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Article

Integrated Assessment of the Quality of Sediments of Open Pit Lakes and the Impact on the Environment

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Abstract: The mining industry is known for the intense environmental impacts it triggers, especially when it is developed in an open environment. Pit lakes are formed in depleted deposits and may be promising opportunities for use by society as well as troubling environmental liabilities. While these artificial basins are increasing numerically in many parts of the world, they are still little known researchers in the Environmental Sciences, which makes their environmental management challenging. The main objective of this study was to evaluate the environmental quality of sediments from three deactivated open-pit gold mines, located in the Mara Rosa, Brazil, through chemical, ecotoxicological and genotoxicology analyses. For this purpose, we collected samples in the dry season boom, and subsequently, we analysed metals. In sequence, acute ecotoxicological and a genotoxicology test (comet assay) were developed with *Danio rerio* fishes, in concentrations of 3.12%; 6.25%; 12.5%; 25%; 50% and 100%, in addition to the control group. The results indicated that the three lakes are environmentally compromised, especially Lago Azul, whose waters and sediments are undergoing an intense process of geological conditioning. Our results did not verify the ecotoxicity of the sediments of any of the lakes, only behavioural alterations in the test organisms exposed to the concentrations of 25%, 50% and 100% of the samples obtained in the Lago Azul. About the sediments, DNA damage at *Danio rerio* was detected in the three investigated environments, although fishes kept in the water sampled at Lago Azul presented the most extension of DNA damages.

Keywords: acid mine drainage; contaminated areas; environmental; heavy metals; public health

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1. Introduction

Because of the increasing demand for minerals, mining activity has become one of the leading industries developed by many countries. Brazil, which holds some of the most significant geological potentials in the world, stands out in this context and should considerably expand its mining complexes in the coming years. However, the environmental management challenges of the sector are substantial and require joint efforts across society. Cases of accelerated decline in the quality of natural resources such as soil, surface water, and groundwater in mined areas are not uncommon, especially in the post-operation phase of mining projects, which are often abandoned without all the recovery measures being implemented. Gold mines stand out in this context, as gold is usually associated with sulfate rocks originally in chemical equilibrium that when in contact with water and air, can foster the emergence of acid mine drainage (AMD). AMD has a high potential for environmental degradation, as it is acidic and rich in dissolved toxic metals, responsible for the emergence of numerous contaminated areas around the world (Antunes et al., 2007).

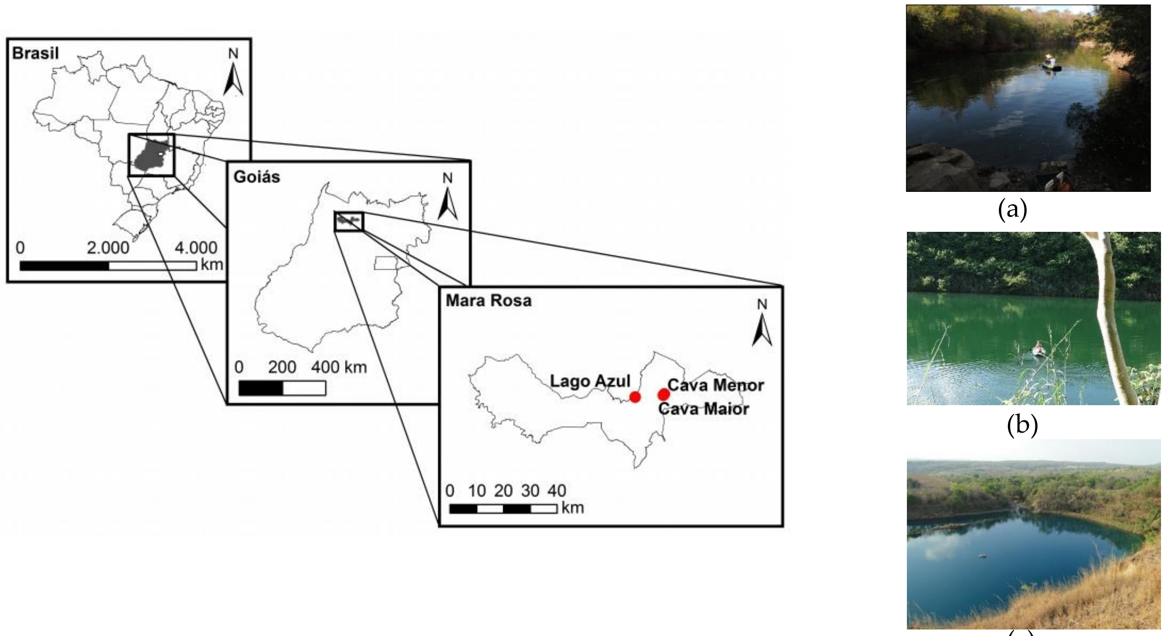
Mining pit lakes, although environmentally complex, have been considered for use as recovery alternatives or in selected human activities. However, studies that have sought to measure the degree of environmental compromise of these artificial lakes are still rare in the literature (Mollema et al., 2015). Esteves (2011) clarify that sediments are one of the most critical components associated with aquatic ecosystems, as they constitute a temporary cumulative stock of toxic chemical compounds. Even if the water column initially presents good quality, contaminated sediments in the bottom can be resuspended through anthropic processes such as water pumping or even natural processes such as thermal stratification (Edberg et al., 2012) and consequently reintroduce toxic elements into the water, making it potentially harmful to living things. Depending on the intended use of pit lakes, more profound assessments are needed to understand better the potential risks associated with these environments.

