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HYDROGEOCHEMISTRY DYNAMICS OF A STEATITE PIT LAKE, BRAZIL

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Abstract. Pit lakes have been one of the most adopted forms of decommissioning open-pit mines after the mineral resource has exhausted, so that a proper use is given to these areas. These lakes are usually narrower and deeper when compared to natural lakes, being almost always surrounded by steep rocky walls. The aim of this work is the analysis of the hydrogeochemical variations of a pit lake formed in an abandoned steatite pit. The lake, even if relatively shallow, is clearly stratified, showing a monomictic behavior, with circulation of water only in cold months (June, July, August and September). The OPPS pit lake can be classified as a tropical hot, monomictic lake. Despite relatively young and shallow (maximum depth of 28 m), the lake is totally stratified, with a clear evolution from stratified to de-stratified along the year, with water circulation occurring during the colder months (mainly July, August and September). The lack of convection flows in ca. 2/3 of the year makes the re-aeration of the lake difficult, leading to the maintenance of reducing conditions in the hypolimnion. A pH between neutral and alkaline is maintained in the pit lake, which leads to a better quality of the water in the lake.

Keywords: Pit Lakes, Mining, Steatite, environmental monitoring, Brazil.

1. INTRODUCTION

A few countries (*e.g.* United States, Canada and Australia) establish procedures and demand measures for the closing of mining sites. In most of the other countries, however, laws, regulations, standards or norms that specifically address such issue are practically non-existent (WBCSD, 2002). The lack of specific laws for closing and/or decommissioning mining sites leads to the abandonment of a large number of quarries, as no attempt to recover these areas is made. Pit lakes are formed when open-pit mining operations are interrupted and/or abandoned without any environmental rehabilitation.

Most of the open-pit mines reach groundwater levels during exploitation and constant pumping is necessary to drawdown the water table, thus assuring the operations of ore extraction. Once the activities come to an end and pumping is stopped, a lake is formed in the open pit. These lakes are in general filled with a combination of groundwater and runoff from adjacent drainage basins (Castro et al., 2000). The filling rate depends on the local hydrologic and climatic characteristics. As mining exposes rocks to weathering, a great potential exists for metals to be released from the now weathered rocks to the lake (Eary, 1999).

According to Castro et al., (2000), pit lakes differ from natural lakes for their higher relative depth, estimated in terms of the maximum depth and width of the lake. These pit lakes are usually of reduced diameter in relation to depth (they are narrow and deep), when compared to natural lakes (Ramstedt et al., 2003) and are almost always surrounded by steep rocky walls (Von Sperling et al., 2004).

In general terms, the hydrogeochemistry of pit lakes reflects the composition of the groundwater previous to mining, the reactions of the filling water (groundwater + rainfall) with the rocks that surround the lake (Miller, 2002), the quantity and quality of the runoff from the terrains adjacent to the pit lake (Castro et al., 2000), and its stratification (Von Sperling et al., 2004). Models to predict the hydrogeochemistry of the water in pit lakes are still new. One of the most complete was conceived by Eary (1999) who, when studying the chemical composition and the equilibrium trend of several lakes formed in open-pit mines, tried to establish geochemical models to predict water quality. As in natural lakes, the chemical characteristics of stratified pit lakes vary with depth. In general, the total dissolved solids and electrical conductivity tend to increase with depth, being many times higher at the bottom in relation to the surface of the lake. This pattern is usually followed by a decrease in both dissolved oxygen concentration and oxy-reduction potential. The morphologic pattern of the pit lakes (deep lakes with a small area) enhances the influence of the circulation of the water in the water quality (Von Sperling et al., 2004).The key to predict and control water quality is to understand the physical and chemical processes that control oxygen availability in the lake (Thomann & Mueller, 1987). The main source of oxygen are: atmospheric re-aeration, photosynthesis, and transport of dissolved oxygen to the lake by groundwater. In most pit lakes, re-aeration is a primary source of oxygen, although the other two sources can play an important role in special circumstances. The dissolved oxygen that comes in touch with oxidizable minerals is responsible for the acidification of the water. To Eary (1999), pH is the basis to understand the chemical dynamics of pit lakes. As oxidizable minerals are usually present in the wall rocks and bottom sediments, when atmospheric oxygen enters the lake, acidification is strongly controlled by the hydrodynamic mixing in the lake. Mixing results from upward and downward water flows inside the lake, as a response to thermal stratification. Stratification slowly develops in pit lakes, as the lake is being filled up. Stratification is incipiently developed in pit lakes of tropical areas, where annual temperature variations are small. The transport of oxygen in these lakes is mostly controlled by wind-induced water flows, groundwater circulation and molecular diffusion, resulting in oxygen transference to the bottom of the lake during the whole year, favoring the oxidation of minerals and acidification of the water in the lake. According to Eary (1999), high solute concentrations generally occur in extreme acid and alkaline pH conditions. Metal (Al, Cd, Cu, Fe, Mn, Pb and Zn) concentrations are high in acid lakes, whereas other metalloids (As and Se) are in general highly concentrated in alkaline lakes, in both situations causing deterioration of the water quality in the lake. According to this model, pH close to neutral would favor low solute concentrations, leading to a better quality of the water in the lake.

The formation of these lakes has been one of the solutions internationally adopted for decommissioned mines, in order to provide a use (habitat for fish and wild animals, recreation, water supply, among others) for the areas degraded by open-pit mining after operation is ceased (Von Sperling et al., 2004). Consequently, the prediction of the water quality in the lake is extremely important both for licensing processes and environmental inspection, as well as for the installation of new mines and expansion of the existing ones. In this context, the aim of this work is to evaluate the hydrogeochemical changes in the water of a pit lake throughout a hydrologic year, which formed in a abandoned steatite mining pit of the Queimado region, Cachoeira do Brumado district (Mariana – Minas Gerais, Brazil).

