HIDROGEOLOGICAL MODEL OF THE ITABIRA IRON ORE DISTRICT

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ABSTRACT

The Itabira Iron Ore District is located in the region called *Quadrilátero Ferrífero* (Iron Quadrangle), a very rich region with plenty of mineral resources (iron, gold, manganese, bauxite etc.). During the last 50 years, CVRD (Companhia Vale do Rio Doce) has exploited about one billion tons of iron ore in Itabira. In 1985, CVRD started dewatering activities of those mines and till now more than 50 million cubic meters of groundwater has been pumped.

The iron ore formation, dated from the Proterozoic inferior, is constituted mainly by hematites and itabirites, represents the main aquifer in the Iron Quadrangle, is called Cauê Aquifer, which contains about 4 billion cubic meters of groundwater. The Itabira Iron Ore District, where CVRD established the mining operations, is formed by the Itabira Syncline, which occupies of 12,4 km².

The city of Itabira has a population of 100 thousands and today its supply of surface water nearly covers the demands. In the near future the city of Itabira will need more water and they are complainig to CVRD that their dewatering activities are causing the water shortage. Because of this CVRD has defined with the county and the environment authorities, a study program to determine qualitatively and quantitatively the environmental impacts caused by dewatering of mines.

In 1998, CVRD has started this study and its final product will be the Itabira Syncline regional hydrogeologic model. This study will make a quantification of the available groundwater resources, as well as a prognosis of what will occur with water resources by the year 2020, when the mine activities will be completed.

Key words: modelling, dewatering, mine water environmental impact, iron ore minning.

INTRODUCTION

This paper summarises the results obtained from the hydrogeologic numerical modelling developed for the iron ore mining district of Itabira, Minas Gerais State, Brazil, where CVRD – Cia. Vale do Rio Doce performs large scale iron ore mining.

This model was developed with the purpose of studying the environmental impacts provoked by the process of lowering the water levels in several large iron ore mines that belongs to the CVRD's Itabira Mining Complex, as well as the behaviour of local water levels and also to quantify the groundwater resources contained in the geological structures that compose the referred world class mining district.

The completion of these studies was necessary for the evolution of the sustainable environmental concepts, in which the water resources are essential to the human survival. In this context, it was necessary that the community of Itabira, located in the neighbourhoods of the mining, know what are the groundwater resources available for the establishment of an integrated plan for the use of the water resources in the area.

GENERAL CHARACTERISTICS

The city of Itabira is located 100 km north-east of Belo Horizonte, the capital of the State of Minas Gerais (Figure 1), and it has a population of approximately 100.000 inhabitants. The regional relief is rugged and mountainous. In the lowest parts the elevations are between 700 to 900 m, supported by a domain of the basement granite-gnaissic rocks. The Itabira city was constructed on these rocks. The drainage is impacted by structural patterns, including fractures and faults, geological contacts and foliations.

Figure 1: Location of the itabira city

The area belongs to two hydrographic basins; to south the Rio do Peixe basin and to north the basin of Rio Tanque, both belonging to Rio Doce's basin. The watersheds divide is formed by the Serra do Itabiruçu, that extends from south-west to north-east, representing the more outstanding topographical feature, sustained by the alignment of the iron formation, with original maximum heights close to 1.400 m.

The pluvial regime is very well marked all over the year, with the humid period in November to February, and the dry period in the months of June to August. The seasonal climate is very well characterised by the pluviometric data, with temperate dry winters and hot and humid summers. The hydrologic regime is very important for the development of the future plans and also for the administration of surface and groundwater resources.

REGIONAL GEOLOGY

The area is covered by litoestratigraphic units distributed from the Archean to the Cenozoic. The Archean units are diversified, represented by the gnaissic-migmatitic complex, that composes the oldest basement; Borrachudo granitoid; supracrustal rocks of the Nova Lima Group and of the Sequence of the Serra da Pedra Branca and also undifferentiated mafics and ultramafics rocks.