Ecotoxicological analyses are understood as advanced alternatives for the monitoring and evaluation of the natural environment. Once, they add aspects to environmental assessments, serving as a basis for the establishment of cause and effect relationships. In this way, making it possible to anticipate the potential risks to the natural environment if it comes in contact with toxic elements. Gagnaire et al. (2015) clarify that sediment particles usually adsorb chemical elements such as metals or dissolved between their pores, which makes the ecotoxicological evaluation of this component important. However, although some research has evaluated the chemical quality of mining pit lakes sediments around the world, studies that have sought to analyse their chemical and ecotoxicological aspects together are still few and recent. Moreover, studies involving the genotoxicity potential associated with pit lakes sediments are unknown. Therefore, the main objective of the present study was to evaluate the environmental quality of sediments of three deactivated gold mines by chemical, ecotoxicological and genotoxicity analyses.

2. Materials and Methods

The city of Mara Rosa (Goiás, Brazil) has lived with gold mining in alluvial prospects for decades, but in recent years, this rudimentary activity has given rise to large open-pit mining companies that have settled in the region but are currently deactivated. The environmental liabilities arising from the mining practices developed in the municipality were not satisfactorily alleviated, being constituted mainly by three pit lakes located in the rural area, in which artificial lakes were formed. In this study, these environments are called Cava Maior (approximately 1.7 ha), Cava Menor (0.7 ha), and Lago Azul (2.8 ha) (Figure 1).

Pit Lakes *Maior* and *Menor*, mined until 1995 and were isolated and partially surrounded by introduced vegetation, and they present some points with exposed rocks. The Lago Azul was also formed in the 90 s, and it is the central tourist spot of Mara Rosa, having a deposit of sterile and a solid bench almost 40 meters in height in its direct surroundings, exposed to rainwater and atmosphere.



(a)

(b)

(c)

Figure 1. Sample areas distribution in Mara Rosa, Goiás State, Brazil. (a) Pit Lake *Menor*. (b) Pit Lake *Maior*. (c) Lake *Azul (Blue Lake).*

3. Results and discussion

Measurements with each bathymetry showed that the bottom morphometry of the three lakes is irregular. The pits lake *Maior* and *Menor* had maximum depths of 17 m and 30 m, respectively. The Lago Azul, in turn, has two predominant morphological features: a small area of lesser depth near its northern margin, with a depth of about 10 m, and another, which constitutes its most considerable part, formed by a depression that reaches 46 m depth.