2. THE STUDY AREA

In the Cachoeira do Brumado district, approximately 40 abandoned sites mined for ornamental rock (specially steatite) were recognized. The exploitation of steatite (*pedra-sabão* or soapstone) in Cachoeira do Brumado has been mostly manual and directed to local handcrafting (mainly the production of rock pans). Rarely are these sites mined by large companies to obtain building stone for exportation and use in fireplaces (Fig. 1). The degraded areas are relatively small, but the extraction was deep and almost always reached the water table. To evaluate the influence of the groundwater in the hydrochemical dynamics in a pit lake, a pit of the old OPPS (*Ouro Preto Pedra Sabão* – Ouro Preto Soapstone) was chosen for this study.

The climate in the region is hot and humid. The average annual rainfall is 1408.728 mm, with a clear separation in a dry (April to September) and rainy (October to March) season. During the year of the present study, the time and duration of both seasons were the same, except for an increase in the average annual rainfall (1815.5 mm). It is important to stress out the atypical behavior of the dry season in 2009, with increase and decrease of rainfall respectively in April, June and September and in May, July and August (Fig. 2). The mean temperature is *ca*. 19°C, with a 6°C thermal amplitude.

The Cachoeira do Brumado district is located in the southeastern part of the Quadrilátero Ferrífero (Minas Gerais – Brazil). According to Raposo (1991), it is an area with a very complex geology. The area is rich in steatite occurrences, which have been correlated with units of the Nova Lima Group / Rio das Velhas Supergroup by several authors (Ladeira, 1980; Baltazar et al., 1993; CPRM, 1996), but their exact stratigraphic position still remains uncertain.

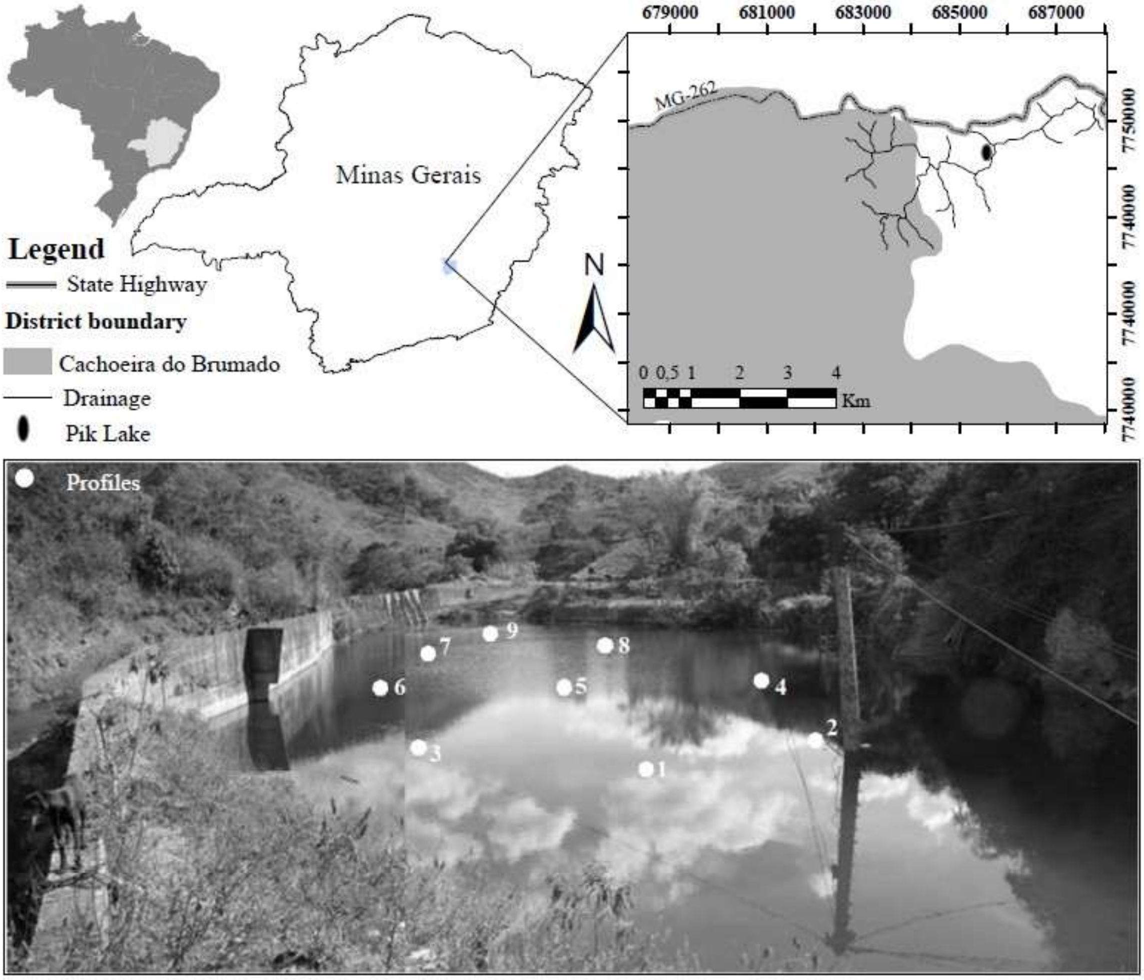


Figure 1. Location of the OPPS pit lake, Cachoeira do Brumado (Mariana).

