DEWATERING OF IRON ORE MINES AND CAPABILITY TO PREDICT ENVIRONMENTAL IMPACTS – THE EXPERIENCE OF MBR

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ABSTRACT

The Águas Claras and Mutuca iron ore mines, reached the watertable in the 80's, starting the dewatering by using series of deep wells. In the 90's, some communities located near the mines, complained about the possible interference in the stream's outflows and so, the areas covered by hydrogeological studies were enlarged in order to embrace the neighbourhood of the mines.

These hydrogeological studies, carried out during the last 15 years, form the basis of the understanding of the groundwater behaviour in the Quadrilátero Ferrífero (Iron Ore Quadrangle). This knowledge has been proved to be effective in the prediction of impacts on the outflows related to the newest MBR's mines - Tamanduá, Capitão do Mato and Pico as well as Capão Xavier deposit.

Key words: mine water, iron ore, environmental impact, hydrogeology

INTRODUCTION

As a consequence of the raising in the international iron ore trade, occurred after the world war II, in order to supply the increasing worldwide steel production, large iron ore mining projects were developed in many countries during the 60's and 70's, with the dominance of Brazil and Australia, that shear 60% of the seaborne trade since the middle 70's.

In the case of Brazil, an iron and steel making industry were implemented in the Southeast of the country, close to the consumer market and also to the iron ore reserves of the Quadrilátero Ferrífero (Iron Ore Quadrangle), a major Brazilian mining district.

Based on the steel making industry, an important industrialisation process occurred in the metropolitan region of Belo Horizonte, capital of the Minas Gerais State, located right to the north of the Quadrilágero Ferrífero. The industrialisation caused a fast growing of the population of this metropolitan region, presently with around three million inhabitants.

The demographic rising increased the demand for water, satisfied only in the 70's, with the construction of a large (surface) water caching system in the centre of the Quadrilátero Ferrífero, the Rio das Velhas System. This system is responsible for more than 50% of the water supply of the Belo Horizonte metropolitan region (Azevedo, 1997).

As a consequence of this fact, the northern part of the Quadrilátero Ferrífero started to be object of three major economic activities: water supply, iron ore mining and urban occupation.

Many iron ore mines reached the water table in the 80's, developing hydrogeological studies to promote the mine's dewatering. These studies improved a lot the understanding of the groundwater behaviour of the Quadrilátero Ferrífero. This is the case of Minerações Brasileiras Reunidas S/A – MBR, an iron ore mining company that, during the last 30 years, have been operating in the northern and western parts of the Quadrilátaro Ferrífero, on environmentally sensible sites, with mines located close to Belo Horizonte, villages and/or water caching areas.

The aim of this paper is to report the development of the hydrogeological studies carried out during the last 15 years and the solutions found to make compatible the iron ore and water exploitations.

GENERAL LOCATION

With 700 km of extension, the Velhas River has its beginning near the city of Ouro Preto and runs north-northwest up to its mouth, at the right margin of the São Francisco River, near to the city of Pirapora, both in the Minas Gerais State (figure 1). On its firsts 70 km – between Ouro Preto and Belo Horizonte - the Velhas River runs over the mining district of the Quadrilátero Ferrífero.

Figure 2 represents the simplified geological map of the Quadrilágero Ferífero as well as the (upper) Velhas River basin, the location of MBR's mines, the major water caching points and cities.

