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Urban Sediment Particle Size and Pollutants in Southern Brazil

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Abstract

Background, aim and scope Studies of particulate-associated pollutants, or PAPs, in urban areas have become necessary due to their potentially deleterious effects on the environment. However, it is not just the sediments themselves which are problematic, but their particle size composition which has a great influence on their capacity to adsorb and transport pollutants. This paper presents the particle size distribution and the concentrations of five metals (Zn, Ni, Pb, Cr and Cu) of urban sediments collected from paved streets and gully pots from 20 cities in southern Brazil. The cities have different characteristics and hence sources of PAPs associated with differing geologies, soil types and type of urbanization. Studies of this type enable elucidation of the relationship between diffuse sources such as streets and the gully pots and the likelihood of the PAPs to subsequently pollute the urban aquatic environment.

Materials and methods Sediment samples were taken at random from paved streets and gully pots in 20 cities in Rio Grande do Sul state, southern Brazil by means of a portable dust vacuum cleaner to avoid loss of finer particles. Their particle sizes were measured using a Cilas® 1180 laser particle analyzer and the concentrations of five metals (Zn, Ni, Pb, Cr and Cu) determined by wet acid digestion (HCl – HF – $HClO_4$ – HNO_3) followed by ICP-AES on the <63μm fraction.

Results It was found that in comparison to sediments collected from the streets, gully pot sediments were more heterogeneous in terms of particle size and also that the sediment samples from the gully pots were predominantly coarser than those originating on the streets. From the gully pots results, analysis of the particle modal diameter enabled the cities to be divided into three categories. The concentrations of metals in the street sediments were similar across all 20 cities, with all concentrations above background values and some above Level II for Brazilian Sediment Quality Guidelines.

Discussion The fact that concentrations of metals in the street dusts were above statutory guideline values and the coarser material was deposited in the gully pots would appear to suggest that the finer, more polluted sediment, is not retained in the gully pots but is transported to the nearest local receiving watercourse. This finding has implications for management strategies for reducing pollution in urban environments.

Conclusions High concentrations of Zn, Ni, Pb, Cr and Cu in the <63 μm fraction of street sediments, in combination with coarse material retained in the gully pots, tend to indicate that metals could be transferred quite rapidly between the diffuse source of pollutants, on impermeable street surfaces, and the receiving watercourse.

Recommendations and perspectives Studies of urban sediment particle size and geochemistry yield data which enable predictions to be made of their behaviour in urban environments. This will inform management strategies such as the possibility of including sustainable drainage (SUDS) in future management plans, in which it is useful to know how efficient the drainage system is from the point of view of silting of the urban aquatic environment and the potential for pollution.

Keywords Urban sediments, Particle size, Metals, Urban watershed

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1 Background, aim and scope

During the course of the last century in South America, as in the rest of the world, population in urban centres increased substantially. Half the global population live in urban centres and such centres have suffered a legacy of pollution which has degraded water and sediments (Taylor 2008). In South American cities the majority of this settlement has happened in a disorganised way, usually not accompanied by any adequate supporting infrastructure, leading to negative impacts on the environment, especially receiving water body quality and biota impacts resulting from contaminated aquatic sediments. In particular, one of the greatest impacts at the watersheds has been the replacement of permeable soils with impermeable surfaces such as roads, roofs, parking lots, and sidewalks that store little water, reduce water infiltration into the ground, and accelerate runoff to ditches and streams (USGS, 2003). As a consequence of these impacts, there is an increase in erosion and hence the transport of urban sediments to water bodies, which according to Taylor (2007) is a complex process. Moreover, sediments are also one of the principal causes of contamination in the urban aquatic environment due to the presence of sediment-associated pollutants. Horowitz (1991) showed that as fine grain size of suspended sediment concentrations increase in urban rivers and streams, the percentage of associated pollutants also increases. Particulate associated pollutants, or PAPs, include both organic and inorganic pollutants in concentrations which vary in accordance with physical factors and local conditions and are considered one of the main components of non-point pollution in urban watersheds. Hence, PAPs include not only heavy metals (cf Salomons and Forstner, 1984; Foster and Charlesworth 1996), but also nutrients such as P and N (Vaze and Chiew 2004), artificial compounds such as PAHs (Anh et al. 1999) and also radioactive nuclides (Charlesworth and Foster 2005) all of which have been found in high concentrations in urban dusts and sediments. According to Bartram and Balance (1996), 65% of the 128 priority pollutants listed by the United States Environment Protection Agency are either only, or mostly, found in association with biota and particulates.

According to Charlesworth et al. (2003a), Poleto and Merten (2007), metal concentrations vary temporally during storms due to input of street runoff containing high levels of elements associated with vehicular traffic and other anthropogenic activities. In general, the highest concentrations are found in dusts from paved streets which are subsequently carried out to the receiving watercourse during storms as polluted suspended sediment. Contamination of the urban watershed is reflected in the geochemistry of fluvial suspended and deposited sediment (De Miguel et al. 2005, Poleto and Laurenti 2008). Such pulses or flushes of sediments (Lawler et al. 2006a; 2006b) delivered to urban water bodies significantly modifies their environmental quality, which can impact on the downstream ecosystem (Poleto and Castilhos 2008). Thus, contaminated sediments are considered as one of the most serious environmental problems. While many metals are essential to the life and function of organisms, others are toxic in small quantities (Dahl 2005). Thus, studies of sediment quality have an important focus in environmental assessments, protection and management of aquatic ecosystems. For example Beasley and Kneale (2002) found that sediment quality is one of the primary limiting factors of macroinvertebrate biodiversity in urban streams.

