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Formation of a deep pit lake: case study of Aguas Claras, Brazil

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Abstract

The paper presents the case study of the current formation of a Brazilian pit lake from an iron ore mining activity. The water used for the filling of the lake comes from rain, ground water and the complementary pumpage from a close river. At its final stage, which will be reached around year 2018, Lake Aguas Claras will have a surface area of 0.67 km2 and the depth of 234 m, which will make it the deepest lake in the country. The filling of the lake began in the year 2001 and a monthly monitoring programme (physical, chemical and biological characteristics) is since then in course The analyses show that Lake Águas Claras presents a very good water quality (well oxygenated, low values of colour and turbidity, limited degree of mineralization, pH slightly alkaline, low nutrient concentrations, excellent bacteriological conditions), together with a remarkable shift in the dominance of phytoplanktonic groups, indicating the high instability of lakes that are undergoing a process of formation. One relevant point in the management of this valuable water resource is to create adequate conditions for the protection of the aquatic environment. Considering the very probable maintenance of these favourable characteristics in future years, the possible uses of the lake will be directed to recreation (swimming, diving, sailing and fishing), amenity value and water supply.

Keywords: *Mine dewatering, Pit lake, Water quality, Water uses.*

1. Introduction

Aguas Claras mine is located south of the city of Belo Horizonte, capital of the State of Minas Gerais, Brazil in the geological region known as Iron Quadrangle (Figure 1). The mining activity started in 1973 and since that time about 300 million tones of high-grade iron ore have been extracted. The average annual production was around 12 million tones. Since the original rock is hematite, which is free from sulphur content, there are no problems related with acidic drainage. In 1981 the water level of the Águas Claras Mine in the Cauê aquifer reached the altitude of 1,165 meters. From that date up till 1990, the drainage was done by open channels, while the mine was in flank. The hydrogeological studies to project the dewatering started in 1986 and recommended the previous dewatering through tubular deep wells. The drilling of the wells started in 1988 and, since that time up till 1999, a group of wells have been operating with a total average outflow of 73 l/s. In the beginning of the dewatering process the outflow was about 100 l/s to 150 l/s. In 1981 the water level of the Águas Claras mine reached the altitude of 1,165 meters. From that date up till 1990, the drainage was done by open channels, while the mine was in flank. The hydrogeological studies to project the dewatering started in 1986 and recommended the previous dewatering through tubular deep wells. The drilling of the wells started in 1988 and, since that time up till 1999, a group of wells have been operating with a total average outflow of 73 l/s. After February 2000, the wells started to be closed and, by the end of 2000, the last one was closed. The water table reached the maximum depth of 275 m below its original position. After the depletion of the mine (in the year 2001), the pit was flooded, generating a deep lake which is still in the stage of formation. This will be the first large pit to be

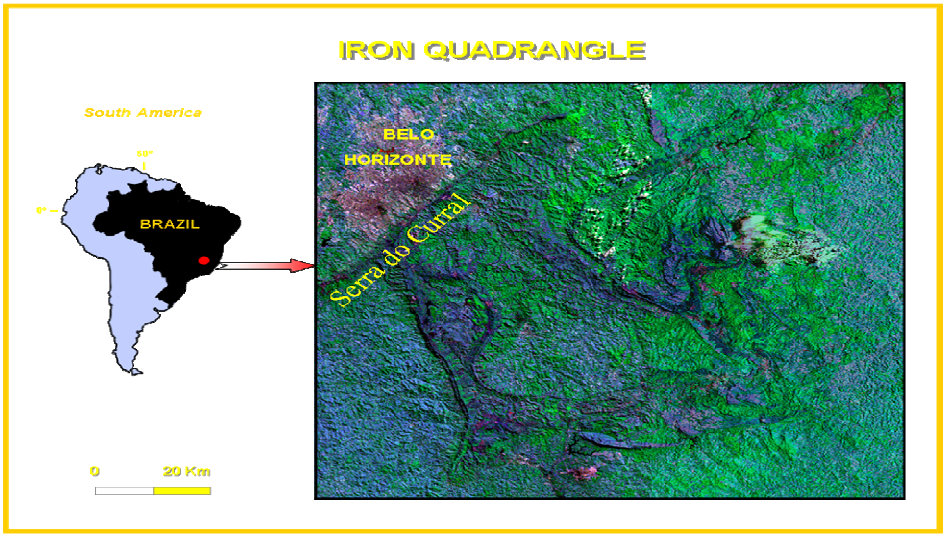

Figure 1. Location of Iron Quadrangle and Aguas Claras mine.

flooded in Brazil.

