

Assessment of loose and adhered urban street sediments and trace metals: a study in the city of Poços de Caldas, Brazil

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Abstract

Purpose This study aims to quantify and characterise sediments accumulated in the street gutters in an urban area of Poços de Caldas, Brazil. The main research questions are: What type of urban areas, e.g. those under construction, produce most sediments and what are the main characteristics of such sediments? What differences, e.g. granulometry, can be found in loose and adhered sediments? What trace metals can be found in the sediments?

Materials and methods Fieldwork was carried out in a residential area of Poços de Caldas, Brazil. Ten samplings

were conducted between May and August 2013 to collect sediments from road gutters. The collected sediments were then divided into ‘loose’ and ‘adhered’, depending on whether they were collected in a first, gentle, sweeping with soft bristled brush or in a subsequent sweeping with a stiff bristled brush. Granulometric curves were drawn for both types of sediments. Fine sediment analyses ($\leq 63 \mu\text{m}$) were performed on samples from the last five samplings. Two techniques were used to look for trace elements: energy dispersive X-ray fluorescence (EDXRF) and inductively coupled plasma-atomic emission spectrometry (ICP-AES).

Results and discussion Larger amounts of sediments were collected after lower intensity rainfall events. Higher intensity events seemed to wash the sediments away. A correlation was found between areas under construction and sediment mass production. A characteristic range of granulometries (medium sand), found in our study is in accordance with studies by other authors. An important presence of heavy metals (Cr, Cd, Pb, Zn, Ni and Cu) was detected and characterised. As and Sn were also detected even though they are not often mentioned in the literature on urban soil pollutants.

Conclusions Areas under construction were found to produce more sediments than other areas. The trace metals found in highest concentrations were Pb and As. The heavy metal concentration decreases after wet periods, showing that they are carried by runoff. It is expected that this study may serve as an input for establishing diffuse pollution control and mitigation strategies for the accumulation of pollutants in the urban environment.

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1 Introduction

Several studies have shown that developing countries are experiencing strong urbanisation (Satterthwaite et al. 2010; Madlener and Sunak 2011; Martínez-Zarzoso and Maruotti 2011). The southeastern region of Brazil comprising the states of São Paulo, Rio de Janeiro, Minas Gerais and Espírito Santo is the most populous part of the country with more than 80 million inhabitants. It is also the most important in terms of industry and trade, generating more than 55 % of Brazil's GDP. The development and growth of urban areas in cities in southeastern Brazil have led to more motor vehicle traffic and changes in land use, especially with respect to soil sealing conditions. The urbanisation process involves the transport of sediments and pollutants (Poletto et al. 2009; Taylor and Robertson 2009) that can be produced by soil erosion and soil movement due to construction works. Sediments are also transported by wind and rain (Badin et al. 2008; Zafra et al. 2009; Zhang et al. 2012) according to the size, shape, concentration, fall velocity and bulk density of particles (Maidment 1993). The soil material carried by overland flow is of particular importance for water quality management, urban management and ecosystem sustainability (de Lima et al. 2008; Deng et al. 2008; Fletcher et al. 2013; de Lima et al. 2011).

Research has shown that urban sediments can be pollutant accumulators and they often occur on streets and in stormwater drainage systems. This has a potential impact on watersheds, the atmosphere and human health (Chary et al. 2008; Taylor and Robertson 2009; Lesven et al. 2010; Zhang et al. 2012; de La Cueva et al. 2014). The three basic types of sediments are mineral detritus, biogenic or organic sediments and anthropogenic particles and compounds (Taylor 2007). Heavy metals are present in the finer fractions of sediments, and their presence normally indicates anthropogenic urban pollution (Taylor 2007). de La Cueva et al. (2014) shows that sources for metals contamination are, e.g., industrial effluents and smoke. Additionally, metal pollutants such as Cd, Cu, Pb and Zn are the most widespread in peri-urban soil. Robertson et al. (2003) studied the geochemical association of metallic contaminants in urban sediments. High levels of Fe, Zn, Pb, Cu and Mn were found and have usually been associated with urban traffic. In the case of street dust, fossil fuel burning and industrial emissions, the level of heavy metal pollution is controlled by where human activities take place and by the prevailing wind direction (Charlesworth et al. 2003; Wang et al. 2005; Zhang et al. 2012). Compared with other forms of pollution, heavy metal pollution can be quite a lot more serious in cities (Wang et al. 2012).

