Uncertainty analysis in groundwater flow models as a tool to support decision making: Assessing the influence of infiltrations from a TSF over an open pit

Ignacio Álvarez[1], Martin Brown[2]

[1]*Itasca Chile, Providencia, Santiago, Chile, ignacio.alvarez@itasca.cl*

[2]*Itasca Australia, Scarborough, WA 6019, Australia, mbrown@itasca.com.au*

Abstract

A large Open Pit excavated in a very low permeability rock mass shows a limited presence of water on its slopes. Infiltrations from the nearby tailing storage facility (TSF) have produced a groundwater mound that extends towards the pit. To understand the potential effect that this flow could generate over the pit slopes and support the decision-making process, an uncertainty analysis was performed on a MINEDW 3D hydrogeological numerical model. Results indicate that while there could be an increase in pit seepage, there is a high probability that increases will be low compared to the seepage currently observed.

Keywords: Uncertainty analysis, numerical modelling, pit seepage, tailings infiltrations

Introduction

It is well documented that the presence of water has a detrimental effect on mining operations (Read & Stacey 2011; Read & Beale 2013). Water pressure acting on the pores, fractures or other discontinuities of the materials that make up a pit slope reduces its stability (Devy & Hutahayan 2021). This can lead to an increase in the risk of the mining operation, having to reduce slope angles and/or implement a drainage and depressurization program, in addition to drilling, blasting, exploitation and haulage problems (Morton & Van Niekerk 1993).

To control and overcome the negative effects generated by the presence of water, it is essential to have a correct understanding of the hydrogeological system (Read & Beale 2013). This is only possible through field characterization campaigns that include obtaining the hydraulic properties of the rock mass, data on anthropogenic and/or natural water inflows and outflows and monitoring of the hydrogeological system (Evan *et al* . 2015). This information is fundamental for the elaboration of a good conceptual model, as well as to support a subsequent numerical modelling work that can be used for the design of depressurization and drainage program (Read & Beale 2013; Evan *et al.* 2015).

Commonly, due to limited resources, the large dimensions of mining projects and the heterogeneity of fractured rock masses, it is not possible to fully characterize the hydrogeological domain of the models, which generates uncertainties related to the lack of information and, reduces the reliability of groundwater model predictions (Read & Beale 2013; Nilsson *et al.* 2006). Hence, decisions should not be made from the results of a single predictive model, but rather from modelling results that include estimates of uncertainty (Middlemis *et al.* 2019).

Situated in an area with low rainfall, high evaporation rates and low natural recharge, the deposit is within a low-permeability fractured rock mass classified as a rock aquiclude. These characteristics explain that to date, observed seepage flows have been low, allowing the mining operation to develop without the need for a drainage and depressurization program. However, since 2015, infiltration from the tailings storage facility (TSF) located 2 km from the pit have been observed in different monitoring boreholes, which have produced a groundwater mound that currently extends 700 m towards the pit. Eventually, the mound could generate a hydraulic connection with the pit, triggering problems for the mine operation due to an increase on in pit seepage and pore pressures on the slopes.

To support the decision-making process associated with the drainage and slope stability of the open pit, an uncertainty analysis was carried out over the 3D numerical hydrogeological model built in MINEDW™ (Azrag *et al*. 1998; Itasca Denver 2019). Results allowed estimating the probability of occurrence and the magnitude of the potential increase in seepage and pore pressures because of infiltration from the tailings.

Conceptual groundwater flow model

Located in the Atacama Desert in the north of Chile, the open pit and TSF are subject to scarce rainfall with an average of 1 mm/year and high evaporation rates with magnitudes close to 2,800 mm/year. The only natural recharge comes from higher elevations located to the east and that moves through the study area following the hydraulic gradient to the west, north and south.

At this site, the geological setting consists of a layer of unsaturated unconsolidated alluvial and colluvial deposits, which overly a rock mass with different fracture degrees and alteration, composed of volcanic and intrusive rocks. The volcanic rocks form the host rock for porphyries in the mine area, therefore they are highly fractured, altered and mineralized in the pit sector because of hydrothermal processes during emplacement of intrusive rocks.