The iron ore forms the main local aquifer, being a semi-confined, heterogeneous and anisotropic with interstitial porosity and fractures .The total porosity determined in laboratory is 50% for the soft hematite and field determinations leaded to an effective porosity of 15%. The semi-confinement is due to the anisotropy of the permeability controlled by the ore banding and by the textural variation. The permeability of coarse hematite is about 3 m/day and the permeability of fine hematite is about 0.3 m/day. The electrical conductivity is about 10 µS/cm, the pH is about 5 to 6, the major anions are bicarbonate and cloride and the major cations are calcium and sodium.

Aguas Claras pit lake will have a final area of 0.7 km2 and the impressive depth of 234 m, which will make it the deepest lentic system in the country. The water used for filling up the lake comes from rain, ground water and the supplementary pumpage of river water from the vicinity of the lake. Rainy season lasts from October to March, while the dry period extends from April to September. The fact of being located in the tropical region of our planet causes an acceleration of all metabolic processes in the warm waters of the lake. This enhanced dynamics is one of the most relevant features of tropical environments. Consequently changes in the water quality don't follow regularly an annual pattern and daily variations can be often more significant.

Open pit mining creates a new type of aquatic habitat, which is formed by force flooding or natural filling of the pit when it is mined out. Pit lakes are generally narrow and deep, enclosed by steep rock walls and usually without a littoral zone. Their morphological features, with a marked meromitic (only partial circulations) character, restrict the hydrobiological growth and the biodiversity in these habitats. Most of the technical papers related to the ecology of pit lakes deals with the formation of acidic environments [1-11].

In addition some other morphological features of Lake Aguas Claras may be mentioned here: mean depth: 87m. This parameter is obtained by dividing the lake volume by the lake surface.

Relative depth: it is defined as the relationship between lake maximum depth and the mean diameter of the lake (i.e., diameter of a circle that has the same area as the lake). The value of 25 % for Lake Aguas Claras indicates that the water body will not perform complete vertical circulations, assuming hence a meromitic behaviour. On the other hand this characteristic can prevent the transport of soluble nutrients from the bottom to the euphotic zone, reducing consequently the probability of the onset of an eutrophication process.

Shoreline development: It reflects the degree of irregularity of the shoreline, which is given by the ratio between shoreline length and the perimeter of a circle that has the same area as the lake. The value of 1.3 for Lake Aguas Claras indicates that the water body will have an approximately circular surface, as is typical for most mining lakes.

Volume development: it is a measure used to illustrate the form of the lake basin, defined as the quotient between lake volume and volume of a cone whose base area is equal to the lake area and whose height is equal to the maximum depth. The value of 1.1 for Lake Aguas Claras point out the existence of a concave form.

2. Methods

A monthly monitoring program has been carried out since the beginning of the lake formation (August/2001).The most relevant physical, chemical and biological indicators for the evaluation of the water quality have been continuously analyzed. All employed analytical methods are based on the recommendations of the Standard Methods for the Examination of Water and Wastewater [12]. Due to the small surface of the lake, there is just one sampling point, which is located in the central part of the water body, corresponding to its maximum depth. Samples have been taken at the surface (Secchi depth) and at the bottom of the lake.

3. Results and discussion

A summary of the evolution of the most relevant water quality parameters is presented below:

Water temperature (Figure 2): Seasonal distribution, according to the local climatology: winter time (May-September), summer time (October-April); the lake presents a monomitic pattern, with only one period of circulation (June-August). In the rest of the year the lake remains stratified.

Dissolved oxygen (Figure 3): There is an influence of the temperature in the rate of atmospheric oxygen transfer to the water, with higher values being obtained in colder months. Algae photosynthetic activity increases DO concentrations in the upper layers, with occasional records of supersaturation.