Figure 1 – Location of the Velhas River Basin

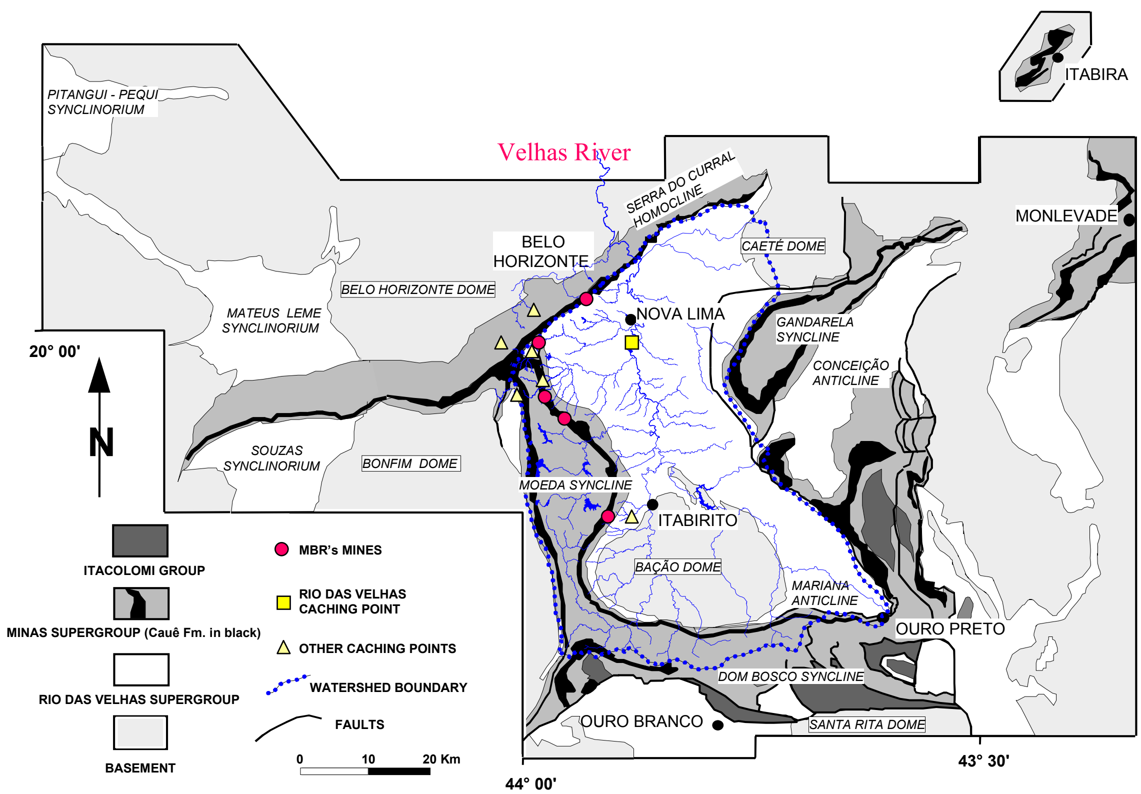

Figure 2 – Simplified geological map of the Quadrilátero Ferrífero (Alkmim et. al.,1998) and (upper) Velhas River Basin

From north to south, the MBR's mines represented in figure 2 are: Águas Claras, Mutuca, Tamanduá, Capitão do Mato and Pico. The Rio das Velhas water caching point is located at the centre of the Quadrilátero Ferrífero, a few kilometres south to the city of Nova Lima (figure 2). There are other water caching areas close to Mutuca, Tamanduá and Pico mines, the last one, supplying the city of Itabirito and the others, Belo Horizonte (figure 2).

HYDROGEOLOGY OF THE QUADRILÁTERO FERRÍFERO

Due to its great economic potential, the Quadrilátero Ferrífero is probably the most well known region in Brazil from the geological point of view. It was mapped at the scale 1:25.000 (Dorr, 1969) and count with more than one hundred publications from several authors.

The pre-cambrian sequence of the Quadrilátero Ferrífero is subdivided in four stratigraphic units: *Archean-Metamorphic Complex, Rio das Velhas Supergroup, Minas Supergroup and Itacolomi Group* (figure 2). These units interact differently with the hydrologic system due to lithologic diversities, controlling the groundwater behaviour.

The Quadrilátero Ferrífero is characterised by a structural style of "domes and keels" where the archean rocks of the basement outcrop at the domes and paleoprotherozoic metasediments at the keels (Alkmim & Marshak, 1998). The basement rocks are dominantly of low permeablity, while the major aquifers are related to the protherozoic sequences. The aquifers of the keels are, in general, surrounded by the impermeable rocks of the domes, forming traps favourable to the water accumulation (figure 2).

The portion of the Velhas River's Basin situated south to the Serra do Curral homocline (near Belo Horizonte) is represented in figure 2 and occupies a surface of 2.250 km^2.

The oldest geological sequence outcropping at this basin is the *Archean-Metamorphic Complex* being represented by the Bação dome (figure 2), that occur at the centre-south of the area. It occupies an area of 400 km^2, what represents 18% of the basin. There are few available information of the hydrogeological characteristics of this unit, however, by analogy with other granite-gnaissic basement terrains, it probably corresponds to a mixed aquifer related to thick cover of soil over granite-gnaissic fractured rocks.

The *Rio das Velhas Supergroup,* correspond to an archean greenstone belt sequence, with volcanic rocks covered by metasediments. Lithologically, predominate rocks of low permeability like schist and phylite, existing also bodies of quartzite and lenses of banded iron formation (uneconomic form the iron ore point of view). This sequence occupies the major part of the basin: 53% or 1.200 km^2. This unit hosts gold mineralization and, the presence of underground gold mines up to 2.000 m deep, without requiring any watertable lowering system, confirm the low permeability of these rocks.

The *Minas Supergroup* occur at the border of the basin getting within it at the western and south limits (figure 2). Occupies an area of 650 km^2 corresponding to 29% of the basin. It overlies, in discordance, the Rio das Velhas greenstone belt and consists in a thick sequence of protherozoic metasediments. From the base to the top occur, with remarkable lateral continuity, a sequence of quartzite, phylite, itabirite (banded iron formation) and dolomite, belonging respectively to the Moeda, Batatal, Cauê and Gandarela formations. Overlying the dolomite, there is a sequence of rhythmites composed by decimetric to metric layers of quarzites alternated with silver coloured phylite of the Cercadinho Formation (basal unit of the Piracicaba Group). The upper units of the Piracicaba Group as well as the Sabará Group (top of the Minas

Supergroup) are composed by clastic (pelitic) sediments with lenses of carbonate, in complex shapes and high lithological diversity.

The phylite of the Batatal Formation acts as aquiclude. The top units of the Piracicaba Group, as well as the Sabará Group, are less known from the hydrogeological point of view. However, as they are mainly composed by low permeability rocks (schist, phylite and lenses of dolomite) they shouldn't form important aquifers. The other units (Moeda, Cauê, Gandarela e Cercadinho) are aquifers (Silva et. al., 1994).

The protherozoic sequence (mainly the Cauê Formation) is crosscut by intrusive dikes of basic volcanic rocks that act as hydrological barriers, splitting the (Cauê) aquifer in independent blocks, without hydraulic connection between them. This kind of structure occur at Mutuca, Tamanduá, Capitão do Mato and Pico mines. In some cases, the presence of such dikes is responsible for the diminution of the effects of the lowering of the watertable, outside the mine site.

