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Heavy metal concentrations and ecological risk assessment of the suspended sediments of a multi-contaminated Brazilian watershed

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ABSTRACT. Metal concentrations in suspended sediments of one of the most polluted rivers in Brazil were measured. Concentrations of Cd, Cr, Cu, Fe, Mn, Ni, Pb, and Zn were determined by inductively coupled plasma while Hg and As were analyzed with hydride generation flow injection atomic absorption spectroscopy. Contamination of As, Cd, Cr, Cu, Fe, Hg, Mn, Ni, Pb, and Zn was assessed using pollution indices, ecological risk assessment, statistical multivariate techniques and comparison with sediment quality guidelines. Suspended sediments of the upstream portion of the Ipojuca River are moderately contaminated, especially with Mn and As. On the other hand, sediments of the downstream section are highly contaminated, mainly with Zn, Pb, and As. Furthermore, the mean E_i (potential ecological risk) values of Pb and As showed considerable ecological risk in the downstream cross section. The comparison of our data with sediment guideline values indicated that the concentrations of Mn and Pb in the upstream section of the Ipojuca River pose a risk to sediment-dwelling organisms, while Pb and Zn are the metals of concern in the downstream section.

Keywords: river pollution; soil conservation; sediment quality; trace elements.

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Introduction

Heavy metal contamination in suspended sediments is of particular concern due to its potential risks to human health and aquatic organisms (Silva et al., 2017). Metal contamination is traceable to a variety of sources, including sugarcane farming (which involves the high use of vinasse, pesticides and mineral fertilizers), domestic sewage, and wastewater from industrial and agricultural operations (Gunkel et al., 2007; Nasehi, Hassani, Monavvari, Karbassi, & Khorasani, 2013).

One of the most well-known approaches for assessing heavy metal contamination in the aquatic environment is the use of sediment quality guidelines (SQGs) in combination with statistical multivariate techniques, calculated pollution indices and/or ecological risk assessments (MacDonald et al., 2003; Varejão, Bellato, Fontes, & Mello, 2011; Garcia, Passos, & Alves, 2011; Yi, Yang, & Zhang, 2011; Weber et al., 2013; Xiao et al., 2013; Zhang et al., 2017). Comparisons between measured data and SQGs are useful to assess the potential biological effects of heavy metals on organisms, to maintain water quality and to trigger remediation actions. Nevertheless, the heavy metal concentrations measured in sediments suspected of contamination must be compared with data from local background samples (Adamo et al., 2005) in order to take into account the concentration of metals expected to occur naturally. This approach has been successfully used to develop guidelines and make management decisions, especially in cases for which adequate data for other approaches are not available (CCME, 1995).

The Ipojuca River is an important water resource in northeastern Brazil. However, due to the industrial and economic development of its surroundings, the Ipojuca River is the fifth most polluted river in the country (SRH, 2010). Despite this situation, information regarding the concentration of heavy metals in the suspended sediments of the Ipojuca River is scarce or nonexistent; most studies on this riverine system have focused on modeling nitrogen and phosphorus in the water (Gunkel et al., 2007; Barros, Sobral, & Gunkel, 2013). Therefore, this study aimed to fill the gap in metal contamination data for the Ipojuca River by (1) determining the heavy metal concentration and its ecological risk in the suspended sediments and (2) distinguishing between natural and anthropogenic sources of metals in the suspended sediments. In addition to studying the suspended sediments and soils, we also provided a snapshot of the heavy metal concentration in granites, a common type of rock observed in the Ipojuca watershed.

Material and methods

Study area

The total length of the river is approximately 290 km, extending from the semiarid to the coastal zone (08°09’50’’– 08°40’20’’ S and 34°57’52’’– 37°02’48’’ W). It drains a catchment area of approximately 3,435 km^2 (Figure 1). The average annual rainfall ranges from 600 to 2,400 mm in the semiarid zone and coastal zone, respectively (SRH, 2010). The pH of the upstream and downstream cross sections range from 6.8-7.5 (SRH, 2010) and do not affect the heavy metal concentrations in the suspended sediments in the broadest sense. The soils in this region are mostly derived from granites (36.74% Entisols, 32.11% Ultisols, 17.77% Alfisols, 8.89% Oxisols, and 4% other soils (USDA, 2010).