The steatite found in the study area constitutes one of the most important commodities of the Quadrilátero Ferrífero. It is a metamorphic rock that occurs sporadically, resulting in rather small mines that soon come to exhaustion, which makes inspection difficult and triggers physical and geochemical impacts on the environment. The rock-forming minerals of the steatite are talc, dolomite, actinolite and chlorite; accessory minerals are pyrite, arsenopyrite, magnetite, epidote and titanite. It is worth mentioning that ultramafic rocks similar to the steatite are rich in trace elements, such as nickel and cobalt (Abrahão & Mello 1998). Steatite mining is clearly harmful because it affects the physical, biologic and social environments the characterize the mining site. The physical impact on the watercourses is evident, moreover around the main extraction and handcraft production centers, featuring the distribution of tailings by erosion processes and by siltation of streams. On the other hand, the geochemical impacts are less obvious, but are of great importance to the environment and to health once steatite has high concentrations of high-toxicity elements such as Cr and Ni (Ripley et al., 1996).

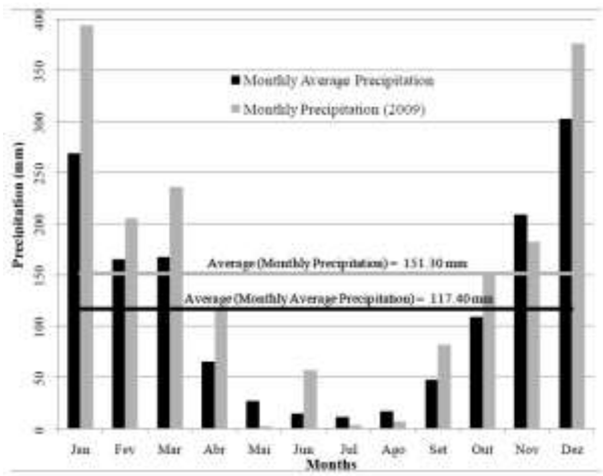


Figure 2. Histogram showing the annual distribution and monthly mean precipitation for the study area (Datas: Fazenda Paraíso station – 1942 to 2009) and the annual distribution and the monthly mean precipitation for the study area in the monitoring year (Data: Fazenda Paraíso Station – 2009) (ANA**,** 2010).

A pit lake formed in the OPPS pit (Fig. 3A), which was a small mine (extraction of blocks for exportation). It was closed approximately four years ago because of its proximity to the Cachoeira do Brumado Brook. The construction of a wall to separate the pit from the watercourse was not enough to prevent it from being decommissioned (Fig. 3B). After being abandoned, a lake of approximately 700m^2 in area and 28 m em of highest depth was formed.

A

B

Figure 3. A – General view of the lake formed in the abandoned OPPS mining pit, Queimado region, Cachoeira do Brumado. The wall seen at the background served as a barrier between the left-hand side of the lake and the Cachoeira do Brumado Brook. B – Partial view of the lake formed in the OPPS mining site, which is separated from the Cachoeira do Brumado Brook by a wall.

3. METHODS

The hydrochemical dynamics of the OPPS pit lake was studied by means of sampling and *in situ* measurements carried out at different depths at the deepest point of the lake (center), in 12 different moments during 2009 (January to December), and at nine points distributed along the margin, including the central point monitored in 2009 (point 6), in September 2010.

Regarding the 2009 campaigns, the determination of the temperature, electrical conductivity (EC), total dissolved solids (TDS), pH, turbidity and dissolved oxygen (OD) were carried out *in situ* at all sampling points of the drainage nets and at every meter of the lake formed in the OPPS mining pit. Temperature, electrical conductivity (EC), total dissolved solids (TDS), and pH were measured using a field and laboratory, portable, previously calibrated multiparameter *Myron L Company*, model 6P. Turbidity was measured using the portable microprocessor turbidity meter HI 93703 (HANNA Instruments). Dissolved oxygen was measured using a DM-4D Digimed equipment. In the 2010 campaign the probe ORIBA U50 was used.

In the 2009 campaigns, water samples were collected at the surface of the lake and at every 5-m depth, except the last, at 3 m from the previous point (0 m, 5 m, 10 m, 15 m, 20 m, 25 m and 28 m). In the 2010 campaign sampling was carried out every two meters, excepting the central point where water was collected at every meter. Sampling was carried out using the *Limnos* sampler. The sample was filtered using a 0.2 μm polycarbonate membrane (Nuclepore), acidified with concentrated nitric acid (pH < 2) and stored in 30 mL flasks at 4 °C. The analyses of major and trace elements (Al, As, Ba, Be, Ca, Cd, Co, Cr, Cu, Fe, K, Li, Mg, Mn, Mo, Na, Ni, P, Pb, S, Sc, Ti, V, Y, Zn) were carried out using an inductively coupled plasma atomic emission spectrophotometer (ICP-AES) SPECTRO, model Ciros CCD. Trace-element analyses were validated using the NIST 1643d standard. The quantification of Fe^{+2} was made in the field, with the aid of a Hach colorimeter, model DR/890.

The methodology for water chemical analysis followed the Standard Methods for Examination of Water and Wastewater (APPHA 2005).

4. RESULTS AND DISCUSSION

For a better visualization of the data, the monitoring results were separated according to the seasons investigated, the hot (January, February, March, April, May, November and December) and the cold (June, August, September and October). The data obtained with the ORIBA probe in September 2010 were also plotted in a separated graph.

The data clearly show that the lake is stratified. Stratification is a response to the surface heating during the hot months, triggering an alteration of the density in deeper layers, characterized by denser and colder waters. This effect helps establishing a thermocline and a metalimnion, thus quickly stabilizing the lake (Figs. 4 A and B). There is a difference in stratification between the deeper and shallower parts of the lake, but a total isothermia is observed during the cold months (June, July, August and September – Figs. 4 A, 4 B an 5 A), followed by a new stratification during the hot months (November to April).