Studies of sediments in urban areas have therefore become necessary in order to understand their physico-chemical characteristics, transport routes in the drainage system and thus to minimise their impacts on the urban aquatic environment (Bian and Zhu 2008; Jartun et al. 2008). Moreover, studies of sediment particle size have demonstrated the influence this has on the adsorption capacity and transport capability of particulates (eg Horowitz 1991, Singh et al. 1999, Lin et al. 2002, Poleti and Laurenti 2008). It is well known that the smaller particle sizes have the highest adsorption capacities due to their larger specific surface area and high Cation Exchange Capacity (Herngren et al. 2005). These properties impact on surface water management strategies, such as the sediment trapping efficiency of roadside gullypots (Butler and Karunaratne 1995).

The main aim of this study was to investigate the relationship between urban sediment particle size and the average concentrations of five metals (Zn, Ni, Pb, Cr and Cu) found on sediments collected from paved streets and gully pots, in 20 cities in southern Brazil with different histories of urbanization. Such data can be used to inform management plans for further development of these cities, in particular the means to manage the more-polluted, finer fraction of urban sediment.

2 Materials and methods

2.1 Location of the study area

The 20 study cities (Fig. 1) are located in Rio Grande do Sul state, southern Brazil. The climate in this region is temperate, subtropical and humid, (Köppen 1936), with hot summers and cold, rainy winters. The mean annual precipitation of the cities varies between 1,250 and 2,000 mm.
Fig 1

The cities were chosen at random from the metropolitan area of Porto Alegre, and have different characteristics, such as geology, number of inhabitants, area, type and degree of urbanization and local economic activities (see Table 1).
Table 1

2.2 Urban sediment sampling

The samples were taken between February and July 2008, following a period of 15 days without rain by means of portable vacuum cleaners (plastic made) to avoid the loss of fine particles (Charlesworth et al. 2003a). Three samples (each sample contained 40 sub-samples) were taken at random from a different 200 m² area of the impervious street of each city (near their centre) as shown in Figure 2. The three samples were mixed to form one composite sample from each city, resulting in 20 composite samples to represent each of the 20 cities in the study. These samples were stored at 0°C until physical (particle size composition) and geochemical analyses were performed. The range of masses of sediment collected from each of the 20 cities was between 100 to 140 g.
Fig 2

2.3 Gully pot sediment sampling

Gully pot (Fig. 3) sediments were taken on the same day as the urban sediments and from the same general location. In the same way as the street sediments, one composite sample was obtained from three areas (three gully pots) of each city from inside the gully pots (bottom) using plastic bags in order to avoid contamination of the material. Then the three samples were mixed to form one sample (composite sample) for each city, resulting in 20 composite samples. These samples were stored at 0°C until particle size analyses were performed. The range of masses for the 20 composite samples was between 410 to 580 g.
Fig 3

2.4 Sediment analysis

Grain size analyses for all the sediment samples were performed using a Cilas® 1180 laser particle analyzer located in the Centre for Density Current Studies (NECOD) at UFRGS. The analyzer distinguishes particles ranging from 0.04 µm to 2,500 µm. Analyses were performed according to the methodology used by Poleto et al. (2006; 2007) and also reported in Muggler et al. (1997), Konert and Vandenberghe (1997), Buurman et al. (1997), Buurman et al. (2001), Dur et al. (2004) and Bortoluzzi and Poleto (2006). As pre-treatment (only for grain size analysis), the organic matter was removed with H_2O_2 and dispersion carried out by ultra-sound (35 W for 2 minutes).

The total concentrations of metals were determined for the street dusts using duplicates of the <63µm fraction by wet acid digestion (HCl – HF – $HClO_4$ – HNO_3) to total destruction as cited by Horowitz et al. (2001) and Poleto and Teixeira (2006). Whilst other elements were analysed, only Zn, Ni, Pb, Cr and Cu will be presented here because they are most frequently found in high concentrations in urban areas. The analysis was carried out by inductively coupled plasma spectroscopy (ICP), detection limits for which are given in Table 2. Mean background values from southern Brazilian vegetated areas (Poleto 2007) were used to compare the results (Table 2).
Table 2

2.5 Quality control

All the baskets, equipment and glassware involved in the collection procedure and the concentration of the sediments for later freezing were washed with distilled water, soaked in a 14% (v/v) nitric acid solution for 24 hours and rinsed again with deionized water. The analytical reagents and the extracting solutions used for the analyses were Merck®, which have a high degree of pureness. Water used for the dilutions was extra-pure type (Milli-Q®) since simple distilled water could contain organic complexes of metallic ions. Two reference materials (SGR-1b and SCO-1) and blank samples were used for quality control.