Due to alluvial deposits that are naturally unsaturated, the fractured rock constitutes the most relevant hydrogeological unit in the area. However, hydraulic tests have shown that rock mass permeability is low and has the characteristics of an aquiclude. This means that the flow and hydraulic properties of the rock mass depend on its fracture degree and the interconnectivity of the fractured zones, as well as on the presence of large structures which act as low permeability flow barriers or as high permeable flow conduits (Read & Beale 2013). Due to this condition, a high spatial heterogeneity and compartmentalization occurs, which is associated with a high uncertainty about the distribution, orientation, dimensions, and hydraulic properties of the fractures at different scale (Nilsson et al. 2006).

Two regional systems of low permeability faults are the most important structures, which divide the study area into three compartmentalized subdomains, which have independent hydraulic behaviors (fig. 1a). Monitoring boreholes located downstream of the TSF, in the western subdomain, and upstream of the pit, in eastern subdomain, record water levels which remain constant, showing that the regional water table in these areas is not influenced by mining activity. Unlike the central subdomain that is affected by the excavation of the pit and the infiltration at the TSF.

Conceptual model defined three main hydrogeological units based on the available groundwater level data, hydraulic tests, geological model and RQD measurements. In the pit area, the rock basement has been subdivided into three subunits due to the presence of rocks with genetic and mineralogical differences. Additionally, three hydrogeological units were conceptualized to represent the regional faults zones (RFZ) outside the pit and the in-pit faults systems, one that groups conductive faults (CF) and another, grouping barrier faults (BF) (fig. 1a).

Because of the low permeability of the fractured medium, natural groundwater flow through the study area has been estimated to be from 0.5 to 2.5 L/s. Besides the low natural recharges, anthropic recharges from the eastern sector of the TSF have been estimated to be from 1 to 10 L/s. On the other hand, in pit seepage has been estimated between 5 to 6 L/s.

MINEDW numerical groundwater flow model

Modelled area has an irregular geometry with an E-W width and N-S length of 14.5 and 10 km, respectively, and a depth of 2,390 m. The thickness of the model is large enough to model the projected final pit in 2040 (fig. 1a; 1b). Model has a total of 4,415,820 nodes and 8,551,955 elements.

TSF is in the center and the open pit in the east of the model domain. Constant hydraulic head boundary conditions were established at five edges of the model, considering pre-mining and current water

