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MULTIVARIABLE MODELING TO PREDICT MUD ENTRANCE IN BLOCK CAVING OPERATION

TESIS PARA OPTAR AL GRADO DE MAGÍSTER EN MINERÍA

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Resumen

Un problema de la minería de hundimiento en la actualidad, es la ocurrencia de bombeos o estallidos de agua-barro. Dicho fenómeno se define como el ingreso violento de una mezcla de material fino y agua hacia labores productivas. Para enfrentar este problema, se han aplicado medidas como: programas de drenaje, estrategias de planificación y operación conservadoras, y la no extracción de mineral saturado. Considerando lo descrito, el presente trabajo describe el modelamiento multivariable para predecir el ingreso de agua-barro a puntos de extracción en minería de hundimiento.

En la primera parte de este trabajo, se realizó la identificación de variables relevantes que incidieron en el ingreso de agua-barro al sector Diablo Regimiento, así como una cuantificación de reservas remanentes no extraídas por cierre temprano de puntos de extracción. Las variables identificadas como relevantes fueron: vecindad con agua-barro, uniformidad del tiraje, distancia a topografía, porcentaje de finos, altura extraída acumulada, humedad, distancia horizontal a puntos con barro en sector superior antiguo, ubicación bajo puntos con barro en sectores antiguos, presencia de agua-barro en punto de la misma batea, y pertenencia al área de inicio.

En la segunda parte de este trabajo, se realizó la creación de modelos predictivos del ingreso de agua-barro a los puntos de extracción del mismo sector. Lo anterior se realizó en base a observaciones en los puntos: humedad y finos, además de variables del entorno. Para la creación de los modelos se usó Regresión Logística como técnica predictiva para eventos dicotómicos. Se elaboraron 12 modelos, 3 de los cuales presentaron una alta calidad predictiva. Dichos modelos fueron evaluados mediante indicadores de calidad de predicción. El mejor de los modelos resultó con una Sensibilidad de 89%, Especificidad de 71% y Área bajo la curva ROC de 0,88. Dicho modelo consideró las variables: humedad, vecindad con agua-barro, uniformidad del tiraje, altura extraída acumulada, y distancia a puntos con barro en sector superior.

En la tercera parte de este trabajo, se realizó la aplicación de la técnica elaborada para predicción, a un caso de diseño minero de un sector en etapa de Ingeniería Básica. Respecto de este caso de aplicación, se demostró que la técnica de predicción desarrollada, resulta útil en la resolución de problemas de ingeniería, tanto de planificación como de diseño minero.

En base a los trabajos realizados, se concluye que el uso de Regresión Logística es confiable para predecir el ingreso de barro. Además, los modelos predictivos permiten identificar qué variables son las más incidentes en el ingreso de este material. De esta forma, esta técnica es útil en la resolución de problemas de ingeniería, tanto de planificación como de diseño minero.

En base a lo anterior, se identifican las siguientes potencialidades en la técnica desarrollada: (1) Análisis de riesgo: permite crear mapas de riesgo de ingreso de agua-barro a un sector; esto es útil en proyectos mineros en etapas de ingeniería, pues permite tomar decisiones sobre su diseño. (2) Planificación minera: al poder predecir dónde ocurrirá el ingreso de agua-barro, se pueden analizar diferentes planes mineros; así se puede determinar el volumen de reservas explotables de cada plan. También permite definir zonas de extracción controlada para minimizar la pérdida de reservas. (3) Operación: la técnica permite tomar decisiones sobre qué puntos privilegiar la extracción y sobre cuáles realizar extracción controlada.

Abstract

A problem in caving mining today is the occurrence of mud rushes. This phenomenon is defined as the violent entry of a mixture of fine material and water into the galleries of a mine. To face this problem, measures have been applied such as: drainage programs, conservative planning and operation strategies, and the non-extraction of saturated mineral. Considering what has been described, the present work describes the multivariate modeling to predict the entry of mud water to drawpoints in caving mining.

In the first part of this work, the identification of relevant variables that influenced the mud entrance to the Diablo Regimiento sector was carried out, as well as a quantification of remaining reserves not extracted due to early closure of drawpoints. The variables identified as relevant were: mud proximity, drawing uniformity, distance to topography, percentage of fines, accumulated drawn height, moisture content, horizontal distance to drawpoints with mud in the upper old sector, under drawpoints with mud in the upper old sector, presence of mud at drawpoint of the same drawbell, and belonging to the cave initiation area.

In the second part of this work, the creation of predictive models of mud entrance to the drawpoints of the Diablo Regimiento sector was carried out. This was done based on observations at drawpoints: moisture and fines, as well as environmental variables. For the creation of the models, Logistic Regression was used as a predictive technique for dichotomous events. Twelve models were developed, 3 of which had a high predictive quality. These models were evaluated using predictive quality indicators. The best of the models resulted with a Sensitivity of 89%, Specificity of 71% and Area under the ROC curve of 0.88. Said model considered the variables: moisture content, mud proximity, drawing uniformity, accumulated drawn height, and horizontal distance to drawpoints with mud in the upper old sector.

In the third part of this work, the application of the technique developed for prediction was carried out, to a case of mining design of a sector in the Basic Engineering stage. Regarding this application case, it was shown that the developed prediction technique is useful in solving engineering problems, both in planning and in mining design.

Based on the work carried out, it is concluded that the use of Logistic Regression is reliable to predict the entry of mud. In addition, predictive models allow identifying which variables are the most incidents in the entry of this material. In this way, this technique is useful in solving engineering problems, both planning and mining design.

Based on the above, the following potentialities are identified in the developed technique: (1) Risk analysis: it allows creating risk maps of mud water entering a sector; this is useful in mining projects in the engineering stages, as it allows decisions to be made about their design. (2) Mining planning: by being able to predict where the entry of mud will occur, different mining plans can be analyzed; thus, the volume of exploitable reserves of each plan can be determined. It also allows the definition of controlled extraction zones to minimize the loss of reserves. (3) Operation: the technique allows making decisions about which drawpoints to favor extraction and which drawpoints to carry out controlled extraction.

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Introduction on work thesis

Caving mining currently represents a low-cost and massive exploitation option. However, its productive and economic attractiveness is affected by some challenges that operations must overcome. Such is the case of the mudflows, defined as violent inflows of a mixture of fine material and water into productive work. This phenomenon has caused damage to equipment and infrastructure, and even loss of life.

To address this problem, various measures have been taken: drainage programs, planning strategies and conservative operation, and redefinition of reserves that do not consider the extraction of columns of saturated ore. Mainly this last measure involves leaving significant amounts of ore unexploited.

The objective of the present investigation was to develop a technique that would allow predicting the mud entrance to the drawpoints, which would include operational variables. To achieve the above, the following general methodology was followed:

1. Identify relevant variables that allow characterizing the mud entrance in underground mining. In particular, we proceeded with the Diablo Regiment sector of the El Teniente Mine.

2. Choose a technique that allows predicting dichotomous events, to later create predictive models with acceptable quality, which consider operational and location variables.

3. Apply the developed technique to a real mining engineering and design problem.

The application of the 3 previous steps is described below in the following articles:

> Paper 1: Statistical analyses of mud at Diablo Regimiento sector at El Teniente´s Mine, presented in Caving 2014.
>
> Paper 2: Predictive models to estimate mud entry in Cave Mining - Diablo Regimiento Sector, El Teniente Mine.
>
> Paper 3: Predictive models of wet muck entry for caving mining: application for the determination of dry reserves in the Andesita Project.

Paper 1: Statistical analyses of wet muck at Diablo Regimiento sector at El Teniente´s Mine

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Abstract

Mudrushes have plagued block and panel caving operators with many fatalities and can have posed a major hazard to safety in block and panel caving mining. Closing drawpoints with a high mudrush potential can be introduced as an effective way of preventing mudrush hazards. Since draw point closure is due to mudrush potential, not dilution, different amount of remnant saturated ore (RSO) would be remaining in the block column. Tonnage and grade of RSO in this group were calculated based on the actual situation of closed drawpoints. The second group contains drawpoints located in a zone with a high potential mud entrance. In this group, the RSO that could potentially be removed once mud enters in drawpoints was predicted based on the historical extraction data. The results indicated that RSO is itself an interesting quantity in terms of tonnage and average grade. Respecting to occurrence of mud, the initial inflow of mud was associated to drawn heights and draw uniformity that are similar to in situ height of the initial entrance area. It is proposed that the subsequent entry of mud resulted not only in relation to the connection with higher mined levels, but other mechanisms, such as the entry of water directly from surface.

1 Introduction

A flow of mud in block/panel caving, called “mudflow”, “mudpush” o “mudrush”, is defined as a sudden and violent inflow of a mixture of water and fines to mine openings, with a high injury, death and damage potential. A mudflow can damage equipment, cause operating losses and even, can cause fatalities (Butcher et al. 2005).

The existence of mud at broken columns can cause two effects: mudflows, either violent mudflows or less violent spills of mud; and the redefinition of reserves due to the cutting of the drawable heights. The last with the purpose of not including mud drawing in mine planning due to safety actions and technical capability (Barahona 2014, pers. comm., 03 February). This meant that there is ore that cannot be extracted which has been termed remnant saturated ore (RSO). There is a need to quantify the economic potential of RSO in drawpoints which have been closed to prevent the hazards of mud-water. Nowadays, three statuses have been defined to face the mudrush hazard in El Teniente's sectors:

1. Mud-water status, or critical zone, has the most probability of mudrush occurrence and, thus have been closed forever to prevent the entrance of mud. A wet muck classification matrix has been developed, to define the mudrush risk considering fine material and moisture percentage (Becerra 2011).
2. Limited status, which is happened in the drawpoints surrounding the mud-water status. These drawpoints have the hazard of lateral immigration of mud from the critical zone. Therefore, the extraction rate from these drawpoints is limited. The result of extracting the limited status drawpoints is mud immigration to operative drawpoints.
3. Barrier status, in which some drawpoints's ore columns are used as a barrier to control the entry of mud. The content of moisture and fine material in these drawpoints are not necessarily critical but they are estimated as high risk points based on the flow direction of mud. Due to a null extraction in this statue, the lateral advance of mud is paused or delayed (Vargas 2013, pers. comm., 30 September).

In order to minimize the problem of dealing with mudrush in production areas, a number of researchers have suggested to draw uniformly (Widijanto et al. 2012; Laubscher 2000). This strategy would allow the extraction of mud in many drawpoints, as a result, would prevent mud concentration in just a few drawpoints. An extensive dewatering program can also reduce water which leads to the wet muck runs (Barber et al. 2000). Drainage strategy can be implemented in both surface water, which enters the cave through rain falling onto the subsidence, or underground water. (Samosir et al. 2008; Barber et al. 2000).

In this article the economic potential of RSO in the closed drawpoints as well as those that could be closed in the future due to the ingress of water-mud was calculated. Furthermore, the historical databases of resources, reserves and extraction conditions at a mine of El Teniente known as Diablo Regimiento was used to define the relationship between the appearance of mud and the drawn strategy based on the back analysis statistical method. It should be noted that this database includes all resource and production history of Diablo Regimiento from the initial date of extraction to November 2013.

2 Economic potential of RSO

The economic potential of the RSO at Diablo Regimiento was calculated based on the column model and production data history of each drawpoint. Through this database it is possible to identify grade, tonnage and density of each bench in every draw column. Due to mudrush hazards, some draw points have been closed before reaching the economic drawable heights; therefore, two groups of drawpoints are introduced to determine the accurate RSO as:

- Drawpoints affected by mud-water: This group includes drawpoints with mud rush hazards which are categorized in three statuses (Mud/Water, Limited and Barrier). To evaluate RSO, both economical and marginal drawable heights are considered, under which the minimum and maximum RSO defined respectively. Table 1 shows the results in each drawable height. As it is indicated in table 1, in the case of marginal drawable height, two different cutoff grade was taken into consider.
- Drawpoints not affected by mud-water: This group includes drawpoints located in the zone under upper mined levels which are already drawn (from East to West, they are Regimiento, Puente and Fortuna). The drawpoints are considered with a high mud entrance potential. It should be noted that the drawpoints considered in the previous section were excluded.

Table 1 shows the results of RSO calculation based on marginal drawable height for two various cut off grades. As illustrated in table 1 the minimum RSO is 11.8 Mt ore material with the average grade of 0.63%.

3 General analysis of mud occurrence at Diablo Regimiento

According to critical matrix used in El Teniente copper mine (Becerra 2011), if the percentage of fine material and moisture content in a drawpoint reaches the critical value the status of drawpoint will changes to Mud/Water status. In this situation the drawpoint will be closed to prevent the hazard of mudrush. In this paper the historical database of closed drawpoints is considered as a situation that mud occurrence.

3.1 Closure grades

Closure grade is defined as the final extracted grade of a drawpoint which is closed due to the mudrush hazards. In figure 1 the closure grade of different drawpoints at Diablo Regimiento is illustrated. It can be concluded from this figure that most drawpoints are closed with high copper grades.

Table 1: RSO at Diablo Regimiento

Drawpoints considered	Considerations	RSO (Mt)	Average grade (%CuT)	Total of RSO (Mt)	Average grade (%CuT)
Affected by mud-water	Initial reserves at Diablo Regimiento	4.4	0.72%	4.4	0.72%
Affected by mud-water	Considering marginal heights; cutoff grade equal to 0.4%CuT	14.9	0.62%	26.6	0.57%
Not affected by mud-water		11.7	0.51%		
Affected by mud-water	Considering marginal heights; cutoff grade equal to 0.5%CuT	11.4	0.67%	18.8	0.63%
Not affected by mud-water		7.4	0.57%		

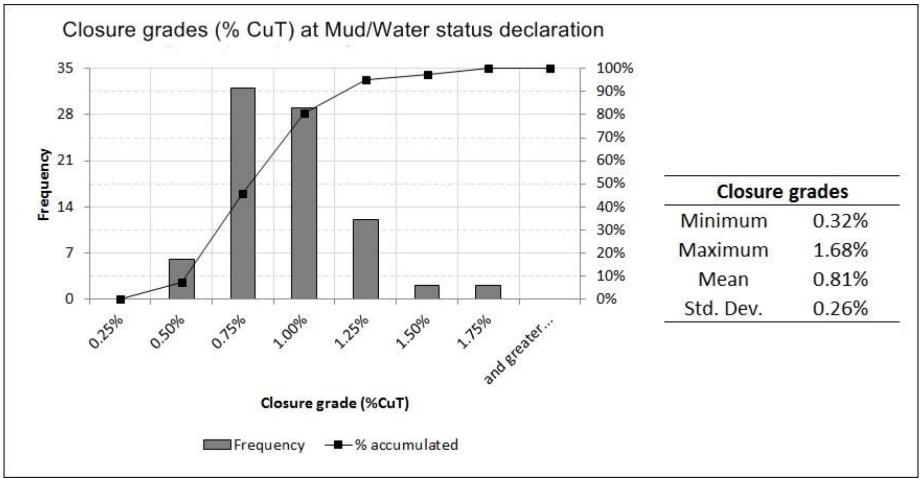


Figure 1: The frequency of closure grades at Diablo Regimiento

3.2 Drawn heights

The drawn heights were calculated using daily drawn databases as well as resources model per bench and drawpoint. The historical database of Diablo Regimiento is used to analyses closed drawpoints in the case of closure sequence and drawn heights.

3.3 Closure Sequence

A plan view of closed drawpoints at Diablo Regimiento is illustrated in figure 2. It is observed in figure 2(a) that the initial mud entry drawpoint is at the center of the Diablo Regimiento sector, and it coincides with the drawpoints where extraction began in order to generate the dome. Subsequently, the mud was always appearing in neighboring points, and then appeared in the east sector. Based on the drawn height in figure 2(b) it is possible to compare the extraction height at different part of Diablo Regimiento sector.

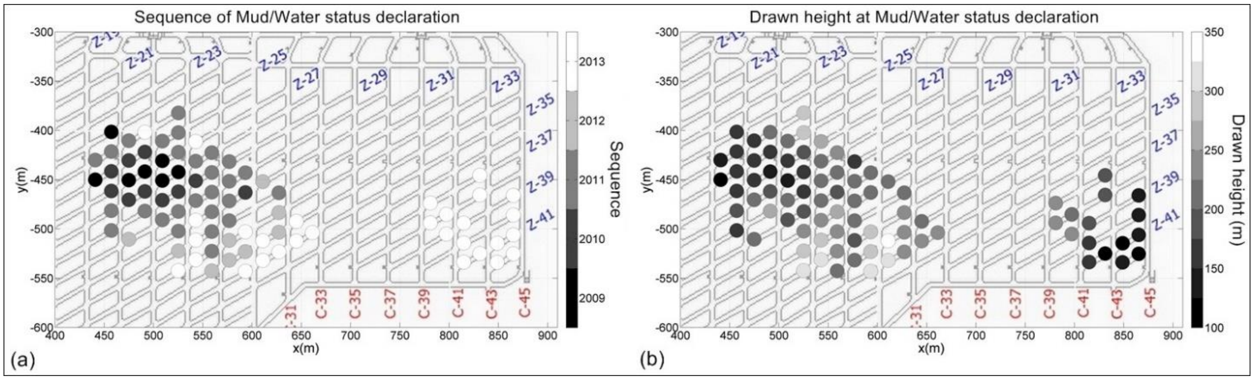
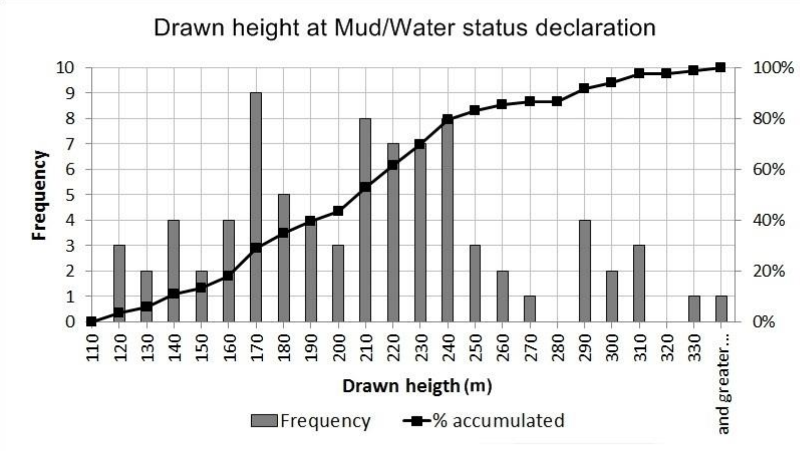


Figure 2: (a) Closure sequence and (b) drawn height of closed drawpoints

3.4 Drawn heights at closed drawpoints

Figure 3 shows the frequency of drawn heights in closed drawpoints at Diablo Regimiento sector. The high variability is illustrated for different drawpoints. Based on figure 3 and 2(b), it appears that the lower elevations correspond to the drawpoints that begin connecting with mined and caved upper levels; that is the center of the sector and the east side. Subsequently, the neighboring points to the aforementioned are associated to a greater drawn height before the apparition of mud.



Drawn height (m)	
Minimum	111
Maximum	330
Mean	207
Std. Dev.	52.4

Figure 3: Drawn height frequency of closed drawpoints

It is observed that 30% of the drawpoints in Mud/Water status, were at a lower or equal to 170 m height drawn, corresponding to the approximate distance between Diablo Regimiento and mined upper levels. In addition, at that height is where the highest frequency of closure drawpoints occurred. Occurrence of mud in these drawpoints may be through to the accumulation of water and mud in the overlying Regimiento sector (Diablo Regimiento is below Regimiento). However, the entry of mud at a greater drawn height may be attributable to the draw maintaining an irregular drawing profile combined with the accumulation of mud-water on the surface. Mud entrance below 170 m may be due to vertical or lateral migration of mud already within broken columns.