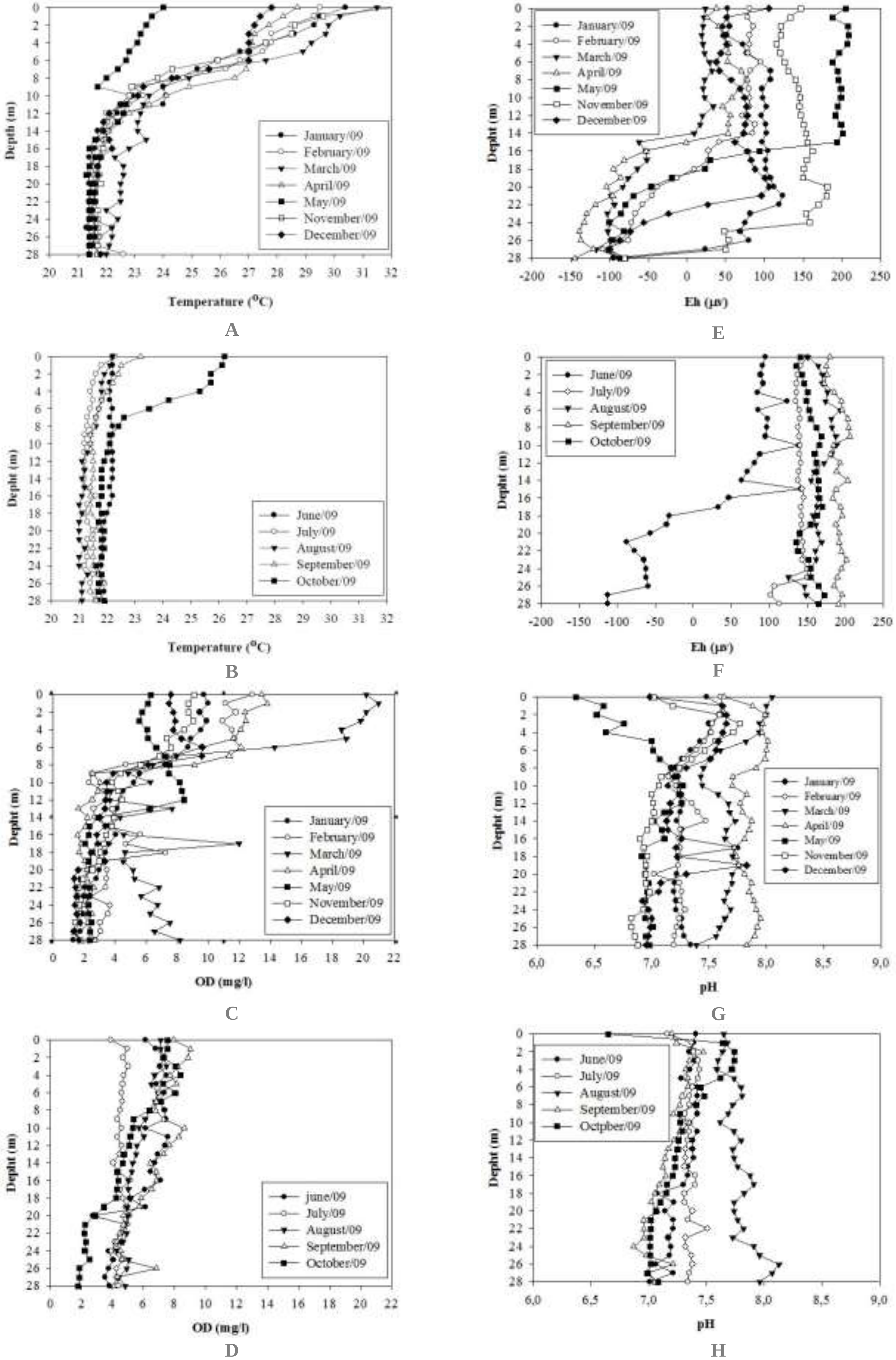


Figure 4. Graphs showing the monitoring results for the OPPS pit lake in 2009. Temperature (A and B); dissolved oxygen (C and D); Eh (E and F); pH (G and H).

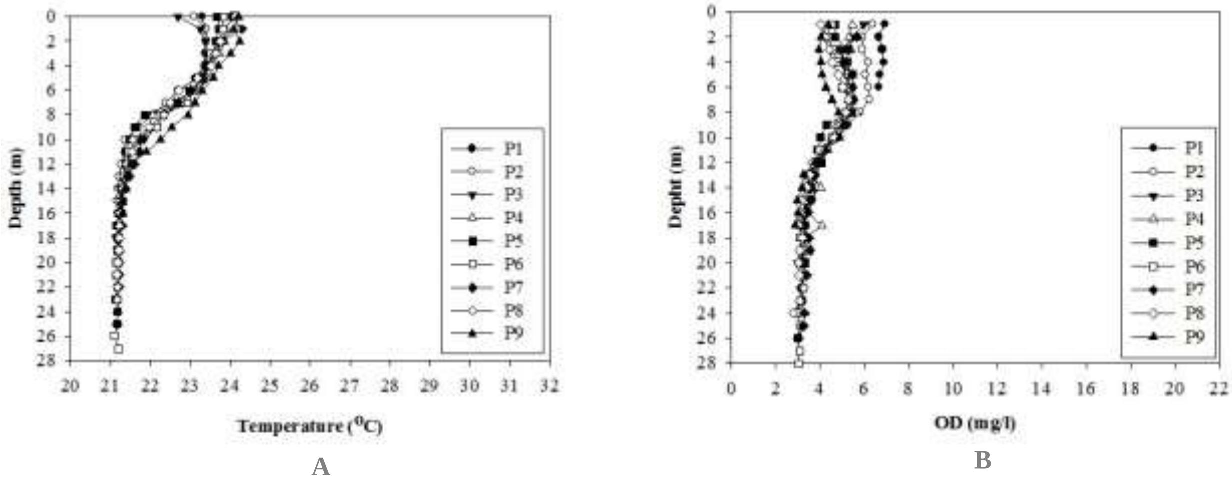


Figure 5. Graphs showing the variation of temperature (A) and dissolved oxygen (B) with depth along the OPPS pit lake in 2010.