Based on an analysis of soil aggregates, Xiao et al. (2016) show that the distribution of heavy metals in the soil is affected both by the soil type and the soil aggregate structure. The concentration of heavy metals is usually higher for smaller sediment particle size. Particles tend to be smaller with the

increase of continuous dry days (Sakai et al. 1986; Viklander 1998; Zafra et al. 2009). Wong et al. (2006) and Martinez and Poletto (2014) show that the metals most commonly found in fine-grained sediment in urban environments are Cd, Cr, Cu, Ni, Pb and Zn. Studies clearly indicate that Zn, Cr and Cu are more moveable than Ni, Co and Pb, i.e. Zn, Cr and Cu are more available to plants, thus potentially posing an increased risk to humans (Chary et al. 2008). Poletto et al. (2009) found high concentrations of Cr, Cu, Ni, Pb and Zn in the fraction <63 µm of sediments collected on streets and also on coarse material retained in street drains, thus showing that the metals can be transferred very quickly from diffuse pollutant sources on impermeable surfaces to the drainage network.

The main objective of this study was to quantify and characterise the amount of sediments deposited on urban streets, with different land uses and to identify the presence of heavy metals in the finer fraction of those sediments. Field sampling took place from May to August 2013 in a new neighbourhood of the city Poços de Caldas (Minas Gerais, Brazil). In the study area, distinct zones were identified as built areas, areas under construction and no construction areas.

2 Materials and methods

2.1 Study area

The study area (Fig. 1) is a residential area of the city of Poços de Caldas, in Minas Gerais (Brazil), with an area of ~22 ha (~9 ha suburban housing, ~5 ha paved/impermeable and ~8 ha permeable/natural).

According to the Köppen classification, the local climate is classified as Cwb—mesothermic with wet summers (October to March with average temperatures of ~20 °C and total rainfall of ~1400 mm) and dry winters (April to September with average temperatures of ~15 °C and total rainfall of ~300 mm) (e.g. Antunes 1986; Santos et al. 2008). The city of Poços de Caldas is fully inserted into a volcanic crater, which was originated by the intrusion of alkaline silicate rocks followed by carbonation, tectonic, erosive and sedimentary processes (Schorsch and Shea 1992). Main features of local geomorphology are: hills and small hills of crystalline Precambrian rock; mountains with narrow peaks, hills, small hills with rounded peaks, floodplains, colluvium ramps near rivers and talus deposits on mountain slopes (Zaine et al. 2008). The soils found in the region are Entisol, Cambisols or Haplic Cambisols (Moraes 2008).

The area where the fieldwork took place in 2013 is exclusively for residential purposes with 250 m² plots. These plots have been quickly occupied, typically by single- or two-storey houses; some four-storey buildings were also built. The surroundings are mainly agricultural and peri-urban without any industrial activity. Traffic mainly consists of cars and

Fig. 1 Location of the study area, Minas Gerais, Poços de Caldas, Brazil



relatively infrequent public transport vehicles (buses). Streets are paved and there is a fully operational urban drainage system, with concrete intakes and without visible accumulation areas of water and/or sediments.

To assure the spatial representativeness of the samples, the study area was divided into 12 sampling sections grouped in five zones (Fig. 2). Three main land uses were identified in the study area: finished houses and buildings ('built area'), areas where construction works are being carried out ('under construction') and, finally, areas where the land plots were

unoccupied or corresponded to open/green spaces ('no construction'). Therefore, the delimitation and number of sections and the grouping of sections into zones, took into account the similarity of land use, the slope of streets and the time needed so that all samples could be collected in less than 4 h. To assure that the sediments were produced and transported locally, the study area is inserted in the same small drainage basin (see the delimiting line in Fig. 2) with both riverbanks represented by sections grouped in zone 1 in the left bank and zones 2, 3, 4 and 5 in the right bank. Table 1 summarises the basic information on the sampling sections and zones.

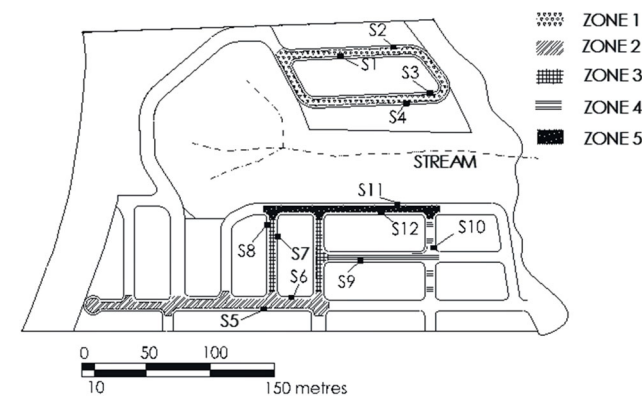


Fig. 2 Location of the street sampling sections in the five zones, inserted in the small urban basin

2.2 Sediment sampling procedure

Sediments were collected in ten samplings between 21 May 2013 and 27 August 2013, in street areas open to traffic. Meteorological information was available 2.5 km from the study area. All sampling sessions were carried out between 7:00 am and 11:00 am, with an interval of at least 7 days, ensuring a dry period (without rain) of at least 24 h before each campaign.

Sediments were removed by brushing, as proposed in Charlesworth et al. (2003). Each sampling area was 1.00 m² (1.00 × 1.00 m), always close to the sidewalks, since most sediments accumulate there (90 % according to Butler and Clark 1995). Figure 3 illustrates the removal of the dry sediments from the impermeable street surfaces of concrete and asphalt.

