AcquaTailings: A Tool for Streamlining Mining Water Budget

Gustavo Pereira, Hugo Rocha, Danielle Hoffert, Paulo Paiva

GeoHydroTech Engineering, São Paulo, Brazil,

gpereira@ghtengenharia.com.br, hrocha@ghtengenharia.com.br, dhoffert@ghtengenharia.com.br, ppaiva@ghtengenharia.com.br

Abstract

Acquatailings is a Graphical User Interface (GUI) tool developed in-house by GeoHydroTech Engineering to streamline the assessment and prediction of mining water budgets in tailing dams. It enables the quick examination of the sensitivity of the results to the various input variables used in this type of study, such as the physical characteristics of the watershed and of the spillway, dry/bulk density of the mined material and the solid rate of the processed pulp, as well as water fluxes captured from adjoining streams or lost through infiltration.

Acquatailings is capable of resolving monthly predictions of several mining water parameters that are important in the design, construction schedule, and operation of tailing dams. These variables include: the dam water level, flooded area, water volume, storage capacity, water deficit, meteorological balance, water/sediment occupation, and the spillway water volume, as well as a three-dimensional, cross-sectional illustration of the water level in the dam. This tool also enables the visualization of other graphical outputs, such as normal intervals for precipitation and evaporation, and elevation-area-volume plots.

Simulations are obtained using three climatic scenarios that span the entire spectrum of likely environments that this mining site may observe: dry threshold, normal, and wet threshold. The former scenario yields a combination of reduced monthly precipitation and enhanced monthly evaporation, albeit at the limit of what can be climatologically considered normal. The latter scenario is created with the opposite setup (increased monthly precipitation and suppressed evaporation), whereas the normal scenario uses monthly median values for these variables.

The capabilities of this new tool are showcased in this study, using a dataset from a mining site in the northern part of Brazil. The region is characterized by a tropical savanna climate, with warm temperatures year-round, abundant annual rainfall, and pronounced wet and dry seasons. The precipitation in the region is also heavily influenced by cycles of the El Niño Southern Oscillation. Thus, Acquatailings was used to enable the proper long-term planning of mining water budgets for a tailings dam in the aforementioned region, ahead of the current 2015-2016 El Niño cycle.

Key words: mine water, simulation, tools, water budgets, climate

Introduction

Water balance studies are a fundamental step in the design, construction schedule, and operation of the tailings management facilities used in the mining industry. They are paramount not only to determine the stability of the balance in a given site, but they also allow for project managers to better understand the likelihood of scenarios where water scarcity or excess can develop. According to Papageorgiou et al. (2003) the vast majority of failures in tailings dams during the 1980s and early 1990s were a result of inappropriate water management. Consequently, examining the volatility of water budget results to the various contributing factors used in their calculation is essential to fully grasp the range of conditions for which a site manager must prepare, such as variations due to climatic oscillations.

In order to expedite the sensitivity of our hydrological balance studies to various mining and hydrometeorological conditions observed at tailing dams, GeoHydroTech Engineering spearheaded a project to develop, in-house, a new software tool in the form of a user-friendly Graphical User Interface (GUI): *AcquaTailings*. This tool is useful to assess the uncertainty of the results due to climatic variation and unmeasurable empirical parameters, such as the system's efficiency and runoff coefficients. This software was designed to quickly simulate monthly forecasts for a myriad of mining water variables, such as the dam's water level, flooded area, and water volume, as well as its storage capacity (for sediment and water), and the reservoir's proportional occupation by water and sediment. It also calculates any potential water deficits at the dam site, the meteorological balance (i.e. the total monthly natural gain/loss of water at the reservoir solely due to precipitation and evaporation), and any volume of water released through a spillway. *AcquaTailings* is capable of producing an animation illustrating a three-dimensional cross-section of the water level in the dam, as well as the normal intervals for precipitation and evaporation, and elevation-area-volume plots. Figure 1 displays a picture of the *AcquaTailings* GUI workspace.

