Test Method	Standard	Laboratory
Particle Size Distribution	Sieve & Hydrometer Analysis	LNV 105-86 &ASTM D-426	CESMEC
Solids Density	Hydrometer Analysis	ASTM D-426	CESMEC
Atterberg Limits	Atterberg Tests	Norma 1517-I-II	CESMEC
Initial Void Ratio	Settlement Tests	N/A	CESMEC
Hydraulic Conductivity	Tri-axial Permeameter	ASTM D-5084	DICTUC

Table 2. Summary of intrinsic tailings properties.

Site visit	Statistic	Liquid limit (%)	Plastic limit (%)	Plasticity index	Fines Content (<200#) (%)	*Gs* (-/-)
Summer 2003 Field Investigation						
February '03 Visit (n = 18)	Average	n.d.	n.d.	n.d.	55	2.62
	Min	n.d.	n.d.	n.d.	38	2.54
	Max	n.d.	n.d.	n.d.	96	2.69
Winter 2002 Field Investigation						
1st Site Visit (n = 22)	Average	26.2	19.9	6.3	58	2.72
	Min	21	17	3	39	2.70
	Max	30	23	10	76	2.74
2nd Site Visit (n = 19)	Average	24.4	18.3	6.2	55	n.d.
	Min	21	17	3	34	n.d.
	Max	28	20	10	65	n.d.
3rd Site Visit (n = 19)	Average	n.d.	n.d.	n.d.	53	n.d.
	Min	n.d.	n.d.	n.d.	30	n.d.
	Max	n.d.	n.d.	n.d.	66	n.d.
Total	Average	25.4	19.1	6.2	55	2.68

n.d. = not determined

tailings.

The saturated hydraulic conductivity of the tailings (determined on remoulded tailings samples in the laboratory) ranged from $2.5*10^{-6}$ cm/s to $5.0*10^{-7}$ cm/s. The geometric mean of all K_{sat} measurements was $1.4*10^{-6}$ cm/s. The K_{sat} values determined in the laboratory were consistent with estimates of field saturated permeability ($< 1*10^{-6}$ cm/s) for freshly deposited (saturated) tailings determined with the Guelph permeameter (e.g. $<1*10^{-6}$ cm/s near test pit C6, Fig. 1). In contrast, significantly higher field-saturated permeability values were determined for tailings with similar grading on older, desiccated tailings beaches (e.g. $K_{fs} = 3.7*10^{-5}$ cm/s near test pits C4 and C9). The higher *in-situ* estimates of permeability determined on the older, desiccated tailings beaches likely reflect the presence of secondary permeability introduced during air-drying of these tailings (e.g. desiccation cracks).

Settlement tests were carried out in the laboratory with reconstituted slurry samples to evaluate the settlement behavior of tailings of variable fines content. The settlement tests indicated that most tailings samples had settled almost completely (>95% settlement) within 12 hours. The final void ratio of the settled (but undrained) tailings ranged from a low of 1.12 to a high of 1.44 but showed no correlation with the fines content of the sample used during the tests ($R^2 = 0.08$ using linear regression). The average initial void ratio for the Collahuasi tailings was determined to be ~1.3. Very similar results were obtained using large-scale settlement tests carried out in 200L drums backfilled with total tailings under field conditions (RGC, 2003).

2.3 *Implications for Water Recovery*

The geotechnical properties of the Collahuasi tailings relevant for estimating water losses and water recovery during tailings deposition are summarized in Figure 3. According to the water balance model developed by AMEC (2001) and used by ARCADIS (2002), the only water potentially available for recycle is the water released during initial settlement of the tailings. The amount of water released during initial settlement is defined as the difference between the void ratio of the slurry (~2.61) and the initial void ratio of the tailings (after initial settlement but prior to consolidation). Based on the results of this characterization study, the initial void ratio does not vary much with the fines content of the tailings (see Figure 3). The initial void ratio for tailings with an average fines content of 55% (representative of total tailings) is about 1.3.

