



## Assessing the impacts of mining activities on zooplankton functional diversity

Avaliando os impactos das atividades de mineração sobre a diversidade funcional do zooplâncton

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**Abstract: Aim:** Mining activities generate countless environmental impacts, including heavy-metal contamination, sorting and increased turbidity. In aquatic ecosystems these impacts can drastically affect the initial links of the food chain, such as zooplankton. **Methods:** To evaluate how the different mining activities can influence the structure and functional diversity of zooplankton, we investigated the geochemical characteristics of the water and sediment in two small impoundments impacted by different mining activities (kaolin and iron extraction). We also explored zooplankton composition, species diversity and functional diversity (feeding guilds taxa). **Results:** As expected, the water and the sediment of both of the reservoirs showed high concentrations of trace elements, particularly Al, Ba, Fe, Mg, Mn, Sr and Zn. Zooplankton biomass and diversity were markedly reduced ( $< 12 \mu\text{g.DW.L}^{-1}$  and  $H' < 1.5$ , respectively), and negatively correlated with turbidity and total suspended solids. Small microphages dominated the trophic composition of zooplankton, and an alternation of trophic guilds was not observed, since the dynamics of raptorial organisms was essentially linked to the temporal fluctuation of a single species of rotifer (*Polyarthra* cf. *dolichoptera*). **Conclusions:** In addition to changes in the aquatic habitat and zooplankton composition, the functional niches were also affected by the mining impacts. The use of the functional diversity analysis can emerge as a valuable approach to understand how zooplankton communities respond to drastic environmental changes.

**Keywords:** mining; impact; zooplankton; functional diversity.



**Resumo: Objetivo:** as atividades de mineração originam inúmeros impactos ambientais, incluindo contaminação por metais pesados, assoreamento e aumento da turbidez. Nos ecossistemas aquáticos, esses impactos podem afetar drasticamente os elos iniciais da cadeia alimentar, como o zooplâncton. **Métodos:** Para avaliar como as diferentes atividades minerárias influenciam a estrutura e a diversidade funcional do zooplâncton, investigamos as características geoquímicas da água e do sedimento de dois pequenos açudes impactados por diferentes atividades de mineração (extração de caulim e de ferro). Também exploramos a composição, diversidade de espécies e diversidade funcional (taxa de guildas alimentares) do zooplâncton. **Resultados:** Como esperado, a água e o sedimento dos dois açudes apresentaram altas concentrações de elementos-traço, particularmente Al, Ba, Fe, Mg, Mn, Sr and Zn. A biomassa e a diversidade de espécies do zooplâncton foram extremamente reduzidas ( $< 12 \mu\text{g.PS.L}^{-1}$  and  $H' < 1.5$ , respectivamente), negativamente correlacionadas com a turbidez e sólidos em suspensão. Pequenos micrófagos dominaram a composição trófica do zooplâncton em todo o período de estudo, e não foi constatada uma alternância das guildas tróficas, uma vez que a dinâmica dos organismos raptoriais foi essencialmente vinculada à flutuação temporal de uma única espécie de rotífero (*Polyarthra* cf. *dolichoptera*). **Conclusões:** Em adição às mudanças no habitat aquático e na estrutura da comunidade zooplancônica, os nichos funcionais do zooplâncton também foram afetados. A utilização da análise da diversidade funcional pode emergir como uma ferramenta valiosa para entender como a comunidade zooplâncton responde a alterações drásticas no ambiente.

**Palavras-chave:** mineração; impactos; zooplâncton; diversidade funcional.

## 1. Introduction

The process of mineral extraction inevitably produces a large volume of unwanted material (non-ore-bearing material and tailings), generating multiple impacts on the environment, principally on aquatic ecosystems (Rösner 1988; Earman & Hershey, 2004; Muscatello & Janz, 2010; Ward et al., 2012). The load of mining-generated particulate matter on the adjacent aquatic ecosystems causes significant alterations in turbidity and several other physical-chemistry parameters, silting of waterbodies, accumulation of mining wastes over the natural sediments, and impacts in the functional processes and aquatic biodiversity (Roland & Esteves, 1993). The zooplankton assemblage is a sensitive indicator of the ecological status of an aquatic ecosystem, since it can respond to environmental changes with rapid modifications in the species composition and structure (Jeppesen et al., 2005; Sousa et al., 2008). Moreover, since the zooplankton is closely related to primary producers (phytoplankton) and other links of the aquatic food chain (fish and benthos), impacts on the zooplankton can spread along the entire aquatic food chain.

Inorganic particulates that are generated in high amounts during mineral extraction may affect the zooplankton community in different ways. One is the reduction of light penetration in the water, leading to a decline in primary productivity (Grobelaar, 1989). Another consequence is the possibility that zooplankton will ingest inorganic particles associated with phytoplankton, reducing

the nutritional value of the algal food (Arruda et al., 1983; McCabe & O'Brien, 1983; Hart, 1988), affecting their weight, body size and feeding behavior.

Functional diversity is a biodiversity measure based on functional traits of species, and is considered a promising approach to better understand the underlying principles that govern community dynamics (Tilman, 2001; Mason et al., 2005). Because of the potential relationship between functional diversity and the function and maintenance of important ecosystem processes (Petchey & Gaston, 2002; Vogt et al., 2010), the use of the functional characteristics of zooplankton can be used an efficient approach for evaluating impacts on the structure and functioning of aquatic ecosystems (Klug et al., 2000; Vogt et al., 2013). Zooplankton exhibits a considerable diversity of ecological feeding strategies, which includes a diverse range of behavioral, morphological, physiological and life history traits (Litchman et al., 2013). The complete representation of this feeding diversity influence zooplankton communities and aquatic ecosystem in general.

Recent studies have suggested that trophic asymmetry (temporary dominance of a trophic group) may be an important recurring feature of the ecosystem response to anthropogenic stress, and thus a reliable indicator of environmental impacts (Fischer et al., 2001; Hogsden et al., 2009). Other studies have indicated that the occurrence of alternating peaks between microphagous and raptorial species is a function of the resilience

mechanisms of aquatic ecosystems, related to functional diversity (Walker et al., 1999; Hampton, 2005).

Functional diversity has been claimed to be the most effective diversity measure to assess the positive effects of biodiversity on ecosystem functioning and services. Therefore, efforts toward the description of the traits structure of the communities could provide a more realistic picture of how biodiversity influences ecosystems, representing an important tool for conserving species and ecosystems (Tilman et al., 2001; Balvanera et al., 2006; Laureto et al., 2015).

The main objectives of the present study were to determine the associations between different mining activities (iron and kaolin extraction) and various physical, chemical and biological aspects of two artificial impoundments located in the Iron Quadrangle (Minas Gerais state, southeast Brazil), with particular emphasis on the composition, diversity and trophic structure (trophic ratio) of the zooplankton assemblages. We hypothesized that: (i) microphagous species would increase with decreased water transparency, due to the enhance in turbidity and concentration of inorganic particles in the water and (ii) zooplankton would have a more diverse array of traits, with microphagous and raptorial species alternating in their quantitative dominance of the assemblage, in response to the seasonal changes in wastewater discharge from mining activities.

## 2. Material and Methods

The collections were carried out in two artificial impoundments, located in the northern part of the upper basin of Mata Porcos stream, between 20°13'45" and 20°21'14" S and 45°58'15" and 43°52'43" W. Figure 1. The impoundment termed IRONR (Iron Reservoir) was formed during artisanal gold mining in the 18th and 19th centuries, and was recently impacted by mining and processing of iron ore. The reservoir has an area of about 0.05 Km<sup>2</sup>, perimeter 1.7 Km and mean depth of 6.75 m. The second impoundment, termed KAOR (Kaolin Reservoir), with an area of 0.03 Km<sup>2</sup>, perimeter 1 Km and mean depth of 4.25 m, receives the outflow from a kaolin open-pit mine that has been inactive for about five years. These reservoirs are enclosed within a well-defined watershed with mining wastewater inputs that can be well identified, what make them unique for the study of mining impacts. The water level in the reservoirs can rise up during the seasonal

rainy period, but it is controlled by one small spillway, which discharge the water directly in the Mata Porcos stream. It was not possible to select a reservoir or lake as an ecosystem control in the watershed, in function of the intense and widespread mining activities in the region.