These figures demonstrate depths that, if compared to the surface areas of the three wells studied, are disproportional, a common feature in the case of mining lakes. In this sense, according to authors such as Skipperud et al. (2013), the morphometry of mining lakes is the result of a combination of factors such as geological conditions of mineral deposits, excavation technology and depth of groundwater, which makes each pit unique in morphometric terms.

The results of the metals in the water and sediments are listed in Tables 1 to 3.

Table 1. Insert Table 1

Table 2. Insert Table 2

Table 3. Insert Table 3

In terms of water quality, the three environments presented similar behaviour: the concentrations of almost all the quantified metals were predominantly increased in the direction of the surface to the bottom, a typical result for mining an. The waters of the pit lakes *Maior* and *Menor* were compromised qualitatively, as several analytes exhibited concentrations above the established maximum limits: aluminium, arsenic, cadmium, copper, iron, and manganese in the first; and aluminium, copper, and manganese in the latter. In this case, we expected that the elements are in disagreement with the Brazilian legislation and they were practically the same for both lakes, once because they are located in the same geological environmental. As water quality is usually a reflection of the chemical composition of the soil with which water has contact (Gagnaire et al., 2015), we concluded that both wells presented similar geochemical conditioning.

In Lake *Azul*, its waters presented high concentrations of aluminium, arsenic, cadmium, lead, cobalt, copper, chromium, iron, manganese, nickel, and zinc. Considering the acidity of its waters (pH <4.50), the presence of large amounts of rocks and barren areas, exposed to the weather, in its immediate vicinity and the probable processes of evaporation concentration. It is verified that the water volume accumulated in its interior is submitted to more intense methods of mineralisation and geological control, compared to those observed in the other two environments surveyed.

Bowel weathering that favours environmental contamination has also been proven in several studies, such as those conducted by several authors. Lottermoser et al. (2005), for example, identified an intense degradation process at the Mary Kathleen Mine (Australia), finding that open rocks released chemical elements such as copper and nickel, which alter the water quality of a uranium pit.

Additionally, Antunes et al. (2007) investigated the water quality of an abandoned Portuguese mine and found manganese, iron, aluminium, uranium, and strontium above permitted limits. Hrdinka et al. (2013) analysed the water quality of Lake Hromnice, located in the Czech Republic, formed after the closure of a long period of mining activities, and the authors observed increasing concentrations of calcium, magnesium, sodium, potassium, iron, and aluminium.

Regarding the results of the chemical characterisation of the sediments, it was verified that the geological control of the wells studied exerts a strong influence on the chemical quality of this environmental compartment, as the concentrations of the analysed analytes were much higher in the bottom of the pit lakes. In this sense, Pit lake *Minor* sediments presented high levels of cadmium, copper, chromium, mercury, and nickel, and Pit lake *Maior* presented barium, cadmium, cobalt, and nickel. Blue Lake, in turn, offers a higher degree of environmental compromise than the other two, as barium, cadmium, lead, copper, chromium, nickel, and zinc were detected in its sediments several times above the legal limits in force (Table 3).

According to Delgado-Martin et al. (2013), sediments are usually critical in terms of concentrations of potentially toxic chemical elements, which occur mainly because of their high sorption capacity associated with particle accumulation. To avoid soil contamination is crucial to consider the potential contaminants in the soil.

Some studies on pit lakes have had geochemical approaches that included sediment analyses, such as those conducted by several authors. So, Lottermoser et al. (2005), for example, investigated the transfer of contaminants from deposits of rock and mineralised soil deposits into sediments and other environmental components of an Australian uranium mine. They observed accelerated mineral wear processes in the area as a whole, especially in rocks and walls of the open pit mine, which favoured the mobility of metals and negatively altered the quality of the pit lake water. In the sediments and as evidenced in this research, the authors also observed high concentrations of analytes such as arsenic, copper, nickel, lead, and zinc.