The rocks of the Minas Supergroup and the intrusive mafic rocks in this set constitute Proterozoic units, while dikes of basic rocks of Mesozoic age cut the oldest units faintly. Finally, several strata of Cenozoic age represented by coluvial and talus deposits close the local stratigraphic column.

The gnaissic migmatitic complex occurs in an extensive area and most of the urban area of Itabira has been located in this unit. It is constituted by a group of gnaissified granitoids with intercalations of amphibolites, quartzites, schists and paragnaisses. The Borrachudo granitoid occurs in the extreme east of the region.

The Nova Lima Group involves the rocks of the Minas Supergroup and forms a strip that goes from the area of the Cauê Mine extending to south, beyond the mapped domain. It is composed of a variety of schists of metassedimentary and vulcanoclastic origin and the most common litologies are quartz clorita schists, quartzites, quartz sericite schists etc, with subordinated intercalations of silisic metacherts as well as amphibolites and metabasites. Gnaisses lenses and granitoids occur as nested structures within the Nova Lima schists and this fact can be observed on the walls of the Cauê, the Chacrinha and the Dois Córregos mines.

The Minas Supergroup forms the Serra do Itabiruçu or Esmeril, it has been built-in in the Nova Lima Group and it is represented by rocks of the Caraça, Itabira and Piracicaba groups. The rocks of the Caraça Group are very restricted and they just outcrop in a small strip in the vicinity of the highway access to Itabira.

The Itabira Group is essentially formed by the Cauê Formation, constituted by itabirites of oxide facies, rocks that are characterized by alternate bands of granular quartz and bands of hematite, magnetite and martite.

The largest itabirites concentrations are located at the Cauê, Dois Córregos and Conceição mines, being frequently observed bodies of inserted metabasics, that are interpreted as intrusive rocks or sinsedimentar volcanics. Hematite ore bodies in form of lenses often occur with two dozens of meters of thickness.

Between the Cauê and the Piracicaba formations there is frequent the presence of a decametric level of decomposed rock containing manganese and clay materials, interpreted as a thin strip of the Gandarela Formation.

The Piracicaba group closes the pre-Cambrian history of the area and it is formed by ferruginous quartzites, quartz sericite schists and phylites and more rarely carbonatic schists and manganesiferous dolomites. This package is shown quite foliated with subvertical structuring, and it occupies the nucleus of the structure, being involved by roks of the Cauê Formation.

Diabase dikes, possibly related to the Mesozoic age, subvertical and of thickness several meters, occurs in fractures striking NW-SE. These features are noticed at the Chacrinha, Dois Córregos and Conceição mines. Covering the whole sequence schists deposits of gravitational flow of debris constituted by levels of hematite, unconsolidated pebbles topped in general by red sandy-clay material and laterites.

STRUCTURAL INTERPRETATION OF THE IRON ORE DISTRICT

The large synclinal structure of Itabira (Figure 2) was defined by Dorr and Barbosa (1963) and was reinterpreted by Magalhães and Hasui (1998) as a large drag synform or, alternatively, as the overlap of mega chips or blocks, as a result of thrust tectonic. The south-east flank is discontinuous as a result of strong stretching and in the north-east flank occur large drag folds: Conceição, Dois Córregos and Cauê, where the largest thickness of the iron ore formation has been located.