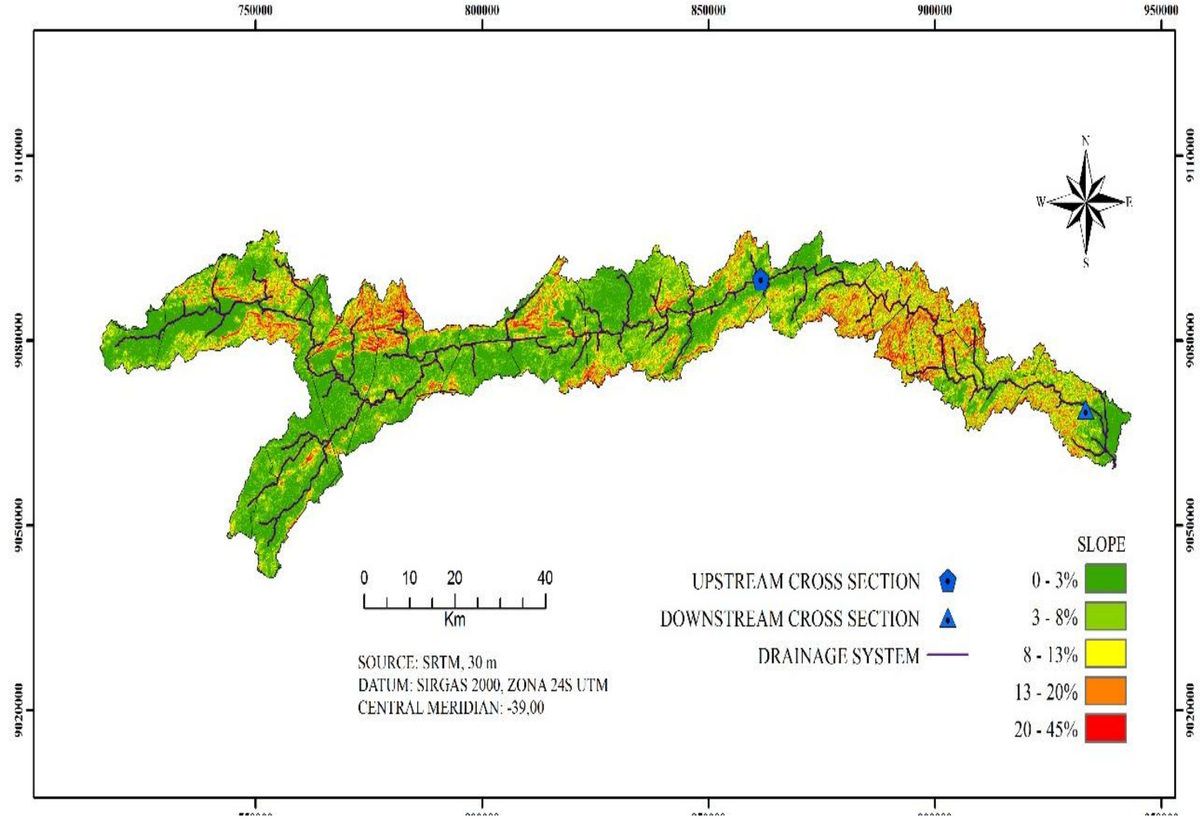

Figure 1. Location of the upstream and downstream cross sections.

Sampling sites and measurements

Suspended sediment samples were collected from upstream (08º13’10’’ S – 35º43’09’’ W) and downstream cross sections (08º24’16’’ S – 35º04’03’’ W), as previously described in Silva et al. (2017). These samples were collected using a US DH–48 sampler according to the equal-width-increment (EWI) method that allows a representative sampling to be obtained. A total of 120 samples composed 24 composite sediment samples (i.e., twelve samples for each cross section). Before the analysis, samples were stored in polyethylene bottles.

Heavy metals analysis

Heavy metal background values for the watershed soils were determined in areas of native vegetation or minimal anthropic influence (Silva, Nascimento, Cantalice, Silva, & Cruz, 2015). Aliquots (0.5 g each) of the soil and suspended sediment samples were ground and passed through a 0.3-mm-mesh stainless-steel sieve (ABNT No. 50). They were then digested in Teflon vessels (12 mL acid solution - HNO_3:HCl, 3:1) in a microwave oven (USEPA, 1998). Standard operation procedures and analytical data quality controls, such as the use of calibration curves and high-purity acids, curve recalibration, the analysis of reagent blanks and the use of standard reference materials 2709a San Joaquin Soil (As and Hg) and 2710a Montana I Soil (Cd, Pb, Zn, Cu, Ni, Cr, Fe, and Mn) (National Institute of Standards and Technology [NIST], 2002), were followed. The NIST recoveries ranged from 82.6 to 115.7%. All analyses were performed in duplicate.

