On the effect of climate change on water balances of tailings reservoirs

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ABSTRACT
Knowledge on meteorology and hydrology of watersheds and their relationship with global climate has attracted considerable attention of many researchers in recent years. Forecasts available have suggested that the increase in global average temperature can have an effect on precipitation and evaporation regimes. This paper evaluates the effects of climate change on water balance simulations for a reservoir in Minas Gerais State, Brazil, designed for containing tailings and supplying water to an ore processing plant. Comparisons are made between current and impacted scenarios in order to determine differences in water availability.

RÉSUMÉ
Le connaissance des relations de meteorologie et hidrologie des basins hydrographiques avec global climat ont recentement retrouvée considerable attention des researcheurs. Les prévisions disponibles ont dit que la augmentation de la temperature moyenne globale peu affecter les régimes de la pluie et de l´evaporation. Cet article apprécie les effects de la change du climat sur le balencement d´éau d´un reservoir en Minas Gerais, Brazil, qui est dessiné pour contention des rejets et comme source d´éau au process minerale. Des comparaison entre balencements sous le climat actuelle e changée sont effectué, en montrant les différences sur l´éau disponible.

1 INTRODUCTION

Knowledge on meteorology and hydrology of watersheds and their relationship with global climate has attracted considerable attention of many researchers in recent decades. The discussion in question is about the role of greenhouse gas emissions associated with human activities which, in theory, have led to changes to the Earth's weather patterns and, as a result, an increase in global average temperatures.

Despite recent advances in climate modeling, understanding and prediction, climate is a complex interaction between direct physical and feedback processes, the greenhouse effect being one of them. Forecasts available have suggested that the increase in global average temperatures can have an effect on the precipitation regime, albeit uncertain, because of simulation model calibration difficulties due to the complexity of Earth's atmosphere processes.

Thus, current dam design and operation concepts may prove inadequate in the light of future periods of scarcer water and more frequent storms, which could possibly jeopardize the use of reservoirs for their intended purposes or even raise related hydrologic or geotechnical risks.

Tailings reservoir water balances must associate hydrometeorological, geotechnical and ore processing variables to maximize tailings storage and water abstraction, in spite of the vicissitudes of hydrometeorological variables. Possible changes in rainfall and evaporation patterns and concurrent water stress gains prominence in water balance simulation and reservoir operation.

This paper evaluates climate change effects on water balance simulations for a reservoir in the State of Minas Gerais, Brazil, designed for containing tailings and supplying water to an ore processing plant, as proposed by IPCC for the 21st century. Current and impacted scenarios are compared and differences in water availability analyzed.

2 TAILINGS DAM WATER BALANCES

The water balance for a tailings dam reservoir differs significantly from the water balance for a water storage reservoir: the surface area of solids must be estimated for each time interval to allow for correct calculation of water balance fractions, which has an impact on anticipated water levels and spilling probability. These aspects can be looked into in hydrological and geotechnical terms.

2.1 Geotechnical terms

The geotechnical factors that may affect a tailings dam's water balance can be divided into two types:

- *Water Release from Slurry After Solids Sedimentation* (W_{SS}): in Brazil and worldwide, tailings are usually transported from a plant to a reservoir as slurry with low percent solids by weight (S of less than 40%), and once slurry reaches the reservoir, solids settle down and excess water is released and added to the reservoir volume;
- *Water Release from Settled Solids After Solids Consolidation* (W_{SC}): after settlement, solids are subjected

to stress from settlement of upper sediment layers, which leads to different levels of consolidation according to tailings and foundation characteristics and also the drying phases of tailings beach. These phenomena lead to a reduction in void-to-solids ratio, releasing water to reservoir.

In the early stages of the design process, when no information on tailings consolidation is available, unity to deposited solids void ratio is assumed, which in general holds true for most cases of tailings dams.