3 Results

3.1 Street sediments

Figure 4a, 4b and 4c show the particle size distribution of the composite street sediment samples from the 20 cities. These Figures show that the particle size distributions are bi-modal and most of the distributions have peaks at the 80 µm and at the 300 µm size points. Street sediments from most of the cities have a peak in the finer particle size fraction (ca. 80 µm), with fewer cities having second peaks at about 300 µm and just a single city (Dois Irmãos) with the coarsest peak at about 550 µm. Even the peaks were not to much similar in size for each city (Fig. 4a, 4b and 4c), it is possible to verify that the standard deviations in relation to the average are relatively small as shown in Figure 4d. The samples presented a great variation in relation to size distribution but there is an obvious peak at a diameter less than 100 µm, or of silt particle size.
Fig 4

Table 3 shows that the incidence of finer material in the street dusts was reasonably high, with all cities having a D50 of <130 µm and most cities having a D50 of <100 µm (i.e. very fine sand). The differences between the characteristics of the cities may be reflective of the granulometry of the urban sediments as a combination of complex anthropogenic environment (different particles sizes and materials, shapes, mineralogy and from various sources, e.g., anthropic and natural ones).
Table 3

3.2 Gully pot sediments

Figure 5a, 5b and 5c show the particle size distributions for the composite gully pot sediment samples from each of the 20 cities. Unlike the street sediment samples, which are typically bi-modal, the gully pot sediments tend to have one distinct peak (i.e. uni-modal), sometimes with a much smaller secondary peak. From Figure 5a, 5b and 5c, it would appear that the modal diameters of the sediment appear to be characteristic of individual cities, such that they may be split into three distinct categories as shown in Table 4. However, the city categories do not appear to have a relationship with the underlying geology (compare Tables 1 and 4) since, whilst Category 1 is all from the same lithology (Group B, basalt), only three of the eight cities underlain by basalt are represented in Category 1. Similarly, Categories 2 and 3 have a mixture of lithological types (i.e. mix of the three geology groups). The same is true for the rest of the city characteristics shown in Table 1, suggesting that perhaps anthropogenic impact (such as type and degree of urbanization) may dominate the particle size composition of the gully pot sediment.
Fig 5

Figure 5a, 5b and 5c show the modal diameter of particles in increasing order from 100, 250-300 and 550 µm. According to Wentworth (1922), Interagency Committee on Water Resources, Subcommittee on Sedimentation (1957) and cited by Mudroch and Azcue (1995), these particle diameters correspond to very fine sand, medium sand and coarse sand. In contrast to the results of particle size distribution for street sediments, the finer particle sizes are represented less and the coarser sizes are represented more so in the gully pot sediments. Those cities with larger modal diameters (i.e. 250-300 and 550 µm), also have peaks at the finer end of the scale, however, the group which is dominated by the finest modal diameter (Category 1: 100 µm) has no other, coarser peaks. Figure 5d also shows the greater variability in particle size diameters of gully pot sediments compared to street sediments, particularly between 250 and 600 µm.
Table 4

3.3 Metals in street sediments

The concentrations of metals in the street sediments (<63µm) varied between the cities (Fig. 6). In particular, Zn exhibited the greatest variation with mean of 256 µg g^{-1}, standard deviation of 128 µg g^{-1} and coefficient of variation (CV) of 50%. The other elements showed also significant variations: for instance Ni had a mean of 62 µg g^{-1}, standard deviation of 24 µg g^{-1} (CV = 39%); Pb had a mean of 52 µg g^{-1}, standard deviation of 31 µg g^{-1} (CV = 59%); Cr had a mean of 157 µg g^{-1},

standard deviation of 53 μg g^{-1} (CV = 34%) and Cu had a mean of 114 μg g^{-1}, standard deviation of 46 μg g^{-1} (CV = 41%). This greater variation between cities is given the differences in land use shown in Table 1, and they had their own distinct characteristics such as degree of industrialisation and patterns of traffic movements. However, the high concentrations of these elements (maximum values: Zn = 610 μg g^{-1}; Ni = 100 μg g^{-1}; Pb = 110 μg g^{-1}; Cr = 240 μg g^{-1}; Cu = 230 μg g^{-1}) reflected the influence of anthropogenic activities even in the less urbanised cities. The maximum value of Zn was found in Porto Alegre where the Figure 4c shows the major volume percentage of fine sediments. But the others maximum values, Ni in Taquari, Cr in Morro Reuter, and Pb and Cu in Lajeado, did not show the same situation. The minimum values for the five elements were found in Capela Santana (Zn = 110 μg g^{-1}; Cu = 43 μg g^{-1}), Viamão (Ni = 17 μg g^{-1}; Cr = 35 μg g^{-1}) and Picada Café (Pb = 16 μg g^{-1}). Picada Café and Capela Santana have the second major peaks of fine sediments in their Groups and the sediments in Viamão have the most uniform fine size distribution in its Group. For all five metals, most of the composite sediment samples representing the 20 cities had concentrations above background levels (Fig. 6), although in the case of Pb there were also several cities with values below background levels.
Fig 6

4 Discussion

Gully pot sediments have enabled the cities to be divided into three categories according to their particle size distribution, which was more variable than that collected from the streets as indicated by their standard deviations, D10, D50 and D90 (Table 3, Fig. 4d and 5d). The modal diameter of the gully pot sediments showed that they were predominantly coarser in comparison with the relatively finer street dusts. The results indicate that coarser material is preferentially retained in the gully pot and that the finer, more polluted material is likely to be carried in suspension out of the gully pot with high velocity storm flow across the impermeable road surface. Since the gully pot was originally designed to capture the coarser fraction of the urban sediment load, then the trapping of the coarser fractions in the gully pots was predictable, however, there may be potential to incorporate gully pots capable of capturing finer particles during the development of Brazilian cities. Thus, there is a big challenge that is to redesign the gully pots to make them more trap efficient and then how to clean them and dispose these contaminated sediments in adequate place.