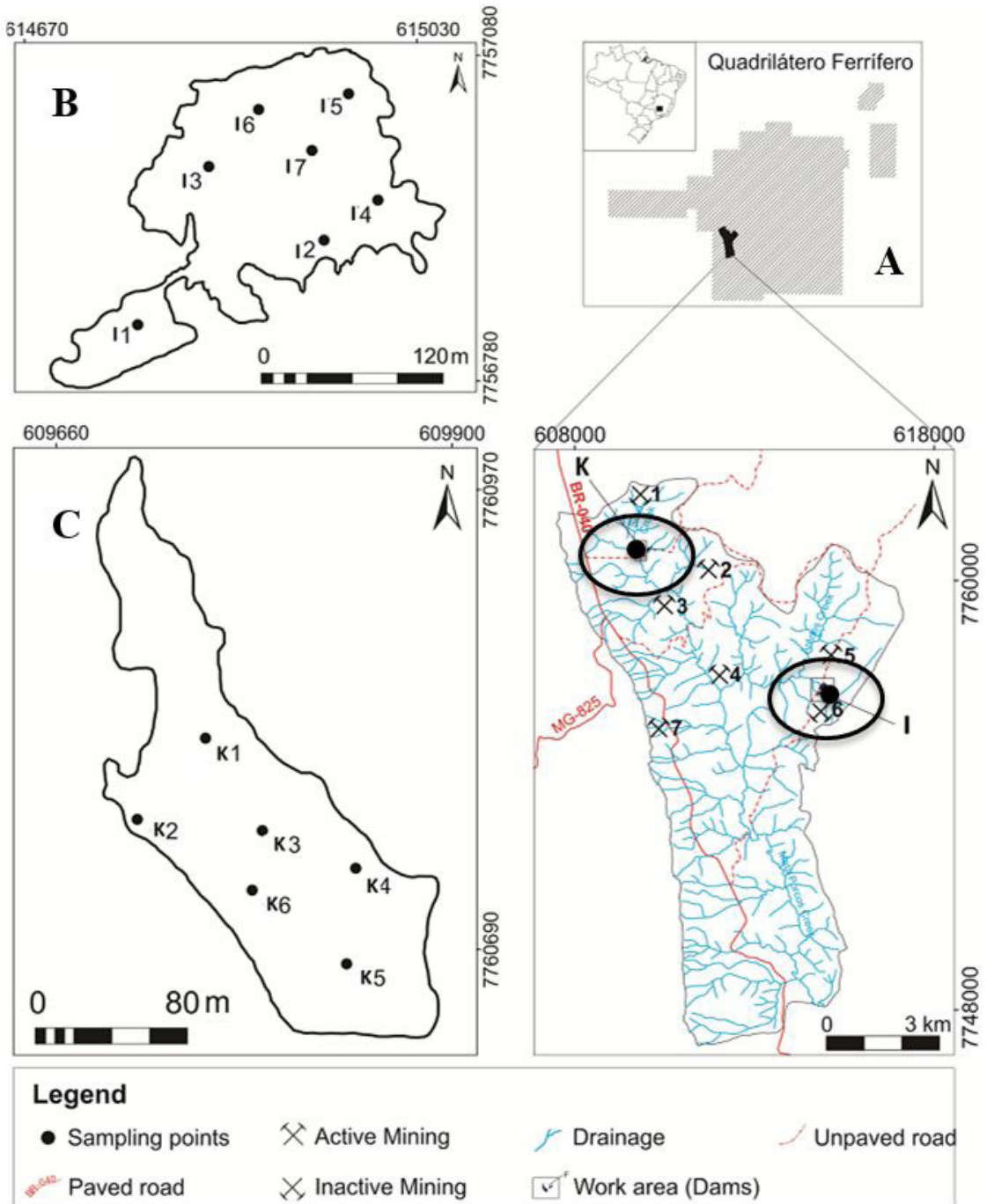
Water and sediment samples were collected quarterly from September 2011 to December 2012, encompassing the seasonal dry periods (September 2011, May and September 2012) and rainy periods (February and December 2012). At each collection point (seven in IRONR and six in KAOR), vertical profiles were taken for limnological characterization, by obtaining water samples with a Van Dorn bottle

(5 L). The samples were collected from the surface to the bottom, with a minimum of three samples in the water column (surface, middle and bottom), according to the light attenuation coefficient, estimated with a Secchi disk.

The pH, temperature (°C), electrical conductivity ( $\mu\text{s}\cdot\text{cm}^{-1}$ ) and total dissolved solids ( $\text{mg}\cdot\text{L}^{-1}$ ) were determined with an Ultrameter II multiparameter instrument. Dissolved oxygen ( $\text{mg}\cdot\text{L}^{-1}$ ) was measured with a Hanna oxygen meter (model HI 93703) and turbidity with a Hanna turbidity meter (model HI 9146). Water transparency (m) was estimated with a Secchi disk. The concentrations of nitrite ( $\text{NO}_2^- \cdot \text{N}$   $\mu\text{g}\cdot\text{L}^{-1}$ ), nitrate ( $\text{NO}_3^- \cdot \text{N}$   $\mu\text{g}\cdot\text{L}^{-1}$ ) and phosphate ( $\text{PO}_4^{3-}$   $\mu\text{g}\cdot\text{L}^{-1}$ ) were obtained colorimetrically (HACH® colorimeter. Photometric accuracy:  $\pm 0.005$  Abs at 1.0 Abs. Photometric measuring range: 0 to 2 Abs).

The concentrations of the main cations ( $\text{Na}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{K}^+$  and  $\text{Mg}^{2+}$ ) and trace elements (Al, As, Ba, Be, Ca, Cd, Co, Cr, Cu, Fe, K, Li, Mg, Mn, Mo, Na, Ni, Pb, Sn, Sr, Ti, V and Zn) were determined in water and sediments through inductively coupled plasma spectrometry (ICP-OES). Water subsamples (50 ml) were filtered in a 0.45  $\mu\text{m}$  membrane and acidified with  $\text{HNO}_3$  to pH < 2, to stabilize the metals. The sediment samples were collected with a Birge-Ekman grab. In the laboratory, the sediments were dried in an oven at 60°C, ground with a porcelain mortar and pestle, and immediately after were dried and sieved in a < 0,063mm nylon sieve. For determination of the main and trace elements, 200 mg of dried sediment was digested with  $\text{HNO}_3$  (65% v/v),  $\text{HClO}_4$  (60% v/v) and HF (40% v/v). The residue was dissolved in 20 ml  $\text{HNO}_3$  for 24 h prior to ICP-OES analysis.

Concentrations of chlorophyll-a were determined spectrophotometrically after the water was filtered through fiberglass filters (Whatman



**Figure 1.** (A) Map of the Mata Porcos watershed and approximated localization of the reservoirs. (B) General view of Sampling points from Iron reservoir (I). (C) Sampling points from Kaolin reservoir (K).

934-AH) and the pigments extracted with ethanol at room temperature for approximately 20 h (Jespersen & Christoffersen, 1988).

Zooplankton samples were obtained with a Van Dorn bottle. Water samples (50 L) were collected every 1 meter, from the water surface to the bottom, and filtered in a plankton net with 68 µm mesh size. The material collected was stored

in polyethylene bottles and preserved with neutral 4% formalin solution. In the laboratory, the entire samples were analyzed in an optical microscope. Since no significant differences between the values from surface and bottom samples were observed (ANOVA, N = 105 for KAOR and N = 360 for IRONR), median values were selected to describe physical, chemical and biological parameters.



The size of the organisms in each group was measured for around 30 animals (or fewer for less abundant taxa), under an optical microscope with a graduated eyepiece. Combined with the density data, the measured lengths of the organisms were used to estimate the biomass of each genus/species, in  $\mu\text{g}$  dry weight per liter ( $\mu\text{g DW.L}^{-1}$ ).

For biomass of microcrustacean species, the equations developed by Bottrell et al. (1976) were used:  $\ln W = 1.7512 + 2.6530 \ln L$  for cladocerans, and  $\ln W = 1.9526 + 2.3990 \ln L$  for Copepoda. For rotifers, the biomass was obtained according to Ruttner-Kolisko (1977) biovolume formulas. The biovolume was then calculated as the wet weight, taking the specific density to be 1.0 and the conversion from wet weight to dry weight was performed assuming a multiplication factor of 0.1 (Doohan, 1973, according to Bottrell et al., 1976).