Due to a differential erosion process, the units of the *Minas Supergroup* (including the aquifers) occupy the highlands and the archean basement, the lowlands. The Protherozoic sequence is surrounded, at the flanks and in depth, by low permeability rocks (i.e. phylite and schist) making difficult the flow of the groundwater, stored in the plateaus (higlands), to the lower regions at the vinicity. Because of this, the watertable at the plateaus are, in general, 200 to 400 m higher than the topographical surface at the lowlands, composed by the archean basement (schist of the *Rio das Velhas Group* and granite-gnaisse terrains).

Hydrogeological studies carried out in small basins of this region (Rubio et. al., 1997; Amorim & Alkmim, 1998; Rubio et. al., 1998; Amorim et. al., 1999; Amorim & Alkmim, 1999), describe an important and very frequent type of aquifer: the **shallow circulation related aquifers**. They are composed by coluvial soils, talus deposits and debris materials that occur on the valleys of the lowlands, over impermeable basement. They form independent systems, where the recharge is the direct rainfall over the basin and the discharge occur as hypodermic flows to the streams. Once they are not hydraulically connected with the protherozoic aquifers, the lowering of the watertable, carried out, by the mining companies, at the Cauê aquifer, do not affect these shallow systems, even when they are located close to the mines.

CHARACTERISTICS OF THE CAUÊ AQUIFER

The Cauê Formation, that hosts the iron ore reserves, consists of (oxide facies) banded iron formation formed by (1 mm to 1 cm thick) bands of iron oxides intercalated with bands (with similar thickness) of quartz and/or dolomite, named *Itabirite* in Brazil. The fresh rock (protore) averages 35 – 45% Fe. Its origin is sedimentary chemical.

From the hydrogeologic point of view, it forms a complex, heterogeneous and anisotropic aquifer, sometimes acting as impermeable rock. Being a metamorphic rock, the porosity of the itabirites is secondary, associated to fractures and to the voids of the leaching in the soluble facies.

The fresh itabirite is a hard rock and, if not fractured, shows low permeability. Nevertheless, it is not resistant to the chemical weathering and so, the Cauê Formation is normally characterised by thick alteration mantle that, in some cases, can get to 500 m in depth (i.e. Tamanduá and Águas Claras mines).

The most frequent high grade iron ore is the *soft hematite*, generated by supergenic enrichment processes. It is formed by the preferential leaching of the dolomite, on the variety *dolomitic itabirite*, or the quartz, on the (standard) *siliceous itabirite*, leaving a residual iron enriched rock (66 – 69% Fe). If the leaching is not complete, an intermediary enriched rock (50 – 58% Fe) is generated. Anyway, this enrichment is promoted by the circulation of meteoric water through the iron formation and, because of this, the high grade supergene ore is always related to groundwater flows.

There is another kind of high grade ore that, despite not being genetically related to the groundwater circulation, plays an important hydrogeological role: the *hard hematite*. As a consequence of a combination of sedimentary and metamorphic processes, some lenses (varying in tonnage from less than one to more than 50 million tonnes) of hard hematite (67 - 69% Fe) are formed. They are hard rocks, showing sharp contacts with the other types of itabirites and forming bodies of complex shapes. They are commonly fractured, showing high transmissivity and, because of that, the dewatering wells installed in these bodies are the best ones in productivity.

Due to the tectonic events that acted on the Quadrilátero Ferrífero, the Cauê Formation usually shows dips between 40º and 90º. In general it is a free aquifer, laterally confined by phylites of the Batatal Formation (stratigraphic base) and dolomites of Gandarela Formation (stratigraphic top) that, excluding one important exception, are not hydraulically connected with the iron formation. Intrusive dikes may, also, promote lateral confinement within the Cauê unit.

SURFACE HYDROLOGY OF THE DIFFERENT TYPES OF AQUIFERS

The lateral confinement of the Cauê aquifer may, in some places, be disrupt due to the existence of geological faults and/or effects of the erosion, exposing the watertable and promoting the natural discharge of this aquifer to the surface. This kind of spring can be affected by the lowering of the watertable for mining purposes, depending on the distance of the mine, the existence of barriers between the mine and the spring, the altitude of the spring etc. The identification of these discharge points is an important part of the studies, carried out by MBR, around the mine sites, in order to predict impacts of the lowering of the watertable developed in the mines. This identification is done by geological mapping, springs inventory and outflow control.

Due to their different origins, the springs related to deep circulation can be differentiated from the shallow circulation waters by the following distinctive hydrologic characteristics:

(a) variability of the outflows

The deep circulation on the Cauê aquifer promote a high capability of regulation for these systems and, as a consequence of this, their related springs have low seasonal variability of the outflows, compared to the ones typical of the shallow aquifers. This is presented on figure 3, where the control points named Fechos aux., Mutuca aux., Catarina aux. and Cata Branca are discharge points of the Cauê Formation and the others are related to shallow aquifers.

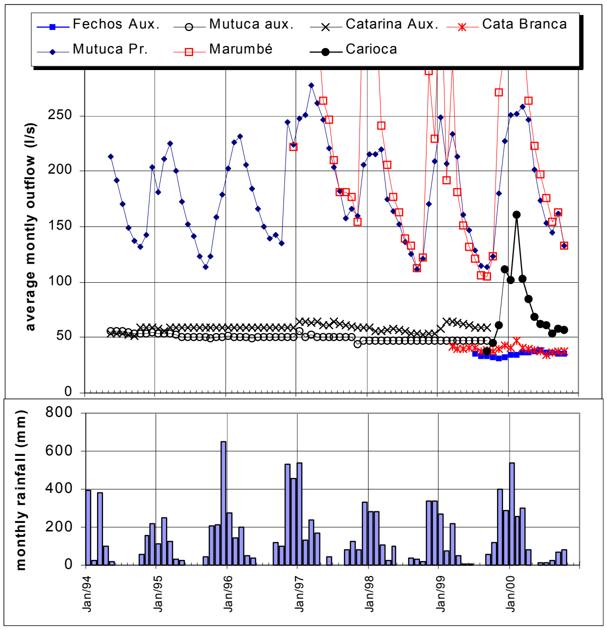

Figure 3 – Average monthly outflow in different watersheds.

