Evaluation of the Effects of Climate Change on Water Infiltration on Thickened Tailings in the Atacama Region

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ABSTRACT

Chile is a country with high vulnerability associated with Climate Change, given among other factors, due to the need for development and growing social and environmental conflicts. This motivates the implementation of adaptation, transformation and mitigation measures at all aspects, to deal with climatological phenomena, which despite its future uncertainty, its development is a proven fact by robust and bulky scientific evidence.

Motivated by the call from COP25 and the IPCC to assess adaptation and mitigation of effects and consequences of Climate Change, SRK Chile proposed to analyze the response of infrastructure associated with mining in northern Chile, considering General Circulation Models (GCM) downscaled for Atacama region at different elevations, based on the models considered by Chilean Water Directorate (DGA) in its Update of the National Water Balance of Chile (NWBC). This study considers Representative Concentration Pathways RCP 8.5 (most pessimistic scenario) as scenarios to evaluate, same as DGA – NWBC.

To observe the effects of these scenarios we applied the GCM as boundary conditions in 1D numerical infiltration models using the software Hydrus. In the simulations water fluxes in a column of thickened tailing above natural soil is analyzed for different precipitation regimes from GCMs. Standard values according to our experience for the hydraulic and geometry properties of the materials forming the columns are used.

The results of this study shed light upon the future precipitation's scenarios affect the available water in the infrastructures at different elevations, providing a quantitative comparison of the infiltration fluxes within the tailing for the GCMs in the Atacama region.

INTRODUCTION

Chile is a country where mining engineering, technology and infrastructure is quite developed, playing a key role in one of the most important economic activities of the nation. At the same time, Chile has a high vulnerability associated with Climate Change, due to the growing social and environmental conflicts. These two issues motivate the implementation of adaptation, transformation and mitigation measures at different industrial aspects, to deal with climatological phenomena, which despite its future uncertainty, its development is a proven fact by robust and bulky scientific evidence.

In this work we to analyze the response of infrastructure associated with mining in northern Chile, considering General Circulation Models (GCM) downscaled for Atacama region at different elevations, based on the selected models considered by Chilean Water Directorate (DGA) in its Update of the National Water Balance of Chile (NWBC). The present study considers Representative Concentration Pathways RCP 8.5 (most pessimistic scenario) as scenarios to evaluate, same as DGA – NWBC.

We applied the GCMs as boundary conditions in 1D numerical infiltration models, using the software Hydrus, in order to assess the effects of these scenarios in this specific mining infrastructure. In the simulations, water fluxes in a column of thickened tailing, disposed above natural soil, is analyzed for different precipitation and evaporation regimes from the analysis of the GCMs. Standard property values for the columns are used, according to SRK experience regarding hydraulic and geometry properties of column's materials.

METHODOLOGY

Site Description

The analyses were carried out in the Atacama Region of Chile, one of the less meteorologically controlled regions of the country and where several active mine sites are developed. As climate conditions in the region varies west to east due to the orographic complexity, four sites distributed from the coast to the high Andes zone were selected, in order to represent different climatic conditions. Three of these sites corresponds to the location of one meteorological DGA station (see Table 1 and Figure 1).

Table 1: Stations Characteristics

Station Name	UTM WGS84 H19S		Geographic Coordinates		Elevation	Rainfall time span	Temperature time span	Mean Annual Rainfall (mm)**
	East (m)	North (m)	Lat (°)	Lon (°)	(msnm)			
Tal-Tal	350731.5	7189025.8	-25.41	-70.48	9	1987 - 2015	N/I	10.5
Copiapó	368189.4	6970697.3	-27.38	-70.33	385	1971 - 2019	1984 – 2019	17.1
Pastos Grandes	443874.4	7000411.6	-27.12	-69.57	2260	1966 - 2019	N/I	31.4
High Andes*	471102.0	6953581.0	-27.54	-69.29	4595	N/I	N/I	158.0

*: High Andes is not a station, it refers to the representative site.