These results imply that about 50% (= 1.3/2.61) of the water released with the slurry is potentially available for recycle. Note, however, that the amount of water actually recycled is significantly lower than 50% due to potential evaporation losses from flooded areas and rewetting losses into under-

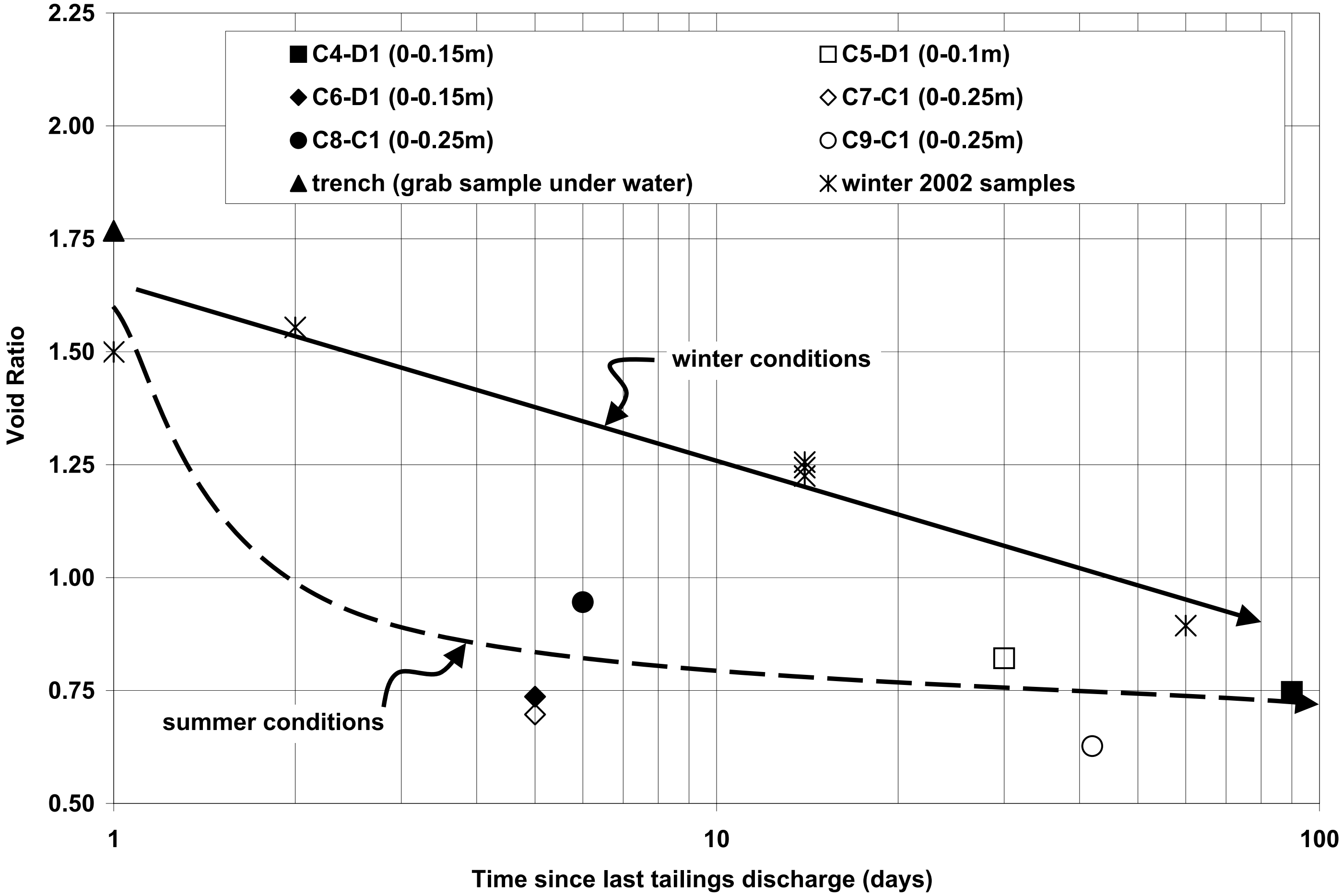

Figure 2. Void ratio as a function of time since last tailings deposition.