W_{SS} can be calculated from the difference between *Total Slurry Water* (W_{ST} – m³/h) and *Water Trapped in Settled Solids Voids* (W_{TV} – m³/h):

$$W_{SS} = W_{ST} - W_{TV} \qquad [1]$$

W_{ST} is a process parameter that characterizes tailings slurry and can be calculated from *Percent Solids of Slurry by Weight* (%S), *Ore Processing* (*P* – t/h) and *Water Density* (ρ_W – t/m³):

$$W_{ST} = \frac{\mathrm{P} \cdot (1 - \%S)}{\%\mathrm{S} \cdot \rho_{\mathrm{w}}} \qquad [2]$$

W_{TV} é a fração de água que permanece retida nos vazios dos sólido depositados e pode ser calculada a partir do índice de vazios (e), da massa específica do grão (Gs), da produção mineral (P - t / h) e da densidade da água (ρ W - t / m³):

$$W_{TV} = \frac{e \cdot P \cdot \rho_w}{G_s} \qquad [3]$$

Replacing equations (2) and (3) in (1):

$$W_{SS} = \mathrm{P} \cdot \left[\frac{(1 - \%S)}{\%\mathrm{S} \cdot \rho_{\mathrm{w}}} - \frac{e \cdot \rho_w}{G_s} \right] \qquad [4]$$

Equation (4) shows how process and geotechnical tailings parameters affect water release from tailings after solids sedimentation inside tailings reservoir and, consequently, water balances of these structures.

Another mechanism that affects a tailings reservoir's water balance is the consolidation of deposited tailings. The classical geotechnical approach to solids consolidation, as proposed by Terzaghi, is not able to yield accurate tailings consolidation results due to the major distortions involved (Gjerapic et al, 2008; Pereira, 2006).

Many authors have addressed this issue, and extensive theories, laboratory tests and computer algorithms have been developed to support their views (Oliveira Filho & van Zyl, 2006). One of the results of this effort is a curve relating mean void ratio of a tailings column and its height. This curve can be built into tailings beach management programs to calculate mean dry density of settled tailings and accurately estimate reservoir capacity.

One aspect that affects tailings consolidation is the exposure of tailings beach to periods of desiccation. Climate changes can affect the rate of consolidation by changing the exposed surface area of beaches and reservoirs.

2.2 Hydrological aspects

Reservoir water balances involves determination of inputs (tailings solids and water) and outputs (water only) as stated below:

$$\Delta \mathrm{V} = \left[(\mathrm{V_r} + \mathrm{Q} + \mathrm{P} + \mathrm{W_{SS}}) - (\mathrm{C} + \mathrm{E} + \mathrm{Perc}) \right] \cdot \Delta t \quad [5]$$

In Equation (5), *ΔV* is storage change (m³) over an interval of time *Δt* (month), V_r is volumetric rate of tailings deposition (m³/month), *Q* is reservoir inflow from upstream catchment area (m³/month), *P* is direct rainfall onto reservoir water surface (m³/month), W_{SS} is the water released from tailings after settlement (m³/month), *C* is the amount of water drawn to supply the process (m³/month), *E* is direct evaporation from reservoir water surface (m³/month), *Per*c is losses due to percolation through dam embankment and foundation (m³/month).

Water balance is simulated from an initial storage condition, following a filling phase, and includes computing inflow and outflow as determined from hydrological monitoring data (rainfall, runoff, evaporation) on a monthly basis. Initial storage is determined similarly during the reservoir filling phase, assuming no tailings discharge.

In most cases, reservoir supply capacity is estimated using Rippl diagram (Tucci, 1997), in which volumetric deficit is evaluated from an historic flow record, with the maximum deficit being equal to the amount of water needed to secure a 100% guaranteed water supply.

However, this method relies on historic data characteristics, like most hydrologic methods, and climate change can affect such behavior in the future. This method also fails to reflect the natural variability of the flow series and the effects of tailings storage on the reservoir.