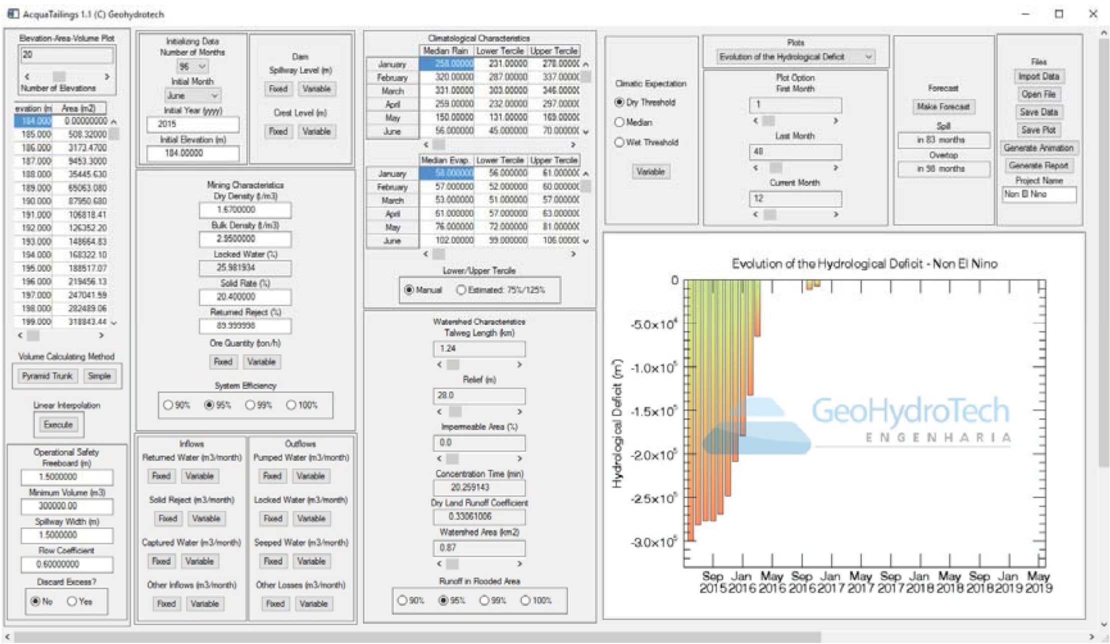

Figure 1 *Screen Capture of the AcquaTailings Graphics User Interface.*

Data & Methodology

The method for calculating the bulk of the prognostic variables in *AcquaTailings* is fundamentally based on the continuity equation. As such, the reservoir's water budget is calculated as:

$$V_f = V_i + C_1 \cdot \frac{P \cdot A_D}{\Delta t} + C_2 \cdot \frac{P \cdot A_F}{\Delta t} + Q_{RW} + Q_{RJ} + Q_{NW} + Q_{OG} - Q_{PW} - Q_{OS} - Q_{LW} - \frac{E \cdot A_A}{\Delta t} - Q_{OL}$$

Where:
V_f = final volume at the beginning of each month (m^3);
V_i = initial volume at the end of each month (m^3);
C_1 = runoff coefficient over dry land;
C_2 = runoff coefficient over flooded areas;
P = monthly precipitation (mm);
A_D = dry watershed area (m^2);
A_F = flooded watershed area (m^2);
Q_{RW} = water flowing back into the reservoir (m^3/month);
Q_{RJ} = solid reject flow into the reservoir (m^3/month);
Q_{NW} = new water captured into the reservoir (m^3/month);
Q_{OG} = other inflows (m^3/month);
Q_{PW} = flow of water pumped out of the reservoir to the mining plant (m^3/month);
Q_{OS} = outflow of water due to seepage (m^3/ month);
Q_{LW} = water flow locked in the reject (m^3/ month);
E = monthly evaporation (mm); and
Q_{OL} = other outflows (m^3/month).