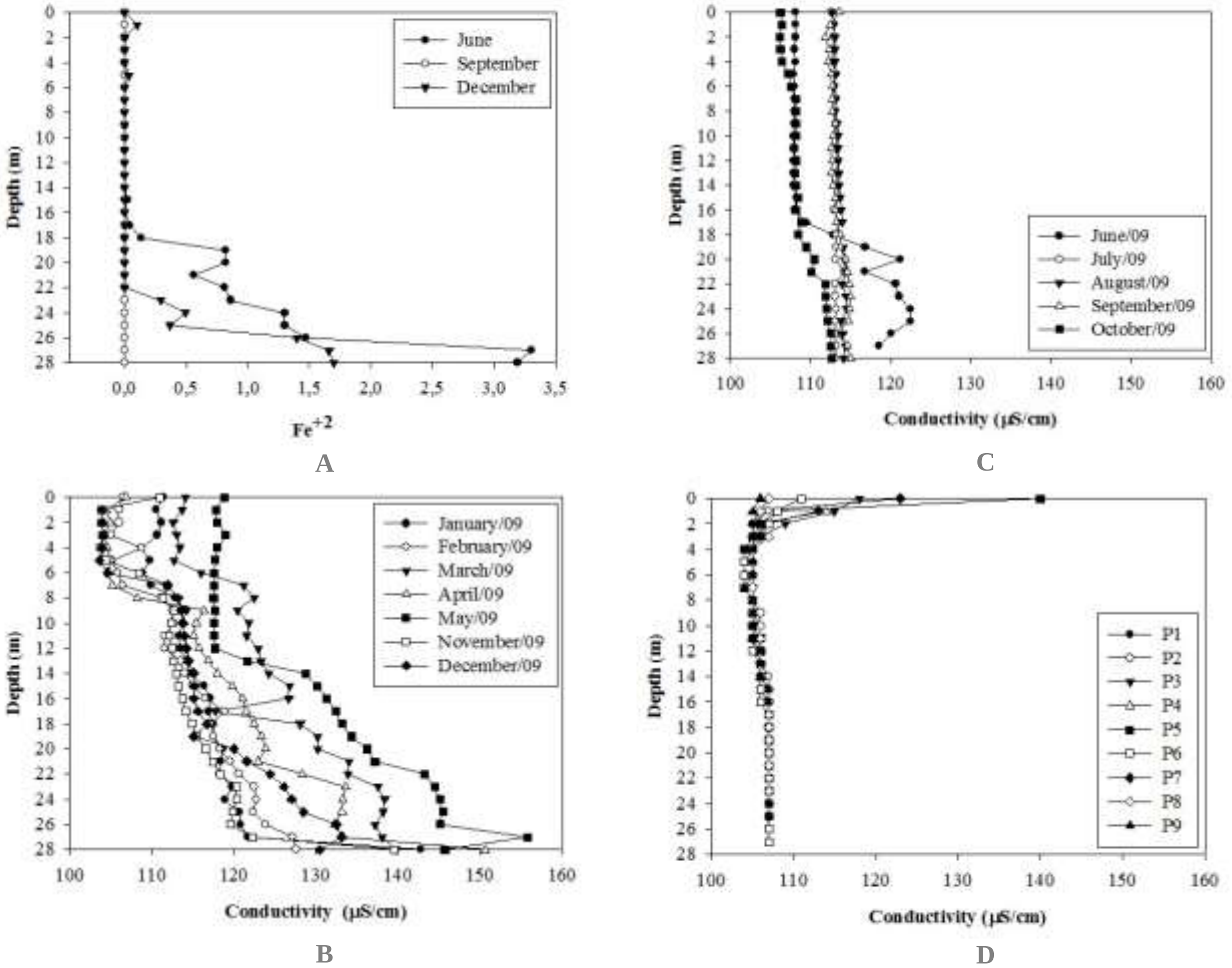


Figure 6. A) Fe^{+2} concentration in the water column; B) and C) conductivity data throughout 2009; D) conductivity data along the lake in 2010.

October and May show a transition between the two stages (Figs. 4 A and B). All the points sampled present the same pattern, with isothermia occurring in the cold months (Fig. 5 A). Lakes with such behavior have already been described by other authors, *e.g.* in Africa (Lake Vitoria – Talling), United States (Lake Conway, Florida – Ewel & Fontaine, 1983), south of Europe and in Brazil (Lake Helvécio, Vale do Rio Doce – Tundisi & Saijo, 1997).

