INCORPORATION OF HYDRO GEOLOGICAL ASPECTS AND OPERATIONAL CONSTRAINTS IN STRATEGIC MINING PLANNING

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ABSTRACT

Developing mine sequencing involves many factors and a large amount of information, consequently the profitability of the project will strongly depend on the production schedule. A mining project may be conditioned to non-optimal sequencing, which may affect the economic results of the project and also lead to an inadequate utilization of mineral resources. During the mine sequencing it is necessary to make decisions for each block during extraction, such as: 1) whether or not a particular block should mined; 2) If mined, when it should be extracted; 3) Once extracted, how and when it should be processed. These decisions define the annual cash flow of a given project and the number of periods that the mine will be operated, impacting the project´s net present value (NPV). The decision of how many blocks should be extracted in a given period and how they should be processed not only defines the cash flow for a particular year, but also impacts on future schedules. Normally, the final pit limit is optimized for a fixed set of parameters (price, costs, resource model, etc.), knowing that changes in these parameters will have impact on the life of mine plan. Uncertainties (as grades, stripping ratio, market, groundwater level, etc.) are included only as a post-analysis of variability and sensitivity of the results of the abovementioned factors. The conventional method of sequencing a mine is divided into three main steps: First the delineation of the final pit; second, subdividing the final pit in operational pushbacks and third, sequencing blocks in each of these pushbacks, taking into consideration the mine, processing plant and market capacities. However, there are some aspects that are not necessarily incorporated into the conventional mining system, including mining ore below the water table. This aspect imposes some vertical mining advancement constraints that must be considered. The objective of this study is to demonstrate the relevance and impact on the NPV result from the groundwater as a constraint related to the need for water table drawdown, also considering grades and stripping ratio (SR) variability during the mining sequence for a phosphate mine. The methodology adopted considers adjustments when determining each pushback within the limit of the final pit, trying to respect the constraints and pursuing global profitability as the main goal of the optimization process.

KEYWORDS

Sequencing, Constraints, Groundwater Level, NPV

INTRODUCTION

Mine planning aims for the rational use of mineral deposits and project´s profitability involving the application of a set of techniques for decision-making and the selection of the best alternatives for the life of the mine, whose goal is to achieve the best production sequence. Like any other project, mining industry has the basic economic objective of maximizing its future wealth. However, it is characterized by targeting the economic use of an exhaustible, non-renewable capital good, which differentiates it from other industries. So, the maximization of future wealth should be carried out in a defined period, i.e. during the existence of the mineral reserve. In economic terms, it can be more appropriately expressed as follows: the purpose of the mining industry is to maximize the net present value (NPV) of future cash benefits throughout mine life (COSTA, 1979).

Mineral deposits have their formation dictated by natural laws which present several challenges and conflicts that should be better investigated to comply with the needs of the mining enterprise. The distribution of variables representing the quality of minerals such as grain size, grade, groundwater level and amount of waste to be removed hinder or even make the economic exploitation of a mineral deposit impossible. Problems can occur in non-planned mining, such as ore exploitation with an average grade above the necessary, irreparably impoverishing the remaining reserve; prematurely exhaust the mine due to the removal of overburden poorly planned or immediate mining without taking into account the future of the ore availability. Another increasingly common constraint in mining operations is the control of groundwater level due to the increasingly deepening of the pit bottom which prevents mine operations in some sectors or even in the whole mine for a certain period of time.

Mine planning allows to anticipate the occurrence of problems which can be avoided in the future or, when it is not possible, at least minimize its consequences. As it is an anticipated simulation of the mining routine, this planning permits to know *a priori* the possibility of controlling quality variables, evaluate groundwater level behavior over time and the best use and allocation of mining equipment. Moreover, it enables to establish the schedule of waste generation/disposal and / or tailings, providing subsidies for better use of the mineral resource, seeking to minimize environmental impact.

Production scheduling must meet the evolution of environmental needs, the challenges offered by this development and related aspects such as: changes in government policies; changes in technology; changes in the global economic situation, including prices, workforce and raw materials; changes in the nature of competition: changes in social life and activities; drastic changes in the political situation of the region. Therefore, mining sequencing must carefully consider economic, social, environmental, political and technological factors. However, it is essential to take into account possible constraints so as not to jeopardize the viability of the enterprise.