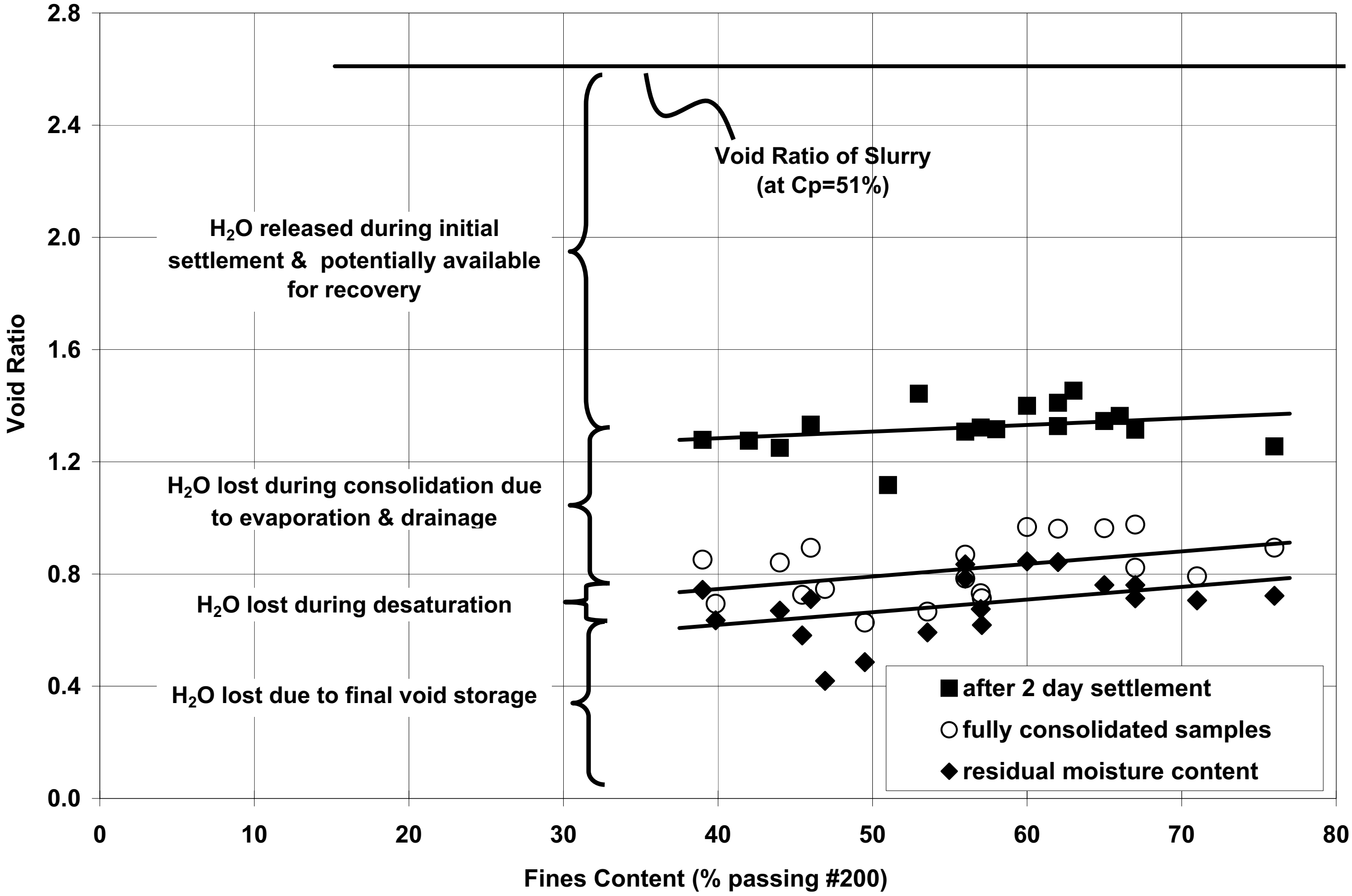

Figure 3. Interpretation of field and laboratory results for water balance analysis.

lying tailings during runoff of this free water to the pond (see Wels & Robertson, 2003).

The initial "entrainment losses" (representing about 50% of all water released into the impoundment) can be further subdivided into three individual loss categories (see AMEC, 2001): (i) Stage 1 evaporation (consolidation), (ii) Stage 2 evaporation (desaturation) and (iii) final void storage. Figure 3 provides quantitative estimates of these losses for the range of gradings encountered at Collahuasi. Based on the field measurements of void ratios and residual degree of saturation in consolidated tailings, Stage 1 and Stage 2 evaporation losses are estimated to represent on average about 19% and 4.5% of all water released with the slurry into the tailings impoundment (assuming e_{final} = 0.75 and S_r = 85%). This leaves an estimated 26% of all water released with the slurry into the impoundment for final void storage.