The collected sediments were classified as loose or adhered. Loose sediments were collected first by gently sweeping the 1.00 m² sampling area with a 170 mm brush with soft nylon bristles. We opted to use brushes without any metallic parts to avoid contamination of samples. The loose sediments include loose materials of various granulometries, including small stones and gravel. To collect the adhered sediment, the same area was brushed firmly with a stiff nylon brush, trying

Table 1 Characteristics of the different zones and sampling sections

Sampling sections	Zones	Slope (%)	Characteristics		
			Built areas (%)	Under construction areas (%)	No construction (%)
S1	Z1	10	32.24	27.19	40.57
S2		10			
S3		7			
S4		7			
S5	Z2	10	43.00	16.60	40.40
S6		10			
S7	Z3	7	46.40	10.44	43.16
S8		7			
S9	Z4	9	49.40	14.80	35.80
S10		4			
S11		7			
S12	Z5	7	12.12	3.80	84.09

to apply the same force with the brush throughout all the experiments (Zafra et al. 2009). A 75 mm soft brush was then used to sweep off the sediments. The swept sediments were

collected with a plastic shovel, placed in labelled plastic bags, stored in dry thermal boxes and taken to the laboratory for processing. All the sediment samples were then oven dried at 105 °C for 24 h.

It should be noted that, in the first sampling, the collected sediments had accumulated for an unknown period of time. In samplings 2 to 5, the sediments were weighed separately for all sections and for loose and adhered materials. All sediments from samplings 6 to 10 were lumped together for analysis. In all cases, the granulometric curves were determined following the procedure suggested in Dotto (2006).

2.3 Heavy metals

Fine sediment analyses (fraction of 63 µm or less) were performed on composite samples of the last five samplings. Two techniques were used to look for the presence of trace elements: (i) analysis by energy dispersive X-ray fluorescence (EDXRF) for the mineralogical composition of the sediments and the trace metals common in urban areas (Cd, Cr, Cu, Ni, Pb and Zn), and (ii) analysis by inductively coupled plasma-atomic emission spectrometry (ICP-AES) for the total mass of heavy metals per square meter of street.

Statistics were used to assess the temporal variability of the concentration of the elements found on the samples. These were compared with the limit values present in Brazilian Regulations.

3 Results

3.1 Sediment mass

Details of the total mass of sediments collected in each sampling for all the zones, as well as the daily rainfall, are



Fig. 3 Collection of sediments by sweeping and brushing the 1 m² urban street sampling areas

presented in Fig. 4 (left). The first sampling on the 21st of May yielded a large amount of sediments, almost 6000 g, but it was disregarded as it was considered a clean-up sampling. Figure 4 (right) shows a strong correlation ($R=0.93$) with statistical significance ($p<0.05$) between the increase of accumulated sediment production and the accumulated rainfall volume.

The mass of sediments collected in the four field samplings of 4, 11, 18 and 25 June is presented in Table 2 by section (12 sections) and by sampling to enable a search for a trend in the accumulation of sediments in the street pavements. This data is presented in Fig. 5 through a boxplot of the sediment mass collected in each campaign.

Figure 6 (left) shows the sediment production for each zone and type of land use. This production corresponds to the total mass collected in all sections and all sampling sites per number of samplings (4) and sections of the respective zone. Therefore, it represents the average production for each section. The linear regression lines between sediment production and land use is shown in Fig. 6 (right). Land uses areas considered in the study are ‘built’, ‘under construction’ and ‘no construction’ areas. Only in the under construction areas was found to exist a moderate correlation ($R=0.89$) with statistical significance.

3.2 Granulometric curves

The granulometric curves were constructed by sieving the collected sediments. Figure 7 (left) presents the granulometric curves for all the 12 sections (averaged for all the campaigns), separately for the loose (top) and the adhered (bottom) samples. The variability of grain size across the 12 sections per sieve size is shown in Fig. 7 (right).

The loose sediments have a wider dispersion of granulometries than the adhered sediments. From the granulometric curves, it is observable that the adhered sediments of $d_{50}=0.22$ mm are finer than the loose sediments of $d_{50}=0.51$ mm. As expected, that wider dispersion of granulometries highlights the coarser quality of loose sediments and also shows how the granulometry changes from section-to-section because of changes in the sediment availability, deposition and transport capacity of runoff both in unpaved and paved urban surfaces. The strong correlation ($R=0.99$), with statistical

Fig. 4 Total mass collected in the study area (solid bars) and daily rainfall (hatched bars) during the field work. The sediments collected in the first sampling (21 May), totalling 5962 g, were disregarded