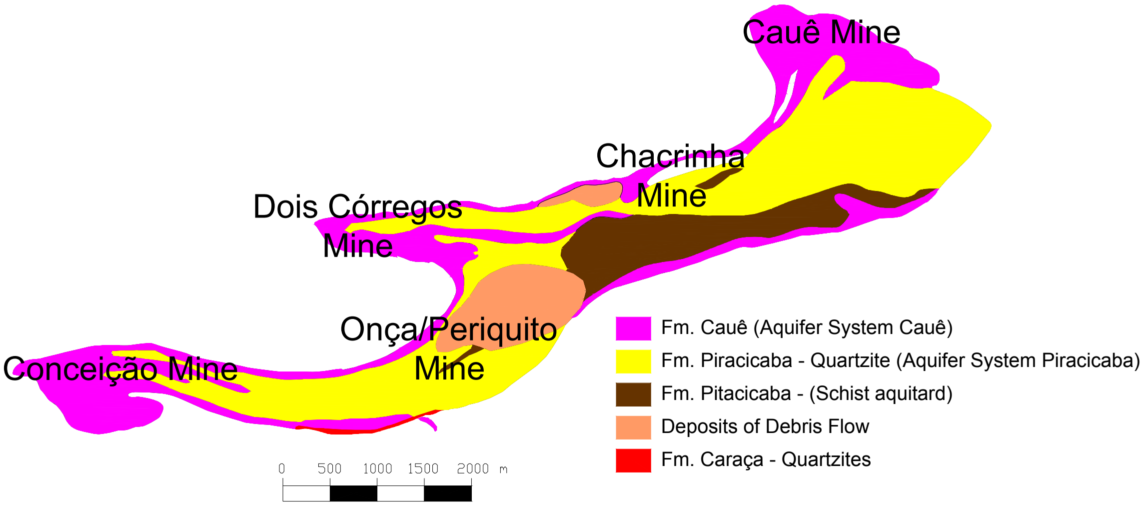

Figure 2: Geological map of Itabira iron ore district

The proposed kinematic model indicates an initial tectonic regime of oblique thrusting, in a ductile regime, with transport of east masses to west. This has generated nested tectonics and stratigraphic inversions, with the overlap of older units onto the newest ones.

Later, with the increase of resistance to the initial thrusting regime, a superimposition of a wrenching tectonics, of the dextral type occurred. This created the wrenching zones of Conceição, Dois Córregos, Cauê and of the Serra da Pedra Branca. This wrenching movement has generated the great drag folds of Conceição, Dois Córregos and Cauê. The southern flank of the synclinal of Itabira was included in the shear zone of Conceição, and the syncline is notably narrowed due to the great stretching.

This way the iron formation delineates two strips that can be continue in depth, but on the other hand form portions of repeated packages in juxtaposed chips. The fact that the iron formation in the south flank are not continuous, can be an indication that the iron formation were constituted by two chips; a model that can be repeat for the whole structure.

CHARACTERIZATION OF THE HYDROGEOLOGIC UNITS

The hydrogeologic units were defined according to the main litostratigraphic units, based on their lithologic characteristics. The Table 1 shows the association between the regional stratigrafic column and the present hydrogeologic units. There were identified six aquifer systems, correlated to the present regional lithologies that are, in order of hydrogeologic importance, as follows:

The Itabira Aquifer System, that embraces rocks of the Cauê and Gandarela formation, with homonymous aquifers, with the last one not represented in the study area, due to the small areal extent of the rocks that form it. The aquifer has a recharge area on the higher terrain, including the areas where the mines are located. The areas of natural discharge, where springs exist, are located in the southern part of the structure. Hydrochemically the water of the Cauê aquifer has a low salinity and low mineralization;

The Piracicaba Aquifer System, corresponding to the quartzites – quartzite aquifer, and schists – schist aquitard. It has a recharge area in the higher terrains, and the area of natural discharge, where springs are found, is located on the southern part of the structure. Hydrochemically they represent aquifers with average salinity. These Aquifers are classified as bicarbonate calcium-maganesiun types;

The Nova Lima Aquifer System, being subdivided into Aquifers in BIFs (banded iron formations) with small extension in the area, Aquicludes and aquitards in altered schist, Zones of Fractured Aquifers in fresh schists. They have a recharge area located on the whole exposed extension of the weathered rocks. The area of natural discharge constitutes small springs in the depth of the valleys where the water table surface is exposed. Hydrochemically they are aquifers with water possesses higher salinity and are more mineralisation;

The Crystalline Aquifer System, subdivided into aquifer zones located in lineaments represented by prominent fractures or fractured fresh rocks and aquitard in the weathered zone. It has a recharge area spreaded for the whole exposed extension of the rock when altered and the area of natural discharge in small springs in the bottoms of the valleys and also in the basis of the eroded soils called *voçorocas*;

The Coluvial Aquifer System, corresponding to the colluvial, deposits of debris flow. It possesses a recharge area for the whole exposed extension of the colluvial soils and the area of natural discharge, which is represented by small springs in the bottoms of the valleys, when the water table is exposed. This type of aquifer contributes mainly as recharge factor to the subjacent aquifers;

The Caraça Aquifer System, subdivided into aquifers in quartzites and aquicludes in schists, with limited occurrence in the area.