3 WATER BALANCE ANALYSIS

3.1 *Model Development*

The water balance model presented here is a simplified version of a water balance model, which had been developed by AMEC and RGC in earlier water balance studies for Collahuasi (AMEC, 2001). A reconciliation of the AMEC model assumptions with field observations and available monitoring data from the Tranque de Pabellon indicated that it would be problematic to calibrate this model. The main problems encountered in applying this model to the Collahuasi tailings impoundment included:

1. The AMEC model was developed for estimating average annual water losses. As such many model input parameters (and therefore loss terms) are assumed constant, while field observations suggest that they vary significantly in time (e.g. rewetting losses, beach evaporation).
2. The AMEC model attempts to provide a complete mass balance accounting for all water inputs and outputs. This approach requires the use of several additional input parameters, which are not well known and are difficult to calibrate using water recovery data only (e.g. a distinction between Stage 1 and Stage 2 evaporation; lack of data to calibrate seepage losses).

For the reasons listed above, a simplified model was developed which only considers water losses occurring from the active ("flooded") beaches during active discharge. While this model is more simplistic in its formulation it provides 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 general approach of this simplified water balance model is described in Wels & Robertson (2003). Briefly, the model estimates the amount of water that is lost during active tailings discharge (tailings slurry is the only significant water input at Collahuasi) Four different water losses are simulated in the model: (i) entrainment losses during initial deposition, (ii) evaporation losses occurring on the flooded areas of the active beach, (iii) rewetting losses occurring on the flooded areas of the active beach, and (iv) evaporation and seepage losses occurring in the reclaim pond. For a detailed description of these loss terms and their mathematical formulation the reader is referred to Wels & Robertson (2003).

Based on field observations and air photo interpretation (RGC, 2003) the water balance model described in Wels & Robertson (2003) was slightly modified for use at Collahuasi. First, "repeated wetting losses" were assumed to be negligible (due to the much smaller size of the impoundment). Second, the size of the active (flooded) beach for a given discharge point was assumed to grow over time according to the following general log-normal relationship:

$$\mathit{Active\ Beach} = C \cdot \ln(t) + A_1 \qquad (1)$$

where t = time since start of discharge at a given discharge point; A_1 = size of active beach after 1 day of discharge; C = slope of the log-normal relationship.

In practice the slope factor, C, was determined from the (estimated) sizes of the active beach area after 1 and 30 days of discharge (A_1 and A_{30}, respectively) as follows:

$$C = (A_{30}-A_1) / (\ln 30) \qquad (2)$$

The size of the active beach areas was initially bound by results of mapping of the active discharge areas for discharge point D-4C/L (RGC, 2003). Based on the available data, the size of the active beach area was estimated to lie in the range of 10-20 ha after 1 day of discharge and in the range of 40-100 ha after 30 days of discharge (assuming ~50% of total tailings discharge). These initial guesses of A_1 and A_{30} were subsequently updated to calibrate the water balance model using monthly time steps (see below).

3.2 *Model Calibration*

The updated water balance model was calibrated for the period July 2002 – February 2003 using monthly time steps. The total water losses during the 8-months monitoring period averaged 41,835 m^3/day or 70% of all process water discharged into the impoundment. This represents an average "make-up" water requirement of 0.605 m^3/t of ore processed.

The average water recovery was 17,143 m^3/day (or 28.5% of all process water discharged with the tailings). The updated model was calibrated using the observed water losses and recovery rates.

The water recovery model has a total of 12 parameters, including two climate parameters (PE, f_{pan}), seven tailings parameters (Gs, e_0, e_f, S_{dry}, D_{RW}, f_{rew} and K_{pond}) and three parameters related to tailings management (A_{pond}, A_1 and A_{30}). The majority of these parameters were estimated based on field investigations and/or on-site monitoring and were not further varied during model calibration (Table 3). The remaining model parameters (e_o, D_{RW}, A_1 and A_{30}) were varied systematically during model calibration until a good fit with the estimated monthly total water losses were obtained.

Note that precipitation was very low during the calibration period (only 45 mm were recorded between July 2002 and February 2003 representing only 5.6 mm per month). Hence, the water input due to direct precipitation onto the recycle pond and runoff from beaches and the surrounding catchment (even with a high runoff coefficient) would have been very small (estimated to be less than 2% of total water inputs even during the wettest month). Hence, water inputs due to precipitation and runoff were assumed to be negligible and were not considered during model calibration.

A number of different combinations of e_0, A_1, A_{30} and D_{RW} were simulated within their likely estimated range (Table 3) in order to determine the best fit of simulated and observed total water losses. The best "fit" of simulated and observed monthly water losses were obtained using the following set of model parameters: $e_0 = 1.3$; $D_{RW} = 0.5$ m; $A_1 = 20$ ha & $A_{30} = 75$ ha.