Concentrations of Cd, Cr, Cu, Fe, Mn, Ni, Pb, and Zn were determined by optical emission spectrometry (ICP-OES), while As and Hg were determined by an atomic absorption spectrophotometer coupled to a hydride generator. In addition, the mineralogical composition (%) of granites, one of the most predominant rock types across the Ipojuca catchment, was determined in the fresh rock samples collected near the studied sites. Mineral identification was carried out using a petrographic microscope. Polished thin sections were prepared based on Murphy (1986).

Assessment of the sediment pollution

Contamination in the suspended sediment was assessed by the enrichment factor (EF) and compared with the SQGs. As background values, we used four composite uncontaminated soil samples from each cross section (Silva et al., 2015). To discriminate between the natural and anthropogenic sources of heavy metals in the suspended sediments, the EF was calculated as:

EF = metal/Fe sample / (metal/Fe) background (1)

The EF values were interpreted according to Sakan, Djordjevic, Manojlovic, and Predrag (2009). Iron was used as a normalizer based on several advantages that have been described in the literature (Varol & Şen, 2012; Thuong, Yoneda, Ikegami, & Takakura, 2013); however, it should be noted that other elements, such as Al or Li, have been widely used (Dung, Cappuyns, Swennen, & Phung, 2013). Furthermore, the pollution load index was calculated following the equation below:

$$PLI = (CF_1 x CF_2 x CF_3 x \dots CF_n)^{1/n} \quad (2)$$

This index integrates the CF values (ratio between the concentration of each heavy metal and the background value) for the entire cross section. PLI > 1 indicates metal pollution, and PLI < 1 means there is no metal pollution (Tomlinson, Wilson, Harris, & Jeffery, 1980).

The potential ecological risk index (RI) was calculated following Hakanson (1980), as described below:

$$RI = \sum_{i=1}^{n} E_i = \sum_{i=1}^{n} T_i CF = \sum_{i=1}^{n} T_i \frac{C_s^i}{C_b^i} \quad (3)$$

where: Ei is the potential ecological risk factor of the metal i; T_i is the toxic response factor of the metal i (Hg = 40, Cd = 30, As = 10, Cu = Ni = Pb = 5, Cr = 2, and Zn = 1; Hilton, Davison, & Ochsenbein, 1985); and C_s^i and C_b^i are the concentration and background value of the metal i in the sample, respectively. RI represents the sensitivity of the biological community to the toxic metals ($E_i < 40$ = low; $40 \leqslant E_i \leqslant 80$ = moderate; $80 \leqslant E_i \leqslant 160$ = considerable; $160 \leqslant E_i \leqslant 320$ = high and $E_i \geqslant 120$ = very high; Ri < 95 = low; 95 ⩽ Ri ⩽ 190 = moderate; $190 \leqslant E_i \leqslant 380$ = considerable; Ri > 380 = high) (Hakanson, 1980).

The heavy metal concentration in the suspended sediments was compared with the SQGs aiming to protect the aquatic environment (CCME, 1995). The numerical thresholds required to maintain the quality of the aquatic environment are summarized in Tables 1 and 2.

Statistical analysis

Descriptive and multivariate statistical techniques were used to evaluate the river data set. Principal component analysis (PCA) allowed natural and anthropogenic origins to be distinguished for metals in the suspended sediments. Varimax rotation was applied to highlight the contribution of the most important variables. Then, cluster analysis (CA) was applied using Ward's method and the Euclidean distance as a measure of similarity. Both techniques were applied to standardized data in order to improve interpretation and avoid misclassification.

Results and discussion

Heavy metal concentrations in suspended sediments

The heavy metal concentration found in the suspended sediments (fraction < 63 μm) of the upstream cross section was lower than the average concentration found in the sediments of the Shing Mun, Tinto, Tigris, Lich, and Langat Rivers (Sin, Chua, Lo, & Ng, 2001; Morillo, Usero, & Gracia, 2002; Varol, 2011; Varol & Sen, 2012; Thuong et al., 2013; Lim, Aris, & Ismail, 2013). In the downstream cross section of the Ipojuca River, the metal concentrations were higher than those in the Langat River (Lim et al., 2013) but lower than those in the Shing Mun, Tinto, Tigris, and Lich Rivers. Such differences probably reflect the different anthropogenic inputs into each catchment area. For instance, the high Cu concentration in the Tigris River (Varol, 2011) can be attributed to metallic discharges from a copper mine plant; likewise, the high concentrations of Cd, Cu, and Zn in the sediments of the Shing Mun River were linked to the large surface runoff discharges into the river from various cottage industries in the region (Sin et al., 2001).