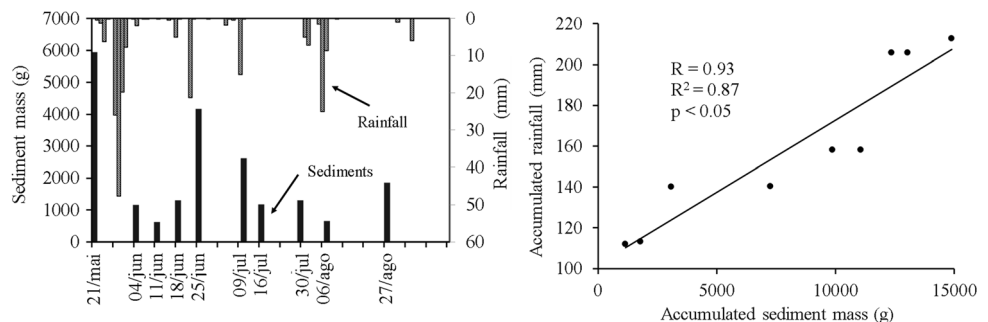


Table 2 Sediment mass per section collected during the first four campaigns and median, average, standard deviation and coefficient of variation by campaign

Section	04 Jun	11 Jun	18 Jun	25 Jun
S1	9.27	22.80	2.54	3600.00
S2	37.17	4.78	24.24	13.60
S3	235.36	33.41	342.94	219.70
S4	74.87	237.76	92.74	73.93
S5	24.98	167.54	22.74	42.68
S6	15.68	21.67	75.69	30.56
S7	3.54	9.18	1.50	20.06
S8	243.81	29.05	47.67	72.51
S9	6.86	9.98	1.63	16.56
S10	497.37	61.77	683.83	51.70
S11	2.12	16.83	3.25	7.42
S12	13.67	11.19	10.68	14.43
Median	20.33	22.24	23.49	36.62
Average	97.06	52.16	109.12	346.93
Standard deviation	152.96	73.44	204.54	1026.08
Coefficient of variation	1.58	1.41	1.87	2.96

significance, between the averaged granulometric curves for loose and adhered sediments is shown in Fig. 8. The average particle size by sampling zone, both for loose and for adhered sediments is presented in Table 3.

3.3 Trace elements

Table 4 presents the concentrations of trace metals obtained by EDXRF (NiO, PbO, CuO and ZnO) and ICP-AES (Cd, Cu, Cr, Sn, Ni, Zn, As and Pb). No trace of PbO was present in the samples collected in the field campaign of 07 August. This measurement was disregarded because PbO and Pb were found in all other campaigns. Statistical parameters are used to characterise the trace metals (e.g. average, median, standard deviation, coefficient of variation) and limit values established by the Brazilian Regulations are presented. Data from campaigns are presented chronologically and the concentration of trace metals by increasing median values, firstly by EDXRF and followed by ICP-AES. Average median concentration of

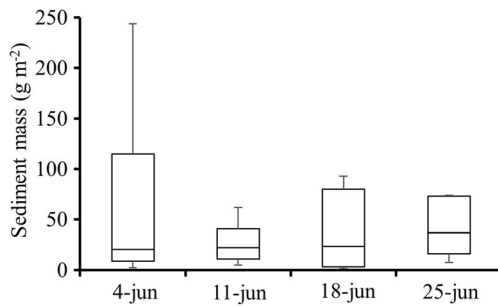


Fig. 5 Dispersion of sediment mass (loose and adhered sediment) per campaign

Cd, Ni, As and Pb are above the referred limit values. Figure 9 shows the concentration of all trace metals detected by EDXRF and ICP-AES per campaign (results from both methods are presented together because both show similar concentrations). Measured rainfall events (daily amounts) that occurred between fieldwork sampling campaigns are also shown. A statistical analysis on the concentrations of trace metals is shown in Fig. 10, where the limit values for these elements accordingly to the Brazilian Regulations are also presented.

Oxides of Cd, Cr, Cu, Ni, Pb and Zn were investigated with EDXRF where only ZnO, CuO, NiO and PbO were detected. Pb was the trace element with the highest concentration using the ICP-AES technique and Cd was found to have the smallest concentration.

4 Discussion

The results obtained led to the following analysis with respect to deposited sediments and trace elements found in them. Sediments were collected in 12 sections and divided into loose and adhered. Heavy metals were analysed in the finer fraction of the sediments, where all the collected material was gathered in a single composite sample.

4.1 Sediment mass

There is no clear correlation of the sediments yield with the previous rainfall events as see in Fig. 4 (left). However, low-

intensity rainfall events generally lead to an increase in sediment accumulation. Larger amounts of sediments were found after lower rainfall events, whereas higher events most likely have the power to wash away the sediments. For example, the rainfall event of 21st of May with accumulated rainfall depth over 40 mm washed away the sediments accumulated at the time of the first field sampling.