Estratigraphic Colum			Aquifer System	
AGE	Group / Formation	Litology	Aquifer System	Units
QUATERNARY		Deposits of talus, colluvial and fluvial type of trasported soils, gravel, sand and clays.	Colluvium	Colluvium
Paleocene		Deposits of gravel with iron formation fragments and colluvial of lateritic sand-clays.		
Jurassic Cretacic		Diabase dykes.	Aquiclude	Aquiclude
		Metabasic rocks tardi-tectonic.		
Lower Proterozoic	Piracicaba Group	Ferroginous quartzite, quartze sericitic schists and philites. Rarely carbonatic schists and manganiferous dolomite.	Piracicaba	Quartzit Aquifer
				Aquitard
	Gandarela Formation	Iron-manganiferous dolomite, schists, originally from carbonatic rocks.	Itabira	Aquiclude
	Cauê Formation	Itabirites, hematites, rarely manganiferous levels		Cauê Aquifer
	Caraça Group	Quartzite micaschist.	Caraça	Aquifers and Aquicludes.
Archean	Nova Lima Group	Schists, metabasites, metaultrabasites; rarely silicious and ferruginous metachert, banded iron formation and quartzites.	Nova Lima	Aquifer in metacherts and banded iron formation.
				Aquifer zones located in hard schist lineation fractures.
				Aquitard in weathered schists.
				Aquiclud in very argilous weathered schists.
	Borrachudo	Porphirodic gneiss.	Cristaline	Aquifer zones located in lineation fractures.
		Banded and migmatitic gneisses		

Table 1: Association between the regional stratigrafic column and the present hydrogeologic units

SYNTHESIS OF STRUCTURAL FRAMEWORK OF THE AREA

The interrelationship of the main aquifer systems is notably governed by the “Synclinal of Itabira”, delineated by the supra-crustal rocks, fitted in a granite-gnaissic substratum, whose waters don't interact with the waters that circulates in the syncline structure. All the collected piezometric data shows a hydrogeologic compartmentalisation that reveals an almost total independence of the waters of restitution of the granite-gnaissic basement (generically denominated crystalline rocks) of those that circulate inside the supracrustal rocks and that represent the main regional aquifer.

Thus, there can be identified two great different compartments: the first represented by the supracrustals and the second constituted by the granite-gnaissic basement rocks, which embrace most of the municipal area of Itabira. Among these two great compartments, there is a strip of variable width of green schists, correlated to the Nova Lima Group, that is in contact with the iron formation. It presents a predominant argylous character due to the weathering decomposition and constitutes an important hydraulic barrier, isolating the two great compartments, from each other. Therefore, it can be concluded that the impermeable substratum physically limits the Cauê and Piracicaba aquifer systems, from the aquifer system constituted by the crystalline terrains. Thus, there is not any hydraulic relationship between the groundwaters from the Cauê and Piracicaba aquifer systems and the Nova Lima and Crystalline aquifer systems.

The iron formation in Itabira delineates two strips that can be continuous in depth, but it is also admitted, alternatively, that they can be portions of packages repeated in juxtaposed chips or blocs. The fact that the iron formation, originated from the south flank of the Conceição Mine, is not linked in surface with the exposed layer of Água Santa / Morro of Cruzeiro / Povoado dos Pinheiros can be an indicator that the south flank can be constituted by two blocks, each one with segments of the iron formation. In other words, it can be said that the existence of the fold is possible, although generated by another mechanism different from the one considered until now, but it is also possible that this structural feature is represented by three piled up chips whose limits can not be yet defined. These alternatives are extensive for the Piracicaba Group.