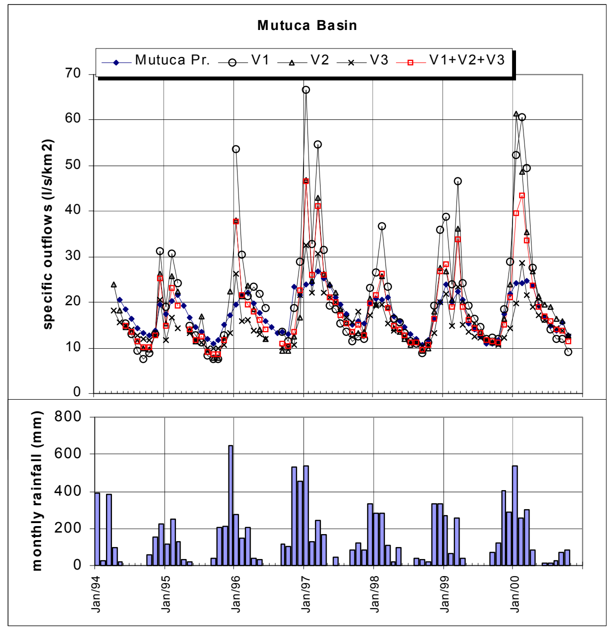

Figure 4 – Specific monthly outflow in different control points of the Mutuca watershed

(b) Punctual or diffuse spring up

The shallow aquifers are characterised by having an uniform unitary contribution along the stream, because the aquifer is almost uniformly distributed over the basin. This can be seen in figure 4, that represents the specific outflow, measured in different points of the same (swallow circulation related) basin. The discharge point of the Cauê Formation, on the other hand, are characterised by punctual spring up, structurally (fault) and/or topographically (erosion) controlled.

The above distinctive characteristics, allied to a good geological knowledge, make relatively simple the identification of the discharge points of the Cauê aquifer in the field, what is fundamental for planning the mitigation measures, to be adopted in case of interference of the watertable's lowering.

At the MBR's mines sites, this survey have already been done, including around the future mines, and all the discharge points count with systematic monitoring programmes. Despite the fact that no significative impact have been detected so far, the hydrogeological studies point out that reduction of the outflows may occur in some deep circulation related discharge points. In each case, the mitigation measure have already been planed and, in some cases, implemented (before the impact).

MBR'S MINES DEWATERING AND RELATED ENVIRONMENTAL IMPACTS

Águas Claras Mine

The Águas Claras Mine reached the watertable in 1981 and, up to 1990 the drainage was done by channels. The tubular deep wells started to operate in 1988 and, by 1990, the mine was completely dry and operating in safe conditions (Bertachini, 1994).

From 1981 to 1988 the average outflow of the drainage channels was 22 l/s and the watertable was lowered in 61 m, from the original altitude of 1.174 m to 1.113 m. From 1989 to 1999, with an average pumping rate of 73 l/s, the wells promoted the lowering of the watertable to the level 900 m, corresponding to 274 m below its original position.

The Águas Claras Mine is located in the south-east flank of the Serra do Curral homocline (figure 2). Just in the opposite north-west flank of the ridge, there is the municipal Mangabeiras Park of Belo Horizonte, implemented in 1982, over a former iron ore mine. There is a small stream that runs over the park, the Mangabeiras Creek. Its highest springs are at 1.165 m of altitude. At the centre of the park, the stream is at 1.050 m of altitude.

In the dry season of 1989, right after the beginning of the pumping at Águas Claras Mine, the Mangabeiras Creek showed a (visual) anomalous reduction of the outflow, what was attributed to be a consequence of the mine's dewatering. In 1990, hydrogeological studies were carried out, by MBR, at the Mangabeira's Park, concluding that the the Mangabeiras Creek is related to the Cercadinho aquifer, not connected with the Cauê aquifer, due to the presence of the Gandarela Formation in the middle, acting as a barrier. The reason pointed out to explain the low outflow was the anomalous dry season at that year (Bertachini, 1994).

Eleven years after the development of that study, being close to the mine's closure and having achieved the maximum lowering of the watertable, the monitoring programme implemented at the Park, shown to be correct that interpretation.