This study has highlighted the poor quality of these sediments and whilst Charlesworth and Lees (1999) demonstrated that some heavy metal concentrations decrease through the source-transport-deposit process, possibly due to the selective onward transport of finer material, the concentrations of metals found in the sediments of the present study are of concern. Many studies are showing that fine-grained sediment fluxes (especially fine sediment delivery to rivers and sediment transport in rivers) are generally increasing throughout the world in catchments that are impacted by human activities, such as deforestation, agriculture, construction and mining activities (Wolman and Schick 1967; Trimble 1983; Dearing et al. 1987; Soutar 1989; Dedkov and Mozzherin 1992; Walling 1995; Foster and Lees 1999; Walling and Fang 2003; Owens 2005; Owens et al 2005). In his studies in the Southern Brazilian Cities, Poleto (2008) found suspended sediments with high concentrations of organic matter (5.44% [m/m]). Flocculation of cohesive materials and settling of flocs on the riverbed result in the formation of surficial fine-grained laminae (SFGL) that represent a significant potential sink for contaminants bound to cohesive sediment (Droppo and Stone 1994; Stone and Droppo 1994). Therefore, the fine sediment transport that is occurring through the urban basis to receiving water can be impacting seriously these aquatic ecosystems.

Despite the great variability (presented in section 3.3) of concentrations of metals (Zn, Ni, Pb, Cr and Cu) observed between the 20 cities, the most cases their concentrations exceeded background values (Fig. 6). Not necessarily the cities with the most volume percentages or peaks of fine sediments presented the higher concentrations of metals. It is likely that the differences in sediment particle size and geochemistry found were a combination of several factors, such as the geology, soil type, areas of active construction in each city, patterns of traffic movements, type of drainage system, makeup of the road surface and others anthropogenic activities. However these factors may also be affected by typically Brazilian structures and processes, for instance the common practice of using hard packed soil roadways which will influence erosion rates and hence the transport of PAPs and differences in the efficiency of urban cleaning and maintenance of the drainage systems which could also have influenced the results of this study.

It is perfectly clear that these fine street sediments are moving through the gully pot systems to receiving watercourses and then adding a much more important impact for aquatic ecosystems downstream. The mechanisms of sorption (adsorption/desorption) which occur between the particulate and the metals is manly influenced by the pH and the potential redox (Eh) of the aqueous system but also by different kinds of suspended matter (Poleto and Laurenti 2008). However, different aquatic environments will also present different characteristics which concern the solubility of the metals and, consequently, in relation to its geochemical or biological availability. According to the intensity of the sediment-metal association (not-available metal, potentially available metal and/or strongly available metal) the element will be available in the environment in diverse fractions (Apte and Batley 1995; Filella et al. 1995), and then to cause a bigger impact in the aquatic ecosystem.

There is therefore a clear need in cities in Brazil for further studies of urban sediments such as their speciation and mineralogy, which could improve the understanding of the characteristics of urban sediments and their potential to damage the urban aquatic environments. Such information could inform future strategies for the management of fine polluted sediment.

5 Conclusions

The main findings of this study are summarized as follows:

- Street dusts were finer and on average more homogeneous than those of gully pots, and therefore were potentially more reactive and capable of transporting more metals;
- The concentrations of Zn, Ni, Pb, Cr and Cu were high in comparison with background;
- High metal concentrations in the street sediments in combination with coarser particle sized sediments in the gully pots, indicated that the metals could be transported between the diffuse sources of pollutants found in street dusts and receiving watercourses.

6 Recommendations and perspectives

Further broader studies of urban sediments may permit better predictions of the behaviour of such sediments in relation to the pollutants they transport. This kind of information can provide the means of formulating management strategies focused on the way in which fine polluted sediment is transported in the urban environment, and in particular from the perspective of Brazilian cities.

In terms of the actual drainage system, it might be possible to design gully pots whose function it is to capture finer sediment, or, as Brazilian cities develop, to incorporate suitable sustainable urban drainage (SUDS) devices such as swales, filter strips or porous paving systems to trap and in some cases break down the pollutants (Charlesworth et al. 2003b).