**: Estimated from CR2MET gridded product.

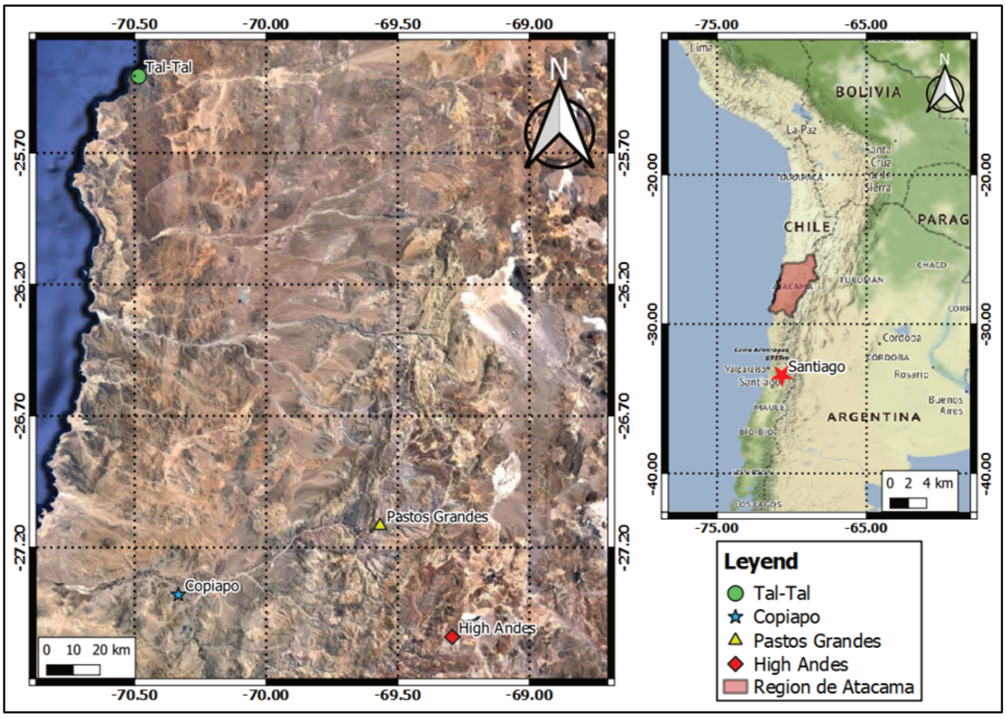

Figure 1. Regional context and evaluation points (WGS84, base Google Satellite)

Ground Base Information

Due to the lack of meteorological variables as temperature and evaporation/evapotranspiration, and some gaps in the rainfall time series of DGA stations, meteorological model inputs must be complemented with other type of databases. This motivates the use of satellite-based estimations (SBE) and gridded meteorological products, that play a key role in hydrological and hydrogeological assessment and design regarding mining and climate change evaluations. We use DGAs meteorological data from National Water Balance of Chile (NWBC) called CR2MET as a complementary observational database. This gridded product is public and delivers Rainfall and Temperature at daily and monthly timescale, with data from 1979 to 2016, and spatial resolution of 0.05° latitude-longitude (equivalent to 5 x 5 km). For evapotranspiration estimations we use the Oudin formula from R package airGR, due to its simplicity.

General Circulation Models (GCMs)

General Circulation Models (GCMs) represent physical processes in the atmosphere, ocean, cryosphere and land surface. They are the most advanced tools currently available for simulating the response of the global climate system due to the increasing greenhouse gas concentrations and have the potential to provide geographically and physically consistent estimation of regional climate change which are required in impact analysis. GCMs use a three-dimensional grid over the globe (see

Figure 2), having a horizontal resolution between 250 and 600 km, with 10 to 20 vertical layers in the atmosphere and sometimes as many as 30 layers in the oceans. As the GCMs are evaluated following the guidelines from the International Panel on Climate Change (IPCC) at several research institutions and considering different Representative Concentration Pathways (RCP) (see Figure 2), around 80 to 100 different models for each scenario with climate change projections until 2100 can be found for each site.