In order to assess the trophic dynamics of zooplankton, we used the feeding-guild ratio (GR), which evaluates the proportion between microphagous and raptorial species, i.e., is an index based on a functional trait (feeding strategy), according to Obertegger et al. (2011). For this, the species were classified into feeding guilds.

The following characteristics were selected to group the feeding guilds: rotifers with malleate, malleoramate, ramate and uncinata trophi were classified as little-selective collectors (which collect many food items simultaneously and less selectively) and were therefore designated as microphages. The genera of rotifers included in this classification were: *Brachionus*, *Collotheca*, *Conochilus*, *Euchlanis*, *Filinia*, *Floscularia*, *Kellicottia*, *Keratella*, *Lecane*, *Notholca*, *Testudinella* and *Trichotria*. Since microphagous zooplankters have a wide range of body size (Rothhaupt, 1990), they were classified in two groups: small microphages (SMIC) ( $\leq 249 \mu\text{m}$  in size) and large microphages (LMIC) ( $>250 \mu\text{m}$  in size). Members of the rotifer genera *Ascomorpha*,

*Asplanchna*, *Gastropus*, *Ploesoma*, *Polyarthra*, *Synchaeta* and *Trichocerca* have cardate, forcipate, incudate or virgate trophi, and actively capture particles; these were designated as raptorial (RAP). Table 1.

The classification in feeding guilds was also extended to the other microcrustaceans, considering their size and feeding functionality, according to the recommendations of Bertani et al. (2012). Cladocerans were classified as LMIC, because the identified species (essentially members of the family Bosminidae) are predominantly nonselective filter-feeders (DeMott, 1982; Bleiwas & Stokes, 1985). According to Melão & Rocha (2004), the cyclopoid copepod *Tropocyclops prasinus* (Fischer, 1860), the dominant species in the reservoirs, is omnivorous and has different ontogenetic feeding requirements during the different stages of its life cycle (nauplius, copepodite, adult). Therefore, cyclopoid nauplii were classified as SMIC and copepodites as LMIC. Adult cyclopoids were classified as RAP. The ratio among trophic groups (GR') proposed by Smith et al. (2009) and modified by Obertegger et al. (2011) was adapted to include planktonic microcrustaceans. The GR' is calculated from the formula:  $\text{GR}' = \frac{\Sigma (\text{Raptorial biomass} - \text{Microphage biomass})}{\Sigma (\text{total zooplankton biomass})}$ , and the values of GR' range from -1 to 1. Values  $< 0$  indicate a dominance of microphages, and values  $> 0$  indicate a dominance of raptorial feeders.

Before statistical parametric analysis, the data were log-transformed and tested for normality (Shapiro-Wilk test). The analysis of variance (ANOVA) was used for the comparison among functional groups in each mining impoundment and among limnological parameters, using SAS software (Version 9.1; SAS Institute, Cary, NC). The degree of association between limnological parameters and zooplankton biomass was evaluated using Pearson's

**Table 1.** Functional groups of the zooplankton according to their feeding mode and body size, following the classification proposed by Obertegger et al. (2011), with adaptations.

Functional Group	Taxa
<b>Small Microphagous</b> – small body size ( $\leq 249 \mu\text{m}$ ). Rotifers: trophi malleate, malleoramate, ramate and uncinata.	Rotifers: <i>Anuraeopsis fissa</i> , Bdelloidea, <i>Collotheca</i> spp., <i>Hexarthra mira</i> , <i>Keratella cochlearis</i> , <i>Kellicottia bostoniensis</i> , <i>Lecane</i> spp., <i>Lepadella patela</i> , <i>Macrochaetus</i> sp., <i>Proales</i> sp. Copepods: Cyclopoida nauplii.
<b>Large Microphagous</b> – body size $\geq 250 \mu\text{m}$ . Rotifers: trophi malleate, malleoramate, ramate and uncinata.	Rotifers: <i>Brachionus falcatus</i> , <i>Euchlanis dilatata</i> , <i>Hexarthra mitra</i> , <i>Platyas quadricornis</i> . Cladocerans: Bosminidae, Ilyocriptidae. Copepods: Cyclopoid copepodits.
<b>Raptorial.</b> Rotifers: cardate, forcipate, incudate or virgate. Prey actively captured and killed.	Rotifers: <i>Cephalodella gibba</i> , <i>Polyarthra</i> cf. <i>dolichoptera</i> , <i>Synchaeta</i> sp., <i>Trichocerca pusilla</i> , <i>T. similis</i> . Copepods: Cyclopids adults.

correlation. A Principal Components Analysis was performed based on a correlation matrix with centering and standardization of the data, in order to identify the major environmental and biological patterns in the data set. The ordination was performed with the statistical software Minitab®16.

### 3. Results

#### 3.1. Water and sediment limnology and geochemistry

Limnological conditions, particularly water transparency (Secchi disc depth), varied widely in both impoundments, as shown in Table 2.

No seasonal trends for water temperature and dissolved oxygen were observed in the reservoirs (ANOVA,  $F = 85.4$ ;  $p > 0.05$ ). The mean pH values did not differ between the reservoirs; the water varied from acidic to alkaline (5.4 to 7.4). Turbidity was generally higher in KAOR (ANOVA,  $F = 88.9$ ;  $p < 0.001$ ), and as expected, the lowest values of transparency were recorded in this reservoir (0.8 m) (ANOVA,  $F = 88.9$ ;  $p < 0.001$ ). Conductivity ( $\mu\text{S}\cdot\text{cm}^{-1}$ ) was also higher in KAOR (ANOVA,  $F = 76.5$ ;  $p < 0.001$ ), during all the studied period, when compared to IRONR. The TSS concentrations showed a clear seasonal pattern between the reservoirs (ANOVA,  $P < 0.01$ ), with the highest values observed in KAOR (mean  $9.2 \text{ mg}\cdot\text{L}^{-1}$ ). Low concentrations of nitrite and nitrate were observed in the water of IRONR and KAOR (< than  $13 \mu\text{g}\cdot\text{L}^{-1} \text{NO}_2^-$ -N, and maximum of  $22 \mu\text{g}\cdot\text{L}^{-1} \text{NO}_3^-$ -N). Phosphate concentrations were also very low (maximum of  $1.2 \mu\text{g}\cdot\text{L}^{-1} \text{PO}_4^{3-}$  in IRONR and minimum of  $0.7 \mu\text{g}\cdot\text{L}^{-1} \text{PO}_4^{3-}$  in KAOR). Chlorophyll *a* concentrations were also very low in both reservoirs (maximum of  $1.3 \mu\text{g}\cdot\text{L}^{-1}$  and minimum of  $0.1 \mu\text{g}\cdot\text{L}^{-1}$ ).

A wide diversity of elements was found in the water of the reservoirs, particularly Al, Ba, Ca, Fe, Mg, Mn and Zn. In Kaolin Reservoir, the Ca, Mg and Mn concentrations were extremely high (Ba from  $23.9$  to  $46.3 \mu\text{g}\cdot\text{L}^{-1}$ ; Ca from  $0.7$  to  $1.6 \mu\text{g}\cdot\text{L}^{-1}$ ; Mg from  $0.5$  to  $0.6 \mu\text{g}\cdot\text{L}^{-1}$ ; Mn from  $66.3$  to  $128.3 \mu\text{g}\cdot\text{L}^{-1}$ ). In Iron Reservoir, Al, Ca, Fe and Zn were the most common metals and semi-metals in the water (Al from  $8.3$  to  $33.7 \mu\text{g}\cdot\text{L}^{-1}$ ; Ca from  $0.2$  to  $0.4 \mu\text{g}\cdot\text{L}^{-1}$ ; Fe  $0.1$  to  $0.2 \mu\text{g}\cdot\text{L}^{-1}$ ; Zn from  $15.3$  to  $68.9 \mu\text{g}\cdot\text{L}^{-1}$ ) (Table 2).