The first campaign presents the largest variability in the collected sediment mass, followed by the third, fourth and second campaigns (Fig. 5). Rainfall over the seven days prior to each sampling campaign is higher in the first (30 mm) and third (27 mm) campaigns, diminishing on the second (1 mm) and fourth (0.25 mm), this shows the importance of rainfall in the sediment sample variability. Nonetheless, a temporal analysis allows to verify that the median values of the four campaigns are similar, ranging from 20.32 to 36.62 g m⁻². The median value for the sediment production is much closer to the first quartile than to the third quartile in all campaigns, thus showing positive skewness. A link can be found between land use and sediment mass produced, namely, the ratio of constructed and under construction areas. For example, the highest sediment mass was found in the area where most construction work was being done.

Figure 6 (left) shows that Z1 had the highest average accumulated sediment mass per sampling zone (~314 g m⁻² sampling⁻¹). This is because Z1 has a higher percentage of area under construction than the other zones (27 %). The faster execution of construction works in Z1 and its ‘strap’ shape, favoured an increase in traffic and the casual spread of (construction) materials over the gutters, which is common, given the usual construction methods in Brazil, where the use of prefabricated components is almost negligible. When comparing the percentage of unoccupied construction plots in the studied areas, it is easy to see that Z1, despite its area of unoccupied plots being similar to that of Z2 and Z3, showed an accumulation of sediments about 6× higher than Z2 and Z3. This shows that the most important variable for sediment accumulation is the type of occupation (in this case, the highest ratio of construction areas). Z2 and Z3 had a similar ratio of sediment accumulation and land plot occupancy. However, Z3 has a slightly larger accumulation of sediments than Z2 (~53 and ~50 g m⁻² sampling⁻¹, respectively).

Fig. 6 Relation of sediment production and land use. Note that mean production is per area unit and per sampling (left). Correlation between land use types and sediment production (right)

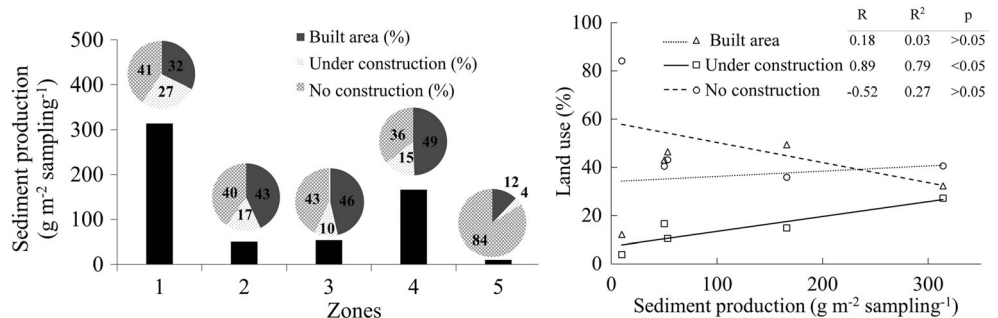
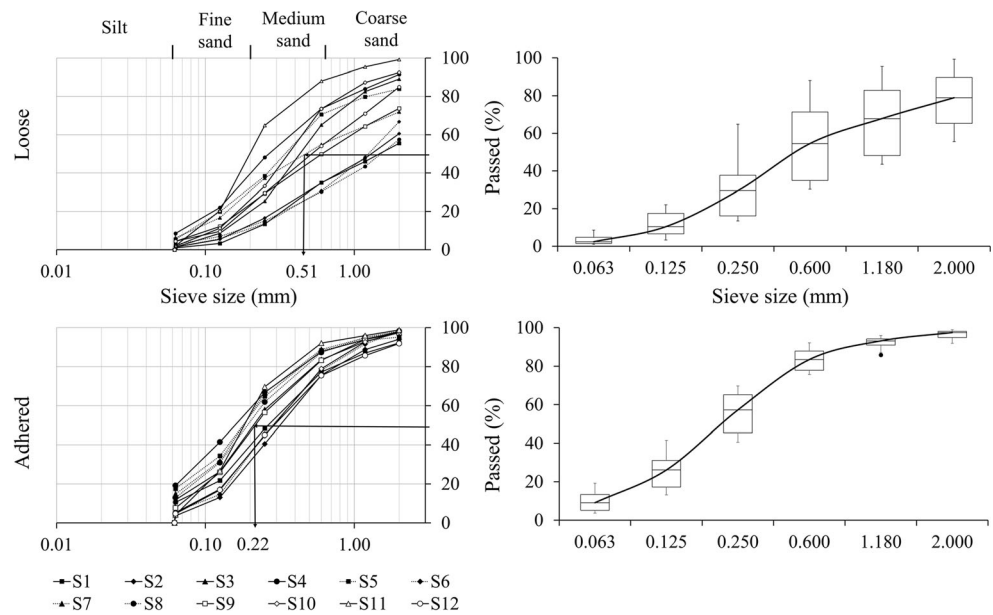