Hardness: values between 33 mg/L and 55 mg/L; low to moderate hardness.

Turbidity: clear seasonal variations (increase in the rainy period); 84 % of the recorded values are under 10 NTU, indicating the prevalence of very clear waters.

Colour: very low values, most of them under 1 mg/L.

pH: ranges from 6.4 to 9.6 (Figure 4), with higher values at the surface of the lake (primary production, CO_2 absorption) in comparison with the bottom (decomposition of organic matter, CO_2 release).

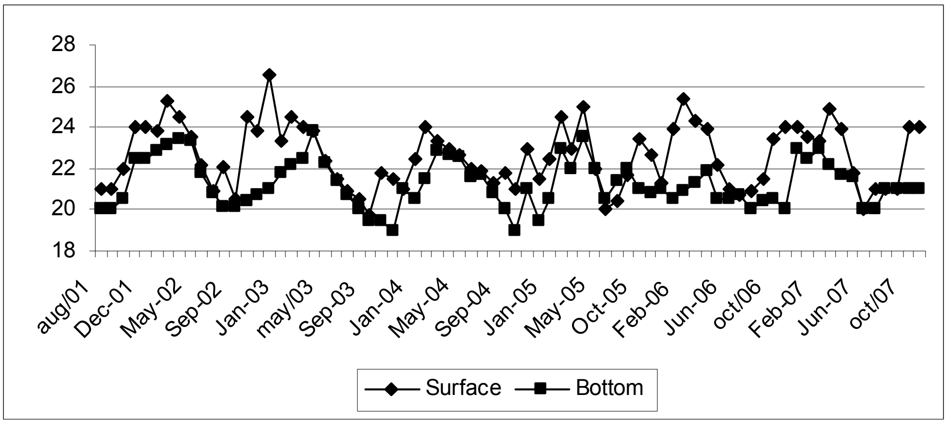

Figure 2. Water temperature

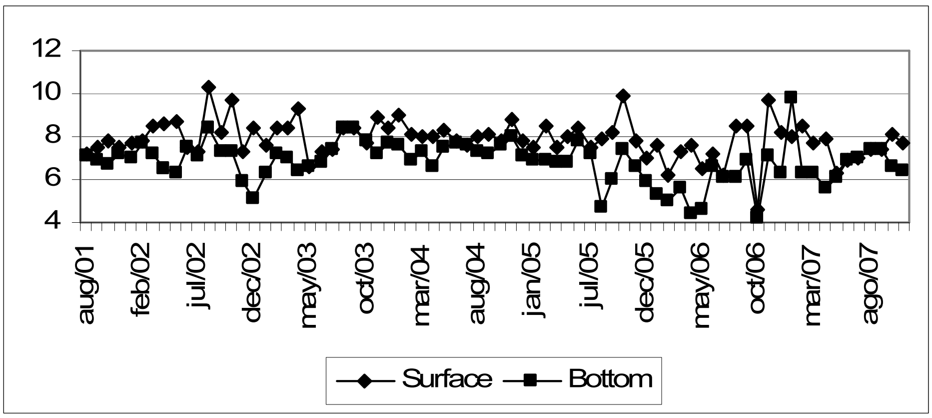

Figure 3. Dissolved oxygen

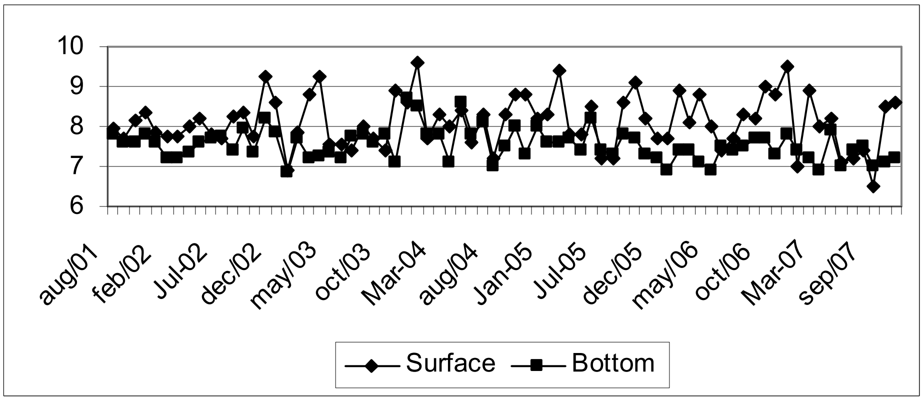

Figure 4. pH

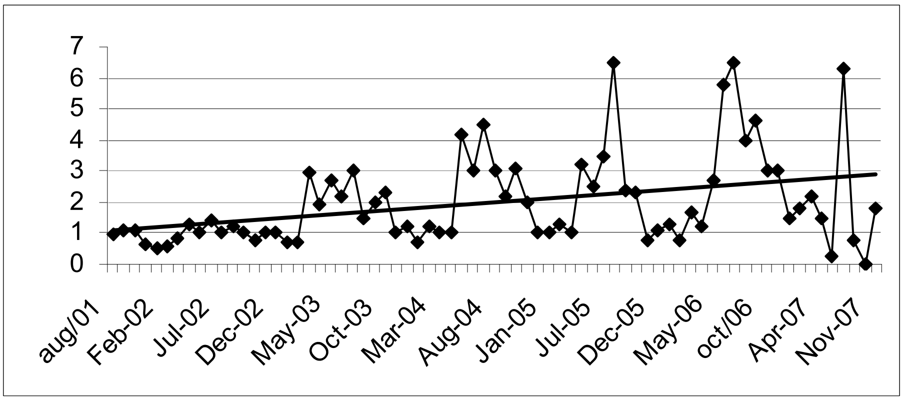

Figure 5. Secchi depth

Secchi depth (Figure 5): between 0.5 m and 6.5 m, with higher values registered at the winter time; an increasing trend can be observed.

Nutrients: almost all values of soluble phosphorus are below 0.01 mg/L, with a maximum concentration of 0.02 mg/L. In a future scenario this soluble fraction will probably predominate at the bottom of the lake as consequence of internal fertilization process. Ammonium nitrogen shows values between < 0.05 mg/L and 0.9 mg/L, while for nitrate nitrogen the concentrations range from < 0.01 mg/L to 1.3 mg/L; these results are consistent with the good oxygenation conditions in the lake. There is a trend in decreasing TN/TP values as the lake is being filled, indicating a possible nitrogen limitation in the future.