Figure 4 shows monthly time trends of simulated water losses for the "calibrated" model (in m^3/day). The observed water losses are shown for comparison (red line). The vertical bars (in red) represent error bars for the observed total water losses (primarily a function of the uncertainty in pond storage).

The model reproduces the observed monthly water losses quite well, in particular for the months of July-August and October-December 2002. The simulated water losses for the entire 8-month period also agree very well with the observed water losses during this calibration period (<2% error). The overall good match of simulated and observed water losses supports our modeling approach, in particular considering the good match of all model parameters with our initial estimates from field and/or laboratory testing.

Note that the calibrated model overpredicted water losses in September 2002 and in particular in January 2003 and underpredicted water losses for February 2003. There are several potential reasons for the relatively poor match of the model predictions for those three months. In January 2003, the majority of tailings discharge occurred in areas close to the recycle pond (from discharge points B1, 8 and 9, Fig. 1), which could have resulted in below-average water losses due to smaller active beaches (the current version of the model assumes only one

Table 3. Summary of Input Parameters for Water Recovery Model

Parameter	Symbol	Model Input
Specific Gravity of Tailings Solids	G_s	2.72
Void Ratio of Tailings after Completion of Initial Settlement	e_0	1.20 – 1.40*
Final void ratio of Tailings (after full consolidation)	e_f	0.75
Pan Evaporation	PE	Long-term monthly average PE for Pampa Ujina (mean annual average = 7.0 mm/day)
Pan factor	f_{pan}	0.9
Active Beach Area (per discharge point):		
After 1 day discharge	A_1	10-20 ha*
After 30 days discharge	A_{30}	40-100 ha*
Average effective depth of rewetting	D_{RW}	0.5 – 1.0 m*
Fraction of Active Beach experiencing rewetting	f_{Rew}	0.75
Average degree of saturation of inactive tailings beach prior to re-wetting:	S_{dry}	
Summer		0.77 – 0.83*
Winter		0.90
Surface Area of Recycle Pond	A_{pond}	Variable
Vertical Permeability of Slimes underlying pond	K_{pond}	$2*10^{-7}$cm/s