Fig. 7 *Left*, granulometric curves of loose (*top*) and adhered (*bottom*) sediments. *Right*, dispersion of passed sediments per grain size of loose (*top*) and adhered (*bottom*) sediments. Numbers (S1 to S12) refer to sampling sections (see Table 1)



Although these small differences can be ascribed to the low variability in occupancy rates, the higher accumulation in Z3 can also be ascribed to the street longitudinal slope since Z2 has a 10 % slope while the Z3 slope is 7 % (see Table 1). Steeper slopes favour the sediments being washed away by rainfall induced overland flow, whereas gentler slopes encourage the deposition of sediments (carried by wind and other processes). Nevertheless, even though Z4 only has 15 % of plot area under construction a major accumulation of sediments was found in that area (~166 g m⁻² sampling⁻¹), which can be attributed to the gentler slope in that section (4 %). An important relation of slope and sediment accumulation can be found when comparing Z2 and Z4. Although Z2 has a larger percentage of plots under construction than Z4, Z2 has a much steeper slope than Z4, and only one third of the average accumulated mass of sediments of Z4 was found in Z2, because the sediment accumulation in gutters with steeper slopes tends to be lower because the water flow is faster with higher streampower. Compared with the other zones, Z5 had

the lowest mass of accumulated sediments per area unit. A detailed comparison between Z5 and Z1 shows that the key variable in the sediment accumulation process is the ‘type of occupation’. Z5 has 84 % of land plots unoccupied and only 4 % of plots under construction. Since Z1 and Z5 have similar slopes, it can be concluded that the percentage of unoccupied land plots was the major factor in the accumulation process. The smaller accumulation in Z5 proved to be particularly influenced by a large area under permanent protection and an area of community amenities, which still are very permeable surfaces with indigenous vegetation, both of which are barriers to the wind in the sediment deposition process.

This demonstrates the complex nature of the sediment accumulation process: in particular, variables such as the type of occupancy (green cover, imperviousness of soil and construction activity) and slope (topography of the areas under study and the geometry of the gutters) have a major influence on the process.

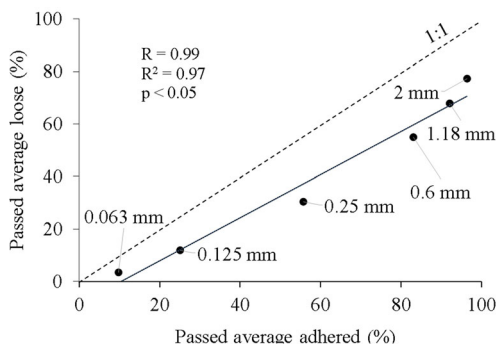


Fig. 8 Correlation between passed average loose and adhered sediments

Table 3 Sediment characteristic diameters, d_{50} (μm), of the different zones

Zone	Origin of sediments	d_{50} (μm)
Z1	Loose	940
	Adhered	200
Z2	Loose	700
	Adhered	220
Z3	Loose	1500
	Adhered	200
Z4	Loose	400
	Adhered	290
Z5	Loose	360
	Adhered	230

Table 4 Metal trace concentration by EDXRF and ICP-AES with statistics per element

Samplings dates (2013)	Elements/techniques											
	EDXRF				ICP-AES							
	NiO	PbO	CuO	ZnO	Cd	Cu	Cr	Sn	Ni	Zn	As	Pb
	Concentration ($\mu\text{g g}^{-1}$)											
10 Jul	120	110	150	270	18	70	100	100	240	270	310	490
16 Jul	90	80	120	240	13	50	90	80	120	240	260	380
29 Jul	80	120	140	290	17	60	80	100	130	300	330	450
07 Aug	100	–	120	280	13	50	70	80	150	270	280	380
27 Aug	60	100	140	260	15	70	80	90	80	250	300	400
Limit values					8	400	300		100	1000	55	300
Average	90.0	102.5	134.0	268.0	15.2	60.0	84.0	90.0	144.0	266.0	296.0	420.0
Median	90.0	105.0	140.0	270.0	15.0	60.0	80.0	90.0	130.0	270.0	300.0	400.0
Standard deviation	22.4	17.1	13.4	19.2	2.3	10.0	11.4	10.0	59.4	23.0	27.0	48.5
Coefficient of variation	0.24	0.16	0.10	0.07	0.15	0.16	0.13	0.11	0.41	0.08	0.09	0.11
	(low)	(medium)	(low)	(medium)	(low)	(low)	(medium)	(low)	(high)	(medium)	(medium)	(low)

4.2 Granulometric curves

The granulometric curves of the loose and adhered sediments show that latter are finer (see Fig. 7). In sections S1, S2, S6 and S8, the loose sediments have a d_{50} of coarse sand while in the other sections they are characterised as medium sand. This agrees with the findings of Dotto (2006) and Zafra et al. (2008) in studies on loose sediments found in urban areas. Medium and fine sand were found to be the main type of sediment in the adhered fraction. No evidence of clear relation was found between the granulometry and the characteristics presented in Table 1. This shows that other variables influence the characteristics of the accumulated sediments, such as the intensity and average speed of traffic, direction and strength of prevailing winds, rainfall intensity and type of construction process. Nevertheless, it can be seen that even though sediment accumulation is a complex phenomenon it is possible to

establish a characteristic range of granulometries found in urban areas (medium sand) that agrees with studies by other authors. This is particularly important for the design of sediment trap structures and also for the management and treatment of these sediments to improve environmental conditions, e.g. in urban streams and waterbodies.