Analyzing the drawn height of closed drawpoints (figure 4) observed that as mining production progresses, the range of possible heights closed drawpoints is increased. It can be concluded from figure 4 that the first mud entrance is due to connection with upper sectors; but in other drawpoints that were extracted latter in the sequence, it may have been other reasons for mud entrance (water from other sources).

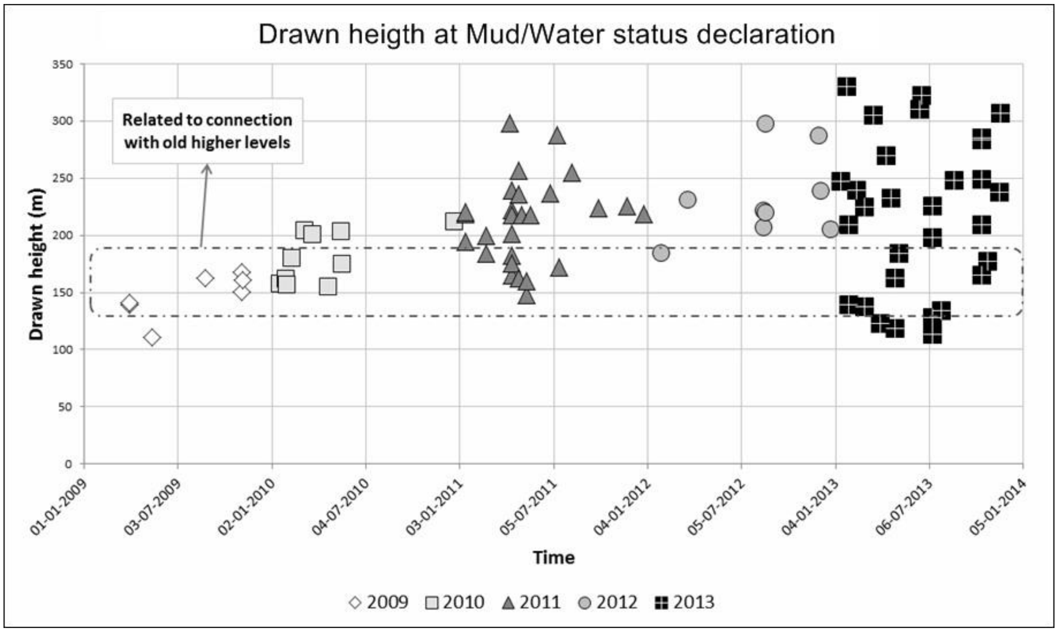


Figure 4: Evolution of accumulated drawn height at Mud/Water status declaration

According to the analysis of the data the following could be concluded:

- Block caving commencement in virgin areas has a great influence on the potential of mud entrance to the sector. For example, the dome shape of cave back in the center of a mine sector causes an early interaction to the surface or to mined levels located above. This creates channels through which fine material and water would entrance to production level.

- In general an effective way of avoiding mud ingress is through uniform draw so as to bring the ore/mud interface as horizontal as possible.
- It is important to detect the sources of water and mud and to define a strategy for dewatering and for a draw strategy to face high potential areas for mud ingress.

4 Determining the probability of mud entrance

As it is illustrated, the RSO could have an important role on the reserves evaluation; therefore the mid and long term production planning would be changed based on RSO. Since RSO is the result of mud occurrence in draw columns, it is essential to determine in advance the entrance of mud in drawpoints. As a result, a model is proposed to predict the probability of mud occurrence employing a logistic regression. This model can be used as a mine planning tool. The main data which are considered in this model are temporal evolution of draw rate, fine material content, drawn height and season of the year. The last is due to a correlation that could exist between water seasons and drawpoints closed due to mud. Some aspects related to mudflows are described below.

A logistic regression model is proposed in this study to predict the Mud/Water status   based on historical data gather at Diablo Regimiento sector. Logistic regression is a technique for making predictions when the dependent variable is a dichotomy, and the independent variables are continuous and/or discrete. In order to predict the risk of mudrush hazard, a logistic regression used with dependant variable (p) as the probability of persistence of mud. For each drawpoint the obtained value of p shows if there is mud in the column (p=1) or not (p=0).

Formally, logistic regression model is defined as equation (1).

$$\ln\left(\frac{p}{1-p}\right)=\beta_0+\beta_1\cdot X_1+\ldots+\beta_n\cdot X_n \qquad (1)$$

Solving for p, this gives equation (2).

$$p=\frac{1}{1+e^{-(\beta_0+\beta_1\cdot X_1+\ldots+\beta_n\cdot X_n)}} \qquad (2)$$

Where β_i *(i=0 ,…, n)* are the estimators and X_i *(i=1 ,…, n)* the independent variables including:

- X1: Draw rate
- X2: Fine material content
- X3: Drawn height
- X4: Season

The variable season added to this model because in the probability of mud occurrence in spring is more than other seasons of the year.

The estimators obtained for equation (1) are shown on equation (3).

$$\ln\left(\frac{p}{1-p}\right)=14-15\cdot X_1-0.142\cdot X_2+0.014\cdot X_3+0.174\cdot X_4 \qquad (3)$$

Based on logistic regression model, the persistence of mud in various drawpoints in Diablo Regimiento sector evaluated. Figure 5 shows the results. It is illustrated in figure 5 that this method enables to predict mud occurrence in different part of the sectors. Moreover, the precision of model is 74%.

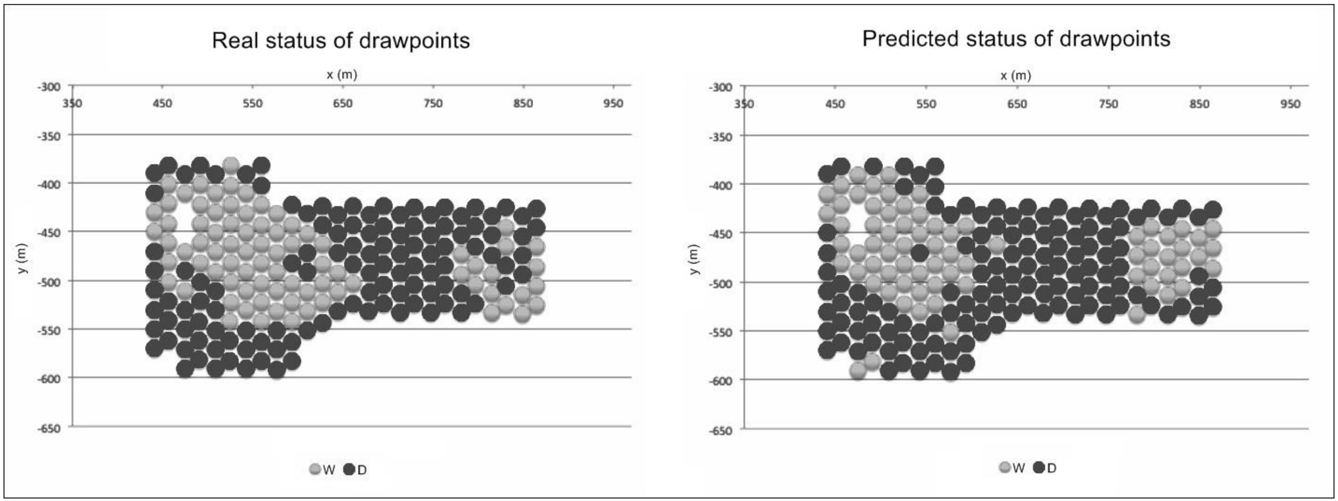


Figure 5: Status of drawpoints on Diablo Regimiento sector; (a) real status of drawpoints and (b) predicted status of drawpoints (W: wet drawpoints; D: dry drawpoints)

5 Conclusions

In this paper, statistical analyses of database at Diablo Regimiento sector was used to study the effect of different parameters on mud occurrence in drawpoints. Based on this study, it is concluded that the accumulated drawn height could be the most influence parameter in controlling mud entrance.

According to data analysis in this research, it is concluded that in the case of irregular profile of drawn heights, uniformity and continuously strategy cannot solve the mudrush problem. In this situation, first objective of short term production should be obtaining a uniform drawn height profile. After reaching this objective, uniformity and continuously strategy seems to reduce the above mentioned problems.

Moreover, in this study the economic potential of RSO is evaluated. Even though closing drawpoints is the best way to ensure safety in production level, the results of economic evaluation shows that RSO are potential to provide at least one half year production of this sector.

Finally, it is illustrated that logical regression method can be used to predict the mudrush hazards in different part of sector. Further research needs to be conducted in order to evaluate the mud potential ingress for mine planning purposes.

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7 Bibliography

Barber, J, Thomas, L, Casten, T 2000, ‘Freeport Indonesia’s Deep Ore Zone Mine’, in Proceeding of Massmin 2000, Brisbane, Queensland, 29-October-2-November 2000, ed. G.C., The Australasian Institute of Mining and Metallurgy, pp 289-294.

Becerra, C 2011 Controlling Drawpoints Prone to Pumping - El Teniente Mine, in International Seminar on Geology for the Mining Industry, 8-10 June 2011, eds. J. B., R. K. & K. O., Antofagasta.

Butcher, R, Joughin, W & Stacey, T 2000, Methods of Combating Mudrushes in Diamond and Base Metal Mines, SRK Consulting, The Safety in Mines Research Advisory Committee (SIMRAC), Braamfontein.

Butcher, R, Stacey, TR & Joughin, WC 2005, ‘Mudrushes and methods of combating them’, The Journal of The South African Institute of Mining and Metallurgy, SAIMM, Volume 105, pp 817-824.

Laubscher, D 2000, A Practical Manual on Block Caving, ICS.

Samosir, E, Basuni, J, Widijanto, E & Syaifullah, T 2008, ‘The Management of Wet Muck at PT Freeport Indonesia’s Deep Ore Zone Mine’, in Proceeding of Massmin 2008, Luleå, Sweden, 9-11 June 2008, eds. H. S. & E. N., Luleå University of Technology, Luleå, pp. 323-332.

Widijanto, E, Sunyoto, WS, Wilson, AD, Yudanto, W & Soebari, L, ‘Lessons Learned in Wet Muck Management in Ertsberg East Skarn System of PT Freeport Indonesia’.

Paper 2: Predictive models to estimate mud entry in Cave Mining - Diablo Regimiento Sector, El Teniente Mine

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Abstract

Cave mining is now proceeding rapidly into deep and uncertain environment, where mine planning, design and operation would involve a number of major risks and hazards. Mud inflow is a phenomenon that can plagued caving operation with many obstacles such as fatalities, damage, dilution, production delay or mine closure. Even though the source of mud and mud flow mechanisms are generally understood, there is still much confusion in prediction the mud entrance into operating area; due to the complex nature of cave dynamics and water distribution. This research introduces a statistical multivariate approach, logistic regression, as an effective tool to estimate mud entrance into draw-points. Accordingly, an extensive statistical analysis of the past mud entrance database were applied to develop a multivariate model to predict mud susceptibility area in an operation sector of El Teniente copper mine, Codelco, Chile. The model shows that moisture of muck pile is the most effective parameter in wet muck declaration. Additionally, percentage of fines, extraction height, draw-point location, draw strategy and topography were considered in the estimation model. The developed model will provide a guide in long and short term mine planning to prevent the high-level risk of mud flow in caving operations.

1 Introduction

Increasing the depth of mining operations becomes fundamental due to the incremental demand of metals and the depletion of the shallower high-grade orebodies. Besides, technological developments make deep mining operations feasible. Block/ panel caving are classified as large-scale production methods applicable to deep low-grade massive deposits. The recent challenge of the mining companies which applying caving methods is to ensure continued sustainability of high productive deep mining in future. Therefore, it is essential to represent innovative approaches to address operational restrictions. When mining goes deeper, evaluating the rock mass behavior and conditions for caving become more complicated. The limited and poor-quality data, unexpected changes in conditions as well as natural variability are the source of all risks in cave mining.

Mud rush or mud inflow has been recognized as one of the main risks to safety and to productivity in cave mining (Brown 2007). Despite the low probability of mud inflow into operational area, it presents high impact risks in mining (McCarthy et al., 1998). As an example, a statistical analysis of water and mud inflow of England, Scotland, India and the USA reports that until 1995, a total of 33 inundations in these mines result an average of 31 and the maximum of 375 fatalities (Vutukuri et al., 1995). Underground caving operations are naturally affected by mud and debris inflow. Since these methods are connected to surface or previous mining area with a broken subsidence zone; where is potential to accumulate water. Jakubec et al (2012) investigated the cause of mud inflow base on the study of this phenomenon in a number of mines in Zambia, South Africa, Indonesia, China and Canada. Although mud rushes can have different origins, almost always four elements are required for a mud rush to occur: water, fine material, a disturbance of mud, and discharge point (Butcher et al. 2000). Therefore, any study of mud entrance to working area has to consider all operational and natural issues and their combination which generate each of these elements.

Hitherto mud rush studies in caving operation are mostly considered the source of mud, mud rush mechanisms, statistical analyses of mud entry, warning signs of mud inflow and risk assessment of mud flow (Butcher et Al. 2005; Brown 2007; Ross et al. 2012; Jakubec et al. 2012; Holder et al. 2013; Valencia et al. 2014 and, Navia et al. 2014). Butcher et al. (2000) suggested a mud rush prevent approach based on three aspects: Keeping fine material far enough from the mining operations; prohibiting water ingress into muck pile and, proper definition of draw strategy to inhibit the discharge of hang ups, air blasts and mud pockets. As a result, draw control discipline, comprehensive monitoring as well as standard operating procedures will minimize the risk of mud entrance into working area.

Many efforts have been executed to mitigate the risks associated with mud entry into drawpoints. The Wet Muck Classification Matrix can be assigned as one of the most common approaches to control the hazards of mud flow occurrence. This matrix is generated based on the mine conditions to present the required percentage of fine material and moisture to produce the mud flow. Table 1 shows the wet muck classification matrix at El Teniente copper mine, Chile. This matrix is used to investigate the draw-points with the most probability of mud rush occurrence. The mine policy is to close the mud-water status or critical draw-point to prevent the entrance of mud and increase safety (Becerra 2011).

Table 2: Wet Muck Classification Matrix at El Teniente copper mine.

Moisture content	Material size (G) ≤ 25 cm		
	G < 30% (Coarse material)	30% ≤ G < 70%	G ≥ 70% (Fine material)
< 4%	🟩	🟩	🟩
4% - 7%	🟨	🟨	🟨
7% - 10%	🟨	🟨	🟥
≥ 10%	🟥	🟥	🟥

🟩 Normal condition
🟨 Mud observation
🟥 Critical risk

PT Freeport, Indonesia applies remote technology to safety handle wet muck (Hubert et al, 2000). Samosir et al (2004) believed that wet draw-points must be extracted in order to removing water from the caved muck and to minimizing wet area distribution into other draw-points. Further achievement to minimize the problem of dealing with mud rush in production areas is drawing uniformly (Laubscher 2000; Widijanto et al. 2012). This strategy would avoid mud accumulation in a few draw-points. A comprehensive dewatering program can also reduce water amount which leads to the wet muck runs (Barber et al. 2000).

Mud flow prediction is complicated due to the complex nature of cave dynamics and water distribution. In this study Diablo Regimiento sector of El Teniente mine was considered as a case study. Based on the statistical database of this sector, each draw-point was given a code typically "1" and "0" to express the "presence" or "absence" of mud, respectively. Applying logistic regression (LR), it is possible to describe the relationship between a dichotomous variable (i.e. the presence and absence of mud in this study) and a set of explanatory variables (x_1, x_2, …, x_n). In this study, Logistic Regression was used to develop a multivariable model to predict high level risk draw-points in caving operations. Implementation of this method requires the extensive statistical evaluation of all effective parameters in mud presence in working area, which has been accomplished in this paper. The results of this study enable project manager to make the final determination of level of risk that would be occurred during mining operation.

2 Case Study

The objective of this study is to analyze and predict the mud entrance risk at one of the world's largest copper-molybdenum underground mines, El Teniente which is owned by Codelco, Chile. This mine is located at the 70 km south-

Southeast of Santiago in the Andes mountains, Chile. The mine uses block and panel caving methods to extract ore with the daily production rate of about 140,000 tonnes and the mean grade of 0.86% copper. Mining is carried out at different levels around a non-mineralised formation called the Braden Pipe that houses mining infrastructure of each level. The current mine level contains six mining blocks around the Braden Pipe at different elevations including the Esmeralda, Reservas Norte, Diablo Regimiento and Pipa Norte mining blocks (Figure 1). More than 2400 km of underground drift together with 1500 km of underground roads have been developed in the mine. The mine is accessed by a 3.5 km tunnel and the ore is transferred to the surface through a railroad system (CODELCO 2013).

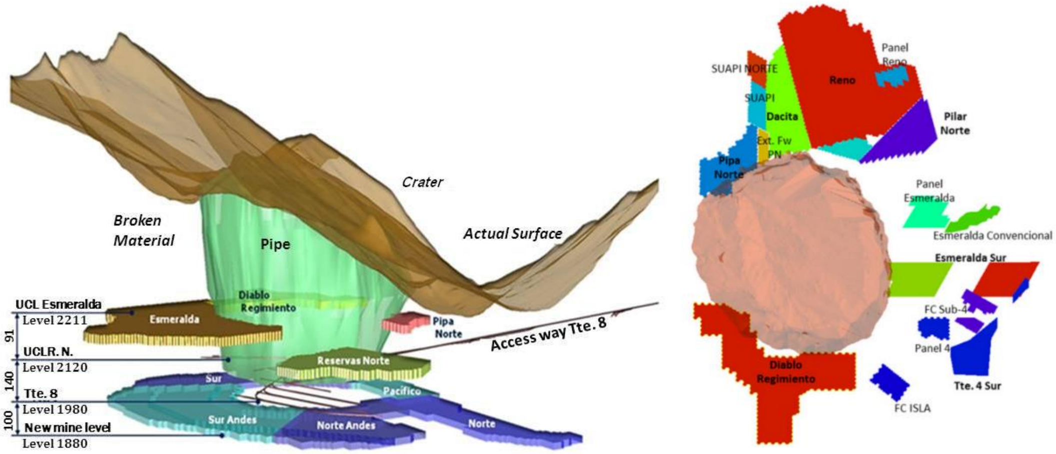


Figure 6: 3D and plan views of the location of different sectors at El Teniente mine (CODELCO 2009).

Located in Ands mountain range, the main source of water inflow into the mine is surface water, especially winter snow melting during spring (Ferrada, 2011). However, underground water and the water which is used for hydraulic fracturing are the other sources of water appearance in the operating area. The study of historical database of water and mud inrush into El Teniente mine shows that totally six mud rushed occurred in different sectors of mine from 1989 to 2010. Due to the extreme impact of mud rush on operation, safety and cost performance, the mining policy is to prevent this phenomenon by closing the draw points with mud persistence since mud entrance is the warning of mud rush.

Among the 14 operating sectors in 2011, five sectors have been deal with the problem of mud entrance which Diablo Regimiento (DR) is one of them. DR sector is placed in the south part of the deposit and under three previous mined sectors which one of those (Regimiento) had been closed due to the existence of mud. This sector is divided into five planning phases, three of them are under extraction with a production rate of 28,800 tonnes per day. Mud entrance study of this sector showed that the initial entry of mud into DR was due to the connection of this sector to the upper mined sectors. Once mud flows into the caved column, it immigrated laterally into other parts of DR due to draw control and mine planning strategies.

In this research, a statistical multivariable approach, logistic regression, was applied to predict mud entrance probability at DR based on the historical data of moisture, size distribution, and production characteristics of 227 draw-points. In total 68 draw-points have been closed in DR owing to the high level of mud rush risk considering wet muck classification matrix (Table 1). A mud entrance hardly happened as the result of a single cause or fault. The results of study the mud source in this sector shows that no single mechanism causes the mud entrance, it can be generated externally, internally or a combination of both.