However, the DGA in its NWBC has selected four models considering RCP8.5, the most pessimistic scenario, with the follow criteria: 1) Correlation with historic simulations with low frequency phenomena such as ENSO (El Niño Southern Oscillation) and SAM (Southern Annular Mode); 2) Climatic sensibility analysis; 3) Analysis of deltas of temperature and precipitation at regional scale. Thus, the selected models used in this study were:

- Extremely low sensibility: CSIRO-Mk3-6-0 (CSIRO)
- Moderate to low sensibility: CCSM4 (CCSM4)
- Moderate to high sensibility: MIROC-ESM (MIROC)
- Extremely high sensibility: IPSL-CM5A (IPSL)

The DGA's NWBC models were statistically downscaled using a method called Delta Quantile Mapping (DQM), gridded and resampled to coincide with CR2MET spatial resolution (0.05° latitude-longitude), considering a time span from 1979 to 2060. For the present study we use DGA selected models and the same time period of DGA analysis, scaled for each of the locations of interest.

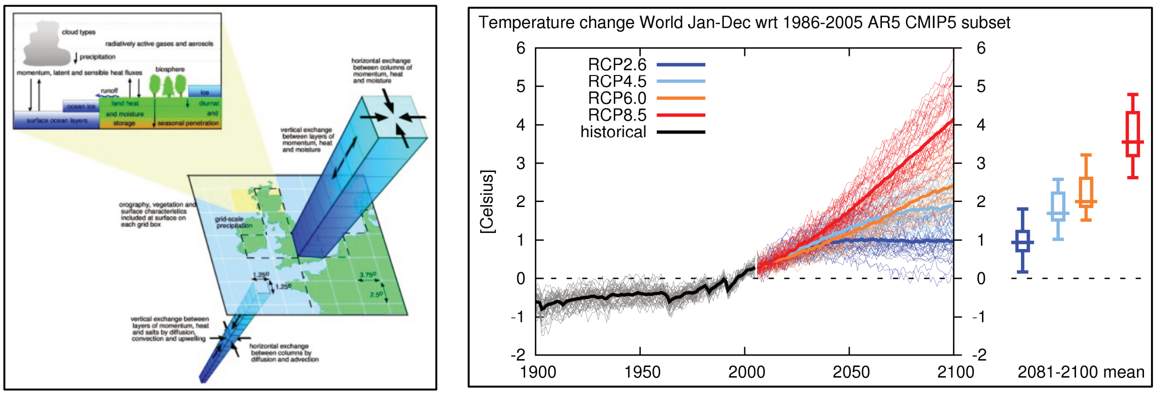

Figure 2. General Circulation Models schematic figure (IPCC) and Representative Concentration Pathways considering Temperature Change (LAMPS, York University, Canada)

Numerical Model

For the evaluation of the water infiltration given the different sites and the different GCMs, we computed numerical models using the software Hydrus for a 1D column (Rassam et al, 2018). The column consists in 10 meters of thickened tailing material and 10 meters of natural soil. We defined the material in the thickened tailings as sandy loam to loamy sand with moisture 22%, density of 1.48

ton/m3 and fine-grained percentage above 66%. The permeability for this material is assumed as 5x10-1 m/d and the suction curve showed in Figure 3, characterized the hydraulic properties of the material. For the natural soil, we defined a layer of sandy gravels, representative of a typical northern Chile soil coverage, with low moisture values related to the hyper-arid climate in the area, gravel content of 43%, sand content of 53%, and low fine-grained percentage of 4% in average. The density is set 2.01 ton/m3 and permeability of 0.1 m/d. Figure 3, also shows the suction curve for the soil material and Table 2 summarize the hydraulic properties of the materials used in the modelling.