Electric conductivity*:* Values range from 55 µS/cm (surface) to 113 µS/cm (surface); since May/04 they are situated in the narrow range of 70-80 µS/cm, indicating that a stability in the amount of dissolved salts has been reached.

BOD*:* Around 96 % of the concentrations are under 2 mg/L, with the maximum value of 5.8 mg/L; these results point out to a virtual absence of organic contamination.

Fe and Mn*:* Iron concentrations range from < 0.05 mg/L (surface) to 1.73 mg/L (bottom). These values are typical for drainage basins with high iron contents from geochemical origin, as is the case of Lake Aguas Claras; manganese concentrations range between < 0.05 mg/L and 0.17 mg/L (at the bottom);

Chloride: constant low values, from < 0.25 mg/L to 1.7 mg/L.

Heavy metals: (Al, As, Cd, Cr, Cu, Hg, Pb) and other pollutants (phenols, oil and grease, cyanide): virtually absent, only aluminum has been occasionally detected (0.12 to 0.22 mg/L).

Bacteriology: very good bacteriological quality; about 90 % of the results of faecal coliforms, Escherichia coli and faecal streptococci are lower than 2 MPN/100mL.

Hydrobiology: the most relevant aspect in the hidrobiology of Lake Aguas Claras is the frequent shift in algae dominance (Figure 5). In a first phase (some few months after the beginning of the filling) there was the dominance of Chlorophyta and Cyanophyta; in a second moment (period of about 4 years): dominance of Chrysophyta and Pyrrophyta; in a third phase (2006) a short period of Cyanophyta dominance, followed by the