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Table 1

Cities	Population	Area (km²)	HDI[1] (YEAR=2000)	per capita GDP (US$)	Principal activity
Group A - Geology: Sandstone and Basalt					
Venâncio Aires	66,898	773.2	0.793	6,673	Industrial (tobacco, tea)
Taquari	27,981	350.0	0.794	5,200	Industrial (wood)
Lajeado	67,145	90.4	0.838	8,117	Agro-industrial
Bom Retiro do sul	11,678	102.3	0.790	4,181	Agro-industrial
Estrela	29,071	184.0	0.829	6,560	Agro-industrial
Montenegro	59,606	420.0	0.833	8,257	Industrial (furniture, mechanical)
Mato Leitão	4,074	45.9	0.801	7,949	Agro-industrial
Group B - Geology: Basalt					
Novo Hamburgo	256,185	223.6	0.809	6,634	Industrial (tannery, footwear)
Ivoti	19,306	63.1	0.851	7,680	Agro-industrial
Dois Irmãos	29,253	65.2	0.812	7,575	Industrial (furniture, footwear)
Picada Café	5,059	85.1	0.819	8,205	Agro-industrial
Morro Reuter	5,551	88.1	0.834	5,104	Residential
Nova Petrópolis	19,136	291.1	0.847	5,694	Industrial (footwear, textile)
Portão	29,302	159.9	0.831	9,005	Industrial (tannery)
Estância Velha	40,531	52.4	0.808	5,781	Industrial (tannery, footwear)
Group C - Geology: Granite					
Viamão	260,133	1,494.3	0.808	2,356	Agro-industrial
Porto Alegre	1,420,667	497.0	0.865	8,901	Industrial (several)
Capela de Santana	11,413	184.0	0.764	2,704	Agro-industrial
Guaíba	97,677	377.0	0.815	5,045	Industrial (paper)
Eldorado do Sul	33,747	509.7	0.803	10,291	Residential

[1] HDI - Human Development Index (0 and 1.0): 0 = undeveloped; 1 = developed.

Table 2

	Zn	Ni	Pb	Cr	Cu
ICP-AES detection limits for sediment	3.0	0.2	2.0	0.4	0.4
Background	47.45	4.89	3.13	15.63	11.61

Table 3

Cities	Street dusts				Gully pot sediments			
	D10	D50	D90	D50 Class	D10	D50	D90	D50 Class
Group A - Geology: Sandstone and basalt								
Venâncio Aires	37.0	95.0	232.0	Very fine sand	1.5	23.1	65.7	Coarse silt
Taquari	13.0	117.0	249.0	Very fine sand	44.3	216.7	347.8	Fine sand
Lajeado	19.0	100.0	247.0	Very fine sand	40.0	180.2	325.6	Fine sand
Bom Retiro do Sul	25.0	87.0	243.0	Very fine sand	8.1	218.6	536.5	Fine sand
Estrela	46.0	97.0	200.0	Very fine sand	3.1	90.9	277.8	Very fine sand
Montenegro	31.0	96.0	247.0	Very fine sand	16.0	228.4	377.0	Fine sand
Mato leitão	6.5	55.0	202.0	Coarse silt	3.4	52.4	238.5	Coarse silt
Group B - Geology: Basalt								
Novo Hamburgo	32.0	82.0	180.0	Very fine sand	58.4	216.4	359.5	Fine sand
Ivoti	14.0	115.0	246.0	Very fine sand	2.1	21.8	60.9	Coarse silt
Dois Irmãos	7.0	57.0	450.0	Coarse silt	4.7	139.9	356.3	Fine sand
Picada Café	19.0	85.0	205.0	Very fine sand	13.7	130.3	313.6	Fine sand
Morro Reuter	30.0	122.0	248.0	Very fine sand	2.1	20.8	57.1	Coarse silt
Nova Petrópolis	8.5	71.0	190.0	Very fine sand	4.7	63.3	301.1	Very fine sand
Portão	14.0	77.0	225.0	Very fine sand	15.0	157.0	293.9	Fine sand
Estância Velha	6.5	28.0	188.0	Coarse silt	79.2	236.4	375.3	Fine sand
Group C - Geology: Granite								
Viamão	3.0	26.0	76.0	Coarse silt	2.4	31.4	76.9	Coarse silt
Porto Alegre	14.0	77.0	225.0	Very fine sand	47.9	219.6	359.3	Fine sand
Capela de Santana	27.0	92.0	243.0	Very fine sand	101.7	321.6	555.8	Medium sand
Guaíba	17.0	112.0	247.0	Very fine sand	96.4	410.7	628.8	Medium sand
Eldorado do Sul	25.0	91.0	210.0	Very fine sand	17.2	219.2	373.3	Fine sand

Table 4

Category 1	Category 2	Category 3
Nova Petrópolis, Dois Irmãos, Picada Café	Venâncio Aires, Morro Reuter, Viamão, Taquari, Eldorado do Sul, Mato Leitão, Estância Velha, Porto Alegre, Portão, Lajeado, Ivoti, Estrela, Montenegro, Novo Hamburgo	Guaíba, Capela de Santana, Bom Retiro do Sul