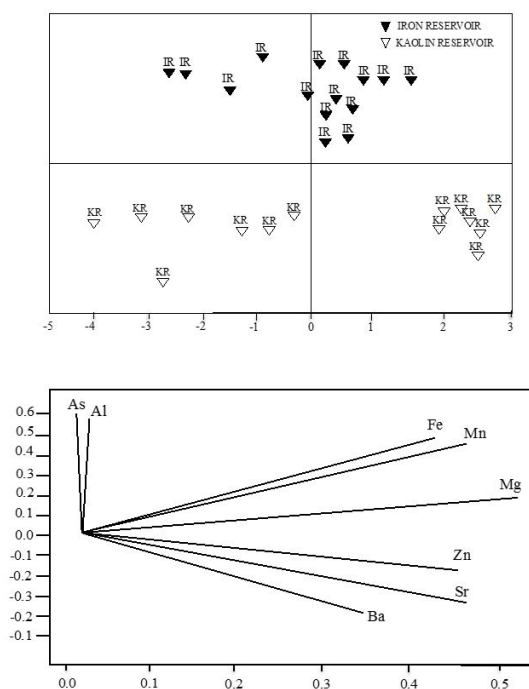
In the reservoir sediments, high concentrations of the metals and semi-metals Fe, Al, Mg and Ca were registered. In both reservoirs, Fe was the most abundant element, exceeding  $270,000 \text{ mg}\cdot\text{kg}^{-1}$  in IRONR. Al concentrations were also

high, reaching up to  $38.3 \text{ mg}\cdot\text{kg}^{-1}$  in IRONR and  $14.2 \text{ mg}\cdot\text{kg}^{-1}$  in KAOR. Another element found in high concentrations in IRONR bottom sediments was arsenic (As), reaching levels higher than  $100 \text{ mg}\cdot\text{kg}^{-1}$ . Mean concentrations of Manganese (Mg) were above  $500 \text{ mg/kg}$  in IRONR and KAOR (Table 3).

A statistical summary of metal trace elements in IRONR and KAOR water is shown in Figure 2, resulting from the principal components analysis (PCA). The first two components were responsible for 85.9% of the total variance of the data, mainly constituted by As, Al, Fe, Mg and Mn, which were common to both reservoirs. Ba, Sr and Zn were the main elements separating IRONR and KAOR, confirming the signature of the local mining activities in the environmental aspects of the reservoirs.

#### 3.2. Zooplankton composition and diversity

Zooplankton diversity and richness ( $H'$ ) were very low in both reservoirs. Thirty-eight taxa were recorded at all, with the highest richness observed for Rotifera (27 species, 6 of them raptorial and 21 microphagous). Cladocera was represented by 5 microphagous species, and Copepoda by 4 species (raptorial in the adult stage, and microphagous in the nauplius and copepodite stages). In Iron Reservoir, 27 species were recorded, 13 of them



**Figure 2.** Plot of the Principal Component Analysis (PCA) for reservoirs, considering the main trace elements concentrations in the water and sediment.

**Table 2.** Limnological and geochemical variables of the water of the reservoirs.

	IRON DAM						KAOLIN DAM					
	Dry Period			Rainy Period			Dry Period			Rainy Period		
	Mean	Min-Max	SD	Mean	Min-Max	SD	Mean	Min-Max	SD	Mean	Min-Max	SD
pH	6.1	5.7-6.3	0.2	6.1	5.4-6.4	0.3	7.1	6.8-7.1	0.1	6.8	6.7-6.8	0.1
Conductivity ( $\mu\text{S}\cdot\text{cm}^{-1}$ )	3.4	2.9-4.9	0.2	7.2	4.7-18.1	0.3	14.5	14.1-16.2	0.8	13.7	12.1-14.9	0.9
Turbidity (NTU)	4.1	2.7-7.9	0.2	12.8	10.8-16.1	0.4	8.4	4.6-11.7	2.5	29.9	24.4-39.0	6.2
OD ( $\text{mg}\cdot\text{L}^{-1}$ )	7.7	5.9-9.3	0.2	6.0	5.0-6.7	0.4	8.1	7.1-9.4	1.3	8.9	8.7-9.1	0.3
Temperature ( $^{\circ}\text{C}$ )	22.1	20.3-22.9	0.2	23.0	20.9-24.8	0.4	23.4	22.8-24.5	0.5	24.6	23.1-25.7	1.0
Alcalinity ( $\text{mg}\cdot\text{L}^{-1}$ )	8.1	6.3-12.4	0.2	10.5	8.2-13.7	0.4	12.3	9.5-13.7	1.3	10.7	9.5-12.4	2.7
Chlorophyll a ( $\mu\text{g}\cdot\text{L}^{-1}$ )	0.9	0.6-1.3	0.2	0.3	0.1-0.4	0.4	0.5	0.3-0.7	0.0	0.2	0.1-0.2	0.1
Secchi Disc (m)	2.3	1.4-2.7	0.3	1.1	0.8-1.1	0.4	2.3	0.6-3.0	0.5	0.8	0.7-0.9	0.0
Total Solids Suspended ( $\text{mg}\cdot\text{L}^{-1}$ )	2.1	1.8-3.1	0.3	4.4	2.9-10.6	0.4	9.2	8.9-10.3	0.5	8.6	7.7-8.9	0.5
Nitrite ( $\mu\text{g}\cdot\text{L}^{-1}\text{NO}_2$ )	1.2	3.1-5.0	0.3	12.4	6.1-24.2	0.4	0.1	0.1-0.2	0.0	0.1	0.0-0.2	0.0
Nitrate ( $\mu\text{g}\cdot\text{L}^{-1}\text{NO}_3$ )	5.7	1.1-19.2	0.3	9.3	1.9-22.0	0.4	4.2	2.1-6.1	2.2	10.4	7.2-18.7	22.0
Phosphate ( $\mu\text{g}\cdot\text{L}^{-1}\text{PO}_4$ )	0.8	0.4-1.6	0.3	1.2	0.6-1.7	0.4	0.7	0.3-1.3	0.3	0.8	0.6-1.1	1.1
Al ( $\mu\text{g}\cdot\text{L}^{-1}$ )	15.6	8.3-33.7	0.3	58.2	45.2-65.6	0.5	-	-	-	34.7	19.4-51.0	9.9
Ba ( $\mu\text{g}\cdot\text{L}^{-1}$ )	5.0	4.2-9.2	0.3	5.9	5.1-6.9	0.5	41.9	24.0-46.3	8.0	50.2	48.2-53.3	5.4
Ca ( $\mu\text{g}\cdot\text{L}^{-1}$ )	0.3	0.2-0.3	0.3	0.5	0.4-0.6	0.5	1.4	0.7-1.6	0.3	1.5	1.47-1.64	0.2
Fe ( $\mu\text{g}\cdot\text{L}^{-1}$ )	0.1	0.5-0.1	0.3	0.1	0.1-0.2	0.5	0.1	0.2-0.9	18.1	0.2	0.1-0.2	0.1
K ( $\mu\text{g}\cdot\text{L}^{-1}$ )	0.2	0.2-0.2	0.3	0.3	0.2-0.3	0.5	0.1	0.1-0.2	0.0	0.3	0.2-0.3	0.1
Mg ( $\mu\text{g}\cdot\text{L}^{-1}$ )	0.2	0.01-0.03	0.4	0.1	0.1-0.1	0.5	0.6	0.5-0.6		0.4	0.4-0.5	0.1
Mn ( $\mu\text{g}\cdot\text{L}^{-1}$ )	15.0	12.4-17.3	0.4	91.2	68.1-109.7	0.5	117.4	66.3-128.6	23.4	237.9	231.4-248.7	41.4
Na ( $\mu\text{g}\cdot\text{L}^{-1}$ )	0.1	0.1-0.1	0.4	0.2	0.2-0.3	0.5	0.2	0.1-0.3	0.1	0.1	0.1-0.2	0.1
Zn ( $\mu\text{g}\cdot\text{L}^{-1}$ )	27.5	15.5-68.9	0.4	9.0	4.2-19.5	0.5	0.3	0.0-0.9	0.4	5.9	0.0-12.5	1.0

only in this impoundment. In Kaolin Reservoir, the zooplankton species richness was lower (23 species), with 8 exclusive taxa (ANOVA,  $P > 0.01$ ) (Table 4).