The mean concentration of Pb in the suspended sediments was higher than those in the suspended sediments of world rivers and continents that have been reported by Martin and Meybeck (1979) and Viers, Dupré, and Gaillardet (2009); in contrast, the mean concentration of Zn in the suspended sediments was higher than those reported worldwide, except for the values in the rivers of Europe (Viers et al., 2009) and the values in the World Rivers reports by Martin and Meybeck (1979). Although these analyses and comparisons with other rivers yield some useful insights, the sources of the heavy metals in the Ipojuca River system are still uncertain; in addition, it is unclear whether these metals pose a risk to aquatic life. To shed some light on this issue, we used additional analyses techniques, namely, the determination of enrichment factors and pollution load indexes, an ecological risk assessment, the identification of mineralogical compositions with a petrographic microscope, a multivariate statistical analysis, and a comparison of the results with the SQGs.

Pollution indices, ecological risk assessment and comparison of the results with the sediment quality guidelines

The mean EF values for the upstream cross section followed the order of Mn (28.73) > As (22.17) > Pb (6.69) > Cu (4.49) > Cd (3.4) > Zn (3.22) > Hg (2.51) > Cr (1.70) > Ni (1.36); those for the downstream cross section followed the order of Zn (22.92) > Pb (15.51) > As (9.67) > Mn (5.48) > Ni (5.38) > Cu (4.49) > Cr (2.68) > Hg (1.32) > Cd (0.95). According to Sakan et al. (2009), the EF mean values were as follows: no enrichment (Cd – downstream); minor enrichment (Ni – upstream, Cr and Hg – both sites); moderate enrichment (Cu – both sites; Cd and Zn – upstream); moderately severe enrichment (Pb – upstream; As, Mn, and Ni – downstream); severe enrichment (As – upstream; Pb and Zn – downstream); and very severe enrichment (Mn – upstream). Moreover, according to the mean PLI values of 1.1 and 3.5 for the upstream and downstream cross sections, respectively, both regions are polluted.

The highest EF values observed in all the suspended sediments were for Mn (54) and Zn (85) at the upstream and downstream sites, respectively (Figure 2a and b); Mn has also been reported as one of the elements with the highest EF relative to the upper continental crust (Viers et al., 2009). Cadmium presented the lowest EF mean value in the downstream cross section (0.95), which is probably related to the low-energy binding of Cd to the soil and sediments. In addition to Mn (upstream), the EF was particularly high for As (upstream) and for Zn, Pb, and As (downstream). The high As EF values seem to indicate a common source at both sites; those for Zn and Pb, which fall in approximately the same range, also suggest similar anthropogenic inputs; and those for Mn may be associated with some upstream inputs or natural processes, as discussed by Ponter, Ingri, and Boström (1992). The mineralogical composition of the most predominant rock type (granite) across the Ipojuca catchment (quartz 34%, plagioclase 28%, microcline 11%, orthoclase 12%, biotite 8%, muscovite 6%, opaque mineral < 1% and allanite < 1%) (Figure 3a and b) also suggests that the Zn, Pb, and As are mainly derived from anthropic sources.