OBJECTIVE

This paper aims at evaluating the impacts of possible constraints, especially water level, on the grade of oscillations and stripping ratio. These impacts are analyzed based on the results of NPV obtained in each mine sequencing.

METHODOLOGY

Considering mine sequencing is essential to the success of a mining entrepreneurship, the methodology used in this study focused on maximizing the financial return for the mining business, especially in the early years of mine operation. Therefore, the delineation of the final pit involves some crucial steps such as: a representative block model, well-adjusted profit function, a consistent cut-off grade with the available mineral reserves and technology. Following with the mine sequencing requires some additional input data, such as current topography; production rates and possible constraints which in this study were the following: the search of ore providing stability in the average grade fed to the process; the search for stability in SR; the vertical feed control considering the level of the groundwater level; environmental limit of pit depth; mining leases.

According to Osanloo, Gholamnejad & Karimi (2008) mining sequencing begins with the determination of production capacity, based on mine operational capacity, the estimates for operating costs and commodity prices. Then, using block model and economic evaluation of each block, an algorithm analysis of the positive blocks as well as of the overlying waste units in order of precedence is made to check if its extraction is economically justifiable. This analysis is based on cutoff grade which checks if the undiscounted profit obtained from a given ore block can pay the undiscounted cost to remove the waste blocks in its precedence. The final pit is then determined using an optimization algorithm in order to maximize the undiscounted cash flow. Within the final pit, stages are designed so that the reserve is divided into multiple nested pits. These procedures are a parameterization using revenue or cost factors to generate smaller pits, for example, from lower revenue per ton of ore, and move to higher pits with higher revenue per ton of ore. Subsequently, operational constraints are imposed to generate the so-called operational advances also known as *pushbacks* which are mining advance stages to reach the final pit and are used as guidelines during the annual production schedule planning. Before determining the extraction sequence, cut-off grade should be set in order to differentiate ore and waste allowing the production plans elaboration.

According to Dagdelen (2001), there are a number of sophisticated software packages in the mining industry which outline the final pit, perform analysis, do pushbacks design and determine mining annual plans. However, it is important to highlight that not all of these steps may be optimized by a single program due to large changes in mathematical scale. The most common approach to this problem is dividing it into sub-problems similar to those shown in Figure 1.

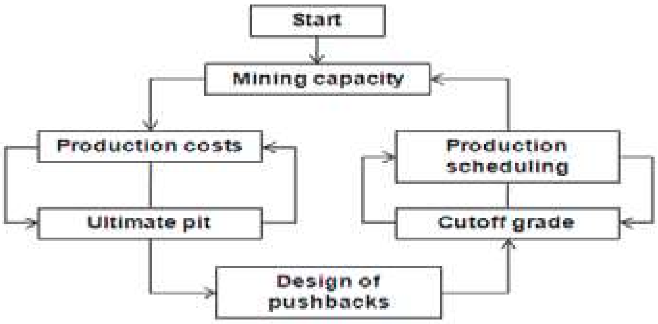

Figure 1 - Steps of traditional planning by circular analysis. Source: Dagdelen (2001).

The main point used to develop the methodology was determining and ranking the most relevant constraints after measuring the project outcome using the NPV. The structure of the methodology proposed in this paper can be seen in Figure 2. The following steps were taken: first, the determination of input block model; second, final pit definition; third, pushbacks were designed primarily with the maintenance of default input parameters suggested by the sequencing software; fourth, NPV was assessed considering only the processing plant capacity; fifth, some mining scenarios were simulated imposing constraints such as ore grade and stripping ratio both individually and later on simultaneously; sixth, the procedure was repeated by changing the number of pushbacks, starting again from pushbacks design. The new sequencing scenarios were simulated from the following number of pushbacks: 3, 5, 7, 10, 12, 15, 17, 20, 22, 25 and 100. For each of those scenarios, evaluation and comparison of NPV were carried out.