The simulations presented in this study are based on a tailings dam built for a copper mining site in the Brazilian State of Pará. This mining site, developed and operated by Avanco Resources Limited, and its watershed are characterized by the following general conditions:

- Dry Density: 1.67 t/m^3
- Bulk Density: 2.95 t/m^3
- Solid Rate: 20.4%
- Returned Reject: 90%
- Watershed Area: 0.87 km^2
- Talweg Length: 1.24 km
- Relief: 28 m

For this site, we chose to make use of monthly precipitation and evaporation data for the city of Marabá, Brazil (obtained from the Brazilian Meteorology National Institute - INMET) as it meets the requirements of a reference station that can be used for climatic studies (World Meteorological Organization 1986). The Oceanic Niño Index (ONI) was obtained from NOAA's Climate Prediction Center to define the periods of El Niño. Warm episodes of the El Niño Southern Oscillation (ENSO), commonly known simply as El Niño, are characterized by ONI values greater or equal to 0.5 ºC (Kousky and Higgins 2007). The monthly precipitation and evaporation data were then divided into two groups. The El Niño dataset contains solely the monthly data during periods when that climatic phenomenon was identified in the ONI dataset. The other group, labeled "Non El Niño", contains the remainder of the dataset. Three statistical parameters were calculated for each of these two data groups to define the range of most likely monthly meteorological conditions: the median, the lower tercile, and the upper tercile. The latter two parameters represent the limits of what could be considered climatologically normal to expect in an El Niño vs. a non El Niño month. In addition to developing forecasts using the median precipitation and evaporation during El Niño and non El Niño years, simulations were also made using a combination of the lower tercile of precipitation and upper tercile of evaporation (dubbed the "dry threshold"), as well as a combination of the upper tercile of precipation and lower tercile of evaporation (hereby named "wet threshold").

The statistical results for the precipitation and evaporation data are presented, respectively, in Tables 1 and 2. In broad terms, Table 1 shows that El Niño years in the region of Marabá are characterized by lower precipitation than non El Niño years, with statistically significant differences ($p < 0.05$) observed between March and June, as well as in December. Trends in the evaporation data (Table 2) are not so obvious, but statistically significant differences are seen during the peak rainy months of March and April, both of which display higher evaporation rates in the region during El Niño years.

Table 1 *Precipitation climatology (in mm) for Marabá, Brazil between 1973 and 2011 during El Niño years and during years without El Niño.*

Month	Lower Tercile		Median		Upper Tercile	
	El Niño	Non El Niño	El Niño	Non El Niño	El Niño	Non El Niño
Jan	230	231	248	258	285	278
Feb	266	287	282	320	319	337
Mar	234	303	246	331	251	346
Apr	170	232	184	259	193	297
May	56	131	67	150	98	169
Jun	12	45	19	56	42	70
Jul	12	15	19	19	25	26
Aug	15	14	25	24	32	26
Sep	46	39	57	46	64	61
Oct	60	80	80	92	100	120
Nov	109	132	133	147	150	193
Dec	170	191	184	213	189	231

Table 2 *Evaporation climatology (in mm) for Marabá, Brazil between 1973 and 2011 during El Niño years and during years without El Niño.*

Month	Lower Tercile		Median		Upper Tercile	
	El Niño	Non El Niño	El Niño	Non El Niño	El Niño	Non El Niño
Jan	58	56	60	58	63	61
Feb	54	52	55	57	59	60
Mar	57	51	58	53	61	57
Apr	67	57	70	61	74	63
May	74	72	78	76	83	81
Jun	98	99	99	102	105	106
Jul	119	118	123	124	132	134
Aug	123	119	131	129	138	142
Sep	109	115	110	124	130	136
Oct	92	95	94	102	104	111
Nov	78	73	82	78	83	85
Dec	65	61	68	64	72	67

In this study we showcase three of the products generated by *AcquaTailings*: The Reservoir's Water Level, the Reservoir's Water Volume, and the Reservoir's Occupied Volume. These products will be initially assessed in a situation when no additional new water is captured from an adjoining stream into the reservoir (i.e. all water in the reservoir is the result of the rainfall and runoff). Five-year forecasts will be generated under El Niño and non-El Niño meteorological conditions for the dry and wet thresholds. Based on these results, a schedule for capturing new water from the stream is proposed and a new set of forecasts is generated.