An alternative approach consists in using synthetic hydrologic time series (Salas *et al*., 1997; Box *et al*., 1994). These series are derived from the selection and calibration of stochastic models, whose inversion leads to equally probable synthetic hydrologic time series. By evaluating the water balance for each of these series, which can amount to hundreds or thousands, one can estimate the storage needed to secure water supply at a desired degree of probability.

Again, a monthly time step is usually adopted as stochastic models may become excessively complex, requiring a huge number of parameters for shorter time steps (Saliba, 2000).

An advantage of this approach is that one can assess the effect of climate changes on water balances by changing stochastic model statistic parameters according to climate model forecasts in terms of rainfall and evaporation changes.

The proposed approach involves analysing the effects of climate change on tailings pond water balances. A one-year mean annual water balance is evaluated, in order to understand how and to what extent a slight increase in annual mean temperature can affect water availability from tailings reservoirs, even though it does not reflect the effects of tailings consolidation or climate statistical variations.

3 REGIONAL CLIMATE

3.1 Key Processes

Climate in South America is strongly influenced by tropical convection, a continental barrier along the Pacific coast of South America (the Andes), and the world's largest rainforest (Amazon Rain Forest). Seasonal evolution of the rainy season is largely the result of air-sea interactions over the Americas' warm pools and the effects of topography on a dominant easterly flow, as well as the temporal evolution of the Atlantic Inter-tropical Convergence Zone (Christensen *et al.*, 2007; Nimer, 1979).

Warm season precipitation maximum seems to be associated with the South American Monsoon System (Vera *et al.*, 2006), which dominates the mean seasonal cycle of precipitation at tropical and subtropical latitudes over South America, and is strongly influenced by El Niño-Southern Oscillation (Lau and Zhou, 2003).

3.2 Regional Climate Projections

Christensen *et al.* (2007) evaluated regional climate projections derived from 21 Atmospheric-Ocean Global Climate Models (AOGCM), whose data are referred to as multi-model data set (MMD).

These climate projections were made using A1B – 21st Century as baseline scenario (Nakićenović and Swart, 2000), which implies a market-oriented world, with the fastest *per capita* growth economy, population growth peaking at 2050 and then declining towards 2100, strong regional interactions in terms of governance and income convergence, and energy sources including all existing (fossil and non-fossil) technologies in a balanced manner.

According to regional climate projections, all of South America is very likely to warm during the 21st century. The annual mean warming is likely to be similar to the global mean warming in southern South America but larger than the global mean warming in the rest of the region (Christensen *et al.*, 2007).

Changes in atmospheric circulation may induce large variability in precipitation changes in mountainous areas. Simulations show consistent quality results in terms of decreasing precipitation at the northern tip of the continent and in southern northeast Brazil (Christensen *et al.*, 2007).

In this paper, these projections were customized for the city of Belo Horizonte, State of Minas Gerais (MG), Brazil, in whose vicinity many tailings dams are located.

3.2.1 Temperature

According to regional projections (Christensen *et al.*, 2007), Minas Gerais' mean annual temperature is expected to have an 2.5ºC to 3.0ºC increase by the end of the 21st century when compared to the late 20th century (Figure 1).