*final value determined during model calibration

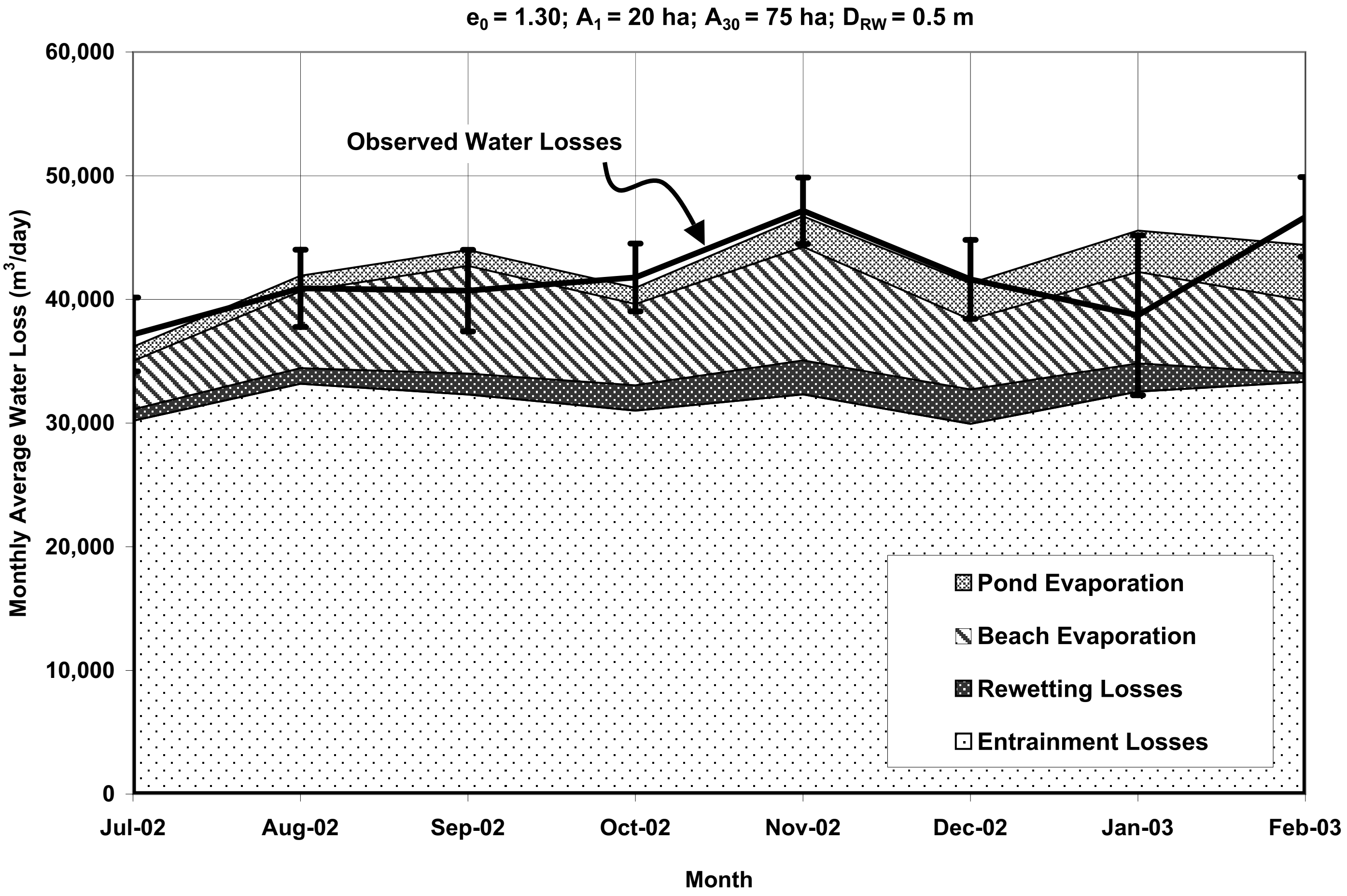

Figure 4. Simulated monthly water losses using calibrated water recovery model (in m^3/d).

growth curve for the active tailings beach independent of the discharge point). It should also be noted that the "observed" water losses calculated for January 2003 have a greater uncertainty than the other months during the calibration period (see red error bar) due to the large size of the storage pond. Hence it cannot be ruled out that some of the discrepancy between observed and simulated water losses is due to the larger uncertainty in the estimated monthly change in pond storage during this month.

The proximity of tailings discharge to the recycle pond may also explain the overprediction of water losses for September 2002 (discharge point B1 was used throughout most of this month). The higher than predicted water losses during February 2003 may have been a result of significant seepage from the recycle pond caused by ponding of free water against the natural surface (fractured rock) and/or dam material (which would not be accounted for by the model).

The calibrated water recovery model gives insight into the relative contribution of different water loss terms. According to the model, entrainment losses represent the largest proportion of all losses (on average ~75% of total water losses). Evaporation losses from active beaches represent the second largest component (on average 15.7% of total water losses). Water losses due to pond evaporation and rewetting represent significantly smaller components of total water losses (5.4% and 4.2%, respectively).

Figure 4 illustrates the temporal changes of the various water loss components over the 8-months calibration period. The largest temporal variations were observed in evaporation losses from the active beach area. However, there were no clear seasonal trends (as might be expected) suggesting that tailings management (influencing the size of the active beach area) has a significant influence on beach evaporation losses, comparable in significance to seasonal variations in potential evaporation rates.

A sensitivity analysis was carried out to determine the sensitivity of various model input parameters to the estimated water losses and recovery (not shown here). Based on this sensitivity analysis the margin of error for predicting monthly water losses was estimated to be in the order of 10-15% (RGC, 2003). The margin of error for yearly water losses is likely lower because some uncertainties tend to cancel out over longer observation periods. We believe that this model uncertainty could be reduced further (to as low as perhaps +/- 5%) by improving model calibration (in particular by reducing the uncertainty in model input parameters such as pond size, size of flooded beaches and daily discharge practice). A period of "model verification" would be required to test our preliminary estimates of margin of error.

3.3 *Implications for Tailings Management*

From a management point-of-view, the total water losses can be subdivided into those losses which can be controlled during tailings management and those that cannot be controlled by discharge practices. Based on our current understanding, initial entrainment losses are predominantly a function of the tailings grading and are therefore only influenced by the milling circuit (finer grinds resulting in higher entrainment losses) and the clay content of the ore mined. In other words, there is little, if any, opportunity to minimize entrainment losses as part of tailings management (Wels & Robertson, 2003).