In spite of the non existence of supporting data, the hidrogeologic model assumes hypothesis of the existence of a syncline, with the rocks of the north and south flank linked together in subsurface. Assuming this hypothesis, the worst alternative is adopted for the potential impact caused by the lowering of water level due to mine dewatering in the regional hydrogeologic context. In other words, assuming the existence of the syncline, it is also assumed the existence of a very larger impact in the circulation of groundwater in the existing aquifers in the area of Itabira.

GROUNDWATER FLOW NUMERICAL MODEL

The numerical model used for the simulation of groundwater flow is called MODFLOW, developed by U.S.G.S / IGWMC (United Sates Geological Survey, Mc Donald and Arlen, 1988). The used software was the Visual Modflow, version 2.61, developed by Guiguer and Franz – Waterloo Hydrogeologic, Inc., Ontario. Visual Modflow is a software that transports for a graphic interface the structure of MODFLOW, facilitating the entrance of data, as well as the visualization of the results. The numerical model was based on all available geological information and hydrogeologic data.

The construction of the numerial model for simulation of the groundwater flow in the Itabira Mining Complex was based on a rectangle of 1270 meters by 6120 meters, embracing the area of concern. The model includes seven zones of blocks of equal conductivity and seven zones of equal storage, corresponding to the six systems of defined aquifers and an aquiclude formed by the intrusive basic rocks (Figure 3). The determination of the initial hydraulic parameters for each aquifer type was based on the interpretation of the pumping tests of the existing wells. Nine blocks were assigned constant load (Constant Head), corresponding to the existing springs located inside of the area of the active cells of the model.

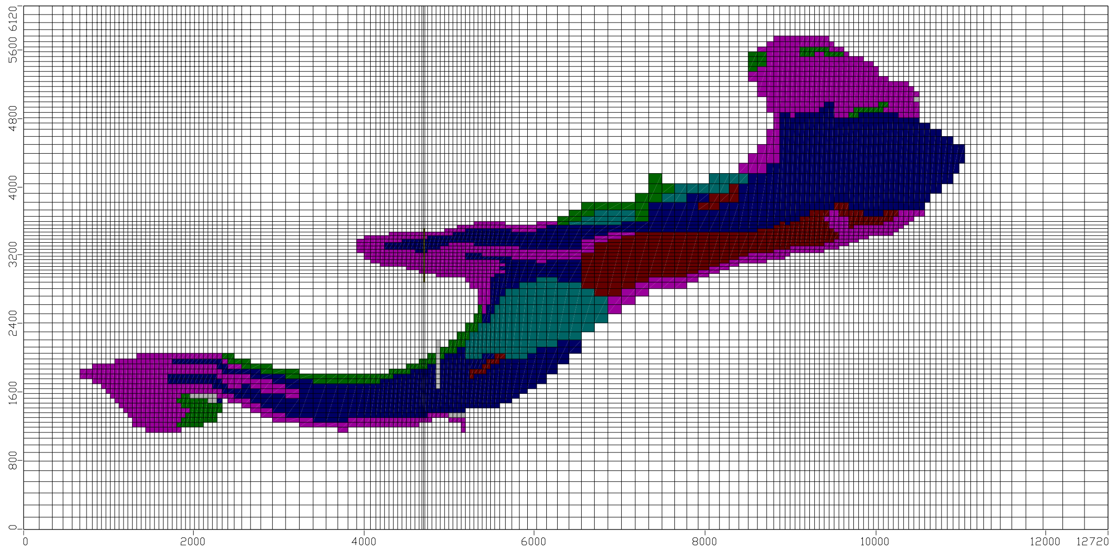

Figure 3: Grid of the numerial model

Initially the numerial model was calibrated for steady state conditions supported by the piezometric data and the previous pluviometric data base as well as the monitored water levels collected in the hydrologic year of 1985. The result of this steady state calibration was considered satisfactory, if an error in water levels was smaller than 7%, taking into account that the resulting piezometric surface of this calibration shows the conditions of initials hydraulic load of the aquifers, before the beginning of the process of mines dewatering.

The recharge in the model was a calibration parameter, and the resulting value was 0,0007 meter /day, that corresponds to 17% of the annual average rain taking into account registers of precipitation for the Cauê and Conceição mines, in the period from 1976 to 1988.