At last, groundwater level was added to establish a new final pit provided that water level elevation, given by a drawdown model at the end of mine life, overlies the original final pit bottom. Thus, the analysis considering this constraint initiated with a new ultimate pit scenario generated between the intersection of the prior pit limit and the water table. Finally, the alternatives were compared not only in terms of NPV, but also average grades fed to the plant and stripping ratio for the first 10 years of mine sequencing.

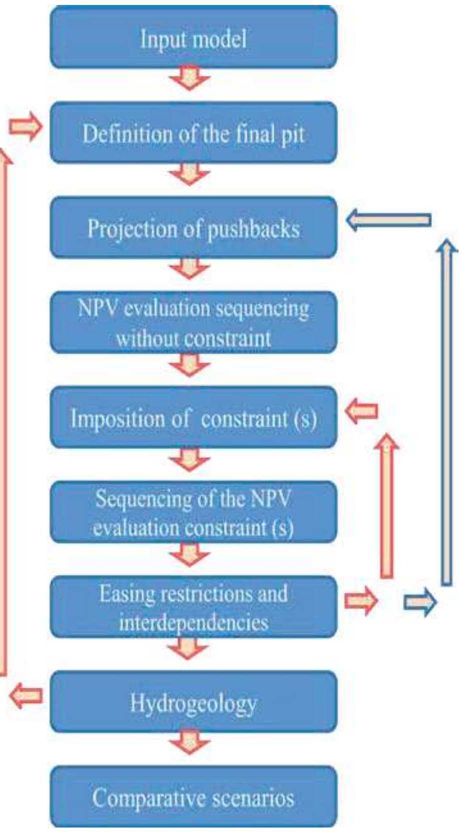

Figure 2 - Methodology used in this work.

CASE STUDY

To illustrate the methodology, a case study in a phosphate deposit located in Araxá Minas Gerais southeastern Brazil was carried out. The phosphate deposit belongs to Barreiro carbonatite complex, named F4, was designed to feed plant II in the Complex with capacity to process around 3.2 million tonnes per year. A reconstruction of the original topography of the mine within the leasing limit granted to Vale Fertilizantes was necessary. Leasing limit is a physical polygon which neither final pit nor mining operations can exceed in any mining scenarios. Figure 3 shows the topography and leasing limit.

The block model has the following dimensions: 25m x 25m x 10m (**x**, **y**, and **z**, respectively) containing 6 typologies: #1 undefined, #2 oxidized ore, #3 cemented ore, # 4 friable silica-carbonated ore, #5 hard silica-carbonated mineral rock and #6 waste. Ore consists of grouping types 2 and 3 and waste by the conjunction of the other types.

The surface drainage is calculated considering the average monthly runoff comprised by part of the total amount of rainfall in the entire area of the natural contribution area, where the mine pit is inserted, plus the runoff from the mining area of the adjacent company which flows into the pit of F4 mine. Considering historical precipitation, a minimum of 372 m^3/hour water pumping capacity is needed, reaching the flow rate of up to 1.231 m^3/hour during the rainy season. However, taking into account the maximum historical 30-year monthly precipitation, the water flow can reach rates ranging from 1.105 to 2.532 m^3/hour up to the exhaustion of the mine. In order to avoid very high flows, in the pit, a peripheral channel drain located next to crest of the final pit is usually suggested, to contain the water income from the external portion of the natural drainage area, reducing the volumes to be pumped out from the pit bottom.

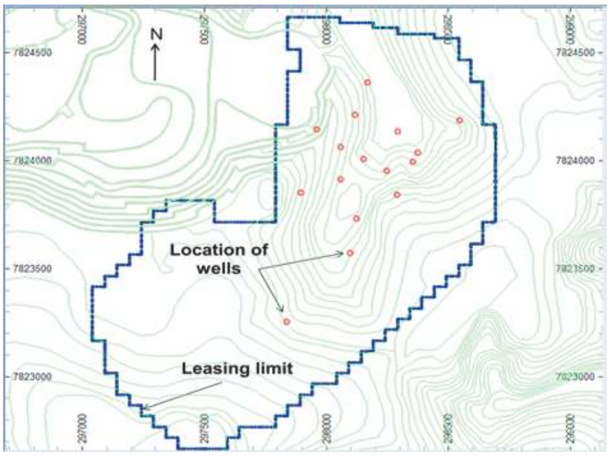

Figure 3 - F4 mine original topography as per September 2009 showing drawdown wells in red and leasing limit in dark blue.