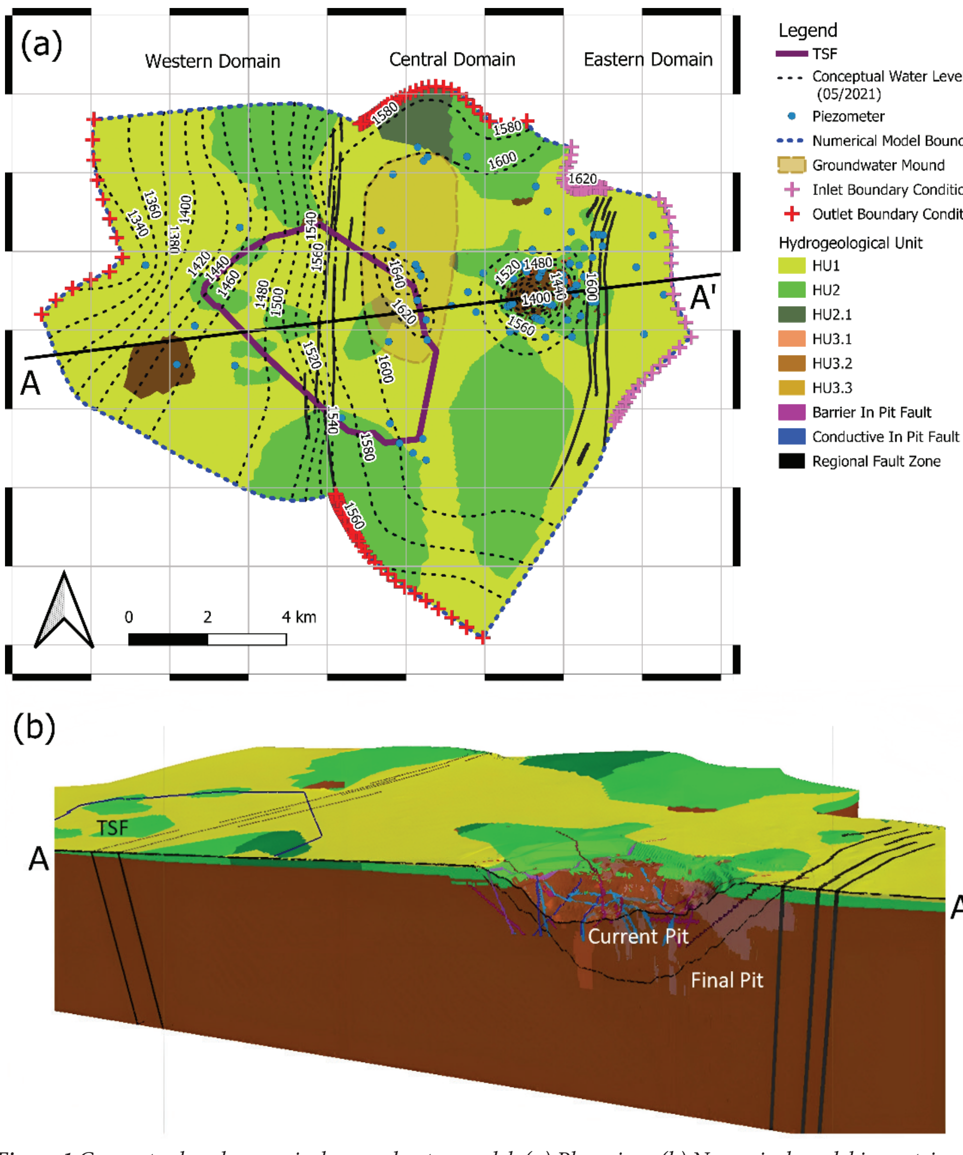

Figure 1 Conceptual and numerical groundwater model. (a) Plan view; (b) Numerical model isometric view

levels (fig. 1a), while a no flow boundary condition was assumed for the rest. The anthropic recharge zone was added according to conceptual model in the northeast of the TSF, while the recharge rate from TSF was calibrated through time using SEEP/W 2D and Hydrus 1D flow models according to tailings deposition records and the groundwater mound evolution.

Hydrogeological units were added as conceptualized. Based on higher permeability observed in hydraulic tests, an anisotropy zone was incorporated in HU2 in the north-eastern sector of the TSF, which allowed modeling the N-S direction of the groundwater mound.

Monthly observed groundwater level data from December 2012 to May 2021 of 67 monitoring boreholes were used for the calibration of the model. Most of the monitoring boreholes are located east of the TSF and in the pit zone (fig. 1a).

A pre-mine topography (2011) and 90 monthly historical topographies that record

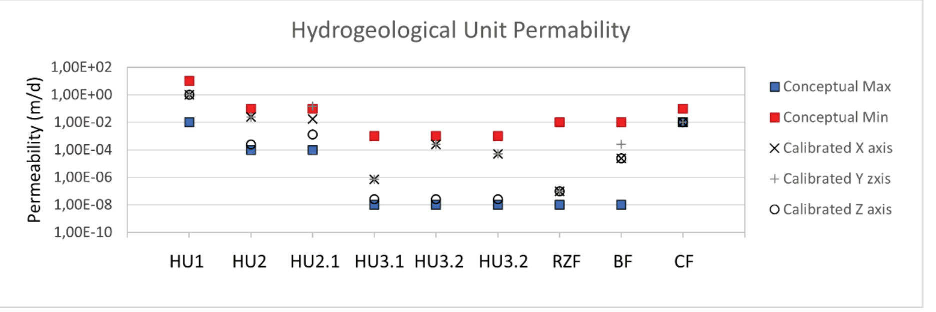

Figure 2 *Conceptual and calibrated permeability for hydrogeological units*

the excavation of the pit from February 2012 to July 2021, were used in the calibration process. Twelve predictive topographies, until year 2040, corresponding to the mining plan were added for the predictive analysis.

Calibration

Steady state calibrated water table levels were used as the pre-mining hydrogeological condition in the transient calibration, which reproduced the evolution of the water table during the mining activity to the final date of calibration. Both calibration stages considered the conceptualized permeabilities (fig. 2) as well as the estimated flow rates in the water balance, among other factors.