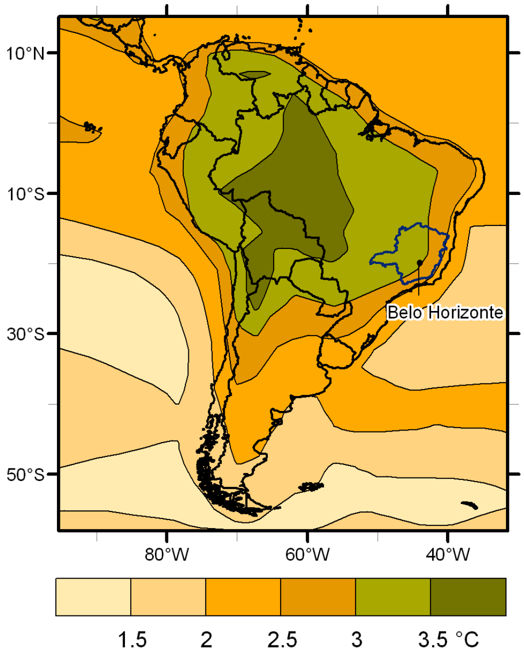

Figure 1. Changes in annual mean temperature over Central and South America, under the MMD-A1B scenario, from 1980-1999 to 2080-2099, as averaged from 21 models (adapted from Christensen et al., 2007, also showing Minas Gerais state, Brazil).

3.2.2 Evaporation

Many methods have been proposed to analyse evaporation and one of the most popular is the Aerodynamic Method (Chow, 1988):

$$E_a = \frac{0{,}622\,k^2 \rho_a u_2}{p\rho_w \left[\ln(z_2/z_0)\right]^2}(1 - R_h)e_{as} \qquad [6]$$

where E_a is the evaporation rate (m/s), k is the von Karman constant, usually assumed as 0.4, u_2 is wind velocity measured 2 m above surface (m/s), ρ_w and ρ_a are water and air densities (kg/m³), R_h is relative humidity (%), p is air pressure (Pa), z_2 and z_0 are roughness height 2 m above and at ground level (m), respectively, e_{as} is saturation vapor pressure (Pa).

For the same location on Earth, none of these variables will vary with temperature other than e_{as}, ρ_w and ρ_a. Thus, Eq. 6 can be rewritten as follows:

$$E_a = Ke_{as}\frac{\rho_a}{\rho_w} \qquad [7]$$

where K is a term that remains constant with temperature (m/s.Pa).

Table 1 shows how e_{as}, ρ_w and ρ_a change with air temperature and how much evaporation would change for the same location on Earth.

Table 1. Effects of temperature on the rate of evaporation.

Temperature (°C)	Saturation Vapour Pressure (Pa)	Air Density (kg/m³)	Water Density (kg/m³)	$e_{as}.\rho_a/\rho_w$ (Pa)
20.0	2,337	1.204	996,0	2.828
21.1	2,503	1.200	995,6	3.016
24.1	2,985	1.188	994,4	3.566
25.0	3,167	1.184	994,0	3.775

Source: Adapted from Chow, 1988.

From Table 1, one can conclude that an increase in mean annual temperature at Belo Horizonte from 21.1°C (INMET, 1992) to 24.1°C (3.0°C raise - Figure 1) will cause the value of the variable term of Eq. 7 ($e_{as}.\rho_a/\rho_w$) to rise from 3.016 Pa to 3.566 Pa, which means an increase of 18.2%.

This factor reflects the increased evaporation due to warmer atmosphere having the ability to hold more water vapour.

Thus, the mean annual rate of evaporation at Belo Horizonte is expected to increase by a factor of 1.182 by the end of the 21st century, which means an annual evaporation of 1,447.6 mm up from the current 1,217.4 mm (Table 2).

Table 2.Monthly evaporation rates (mm) at Belo Horizonte under current and changed climate conditions.

Month	Current	Changed	Month	Current	Changed
Jan.	86.7	103.1	July	105.7	125.7
Feb.	84.7	100.7	Aug.	132.1	157.1
March	95.3	113.3	Sept.	137.2	163.1
April	92.4	109.9	Oct.	117.7	140.0
May	92.8	110.3	Nov.	96.3	114.5
June	92.4	109.9	Dec.	84.1	100.0
-	-	-	Year	1,217.4	1,447.6

Source: Adapted from INMET, 1992.

3.2.3 Precipitation

According to regional projections (Christensen *et al.*, 2007), Minas Gerais' mean annual precipitation is expected to decrease by as much as 10% by the end of the 21st century as compared to the late 20th century (Table 3).

According to mean climate values observed at Belo Horizonte, mean annual precipitation is 1,491.3 mm (INMET, 1992).