Results

Figure 2 reveals the monthly forecasts generated by *AcquaTailings* for the Water Volume (in cubic meters) inside the tailings dam reservoir. The top panel shows the 5-year simulation using the dry threshold of El Niño years, which corresponds to the driest scenario in our study. It reveals a grave drought situation in the reservoir, which displays significant water accumulation only during the first half of 2016. Using the dry threshold for Non El Niño years (second panel), a slightly better picture emerges, with water accumulating during the wet season and depleting during the dry season in the middle of each calendar year. The third panel exhibits a marginally improved condition for the El Niño wet threshold, albeit one where water is still fully depleted in the reservoir during the first few dry seasons. Lastly, using Non El Niño wet threshold conditions, the reservoir manages to store water starting in January 2016, and peaking at 1.5×10^6 m^3 of water at the of the simulation in May 2020.

Figure 3 presents the same set of simulations as the previous figure, but displays the monthly water level. In the absence of any water, the values represent the reservoir floor level (which will progressively rise as the tailings are deposited each month). The red line denotes the elevation of the dam's crest, which undergo two planned heightening construction phases, while the yellow line corresponds to the level at which water from the reservoir begins to flow out through the spillway. It reveals that water levels remain safely under the spillway level in all four simulations, the closest situation being observed in mid-2018 and mid-2020 using the wet threshold of Non El Niño years (bottom panel).

The percentage volume occupation of reservoir by tailings deposits and water is presented in Figure 4. It unveils a time-lapse forecast of the proportional occupation of the reservoir. It is important to keep in mind that every time the dam undergoes a heightening period, the reservoir capacity increases, driving downward the reservoir's occupation percentage values. Once again, in the top panel (El Niño dry threshold) we observe a situation of water scarcity that would, in practice, not allow the mining plant to operate. The second and third panels once again illustrate when the reservoir's water is depleted whilst the tailings accumulation forecasts do not change (even though, in practice, exhausting the water supply would effectively shut down the plant and cease the tailings deposits in the reservoir). Only in the wet threshold for Non El Niño years (bottom panel) we observe a situation where water is consistently present and the reservoir's capacity is near 100% at the end of the simulation.

The aforementioned results reveal the necessity of developing a new water capture plan, from an adjacent stream into the reservoir, in order to maintain a volume of water that can safely enable the continuous operation of the mining plant under all potential climatic scenarios simulated here. An examination of the meteorological balance product in *AcquaTailings* (not shown), indicated that the period from June to November of each year is the most conducive for natural water losses in the reservoir. Thus, we proposed the monthly capture of 40000 m^3 of new water from the adjoining stream during these 6 months for the first 3 years of operation of this tailings dam.

Figure 5 presents the same product displayed in Figure 4, but the monthly forecasts are obtained while incorporating the proposed plan for new water capture. The top panel of Figure 5 (El Niño dry threshold), which represents the case where the hydrological setup of the reservoir is most strained, demonstrates that the suggested plan is sufficient to maintain some water stored in the reservoir even under this difficult scenario. Conversely, by looking at the simulation that uses the wet threshold of Non El Niño years, the proposed schedule of new water capture maintains the water level just below full capacity during its projected peak occupation months (January 2018 and April 2020). Therefore, one can conclude that this would be an ideal plan to prepare for the entire array of climatic conditions under which the tailings dams at this site may need to be ready to operate.