3 Methodology used to build the predictive model

The methodology used for the construction of the predictive models consisted of:

1. Analyze factors that affect the entry of water-mud.
2. Choose a technique that allows predicting events that take binary values.
3. Build databases that describe, through variables, the life of the drawpoints throughout their operation.
4. Determine the variables that have the greatest incidence on the entry of water-mud.
5. Build models to predict the entry of water-mud based on the relevant variables.
6. Evaluate the quality of predictive models

3.1 Retro-analysis of relevant variables

The first step consisted of performing a retro-analysis of the Diablo Regiment sector, with the aim of determining all those factors that have an impact on the problem of the entry of water-mud. For the above, bibliographic analysis and statistical analyzes carried out in previous works were considered. (Navia et al. 2014, Navia 2014, Garcés 2018).

3.2 Choice of Logistic Regression as a predictive technique

3.2.1 Generalities

Logistic regression (LR) is a multivariable tool that has both predictive and explanatory purposes. In the predictive field, it allows predicting a dichotomous result from a set of independent variables that can be continuous, discrete, dichotomous, or a mixture of all of them.

The main reasons for its use are:

- It allows predicting the probability of an event based on a set of one or more predictor variables.
- It allows determining the relative importance of the predictor variables over the dependent variable to be predicted.
- It allows determining an opportunity ratio (odds ratio, OR) that measures the importance of a predictor variable in the response of the variable to be predicted.

The main reasons why this technique was chosen for the development of this study were:

- It is a robust technique, since it does not require that the predictive variables have any particular distribution.
- Its results are easy to interpret.
- For a dependent variable Y that takes "n" possible dichotomous values (0 or 1), the Logistic Regression equation that explains the probability that Y = 1 using "k 1" explanatory variables, is as follows:

$$P\left(Y=1 \mid \hat{\beta}\right) = \hat{\pi}_0 = \frac{1}{1+e^{-x_0 \cdot \hat{\beta}}}$$

Equation 1: Multivariable logistic regression equation.

- x_0': Vector of "k x 1" elements, where the first element is "1" and the rest correspond to the "k 1" explanatory variables.
- β ˆ = (β ˆ_0, β ˆ_1 ')': Vector of "k x 1" elements where β0 is a scalar constant and β1 is a vector with elements corresponding to the explanatory variables.

Multivariate logistic regression (MLR) is an extension of binary logistic regression, so more than one independent variable is considered.

If we consider a set of p independent variables, given by the vector x ^ '= (x1,……, xp), then the conditional probability of a dichotomous event occurring is denoted as P (Y = 1│x) = π (x). In this way, the logit function will be determined by Equation 2.

$$f(x) = ln\left(\frac{\pi(x)}{1-\pi(x)}\right) = \beta_0 + \beta_1 x_1 + \ldots + \beta_p x_p$$

Equation 2: Logit function.

Thus, the probability of occurrence of the event will be determined by Equation 3.

$$P(Y = 1|x) = \pi(x) = \frac{e^{f(x)}}{1 + e^{f(x)}}$$

Equation 3: probability of occurrence of a dichotomous event.

3.2.2 Parameter estimation

Having n independent observations y_i, i = 1, ..., n, in addition to the value of the p independent variables given by the vector x ', adjusting the model requires obtaining estimates of the vector formed by the unknown coefficients that accompany each independent variable: β ^ '= (β_0, β_1, ..., β_p). Such estimates are made using the Maximum Likelihood Method (MLM).

In general terms, the MLM considers the observed data set to obtain the best linear combination of the unknown parameters that would allow obtaining these data. For this purpose, a likelihood function to be maximized is constructed. Such a function is shown in Equation 4 and represents the probability of obtaining the observed data set from the unknown parameters that will be estimated.

$$\boldsymbol{l(\beta) = \prod_{i=1}^{n} \pi(x_i)^{y_i} \cdot [1 - \pi(x_i)]^{1-y_i}}$$

Equation 4: Maximum Likelihood function to be maximized.

Applying natural logarithm, the previous equation can be transformed into Equation 5:

$$L(\beta) = \ln\big(l(\beta)\big) = \sum_{i=1}^{n} [y_i \cdot \ln(\,\pi(x_i)\,) + (1 - \boldsymbol{y_i}) \cdot \ln(\,1 - \pi(x_i)\,)]$$

Equation 5: Modified Maximum Likelihood function to be maximized.

The vector of parameters β is obtained by maximizing the previous expression.

3.2.3 Model quality

To measure the quality of the models, 3 tools were considered:

1. ROC Curves (Receiver Operating Characteristic): the predictive capacity of a model can be measured by constructing the ROC curve, which shows the performance of a predictive model considering the true positive rate and the false positive rate.

2. Area under the ROC curve. The ROC curves for the 3 best models were constructed, and the area under each of them was determined. The larger the area, the better the predictive quality of the represented model.

3. Confusion matrix, precision, sensitivity and specificity. The confusion matrix was constructed for the 3 best models, calculating the precision, sensitivity and specificity of each one.

Table 3: Confusion matrix.

		Estimated Value	
		Negatives	**Positives**
Real Value	**Negatives**	VN	FP
	Positives	FN	VP

- $Precision = \frac{VP+VN}{VP+FP+FN+VN}$

- $Sensitivity = \frac{VP}{VP+FN}$

- $Specificity = \frac{VN}{VN+FP}$

3.3 Construction of database for logistic regression

3.3.1 Generalities in the construction of databases

According to the principle of "the present and the past are keys to the future", databases were constructed that described the endurance of the drawpoints throughout their operation, indicating different values for all the relevant variables to the study of the entrance of water-mud. These databases incorporate physical properties of the mineral, as well as operational and geometric conditions of each drawpoint in different production periods. To perform the predictive model, a database was built that covers the period from 2009 to 2013, denominated "Construction and Calibration", while, to validate the predictive model, the same type of database was generated, but for the period from 2014 to 2015, called "Validation".

When building the databases, they had a huge number of condition records, but a small number of mud-water events: for the Construction and Calibration database, the total number of records was 20.250, of which only 68 corresponded to water-mud events.

These databases have their own bias in the number of extraction records and the number of grain size and moisture records. These 3 variables are not obtained in a systematic way, but depend clearly on the conditions of the operation. In order to remedy this effect, databases were built with a balance of 1 event for every 5 non-events. This was done through a stratified random sampling: strata were defined considering the variable "accumulated extracted height" for each point, which, in other words, represents the "age" of each point.

The objective of carrying out stratified random sampling was to generate databases that were representative and with an appropriate balance.

For the Construction and Calibration database, 34 classes of accumulated extracted heights were defined, each every 10 m, up to a maximum of 340 m. For each class, we considered incorporating 12 records. In a first instance, the events were classified within each class, according to the accumulated extracted height in which they occurred. Subsequently, the missing records for each class were completed. These missing records were selected randomly and without repetition within the records of the complete database, which previously was also classified into classes. In this way, only 340 records of non-events had to be randomly selected, since the remaining 68 corresponded to the mud-water events incorporated, first.

For the validation database, the process was analogous to the one mentioned above.

3.3.2 Causal factors for mud-water ingress

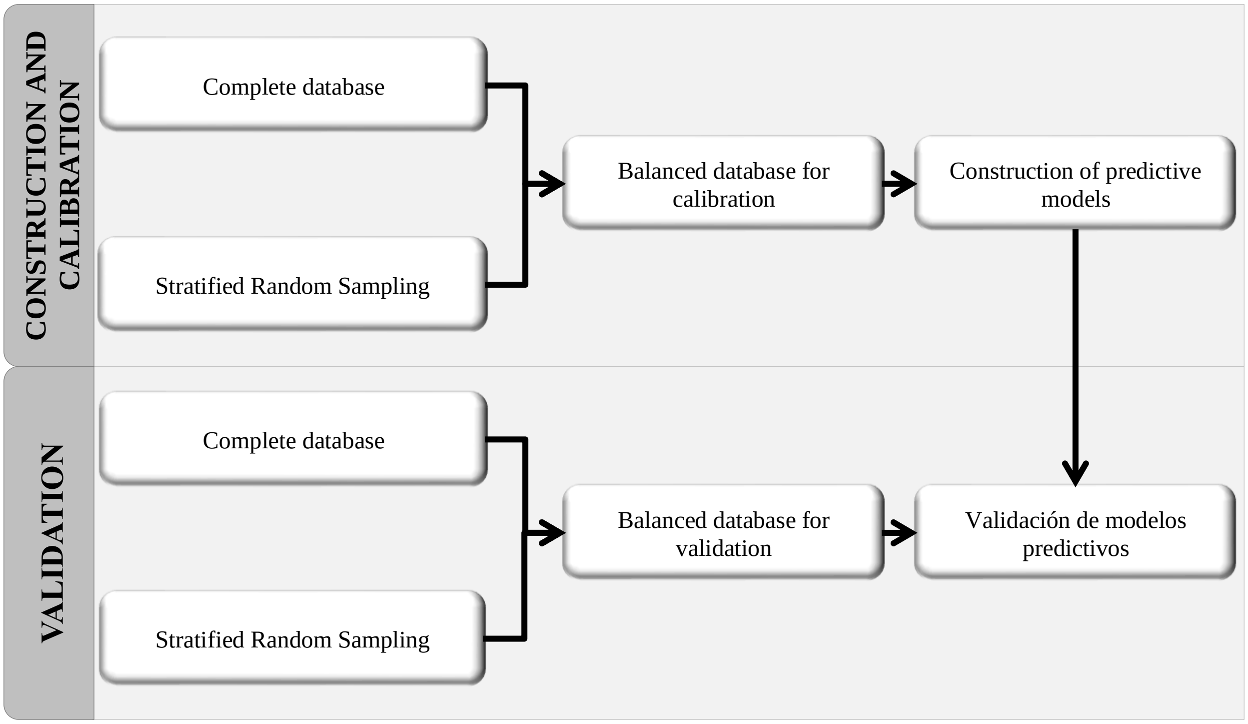


Figure 7: Procedure for the construction of predictive models, from the generation of databases to the validation of the models.

The predictive variables used in this study are: fine percentages and moisture of the extracted ore, location of the drawpoints taking into account the "mud water" state of the adjacent drawpoints, topography and operating parameters such as the extraction rate, the uniformity of the drawing and the sinking initiation strategy. The analysis of the historical data of the Diablo Regiment showed that these variables are the most determining parameters to describe the entry of water-mud to the drawpoints. Some of the predictive variables are stable and do not change during the production period, while other parameters change over time. For example, the location of the drawpoint is fixed, but the percentage of fine material or water content during the extraction of a single drawpoint varies over time. The first variables are considered in short-term production planning. In addition, some variables such as fine percentage and moisture are classified into different classes, while others are not classified as the extraction rate or the distance from the topography. Table 2 explains the variables considered in the logistic model to predict the probability of mud-water entry at each drawpoint. These variables are fully described by Navia 2014.

According to Butcher (2005), the percentage of fine material and the existence of water at the drawpoint are the crucial factors for producing mud-water. These two variables are considered binary variables in the predictive model.

Considering the water-mud classification matrix (Table 1), the fine material variable (Fit) was set to 1 when the percentage of material less than 25 cm at the drawpoint is greater than 70%. Likewise, for an drawpoint of more than 7% water content, the moisture variable (wit) was considered as 1 (Table 2).

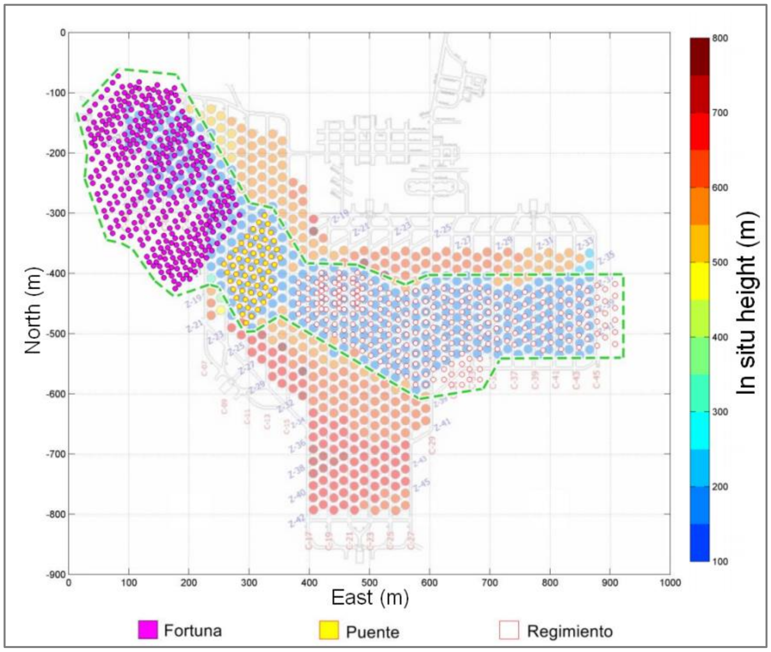


Figure 8: Diablo Regimiento sector and in situ height.

A statistical study of moisture, size distribution and production characteristics of 227 draw-points at Diablo Regimiento (DR) sector was accomplished in this research. DR sector is in the south part of the deposit. This sector is divided into five planning phases, three of which are under extraction with the production rate of 28,800 tonnes per day. DR is placed under three previous mined sectors which one of those (Regimiento) had been closed due to the existence of mud. Mud entrance study of this sector showed that the initial entry of mud into DR was due to the connection of this sector to the upper mined sectors. Once mud flows into the caved column, it immigrated laterally into other parts of DR based on draw control and mine planning strategies. In total 65 draw-points have been closed in DR owing to the high level of mud rush risk considering wet muck classification matrix. A mud entrance hardly happened as the result of a single cause or fault. Hence, all the contributing factors and their combinations should be considered.

In the case of block caving, a build-up of mud water is likely to occur because the cracked area connects to the surface or to old levels and provides a potential water-mud entry point. Therefore, the location of the drawpoint is important when analyzing internal and external sources of mud. Monitoring the surface crater at Diablo Regimiento shows that the mud flow appears at the drawpoints where it is located below the sinking zone with the smallest distance from the potential surface water accumulation area. In addition to the topography of the surface, the presence of mud in the old upward mining sectors DR can motivate the internal entrance of mud. In this study, the binary variable of Li was defined in the predictive model and was set to 1 for all drawpoints that are under the old mining sector with mud water status. In addition, the minimum horizontal distances of each drawpoint from the drawpoints with mud water status in the upper sector (di) were considered.

Table 4: Explanatory variables considered in the construction of a database to perform Logistic Regression models to predict the entry of water-mud to the drawpoints.

Variable	Meaning	Unit	Stable	Binary	Categorized
F_{it}	Percentage of fine material of DP i at the time t. This parameter was considered 1 if more than 70% of material was less than 25 cm.	**%**	**-**	**X**	**X**
W_{it}	Percentage of water of DP i at the time t. This variable was considered 1 if the moisture percentage was more than 3%.	**%**	**-**	**X**	**X**
h_{it}	Vertical distance of DP i from the topography at the time t.	**m**	**-**	**-**	**-**
L_i	The location of DP i. Considered 1 for the DPs which were located under the previous mined sectors with mud existence.	**-**	**X**	**X**	**-**
d_i	Minimum horizontal distance of DP i from the former DP in the upper sector with mud-water status.	**m**	**X**	**-**	**X**
y_{it}	The presence of mud in the DP that belongs to the same drawbell of DP i at the time t.	**-**	**-**	**X**	**-**
n_{it}	Number of neighborhood DPs of DP i with mud status at the time t.	**-**	**-**	**-**	**-**
C_{it}	Caving initiation strategy. Considered 1 for all DPs beneath the active zone.	**-**	**-**	**X**	**-**
r	The ratio of extraction rate to in situ column	Ton/day.m	-	**-**	**-**
U	Uniformity of draw. Considered 1 for semi-uniform or non-uniform draw and 0 for uniform draw.	**-**	**-**	**X**	**-**

Studying the historical data at DR showed that when mud approaches into a draw point, another draw point of the common drawbell will also face the hazard of mud entrance. Hence, the variable y_{it} was considered 1 for all draw points which mud appeared in another draw point of the same drawbell. Moreover, the draw points which are placed at the neighborhood of the drawpoint with mud-water status would have the hazard of lateral immigration of mud; thus, this parameter was also considered in the model (n_{it}).

Caving initiation strategy in block/panel caving method is to create a continuous propagation of caving by generating the active volume at the center of the sector. The historical data analyses at DR showed that mud appeared in the center of sector when the active volume reached the overlying mining sector (Regimiento). Accordingly, a binary variable (C_{it}) was considered in the model and was set to 1 for draw points which are covered by the active zone.

Analyzing different conditions of the first mud observation in a draw point shows the significant influence of the height of broken column on mud entrance into the working area. According to the statistical analyses of historical data at DR, mud entrance mostly occurred after extracting 90% of the in-situ column. Therefore, controlling the tonnage drawn from individual draw-points could avoid creating the conditions that could lead to mud rushes (Laubscher 2000). In this research, the ratio of extraction rate to in situ column was also considered as a predictive variable in the LR model.

Many studies issued uniform draw to avoid dilution entry to operational sector. Since the migration of saturated fine material into the working area could be considered as dilution, the uniformity index behaviour over the life of a cluster of draw-points was also considered in the predictive model. This parameter was calculated for each draw point based on the equations developed by Susaeta (2004). Figure 2 shows the extraction height profile along North-South sections of the first "mud-water" status draw-point at DR during 2005 to 2013. This draw-point (With the ID number of 23-27-H) has been closed on March 2009; due to the high risk of mud rush. In this Figure it is obvious from the annually extraction heights that a specific draw control discipline were applied a no uniform profile with the objective of providing arch failure to insure progressive caving. However, implementing this type of drawing strategy yields preferential flow of mud, which caused mud inflow from the zones with maximum profile height toward the lowest points in the profile (Figure 2).

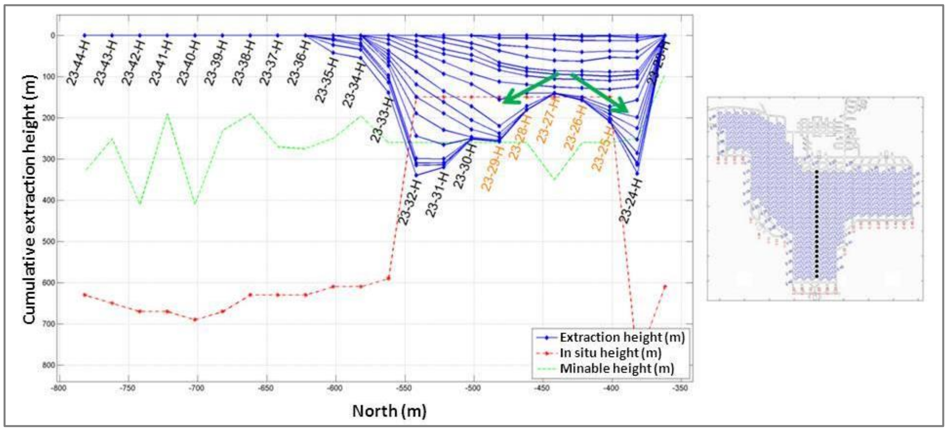


Figure 2: North-South section of extraction height profiles along the first mud "mud-water" status draw-point at DR from 2005 to 2013.

Finally, each chosen variable for the analysis carries a hypothesis regarding the phenomenon of the entry of water-mud. Then, the following table explains each of them, in addition to the underlying hypothesis that supports their choice.