After the steady state modelling, the numerical model was also calibrated in transient regime, using as initial hydraulic load, and the result of the calibration in steady state. The calibration period in transient regime embraced the piezometric data between September,1st 1985 and May 31st 1999, representing a time interval equivalent to 5021 days, divided into 29 periods. The beginning of this interval corresponds to the beginning of the dewatering activities. The final date corresponds to the adopted date of the beginning of the works of mathematical modelling.

As calibration objective the comparison between the measured piezometric data from the mines and the piezometric surface calculated by the model, the rate of wells pumping, observed in a total of 59 piezometers were used. The values of the recharge in the model were calculated through the hydrologic balance accomplished by the SMAP model, considering the precipitation data for the pluviometric stations located one in the Cauê mine and another in the Conceição mine.

To simulate the drawdown conditions in the model, we included drains to simulate the effect of the existing springs in the modelled area. The volumetric flow rates of the springs were object of calibration, through the adaptation of the conductance of the drains. During the period corresponding to the calibration of the transient **regime** it was extracted from the aquifer a total of 63.291.057 m^3 of water through the pumping in deep tubular wells.

The calibration process consisted of the necessary adjustments of the hydrodynamic parameters, mainly in the storage values of the discretized aquifers, while the values of hydraulic conductivity were calibrated in steady state and adjusted mainly during the calibration in transient state. In this way the calibration of the numerical model in transient **state** included the comparison of the measured water level versus calculated level, taking into consideration the time of running the numerical model, comprising 5021 days. Figure 4 shows the curves of calibration of the numeric model for some piezometers used in the calibration.