To simulate the water level during the mine life, a numerical model of transitional arrangements was developed and calibrated for simulating groundwater level drawdown. The purpose of this process is to measure and assess the impact of drainage structures and also to guarantee the water level below pit bottom and thus quantify pumping flow rates needs and possible drawdown impacts. This type of simulation is useful to determine minimum pumping requirements during the mine advancement and also estimate the number of minimal wells and its location to achieve drawdown. The best and also more realistic scenario consists of the combination of drawdown wells with dewatering channels in the lower levels of the pit directing the runoff towards a sump located at the bottom pit where the water it is pumped out from the pit. This method is advantageous because it considerably reduces the number of required wells, although it creates operational difficulties. Figure 3 shows the location for the wells of the first 10 years of mine operation. Another important issue taken into account in this study was the environmental pit bottom limit. F4 mine is located besides Barreiro Hydro mineral Resort where there are several natural fountains. Therefore, the pit bottom cannot deepen below 980m elevation, as lowering the water level beyond this limit can interfere with the fountains flow rate.

Finally, based on the above listed data and profit function calculation (assumption made for mining and process costs, commodity price and process recovery), provided by the company and kept confidential by request, mining sequencing was carried out. The first step was to import the block model and select the working variables, in this case P_2O_5 (phosphate grade). In the subsequent step, the economic model was generated consisting of a grade block model and the economic value for each block.

Within the pit limit, the pushbacks must be sequenced according to annual ore demand respecting the available budget. This is an important step during mine planning to optimize NPV for each scenario considered. Therefore, it is also essential to manage parameters such as: average ore grade consistent with the available technology in the processing plant; waste tonnes to be removed per year; and groundwater level inside the mining areas. One alternative to control these variables in mine sequencing is to adjust pushbacks according to the variation of such constraints. After the adjustment of pushbacks, it is possible to program the sequence of annual exploitation. In this case study the first 10 years of mine operation were analyzed, due to the availability of hydro geological model information.

RESULTS ANALYSIS

Final Pit

The final pit limit represents a boundary in which ore mass and the associated amount of waste can be profitably mined, according to predefined parameters. The economic value of final pit and its respective limit are used as benchmark to compare with the later stages of sequencing, the values found in the final pit base case were 78.3 Mt of phosphate ore with a stripping ratio of 2.87 (t/t).

When the groundwater level was considered as a constraint in sequencing, it was necessary to establish a new final pit shell, since the water table surface was overlying the original final pit bottom in some places. This "new" pit bottom considered the results of the numerical model simulating the groundwater level drawdown, which was based on the number and the flow rates estimated for each drawdown well. The output surface became now the intersection between the original final pit bottom and the simulated water table. The result of the new final pit was 51.0 million tonnes of ore with 4.20 (t/t) SR.

Mining Sequencing

After importing all the data and followed all the steps described in the methodology, it is possible to choose the number of pushbacks to work with. Provided that this is an important step in mining sequencing and that the ideal value to be used is not known, a number of scenarios were simulated in order to find out the optimal number of pushbacks. Thus, the scenarios were simulated with the following number of pushbacks: 3, 5, 7, 10, 12, 15, 17, 20, 22, 25 and 100.

Mining Sequencing Without Constraints

Before start imposing constraints in mine sequencing (grade, SR and groundwater level), it is important to assess the NPV of the project to define a reference for comparison. Afterwards, mine sequencing without a constraint was performed, but controlling the ore mass to feed the processing plant. The results can be seen on the blue curve in Figure 4. All scenarios were simulated with the same software parameters, changing only the number of pushbacks. As it can be seen, when the number of pushbacks is greater than or equal to 15 and less than 25, the mine sequencing NPV reaches US$ 690 million. Considering groundwater level, when the number of pushbacks is greater than or equal to 10, the NPV of the mining sequencing varies between US$ 500 and US$ 550 million as shown by the red curve in Figure 4.