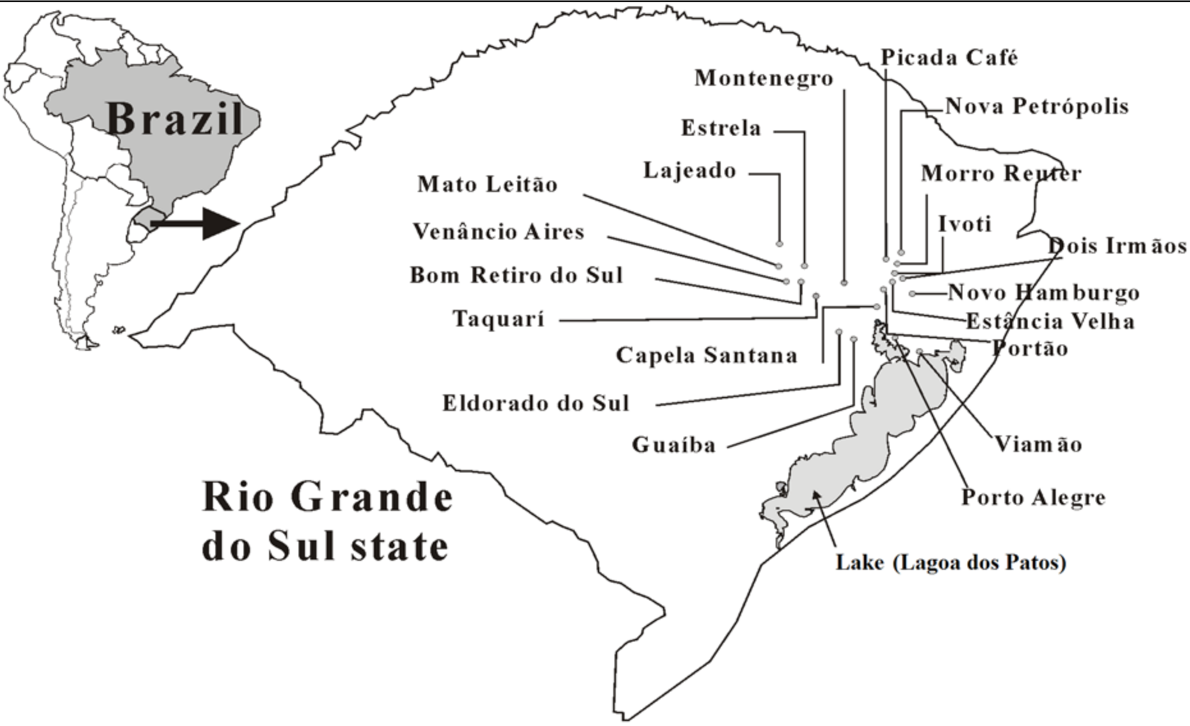

Figure 1

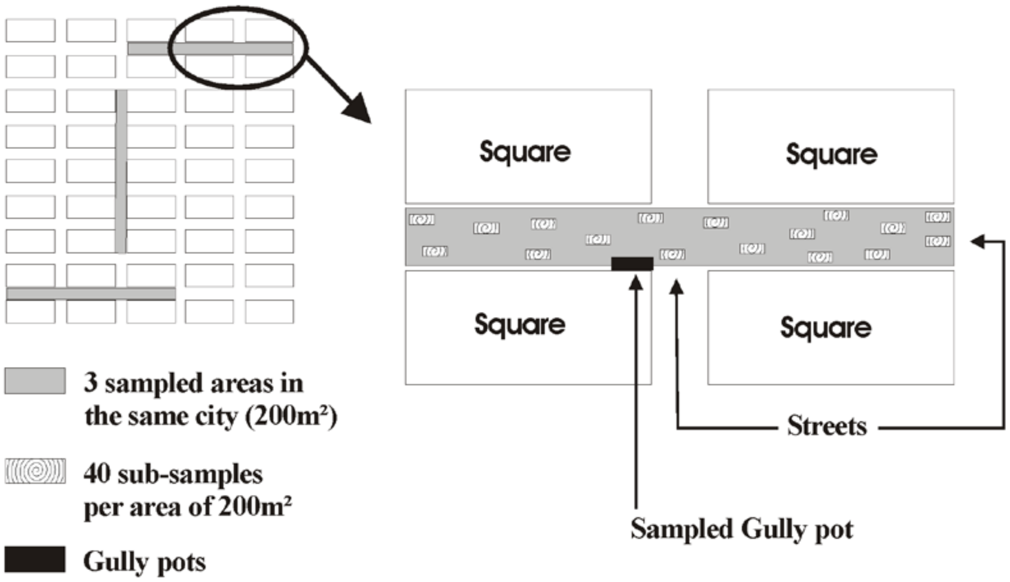

Figure 2

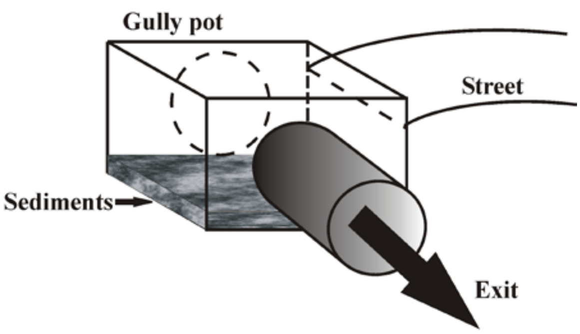

Figure 3

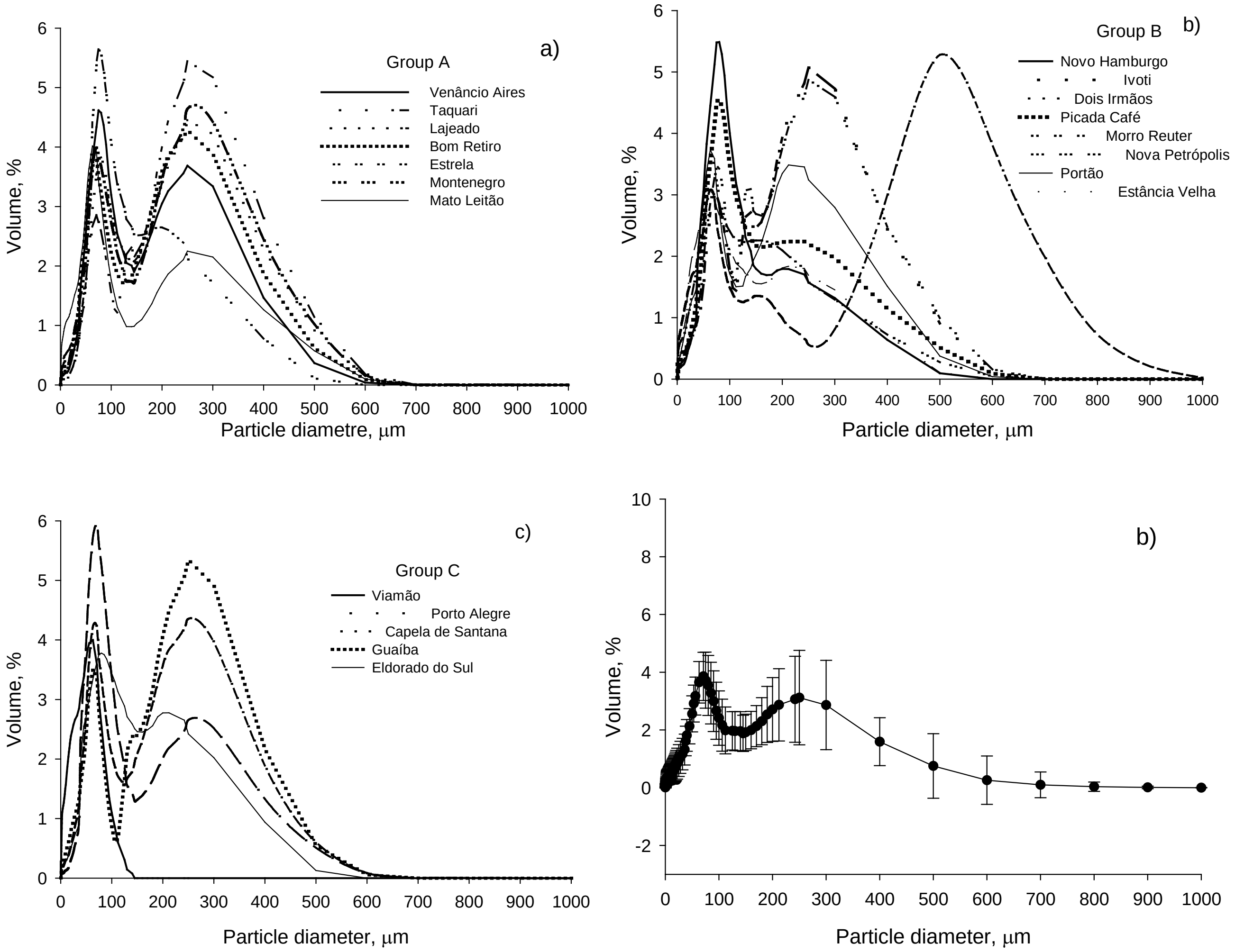
a)
Group A
Venâncio Aires
Taquari
Lajeado
Bom Retiro
Estrela
Montenegro
Mato Leitão
Volume, %
Particle diametre, µm
b)
Group B
Novo Hamburgo
Ivoti
Dois Irmãos
Picada Café
Morro Reuter
Nova Petrópolis
Portão
Estância Velha
Volume, %
Particle diameter, µm
c)
Group C
Viamão
Porto Alegre
Capela de Santana
Guaíba
Eldorado do Sul
Volume, %
Particle diameter, µm
b)
Volume, %
Particle diameter, µm