Mollema et al. (2015) evaluated the potential of an old Dutch pit for public supply purposes. For that, they developed a study to characterise the quality of its water and sediments. It was found that the average concentrations of potentially toxic metals in the bottom particles increased considerably between 2000 and 2010, mainly the cadmium, nickel, and zinc analytes, as observed in the Greater and Lesser Minig Pit Lakes and mostly in the Blue Lagoon. Triantafyllidis and Skarpelis (2006) analysed several samples from the Kirki Mine, Greece, including sediments. As observed for

Lago Azul, marked acidity and high concentrations of toxic elements were found in the waters and at the bottom of the lake, such as iron, lead, zinc, arsenic, and copper.

In general, the authors who investigated the chemical quality of sediments of mining pit lakes highlight the high influence of rainwater and air in this process, as they are weathering elements that, when they are exposed to sulfide minerals present in the soil and near mines, trigger acid drainage. This understanding can be applied to the Greater and Lesser Minig Pit Lakes and the Blue Lagoon, as they constitute environmental liabilities that have not been satisfactorily alleviated and that, as a consequence, they present geological outcrops and piles of tailings directly exposed to the elements, in particular, this last.

In the ecotoxicological tests carried out for sediments, we did not observe the mortality of any test organism. However, samples from Lago Azul at concentrations of 25.0% and more frequently from 50.0% and 100.0%, showed significant behavioural effects on the exposed individuals, who presented moments of intense agitation followed by brief lethargy, behaviour that corroborates the low chemical quality of the sediments of this pit, as already described.

Studies involving ecotoxicological trials of cavity sediments are still rare. According to Antunes et al. (2007), for example, low toxicity results from cava bottom samples were also observed. Those authors evaluated the environmental degradation of a Portuguese uranium mine through the acute seasonal toxicity of water and sediment of the pit lake. The synergistic potential of these substances was measured using algae (*P. subcapitata*), microcrustaceans (*D. magna* and *D. longispina*), and dipterous (*C. riparius*). Regarding the sediments, acute toxicity was not observed for the tested species, except for *D. longispina*. Aluma et al. (2011) used *Daphnia magna* microcrystalline eggs in the sediment toxicity analysis of an Ohio mine area. For this purpose, they were incubated in containers containing water in the presence of substrates with and without metallic contaminants from DAM, observing 0% hatching at the highest concentrations of the analytes of environmental interest.

The results obtained for the percentage of DNA in the tail can be observed in Figure 2.

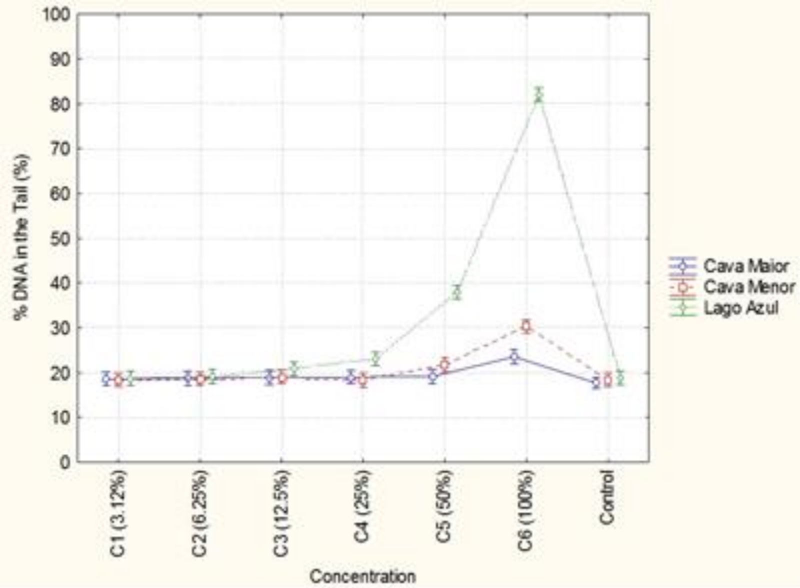


Figure 2. Percentage of DNA in the Tail for the samples of sediments of the Cava Menor, Cava Maior and Lago Azul

Comparatively, the deposits of Lago Azul presented greater genotoxicity than those of the other two environments, with 82% DNA damage at 100% concentration (C6). Cava Menor exhibits 30.27% (C6) of DNA percentage in the tail and the most significant 23.53% (C6). Compared to their respective negative control groups, fishes exposed to the Lago Azul sediments demonstrated increased DNA damages due to from the concentration of 12.5% (C3), while in the Pit lake *Menor* and *Maior*, the interference in genetic level was only perceived from 50% (C5) in the first and 100% (C6) on the last.