Considering the maximum expected decrease in precipitation (10%), mean annual precipitation is expected to drop to 1,342.7 mm.

Table 3 shows monthly adjusted precipitation values, assuming a homogeneous reduction throughout the year.

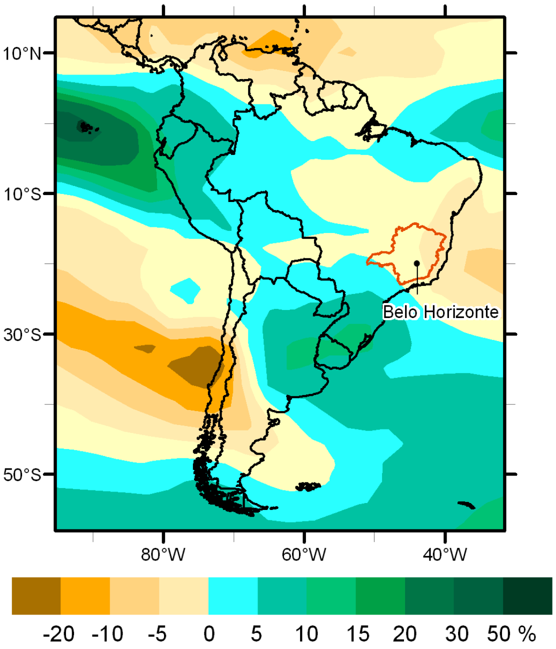

Figure 2. Changes in annual mean precipitation over Central and South America, under the MMD-A1B scenario, from 1980-1999 to 2080-2099, as averaged from 21 models (adapted from Christensen *et al.*, 2007, also showing Minas Gerais state, Brazil).

Table 3. Monthly precipitation (mm) at Belo Horizonte, MG, in 2011 (year-to-date) and 2100.

Month	1961-1990	2100	Month	1961-1990	2100
Jan.	296.3	266.67	July	15.7	14.13
Feb.	188.4	169.56	Aug.	13.7	12.33
March	163.5	147.15	Sept.	40.5	36.45
April	61.2	55.08	Oct.	123.1	110.79
May	27.8	25.,02	Nov.	227.6	204.84
June	14.1	12.69	Dec.	319.4	287.46
-	-	-	Year	1,491.3	1,342.2

Source: Adapted from INMET, 1992.

4 CASE STUDY

To exemplify the effects of tailings ponds on water balances, a hypothetical tailings pond analysis was made, based on Belo Horizonte´s climate data. Following hydrological studies, it was determined that such tailings pond must maintain a minimum 6.0 Mm³ volume of water to enable 1,028 m³/h of freshwater to supply milling process requirements. As explained in section 2, such amount of water is necessary to replace water losses due to the saturation of tailings voids and evaporation losses.

The tailings dam drains a surface area of 20 km², and the reservoir starts with 6.0 Mm³ storage. The reservoir's water surface is linearly interpolated according to constant water storage x water surface area data (Table 4).

Table 4. Water storage versus water surface.

Water storage (m^3)	Reservoir´s Liquid Surface Area (m^2)
1,000,000	1,000,000
6,000,000	4,000,000
9,000,000	6,000,000

Upstream inflow into tailings pond is estimated to be 30% of all rainfall in the rest of the catchment area (16 km^2). Tables 5 and 6 show simulation results for an average year under current and changed climate conditions.

Table 5. Average year water balance for a tailings pond near Belo Horizonte under current climate conditions.