Figure 4

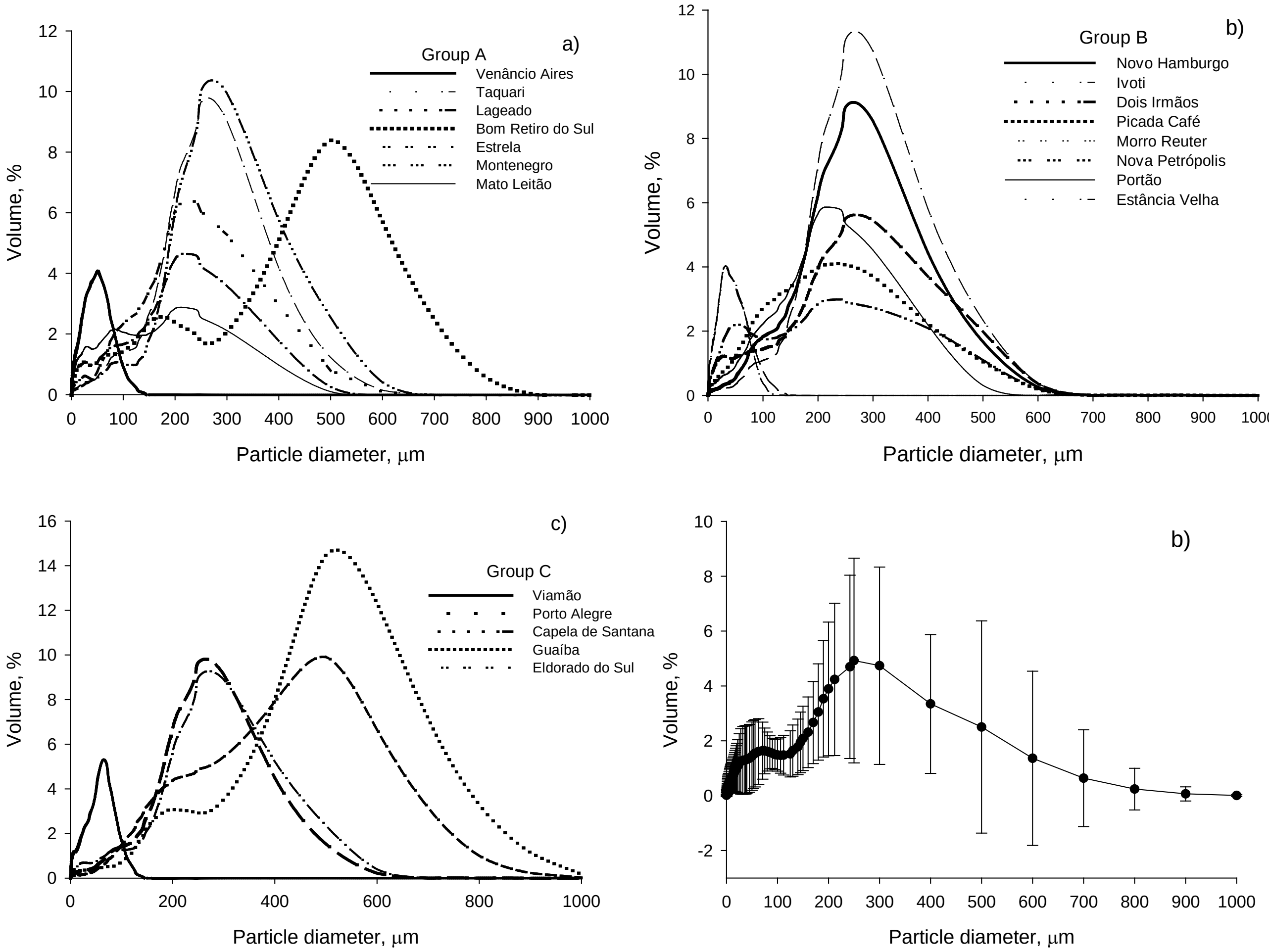

Figure 5

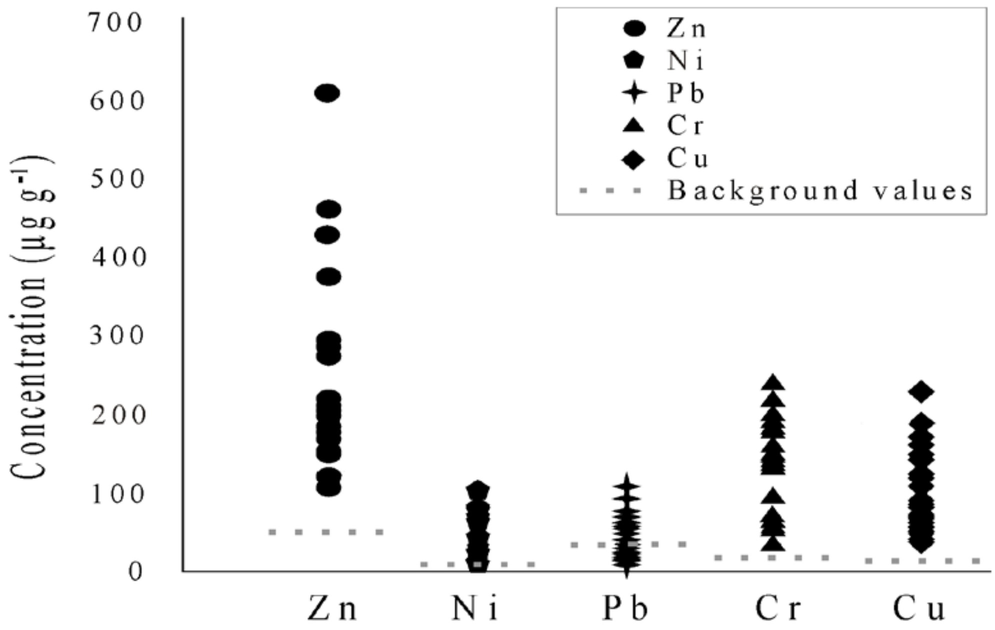

Figure 6