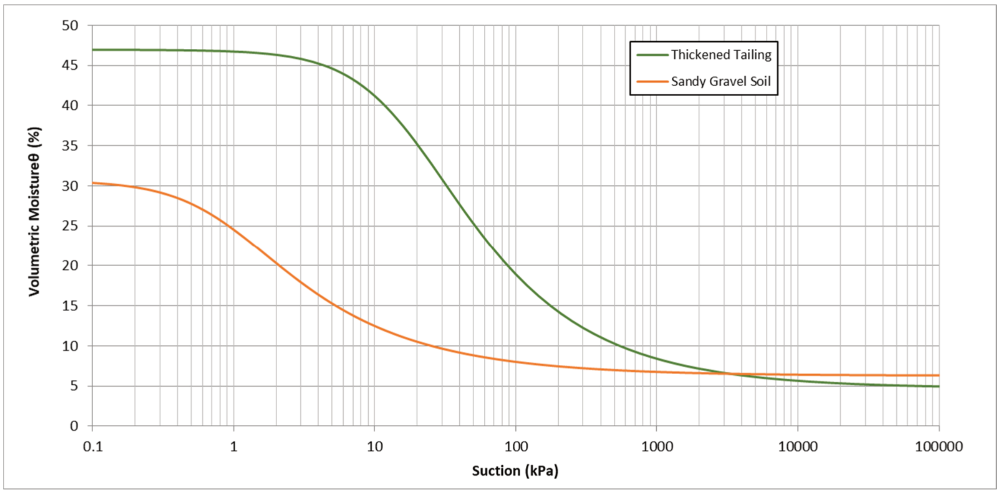

Figure 3. Suction curves for the materials used in this study.

Table 2: Soil Hydraulic Property Model

	Van Genuchten Parameters				Ks [m/d]	θi [–]
	θ_{res} [–]	θ_{sat} [–]	α [1/m]	n [-]		
Thickened Tailing	0.0703	0.462	0.502	1.7661	0.00691	0.24
Sandy Gravels	0.0619	0.304	11.2501	1.5574	0.10000	0.10

The water flow boundary conditions applied in the numerical model correspond to the atmospheric data obtained from the different climate scenarios as precipitation and evaporation rates in the upper boundary with a surface layer of 0.1 m and not allowing the flux in the lower boundary. The column of 20 meters is divided in 400 nodes equally spaced with a size of 5 cm for each element. The initial volumetric water content is set in 24% and 10% for the Thickened Tailing and the Sandy Gravels material, respectively, as is showed in Table 2. The simulations run for 40 years, according to the length of the meteorological data obtained, with a minimum and maximum time step of 0.00001 day and 5 day, respectively. Finally, 5 scenarios including a base case and the 4 General Circulation Models were modelled for the stations Taltal, Copiapó, Pastos Grandes and High Andes.

RESULTS AND DISCUSSION

Hydrology Results

The results of scaling meteorological data show the direct relation between the rainfall rate and the elevation. On the other hand, evapotranspiration shows an inverse trend, with higher amounts in areas of lower elevation (**Error! Reference source not found.**). Regarding GCMs results the comparison between historical period and model estimation was analyzed considering percentage of change at a 20-year window (Table 3). It should be noted that the models were evaluated considering an average between them, to make the comparison between time windows easier. Values of change in rainfall differ depending on location, with no clear tendency. For all the GCM models considered in this study, the estimated rainfall dramatically diminished for the last 20-year window. Estimations of Evapotranspiration shows an increase on its amounts, with small percentages of change than rainfall, but with a clear trend to get higher, the higher get the elevation.

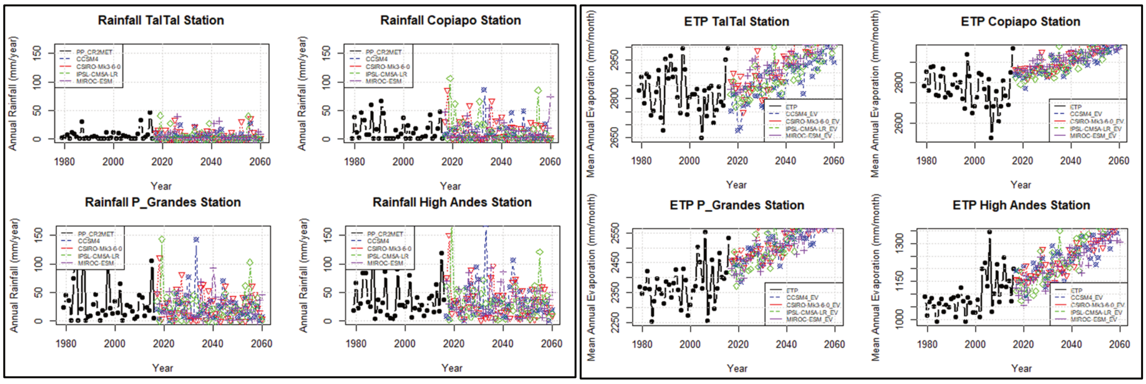

Figure 4. Time series of rainfall and ETP at year time scale.