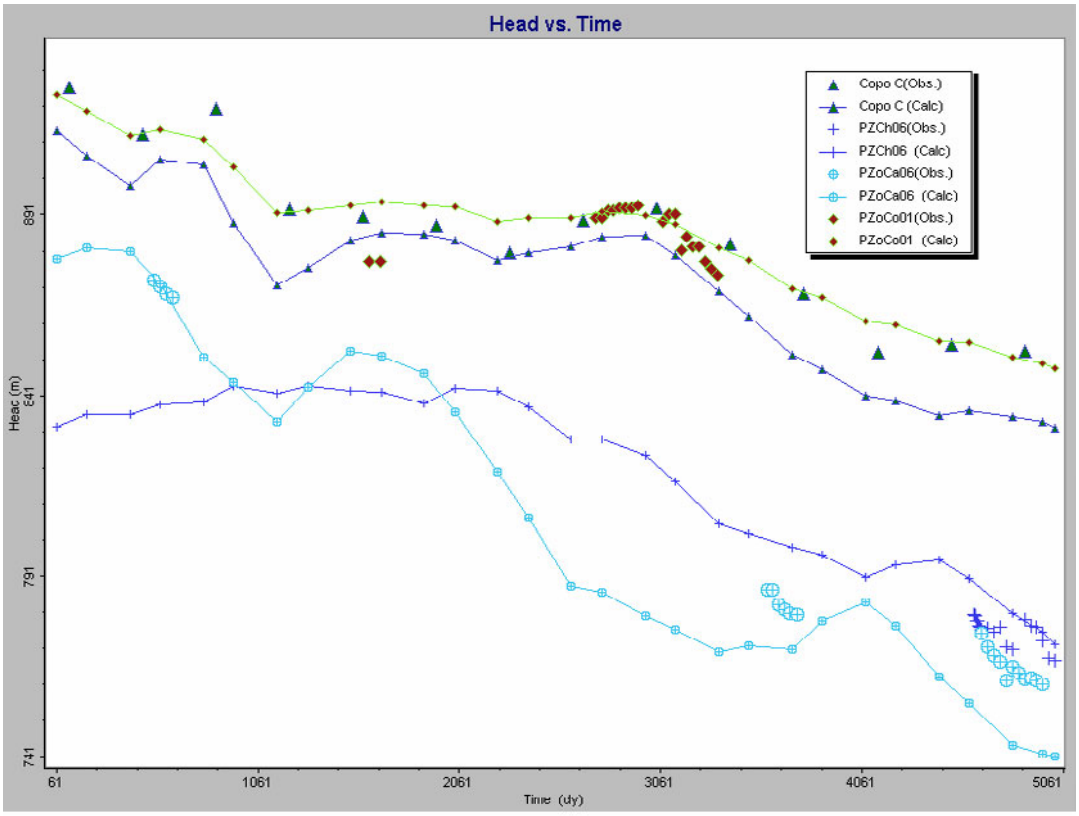

Figure 4: Curves of calibration of the numerical model for some piezometers used in the calibration.

SIMULATION OF THE MAXIMUM WATER LEVEL LOWERING AND ITS RECOVERY

Finally, it was possible to perform prognosis of the regional water level lowering under the condition of the mines dewatering and the subsequent recovery of the water level until the establishment of the pre-mining conditions. The first phase of the study extends until October 2016, while the water level recovery phase, is prolonged up to 2040.

During the lowering period, the mines will be sequentially decommissioned, in such a way that the performed simulations considers not only the lowering of the water level by the mines operation, but also the recovery of water levels after the stoppage of the water wells pumping in each mine. The results showed that to reach the final water levels it will be necessary to produce from the aquifers around 118.546.440 m3 of water.

To represent hydraulic properties of the excavated rocks, new hydraulics properties, as permeability and storage were defined. These new values represent and simulate the generated voids (that can be filled with water) with a hydraulic conductivity (K) of 9999999 m/day and a storage (S) of 0.999999.

Besides the underground recharge, it was necessary to consider in this simulation that all precipitation on the excavations will be accumulated in the mines causing the formation of lakes in the bottom of the pits and causing a faster recovery of the aquifer water levels.

QUANTIFICATION OF THE GROUNDWATER RESOURCES

The quantification of available groundwater was calculated by the numerical model, contemplating the existing aquifers. This quantification is presented as Regulating Reserve that represents the amount of free water stored by the aquifer to the course of the recharge in one hydrologic year. Geological or permanent groundwater reserve is the not, renewable groundwater that remains stored independently of the natural volumetric flow rate.

Aquifer	Geological reserves (m^3)	Regulating reserves (m^3)	Total (m^3)
Itabirite	240,610,513	1,509,139	242,119,652
Hematite	65,423,951	290,716	65,714,667
Quartzites	21,060,031	2,044,973	23,105,004
Schists	7,266,778	628,597	7,895,375
Total	334,361,273	4,473,425	338,834,697

Tabel 2: Summary of the geological and regulating reserves

The accomplished calculations, shown in Table 2, presents that the largest portion of the groundwater stored are in the itabirites, followed by the hematites, quartzites and schists. The regulating reserve shows the volume infiltrated in the aquifers during one hydrologic year, is equivalent to a volumetric flow rate of 510 m^3/h or 141 L/s. This value for the regulating reserve is equivalent to the real quantitative impact caused by the dewatering activities, and any additional volume of captured water is considered as exploitation of the aquifer.

THE IMPACTS

The principal negative impacts caused by the lowering of the water levels of the CVRD's mines in Itabira are:

1) Decreasing of the geological groundwater reserves: In order to achieve the necessary water levels for draining the mines, the following volumes of water are to be pumped from the aquifer:

- Measured volume (till May/1999): 63,291,057 m^3
- Calculated volume to be pumped (from May, 1999 to March, 2016): 118,546,440 m^3

The sum of the pumped and to be pumped water volumes results in 175,923,103 m^3 for a period equivalent to 31 years (1985 to 2016). In this period the renewable reserve will be 4,473,425 m^3 of water per year, so in 31 years it represents a volume of 138,676,175 m^3 water. The impact on the permanent groundwater reserve is 37,246,928 m^3 water, in other words, 11% in relation to the initial reserves, that was calculated as 334,361,273 m^3.