Figure 7 shows that a wider range of grain size was found in the loose fraction, across the different sections. Notwithstanding the different types of occupation of the zones under study, the influence of no construction and under construction areas was not found to be a variable that influenced the granulometric distribution of the loose fraction. This can be exemplified by Z4 and Z5, which have very distinct slopes and land use types, but where the granulometric distribution was similar.

The dispersion of grain size increases with the augment of the loose sediments grain size, while the adhered sediments show a contrary trend. Despite the clear differences in the granulometric curves when observed individually (Fig. 7, left)

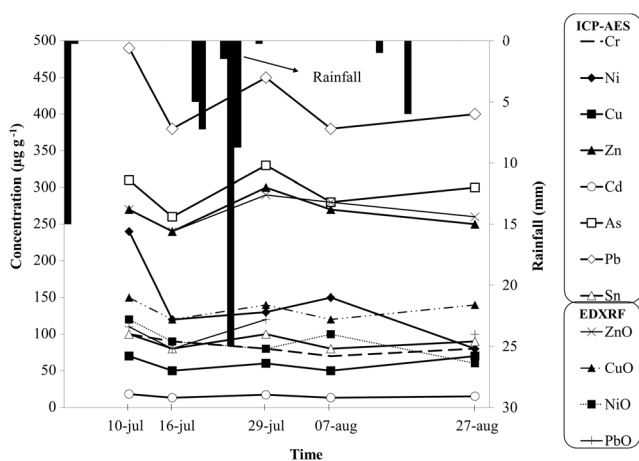


Fig. 9 Trace metals concentration obtained by EDXRF and ICP-AES from the sediments collected during fieldwork. Rainfall events (daily values) during this period are also presented (solid bars)

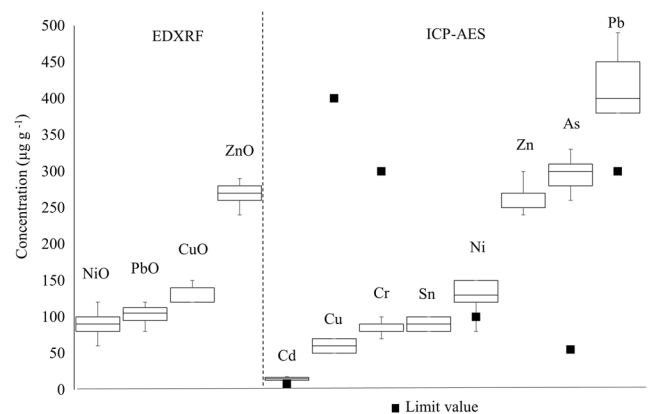


Fig. 10 Dispersion of trace metals concentration obtained by EDXRF and ICP-AES and limit value established by Brazilian Regulations (CONAMA 2013)

and taking into account the average size of passed sediments, there is a relation between the grain size of adhered and loose sediments (see Fig. 8).

Overall, the d_{50} values in Table 3 are compatible with the findings of other authors. Studies on sediments collected from urban gutters, for example, reported granulometries of 400 μm (Dotto 2006) and 600 μm (Vaze and Chiew 2002) for loose sediments and 300 μm for adhered sediments (Vaze and Chiew 2002; Dotto 2006). This similarity of results from different studies shows that, typically, the d_{50} of urban sediments is in the range of a medium sand. Even though the cited authors have used the vacuum method to collect the sediments, there is similarity with our results; sweeping method is also valid for this type of study.

Granulometric curves of the sediments collected in the different zones show that less than 4 % of the sediments are under 63 μm . This fits with the findings of Gastaldini and Silva (2012) on an urban residential area with characteristics similar to the one in the study. The mass of sediments under 63 μm was about 3 % of the total mass of collected sediments. Differences are found in the characteristics of the sediments found by Zafra et al. (2008) and Gastaldini and Silva (2012) on streetways and gutters, namely d_{50} of 352 and 359 μm (medium sand) in the loose sediment samples. In this study, d_{50} was in the range of coarse sand (Z1 and Z3) and medium sand (Z2, Z4 and Z5) for the loose material. Regarding the adhered sediments, Zafra et al. (2008) found d_{50} values of 97 and 103 μm (fine sand), while in our study the d_{50} of adhered sediments was in the range of medium sand. The reported differences can be attributed to the type of surface where the samplings were done, e.g. Zafra et al. (2008) studied streetways with much more intense traffic, but with less area under construction and fewer residential built-up areas.