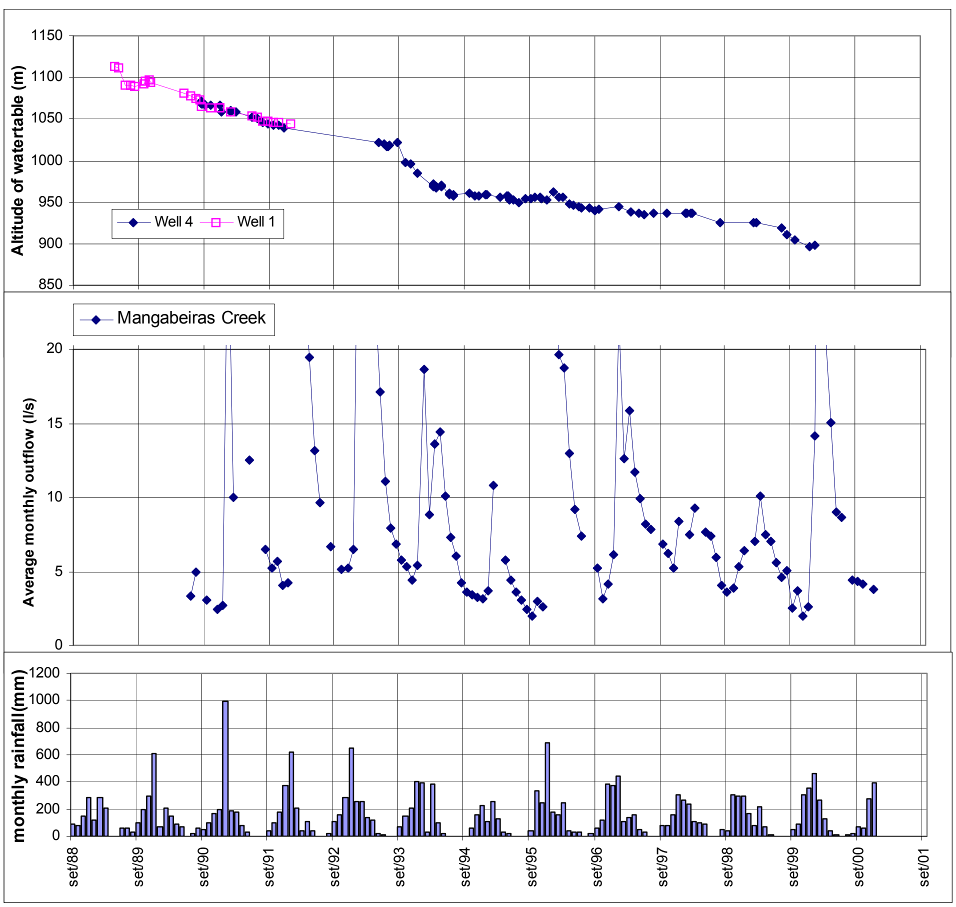

Figure 5 – Temporal evolution of the watertable level at Águas Claras Mine, monthly outflow of Mangabeiras Creek and rainfall rate at Águas Claras Mine

The upper part of figure 5 represents the temporal evolution of the watetable at the mine. In mead 1991, the watertable was at the same altitude of the Mangabeiras Creek at the park and 115 m below its highest spring. At the end of 1999 the watertable was 150 m below the stream at the park and 165 m below the springs.

The central graphic of figure 5 shows the outflows of the Mangabeiras Creek recorded at the park. It can be seen that no impact has occurred. The seasonal variations of the outflows are related to the annual variation between dry and rainy seasons (see lower part of figure 5).

This study, carried out in 1990, is an important reference for MBR, since it marks the beginning of the definition of regional models and the development of methodology to predict environmental impacts related to the lowering of the watertable in the mines.

Mutuca Mine and Capão Xavier Deposit

In 1984, when the bottom of the Mutuca Mine's pit got to the level 1.250 m, the watertable was reached. It was lowered by drainage channels in 37 m (up to level 1.213) by 1988, when the drainage wells started to operate. The average pumping rate or these wells, from 1988 to 1999, was 29 l/s, and the watertable was lowered up to the level 1.050 m, what means 200 m below its original position.

Mutuca Mine is partially located within the basin of the Mutuca Creek, where the water is collected to integrate the water supply system of Belo Horizonte. The water caching point is at 1.100 m of altitude and the springs occur between 1.200 and 1.300 m of altitude.

The hydrogeological studies on this region, with environmental focus, started in 1993, in order to assess the eventual impact of the dewatering to be developed in the future Capão Xavier Mine, also partially located in this basin.

The Mutuca Creek's watershed is mainly located over impermeable basement composed of schists of Nova Lima Group, being typically a shallow circulation related aquifer. In the case of Capão Xavier, the future lowering of the watertable, will cause no impact in this river, due to the lack of hydraulic connection between the aquifers.

As Capão Xavier Deposit and Mutuca Mine are in similar hydrogeological conditions regarding to the Mutuca Creek, the already developed dewatering of Mutuca Mine is the practical confirmation of this model, since it did not interfere on the Mutuca Creek's outflow as can be seen in figure 6.

The hydrogeological study carried out for Capão Xavier, however, identified discharge points of the Cauê aquifer, in other basins, that may suffer interference from the further mine's dewatering. This impact, if occurs, will be mitigated with the mine water, according to an environmental management system, already developed (Amorim et. al., 1999).