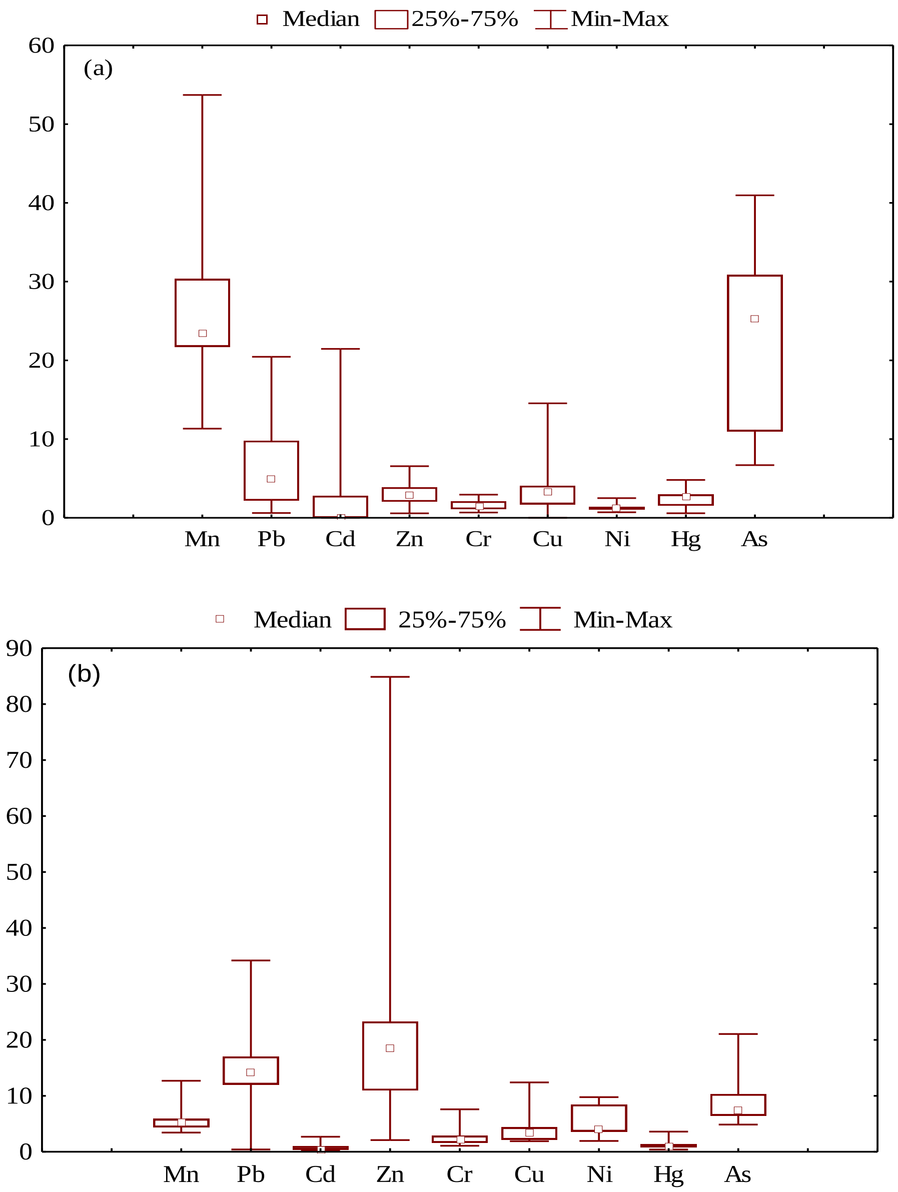

Figure 2. Enrichment factors for heavy metals found in suspended sediments in the upstream (a) and downstream (b) cross sections of the Ipojuca River.

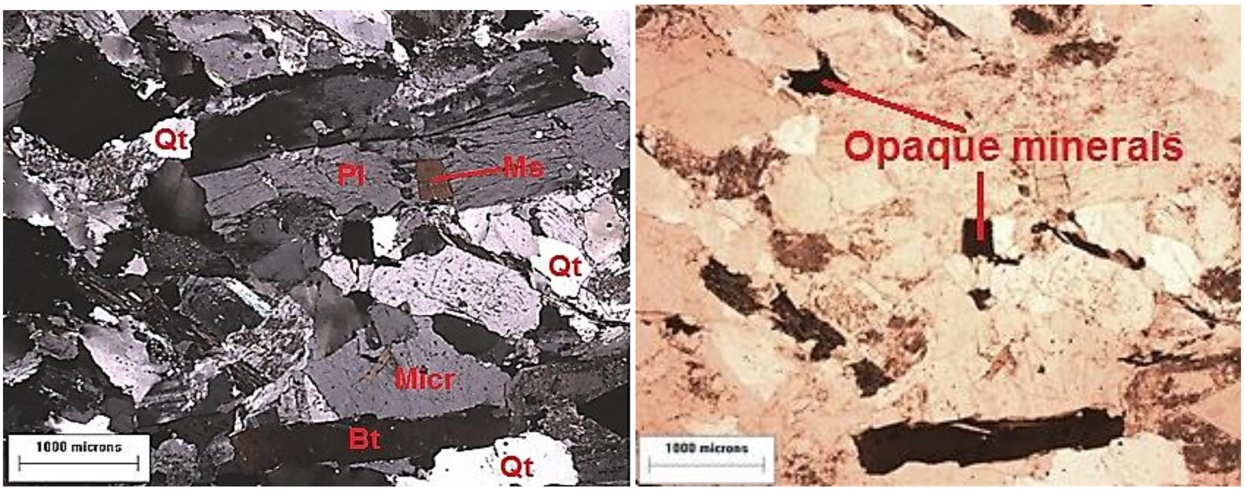

Figure 3. General aspects of the petrographic characteristics of the most predominant rock type (granite) encountered across the Ipojuca catchment, northeast Brazil (a: left). Opaque minerals (b: right). Qt – quartz; Micr – microcline; Bt – biotite; Pl – plagioclase; Ms – muscovite.