Despite the differences found across the literature, generally, the results from other studies on urban sediments match our results. In our work, the d_{50} for the complete samples (loose sediments + sediments adhered) was 600 μm (medium sand), a result in accordance with Dotto (2006), who concluded that sediments in urban gutters are mostly medium sand. Zafra et al. (2008) found a d_{50} for the complete samples within the range of 193 μm (fine sand) to 270 μm (medium sand).

4.3 Trace elements

In the dry spell from 10 to 16 July, the concentration of metals decreased for all oxides, ZnO (11.1 %), CuO (20.0 %), NiO (25.0 %) and PbO (27.3 %). In another dry spell (29 July to 7 August) at decay was again observed. In both periods, the measured concentration was ZnO > CuO > NiO > PbO. A wet spell of 48 mm of rainfall in 12 days (16 to 29 July), increased the concentration of trace elements, ZnO (+20.8 %), CuO (+16.7 %) and PbO (+50 %).

The results from the ICP-AES indicated the same effect. For the first dry spell, the decay was Pb (22.4 %), As (16.1 %), Zn (11.1 %), Ni (50.0 %), Cr (10.0 %), Sn (20.0 %), Cu (28.6 %) and Cd (27.8 %) with Pb > As > Zn > Ni > Cr ≈ Sn > Cu > Cd, and for the last dry spell, it was Pb (15.6 %), As (15.2 %), Zn (10.0 %), Cr (12.5 %), Sn (20.0 %), Cu (28.6 %) and Cd (27.8 %) with Pb > As ≈ Zn > Ni > Sn ≈ Cr > Cu > Cd.

To better understand the values of the coefficient of variation (CV), shown in Table 4, these were classified accordingly to the median (M), interquartile range (IQR) and pseudo-standard deviation (PSD) (Tukey 1977). This classification is based on the use of the M, IQR and PSD, as follows: low if $CV \leq (M - PSD)$, medium if $(M - PSD) < CV \leq (M + PSD)$, high if $(M - PSD) < CV \leq (M + 2PSD)$ and very high if $CV \geq (M + 2PSD)$. With the exception of Ni, all other metals are classified as ‘low’ and ‘medium’; this shows that during the campaigns and despite the variability of the total sediment production (see Fig. 4), there is no evidence of relevant variability of the metal concentrations.

Table 4 shows that the trace metal concentrations for Cd, Ni, As and Pb are above the limit values established in the Brazilian Regulations (Cd, 190 %; Ni, 144 %; As, 538 %; and Pb, 140 %, of the limit values), whilst Cu and Cr are below these limits. A statistical analysis on the concentrations of trace metals is shown in Fig. 10, where the limit values for these elements accordingly to the Brazilian Regulations are also presented. Brazil has several legal documents where limit values for trace metal are established for different purposes, such as, water bodies, soil and agriculture. In this work, values proposed by the National Council for Environment (*Conselho Nacional do Meio Ambiente*, in Portuguese) were used as benchmark (CONAMA 2013). This reference provides the criteria and guiding values for soil quality assessment in the presence of chemical substance, establishing guidelines for the environmental management of areas contaminated by these substances as result of human activities. The limit values for trace metals in residential areas used in this work are defined as the concentration of a substance above which there is a potential, direct or indirect, risk to human health.

5 Conclusions

Sediment production in urban areas is the result of several causes/factors, such as, physiographic characteristics (e.g. slope, length), rainfall, wind and construction works. Since these factors show a very relevant spatial and temporal variability, the search for cause-effects regarding sediment production has always major uncertainty present.

Rainfall showed to influence the sediment production. Higher rainfall volumes led to samples with larger variability of sediment mass when compared with lower rainfall volumes.

The under construction areas showed to produce more sediments when compared with built areas and no construction areas. The loose sediments found in zones with land use of under construction and built areas are coarser (e.g. sand) than in the no construction areas. However, the differences are smaller for the sediments that are adhered to the street pavements.

Adhered sediments are finer than the loose sediments. However, the latter shows wider granulometric variability, per grain size, than the adhered sediments. A very strong correlation was found between the grain size of adhered and loose sediments. The interquartile range of grain size increases with the loose sediments grain size, while the adhered sediments show a contrary trend.

The trace metal concentration in sediments tends to decrease after wet periods due to wash-out processes. Even though the total sediment production shows a relevant temporal variability, there is no evidence of meaningful variability of the metal concentrations measured during this study. The highest concentrations found were for Pb and As trace elements. Cd, Ni, As and Pb are above the limit values established in the Brazilian Regulations.

Taking into consideration both the quantity of sediments produced and their characteristics in terms of concentration of trace elements, it can be concluded that sediments produced in Poços de Caldas (Brazil) could represent a public health issue and therefore require further more detailed studies.

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