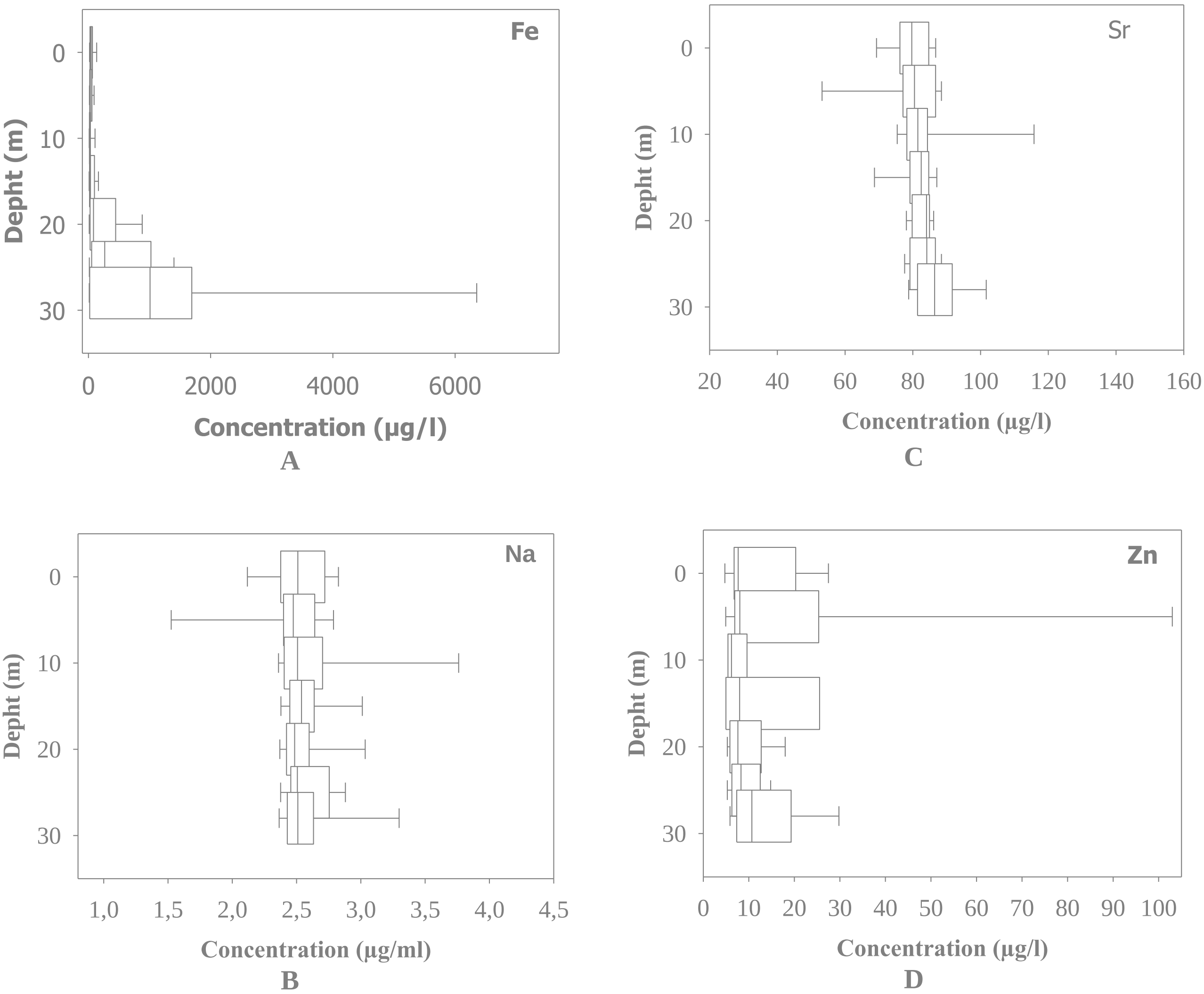
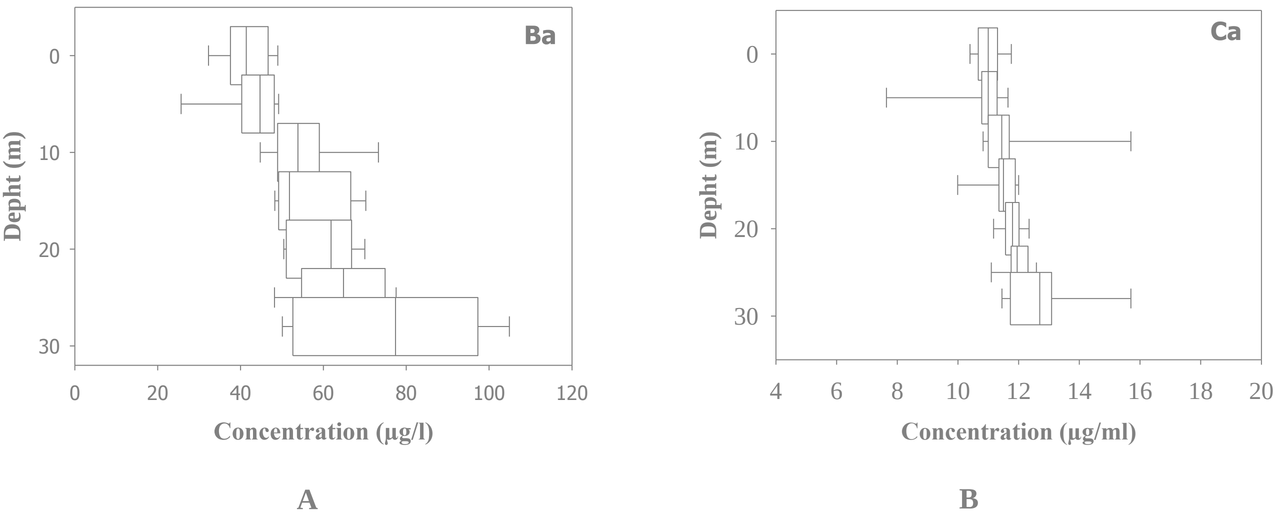


Figure 7. A, B, C and D) Concentration of elements Fe, Na, Sr e Zn, respectively, along the column of water (depth) of the Lake.