Month	Storage (m^3)	Reservoir water surface (m^2)	Reservoir net balance (m^3)	Upstream inflow (m^3)	Water supply (m^3)
Jan.	6,000,000	4,000,000	907,760	1,422,240	764,421
Feb.	7,565,579	5,043,720	608,474	845,329	690,444
March	8,328,938	5,552,625	484,522	708,644	764,421
April	8,757,683	5,838,456	-74,265	260,006	739,762
May	8,203,662	5,469,108	-253,985	121,188	764,421
June	7,306,444	4,870,963	-291,381	63,996	739,762
July	6,339,297	4,226,198	-291,016	74,295	764,421
Aug.	5,358,155	3,614,893	-332,498	67,343	764,421
Sept.	4,328,579	2,997,148	-207,582	206,585	739,762
Oct.	3,587,820	2,552,692	73,875	644,329	764,421
Nov.	3,541,603	2,524,962	380,158	1,193,196	739,762
Dec.	4,375,195	3,025,117	762,692	1,626,533	764,421
Jan.	6,000,000	4,000,000			

Table 6. Average year water balance for a tailings pond near Belo Horizonte under changed climate conditions.

Month	Storage (m^3)	Reservoir water surface (m^2)	Reservoir net balance (m^3)	Upstream inflow (m^3)	Water supply (m^3)
Jan.	6,000,000	4,000,000	736,785	1,280,016	764,421
Feb.	7,252,380	4,834,920	430,253	771,417	690,444
March	7,763,607	5,175,738	292,406	654,417	764,421
April	7,946,009	5,297,339	-173,837	242,947	739,762
May	7,275,357	4,850,238	-306,809	113,714	764,421
June	6,317,841	4,211,894	-316,759	60,105	739,762
July	5,321,425	3,592,855	-310,486	69,550	764,421
Aug.	4,316,069	2,989,641	-338,818	62,921	764,421
Sept.	3,275,751	2,365,451	-222,499	192,834	739,762
Oct.	2,506,324	1,903,794	-2,232	601,464	764,421
Nov.	2,341,134	1,804,681	204,352	1,118,139	739,762
Dec.	2,923,863	2,154,318	446,934	1,538,976	764,421
Jan.	4,145,352	2,887,211			

By comparing Tables 5 and 6, one can conclude that the reservoir can no longer secure a water supply of 1,028 m^3/h under changed climate conditions, as water storage dropped below the minimum required level of 6.0 Mm^3 at the beginning of the following year, even considering average climate values, which is an very optimistic assumption in terms of a mining project risk assessment.

The water abstraction level that will enable the minimum water storage of 6.0 Mm^3 to be maintained early next year should be 800 m^3/h. This means reducing water supply for ore processing by 28.5%.

This demonstrates the potential of damage associated with a 3.0ºC increase in mean annual temperature to tailings dam and other reservoir operations.

Even though such warming seems to be small to most people, its effects on economy would lead to water stresses that can be experienced society and affect water management as well.

5 FINAL REMARKS

This paper has sought to demonstrate the effects of climate change on tailings pond water balances, particularly near Belo Horizonte, MG, Brazil. This city is in the heart of the so-called Iron Quadrangle mineral province, and a number of tailings ponds are located in its vicinity.

Results suggest that even though the increase in temperature foreseen by IPCC studies seems to be small to common sense, its effects on climate variables such as precipitation and evaporation can be much greater.

The water balance was calculated for a hypothetical tailings pond, assumed to be located close to Belo Horizonte, MG, Brazil. Such pond drains a surface area of 20 km^2.

Climate change can lead to an increase in mean annual temperature by as much as 3.0ºC and a decrease of up to 10% in mean annual precipitation at Belo Horizonte (Christensen *et al.*, 2007). Using the Aerodynamic method (Chow et al., 1988), it was estimated that the mean annual evaporation would increase by 18.2%.

Such changes were evenly distributed throughout the year according to recorded climate data (INMET, 1992).

Water balance calculations showed that such changes resulted in a 28.5% reduction in water supply for ore processing.

This demonstrates the potential of damage associated with a 3.0ºC increase in mean annual temperature to tailings dam and other reservoir operations.

Even though such warming seems to be small to most people, its effects on economy would lead to water stresses that can be experienced society and affect water management as well.

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