Rotifers (mainly *Polyarthra cf. dolichoptera*) dominated the zooplankton community, comprising more than 70% of the zooplankton abundance, and reaching 90% of total zooplankton in KAOR. *Bosmina (Eubosmina) tubicen* (Brehm, 1953) and *Bosminopsis deitersi* Richard, 1895 were the dominant species of Crustacea, in addition to cyclopoid nauplii, mainly during the dry period in both systems. Zooplankton density and biomass were extremely low, with a maximum of 45 Ind.L<sup>-1</sup> (September/2012) and 11.7 µg.DW.L<sup>-1</sup> (February/2011) in IRONR. Lowest values were recorded specially in Kaolin reservoir (maximum of 9.8 Ind.L<sup>-1</sup> and 10.1 µg.DW.L<sup>-1</sup>, respectively, in September/2011) (Table 4).

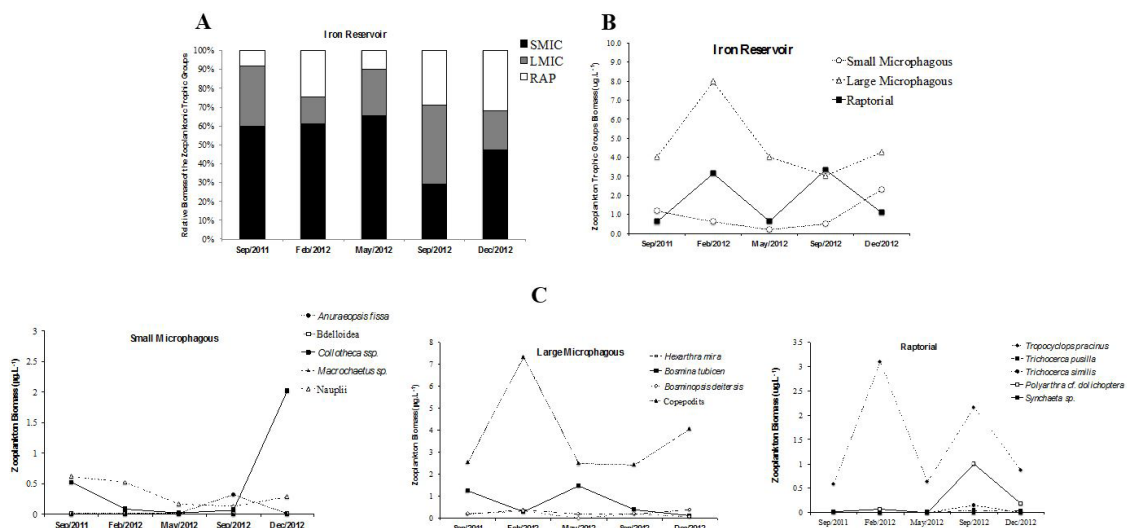
Zooplankton biomass showed a clear negative association with all metals in the water (Tables 5 and 6), specifically for Al ( $r = -0.75$ ;  $P < 0.05$ ), Fe ( $r = -0.76$ ;  $P = 0.001$ ), Mg ( $r = 0.65$ ;  $P < 0.01$ ) and Zn ( $r = -0.88$ ;  $P < 0.001$ ) in IRONR. In KAOR, it was observed the same pattern (Al:  $r = -0.75$ ;  $P < 0.01$ ), Fe ( $r = -0.88$ ;  $P = 0.001$ ), Mg ( $r = 0.68$ ;  $P < 0.05$ ) and Zn ( $r = -0.89$ ;  $P < 0.01$ ). Significant negative correlations were also found between zooplankton biomass with total solid suspended (TSS) and turbidity ( $P < 0.05$ ; negative correlations coefficients  $> 0.6$ ), in both two types of waters, i.e. kaolin impacted and iron impacted water.

### 3.3. Zooplankton functional groups

The temporal distribution of the functional groups and abundances of the dominant taxa in each group are given in Figure 3 and Figure 4. The functional groups were composed as follows:

**Table 3.** Summary statistics [mean ± standard deviation (max-min)] for trace elements concentrations in the sediments of Iron and Kaolin reservoirs.

	IRON DAM	KAOLIN DAM
Ba (mg. Kg <sup>-1</sup> )	75 ± 48 (150-24)	627 ± 114 (767-454)
Mg (mg.kg <sup>-1</sup> )	163 ± 42 (244-124)	224 ± 61 (1405-292)
Fe (mg.kg <sup>-1</sup> )	182160 ± 73836 (275563-88263)	81804 ± 8240 (87478-65446)
Mn (mg.kg <sup>-1</sup> )	770 ± 492 (1427-237)	524 ± 77 (611-390)
Sr (mg.kg <sup>-1</sup> )	6 ± 21 (4-8)	35 ± 6 (41-26)
Zn (mg.kg <sup>-1</sup> )	63 ± 21 (91-32)	197 ± 24 (232-162)
Ca (mg.kg <sup>-1</sup> )	212 ± 27 (248-164)	293 ± 23 (324-273)
Al (mg.kg <sup>-1</sup> )	30516 ± 6753 (38329-20412)	11550 ± 2304 (14240-7857)
As (mg.kg <sup>-1</sup> )	73 ± 30 (39-115)	-



**Figure 3.** Iron Reservoir. (A) Relative biomass (%) of the functional groups (SMIC – Small Microphagous; LMIC – Large Microphagous; RAP – Raptorial). (B) Trophic group biomass (µg.DW.L<sup>-1</sup>). (C) Temporal variation of the zooplanktonic taxa in the trophic groups.



Table 4. Temporal and spatial zooplankton taxonomic composition, density (Ind.L<sup>-1</sup>), biomass (µg.DW.L<sup>-1</sup>) and diversity (H'). □ < 5 Ind.L<sup>-1</sup>; ■ ≥ 5-20 Ind.L<sup>-1</sup>.

	Trophic Group	IRON RESERVOIR					KAOLIN RESERVOIR				
		2011		2012			2011		2012		
		September	February	May	September	December	September	February	May	September	December
<b>ROTIFERA</b>											
<b>Lecanidae</b>											
<i>Lecane bulla</i> (Gosse. 1851)	SMIC	□									
<i>Lecane curvicornis</i> (Murray. 1913)	SMIC	□				□					
<i>Lecane homemanni</i> (Ehrenberg. 1834)	SMIC		□								
<i>Lecane inermis</i> (Bryce. 1892)	SMIC							□			
<i>Lecane leontina</i> (Turner. 1892)	SMIC								□		
<i>Lecane lunaris</i> (Ehrenberg. 1832)	SMIC	□	□	□		□		□		□	
<i>Lecane monostyla</i> (Daday. 1897)	SMIC		□								
<i>Lecane signifera ploenensis</i> (Voigt. 1902)	SMIC	□	□	□		□		□		□	
<i>Lecane stichaea</i> Harring. 1913	SMIC										
<b>Trichocercidae</b>											
<i>Trichocerca pusilla</i> (Jennings. 1903)	RAP	□	□	□		□		□		□	
<i>Trichocerca similis</i> (Wierzejski. 1893)	RAP	□	□	□	■	□		□		□	
<b>Synchaetidae</b>											
<i>Polyarthra</i> cf. <i>dolichoptera</i> Idelson. 1925	RAP	□	□	□	■	□		□		■	□
<i>Synchaeta</i> spp.	RAP	□				□				□	
<b>Trichotritidae</b>											
<i>Macrochaetus collinsi</i> (Gosse. 1867)	SMIC	□	□			□		□		□	
<b>Bdelloidea</b>											
<i>Bdelloidea</i> spp.	SMIC	□	□	□		□		□		□	
<b>Brachionidae spp.</b>											
<i>Anuraeopsis fissa</i> (Gosse. 1851)	SMIC	□			■	□		□		□	
<i>Brachionus falcatus</i> Zacharias. 1898	LMIC							□		□	
<i>Platylas quadricornis</i> (Ehrenberg. 1832)	LMIC							□		□	
<i>Keratella cochlearis</i> (Gosse. 1851)	SMIC							□		□	
<i>Kellicottia bostoniensis</i> (Rousselet. 1908)	SMIC		□	□		□		□		□	

SMIC = Small microphagous; LMIC = Large microphagous; RAP = Raptorial.

Table 4. Continued...