Collins et al. (2008) explained that a genotoxic agent could cause DNA strand breaks, and when they occur, their fragments of various sizes migrate after an electrophoretic run, forming a comet visible in the Comet Assay. DNA damage can be detected even with short exposures and is a clue of acute intoxication promoted by the association of contaminants with exposed organisms.

Then we verified that sediments of the three pit lakes presented genotoxic potential, results that corroborate with chemical data. Zinc, for example, usually acts synergistically with other elements, such as cadmium, and potentiates the degrading effects on exposed organisms. So, cadmium can acutely affect kidneys, liver, pancreas, gonads, and lungs of fishes and trigger problems associated with changes in calcium metabolism, liver damage, and adverse effects on the cardiovascular system.

According to Zagatto and Bertoletti (2008), it was verified that several of the metals detected in the pit lakes examined in this research, are cumulative in organisms and can cause organic changes in their nervous, respiratory, digestive, intestinal, and cardiovascular systems, bone marrow and kidney interference, and destruction of mucous membranes and internal organs. In addition to several types of cancer and that aluminium has a high toxicological potential. Barium, even in small amounts, can cause diarrhoea, respiratory distress, changes in blood pressure and heart rate, paralysis, and muscle weakness in living beings.

In the case of arsenic, a recognised toxic element, that mining is one of the primary sources of this contaminant and that its effects on organisms include the development of many types of cancer, intestinal diseases, vascular diseases, peripheral neuropathies, and diabetes.

4. Conclusions

The waters and sediments of the investigated pit lakes presented concentrations of several toxic chemical elements above the maximum values established by Brazilian legislation, such as arsenic, barium, cadmium, lead, and mercury, which increased in the direction of the surface at the bottom and higher in the sediments. The three pit lakes are environmentally compromised, especially Lago Azul, undergoing intense geological conditioning.

The results of the bioassays did not show the ecotoxicity of the sediments of any of the pit lakes but only behavioural changes in the organisms exposed to the concentrations of 25%, 50%, and 100% of the samples from Lago Azul. However, comet assay demonstrated that pit lakes are environmentally compromised, as fishes showed a gradual increase in the number of cells with t most significant amount of DNA damage, mainly for Lago Azul. Therefore, the evaluated pit lakes exhibit environmental liabilities that demand the attention of public managers and mining industry regarding the risks they present, due to their current environmental conditions.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix B