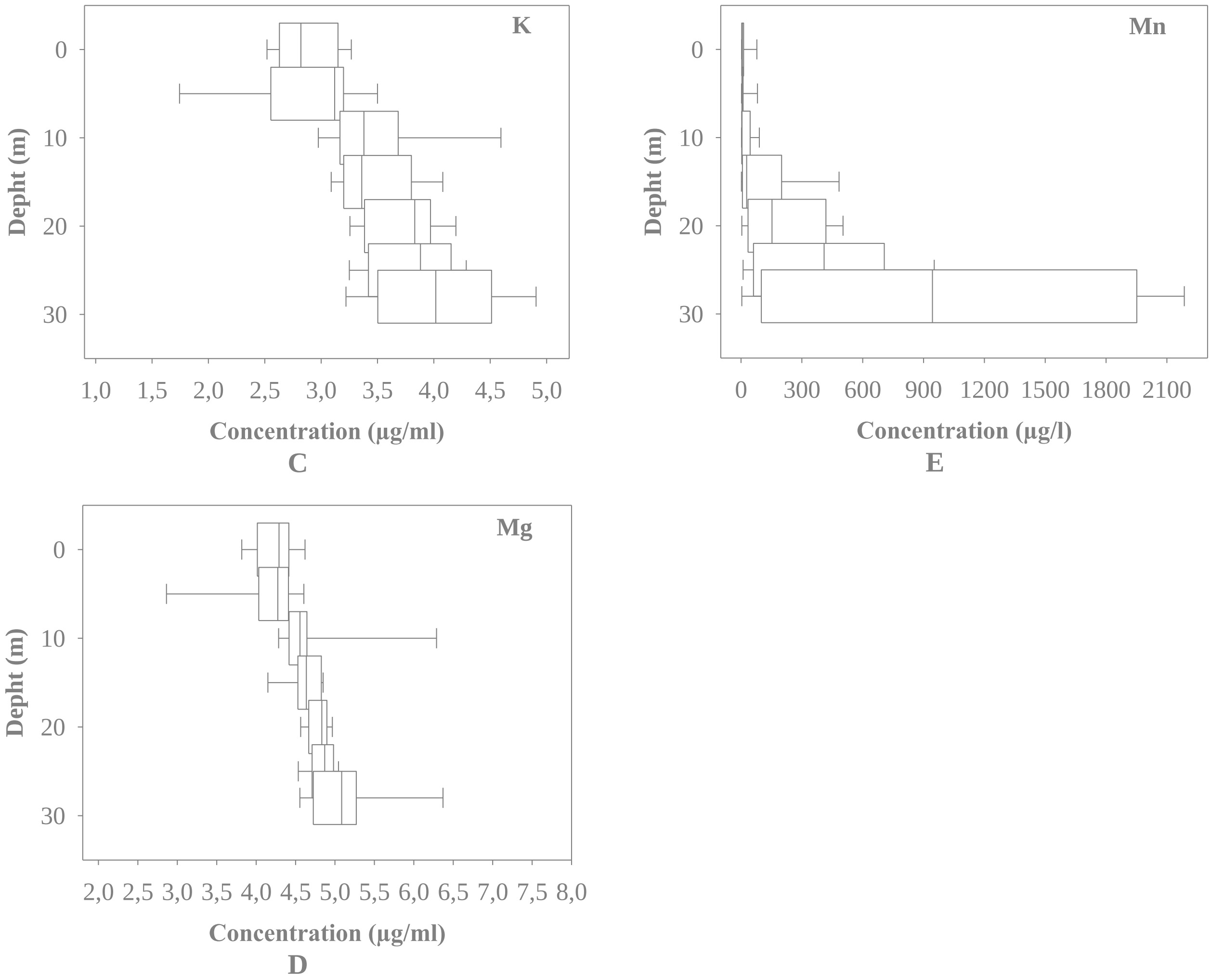


Figure 8. A, B, C, D and E) Concentration of Ba, Ca, K, Mg and Mn, respectively, along the column of water (depth) of the Lake.

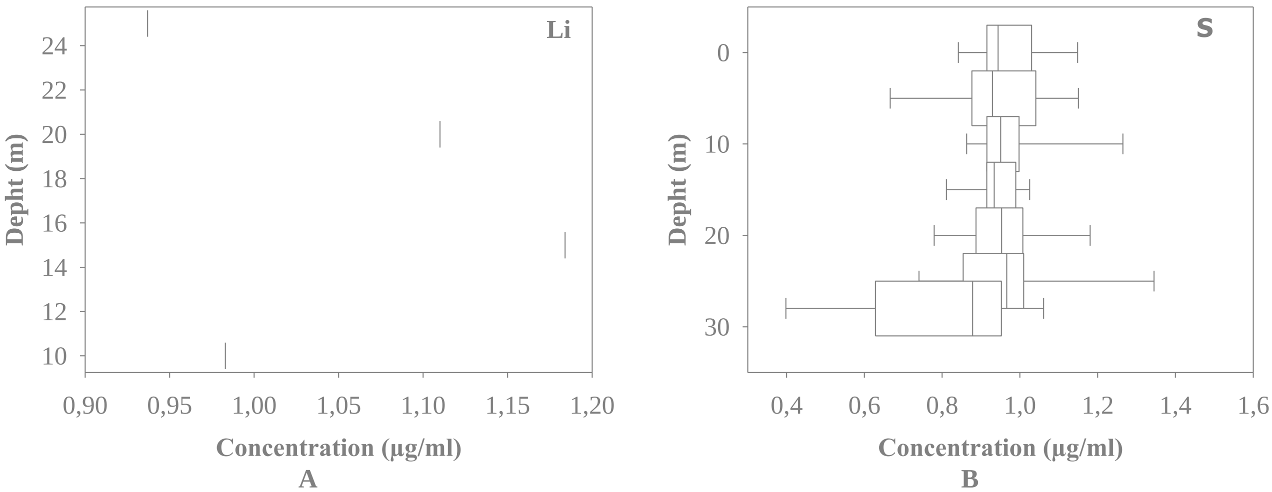


Figure 9. A and B) Concentration of Li e S, respectively, along the column of wa

According to Kalff (2002), this behavior occurs in the so-called “tropical warm monomictic lakes”, which are deep lakes (depths exceeding 40 m) located at low latitudes (0 to 25º).

Table 1. Range (minimum, average and maximum) concentration of the trace elements and higher along the profile lake.