Emphasis was placed on calibrating monitoring boreholes with higher changing hydraulic gradients, located in the recharge zones near the TSF and those affected by depressurization in the vicinity of the pit. The best calibrated model reproduced conceptualized recharge and discharge flows, with inflows and outflows from the edges of 2.2 L/s, pit seepage of 6.7 L/s and recharges from the TSF of 6.2 L/s. Standards recommended by the guidelines (SEA 2012; Barnett *et al*. 2012) were also met, with a mean absolute error (MAE) in water level of 11.7 m (recommended: <45 m), normalized mean absolute error (nMAE) of 3.6% (recommended <5.0%) and a standardized root mean square residual (SRMS) of 5.1% (recommended: <10%). In addition, the extent of the groundwater mound was reproduced.

Predictive simulation

With the calibrated model, a predictive simulation was done until 2040, considering the excavation sequence of the mining plan and the evolution of the TSF recharge obtained from the 2D simulations of the tailing's deposition plan (Base Case). To assess if a hydraulic connection could be generated between TSF and the pit, a hypothetical simulation in which no recharge from the TSF ever occurred (No Recharge Case) was done and used as comparison.

Base Case simulation results show an advance of the mound that extends mainly to the north reaching a maximum advance of 800 m by 2026. The mound remains in this position until 2030 and then begins to gradually recede due to the end of tailings deposition according to the current plan. Advance towards the pit is less noticeable, possibly because it overlaps with the depressurization effect caused by the pit.

Base case predictive simulation shows that the mound will intersect the pit at the beginning of 2023. This connection would increase the seepage by 2.5 L/s at the most compared with the No Recharge Case in 2034.

Uncertainty Analysis

Since the predictive simulation shows a potential hydraulic connection between the TSF and the pit, which could generate an increase in pore pressure and seepage on its slopes, potentially triggering instabilities and causing operational problems (Read & Beale, 2013), an uncertainty analysis was performed over predicted simulations to better support the related decision-making process. The wide range of permeabilities measured in the field suggests a high level of uncertainty related to the heterogeneity of the rock medium (fig. 2), so the uncertainty analysis was focused on the variability of the parameters, using the deterministic modelling approach with linear probability quantification method (Refsgaard *et al.* 2006; Nilsson *et al.* 2006; Middlemis *et al.* 2019).

With the objective of quantifying the risk of the groundwater mound expansion in time, one hundred numerical models were run to perform the uncertainty analysis, considering random different permeabilities for HU2 and HU2.1, that has the higher hydraulic transmissivity between both facilities. To account for a more extreme range of results, the permeability of these units was varied expanding the conceptual upper limit by one order of magnitude (for example 1,0E-04 to 1,0E-01 m/d for HU2).

Results

All the uncertainty models obtained met the standards recommended by the modeling guidelines from water table approach (i.e., SRMS and MAE), therefore, all models could have been considered acceptable (i.e., calibrated) for analysis. However, 23 models were excluded from the probabilistic analyzes