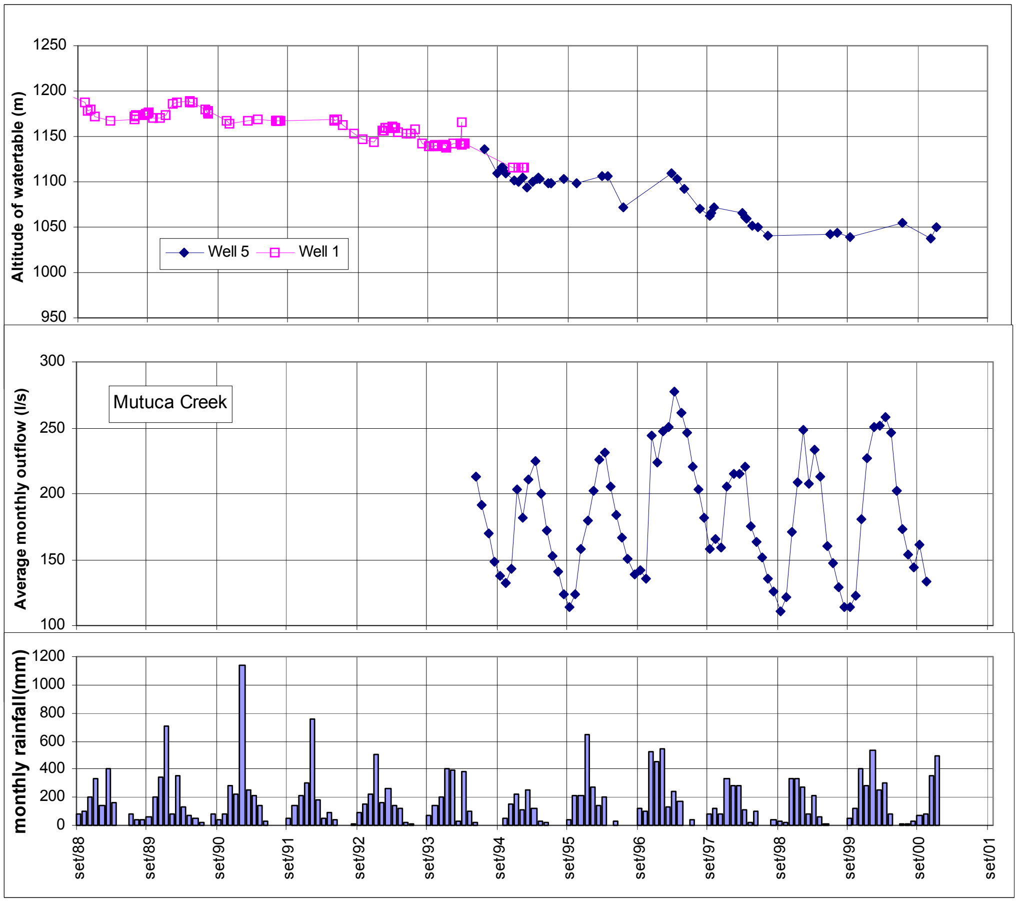

Figure 6 – Temporal evolution of the watertable level at Mutuca Mine, monthly outflow of Mutuca Creek and rainfall rate at Mutuca Mine

Tamanduá and Capitão do Mato Mines

These two mines form a mining complex located in the east flank of the Moeda Syncline. Between the two mines and over the Cauê Formation, there is a village named Morro do Chapéu. The village have three supplying wells that used to collect water from the Cauê aquifer.

The hydrogeological studies carried out in 1994, indicated that the lowering of the watertable to be developed at both mines will impact the production of the Morro do Chapéu's wells, as well as two discharge points of the Cauê aquifer.

The dewatering of these mines didn't start yet but, as part of an agreement with the people of the village, a first dewatering well was anticipated, in order to supply the village. This has been done in 1995 and, since that time, the pumping at the village's wells were stopped and the total village's supply comes from the mine.

A monitoring programme was implemented at the springs and rivers around the mines and, the reduction of the outflows expected to occur on the existing discharge points of the Cauê aquifer, will be replaced with mine water.

Pico Mine

The original position of the watertable at Pico Mine was around 1.350 m of altitude. The dewatering at this mine started in 1994, however, by 1998, the watertable was lowered only in 20 m (up to the level 1.330), with an average pumping rate of 32 l/s. With the installation of a new series of wells, after 1998, the pumping rate was intensified to 130 l/s, promoting, so far, a lowering of the watertable up to the level 1.270 m, 80 m below its original position.

The Pico Mine is located on the east flank of the Moeda Syncline. The protherozoic sequence forms a subvertical unit striking NE-SW. The Cauê aquifer is laterally enveloped at southeast by thick layers of Batatal and Moeda formations, followed by the schist of the Nova Lima Group and finally, by the granite-gnaissic basement (Bação Dome, figure 2).

The hydrogeological study carried out at this mine, in 1998, identified two discharge points of the Cauê aquifer around the mine, where a monitoring programme was started. No impact has been detected, so far, on the two discharge points. The discharge point at the north-east, located 3 km from the mine, is a fault-controlled discharge point, where the water flows trough the named Cata Branca Fault, being the beginning of the homonymous Cata Branca Creek.