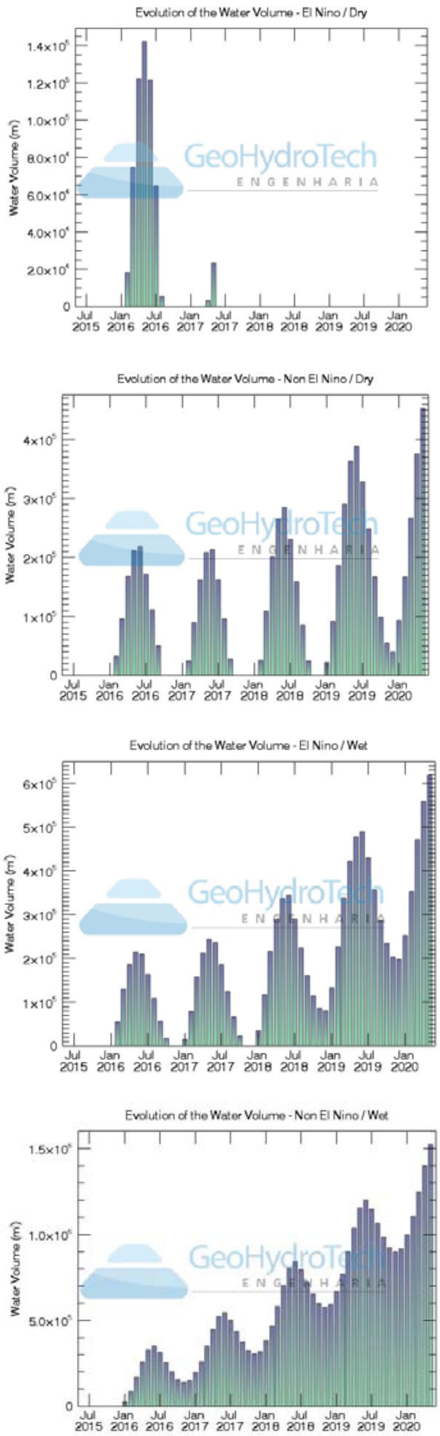

__Figure 2__ Monthly forecasts for the Reservoir's Water Volume under 4 scenarios (top to bottom): Dry Threshold in El Niño Years, Dry Threshold in Non El Niño Years, Wet Threshold in El Niño Years, and Wet Threshold in Non El Niño Years.

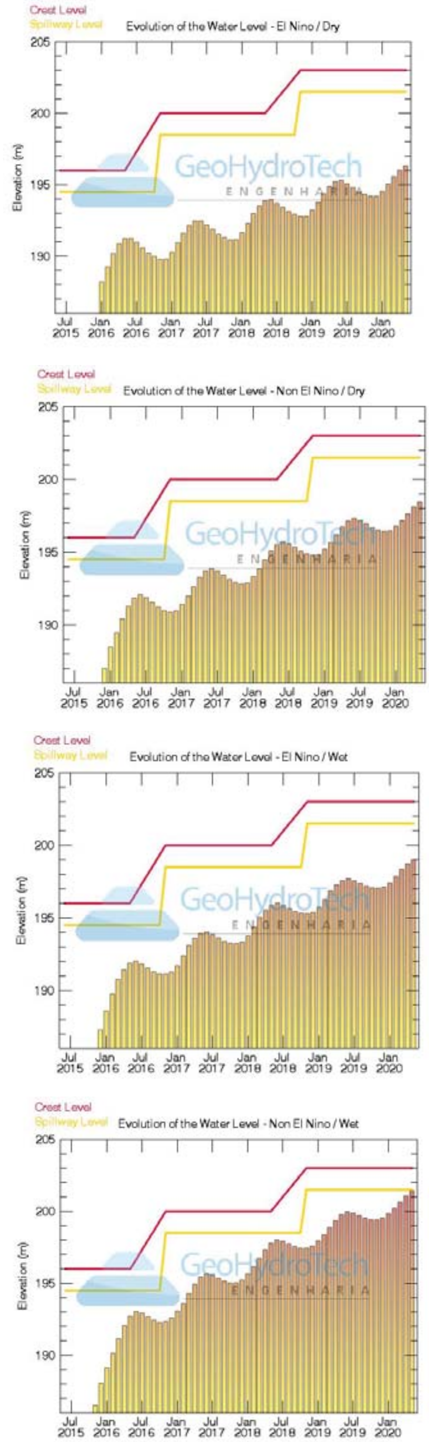

__Figure 3__ Monthly forecasts for the Reservoir's Water Level under 4 scenarios (top to bottom): Dry Threshold in El Niño Years, Dry Threshold in Non El Niño Years, Wet Threshold in El Niño Years, and Wet Threshold in Non El Niño Years. The red line represents the dam's crest level, and the yellow line represents the spillway base level.