	IRON RESERVOIR						KAOLIN RESERVOIR						
	2011			2012			2011			2012			
	September	February	May	September	December	September	February	May	September	December			
<b>Euchlaniidae</b>													
<i>Euchlanis dilatata</i> Ehrenberg, 1832													
<b>Testudinellidae</b>													
<i>Testudinella ohlei</i> Koste, 1972		□											
<b>Notommatidae</b>													
<i>Cephalodella gibba</i> (Ehrenberg, 1830)										□			
<i>Monommata</i> sp.													
<b>Colurellidae</b>													
<i>Lepadella patella</i> (O. F. Müller, 1786)			□										
<i>Paracolurella aemula</i> (Myers, 1934)													
<b>Hexarthridae</b>													
<i>Hexarthra mira</i> (Hudson, 1871)			□										
<b>Proallidae</b>													
<i>Collotheca</i> spp.			□										
<i>Proales</i> sp.			□										
<b>COPEPODA</b>													
<b>Cyclopidae</b>													
Nauplii													
Copepodito													
<i>Ectocyclops</i> sp.													
<i>Mesocyclops</i> sp.													
<i>Microcyclops anceps</i> (Richard, 1897)													
<i>Thermocyclops decipiens</i> (Kiefer, 1929)													
<i>Tropocyclops prasinus</i> (Fischer, 1860)													
<b>Calanoidae</b>													
<i>Notodiaptomus iheringi</i> (Wright S., 1935)													

SMIC = Small microphagous; LMIC = Large microphagous; RAP = Raptorial.

Table 4. Continued...

	IRON RESERVOIR						KAOLIN RESERVOIR						
	2011			2012			2011			2012			
	September	February	May	September	May	December	September	February	May	September	December		
<b>CLADOCERA</b>													
<b>Bosminidae</b>													
<i>Bosmina longirostris</i> (O. F. Müller, 1776)						LMIC							
<i>Bosmina (Eubosmina) tubicen</i> (Brehm, 1953)	■	□	■	□	□	□							
<i>Bosminopsis deitersi</i> Richard, 1895	□	□	□	□	□	□							
<b>Chydoridae</b>													
<i>Alona iheringula</i> (Sars, 1901)						-							
<i>Alona setigera</i> (Brehm, 1931)						-							
<i>Alonella clathratula</i> (Sars, 1896)					□	-							
<b>Ilyocryptidae</b>													
<i>Ilyocryptus spinifer</i> Herrick, 1882	□	□	□	□	□	LMIC							
Diversity (H')	1.1	1.7	1.0	0.9	1.0	0.8	1.1	1.3	1.4	0.6	1.2		
Richness	18	20	17	12	17	15	14	15	14	10	9		
Average zooplankton density (Ind.L <sup>-1</sup> )	12.5	8.7	7.6	45.1	7.6	32.1	10.1	3.2	4.7	9.3	4.9		
Average zooplankton biomass (µg.DW.L <sup>-1</sup> )	5.8	11.7	4.8	6.9	4.8	7.7	9.8	1.6	1.4	6.4	1.4		

SMIC = Small microphagous; LMIC = Large microphagous; RAP = Raptorial.

**Table 5.** Pearson correlation coefficients in Iron Reservoir water for limnological, trace elements and zooplankton biomass ( $\mu\text{g}\cdot\text{L}^{-1}$ ) and trophic groups.

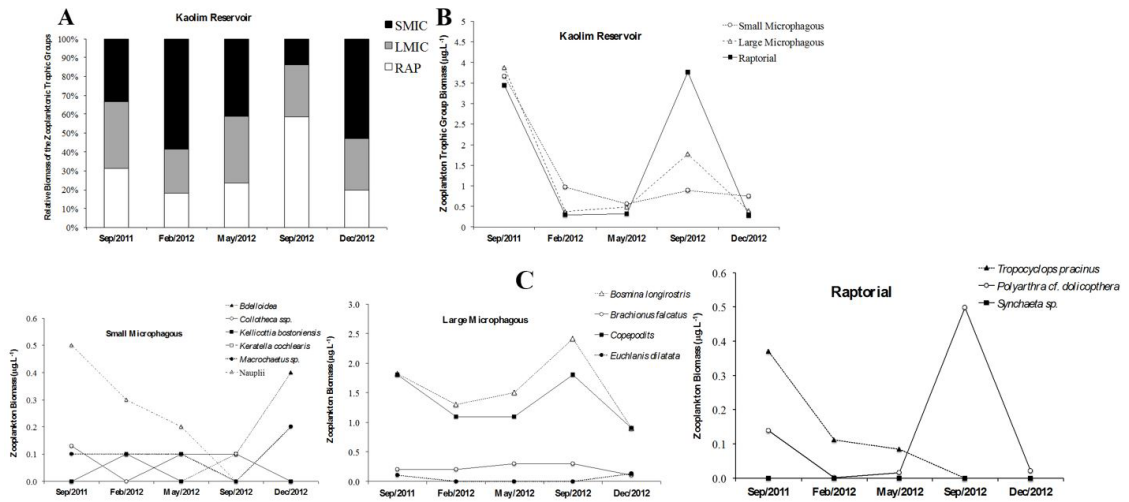
	Cond	TSS	Turb	pH	Secchi	Fe	Mg	Mn	Zn	Al	Ba	DO	Clorophy	ZooBio	SMIC	LMIC	RAP
TSS	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Turb	0.30	0.31	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
pH	0.10	0.08	0.08	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Secchi	<b>-0.60</b>	<b>-0.79</b>	<b>-0.79</b>	-0.18	-	-	-	-	-	-	-	-	-	-	-	-	-
Fe	<b>0.39</b>	<b>0.39</b>	0.29	-0.17	-0.33	-	-	-	-	-	-	-	-	-	-	-	-
Mg	0.04	0.02	-0.33	0.13	0.13	<b>-0.48</b>	-	-	-	-	-	-	-	-	-	-	-
Mn	<b>0.67</b>	<b>0.67</b>	<b>0.72</b>	0.02	<b>-0.79</b>	<b>0.62</b>	-0.25	-	-	-	-	-	-	-	-	-	-
Zn	0.20	0.20	0.79	-0.01	-0.02	<b>0.62</b>	<b>-0.58</b>	0.33	-	-	-	-	-	-	-	-	-
Al	<b>0.50</b>	<b>0.49</b>	0.12	-0.14	<b>-0.38</b>	<b>0.83</b>	-0.33	<b>0.60</b>	<b>0.54</b>	-	-	-	-	-	-	-	-
Ba	<b>0.50</b>	<b>0.50</b>	0.23	0.15	-0.34	0.26	-0.22	<b>0.39</b>	0.34	0.31	-	-	-	-	-	-	-
DO	-0.29	-0.31	<b>-0.52</b>	0.06	<b>0.45</b>	<b>-0.68</b>	<b>0.58</b>	<b>-0.72</b>	<b>-0.77</b>	<b>-0.57</b>	-0.30	-	-	-	-	-	-
Clorophy	<b>-0.54</b>	<b>-0.55</b>	<b>-0.73</b>	-0.06	<b>0.72</b>	-0.34	0.02	<b>-0.79</b>	0.03	-0.22	-0.06	<b>0.40</b>	-	-	-	-	-
ZooBio	0.10	<b>-0.62</b>	<b>-0.68</b>	0.05	<b>0.55</b>	<b>-0.76</b>	0.09	<b>-0.65</b>	<b>-0.88</b>	<b>-0.75</b>	0.12	-0.11	<b>0.56</b>	-	-	-	-
SMIC	0.14	0.15	-0.19	0.62	0.09	0.20	-0.11	0.05	0.29	0.30	-0.02	-0.19	0.06	0.02	-	-	-
LMIC	-0.26	-0.24	0.22	-0.20	0.09	-0.37	-0.12	-0.18	-0.31	<b>-0.46</b>	-0.11	0.14	-0.08	0.01	0.22	-	-
RAP	0.03	0.03	-0.32	-0.03	0.13	<b>-0.46</b>	<b>0.57</b>	<b>-0.38</b>	<b>-0.69</b>	-0.26	-0.25	<b>0.77</b>	0.02	0.05	0.18	0.23	-

Bold values indicate significance at level  $P < 0.05$ .

**Table 6.** Pearson correlation coefficients in Kaolin Reservoir water for limnological, trace elements and zooplankton biomass ( $\mu\text{g}\cdot\text{L}^{-1}$ ) and trophic groups.