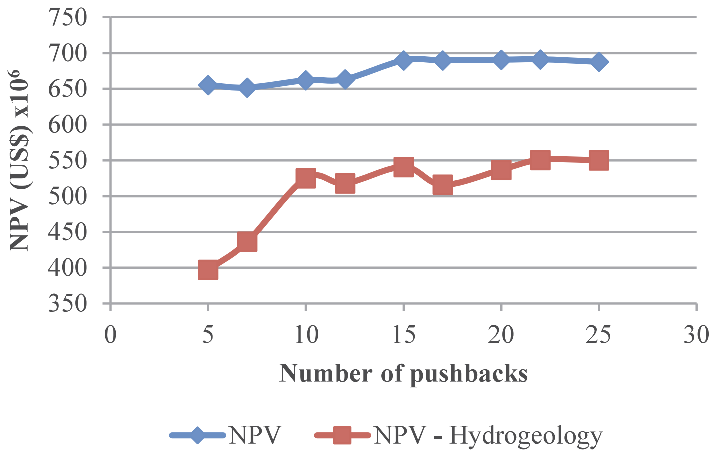

Figure 4 - Comparison of sequencing with and without hydrogeology constraints.

Mining Sequencing Considering The Grade Constraint

Normally, all treatment plants require a minimum grade so that metallurgical and mass recoveries are kept approximately stable. Figure 5 shows the results obtained from sequencing considering the average P_2O_5 grade of 11.5% with variations of ± 1%, as shown in the blue curve, the NPV varies according the number of pushbacks selected. Therefore, the highest NPV found for sequencing was using 22 pushbacks (US$ 536 million). Considering the same parameters when sequencing with water level constraint, requested pushbacks ranging from 10 to 17 obtained a level close to US$ 500 million, as it can be seen in red. But with 25 pushbacks, the highest NPV of US$ 520 million was reached according to Figure 5.

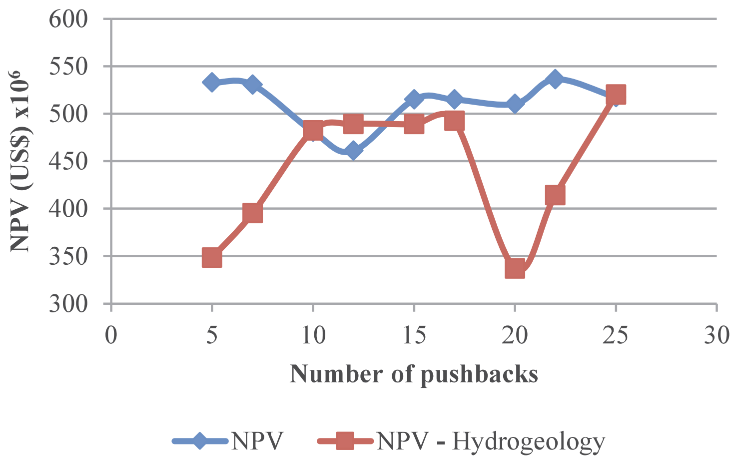

Figure 5 - Comparison of sequencing with and without hydrogeology considering P_2O_5 grade as constraint.

Mining Sequencing Considering SR As A Constraint

The waste mass to be removed can severely affect a mining project. Minimizing, stabilizing and if possible delaying the waste quantities to be moved over the years in a mining operation maximizes NPV. Figure 6 shows the result of sequencing considering SR as a constraint. It is evident that there is a tendency: the higher the number of pushbacks, the higher the NPV after sequencing. The highest NPV (US$ 643 million) was obtained when sequencing the 20 pushbacks scenario as demonstrated in the blue line. Due to the fact that the final pit, considering hydro geological constraints have less ore than the original final pit, the reduction of waste amount is not proportional to the decrease in ore amount, i.e., the increase of SR from 2.87 to 4.20 makes this aspect extremely important for the profitability of the enterprise. Figure 6 shows the behavior of SR in red after mine sequencing according to the number of simulated pushbacks. It can be observed that sequencing using 12 pushbacks provides the highest NPV (US$ 508 million).