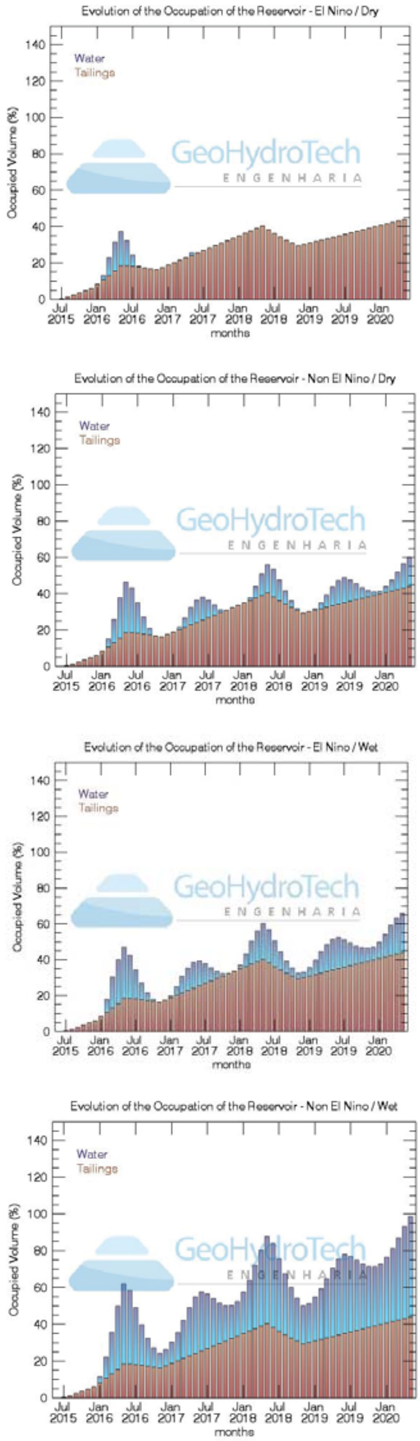

__Figure 4__ Monthly forecasts for the Reservoir's Occupied Volume under 4 scenarios (top to bottom): Dry Threshold in El Niño Years, Dry Threshold in Non El Niño Years, Wet Threshold in El Niño Years, and Wet Threshold in Non El Niño Years. The brown shading indicates percentage occupied by tailings, and the blue shading indicates the percentage occupied by water.