Table 5: Description of each variable considered, and hypothesis for each one of them.

Variables	Description	Hypothesis
Mud Proximity	It indicates how many points in the environment are closed by water-mud	There is a lateral water-mud entry mechanism. If a DP has a muddy neighbor, the DP under study will most likely have income as well.
Drawing uniformity	Indicates if the drawing was uneven / semi-uniform or uniform in the last 5 shifts.	The non-uniform drawing increases the probability of ingress of water-mud, since it deconfines the mineralized column, generating greater permeability and therefore a greater tendency for movement of fines and water.
Distance to topography	Indicates the distance to the topography.	A DP that is located in a low area of topography, presents a greater probability of mud-water ingress than another that is in a higher area. This is because on the surface the water and fine enter through the lower areas.
Percentage of Fines	Indicates what percentage of ore at the point is below 5 cm.	A DP that has fines has a higher probability of water-mud ingress than one that has thicker material.
Accumulated drawn height	Indicates if the drawn height during the life of the point exceeds 90% of its initial in situ height.	A DP whose total drawn height exceeds 90% of its height in situ, presents a greater probability of ingress of water-mud, since the upper break could act as an accumulator of water and fines.
Moisture	Indicates the visual moisture measured at the point.	A DP with higher visual moisture has a greater probability of water-mud entering than one with lower moisture.

Variables	Description	Hypothesis
Horizontal distance to points with mud in the upper old sector	Indicates the horizontal distance to points with mud in the old sector, projecting the old sector over the current one.	A DP that is closer to a muddy PE from an older level has a higher probability of mud-water entering.
Under points with mud in the upper old sector	Indicates if the point is under a point with mud in the old sector.	A DP that is under a DP with mud from an old sector, has a higher probability of entry of water-mud.
Presence of mud at point of the same drawbell	Indicates if the point that shares the same drawbell is closed by water-mud.	A DP that shares a drawbell with another DP with water-mud has a higher probability of water-mud entering.
Belonging to the starting area	Indicates if the point was part of the points with which the sinking began.	A DP that belongs to the caving start area has a higher probability of mud-water ingress. This is because it will be the first area with the highest permeability towards the production level.

3.3.3 Database to determine mud-water entering

A detailed inventory of mud entrance causative variables at DR was constructed by analyzing 227 draw points from 2009 to 2015. The properties of each draw point in each shift were recorded on a standard mud entrance inventory data sheet. This inventory includes 96 records of mud-water status and 42,550 records of safe operating conditions. As mentioned before, the data related to the last 2 years (2014-2015) was used to validate the predictive model.

In this database, the number of safe condition or non-event records is 443 times more than the number of hazardous or event records. In general, statistical analyses of natural hazards needs particular attention, as most of these phenomena are rare events. In this situation, when probabilistic statistical methods, such as LR, are applied, the probability of rare events would be underestimated. This is due to the fact that these methods tend to be biased towards the majority class, which is the less important class (King et al., 2001). Hence, before performing any statistical evaluation it is essential to generate a representative sample from both calibration and validation databases. These samples were produced by selecting an equal number of events and randomly selecting of 5 non-events per each event, for both databases. This type of selection is known as choice-based or endogenous stratified sampling (Van Den Eeckhaut et al. 2006). Table 3 shows the number of records in both databases and in their representative samples.

Table 2: Number of records in databases and their representative sampling.

		Calibration database	**Validation database**
		Aug. 2009 to Nov. 2013	Nov. 2013 to Nov. 2015
Complete database	Events	68	28
	Non-events	20,182	22,368
	Total records	20,250	22,396
Representative sample	Events	68	28
	Non-events	340	140
	Total records	408	168

Among the predictive variables listed in table 2, some of them, such as fine percentage, rely on the operational conditions and specially the extraction height. Since the highest extraction column at DR was 340 meter, 34 classes of accumulative extraction height were defined and all records were classified in these classes. On the other hand, for each 10 meter of extraction height there were approximately 12 records. Then the classes which included mud entrance record were considered. To create the representative samples, for each event five non-event records were randomly selected from the same class.

4 Results and discussion

4.1 Univariate Tests

Univariate tests were carried out to measure the dependence or independence between the variable "water-mud" and each of the 10 dependent variables, considered one by one.

Table 6: Univariate tests results: coeficients, odds ratio and significance.

Variable	**Coeficient (β)**	**Odds ratio (e^{β})**	**Significance (%)**
Accumulated drawn height	2,57	13,09	0,00
Belonging to the starting area	1,33	3,79	0,00
Under points with mud in the upper old sector	0,84	2,33	8,36

Variable	Coeficient (β)	Odds ratio (e^{β})	Significance (%)
Presence of mud at point of the same drawbell	2,73	15,29	0,00
Horizontal distance to points with mud in the upper old sector	-0,04	0,96	4,31
Percentage of Fines	0,03	1,04	0,00
Moisture	1,66	5,25	0,00
Distance to topography	-0,01	0,99	0,31
Mud Proximity	1,44	4,2	0,00
Drawing uniformity	2,42	11,28	0,00

Regarding the univariate tests carried out, it was determined that all the variables have incidence in the entry of water-mud to the Diablo Regiment sector, with the exception of the variable "Under points with mud in the upper old sector". The significance value for said variable exceeds 5%, which does not allow rejecting the null hypothesis that its associated betha value is 0 (it is accepted that its value is 0 and therefore said variable is not explanatory by itself in the income of water-mud).

On the other hand, the variables that alone have a greater incidence on the entry of water-mud are:

1. Presence of mud at point of the same drawbell
2. Non-uniform drawing of the extraction
3. Moisture
4. Mud Proximity

4.2 Logistic regression

The variables already analyzed independently were mixed, generating 12 model proposals, collecting the combined effect of each predictor variable to determine the entry of water-mud.

The variables considered for each model are shown in the following table.

Table 7: Variables considered in the construction of the models.

Variable	Type of variable	Description	Model											
			1	2	3	4	5	6	7	8	9	10	11	12
Mud Proximity	Discrete	Indicates how many points in the surrounding area are closed by mud water	x		x	x	x	x	x	x	x	x	x	
Drawing uniformity	Binary	Indicates if the drawing was non-uniform/ semi-uniform or uniform in the last five shifts.	x	x	x		x	x	x	x	x	x	x	x
Distance to topography	Continuous	Indicates the distance up to the topography	x		x									x
Percentage of Fines	Continuous	Indicates what percentage of ore at the point is under 5 cm		x								x	x	
Accumulated extracted height	Binary	Indicates if the extracted height in the life of the point exceeds 90% of its initial in-situ height.		x	x	x	x	x	x	x	x	x	x	x
Moisture	Discrete	Indicates the visual moisture measured at the point				x	x	x						
Horizontal distance to points with mud in the upper old sector	Continuous	Indicates the horizontal distance to points with mud in the old sector, projecting the active sector on the current one.						x	x					
Under points with mud in the upper old sector	Binary	Indicates if the point is under a point with mud from the older sector									x		x	
Presence of mud at point of the same drawbell	Binary	Indicates if the point that shares the same drawbell is closed by mud water												x
Belonging to the starting area	Binary	Indicates if the point was part of the points with which the sinking began.												x

The following table shows the result of the combined effects analysis of the variables that make up each model. The fourth column "betha exponential" indicates the relevance of each variable with respect to the others that make up each model.

Table 1: Modeling results using multivariate logistic regression.

Model	Variable	Coeficient (β)	Odds ratio (e^β)	Significance (%)
Model 1	Constant	4,44	85,07	20,85
	Distance to topography	-0,01	0,99	2,75
	Drawing uniformity	1,12	3,05	0,98
	Mud neighborhood	1,18	3,25	2,E-09
Model 2	Constant	-5,18	0,01	7,E-16
	Accumulated drawn height	1,90	6,67	4,E-03
	Percentage of fines	0,02	1,02	0,16
	Drawing uniformity	1,90	6,66	2,E-05
Model 3	Constant	-2,64	0,07	52,58
	Accumulated drawn height	1,71	5,51	0,22
	Distance to topography	0,00	1,00	63,94
	Drawing uniformity	0,85	2,34	5,02
	Mud neighborhood	1,13	3,09	1,E-08
Model 4	Constant	-6,19	0,00	5,E-12
	Accumulated drawn height	0,80	2,23	21,61
	Moisture	1,42	4,12	1,E-09
	Mud neighborhood	1,05	2,85	9,E-07
Model 5	Constant	-6,59	0,00	7,E-11
	Accumulated drawn height	0,89	2,44	17,83
	Moisture	1,41	4,11	0,00
	Drawing uniformity	0,71	2,04	18,03
	Mud neighborhood	0,93	2,53	3,E-04
Model 6	Constant	-6,10	0,00	3,E-06
	Accumulated drawn height	0,52	1,68	53,12
	Horizontal distance to points with mud in the upper old sector	-0,02	0,98	47,46
	Moisture	1,42	4,13	3,E-09
	Drawing uniformity	0,77	2,16	15,27
	Mud neighborhood	0,94	2,57	3,E-04
Model 7	Constant	-3,91	0,02	3,E-07
	Accumulated drawn height	1,37	3,92	1,53
	Horizontal distance to points with mud in the upper old sector	-0,04	0,96	16,38
	Drawing uniformity	0,92	2,52	3,44
	Mud neighborhood	1,18	3,24	8,E-09
Model 8	Constant	-4,57	0,01	1,E-14

Model	Variable	Coeficient (β)	Odds ratio (e^{β})	Significance (%)
	Accumulated drawn height	1,81	6,12	0,04
	Drawing uniformity	0,82	2,27	5,52
	Mud neighborhood	1,13	3,10	1,E-08
Model 9	Constant	-5,32	0,00	1,E-09
	Under drawpoints with mud in the upper old sector	1,01	2,74	15,35
	Mud neighborhood	1,18	3,26	0,00
	Drawing uniformity	0,89	2,44	3,88
	Accumulated drawn height	1,49	4,42	0,62
Model 10	Constant	-5,18	0,01	2,E-12
	Accumulated drawn height	1,63	5,12	0,18
	Percentage of fines	0,02	1,02	4,47
	Drawing uniformity	0,74	2,10	8,85
	Mud neighborhood	1,08	2,94	7,E-08
Model 11	Constant	-5,82	0,00	5,E-10
	Accumulated drawn height	1,30	3,68	2,09
	Under drawpoints with mud in the upper old sector	0,94	2,57	18,01
	Percentage of fines	0,02	1,02	5,17
	Drawing uniformity	0,81	2,24	6,57
	Mud neighborhood	1,12	3,07	0,00
Model 12	Constant	6,23	508,21	15,34
	Accumulated drawn height	1,74	5,70	0,11
	Distance to topography	-0,02	0,98	1,17
	Belonging to the starting area	1,58	4,86	0,04
	Presence of mud at drawpoint of the same drawbell	1,38	3,98	0,18
	Drawing uniformity	1,94	6,98	1,E-04

AOC curves were constructed for each of the 12 models in order to determine the predictive quality of each. 3 models with a very similar predictive quality are observed, which are models 4, 5 and 6. A second intermediate group of models is also observed. Finally, a worse model is observed that approaches the diagonal.

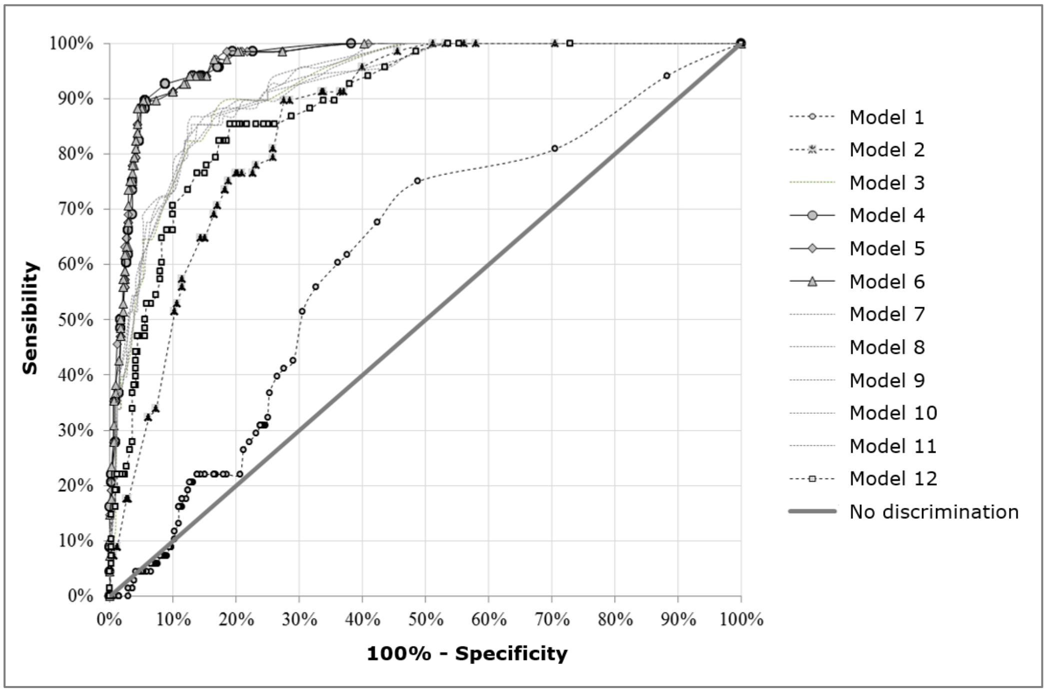


Figure 9: AOC curves for each model considering construction and calibration sample.

The same exercise was carried out on the validation sample, showing that there are 3 models with an appreciable predictive quality, and they turn out to be the same ones previously indicated.

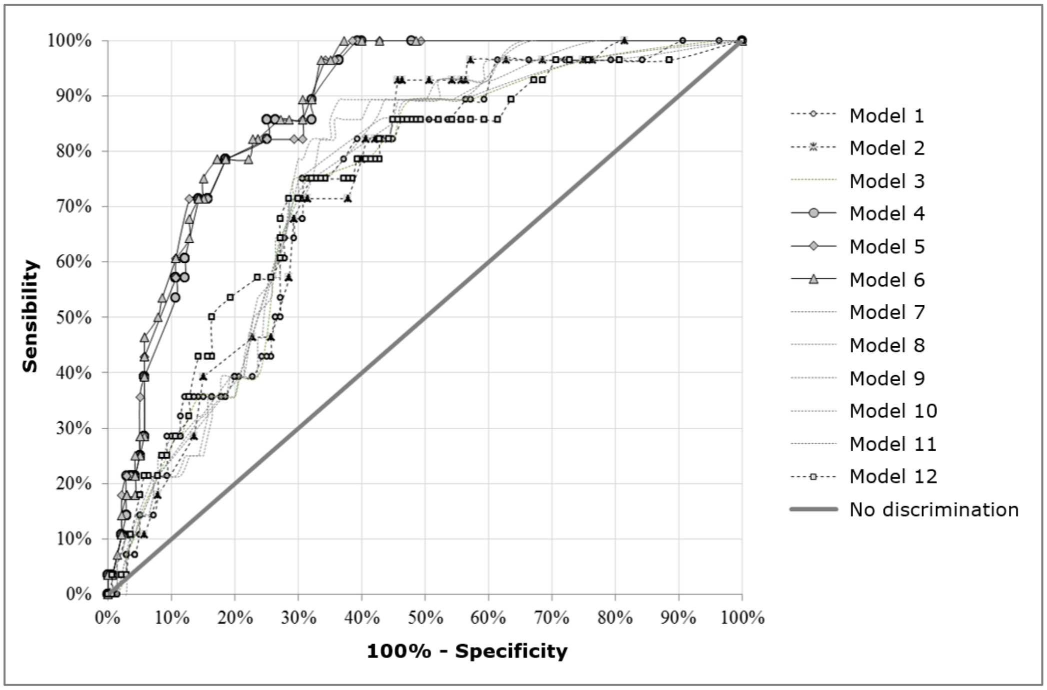


Figure 10: AOC curves for each model considering validation sample.

The area under each ROC curve was calculated, where it is concluded that the best 3 models are: Model 4, Model 5 and Model 6. According to the literature, a model is acceptable if the area under the curve is at least 0,70.

Table 8: Area under ROC curve for each sample: construction and calibration, and validation sample.

Model	Area under ROC curve	
	Construction and calibration sample	Validation sample
Model 1	0,62	0,73
Model 2	0,86	0,74
Model 3	0,92	0,73
Model 4	0,97	0,87
Model 5	0,97	0,88
Model 6	0,97	0,88
Model 7	0,92	0,75
Model 8	0,92	0,74
Model 9	0,92	0,75
Model 10	0,93	0,75
Model 11	0,92	0,76
Model 12	0,89	0,74

Finally, the 3 best models for predicting the entry of water-mud into the Diablo Regimento sector, are represented by the following 3 equations:

Model 6:

$$p(x) = \frac{\exp\left(-6{,}105 + 1{,}419 \cdot x_1 + 0{,}943 \cdot x_2 + 0{,}769 \cdot x_3 + 0{,}521 \cdot x_4 - 0{,}024 \cdot x_5\right)}{1 + \exp\left(-6{,}105 + 1{,}419 \cdot x_1 + 0{,}943 \cdot x_2 + 0{,}769 \cdot x_3 + 0{,}521 \cdot x_4 - 0{,}024 \cdot x_5\right)}$$

Where:

- x1: Drawpoint moisture value, according to the classification used in El Teniente, with discrete values from 1 to 5, where 1 is dry and 5 is humid.
- x2: Number of near areas with water-mud that the drawpoint has, with discrete values from 1 to 6.
- x3: Non-uniform drawing of the extraction, with binary value, where 1 indicates that the run was uneven or semi-uniform in the last 5 turns, and 0 that the draw was uniform.
- x4: Accumulated extracted height, with binary value, where 1 indicates that the drawpoint had 90% of its column removed in situ or more.

- x5: Horizontal distance to points with mud in the upper old sector, with continuous values in meters.

For Model 6, the cutoff probability determined to discriminate whether a DP will present water-mud intake or not, was p = 20%.

On the other hand, the quality indicators that were obtained for this model are presented below.

Table 9: Confusion matrix for model 6.

		Estimated Values	
		Negatives	**Positives**
Real Value	**Negatives**	114	26
	Positives	6	22

Specificity: 81%
Sensitivity: 79%
Model accuracy: 81%

Model 5:

$$p(x) = \frac{\exp\left(-6{,}593 + 1{,}414 \cdot x_1 + 0{,}930 \cdot x_2 + 0{,}713 \cdot x_3 + 0{,}892 \cdot x_4\right)}{1 + \exp\left(-6{,}593 + 1{,}414 \cdot x_1 + 0{,}930 \cdot x_2 + 0{,}713 \cdot x_3 + 0{,}892 \cdot x_4\right)}$$

For Model 5, the cutoff probability determined to discriminate whether a DP will present water-mud intake or not, was p = 19%.

On the other hand, the quality indicators that were obtained for this model are presented below.

Table 10: Confusion matrix for model 5.

		Estimated Values	
		Negatives	**Positives**
Real Value	**Negatives**	114	26
	Positives	6	22

Specificity: 81%
Sensitivity: 79%
Model accuracy: 81%

Model 4:

$$p(x) = \frac{\exp\left(-6{,}189 + 1{,}416 \cdot x_1 + 1{,}049 \cdot x_2 + 0 \cdot x_3 + 0{,}803 \cdot x_4\right)}{1 + \exp\left(-6{,}593 + 1{,}414 \cdot x_1 + 0{,}930 \cdot x_2 + 0{,}713 \cdot x_3 + 0{,}892 \cdot x_4\right)}$$

Finally, for Model 4, the cutoff probability determined to discriminate whether a DP will present water-mud intake or not, was p = 19%.