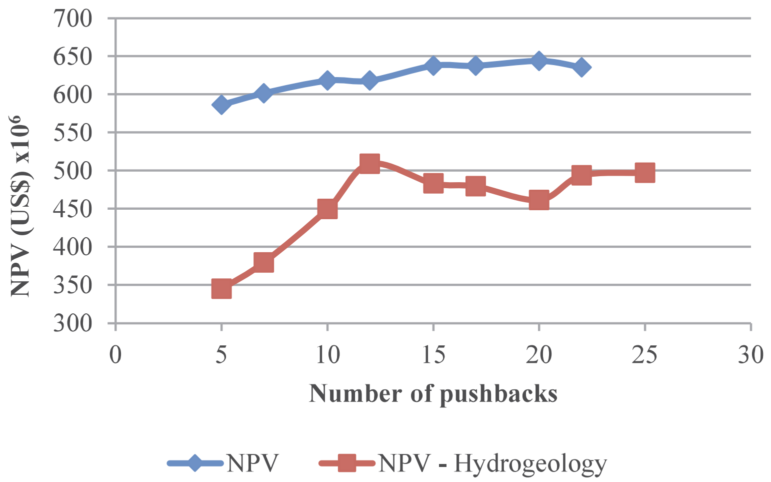

Figure 6 - Comparison of sequencing with and without hydrogeology considering SR as constraint.

Mine Sequencing Considering Grade And SR As Constraints

Mine sequencing considering grade and SR as constraints was also carried out, it is important to highlight that there is an interdependence between these two variables. By analyzing the blue curve in Figure 7 it can be noticed that, from 12 to 20 pushbacks requested, the NPV of the mine sequencing stabilizes at around US$ 600 million. Mine sequencing for 20 pushbacks achieves the highest NPV

(US$ 603 million), considering both grade and SR constraints. In an attempt to stabilize SR at a value closer to final pit SR and to obtain an average grade more consistent with the production target, NPV sequencing decreased about US$ 40 million compared to the NPV sequencing considering only SR.

Mine sequencing should be as close to the reality of mining operations as possible. Which means, a schedule that does not take into consideration all available information, like limitations in the daily mining operations, entails non-compliance with the annual plan. Hence, if the annual plan is not fully implemented, the whole mine sequencing in the following years will be compromised. The red curve in Figure 7 shows the NPV sequencing behavior considering hydrogeology, it can be observed, again, that the sequencing using 12 pushbacks provides the highest NPV (US$ 507 million).

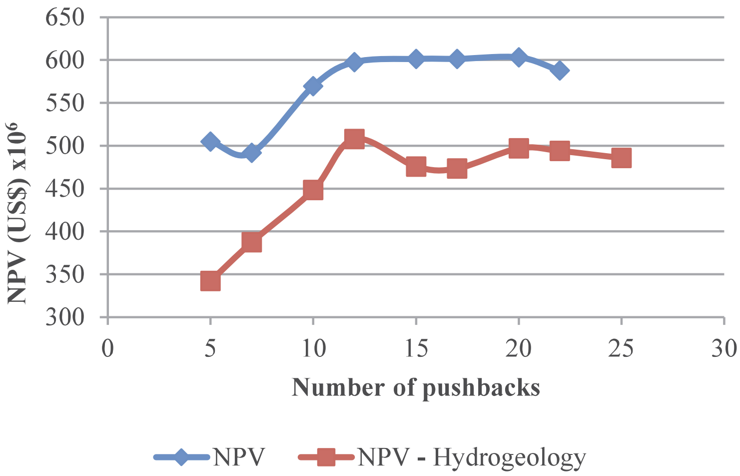

Figure 7 - Comparison of sequencing with and without hydrogeology considering ore grade and SR.

Table 1 shows a comparison of NPV for the first 10 years of the mine sequencing, without considering hydrogeology, highlighted columns (no hydro), for grade and SR (20 pushbacks); and the first 10 years of sequencing, with the same parameters, considering hydrogeology (12 pushbacks), represented in the non-highlighted columns (hydro). Although sequencing have different constraints, the NPV results, ore grade and SR at the end of 10 years are very close, indicating that the sequencing with hydrogeology was well executed. Thus, mining operation conditions are more favorable without water upwelling i.e. sequencing considering hydrology.