	Cond	TSS	Turb	pH	Secchi	Fe	Mg	Mn	Zn	Al	Ba	DO	Clorophy	ZooBio	SMIC	LMIC	RAP
TSS	0.96	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Turb	0.06	-0.01	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
pH	<b>0.44</b>	0.40	0.17	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Secchi	-0.14	-0.12	-0.26	0.30	-	-	-	-	-	-	-	-	-	-	-	-	-
Fe	-0.40	-0.30	-0.09	<b>-0.52</b>	-0.14	-	-	-	-	-	-	-	-	-	-	-	-
Mg	<b>0.74</b>	<b>0.76</b>	-0.21	<b>0.49</b>	0.33	-0.28	-	-	-	-	-	-	-	-	-	-	-
Mn	-0.26	-0.25	0.29	<b>-0.58</b>	<b>-0.48</b>	<b>0.70</b>	<b>-0.46</b>	-	-	-	-	-	-	-	-	-	-
Zn	-0.37	-0.34	0.08	<b>-0.44</b>	-0.27	0.29	-0.40	<b>0.56</b>	-	-	-	-	-	-	-	-	-
Al	<b>-0.59</b>	<b>-0.54</b>	0.07	<b>-0.65</b>	-0.22	<b>0.82</b>	<b>-0.62</b>	<b>0.80</b>	<b>0.49</b>	-	-	-	-	-	-	-	-
Ba	<b>0.69</b>	<b>0.72</b>	-0.02	0.03	-0.26	0.16	<b>0.71</b>	0.23	-0.01	-0.13	-	-	-	-	-	-	-
DO	-0.13	-0.16	<b>0.87</b>	-0.20	<b>-0.48</b>	0.07	<b>-0.41</b>	<b>0.47</b>	0.21	<b>0.26</b>	-0.04	-	-	-	-	-	-
Clorophy	0.29	0.28	-0.15	<b>0.43</b>	<b>0.66</b>	<b>-0.47</b>	<b>0.60</b>	<b>-0.79</b>	<b>-0.46</b>	<b>-0.63</b>	<b>-0.04</b>	<b>-0.41</b>	-	-	-	-	-
ZooBio	0.10	<b>-0.62</b>	<b>-0.77</b>	0.06	<b>0.54</b>	<b>-0.88</b>	<b>-0.68</b>	<b>-0.56</b>	<b>-0.89</b>	0.12	<b>-0.11</b>	0.56	-	-	-	-	-
SMIC	0.38	0.40	<b>-0.50</b>	<b>0.45</b>	<b>0.43</b>	0.07	0.59	-0.74	-0.45	<b>-0.71</b>	0.11	<b>-0.57</b>	<b>0.51</b>	0.05	-	-	-
LMIC	0.36	0.34	0.03	<b>0.72</b>	<b>0.62</b>	<b>-0.61</b>	<b>0.60</b>	<b>-0.80</b>	<b>-0.45</b>	<b>-0.73</b>	-0.01	-0.24	<b>0.79</b>	0.04	<b>0.66</b>	-	-
RAP	<b>0.46</b>	<b>0.46</b>	0.09	<b>0.67</b>	<b>0.49</b>	<b>-0.55</b>	<b>0.69</b>	<b>-0.76</b>	<b>-0.60</b>	<b>-0.73</b>	0.13	-0.14	<b>0.82</b>	0.02	<b>0.52</b>	<b>0.87</b>	-

Bold values indicate significance at level  $P < 0.05$ .



**Figure 4.** Kaolin Reservoir. (A) Relative biomass (%) of the functional groups (SMIC – Small Microphagous; LMIC – Large Microphagous; RAP – Raptorial). (B) Trophic group biomass ( $\mu\text{g.DW.L}^{-1}$ ). (C) Temporal variation of the zooplanktonic taxa in the trophic groups.

SMIC (rotifers *Macrochaetus*, Bdelloidea and *Anuraeopsis*, and cyclopoid nauplii); LMIC (rotifers *Hexarthra*, cladocerans *Bosmina* and *Bosminopsis*, and cyclopoid copepodites) and RAP (rotifers *Trichocerca*, *Polyarthra*, *Synchaeta* and *Collotheca*, as well as adults of the cyclopoid copepod *Tropocyclops*).

The two reservoirs showed very similar patterns in the percentage distribution of trophic groups; the SMIC group was the most abundant and frequent, consisting primarily of cyclopoid nauplii and the rotifers *Collotheca* sp. and *Anuraeopsis fissa* Gosse, 1851. The LMIC group showed a bimodal pattern of abundance in both reservoirs, especially due to higher densities of *T. prasinus* copepodites, *B. tubicen* and *Bosminopsis deitersi*. Seasonal peaks of abundance of the RAP group were observed in both reservoirs, mainly during the dry period; these reflected the quantitative peak of the rotifer *Polyarthra* cf. *dolichoptera* and adults of the copepod *Tropocyclops pracinus*.

The functional groups did not differ significantly between the reservoirs (ANOVA,  $P > 0.05$ ). In KAOR, significant seasonal variations were observed for trophic groups RAP ( $f = 23:21$ ,  $P < 0.001$ ) and LMIC ( $f = 1.11$ ,  $P < 0.003$ ), both of which declined significantly in the rainy season. In this reservoir, the dependence between trophic groups and algal biomass (Chl a) was more apparent, with significant positive correlations for all three groups: small microphages ( $r = 0.51$ ,  $P < 0.001$ ), large microphages ( $r = 0.79$ ,  $P < 0.05$ ), and raptorial feeders ( $r = 0.82$ ,  $P < 0.01$ ). (Table 5 and Table 6).

The proportion among the trophic guilds (GR) reflected the quantitative dominance of the microphages in both reservoirs (GR from -0.03 to -0.79) (Figure 5).

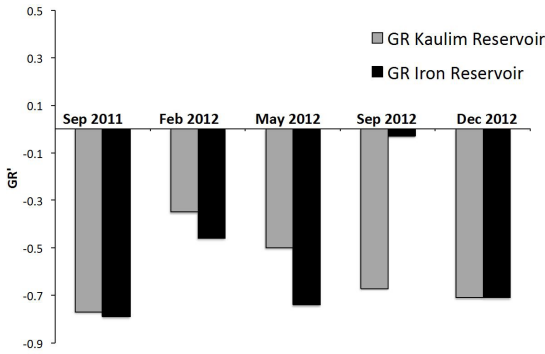
Only in September 2012 (dry season), a distinct shift toward positive values in the GR ratio occurred in IRONR (GR -0.03), mainly due to an increase in RAP abundance in IRONR. In this reservoir, the decrease of microphagous SMIC coincided with a distinct increase of LMIC (mainly cyclopoid copepodites and the cladoceran *B. deitersi*), while the RAP increase (mainly *P. cf. dolichoptera*) was coupled with a decrease of small microphagous rotifers. In KAOR, the increase of microphagous forms (SMIC and LMIC) was followed by a decrease of the RAP group, especially due to higher densities of *Collotheca* sp. No seasonal trends in GR variation were detected (ANOVA,  $P > 0.05$ ).

PCA with seasonal trends of trophic groups confirmed the temporal and spatial dominance of the microphages in the reservoirs, as shown in Figure 6. PCA with trophic groups data resulted in a significant model including two principal components, which explained 87% of the total variation in the data set (Table 7). The first PC (65% of the variance) was strongly correlated with SMIC and LMIC and negatively with RAP, reflecting the assemblage structure of the reservoirs.

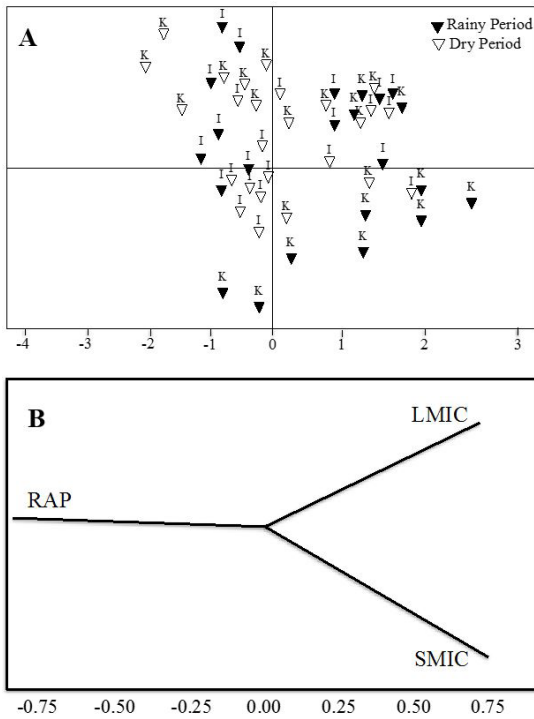
#### 4. Discussion

It has long been recognized that primary production in lakes and reservoirs is strongly affected by turbulence and nutrient concentrations.