In contrast, the other three water loss terms (active beach evaporation, rewetting and pond evaporation) are all influenced by tailings management. Pond evaporation, which accounted for an estimated 5.4% of all water losses, is simply controlled by minimizing the surface area of the recycle pond. For example, maintaining a constant pond size of 15 ha during the 8-month calibration period would have resulted in a reduction in water losses of about 0.022 m^3/t of ore (averaged over 8 months).

The remaining two water loss terms, active beach evaporation and rewetting losses, provide perhaps the most significant potential for water loss savings, because (i) both loss terms are directly influenced by the tailings discharge practice and (ii) those two loss terms account for an estimated 20% of total water losses (15.7% and 4.2% for active beach evaporation and rewetting, respectively). Unfortunately, tailings management strategies designed to minimize rewetting losses will increase beach evaporation losses and vice versa. For example, evaporation losses from active beach areas are reduced by minimizing the size of the active beach areas. This is typically accomplished by frequent changes of the discharge point. However, frequent change of the discharge point will maximize rewetting losses, as rewetting losses are greatest during the initial discharge onto a previously inactive beach area. In practice, tailings management should strike a balance between the goal of minimizing the active beach area and the need to change the discharge points.

The calibrated water recovery model was used to estimate the "optimum" duration of tailings discharge, which would minimize the combined losses of rewetting and active beach evaporation. Figure 5 shows the simulated daily evaporation and rewetting losses as a function of time since start of discharge. Also shown are the resulting combined losses, which represent a cumulative average over the total discharge period (yellow triangles). Rewetting losses are greatest during the first 2 days after which they drop off exponentially. In contrast, evaporation losses are initially small but increase gradually over