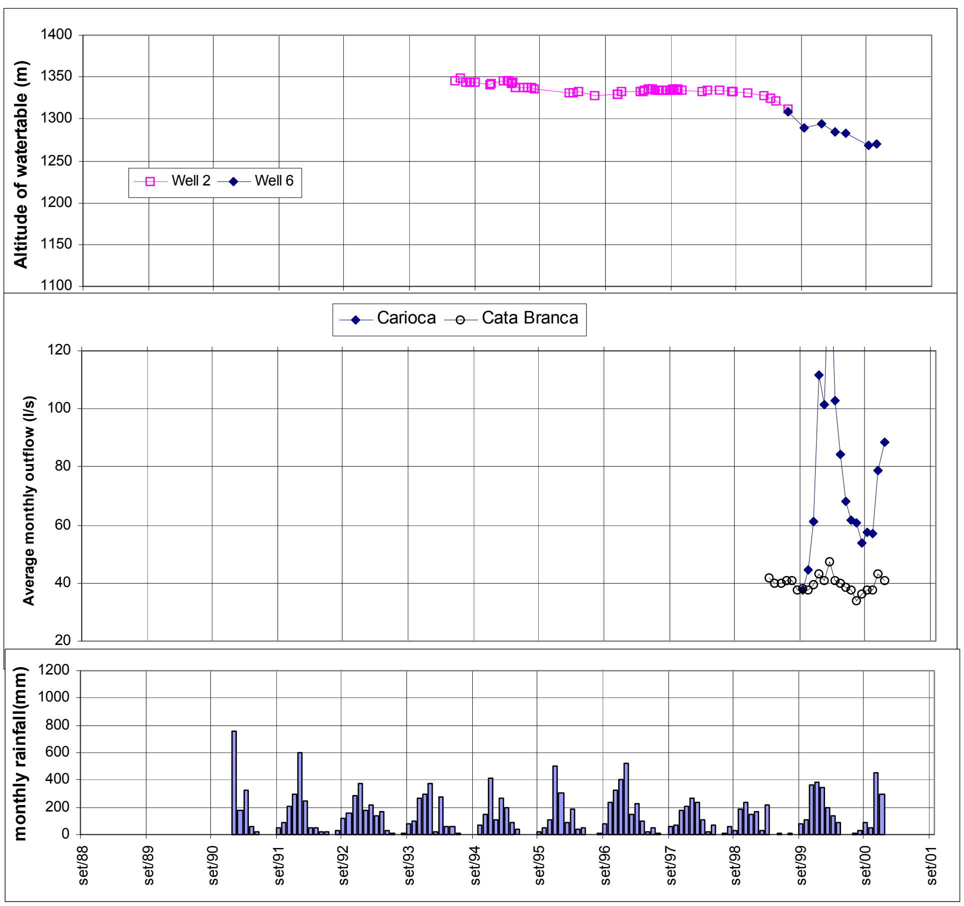

Figure 7 – Temporal evolution of the watertable level at Pico Mine, monthly outflow of Carioca and Cata Branca creeks and rainfall rate at Pico Mine

The other creeks of the basins located southeast of the mine, are shallow circulation related, without connection with the iron formation. One of these creeks, named Carioca, has its beginning close to the mine, over phyilites of the Batatal Formation. About three kilometres downstream on this creek, there is a water caching point, belonging to the Municipality of Itabirito.

In 1999, after two anomalous dry years, a low outflow was detected on the water caching point and, again, it was attributed to be a consequence of the mine's dewatering. A monitoring programme was, then, started at the water caching point, in September 1999. As can be seen in figure 7 (similar to figures 5 and 6), the data indicates that there were no influence of the mine's dewatering on the Carioca Creek's outflow.

REGIONAL BEHAVIOUR OF THE SHALLOW CIRCULATION RELATED AQUIFERS

Figure 8 represents the outflows recorded at Mangabeiras Creek (Belo Horizonte, near Águas Claras Mine), Mutuca Creek (water caching point near Mutuca Mine), Marumbé Creek (near Tamanduá and Capitão do Mato mines) and Carioca Creek (water caching point near Pico Mine).