Table 3: 20-year window average for rainfall and ETP, percentage of change corresponds to the difference from the historical period

Station Name	Annual Rainfall (mm/year) Historical 1997 - 2016	Annual Rainfall (mm/year) Models 2021 - 2040	Annual Rainfall (mm/year) Models 2041 - 2060	% of Change Δ% 2021 - 2040	% of Change Δ% 2041 - 2060	Mean Annual ETP (mm/month) Historical 1997 - 2016	Mean Annual ETP (mm/month) Models 2021 - 2040	Mean Annual ETP (mm/month) Models 2041 - 2060	% of Change Δ% 2021 - 2040	% of Change Δ% 2041 - 2060
Tal Tal	7.5	6	5	20%	34%	2819.2	2861.6	2985.3	-2%	-6%
Copiapó	12.6	13.9	9.8	-10%	23%	2754.7	2878.3	2965.8	-4%	-8%
Pastos Grandes	30	25.4	21.9	15%	27%	2396	2484.1	2590.6	-4%	-8%
High Andes	37.8	33.9	29.4	10%	22%	1126.2	1194.6	1329.1	-6%	-18%

Modelling Results

The results of modelling of the water infiltration show that the moisture in the tailing decrease in time due to the high level of potential evaporation, reaching surface moisture below 10% while the natural soil does not present variation in the initial moisture. As example, Figure , shows a graph of moisture along depth for the simulation in Taltal for the base case scenario, where lines in colors represent the moisture of the materials at different times from 1 day to year 40. The analysis of the water balance obtained for this case and for the other scenarios shows that at the end of 40 year, all the models present a loss of water in the column of approximately 0.99 meters, with no variation between the GCMs nor the stations, as is shown as example in the **Error! Reference source not found.**. This suggest that the water infiltrated into the tailing is evaporated, due to the high rates of evaporation for all the scenarios and stations. In this way the content of water in the system do not varies for the different scenarios, although the total amount of infiltrated and evaporated water does depend on the hydrological conditions.

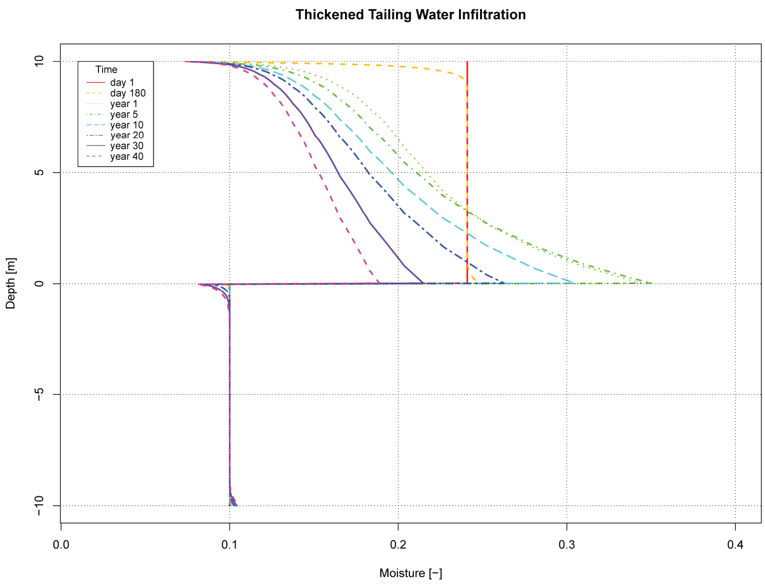

Figure 5. Simulated moisture content along depth in different times for Taltal station in the base case scenario.

Table 4: Water balance for Taltal station.