2) Decreasing of the volumetric flow rates from the associated springs:

The numerical model indicated that since the beginning of the dewatering activities of the CVRD's mines, the reduction of the discharge of water from the springs associated with the pumped aquifers is taking place. The simulations show that this decrease will continue until the end of the operation of all the mines, in the year 2016. Starting from this period, with the recovery of the water level, a small recovery of some springs will take place, arriving to a volume of 391 m^3/day, equivalent to 14.7% of the daily volumetric flow rate calculated by the model for the year 1985, which was equivalent to 2,653 m^3/day.

The unique spring that won't have its volume totally exhausted will be the NA19, located at the Av. Carlos Drumond de Andrade, because this fountain is situated in the lowest elevation.
For the simulated period, based on the year 2040, only the NA14 (Água Santa) and the NA19 will have a recovery of their volumes, which will be around 45% in relation to the volume in May 1999 for the first and 68% for the second spring.

MITIGATING AND COMPENSATORY MEASURES

To mitigate the impacts caused by the overpumping of groundwater in the CVRD's mines in Itabira, the company has established a plan to supply groundwater for the community of a minimum know of 512 m^3/h or 142 L/s. These values correspond to the annual regulating reserve and are understood as the direct impact caused by the pumping.

Besides this fact it is possible to increase the recharge of the aquifer, by filling the pits of the decommissioned mines with water coming from the precipitation and runoff. It is also advisable to maximize the captured volume from the precipitation.

The possible impacts on the already existing wells will be compensated with the installation of new wells in order to compensate the reduced volume flow rate. With a deeper wells the negative effect of the partial penetration will reduced.

CONCLUSIONS AND FINAL CONSIDERATIONS

The presented numerical model quantifies the impacts of the dewatering activities at the CVRD mines in the Itabira iron ore district. The groundwater volume to be pumped in order to achieve water levels required for the mines activities, includes the whole regulatory reserve and approximately 16% of the calculated permanent reservation, during the thirty one years of operation.

Pumping of groundwater from the aquifers will be responsible for the depletion of the water level not only in the area of the mines, but also in the sorrounding areas, causing the reduction of the flow rate of the springs associated with the pumped aquifers, the Cauê and the Piracicaba.

The permanent groundwater reserves, also called *geological* reserves are calculated for the Itabira and Piracicaba aquifer systems, and are estimated as approximately 334 $\times 10^6$ m^3. The minimum value to be obtained is around 260 $\times 10^6$ m^3 in 2016, and will recover to the pre-mining levels around the year 2040. This means that the replacement of these impacts is perfectly feasible by the own natural recovery of groundwater in the studied aquifer systems.

The numerical modeling was completed in most conservative way, so the impacts presented in this study will be larger than the reality, because it was assumed, according to the best knowledge, that the conditions allow maximizing of these negative impacts.

Based on the presented geological model as well as on hydrological evidences, the connection of the aquifers systems presented in the Minas Supergroup with that present in the Nova Lima Group and the Granitic-Gnaissic Complex was rejected. However such fact will be corroborated by the continuous monitoring of the drains, springs and wells networks. This monitoring shall be performed continuouslyfor every hydrologic year, continuously, until the recovery to the initial conditions of the groundwater, or until the attainment of a stable condition of this flow. In other words, the monitoring will be performed till the system achieves its equilibrium.

The mitigation measures presented here will be associated with a joint management of the use of the surface and groundwater resources. This integrated management will be known as an administration that allows the maximization of the use of groundwater in the dry periods, supplying the existing deficit of the surface water resources in this period of the year, and the inversion of the system in the rainy season, with the use of the maximum capacity of the surface resources, leaving inactive the groundwater pumping system, leading to a recovery of the aquifer's storage.

It is pointed out that according to the available data, the exploited aquifers flow rates in more than 140 L/s shall be considered as over-exploitation. The hypothesis of filling the mines excavations with meteoric water will noticeably increase the recharge rate. Besides this it is also clear, that the availability of the water stored in the pits, will also be considered.

With the objective to confirm and improve the proposed hydrogeologic model and to monitor the impacts generated by the mine dewatering, the continuity of the existing monitoring is strongly recommended. Whenever necessary the implementation of new instruments and complimentary studies should be considered.

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