Figure 8 illustrates a comparison of mathematical pits in years: 1, 3, 5, and 10 for sequencing with grade and SR constraints, with and without considering hydrogeology as well as the locations of the drawdown wells planned in the simulation of the hydro geological model. The intersection of these surfaces with the groundwater level wireframe is shown in blue. This groundwater level wireframe comes from the quantity and flow of the drawdown wells. It is important to emphasize that both location and number of wells may change over time, depending on the actual pumping rates obtained. As for the bottom pit, it is evident that the pits, considering hydrogeology, have a wider area where the pumping sump can be placed.

Table 1 - Comparison of NPV results in the first ten years of sequencing with and without hydrology considering ore grade and SR as constraints.

Year	NPV (US$ x 10^6)		P_2O_5 (%)		Waste (t x 10^6)		Stripping Ratio (t/t)	
	Nohydro	Hydro	Nohydro	Hydro	Nohydro	Hydro	Nohydro	Hydro
1	0.43	63.09	12.54	12.67	30.13	11.19	9.38	3.48
2	87.83	53.54	12.53	12.19	0.49	10.51	0.15	3.29
3	63.40	61.46	12.61	13.11	7.25	9.88	2.27	3.09
4	50.93	59.20	12.51	13.70	8.78	10.88	2.74	3.40

5	51.61	47.24	13.08	12.97	9.45	10.84	2.95	3.39
6	45.45	44.86	13.08	13.15	9.65	10.21	3.02	3.19
7	42.20	35.28	13.12	12.57	9.55	10.94	2.98	3.42
8	34.51	30.48	12.59	12.23	9.09	10.70	2.84	3.34
9	29.31	27.45	12.42	12.33	9.60	10.99	3.00	3.43
10	32.38	16.24	13.19	11.01	9.41	11.11	2.94	3.47
TOTAL	**438.05**	**438.84**	**12.77**	**12.59**	**103.39**	**107.24**	**3.23**	**3.35**