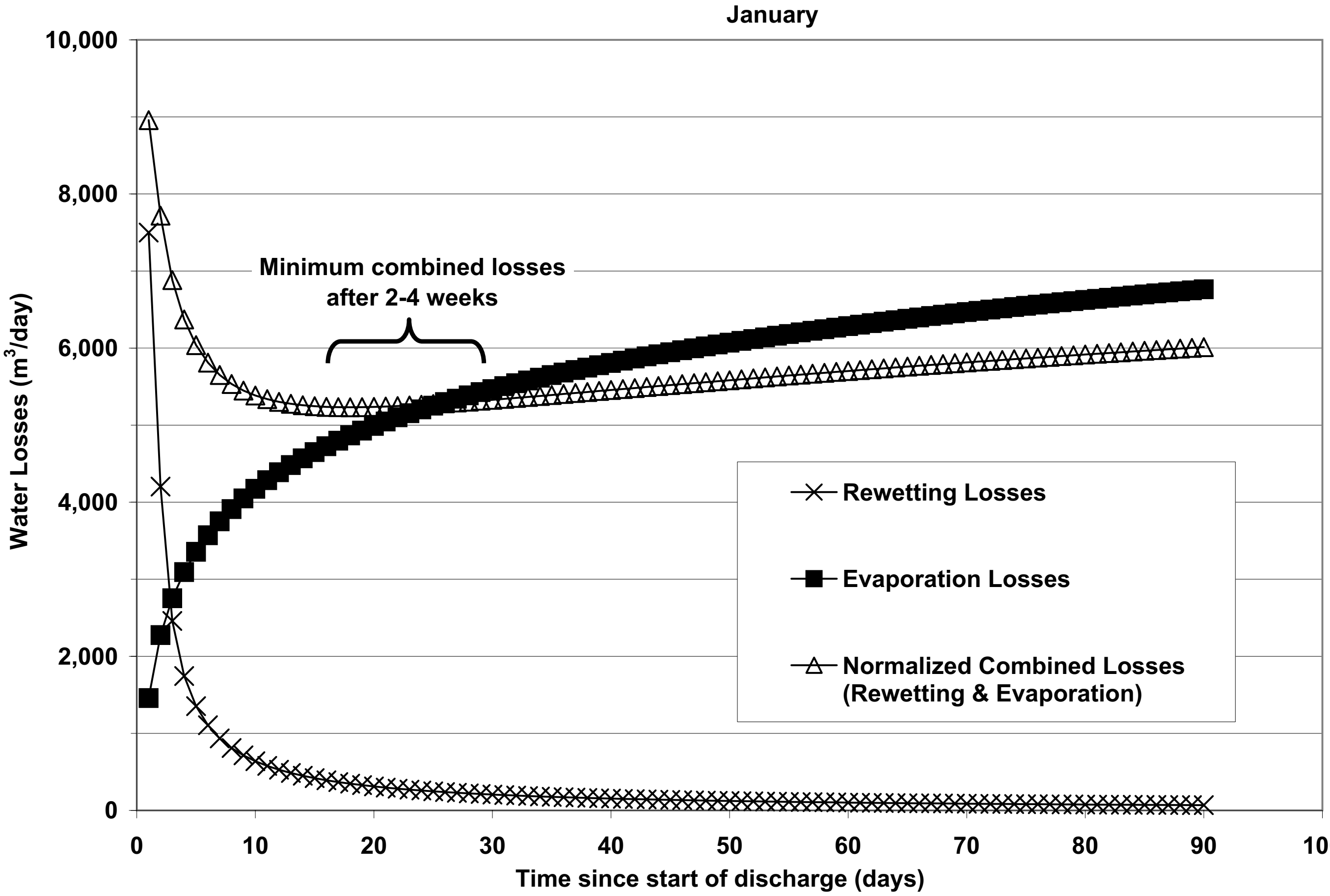

Figure 5. Predicted evaporation and rewetting losses during growth of active beach (January).

time (with the growth of the active beach area). For the first week of discharge, the high rewetting losses more than compensate for the low evaporation losses and the combined average losses are relatively high. In other words, very short duration discharges (< 7 days) should be avoided. For very long discharge periods (say > 1 month) high evaporation losses more than compensate for the low rewetting losses and the combined losses increase again. Hence very long discharge periods (in excess of 1 month) should also be avoided. Based on model simulations we would recommend an average discharge period of about 2-4 weeks to minimize the combined losses of evaporation and rewetting. Note that the "penalty" of increased water losses caused by prolonged discharges from a single discharge point beyond the "optimum" 2-4 weeks rotation is relatively small. For example, model calculations suggest that the use of a 2-month rotation would only increase combined beach evaporation and rewetting losses by 0.008 m^3/t of ore compared to a rigorous 2-week rotation (averaged over the 8-month calibration period).

The above calculations were carried out assuming a random discharge pattern (as practiced during the calibration period). A systematic rotation of discharge points (say in a clockwise direction) would likely reduce the growth of the active beach area due to the fact that the previously deposited tailings beach represents a "shoulder" thus limiting the lateral growth of the next active beach area. In our experience such a systematic rotation may reduce the active tailings beach area by as much as 30% compared to a beach with random discharge. The potential savings in water losses due to this alternative discharge pattern were estimated by calculating the average water losses for the 8-month calibration period assuming a 30% reduction in A_1 and A_{30}. The model suggests that a 30% reduction in active beach areas (all else being equal) would reduce the average water losses by about 0.037 m^3/t of ore.

4 CONCLUSIONS

A water recovery study has been completed for the Pampa de Pabellon tailings impoundment at Minera Doña Ines de Collahuasi, in the high Andes of northeastern Chile. The study included (i) a detailed field investigation to determine *in-situ* properties of the Collahuasi tailings and (ii) calibration of an updated water balance model using water recovery data collected during the period July 2002 to February 2003. The field investigation indicated that the Collahuasi tailings are relatively fine-grained (55% average fines content) and do not show significant hydraulic segregation during placement. The initial void ratio of the Collahuasi tailings is about $e_0 = 1.3$ (±0.1) and the final void ratio (after full consolidation) is approximately $e_f = 0.75$ (± 0.05). The Collahuasi tailings typically maintain a high degree of saturation in the order of 80-90% with significant desaturation (down to 50%) only occurring in the near-surface layers (maximum ~0.3 m) during the warm summer months.

A simplified water recovery model was used to determine water losses as well as recoverable water quantities occurring from the active ("flooded") beaches during active discharge. The total water losses during the 8-months monitoring period averaged 41,835 m^3/day or 70% of all process water discharged into the impoundment. The updated model was calibrated using the observed water losses and recovery rates. According to the model, entrainment losses represent the largest proportion of all losses (on average 74.7% of total water losses). Evaporation losses from active beaches represent the second largest component (on average 15.7% of total water losses). Water losses due to pond evaporation and rewetting represent a much smaller proportion of total water losses (5.4% and 4.2%, respectively). The modeling results suggest that there is only limited potential for improving water recovery rates due to the high initial entrainment losses of these fine-grained tailings.

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