On the other hand, the quality indicators that were obtained for this model are presented below.

Table 11: Confusion matrix for model 4.

		Estimated Values		
		Negatives	**Positives**	
Real Value	**Negatives**	118	22	Specificity: 84%
	Positives	8	20	Sensitivity: 71%

Model accuracy: 82%

4.3 Implementations

It was analyzed whether the models are reasonable, in terms of the probability that each of them can predict is consistent with the value of each of the variables that are entered. Based on the above, 3 cases were analyzed with the values of the variables shown in the table below:

Table 12: Cases evaluated and variable's values.

Variable	**Value of each variable of the drawpoint**					
	Case 1		**Case 2**		**Case 3**	
Moisture	1	DP dry	3	DP with moderated moisture	5	DP with severe moisture
Mud proximity	0	DP without near mud areas	1	DP with 1 near mud areas	2	DP with 2 near mud areas
Drawing uniformity	0	-	0	Draw of the DP was uniform	1	Draw of the DP was semi-uniform or uneven
Accumulated drawn height	0	Its full height has not been drawed in situ	0	Its full height has not been drawed in situ	1	The DP has already had its entire height removed in situ
Horizontal distance to points with mud in the upper old sector	30	-	20	-	10	The DP is 10 m from a DP with mud in the old sector

The results obtained indicate that the 3 models are sensitive in a manner consistent with the value of the variables entered. The above allows to corroborate the hypotheses sustained in Table 12, for the variables considered here.

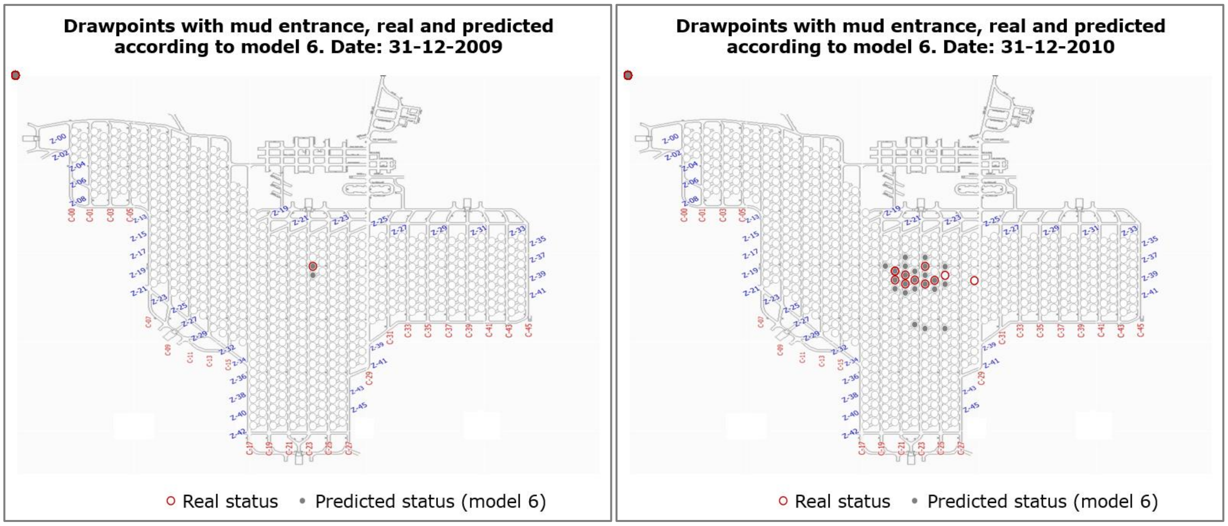
Table 13: Probability of Water-Mud entrance for each case.

Model	**Probability of Water-Mud entrance for each case**		
	Case 1	**Case 2**	**Case 3**
Model 4	0,8%	29,1%	97,80%
Model 5	0,6%	19,5%	98,10%
Model 6	0,4%	19,9%	98,06%

The same procedure was done with each model, varying the variables one by one, maintaining the others constant. Each model was consistent when determining the probability of ingress of water-mud.

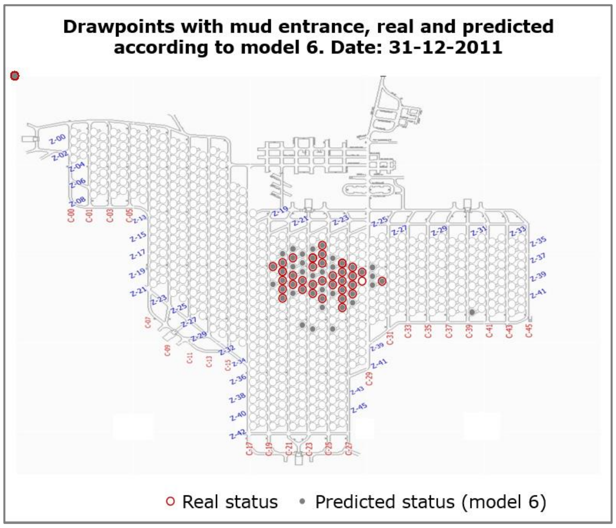
Another procedure carried out was to determine which points can be predicted with water-mud entrance over time, comparing the above with the actual mud input to the draw points. This exercise was carried out with Model 6. The sequence of images below shows the exercise carried out, allowing us to observe that said model allows predicting the entry of water-mud.

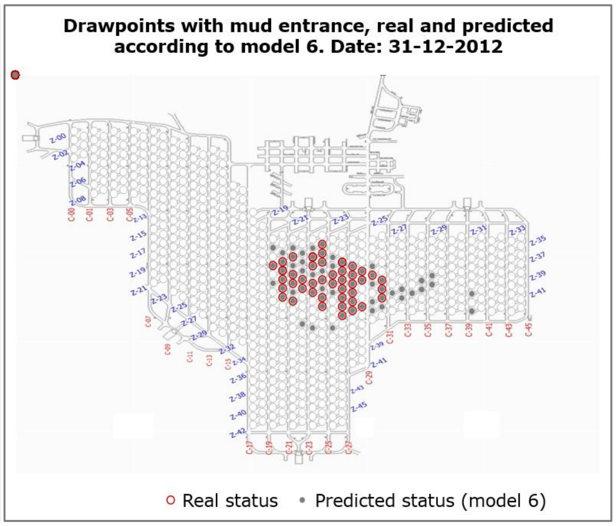
Figure 11: Application of best predictive model (Model 6).

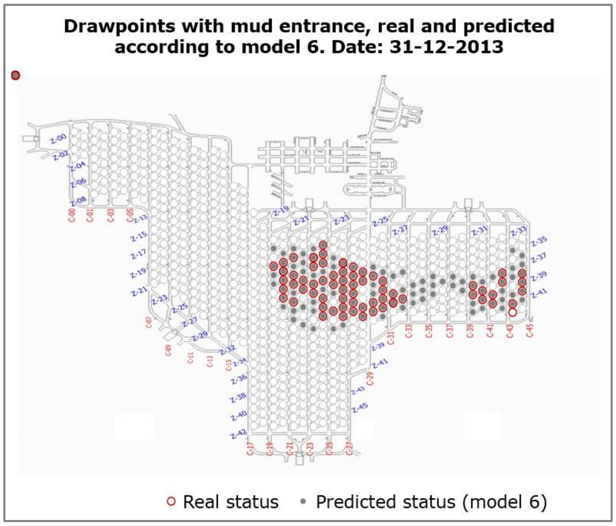


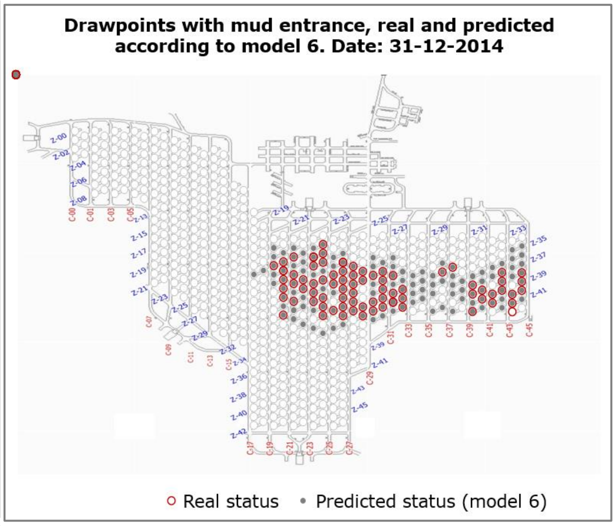
Drawpoints with mud entrance, real and predicted according to model 6. Date: 31-12-2009

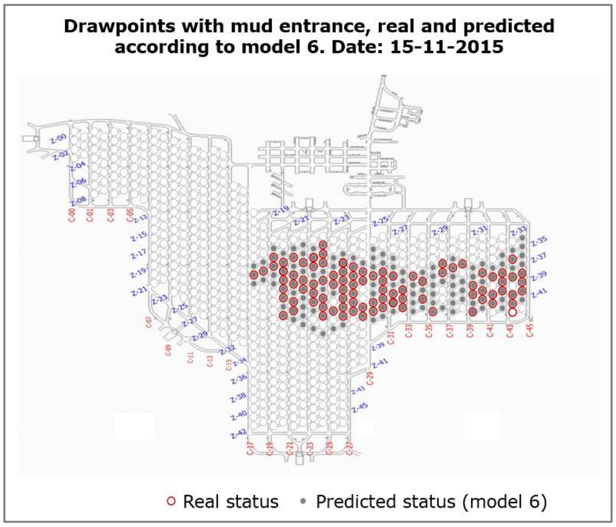
Drawpoints with mud entrance, real and predicted according to model 6. Date: 31-12-2010


Drawpoints with mud entrance, real and predicted according to model 6. Date: 31-12-2011


Drawpoints with mud entrance, real and predicted according to model 6. Date: 31-12-2012


Drawpoints with mud entrance, real and predicted according to model 6. Date: 31-12-2013


Drawpoints with mud entrance, real and predicted according to model 6. Date: 31-12-2014


Drawpoints with mud entrance, real and predicted according to model 6. Date: 15-11-2015

5 Conclusion

Based on the research carried out, it is concluded that the use of the Logistic Regression technique is reliable in predicting the entry of water-mud to drawpoints in block caving. In addition, predictive models allow us to identify which variables are the most incidents in mud-water intake.

The developed technique presents a variety of potential developments:

- Risk analysis: it allows creating risk maps of water-mud entrance to a sector. This is useful both in mining projects in their engineering stages, since it allows making mining design decisions. As there are areas with a higher probability of water-mud entrance, more robust drainage systems are designed, or the use of semi-autonomous or remote-controlled LHD shovels is considered

- Mine planning: by being able to predict where the water-mud entrance will occur, different mining plans can be analyzed, thus being able to determine the volume of reserves to be exploited in a sector. Also, the technique allows to compare different cave initiation points, being able to identify which option is better from the point of view of the recovery of reserves. In terms of medium- and short-term planning, the technique allows defining controlled extraction zones in order to minimize the loss of reserves.

- Operation: in terms of operation, the technique allows decisions to be made on which points to privilege extraction and on which to carry out controlled extraction. The fact of having a probability of water-mud entrance generates an alert and an objective value for decision-making.

6 Bibliography

Barber J., Thomas, L. and, Casten T., 2000; Freeport Indonesia´s Deep Ore Zone mine; in proceeding of MassMin 2000, Brisbane, QIL, Australia, pp. 289-294.

Becerra C. 2011; Controlling drawpoints prone to pumping- El Teniente mine; in International Seminar on Geology for the Mining Industry, Antofagasta, Chile.

Brown E.T., 2007; Block caving geomechanics; 2nd edition, The International Caving Study, 1997-2004; JKMRC: Brisbane; 696 pp.

Butcher R., Joughin W., and Stacey T.R., 2000; A booklet method of combating mudrushes in diamond and base metal mines; The Safety in Mines Research Advisory Committee (SIMIAC); 35 pp.

Butcher R., Stacey T.R., and Joughin W. C., 2005; Mud rushes and methods of combating them; The Journal of the South African Institute of mining and Metallurgy; Vol 105, pp. 817-824.

CODELCO, División El Teniente, 2006; Conexión Diablo Regimiento - Teniente 4, Informe SGM-I-021/2006. Nota interna, Superintendencia de Geomecánica.

CODELCO, 2009. Informe back análisis punto inicio de caving, 10 p. CODELCO, División El Teniente, Rancagua, Chile.

CODELCO, 2013. Informe plan minero plan quinquenal 2013, 369 p. CODELCO, División El Teniente, Rancagua, Chile.

Ferrada, M. 2011, Gravity flow under moisture conditions – Control and management of drawpoint mudflow. In 35th APCOM Symposium, Wollongong, NSW.

Holder A., Rogers A.J., Bartlett P.J., and Keyter G.J., 2013; Review of mud rush mitigation on Kimberley´s old scraper drift block caves; The Journal of the South African Institute of mining and Metallurgy; Vol. 113, pp. 529-537.

Hubert G., Dirdjosuwondo S., Plaisance R. and, Thomas L., 2000; Tele-Operation at Freeport to reduce wet muck hazards; MassMin Proceedings, Brisbane, QID, Australia; pp. 173-179.

Jak~~e~~ubec J., Clayton R. and, Guest A. R., 2012; Mudrush risk evaluation, MassMin Proceedings, Greater Sudbury, Ontario, Canada.

King G. and Zeng L., 2001; Logistic regression in rare events data, Political Analysis 9; pp. 137–163.

Laubscher D. 2000; A practical manual on block caving, International Caving Study.

McCarthy P. L. and Harvey S., 1998; Inrush and Subsidence; Underground Operators’ Conference; Townsville, Australia; pp. 211-216.

Molina, R. E., C. B. Cerrutti, J. O. Henríquez, and R. F., Apablaza, R. A. Morales. 2008 "Preconditioning implementation on rock bulks in Codelco Chile and its results." MassMin,.

Navia I.M., Castro R. and, Valencia M.E., 2014; Statistical analyses of mud entry at Diablo Regimiento sector- El Teniente´s mine; 3rd International Symposium on Block and Sublevel Caving; Santiago, Chile, pp. 372-378.

Navia I.M., 2014; Análisis del ingreso de agua-barro al sector Diablo Regimiento, División El Teniente, Codelco.

Ross I.T. and Van AS A., 2012; Major hazards associated with block caving; MassMin Proceedings, Greater Sudbury, Ontario, Canada.

Samosir E., Brannon C. and, Diering T., 2004; Implementation of cave management system (CMS) tools at the Freeport DOZ mine; MassMin Proceedings; Santiago, Chile, pp. 513-518.

Susaeta A., 2004; Theory of gravity flow (Part 2); MassMin Proceedings; Santiago, Chile; pp. 173-178.

Susaeta A., Rubio E., Henriquez J. and Pais G., 2008; Dilution behavior at Codelco panel cave mines; 5th international Conference and Exhibition on Mass Mining, Lulea Sweden, pp. 167-178.

Valencia M.E., Basaure K., Castro R. and, Vallejos J., 2014; Towards an understanding of mud rush behaviour in block-panel caving mines; 3rd International Symposium on Block and Sublevel Caving; Santiago, Chile, pp. 363-371.

Van Den Eeckhaut, M., Vanwalleghem, T., Poesen, J., Govers, G., Verstraeten, G. and Vandekerckhove, L., 2006; Prediction of landslide susceptibility using rare events logistic regression: a case-study in the Flemish Ardennes (Belgium). Geomorphology, 76(3), pp.392-410.

Vutukuri V. S. and Singh R. N., 1995; Mine inundation- Case histories, in Mine water and Environment, Vol 14, Annual Issue, Paper 9, pp. 107-103.

Widijanto E., Sunyoto W.S., Wilson A.D., Yudanto W. and, Soebari L. 2012; Lessons learned in wet muck management in Ertsberg East Skarn system of PT Freeport Indonesia; MassMin Proceedings, Greater Sudbury, Ontario, Canada.

Paper 3: Predictive models of wet muck entry for caving mining: application for the determination of dry reserves in the Andesita Project

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Abstract

Mudrushes have plagued block and panel caving operators with many fatalities and can have posed a major hazard to safety in block and panel caving mining. Closing drawpoints with a high mudrush potential can be introduced as an effective way of preventing mudrush hazards. However, other preventive measures can be performed in early engineering stages in order to minimize the impacts of the problem during the operation stage. In accordance with the above, the present study applies logistic regression as a predictive technique, to predict the entry of water-mud into the Andesite sector. In this way, the study carried out allows for risk maps of ingress of water-mud to evaluate two starting point options, as well as evaluating the dry reserves that are feasible to recover with each option. Finally, the study allows recommending preventive drainage measures as well as recommending the use of remote control or semi-autonomous LHD.

1 Introduction

Today, block caving mining deals with the challenge of producing at ever greater depths. An inherent problem of block caving is the generation of fine material as a result of the movement of the ore during the extraction process over time. If the addition of water is considered, the fine water combination generates material with the potential to generate wet muck bursts. This problem involves a risk to the safety of the operating personnel.

The appearance of wet muck in a drawing point implies the application of special measures, such as extraction at controlled rates, use of remote controlled equipment, or finally the closure of the point, with the consequent loss of reserves.

Based on the above, when designing a mine, it is relevant to be able to determine the reserves that will be feasible to extract before the wet muck begins to appear at the drawing points.

The objective of this article is to summarize some given uses to the technique developed long ago: prediction of the entry of wet muck in cave mining. For such effects, the work called "Risk analysis of mud water entering the Andesita Project, El Teniente Division, Basic Engineering" is considered in this article.

2 Objective

Estimate the entry of wet muck and the amount of dry reserves in the Andesita sector based on the history of the Division in representative sectors.

At the time of carrying out this study, the Andesita Project was in the Feasibility step, optimizing its mining designs.

The objective of the study carried out was to quantify the risk of wet muck entry in the drawing points of the Andesita sector through the estimation of the maximum extractable heights of dry reserves of the following long-term mining plans:

- Alternative Andesita mining plan: It includes 125 Mt of reserves and an exploitation area of 278,254 m2, its sequence of exploitation begins in the south of the polygon and continues north.
- PND[1] Andesita mining plan: It contemplates 120 Mt of reserves and an exploitation area of 245,558 m2, its sequence of exploitation begins in the center of the industrial estate and continues north and then south.

3 Andesita Project description

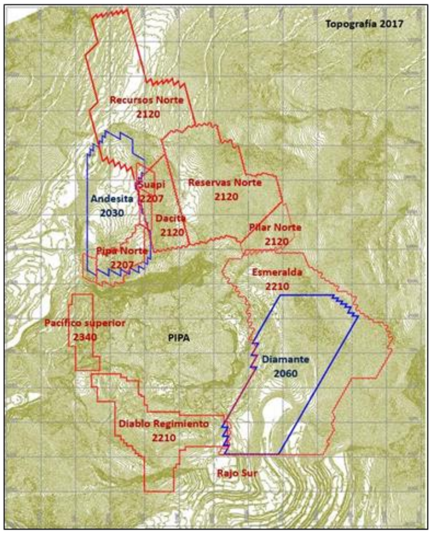

Figure 12: Location of the Andesita project compared to the other sectors in operation of the El Teniente mine.

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[1] PND: *"Plan de Negocio Divisional"*; this refers to El Teniente's annual mining plan.

In general, the predictive models built on the basis of multivariable logistic regression use statistical information to assess the probabilities of the occurrence of a dichotomous phenomenon, that is, the occurrence or non-occurrence of the event. In this way it is possible to estimate the uncertainty generated by the risk of wet muck entry during the decision-making process in the Basic Engineering step of the Andesita project. In this sector, a previously built predictive model was used for the evaluation, to evaluate the Northern Resources sector, which was based on the historical data of North Pipe and Sur Andes Pipe.