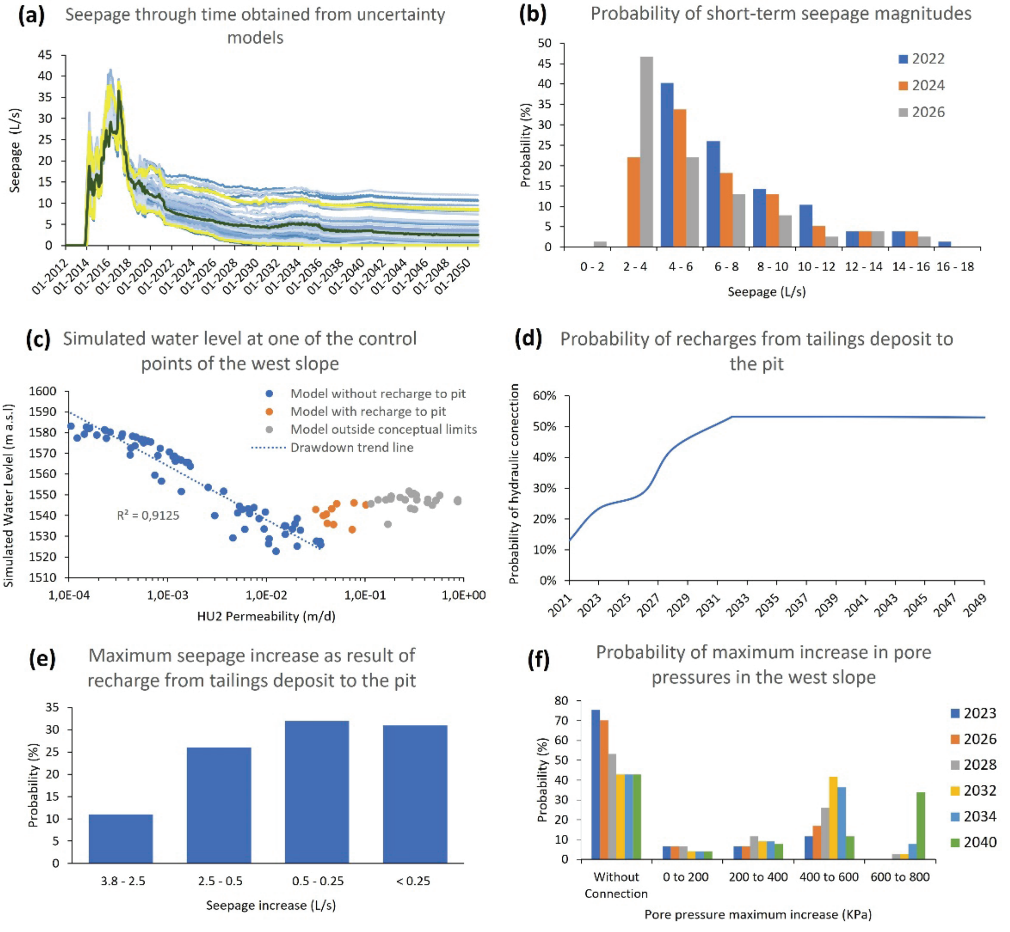

Figure 3 *Results of uncertainty analysis. (a) Seepage over time; (b) Pit seepage magnitudes for short-term; (c) Correlation between drawdown in west slope water level and HU2 permeability; (d) Probability of recharges to reach the pit; (e) Magnitude of the maximum seepage increase; (f) Increase of pore pressure through time*

because they exceeded the conceptualized seepage flow for the current condition by more than two times. These models, which were considered improbable from a mass balance standpoint, correspond to the models that have a permeability outside the conceptual ranges in the HU2.

Accepted models showed seepage flows between 4.9 and 16.4 L/s for the calibration date, all decreasing over time in the predictive simulations (fig. 3a). This is consistent with a pit being excavated into less permeable rock and with an aquiclude that has been drained through time. Since all the models are considered equiprobable, the results can be used to define the probability of the magnitude of the seepage flows for the following years (fig. 3b).

Pit seepage shows a good correlation (R^2 = 0.94) with the HU2 permeability in the models, which is reasonable because this unit has the highest control in the transmissivity of groundwater flow. It should be noted that this correlation doesn't mean that there is necessarily a direct hydraulic connection between the TSF and the pit, since the increase of the HU2 permeability generates an increase in the inflow to the pit from all directions.

Hence, the hydraulic connection between the TSF and the pit seepage was evaluated by analyzing the water level on the west slope of the pit, comparing the effect of depressurization between the models. Since it is expected that for a certain point and same date models with higher HU2 permeabilities will show a greater drawdown due pit depressurization, a correlation should be observed between these two variables. In this way, water table in models deflected from this correlation, would indicate the influence of the mound coming from the TSF (fig. 3c).

Thus, the analysis (fig. 3d) shows that there is a 13% probability that TSF infiltration is already producing recharge in the pit, influencing seepage zones and pore pressures. Over the years, the probability of the hydraulic connection between both operational facilities increases to 23% in 2023, 29% in 2026, 43% in 2028 and 53% in 2032. After 2032, the probability remains constant due to the end of the expansion of the mine to the west and the decrease in infiltrations from the tailings.