The potential ecological risk indices for a single heavy metal (Ei) indicated that the severity of pollution in the upstream and downstream cross sections decreased in the following sequence: As (49.8) > Hg (21.2) > Cd (21.1) > Pb (10.26) > Cu (4.9) > Ni (1.73) > Cr (1.1) and Pb (104.4) > As (88.7) > Hg (48.1) > Ni (26.5) > Cd (23.4) > Cu (22.7) > Zn (20.5) > Cr (7.57), respectively. Except for As (moderate ecological risk), all heavy metals in the upstream cross section showed a low ecological risk. The mean E_i values of Pb and As showed a considerable ecological risk in the downstream cross section; As showed a moderate ecological risk. For other metals (Ni, Cd, Cu, Zn, and Cr), the potential ecological risks were low. The mean RI values of approximately 110 and 342 reveal moderate and considerable ecological risks in the upstream and downstream cross sections, respectively.

For the upstream cross section, As, Cd, Zn, Cr, Cu, Hg, and Ni showed values lower than the SQG probable effect level (PEL) in 100% of the samples. In 25% of the samples, Pb exceeded the threshold effect level (TEL), and in 17% of the samples, Pb exceeded the PEL. The mean available metal concentration for the upstream site followed the order of Fe > Mn > Zn > Pb > Cr > Cu > Ni > As > Cd > Hg (Table 1). According to the SQGs, only Pb showed concentrations that potentially have harmful effects on sediment-dwelling organisms.

Table 1. Comparison of heavy metal concentrations in suspended sediments from the upstream cross section with SQGs.

	Metal concentration in suspended sediment – upstream (mg kg^{-1})									
	Fe	Mn	Pb	Cd	Zn	Cr	Cu	Ni	Hg	As
Min	1,091	518.43	1.40	<DL	18.23	2.25	0.01	1.00	0.01	0.41
Max	6,380	3,216	142.90	0.25	154.13	34.15	11.38	6.75	0.05	2.30
Mean	3,002	1,482	36.27	0.16	63.27	9.10	4.42	3.01	0.02	1.10
SD	1,793	762.44	44.38	0.1	40.86	8.82	3.66	1.77	0.01	0.56
Comparison with sediment quality guidelines										
TEL	na	na	35.00	0.60	123.00	37.30	35.70	18.00	0.17	5.90
PEL	na	na	91.30	3.50	315.00	90.00	197.00	35.90	0.49	17.00
S > TEL	na	na	3	0	1	0	0	0	0	0
S > PEL	na	na	2	0	0	0	0	0	0	0

S = samples; SD = standard deviation; na = data not available; <DL = below detection limit. Note: TEL and PEL (Canadian Sediment Quality Guidelines) are the values used by Brazilian legislation CONAMA (2012).

For the downstream cross section, the concentrations of heavy metals in the suspended sediments were higher than those in the upstream samples, except for Mn (Table 2). The mean metal concentration followed the order of Fe > Mn > Pb > Zn > Cr > Cu > Ni > As > Cd > Hg. The SQG comparison showed that Pb exceeded TEL in 92% of the samples. Notably, Pb was the most harmful heavy metal to aquatic life in the downstream site, as its concentration was higher than the PEL in 75% of the samples (Table 2). In contrast, for the upstream cross section, no metal exceeded the PEL in more than 17% of the samples (two samples). Other metals exceeding the guidelines (percentage of samples) are: (1) TEL: Cd 8%, Zn 58%, Cr 75%, Cu 33%, Ni 25%, As 100%; and (2) PEL: Zn 33%, Cr 25%.

Table 2. Comparison of heavy metal concentrations in suspended sediments from the downstream cross section with SQGs.

	Metal concentration in suspended sediment – downstream (mg kg^{-1})									
	Fe	Mn	Pb	Cd	Zn	Cr	Cu	Ni	Hg	As
Min	10,350	200.52	4.13	0.05	38.58	15.15	10.83	5.15	0.03	6.25
Max	39,845	1,049	682.05	0.51	534.27	332.17	90.28	35.25	0.14	15.07
Mean	28,251	723.59	302.22	0.27	225.20	91.83	37.83	16.62	0.08	9.71
SD	10,057	269.38	224.98	0.18	173.45	85.44	27.34	7.27	0.03	2.63
Comparison with sediment quality guidelines										
TEL	na	na	35.00	0.60	123.00	37.30	35.70	18.00	0.17	5.90
PEL	na	na	91.30	3.50	315.00	90.00	197.00	35.90	0.49	17.00
S > TEL	na	na	11	1	7	9	4	3	0	12
S > PEL	na	na	9	0	4	3	0	0	0	0

S = samples; SD = standard deviation; na = data not available; Note: TEL and PEL (Canadian Sediment Quality Guidelines) are the values used by Brazilian legislation CONAMA (2012).