Taltal	Δ Volumen Column	Δ Volumen Tailings	Δ Volumen Soil	Total Infiltration	Total Evaporation	Numeric Error %
Base Case	-0.9917	-0.9845	-0.0073	0.24514	1.2368	0.016%
CCSM4	-0.9913	-0.9842	-0.00729	0.19007	1.1814	0.016%
CSIRO-MK3	-0.9914	-0.9842	-0.00729	0.26324	1.2547	0.023%
IPSL-CM5A	-0.9914	-0.9842	-0.00729	0.19073	1.1821	0.016%
MIROC-ESM	-0.9914	-0.9842	-0.00729	0.22515	1.2166	0.022%

Figure shows the total amount of water infiltrated and evaporated in every station for the GCMs scenarios. In this graph is clear that the evaporated water is always larger than the infiltrated water, which difference is the water extracted from the initial water content in the tailings. The figure also shows that for each station the differences in the water balance for the 5 scenarios in Taltal and Pastos

Grandes is not significant, whereas it is possible to say that for High Andes station, the scenario CCSM4 present a difference in the water balance with the other GCMs scenarios.

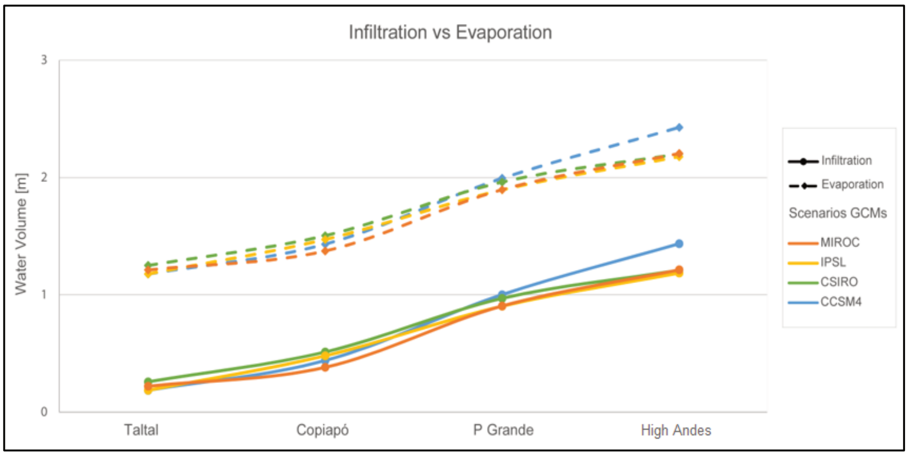

Figure 6. Infiltration and evaporation volume by station.

Overall, even though the results show that no significant differences in the water infiltration is found for the different scenarios, the CCSM4 implies a larger amount of water infiltrated and evaporated for the High Andes station.

CONCLUSION

Results of scaling meteorological data shows how the amount of rainfall has a relation with elevation, a normal trend in the northern part of the country (Table 3). On the other hand, evapotranspiration shows an inverse trend, with higher amounts in areas of lower elevation (Table 3). This is consistent with the conditions of extreme aridity in the intermediate areas at the north of Chile, with high levels of radiation, low air humidity and high temperatures.

Values of change in average rainfall and evapotranspiration differ depending on location, with no clear tendency for rainfall amounts. For all the GCM models considered in the study, rainfall is estimated to get dramatically diminished for the las 20-year window (22% to 34% under the historical period). As shown in Figure 4, future trends depends also on the specific model being evaluated, but is clear that all of them estimate a reduction in rainfall amounts, that will eventually lead to water shortage. Small percentage of change is shown on behalf of evapotranspiration estimations, with values between 6% an 18% (Table 3), showing a clear trend to get higher, the higher get the elevation.

It should be taken into account that the results of the analysis entail a series of aspects that incorporate an important source of uncertainty to the results, like downscaling and interpolation methods for

GCMs, simplified evapotranspiration estimation method, four GCMs instead of all of them, etc. All of this was not analyzed in the present study, but improvement options and subsequent evaluations remain open. Due to the high rates of potential evaporation predicted in in the GCMs scenarios for the next 40 years in the Atacama Region, the water infiltration in the tailings is not significant and the column loses part of the initial water. However, one of the scenarios shows a slightly increase in the infiltrated and evaporated water for the High Andes station, located at the high Andes. These results are exclusive for the Atacama region and probably the effects changes in precipitation and evaporation for the different GCMs scenarios may be relevant in other areas with less extreme hydrological conditions.

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