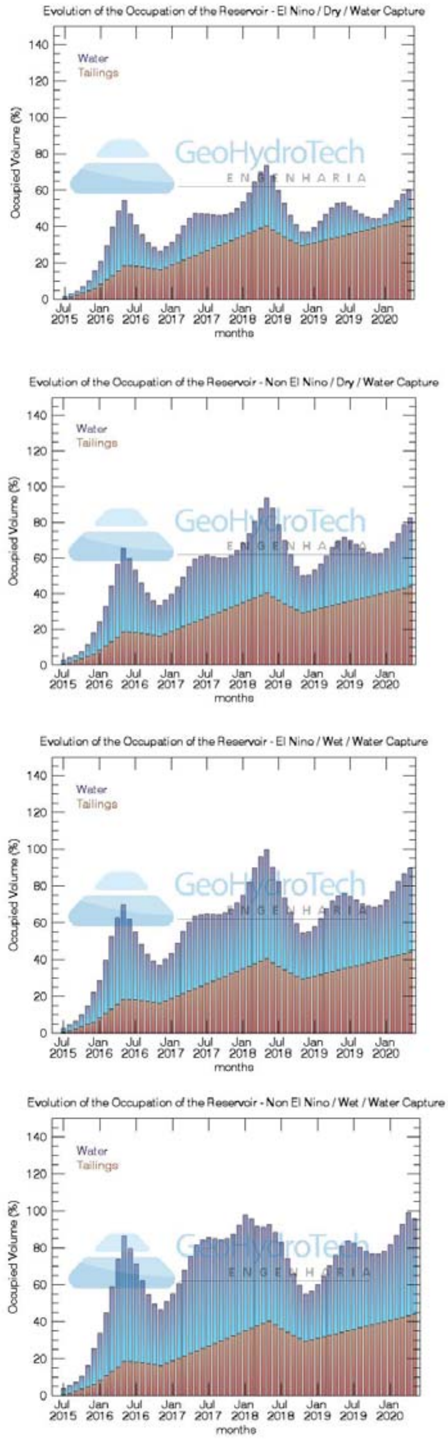

__Figure 5__ Same as Figure 4, but including a proposed schedule of new water capture from an adjoining stream into the reservoir.

Conclusions

Acquatailings is a tool newly developed by GeoHydroTech to produced monthly forecasts of mining water parameters that are useful in planning and operating tailings dams. The usefulness of this tool is showcased for a tailings dam located in the northern part of Brazil, a region known to be significantly impacted by the climatic cycles of ENSO. Warm ENSO episodes (i.e. El Niño) are characterized by below normal precipitation during the rainy season at this tailings dam site. Consequently, we examined the susceptibility of mining water budgets at this location under four climatic scenarios: El Niño dry threshold, Non El Niño dry threshold, El Niño wet threshold, and Non El Niño wet threshold.

The results of this study reveal that this tailings dam, as it was designed, would not be able operate without the capture of a new water. While the dry and wet threshold represent the upper and lower limits of what could be considered climatologically normal in a region, observing five consecutive years of El Niño-like conditions is far less reasonable and, as such, the El Niño simulations represent a more extreme situation under which this mining site may need to operate. Nonetheless, examining these four scenarios provide a safe margin for the mining operator to plan their production. The simulation for the El Niño dry threshold produced the hydrologic setup with greatest water scarcity, whereas the Non El Niño wet threshold generated the environment with greatest abundance of water.

Using the reservoir water volume, water level, and occupied volume products, it was possible to determine that an adequate water budget balance can be reached by capturing 40000 m^3 of new water per month, in the first three years of the simulation, between the months of June and November. The forecasts obtained using this proposed water capture plan was capable of providing a constant supply of water at the reservoir while maintaining the water level within safety regulations (i.e. beneath the spillway base level).

One of the other capabilities of *Acquatailings* that was not explored here, is the ability to quickly determine the sensitivity of the results to various unmeasurable empirical parameters used in the forecast, such as the efficiency of the system, the runoff coefficient in flooded areas (which is impacted by the uneven distribution of tailings and the presence of dead pools). The usage of all features in *AcquaTailings* enables the time-efficient development of sound hydrological balance studies. Furthermore, *AcquaTailings* offers a tool to quickly obtain a better alternative to deterministic studies that are solely based on mean values for all the various components used in this type of study.

Acknowledgements

The authors would like to sincerely express gratitude to Avanco Resources Limited for authorizing the usage of the data for one of their mining projects in this study. In particular, we would like to recognize Antonio Landi Borges and Otávio Monteiro for facilitating this authorization.

References

Kousky VE, Higgins RW (2007) An Alert Classification System for Monitoring and Assessing the ENSO Cycle. Weather and Forecasting 22: 353—371

Papageorgiou G, Fourie A, Blight GE (2003) An investigation of flow failures from breached tailings dams. In: A review of scientific contributions on the Stava Valley disaster, 19th July 1985, Pitagora Editrice, Bologna, Italy.

World Meteorological Organiation (1986) Guidelines on the selection of Reference Climatological Stations (RCSs) from the existing Climatological Station Network. WMO/TD-Number 130, Geneva, Switzerland.