Cluster and principal component analysis

We used cluster analysis to confirm the high concentrations of heavy metals in suspended sediments in the downstream cross section (Figure 4). Based on similarity, 24 measurements were grouped into two statistically significant clusters (linkage distance < 40%). Regardless of the time of year (temporal variability), the concentrations of metals in the suspended sediments of the downstream cross sections were similar. However, the concentrations measured in the downstream site were higher than those measured in the upstream site (spatial variability).

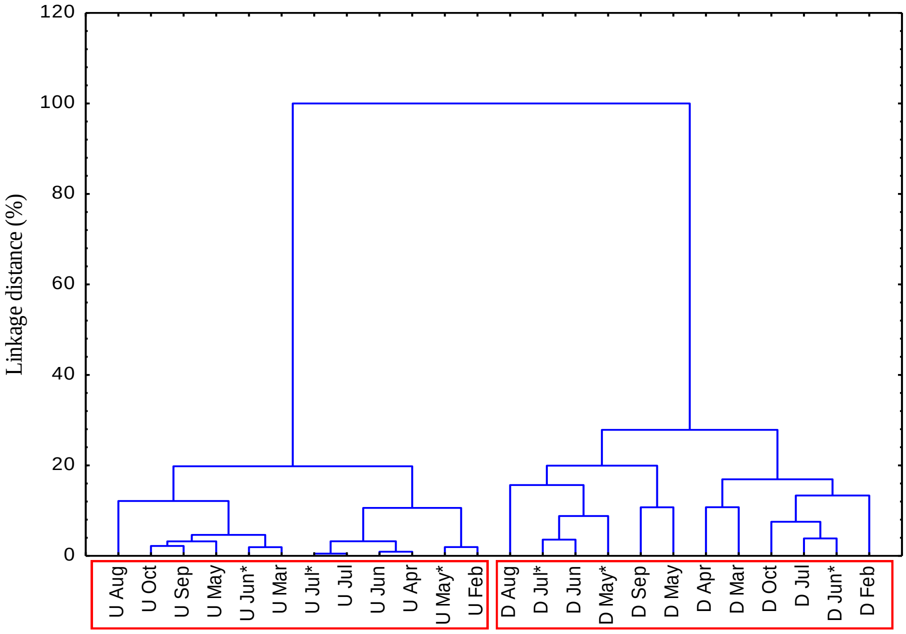

Figure 4. Cluster analysis of metal concentrations in the suspended sediment, according to Ward's method. U = upstream; D = downstream; * = second measurement in the same month.

The cluster for the downstream cross section (Figure 4) shows higher levels of heavy metal contamination, whereas the cluster for the upstream cross section shows moderate levels of contamination. The lack of seasonal variation (wet/dry periods) in the suspended sediments of the Ipojuca River was not observed in the other contaminated rivers (Varol, 2011; Thuong et al., 2013). It is likely that the higher amounts of sediments carried downstream by runoff along the Ipojuca watershed offset the dilution of contaminants by the higher water discharge downstream.

Principal component analysis of the standardized data was used to distinguish patterns among the sediment samples and to identify the contribution of each heavy metal to each PC (Table 3). The entire data set shows PCs with eigenvalues > 1, which explains approximately 80% and 74% of the total variance in the suspended sediment quality in the upstream and downstream cross sections, respectively.

Table 3. Contributions of heavy metals to significant principal components in sediment samples from the Ipojuca River.

	Upstream			Downstream		
Variables	PC1	PC2	PC3	PC1	PC2	PC3
Fe	0.73	0.35	-0.42	0.93	0.11	0.08
Mn	0.92	0.09	0.07	0.75	-0.36	0.36
Pb	0.85	0.18	0.17	0.53	0.60	0.26
Cd	0.37	0.07	-0.76	-0.09	-0.94	0.05
Zn	0.21	0.46	0.83	-0.29	0.57	0.45
Cr	0.91	0.17	-0.19	0.70	0.32	0.05
Cu	0.24	0.88	0.07	0.15	-0.13	0.94
Ni	0.53	0.58	-0.45	0.25	0.11	0.88
Hg	0.00	0.91	0.20	-0.15	0.49	0.63
As	0.62	-0.24	-0.25	0.08	0.64	-0.05
Eigenvalues	4.57	2.29	1.19	3.429	2.189	1.744
EV (%)	45.70	22.94	11.90	34.30	21.90	17.44

Values in bold indicate significant contributions; EV = explained variance. Note: rotation done by Varimax method.