Caving mining is susceptible to wet muck entry because they have the capacity to accumulate surface water and generate fine material in the extraction column (Heslop, 2000; Jakubec et al., 2012). In the case of the El Teniente Division, the presence of old upper sectors with wet muck condition must also be included. In this sense, the variables that participate in the entry of wet muck are mainly associated with the connection of the broken column with the surface or sources of water entry (Jakubec et al., 2013), the generation of fine material at along the extracted height (Brown, 2007) that acts as an internal mud flow mechanism (Butcher et al., 2000) and the contribution of internal (underground) and external (surface) waters. Based on a review of the literature, this study incorporates the following variables into the analysis:

- Percentage of extraction of the column in-situ or accumulated extracted height.
- Average flow of income to analyzed productive sectors (hydrogeology of Quebrada Teniente).
- Height to topography.
- Height of primary in-situ material.
- Location of drawing points under the high risk zone of wet muck entry.
- Proximity of points with presence of mud.

Navia (2014) have determined statistical significance that relates the variables mentioned above and the entry of wet muck into drawing points of the Diablo Regimiento, Esmeralda Bloque mines, Reservas Norte, South Andes Pipe and North Pipe of El Teniente Division.

4 Methodology

The methodology of this work depends on the sector to be evaluated. The general regression analysis methodology is shown below when it is necessary to build a predictive model and subsequently carry out the evaluation. For the Andesita sector, as there is a model already built, the methodology is reduced to step 3. On the contrary, for the coupled Northern Resources sector, the full methodology must be applied.

4.1 Step 1 Collection and analysis of historical databases

The objective of this step is to collect and analyze the database of the representative sectors of the sector to be evaluated. The collected databases are the following:

- Historical extraction of the sectors at the drawing point and on a day scale.
- Water flows measured in gauges on a day scale in units of liters / second.
- Historical states of drawing points.
- Geology and topography of the sector (in-situ block model, after extraction of the sectors).
- Hydrogeological model for El Teniente.
- Sector base polygon.
- Long-term mining plan for the sector to be evaluated.

Once the information is collected, a back-analysis is made of the declared mud points, in terms of the mud entry point (in tonnage and height).

4.2 Step 2 Formulation of a wet muck entry model

The objective of this step is to calibrate a predictive model of mud entry in the drawing points using the logistic regression technique. For this, the activities of this step are as follows:

- Analysis of basic statistics: a statistical analysis is performed between the mud entry points and the study variables. The objective is to determine the relationship that exists between variables such as primary mineral height [m] of an drawing point, accumulated extracted height [m], low or not risk zone, height to topography [m], neighboring mud and monthly flows water inlet [l / s] in the mud inlet to drawing points.
- Univariate analysis: the univariate logistic regression is used to determine the weight of each variable by itself in the mud entry to drawing points.
- Multi-variable analysis: the risk model of mud entry is selected through a multi-variable logistic regression analysis. This indicates for a set of extraction, geometric and flow conditions, the probability or risk of mud entry a mining point.

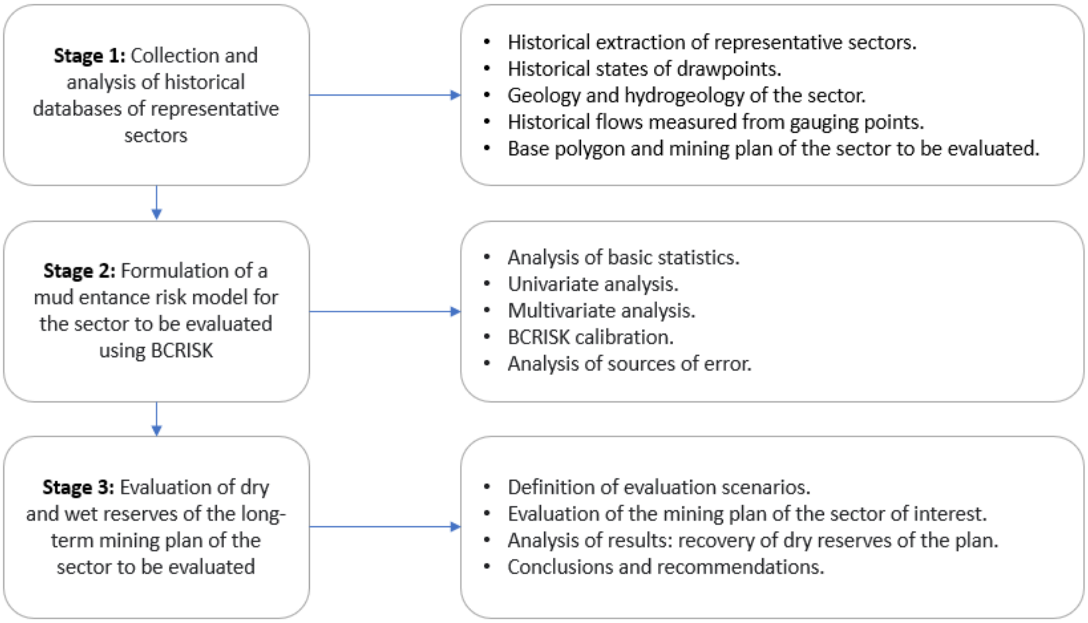
- Model Calibration: In this activity, the model is calibrated with respect to the real data of mud entry at the level of drawing points. The objective is for the model to better predict the PEB or mud entry point in tons per drawing point.
- Analysis sources of estimation error: calibration errors are obtained in the prediction of mud entry at the level of drawing points. Errors are quantified and their source or origin is analyzed.

4.3 Step 3 Evaluation of long-term mining plan reserves

The objective of this step is to evaluate the mining plans of the sector in terms of the reserves recovery of the plan due to the entry of wet muck to drawing points for different scenarios. The activities of this step are the following:

- Evaluation of the mining plan: the Project's mining plan is evaluated for the different defined scenarios. The mining plans to be evaluated depend on the scenarios defined for each sector. These may depend on the amount of water (flow (l / s)), or changes in the extraction sequence and / or tonnage assigned to each point.
- Analysis of results: the analysis of the results obtained is carried out in terms of the recovery [%] of the extracted dry reserves and Cu fines for each plan and scenario due to mud entry.
- Conclusions and recommendations: once the evaluation of the mining plan has been carried out, it is concluded regarding the results of recovery of the dry reserves of the plan [%] and other characteristics for which the analysis is valid. The recommendations of the study focus on future studies to analyze long-term extraction strategies and the implementation of remote control extraction equipment for the given sector with risk of mud entry.

Figure 13 shows an outline of the methodology used in the study.



Stage 1: Collection and analysis of historical databases of representative sectors

- Historical extraction of representative sectors.
- Historical states of drawpoints.
- Geology and hydrogeology of the sector.
- Historical flows measured from gauging points.
- Base polygon and mining plan of the sector to be evaluated.

Stage 2: Formulation of a mud entance risk model for the sector to be evaluated using BCRISK

- Analysis of basic statistics.
- Univariate analysis.
- Multivariate analysis.
- BCRISK calibration.
- Analysis of sources of error.

Stage 3: Evaluation of dry and wet reserves of the long-term mining plan of the sector to be evaluated

- Definition of evaluation scenarios.
- Evaluation of the mining plan of the sector of interest.
- Analysis of results: recovery of dry reserves of the plan.
- Conclusions and recommendations.

Figure 13: Methodology used in the study.

5 Andesita sector analysis

This chapter shows the analysis carried out on the Andesita sector, which is located in the northern part of the El Teniente deposit. This sector, as mentioned above, has the particularity of being located in the lower part of the QT drawbell, so it is highly likely that the flows will be captured by its cavity. However, the development of the North Resources project and its sequence of exploitation is important with respect to this point. The aforementioned sectors are shown in Figure 14, Reservas Norte (NR) and Dacita (DT) are currently in operation and future projects are Recursos Norte (RN) (2020) and Andesita (AD) (2024).

There are two alternatives for the exploitation of North Resources, as an isolated polygon of the North and Dacita Reserves sectors or in a coupled way. The consequences on the Andesita sector are as follows:

- North Resources decoupled: In this case, the cavity of the RN sector intercepts the Quebrada Teniente as soon as its exploitation begins (2020), draining the water flows that come from upper drawbells (Huacha and Huifa). Consequently, the amount of water entering Andesita would be less, reducing the probability of mud water entry under this condition.
- Northern Resources coupled: In this scenario the cavity of the RN sector intercepts the Quebrada Teniente between the years 2027 to 2030,

therefore, the drainage of RN occurs late for the Andesita sector, which begins its exploitation in 2024. Consequently As the flow increases, there is a greater probability of mud water entering the Andesita sector between 2024 to 2027, and then decreases as the RN cavity intercepts the QT.

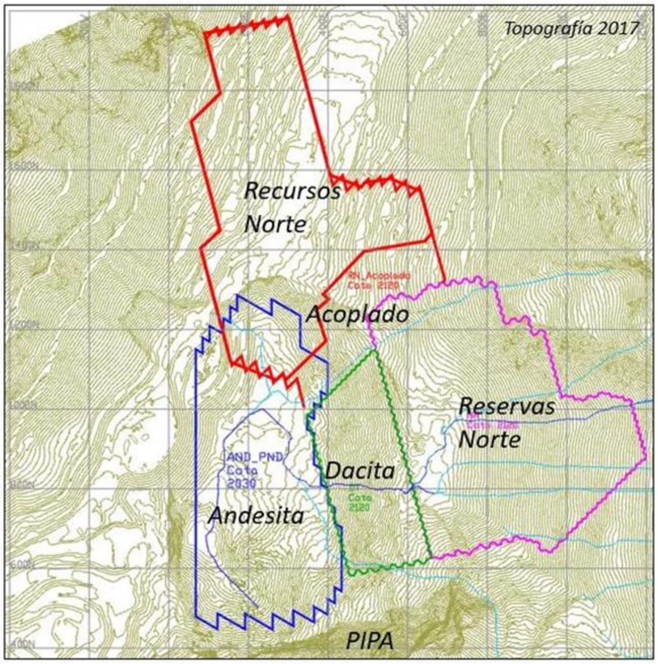


Figure 14: Northern sectors of the El Teniente Mine.

In terms of the evaluation of the income of mud-water from the Andesita project, the closest sectors with mud water income are North Pipe (PN) and Sur Andes Pipe (SP) (see Figure 15), these are in the same drawbell and present edge conditions similar to Andesita, therefore, the best modeling option is to consider them. One of the existing models for Recursos Norte sector was built in 2017; some characteristics of this model are presented below.

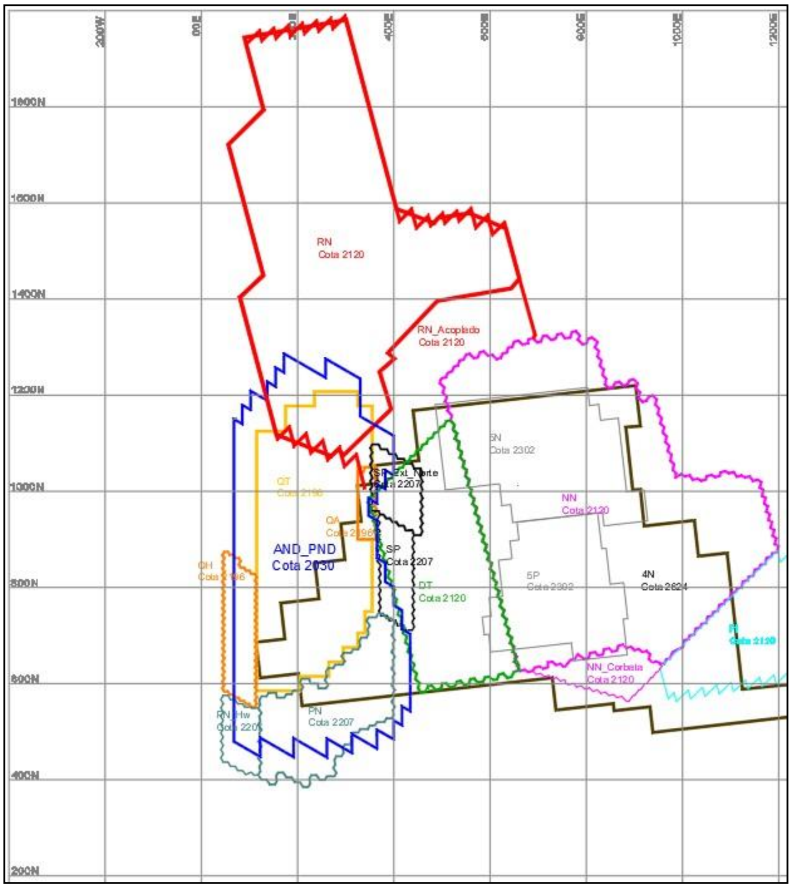


Figure 15: Sectors near to Andesita project.

5.1 Predictive model of mud water input North Pipe and Suapi Sectors

The model was built from the historical information of PN and SP (since 2009) and the variables shown and described in Table 9 were considered. As can be seen, they are practically the same variables that have been considered for the construction of the models historically. In addition, the basic statistics of these variables are shown both for points with a mud state and for those with a non-mud state. The latter is important, because it indicates the conditions under which the model is valid and provides reliable results for the evaluation of a similar sector.

Table 14: Variables predictive model entry of mud-water - PN and SP sectors.

Variable	Description
Average monthly flow rate (l/s)	Determined by a QT water balance (VAI, 2017). The same flow rate is used for all drawing points (so-called equal hydrogeological condition).
% Extraction institutes (%)	Reason between the accumulated tonnage of the point and the tonnage of its column insitu.
Primary height (m)	Height of the primary ore column institutes by drawing point.
Mud Proximity (No.)	Variable that considers the number of near areas (max. 6) that have mud water status when evaluating a point in that neighborhood.
High-risk zone	Established from surface-generated depressions, where preferential water flows are likely to converge. Risk zone defined by DET (Codelco, 2016).

Table 15: Variables statistical summary of the SP-PN model.

Variable	Condition mud dots (94 drawing points)	Condition dots not mud (223 drawing points)
Monthly flow rate average (l/s)	5 / 924 / 105	5 / 924 / 105
% Extraction institutes (%)	3% / 228% / 81%	0% / 279% / 57%
Primary height (m)	20 / 240 / 98	20 / 260 / 114
Mud Proximity (No.)	79% of the mud spots had at least one near area with pre-mud.	62% of non-mud spots do not present a near area with Mud.
High-risk zone	90% of the mud spots in risk zone.	51% of non-mud points out of the risk zone.

The constructed predictive model considers two submodels, according to the mud water entry mechanism, there is a model for vertical mud water entry and a model for lateral entry. Table 11 shows the variables considered in each model and the value of their coefficients.

Table 16: Vertical and lateral model coefficients SP-PN.

Variable	Vertical model Beta (B)	Side model Beta (B)
Extraction ratio	0,573	1,829
Flow rate (l/s)	0,001	0,001
Primary Height (m)	-0,003	-
Risk zone	0,592	1,698
Mud Proximity	-	0,531
Constant	-1,621	-4,056

The models evaluate the probability of each drawing point for each period (given by plan) analyzed, this probability is compared with a cut probability on which it is decided whether the point is declared with mud. In the case of the vertical model, the cut probability considered was 58% and for the lateral model it was 60%. The indicators of the model are shown in Table 12, it is observed that in terms of sensitivity, which is the prediction in quantity of the points declared with mud, the indicator is regular (<70%), on the contrary, the specificity, prediction of points in non-mud state, the indicator is excellent (> 90%), in summary, the global indicator is 83%, which implies a model with very good prediction. The calibration error, according to the simulated tonnage, was 0.9 Mt, which gives an error of 2%, which is excellent considering the other models built in El Teniente.

Table 17: Indicators of model quality.

Indicator	Value
Sensitivity (mud point prediction)	69%
Specificity (Non-Mud Point Prediction)	92%
Accuracy (Mud and Non-Mud Prediction)	83%
Calibration error	0.9 out of 43.3 Mton (2%) regarding to not mud

5.2 Evaluation of long-term mining plans in the Andesita sector

In this chapter, the evaluation of the alternatives of long-term mining plans for the Andesita sector is carried out for two different scenarios regarding the exploitation of the Northern Resources sector. As previously mentioned, the sequence of exploitation of the RN sector affects the total expected flow in the Andesita sector; In the event that the Northern Resources sector develops as a decoupled polygon to Northern Reserves, its cavity will intercept the waters of the QT since 2020, which means that at the start of production in Andesita

(2024) the flow contribution of Water from the upper drawbells will be low. On the contrary, if the Northern Resources sector is developed coupled to Northern Reserves, the intersection is expected to occur between the years 2027 to 2030, with this it is expected that for the Andesita sector between the years 2024 to 2030 the water flows from the superiors drawbells (Huacha and Huifa), and that are not captured by the RN drainage system, enter their cavity increasing the probability of early entry of mud water.

5.2.1 Initial Considerations

To estimate the recovery of dry reserves from the production plans of the Andesita sector, the following criteria were assumed:

- Two long-term production plans are used: PND 2018 mining plan, center start (120 Mt) and alternative south start mining plan (125 Mt). Which differ mainly in the extraction sequence.
- As a conceptual exercise, a third plan, called extended, was evaluated, which was built to quantify the maximum potential of dry reserves in the sector, this was defined from the local height of each point plus 100 meters of broken material, not exceeding in no case the 400 meters of accumulated extracted height.
- The variables used to evaluate the plans were entirely information validated by DET, that is, expected flows, primary height, topography and mining plans.
- During the simulation of the plans, when the entrance of mud through a point is predicted, the extraction speeds of the neighboring points are not modified, that is, no limited points are generated.
- When the model predicts the entry of mud into a drawing point, the simulation closes the point and no more planned reserves can be extracted from that point.

5.2.2 Northern Resources exploitation sequence

The Andesita project (level 2030) is located next to the Recursos Norte project (level 2120). As mentioned above, the exploitation sequences are a relevant aspect to determine the probability of mud water entering and thereby estimate the recovery of dry reserves in the Andesita sector.

In Figure 16 the first case is shown, which consists of Recursos Norte developing as an uncoupled polygon of Reservas Norte, in this case, by the year 2024 (Andesita start) the cavity of this sector will capture the water flows from superior drawbells (Huacha and Huifa), with which the passage of the flow of water towards the Andesita cavity would be low.

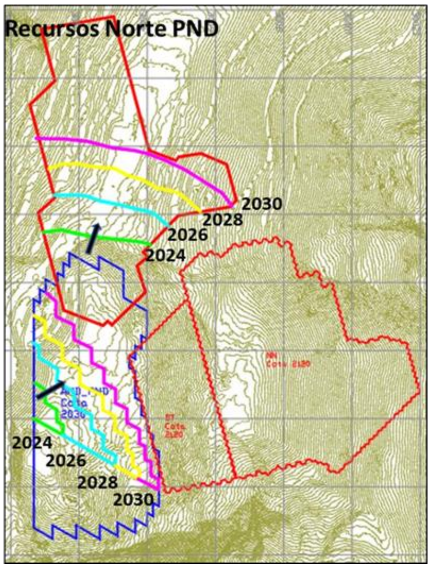


Figure 16: Sequences of exploitation Andesita (cave initiation point on center side) and Recursos Norte (decoupled).

On the other hand, Figure 17 shows the case in which North Resources is developed coupled to North and Dacita Reserves. In this case, by the year 2024, when Andesita begins, the front of incorporation point still does not intercept the Quebrada Teniente, which if it occurs between the years 2027 to 2030. According to this, the Andesita sector would have a greater water flow contribution between the year 2024 and 2030, and then decrease due to the withdrawal of water from the Northern Resources cavity.