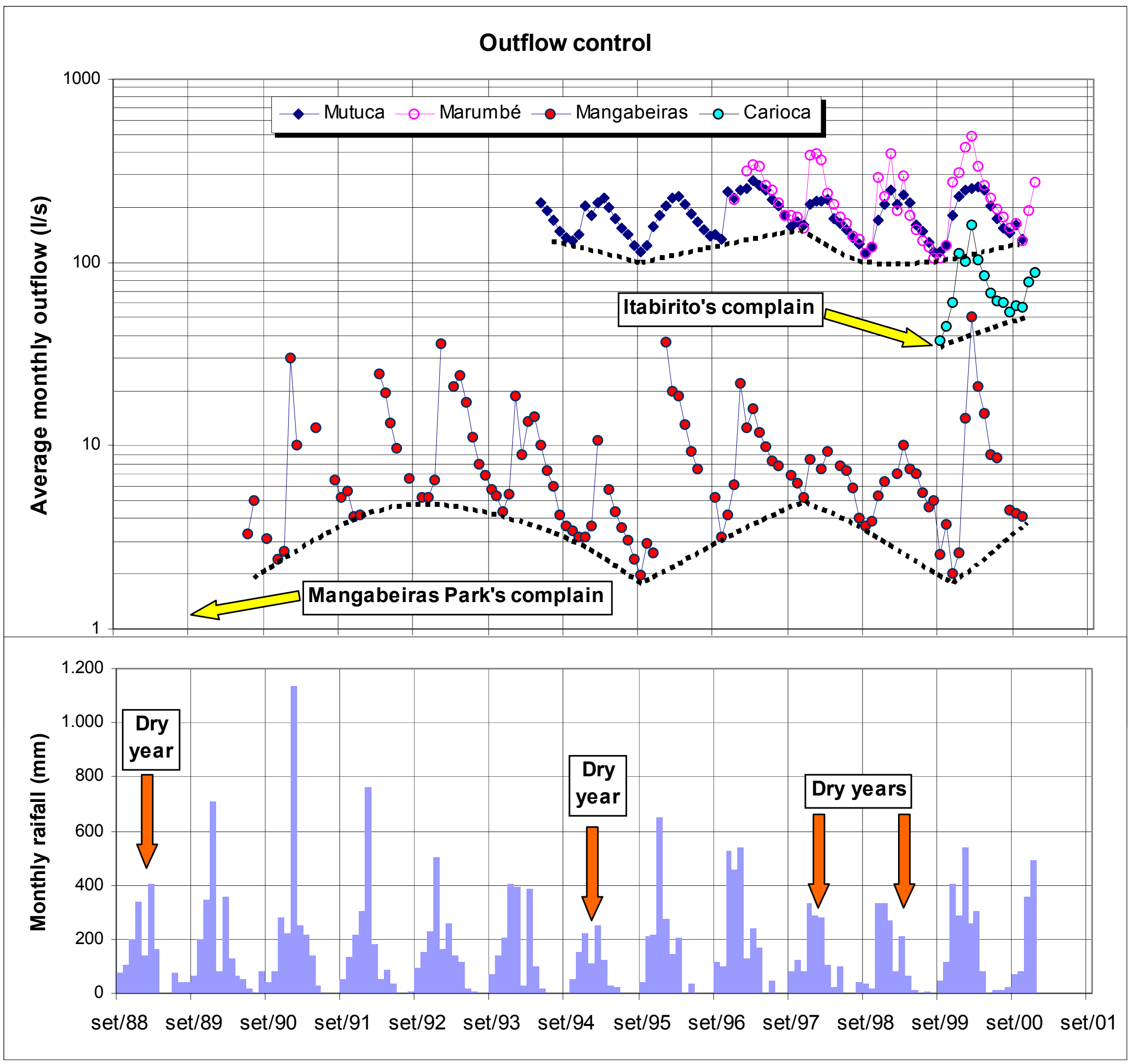

Figure 8 – Monthly average outflow recorded in different basins and rainfall at Mutuca Mine

The outflow of these control points varies between 2 – 20 l/s at Mangabeiras Creek, to 100 – 500 l/s at Marumbé Creek. Despite of that, they show, as common characteristic, high variation among the annual minimum from one year to the other, following similar regional trends (figure 8).

These regional trends are dictated by the rainfall rate, as can be seen on figure 9, where the average outflow of each September (usual minimum) are compared with the total rainfall accumulated on the pervious hydrologic year (from October to September).

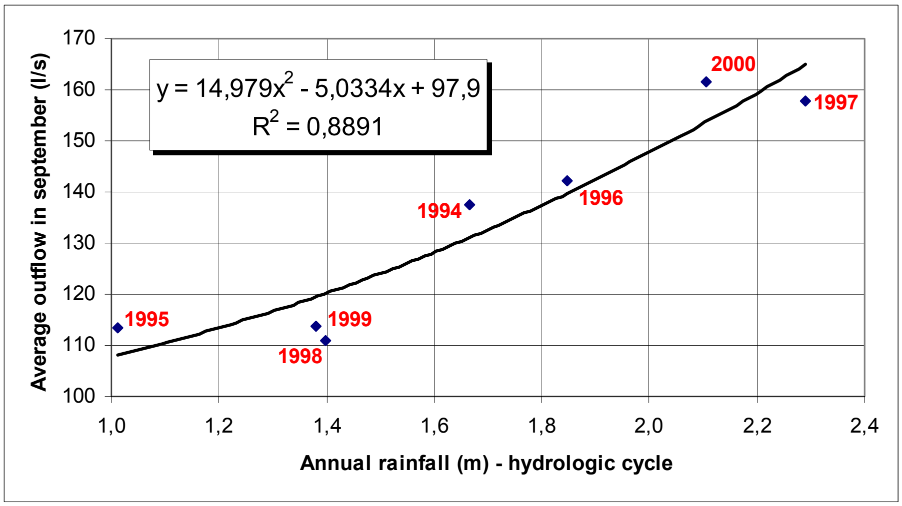

Figure 9 – Mutuca Creek: Average outflow of in September and correspondent (previous) annual rainfall, from October to September

The complains occurred at Mangabeiras Park (1989) as well as at Itabirito (1999) coincided with anomalous dry years where the regional outflows showed correspondent low values. In both cases, the phenomena was not related to mine's dewatering, being a consequence of the relatively rapid discharge (in annual basis) of the shallow circulation related aquifers, followed by a minor recharge occurred in relatively dry years.

DESTINATION OF MBR's MINE WATER

MBR's beneficiation plants work with an water recirculation rate of 90% and so, if available, part of the mine water is utilised in the beneficiation plants to wash the iron ore, avoiding the use of surface water for such purpose. The major part of the mine water, however, go (with good quality) to the streams of the region. Even considering the part of the water that will be used to replace the future reductions on the outflows of some discharge points of the Cauê aquifer, there is an excess of clean water, still to be discharged on the streams.

From a regional point of view, this mine water plays a role of replacing part of the water collected by the water companies to supply Belo Horizonte and Itabirito (see figure 2), contributing for the dilution of the existing impurities on the streams as a consequence of the urban occupation.

Excluding Águas Claras Mine, all the MBR's mining properties are situated upstream the Rio das Velhas water collecting system and so, the mine water, disposed at the streams, is contributing, anyway, to this major water supply system of Belo Horizonte (figure 2).

CONCLUSION

The studies carried out by MBR in the last 15 years, make possible to predict environmental impacts related to the iron ore mine's dewatering on the west border of the Quadrilátero Ferrífero, based on a relatively simple regional model.

The groundwater of the iron formation is, in general, laterally confined by impermeable enveloping rocks. The discharge points of these deep circulation systems, can be identified in the field by using geological mapping associated with piezometric and outflow control.

The shallow circulation related aquifers, are not hydraulically connected with the Cauê aquifer and, consequently, do not suffer impact form the mine's dewatering.

The impacts caused by the mine's dewatering ate mitigated by using the mine water.

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