In the upstream cross section, PC1 (accounting for 45.70% of the total variance) was correlated with Fe, Mn, Pb, Cr, and As; PC2 (accounting for 22.94% of the total variance) was correlated with Cu, Ni, and Hg; and PC3 (accounting for 11.90% of the total variance) was correlated with Cd and Zn. Both PC2 and PC3 at the upstream site represent metals derived from natural sources, as supported by the data in Table 2. In contrast, PC1 appears to represent heavy metals from a mixture of sources, with Fe, Pb, and Cr derived mainly from natural sources, while Mn and As seem to mainly have anthropogenic sources (Table 1 and Figure 2a). Previous studies have reported a mixture of heavy metal sources for river sediments (Thuong et al., 2013; Silva et al., 2017).

In the downstream cross section, PC1 accounted for 34.30% of the total variance and was correlated with Fe, Mn, and Cr; PC2 accounted for 21.90% of the total variance and was correlated with Pb, Cd, Zn, and As; and PC3 accounted for 17.44% of the total variance and was correlated with Cu, Ni, and Hg (Table 3). These results suggest that the heavy metals represented by PC1 were predominantly derived from natural sources, except for Mn, reinforcing the hypothesis that this element is associated with both natural and anthropogenic sources. The strongest contributions to PC2 were from Pb, Cd, Zn, and As; the strongest contributions to PC3 from Cu, Ni, and Hg; these results suggest these two components are derived from different anthropogenic sources (as supported by the data in Table 2 and Figure 2b).

Of all the heavy metals, Mn and As demonstrated the highest concentrations in the suspended sediments of the upstream cross section. Indeed, the suspended sediment samples were substantially enriched in manganese. Previous research has suggested an anthropogenic source for Mn, but high concentrations have been found in both pristine and polluted rivers. According to Andersson, Purcell, Walsenburg, and Ingra (1998), high Mn concentrations might be associated with the formation of authigenic particles in the aquatic environment. This enrichment is provided by natural processes, as observed by Ponter et al. (1992) in the Kalix River (Sweden). Among the possible causes of high Mn concentrations are increases in temperature (optimum range from 15°C to 30°C) under pH values ranging from seven to eight and a large quantity of biogenic particles in suspended sediments. During the measurements of this study, the optimum temperature range was observed in the upstream cross section of the Ipojuca River (24°C – 28.5°C), as well as the presence of a large quantity of biogenic particles. Thus, the precipitation of dissolved Mn was likely mediated by biological activities.

The PCAs for the samples from both sites suggest that the predominant source of As is anthropogenic. This finding might be associated with several small industries near the upstream site that produce leather products. At least 75.9 t day^{-1} of textile wastes are generated in the Ipojuca watershed (CPRH, 2003). At the downstream site, both Pb and Zn represent major concerns. Both the Pb and Zn found in urban soils have been linked to tire residues (Krčmová, Robertson, Cvecková, & Rapant, 2009) and municipal/urban wastes (CPRH, 2003). In addition, Pb has a long half-life in soils and sediments, which can be another possible reason for the high Pb levels in the suspended sediment. According to Horowitz (2009), high Pb concentrations are usually related to petroleum and coal combustion products. Martínez and Poleto (2010), studying the distribution of Pb in urban sediments, noted that commercial areas showed higher concentrations than industrial areas because of the higher vehicular traffic. Further, the negative correlation between Cd (-0.94) and Pb (0.60) shown by PC2 reflects the relative insolubility and high affinity for soil and sediments of Pb, in contrast to the relative solubility and low binding energy of Cd (Wong, Li, & Thornton, 2006).

The major sources of Cd are untreated sewage sludge, mineral fertilizers and wastewater from industrial and agricultural activities (Silva, Nascimento, Araújo, Silva, & Silva, 2016). The major source of both Cu and Zn, found in high concentrations in the suspended sediments, is most likely the sugarcane industry, with its large-scale use of agrochemicals and fertilizers. Another factor that could contribute to the increased concentrations of all the heavy metals in the downstream cross section is the extraction of sand from the bed layers (SRH, 2010), a typical activity in that area that can lead to the resuspension of heavy metals.

Conclusion

The analysis of the suspended sediments showed spatial variability. For example, the suspended sediments in the upstream portion of the river were moderately contaminated, especially with Mn and As, whereas the suspended sediments in the downstream section were highly contaminated, mainly with Zn, Pb, and As. Furthermore, the mean E_i values of Pb and As showed considerable levels of ecological risk in the downstream cross section. The comparison of our data with sediment guideline values indicated that the concentrations of Mn and Pb in the upstream section of the Ipojuca River are likely to pose a risk to sediment-dwelling organisms, while Pb and Zn are the metals of concern in the downstream section.

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