Table 1. **Chemical elements and sediments at Pit Lake *Menor*.**

Concentration of Chemical Elements – Pit Lake *Menor*					LQ	Maximum Allowable Values	
Chemical Element	Water (mg L^{-1})			Sediment		Water^1	Sediment^2
	0.20 m	9.00 m	18.00 m	(mg Kg^{-1})		(mg L^{-1})	(mg Kg^{-1})
Al	0.34±0.00	0.35±0.00	0.95±0.02	13933.52±1006.18	0.046	0.1	-
Sb	<LQ	<LQ	<LQ	<LQ	0.005	0.005	-
As	0.02±0,00	0.01±0.00	0.01±0.00	5.20±0.72	0.008	0.01	5.9
Ba	0.03±0.00	0.03±0.00	0.05±0.00	233.06±14.16	0.011	0.7	-
B	<LQ	<LQ	<LQ	3.92±0.33	0.054	0.5	-
Cd	<LQ	0.001±0.000	0.006±0.000	6.62±0.12	0.001	0.001	0.6
Ca	82.02±0.72	82.65±0.67	87.48±0.72	5034.71±575.06	0.563	-	-
Pb	<LQ	<LQ	<LQ	7.11±0.54	0.004	0.01	35.0
Co	<LQ	<LQ	<LQ	15.61±0.33	0.005	0.05	-
Cu	0.04±0.00	0.04±0.00	0.05±0.00	136.10±0.55	0.005	0.009	35.7
Cr	<LQ	<LQ	<LQ	65.32±0.95	0.003	0.05	37.3
Fe	<LQ	<LQ	0.64±0.02	21550.45±302.71	0.339	0.3	-
P	<LQ	<LQ	<LQ	<LQ	0.02	0.03	-
Mg	37.30±0.50	37.30±0.30	39.35±0.40	12069.70±134.60	0.155	-	-
Mn	0.15±0.00	0.16±0.00	0.33±0.00	452.90±3.25	0.108	0.1	-
Hg	<LQ	<LQ	<LQ	0.19±0.09	0.047	0.0002	0.17
Mo	<LQ	<LQ	<LQ	2.34±1.22	0.01	-	-
Ni	<LQ	<LQ	<LQ	46.08±2.99	0.012	0.025	18.0
K	10.24±0.12	10.20±0.08	9.97±0.08	4817.49±7.16	0.648	-	-
Ag	<LQ	<LQ	<LQ	<LQ	0.03	0.01	-
Se	<LQ	<LQ	<LQ	<LQ	0.013	0.01	-
Na	13.01±0.52	12.67±0.10	12.67±0.06	289.55±13.84	0.208	-	-
V	<LQ	<LQ	<LQ	45.72±2.01	0.023	0.1	-
Zn	<LQ	<LQ	<LQ	70.42±0.74	0.032	0.18	123.0

Legend: Values in black are above the permitied Brazilian values / LQ: Limit of Quantification / ^{1} – Values to water Class 2 (CONAMA 357/2005) / ^{2} – Values of CONAMA Resolution 454/2012 (BRASIL, 2012).

Table 2. Chemical elements and sediments at Cava Maior.

Concentration of Chemical Elements – Pit lake Maior					LQ	Maximum Allowable Values	
Chemical Element	Water (mg L^{-1})			Sediment		Water[1]	Sediment[2]
	0.20 m	15.50 m	31.00 m	(mg Kg^{-1})		(mg L^{-1})	(mg Kg^{-1})
Al	0.33±0.00	0.33±0.00	0.49±0.08	16000.19±948.06	0.046	0.1	-
Sb	<LQ	<LQ	<LQ	<LQ	0.005	0.005	-
As	0.01±0.00	0.01±0.00	0.01±0.00	0.46±0.23	0.008	0.01	5.9
Ba	0.06±0.00	0.06±0.00	0.06±0.00	663.09±43.46	0.011	0.7	-
B	<LQ	<LQ	<LQ	4.73±0.21	0.054	0.5	-
Cd	<LQ	<LQ	0.001±0.000	11.23±0.19	0.001	0.001	0.6
Ca	29.50±0.80	29.90±0.32	29.41±0.14	3656.64±153.31	0.563	-	-
Pb	<LQ	<LQ	<LQ	15.18±0.57	0.004	0.01	35.0
Co	<LQ	<LQ	<LQ	99.84±1.61	0.005	0.05	-
Cu	0.04±0.00	0.04±0.00	0.04±0.00	10.87±0.10	0.005	0.009	35.7
Cr	<LQ	<LQ	<LQ	29.60±0.32	0.003	0.05	37.3
Fe	<LQ	<LQ	<LQ	37946.33±390.98	0.339	0.3	-
P	<LQ	<LQ	<LQ	<LQ	0.02	0.03	-
Mg	13.65±0.51	13.48±0.14	13.02±0.07	9314.83±77.08	0.155	-	-
Mn	0.16±0.00	0.16±0.00	0.33±0.00	509.53±3.57	0.108	0.1	-
Hg	<LQ	<LQ	<LQ	0.160±0.01	0.047	0.0002	0.17
Mo	<LQ	<LQ	0.002±0.000	3.02±0.31	0.01	-	-
Ni	<LQ	<LQ	<LQ	19.84±0.37	0.012	0.025	18.0
K	6.90±0.28	6.79±0.03	6.79±0.03	5992.26±8.15	0.648	-	-
Ag	<LQ	<LQ	<LQ	21.65±0.02	0.03	0.01	-
Se	<LQ	<LQ	<LQ	2.33±1.53	0.013	0.01	-
Na	26.66±0.20	26.75±0.43	27.36±0.31	214.96±14.30	0.208	-	-
V	<LQ	<LQ	<LQ	70.14±0.53	0.023	0.1	-
Zn	<LQ	<LQ	<LQ	98.56±1.79	0.032	0.18	123.0