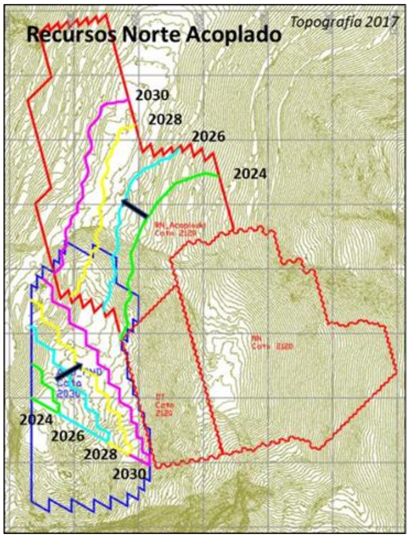


Figure 17: Sequences of exploitation Andesita (cave initiation point on center side) and Recursos Norte (coupled).

What is shown in Figure 18 is analogous to Figure 17 in terms of what happens with Recursos Norte, but it is observed what the sequence of exploitation of Andesita would be like with the start from the south of the polygon. In this case, the water flows coming from the upper drawbells would drain in the same way as explained in the previous paragraph.

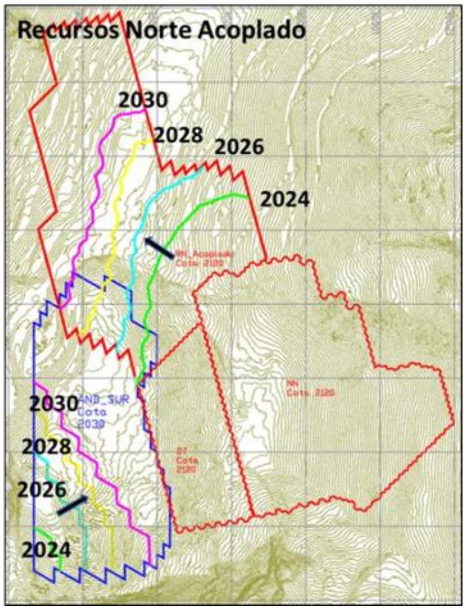


Figure 18: Sequences of exploitation Andesita (cave initiation point on south side) and Northern Resources (coupled).

5.2.3 Flow rates of water for the Andesita project

Once defined the possible scenarios for Andesita with respect to the Northern Resources sequence, it is essential to identify the expected flows for each of the cases shown. These flows were obtained from the information reported in the report "Estimate of infiltration flows to the crater area of the Andesita project and PDA projects" (Brzovic, 2018).

The first case is when Andesita is exploited under a decoupled Northern Resources condition, in this case the water flows entering the Andesita cavity are those coming from its own crater plus those flows that are not drained by the Northern Resources cavity. It should be noted that the flows that enter the Northern Resources cavity are those that are not captured by the drainage system, for which an efficiency of 70% is considered. Figure 19 shows the different flow alternatives considered to evaluate this scenario: the first is that the flows that enter the Andesita cavity are only those that intercept their own crater (max. 300 (l / s)), the second alternative is that in addition to the flows of the Andesita crater an efficiency of 75% of drainage of the RN cavity is considered (25% flow rate RN max. 500 (l / s)) and the third is that it be considered 50% of drainage efficiency of the North Resources cavity (50% flow rate RN max. 700 (l / s).

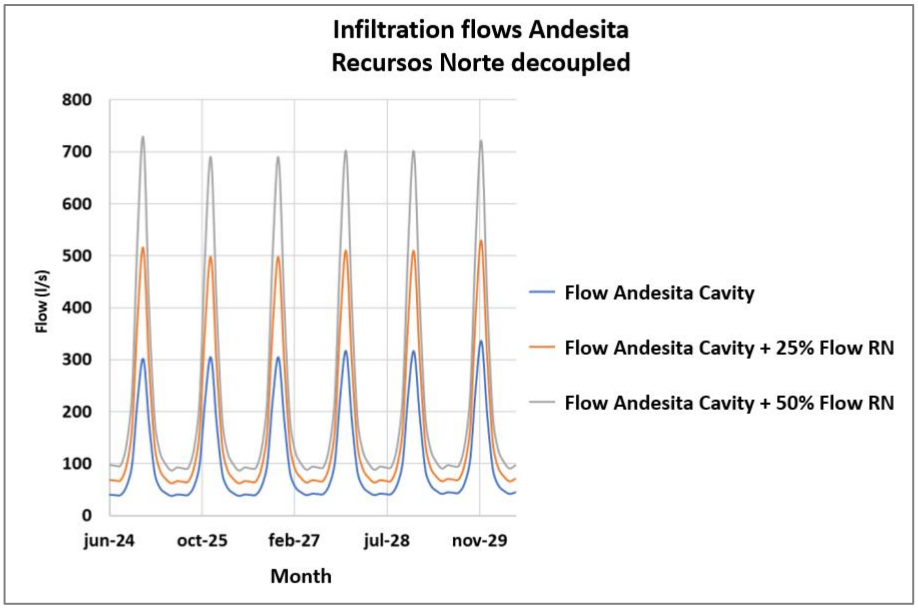


Figure 19: Flow distribution for Andesita project (decoupled RN).

The second case is when Recursos Norte is developed coupled to Reservas Norte, in this case it is assumed that, according to the interception of the QT by Recursos Norte, the flows that enter the Andesita cavity gradually decrease. The expected flows can be seen in Figure 20 and were constructed as follows:

- 2024-2026: It is expected that the flows that enter the Andesita cavity are those of its own crater, more than 100% of the flows from the Teniente gorge (Huacha and Huifa drawbell) that are not captured by the drainage system.
- 2027: Andesita crater flow + 75% QT flow not captured by drainage system.
- 2028: Andesita crater flow + 50% QT flow not captured by drainage system.
- 2029 and onwards: Andesita crater flow + 25% QT flow not captured by drainage system.

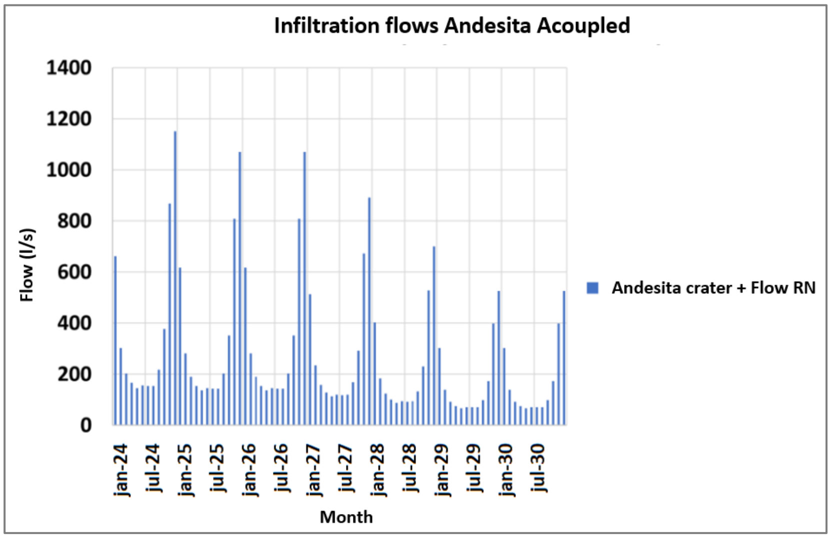


Figure 20: Flow distribution for Andesita (coupled RN).

There are two risk zones considered for the Andesita sector, the first is shown in Figure 21a, defined by geology (Codelco, 2017) based on the information on the closure of historical mud points in higher sectors (in this case the QT mine). The second is seen in Figure 21b, defined from the possible surface water accumulation areas, since the topography in this sector is not flat, as seen in Figure 22. The reason why a second risk zone is due to the fact that the first gives a high and similar risk to most of the drawing points, since, as observed, the entry of water into the cavity would occur in a sectorized manner.

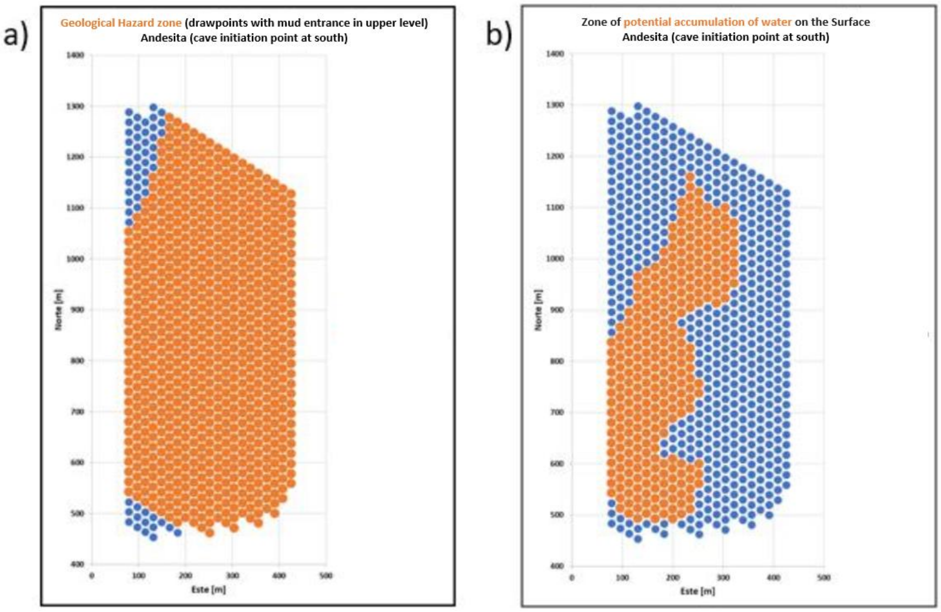


Figure 21: Andesita sector risk areas.

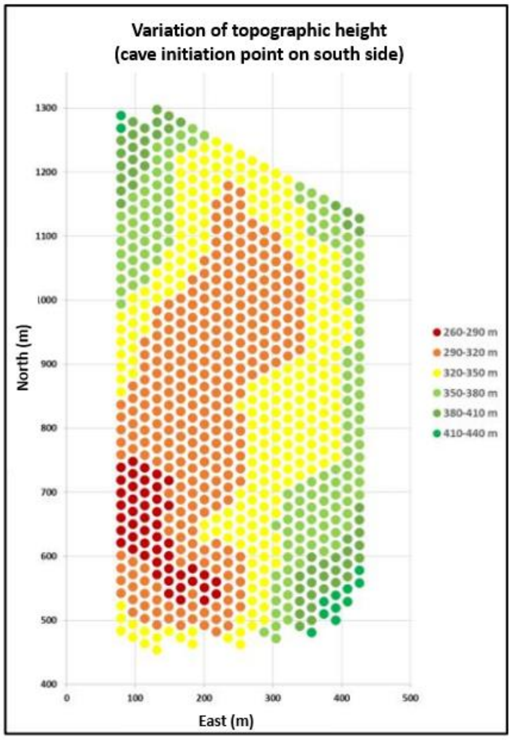


Figure 22: Heights to topography (2017) by drawing point in the Andesita sector (cave initiation point on south side).

5.2.4 Andesita Evaluation of long-term mining plans for the Andesita project

Considering the criteria described above and the multivariable model (SP-PN), the production plans of the Andesita project are evaluated to estimate the recovery of dry reserves. Table 13 shows the tonnage associated with each production plan, and Figure 23 and Figure 24 show the planned heights per drawing point for each plan. In addition, Figure 25 shows the incorporation sequences of each start, the PND starting at the center of the polygon and advancing, first, north and then south, and the alternative plan that begins in the south and go north. It should be noted that the extended conceptual plan (points with insitu height plus 100 meters of broken material (400 maximum)), was built from the other two plans.

Table 18: Andesita sector long-term production plans.

Plan	Tons [Mt]
PND (center initiation)	120
Alternative (south initiation)	125
Extended (center initiation)	160
Extended(south initiation)	183

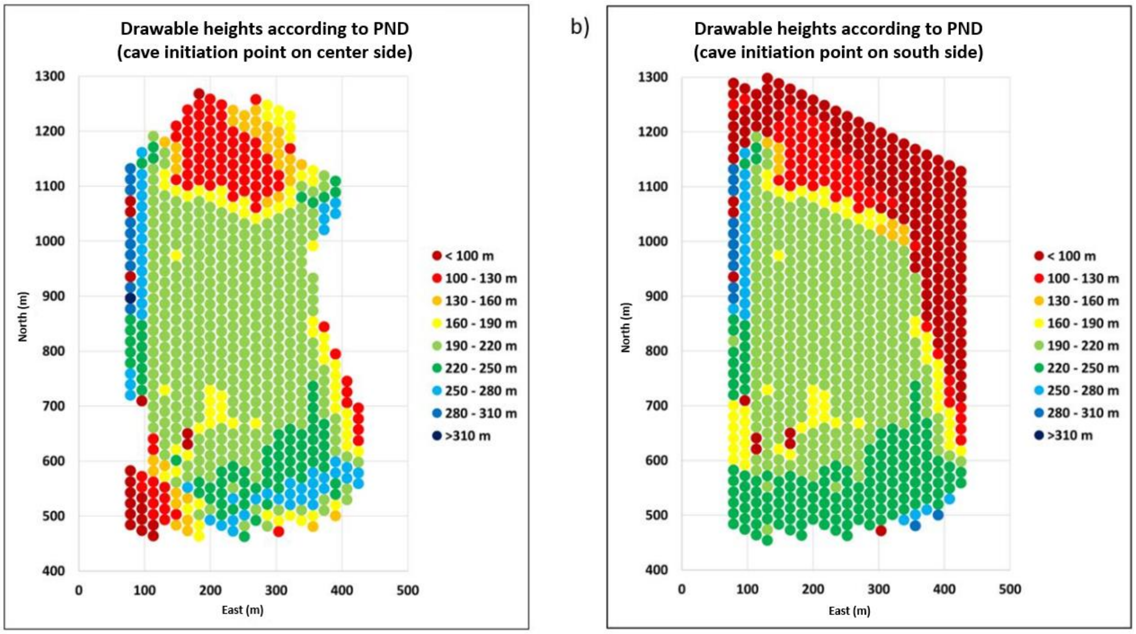


Figure 23: Andesita sector long-term production plans.

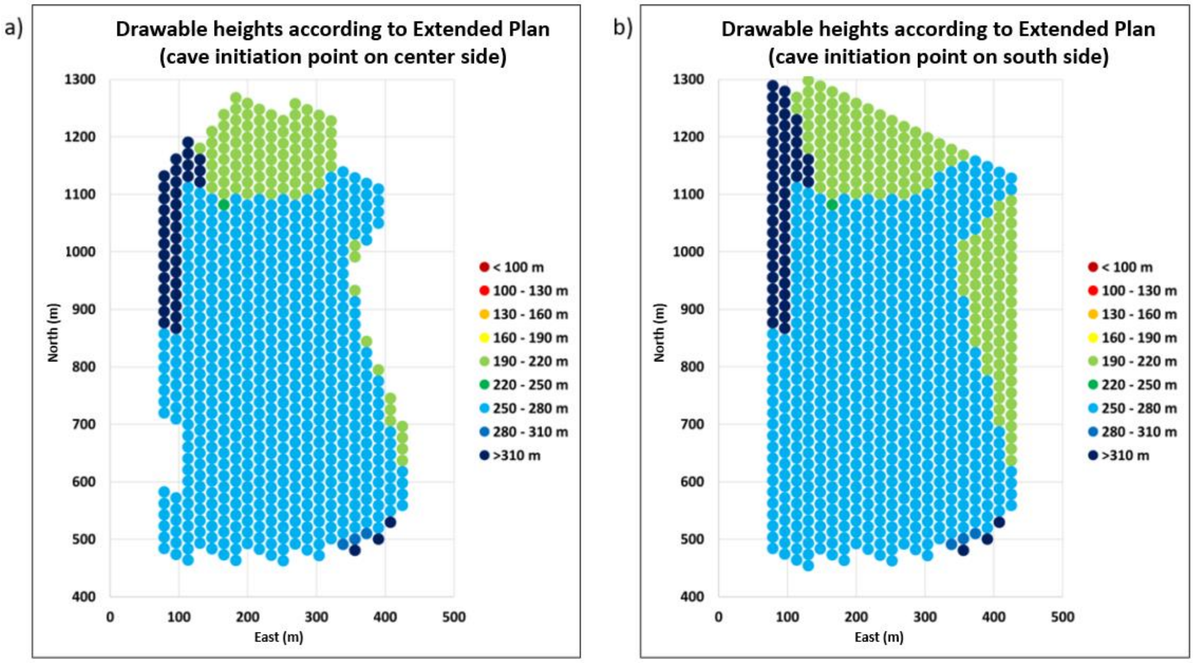


Figure 24: Extended production plans in the Andesita sector.

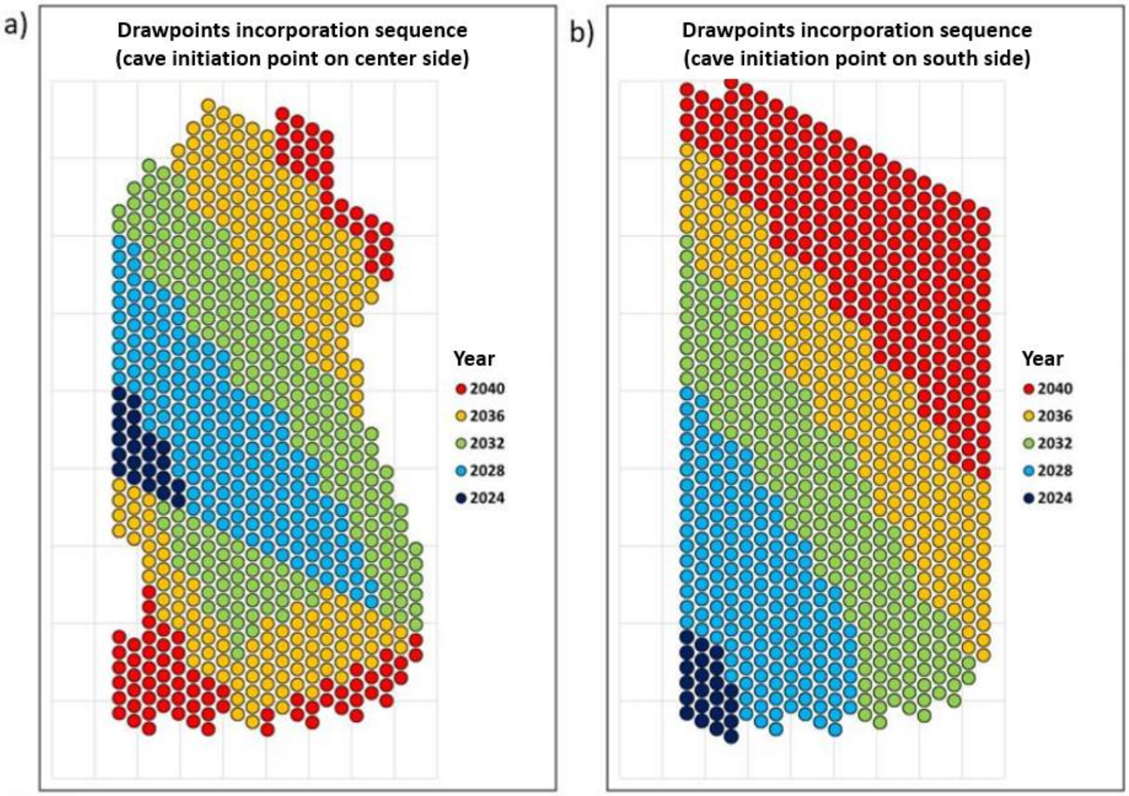


Figure 25: Sequence of incorporation of points.