**Figure 5.** Temporal variation of the trophic ratio (GR).



**Figure 6.** Plot of the Principal Correspondence Analysis (PCA) for trophic groups based on seasonal trends (A) and trophic groups abundance (B). LMIC = Large microphagous. SMIC = Small microphagous. RAP = Raptorial.

**Table 7.** Summary statistics of Principal Component Analysis for zooplankton trophic groups.

	PC1 (65%)	PC2 (22%)
Small Microphagous	0.589	-0.536
Large Microphagous	0.473	0.835
Raptorials	-0.655	0.121

The low phytoplankton biomass of the studied reservoirs is probably related to the intense turbidity and very low nutrient availability, especially in KAOR. The high concentration of TSS in KAOR,

specially during raining season, must be related to enhance in the suspended particles concentration, derived from sediment load transported into the reservoir by the creek that erode and carry sediments from the abandoned kaolin mine upstream. These suspended particles reduce water transparency and, consequently, primary production.

The analysis of metals in the water and sediment resulted in confirmation of the local signatures, possibly linked to the geogenic origin as well as the mining activities, enhanced mostly by the specific patterns of the trace elements such as Al, Ar, Zn and Ba, as indicated by the PCA analysis. Previous studies conducted in shallow tropical reservoirs (Friese et al., 2010) indicated that high concentrations of metals in aquatic systems are strongly related to anthropogenic influence, especially from the iron and steel industries, which contribute to increase Fe, Sr and Zn concentrations; while Al, K, Mg, Na and Ca concentrations can be probably related to the geogenic origin of the watershed. The local watershed geology of the Iron Quadrangle and its intense anthropogenic use (diversified mining enterprises) makes it difficult to confirm that mining activities are the main source of certain elements such as Fe and Al in the IRONR and KAOR water and sediments. Therefore, the high concentrations present in the sediments of these two aquatic ecosystems suggest that the intense drainage of these elements into local reservoirs is amplified by the mining activity. Fe values greater than 300,000 mg/kg in the sediment contrast with much lower Fe concentrations observed in the sediment and water of lakes in the Iron Quadrangle that are not directly influenced by mining (Leite et al., 2010; Rodrigues et al., 2012)

The presence of mineral tailings on the sediment can prevent the exchange of nutrients with the water column, affecting the complex biotic interactions in the aquatic food web (Routh et al., 2004; Liu et al., 2014). In addition, the presence of heavy metals in the sediment amplifies the temporal scale of the impacts, because of the temporary mobilization of elements and materials, besides chemical speciation, which can occur over a variety of scales, from hours (e.g., tidal influences), to months (seasonal processes), to years (e.g., climate change) (Birch et al., 2001). Iron is highly soluble in strongly acidic water (Jiann et al., 2013). The alkaline characteristics of the water in the local reservoirs can exercise a positive effect by retarding iron solubility.

Metal toxicity is of particular concern in sediments of lakes. In aquatic ecosystems, the

sediments can be an important compartment for recovering aquatic biodiversity, by harboring resistant structures such as seeds, resting eggs and other dehydrated forms. The viable diapausing eggs in lake sediments can slow the rate of elimination of a species as well as increase the rate of return of a species to the water column (Hairston Junior et al., 1995). High concentrations of heavy metals in these reservoirs can significantly decrease the success of recovering zooplankton biodiversity, by affecting not only the cues necessary for hatching (light, temperature and oxygen) but also due to the chronic exposure of the resting forms to a wide variety of heavy metals. The toxicity of trace metals is largely dependent on their concentration in fresh water and in aquatic sources of food. Both sources are integrated into accumulated concentrations in higher trophic-level organisms such as zooplankton a critical link in the aquatic food chain. Future studies will be needed to determine if zooplankters can contribute to the transfer of trace metals in local freshwater ecosystems as described by Caumette et al. (2011) and Ward et al. (2012).

The two reservoirs studied were colonized by cosmopolitan zooplankton species, particularly the rotifers *Polyarthra* cf. *dolichoptera*, *Tricocherca similis* and *Anuraeopsis fissa*. These generalist cosmopolitan species were reported to be able to tolerate heavy metal toxicity, which can explain their relatively good performance in these impacted reservoirs (Virro and Haberman, 1993; Deneke, 2000; Bielanska-Grajner & Gladysz, 2010). The number of zooplankton species and their composition are clearly responses to the local ecological conditions, including high turbidity and low phytoplankton biomass. Some of the species have been found in similar habitats (Bozelli, 1996; Maia-Barbosa & Bozelli, 2006), such as the cladocerans *Bosmina* (*Eubosmina*) *tubicen* and *Bosminopsis deitersi*.

Disturbed lakes tend to lose sensitive native species, and support simplified food webs that are dominated mainly by tolerant or very resilient species (Harig & Bain, 1998). In both reservoir systems, the zooplankton shared very low biomass and diversity, as observed in other environments impacted by mining (Wollmann et al., 2000; Garrido et al., 2003; Vandysh, 2004). Furthermore, correlation coefficients corroborated the negative effects of the high turbidity to zooplankton community characteristics. The low zooplankton density and biomass is one of the principal indications of the conditions restricting the full

establishment of the zooplankton community in IRONR and KAOR.

In aquatic ecosystems, the availability and quality of food are considered to be crucial biotic constraints on the life history and survival of zooplankton, especially small freshwater herbivores (Romanovsky, 1985; De Mott, 1988; Elser, 2000; Czerniawski & Domagala, 2014). Several studies indicate that suspended sediments may affect the abundance of cladocerans, by decreasing their survival and fecundity (Hart, 1987; McCabe & O'Brien, 1983). In other tropical systems with high turbidity, small cladocerans such as *Bosmina* and *Bosminopsis* can reach significant densities (Zettler & Carter, 1986). The feeding mode of these crustaceans may be the key to their survival in these restrictive environments. These small cladocerans ingest suspended sediment particles as well as particles in a size range of 1-15  $\mu\text{m}$ , with equal efficiencies, and their ingestion of sediments is associated with decreased ingestion of phytoplankton cells (De Mott, 1982). Inorganic particles may be an alternative food source for cladocerans, which under natural conditions of low algal productivity and large amounts of suspended particles, can use the organic substrate adsorbed by mineral particles, since these particles are within the size range of the normally consumed algae particles (Arruda et al., 1983; Kirk, 1991).

In general, in both reservoirs the temporal pattern of trophic groups was very similar for microphages and raptorial, especially in KAOR, where these groups showed synchronous temporal trends. This indicated that in both reservoirs, small and large microphagous forms were able to coexist with competitors that share basically the same, in this case, restricted food resource (*i.e.*, low phytoplankton biomass).

Nevertheless, the GR' results confirmed the low functional biodiversity of zooplankton, with a regular constancy of microphagous species in all seasons. Distinct variations in the dominance of microphages were related more to changes within the group (small and large microphages) than to variations between the microphage and raptorial trophic groups. The use of measurements of functional diversity in aquatic ecosystems provides a greater understanding of the mechanisms that determine the community composition and response to major environmental shifts (Vogt et al., 2010, 2013). The exclusive dominance of microphages in these reservoirs reveals that redundant functional species were the main attribute of the zooplankton

assemblages. This trophic homogeneity is probably related to local environmental constraints (e.g., food resources, turbidity, metal contamination).

The possibility of exploiting functional groups in zooplankton is an emerging question, addressed by Barnett & Beisner (2007) and Rejomon et al. (2010). The results obtained in the present study indicated that this approach could greatly enhance our ability to predict how changes in environmental conditions in aquatic ecosystems impacted by mining could affect the zooplankton assemblages and, for instance, control interactions in the upper trophic levels of the aquatic food chain. Considering that the use of functional traits can provide insight into how species contribute to ecosystem processes (Petchey & Gaston, 2002), the identification of resilient zooplankton species can allow us to predict which species are essential for the maintenance of the primary ecological processes in impacted aquatic ecosystems.

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