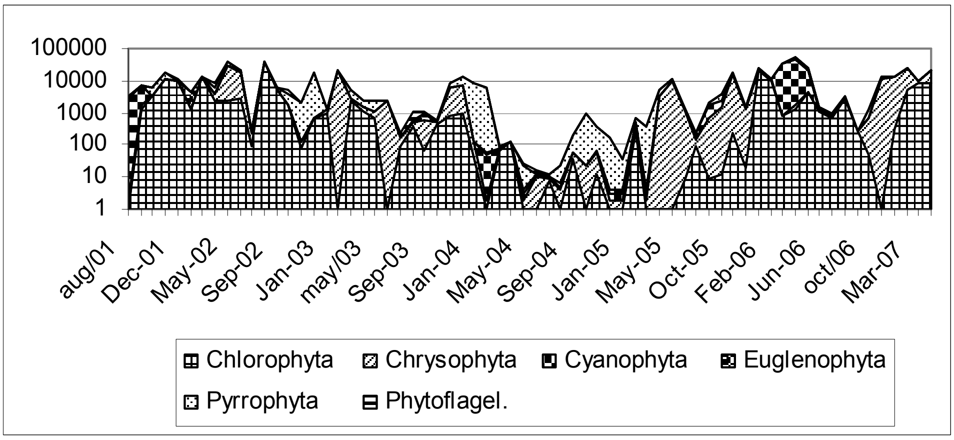

Figure 6. Phytoplankton

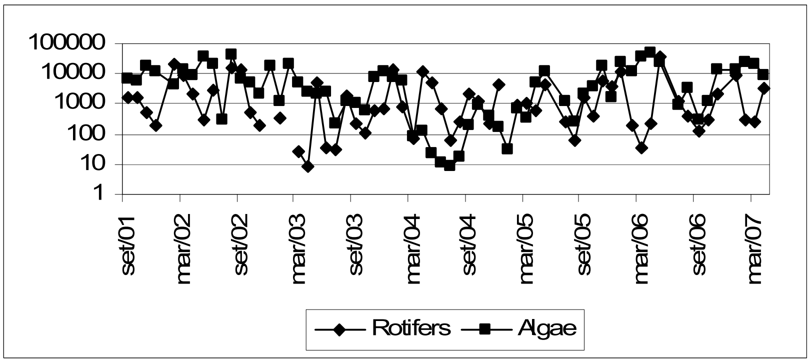

Figure 7. Rotifers x Algae.

current prevalence of Chlorophyta and Chrysophyta. It should be stressed that blue-green algae are a serious concern in Brazilian lentic waters, since the first worldwide registers of human deaths due to ingestion of cyanotoxins happened in 1996 in the city of Caruaru, Brazil [13]. These frequent alternations in the algae dominance are typical of aquatic systems that are undergoing a process of formation, such as mining lakes. Due to an enhanced nutrient concentration in the dry season there is a trend in obtaining higher algal densities in the winter time (May to August) and in the period following the end of the rainy season. This pattern is a common feature in many Brazilian lentic systems [14, 15], possibly as a consequence of the onset of favourable limnological conditions (decrease in turbidity, weaker winds) after the end of the wet period.

A clear alternation in the dominance of Rotifera and Crustacea can be observed In the composition of the zooplankton community . The occurrence of frequent density variations can be probably associated to the natural instability of the new aquatic system. Peaks in the zooplankton population have been observed in the dry period (winter time), which could be caused by enhanced salinity due to evaporation. Researches in Brazilian lakes have shown an increase in zooplankton abundance in the rainy season [16], while some authors present rain as a lost factor for the zooplankton [17]. A well established correlation between rotifers and algae can also be observed (Figure 7), confirming the pattern which is extensively found in temperated lakes [18].

4. Conclusions

The evaluation of a monthly monitoring programme in Lake Águas Claras shows that the lake presents a very good water quality (well oxygenated, low values of colour and turbidity, limited
degree of mineralization, pH slightly alkaline, low nutrient concentrations, excellent bacteriological conditions), together with a marked shift in the dominance of phytoplanktonic groups, indicating the high instability of lakes that are undergoing a process of formation. The possible uses of the lake will be directed to recreation (swimming, diving, sailing, fishing), amenity value and water supply. Moreover the results of this extensive monitoring program could be used as background for water quality characteristics in other natural and protected areas in the region as well as for

other Brazilian pit lakes originated from iron mining activities.

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