Given all the characteristics of the scenarios proposed for the sector, in terms of plan, Andesita sequence, Northern Resources sequence, flows and risk areas, the different evaluation alternatives are shown in Table 14. The evaluation is divided into two large groups that are differentiated by the sequence of Northern Resources, in the case of decoupled Northern Resources, the effect of considering different contributions of flows that are not captured by the Northern Resources cavity (0%, 25% and 50%) will be evaluated as well as well as evaluating the alternative plan. On the other hand, in the case of Northern Resources coupled, the two plan alternatives will be evaluated and added to that the effect of considering a risk zone defined by the accumulation of surface water. Extended plans will be discussed additionally at the end of the analysis.

Table 19: Evaluation alternative plan (PND and Alternative) for the Andesita sector.

Case	Northern Resources Sequence	Andesita Plan	Considered Flow	Risk Zone
1	Disengaged	PND center initiation	Crater AD + 0% RN Flow	Upper Mud
2	Disengaged	PND center initiation	Crater AD + 25% RN Flow	Upper Mud
3	Disengaged	PND center initiation	Crater AD + 50% RN Flow	Upper Mud
4	Disengaged	Alternative south initiation	Crater AD + 25% RN Flow	Upper Mud
5	Engaged	PND center initiation	Crater AD + Variable contribution of RN (100% a 25%)	Upper Mud
6	Engaged	Alternative south initiation	Crater AD + Variable contribution of RN (100% a 25%)	Upper Mud
7	Engaged	PND center initiation	Crater AD + Variable contribution of RN (100% a 25%)	Water accumulation
8	Engaged	Alternative south initiation	Crater AD + Variable contribution of RN (100% a 25%)	Water accumulation

Table 15 shows the results for each of the evaluated cases, in general terms, it is observed that the recovery of dry reserves of the evaluated plans can be total (100%), as it can also be very low (61 %). The following paragraphs analyze the most probable results and scenarios for the Andesita sector.

Table 20: Results evaluation of scenarios and alternatives of exploitation of the Andesita sector.

Case	RN	AD Plan	Flow	ZR	Tonnage [Mt]	Recovery of Dry Reserves [%]	Recovered Tonnage [Mt]
1	Dis	PND	AD + 0%RN	B.S.	120	100%	120
2	Dis	PND	AD + 25%RN	B.S.	120	98%	118
3	Dis	PND	AD + 50%RN	B.S.	120	65%	78
4	Dis	Alt	AD + 25%RN	B.S.	125	100%	125
5	Eng	PND	AD + RN var	B.S.	120	61%	73
6	Eng	Alt	AD + RN var	B.S.	125	70%	88
7	Eng	PND	AD + RN var	Acum	120	87%	104
8	Eng	Alt	AD + RN var	Acum	125	90%	112

For the cases in which Recursos Norte is decoupled to Reservas Norte, the recoveries for the PND plan range from 65% to 100%, the variation depends on the amount of water that is considered to enter the Andesita cavity from the no natural catchment of the Northern Resources cavity, the most likely scenario is that 25% of RN flows will go to Andesita, in this sense for the PND plan 98% of dry reserves would be recovered and for the alternative plan 100% . In conclusion, the development of North Resources decoupled from Reservas Norte favors the recovery of dry reserves from the Andesita project.

In the cases in which Recursos Norte is coupled, the situation changes because, for both the PND plan and the Alternative plan, the recovery of reserves is 61% and 70% respectively. This low recovery is given in part by the width of the upper mud risk zone, which causes the entry of mud to be too early for all the points.

A more probable scenario is when the surface water accumulation zones are considered as a risk zone. In this case, 87% and 90% of dry reserves are recovered for the PND plan and the Alternative plan. Figure 26 shows the maximum removable heights of dry reserves by drawing point and compares them with the heights planned for the center start plan. On the other hand, Figure 27 shows the same for the South start plan. As can be seen, the loss of dry reserves occurs mainly in the central zone of the polygons, given by the risk zone.

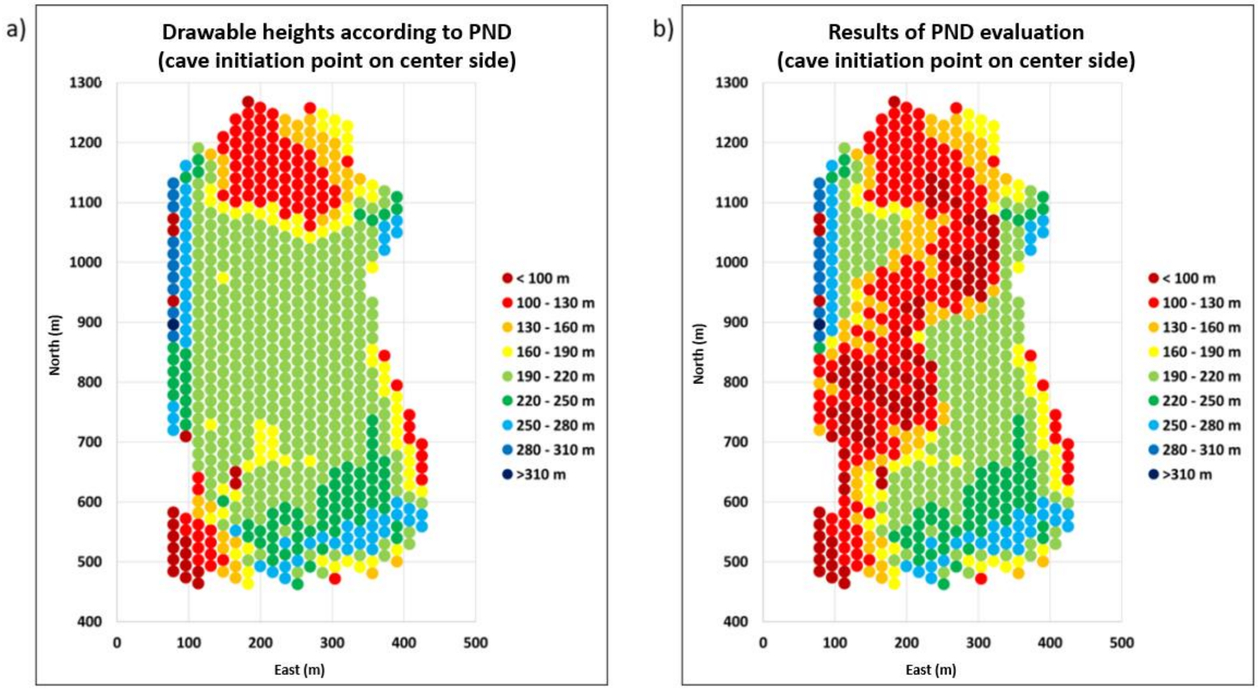


Figure 26: Maximum removable heights for Andesita plan. a) Planned heights b) Maximum heights of dry reserves.

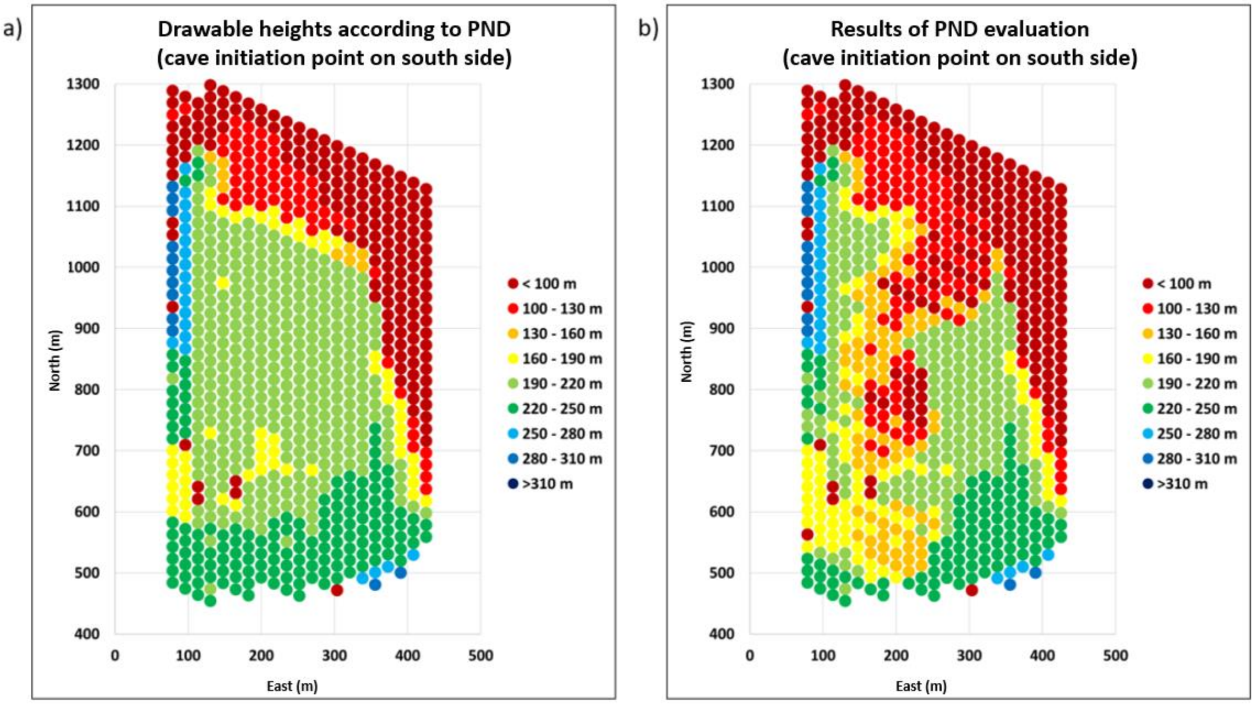


Figure 27: Maximum removable heights for the Andesita plan. a) Planned heights b) Maximum heights of dry reserves.

In the previous analysis, a large number of scenarios were evaluated. In the case of extended plans, only the most probable cases were evaluated for each of the plans, center and south start. Table 16 shows the characteristics of the evaluations carried out with the extended plans.

Table 21: Characteristics evaluation of extended plans beginning in the center and south.

Case	Northern Resources Sequence	Andesita Plan	Considered Flow	Risk Zone
1	Engaged	Extended PND	Crater AD + Variable contribution of RN (100% a 25%)	Accumulation Zone
2	Engaged	Extended Alternative	Crater AD + Variable Contribution RN (100% a 25%)	Accumulation Zone

The results of the simulations are shown in Table 17, it is observed that the maximum potential of dry reserves for the central Andesita case is 130 Mt and for the southern Andesita case is 147 Mt, if compared with the plans previously evaluated 120 and 125 planned reservations, respectively, are exceeded. In Figure 28 and Figure 29 the PND and Alternative plans are compared with the results of the maximum heights to be extracted from dry reserves. It is observed that planning should go to deliver more tonnage to those points located more towards the ends of the polygons, limiting the tonnage of those points in the risk area.

Table 22: Results simulations extended plans Andesita central and south.

Case	RN	AD Plan	Flow	RZ	Tonnage [Mt]	Recovery of Dry Reserves [%]	Recovered Tonnage [Mt]
1	Eng	PND ext	AD + variable RN	Acum.	160	81%	130
2	Eng	Alt ext	AD + variable RN	Acum.	183	80%	147

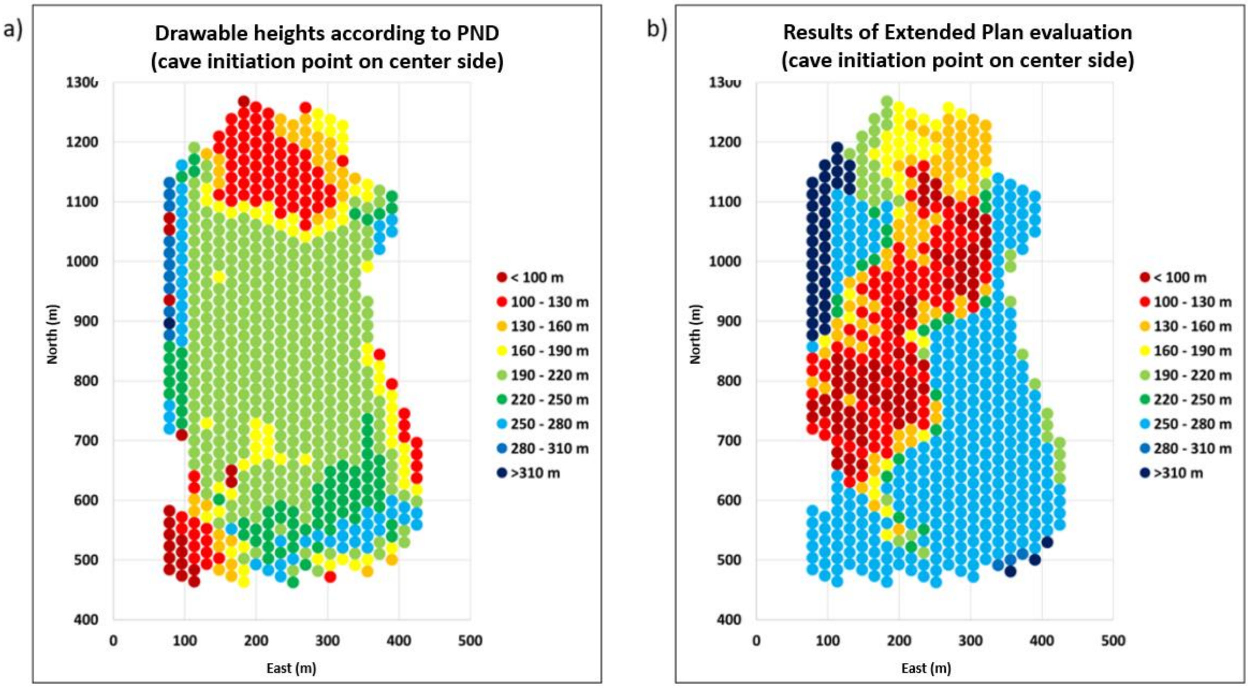


Figure 28: Comparison between a) Plan PND Andesita (center side) and b) Maximum heights to extract from dry reserves.

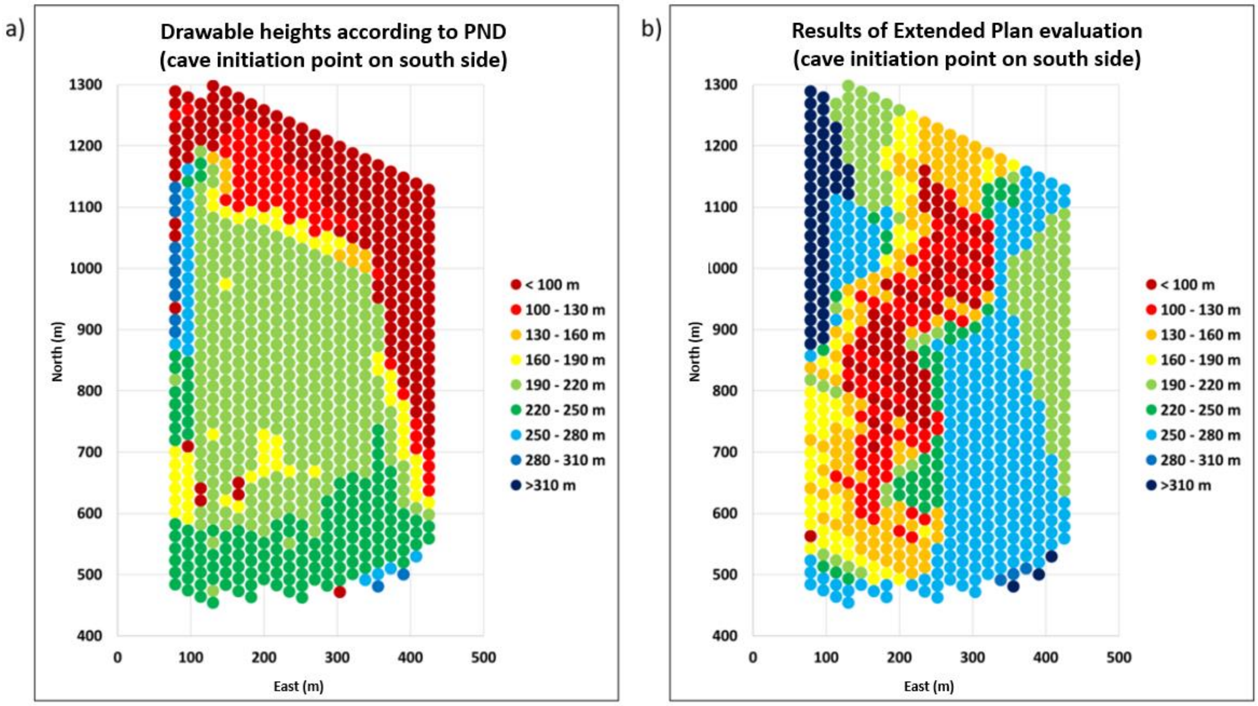


Figure 29: Comparison between a) Southern Andesita Plan and b) Maximum heights to extract from dry reserves.

6 Conclusions

The conclusions of this study are the following:

Andesita presents a challenge with respect to controlling the entry of water into its cavity, since high water flows are estimated in the sector. From a dry reserves point of view, the plan requirement is met for the following conditions:

- Efficiency of 70% of the North Resources collection system.
- Drainage through the Reno-Dacita cavity with increasing efficiency from 2024 to 2030 from 0% to 75%.
- Maintain topographic control.
- The removable heights are adjusted.

In the case of the Andesita sector, the sequence of exploitation of Northern Resources coupled is directly related to the amount of dry reserves to be extracted. If Recursos Norte is developed coupled to Reservas Norte, the flow of water entering Andesita between 2024 to 2030 would increase, thus decreasing the amount of dry extractable reserves of Andesita. Even under this condition it is possible to meet the required tonnage.

The recommendations of this study are as follows:

- It is recommended to evaluate long-term extraction strategies that allow increasing the amount of dry reserves by extraction with manual shovels through the definition of extraction speeds (t / m2-day) for extractable heights per point at month scale for high and low risk areas.
- Since all models were built using extraction information by manual shovels, they are valid under that condition. If it is extracted using remote controlled blades, the extraction condition changes. Given this scenario, it is recommended to build predictive models of mud entrance for TC extraction to evaluate strategies in Andesita. For this, the remote-command extraction database carried out in DR and Reno must be used.
- It is recommended to include the rock type variable in future models from El Teniente, to differentiate sectors such as Dacita, in which the generation of fines would be less than in other rocks and with it the amount of mud.

7 Bibliography

Brown, E. 2007. Block Caving Geomechanics. Brisbane: University of Queensland Press, 2007.

Brzovic, 2018. Estimación de caudales de infiltración hacia el área del cráter de explotación del proyecto Andesita y de proyectos PDA. Periodo 2023-2030

Butcher, R., Joughin, W., Stacey, T. 2000. Methods of Combating Mudrushes in Diamond and Base Metal Mines. The Safety in Mines Research Advisory Commite (SIMRAC).

Codelco, 2016. Hidrogeología y potencial riesgo de ingreso agua y barro a mina El Teniente. GRMD-SGL-INF-0042-2016.

Codelco, 2017. Topografía 2017. Definición de canalón para Recursos Norte.

Hosmer, D., Lemeshow, S., Sturdivant, R.2013. Applied Logistic Regression. Third Edition. Jakubec, J., Clayton, R., Guest, A. 2013. Mudrush Risk Evaluation.

King, G., & Zeng, L. (2001). Logistic regression in rare events data. Political analysis, 9(2), 137-163.

Navia, I. 2014. Statistical analyses of mud entry at Diablo Regimiento sector El Teniente's Mine. Proceeding of Third International Symposium on Block and Sub-Level Caving. Santiago, Chile.

VAI, 2017. Saneamiento Hidráulico Proyecto Recursos Norte. "Actualización del Modelo Hidrogeológico Conceptual Quebrada Teniente" Revisión 0.