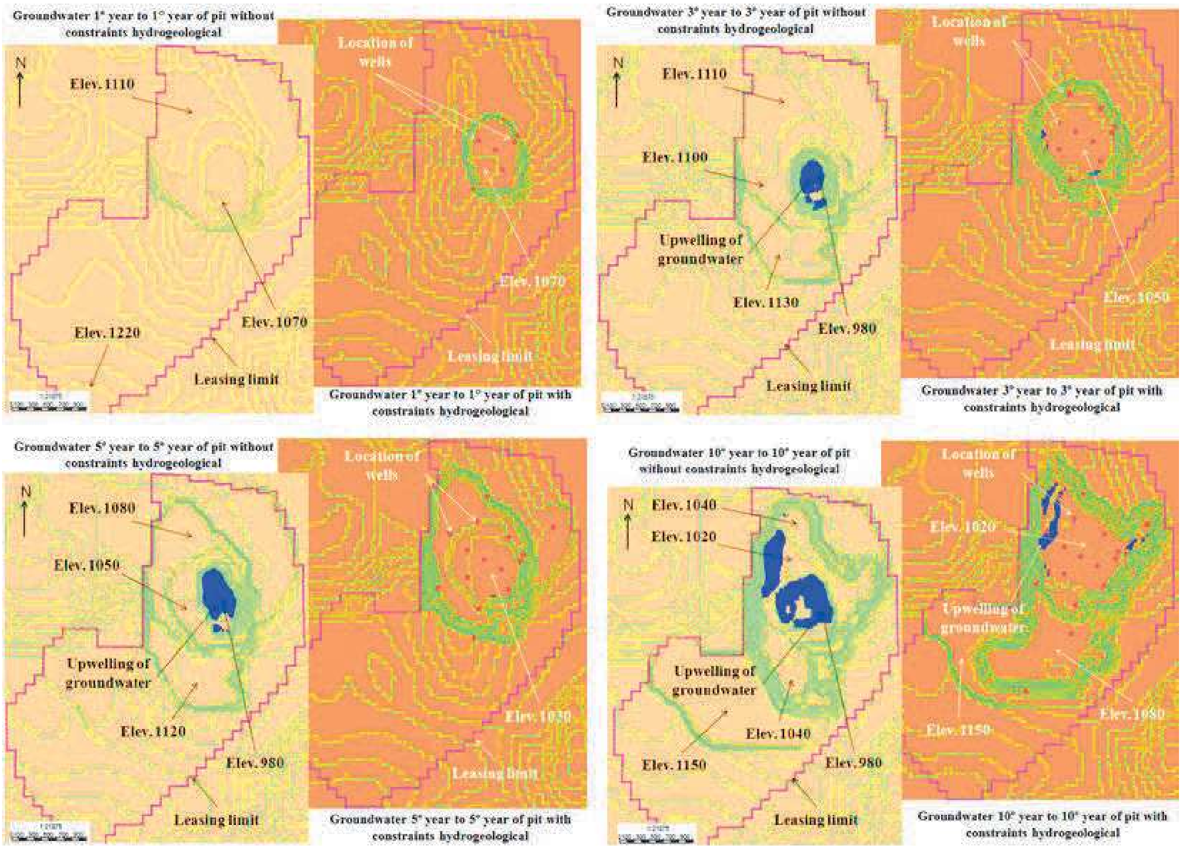

Figure 8 – Comparison of sequencing considering ore grade and SR constraints with and without hydrogeology in years 1, 3, 5 and 10

CONCLUSIONS

Mine sequencing is the core of mining planning allowing a strategic view of pits evolution over time. The constraints and their stabilization attempts have great influence on the pit geometry and hence a huge impact on the project´s NPV. Proper knowledge of the deposit and mining operation is required in the preparation of the production sequence, as fail to comply with the annual plan affects not only the current plan, but also throughout the established mining sequencing. As demonstrated in sequencing without regard to hydrogeology, the final pit has 78.3 million tonnes of phosphate ore and SR 2.87 (t/t). When sequencing without considering ore grade and SR constraints, but taking into account the annual mass fed to the processing plant, the highest NPV was US$ 690.9 million; by considering ore grade constraint, NPV was US$ 536 million. Both values were obtained in the simulation with 22 pushbacks. When SR was taken into account, the highest NPV obtained was US$

643 million with 20 pushbacks. In turn, considering both constraints, the highest NPV was US$ 603 million. Therefore, it is evident that there is an interdependence between these two variables.

In the sequencing considering hydrogeology, the final pit was rebuilt reducing it to 51.0 million tonnes of ore and increasing the SR to 4.20 (t/t). In the mine sequencing considering the annual mass of the processing plant, but without considering ore grade and SR constraints, NPV was US$ 500 million, in the simulation with 22 pushbacks. For the production schedule with the ore grade constraint, the highest NPV was US$ 520 million, with 25 pushbacks. The sequencing considering SR, the highest NPV was US$ 508 million with 12 pushbacks. Taking both constraints, ore grade and SR into consideration, the highest NPV, US$ 507 million, occurred with 12 pushbacks. Again, the interdependence between ore grade and SR constraints is evident. Due to the large impact of groundwater level on the project NPV´s, regardless the number of considered constraints, a new simulation study considering the inclusion of drawdown wells is justifiable. As a result, it may be necessary to set up a project to measure the environmental impacts in F4 mine region, which may lead to an additional request to extend the current groundwater pumping permit provided by state the environmental agency.

In order to demonstrate the accuracy of mine sequencing, considering hydrogeology, a comparison of the first 10 years of the production plan was made comparing to the sequencing without considering groundwater level. For this comparison, SR and ore grade were considered, as demonstrated in Table 1. The results are very similar as maximum variation of 4% occurred for: NPV, grade, waste and SR parameters. Although, it is important to say that the NPV results obtained are something that can be visually differentiated, presenting completely different mine sequences. Therefore, we can conclude that the groundwater level constraint (hydrogeology) for the first 10 years of sequencing is much more a matter of mining operations management and fulfillment of annual plans than financial. However, the operation of the mine is facilitated as far as water upwelling is concerned, considering the sequencing with hydrogeology.

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