Depth (meters)		Ba	Ca	Fe	K	Li	Mg	Mn	Na	S	Sr	Zn
		μg/L	μg/mL	μg/L	μg/mL	μg/mL	μg/mL	μg/L	μg/mL	μg/mL	μg/L	μg/L
0	Minimum	29,8	10,3	15,4	2,5	<Q.L	3,8	<Q.L	2,1	0,8	87,4	<Q.L
	Average	41,4	11,0	52,2	2,9	<Q.L	4,2	15,9	2,5	1,0	79,8	8,7
	Maximum	49,6	11,8	162,0	3,3	<Q.L	4,7	23,6	2,9	1,2	66,4	31,6
5	Minimum	15,3	4,7	<Q.L	1,1	<Q.L	1,9	<Q.L	0,8	0,5	74,1	<Q.L
	Average	42,1	10,6	40,8	2,9	<Q.L	4,1	14,6	2,4	0,9	78,4	21,8
	Maximum	49,7	11,8	65,2	3,7	<Q.L	4,6	10,5	2,9	1,2	88,3	31,6
10	Minimum	44,7	10,8	12,2	2,8	1,0	4,3	<Q.L.	2,4	0,8	75,3	<Q.L
	Average	55,3	11,9	34,9	3,5	1,0	4,8	22,8	2,7	1,0	85,4	7,3
	Maximum	85,1	19,6	109,3	5,2	1,0	7,9	98,4	4,4	1,5	146,0	11,0
15	Minimum	47,7	9,0	<Q.L	3,0	1,2	3,8	<Q.L	2,4	0,9	62,1	4,7
	Average	57,0	11,4	58,9	3,5	1,2	4,6	120,3	2,6	0,9	81,0	17,5
	Maximum	72,0	12,0	159,1	4,2	1,2	4,9	343,3	3,1	1,0	87,5	67,5
20	Minimum	50,2	11,2	<Q.L	3,2	1,1	4,5	<Q.L	2,4	0,7	77,7	<Q.L
	Average	60,4	11,8	253,3	3,7	1,1	4,8	219,9	2,6	1,0	82,8	9,3
	Maximum	71,5	12,4	884,0	4,3	1,1	5,0	472,0	3,1	1,3	86,3	18,0
25	Minimum	47,8	11,0	<Q.L	4,4	0,9	4,4	<Q.L	2,4	0,7	76,2	<Q.L
	Average	64,6	12,0	500,1	3,8	0,9	4,8	416,5	2,6	1,0	83,3	9,4
	Maximum	78,7	12,8	1.486,0	3,2	0,9	5,1	1.046,0	2,9	1,6	88,3	14,8
28	Minimum	51,3	11,4	9,1	3,2	<Q.L	4,5	2,8	2,4	0,3	77,2	<Q.L
	Average	77,5	12,8	1.526,6	4,0	<Q.L	5,1	997,3	2,6	0,8	87,6	13,3
	Maximum	107,0	17,0	7.579,0	5,0	<Q.L	6,9	2.202,0	3,4	1,1	110,0	29,8
Q.L		0,348	0,013	7,980	0,071	0,954	0,002	1,170	0,015	0,064	0,145	3,840

Q.L. = Limit of quantification of equipment

For this author, shallower tropical lakes should have a polymictic behavior. The OPPS lake, despite relatively shallow, is very small in area, factor that diminishes the influence of wind and makes the formation of convection flows very difficult during the whole year.

The existing stratification practically during eight months of the year impedes the formation of convection flows in the lake, resulting in a permanent cold and weakly oxygenated hypolimnion (Figs. 4 A, B, C, D and 5 A and B). The lack of flows and oxygenation promotes the formation of reducing environments. July, September, August and October are the only months during which oxidizing environments exist along the water column (Figs. 4 E and F). The hypolimnion reducing environment that lasts for most part of the year prevents the generation of acid drainage in the lake, maintaining a pH between neutral and alkaline during the whole year (Figs. 4 G and H). The slightly acid values found on the surface of the lake during some months (Figs. 4 G) are related to rain and the entry of superficial runoff. In reducing environments, the oxidation state of some elements (Fe and Mn, for example – Fig. 6 A) change, making them soluble and causing an increase in electrical conductivity in the hypolimnion (Figs. 6 B, C and D), especially close to the bottom, where the concentration of Fe(II) present in the water is increased (Fig. 6A).

Table 1 shows the variation in concentration of elements along lake profile. The major and trace elements analyzed do not show a definite pattern, occurring different concentrations behaviors with increasing depth. Some elements exhibit little change in concentration with increasing depth, which remain substantially constant along the profile of the lake (eg, Fe, Na, Sr and Zn – Figs. 7 A, B, C and D). Others have their concentration slightly increased with depth (eg, Ba, Ca, K, Mg and Mn – Figs. 8 A, B, C and D) and rare exhibit inverse relationship, decreasing with depth (eg, Li, S – Figs. 9 A and B).

Models for predicting the geochemistry of water in pit lakes are still recent. One of the most complete is the one proposed by Eary (1999), who studied the chemical composition and the tendency to equilibrium in several lakes formed in open pit mines, trying to establish geochemical models to predict the quality of the waters. According to his model, high concentrations of solutes generally occur under extreme conditions of acid and alkaline pH. Combinations of metals (Al, Cd, Cu, Fe, Mn, Pb and Zn) are elevated in lakes acids, while those of metalloids (As and Se) are generally higher in alkaline lakes (Eary, 1999). Waters with near neutral pH, similar to the studied lake, did not favor the occurrence of high concentrations of solutes. In lake studied the hydrolysis of iron (II), manganese and other transition metals buffered pH near 7, favoring the maintenance of water quality.

5. CONCLUSION

The OPPS pit lake can be classified as a tropical hot, monomictic lake. Despite relatively young and shallow (maximum depth of 28 m), the lake is totally stratified, with a clear evolution from stratified to de-stratified along the year, with water circulation occurring during the colder months (mainly July, August and September). The lack of convection flows in *ca.* 2/3 of the year makes the re-aeration of the lake difficult, leading to the maintenance of reducing conditions in the hypolimnion. A pH between neutral and alkaline is maintained in the pit lake, which leads to a better quality of the water in the lake.

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