Increase in seepage was quantified through predictive simulations without infiltrations from the TSF using six models with different ranges of HU2 permeability. The results show that in the most unfavorable scenario the maximum increase in the inflow to the pit could be of 3.8 L/s during the forecast period, although it is very likely that the increase in flow would be low, with a probability of 63% that would be less than 0.5 L/s (fig. 3e).

Likewise, this recharge to the pit would generate greater pressures on the west slope, which in some cases would generate an increase in groundwater levels over time instead of the expected decrease due to depressurization. In the most unfavorable case analysed, this increase could raise groundwater levels up to 25 m compared to the current condition by the year 2032 and generate levels 75 m higher than the cases without hydraulic connection during the year 2028. Additionally, the analysis shows that there is a probability of 42% of having pore pressure increases between 400 and 600 KPa on the west slope during the year 2032 and 34% that it would increase between 600 and 800 KPa by 2040 (fig. 3f).

Discussion and Conclusions

Uncertainty analysis results indicate there is a probability of 53% that TSF infiltrations will result in seepage to the pit in the coming years due to a hydraulic connection between the TSF and the pit. However, there is a probability of 63% that the increase in seepage will be low, and less than 0.5 L/s compared to the models without recharge from the TSF. Even though there is a probability of 11% that the increase could be greater than 2.5 l/s, all analyzed simulations show that the seepage will decrease over time to values under those currently conceptualized and observed.

Recharges to the pit would also increase pore pressures in the west slope of the pit, with a probability of 45% that they would increase more than 400 KPa from 2032 onwards. The implication of these increases is uncertain and should be further studied with adequate pit slope stability analysis.

This analysis has shown that the effects associated with infiltration from the TSF correlate and depend on the permeability of HU2, which reinforces the need to keep the hydrogeological characterization of this unit. It has also allowed estimation of the possible impacts that infiltrations from the TSF would have on the pit and their probabilities of occurrence. This provides useful information to support decision-making in terms of risks assessments for the operation, and the generation of prevention plans.

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References

Azrag E, Ugorets V, Atkinson L (1998) Use of a finite element code to model complex mine water problems. Proceedings of Symp on Mine Water Environ Impacts, International Mine Water Association, Johannesburg.

Barnet B, Townley LR, Post V, Evans RE, Hunt RJ, Peeters L, Richardson S, Werner AD, Knapton A, Boronkay A (2012) Australian Groundwater Modelling Guidelines – June 2012. National Water Commission Australia, Waterlines Report Series No. 82, ISBN:978-1-921853-91-3.

Beale G, Read J (2013) Guidelines for evaluating water in pit slope stability. CSIRO Publishing, Collingwood.

Devy S, Hutahayan P (2021) Groundwater Effect on Slope Stability in Open Pit Mining: A Case of West Kutai Regency, East Kalimantan, Indonesia. Jour. of Geosc., Eng., Env., and Tech., 6(4): 192-205.

Evan, G, Henriquez, F, Ugorets V (2015) Pit Slope Optimization Based on Hydrogeologic Inputs. IMCET – Int'l Mining Congress and Exhibition of Turkey.

Itasca Denver Inc (2020) MINEDW – 3D Groundwater Flow Code for mining applications in 3D. Denver.

Middlemis H, Walker G, Peeters L, Richardson S, Hayes P, Moore C (2019) Groundwater Modelling Uncertainty – Implications for decision-making. Summary report of the national groundwater modelling uncertainty workshop, 10 July 2017. Flinders Univ, National Centre for Groundwater Research and Training, Australia.

Morton K, Van Niekerk F (1993) A phased approach to mine dewatering. Mine Water Environ. 12: 27-33.

Nilsson B, Højberg A, Refsgaard J, Troldborg L (2006) Uncertainty in geological and hydrogeological data. Hydrology and Earth System Sciences Discussions, European Geosciences Union 3(4):2675-2706.

Read J, Stacey P (2009) Guidelines for Open Pit Slope Design. CSIRO Publishing, Collingwood.

Refsgaard J, Van der Sluijs J, Brown J, Van der Keur P (2006) A framework for dealing with uncertainty due to model structure error, Adv. Water Resour., 29:1586–1597, doi: 10.1016/j.advwatres.2005.11.013

Servicio de Evaluación Ambiental (SEA) (2012) Guide for the use of groundwater models in the SEIA [in spanish]. Santiago, Chile.