Legend: Values in black are above the permitied Brazilian values / LQ: Limit of Quantification / [1] – Values to water Class 2 (CONAMA 357/2005) / [2] – Values of CONAMA Resolution 454/2012 (BRASIL, 2012).

Table 3. Chemical elements and sediments at Lago Azul.

Concentration of Chemical Elements – Lago Azul					LQ	Maximum Allowable Values	
Chemical Element	Water (mg L^{-1})			Sediment		Water^1	Sediment^2
	0.20 m	23.00 m	46.00 m	(mg Kg^{-1})		(mg L^{-1})	(mg Kg^{-1})
Al	1.14±0.03	1.14±0.00	20.58±0.21	31147.88±510.03	0.046	0.1	-
Sb	<LQ	<LQ	<LQ	<LQ	0.005	0.005	-
As	0.009±0.002	0.01±0.00	0.02±0.00	3.36±1.50	0.008	0.01	5.9
Ba	0.04±0.00	0.04±0.00	0.03±0.00	2011.52±38.81	0.011	0.7	-
B	<LQ	<LQ	<LQ	5.14±0.41	0.054	0.5	-
Cd	0.007±0.000	0.007±0.000	0.031±0.000	34.78±0.06	0.001	0.001	0.6
Ca	43.98±1.84	44.59±0.31	96.36±1.08	1097.05±17.91	0.563	-	-
Pb	<LQ	<LQ	0.04±0.00	75.76±1.31	0.004	0.01	35.0
Co	0.04±0.00	0.04±0.00	0.29±0.00	6.35±0.07	0.005	0.05	-
Cu	0.16±0.00	0.16±0.00	0.54±0.00	526.51±7.39	0.005	0.009	35.7
Cr	<LQ	<LQ	0.06±0.00	978.08±7.09	0.003	0.05	37.3
Fe	<LQ	<LQ	4.39±0.05	102618.60±406.91	0.339	0.3	-
P	<LQ	<LQ	<LQ	<LQ	0.02	0.03	-
Mg	40.17±1.76	40.50±0.24	130.86±1.33	15746.37±147.52	0.155	-	-
Mn	1.31±0.01	1.32±0.01	3.85±0.01	205.69±1.16	0.108	0.1	-
Hg	<LQ	<LQ	<LQ	<LQ	0.047	0.0002	0.17
Mo	<LQ	<LQ	<LQ	18.65±1.14	0.01	-	-
Ni	0.26±0.00	0.26±0.00	1.33±0.00	125.01±1.30	0.012	0.025	18.0
K	8.69±0.32	8.71±0.03	14.07±0.04	13473.13±129.35	0.648	-	-
Ag	<LQ	<LQ	<LQ	<LQ	0.03	0.01	-
Se	<LQ	<LQ	<LQ	3.21±2.02	0.013	0.01	-
Na	7.97±0.33	7.98±0.04	20.03±0.20	707.56±0.84	0.208	-	-
V	<LQ	<LQ	0.02±0.00	142.04±1.20	0.023	0.1	-
Zn	0.85±0.01	0.87±0.01	3.51±0.01	291.41±1.45	0.032	0.18	123.0

Legend: Values in black are above the permitied Brazilian values / LQ: Limit of Quantification / ^{1} – Values to water Class 2 (CONAMA 357/2005) / ^{2} – Values of CONAMA Resolution 454/2012 (BRASIL, 2012).

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