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Can the contamination of urban street sediment be used as an indicator for traffic density? A case-study in the city of Leuven, Belgium.

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Abstract

The concentration, in urban street sediment, of 13 chemical elements was measured in the city of Leuven, Belgium. A total of 77 locations were sampled in pedestrian zones, streets with limited traffic, streets with much traffic, and on the ring road that has very busy traffic. The data were compared to NO_2 concentrations measured by the CurieuzeNeuzen-Vlaanderen project, a large-scale study with 20,000 sampling points all over Flanders (the northern part of Belgium). NO_2 is a frequently used indicator for traffic pollution. In Leuven the highest enrichment (strongest pollution) was measured for Cu, Sb, Pb and Zn. These elements could be related to brake wear and tire wear, respectively. For Cu and Zn the concentrations in Leuven exceed those in most of the other cities investigated in the literature. Moderate enrichment was measured for Cd, Cr, Ni and S. The other elements (As, Co, Fe, Mn and V) showed concentrations close to the background value in unpolluted soil. The Integrated Pollution Index (IPI) for Leuven is 8.15, which, according to criteria proposed by the literature on street sediment, classifies Leuven, on average over its surface area, as a "very highly polluted" city. As expected, for Cu and Sb the highest contamination is found on the ring road and the busy traffic circulation loops. For Zn and Pb, on the other hand, the highest contamination occurs in the city center, in the pedestrian zone where no traffic is allowed except for buses and taxis. We hypothesize that this is a result of historic accumulation of these elements at the time traffic was still allowed in this zone. In Leuven the chemical composition of street sediment did not correlate to the NO_2 concentrations.. This study shows that measurements of current pollution by traffic are not sufficient to determine the health risk because much exposure to toxic substances may be caused by resuspension, by traffic or wind, of substances that have accumulated in the city over time, sometimes decades ago, when regulations were much less stringent then today.

Key words: street sediment, dust, heavy metals, pollution, traffic

Highlights

- A total of 13 chemical elements were measured in urban street samples
- Strongest pollution can occur in dense traffic or in traffic-free pedestrian zones
- Pedestrian zones can be heavily polluted by historic accumulation of contaminants
- Pollution of urban street sediment was not found a good indicator for traffic density

1. Introduction

Cities are important sources of dust production. Two types of dust are produced in cities: (1) gases and particles produced by combustion processes, and (2) mineral particles (Lu et al., 2009; Al-Awadhi and Aldhafiri, 2016). The first group includes vehicle exhaust and other combustion gases such as carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO_2) and volatile organic compounds (VOCs), and fine solid particles produced during combustion such as diesel soot. The second group consists of mineral particles originating from street works, building and infrastructural works, parks, vacant lots vulnerable to wind or water erosion, and similar sources. These mineral particles are much coarser than combustion dust. At roadside locations, most traffic exhaust particles are 10-30 nm in diameter (Gidhagen et al., 2004) whereas the mineral particles are often coarser than 100 µm and can sometimes even be coarser than 2 mm (El-Hasan et al., 2006). The term “street dust”, which is abundantly used in the literature, is somewhat misleading because in most studies it is applied to any size of loose mineral particles on the road or sidewalk. Dynamically, dust refers to particles smaller than approximately 60 µm in diameter, which are usually transported in true suspension (Pye and Tsoar, 1990). This study uses the term street (or road) sediment to describe the loose mineral particles on the road surface.

If not too coarse, both combustion-generated dust and mineral particles are easily resuspended by traffic (Amato et al., 2011). In contrast to combustion dust, which can easily be evacuated by wind due to its very small size (but which is continuously re-produced by traffic or other human activities), the coarser mineral particles will settle rather quickly and may remain in the city for a long time. Mineral road sediment has been identified as one of the most significant sources of fugitive dust in cities. In Stockholm, road sediment was found to account for up to 90% of PM10 in the city during winter (Meister et al., 2012). In Berlin, about 45% of the local traffic contributions to roadside PM10 concentrations were due to suspended soil material, the remaining 55% being the result of vehicle exhaust and tire abrasion (Lenshow et al., 2001). Other studies also concluded that in cities, the importance of the non-exhaust emissions is comparable to, or even higher than that of emissions from vehicle exhaust systems (for a detailed literature review, see Amato et al., 2011).

As outlined above, street sediment originates from a variety of sources, among which road works, infrastructural works, building constructions, and vacant lots are the most prominent visible examples. However, degradation of pavements, especially asphalt concrete, is also an important source of street sediment as asphalt concrete usually contains, besides gravel fragments and bitumen, also finer sand and/or silt-sized sediment. A similar less visible source is sand used to fill the space between sidewalk tiles. Sand and dust washed from cars and their tires are other sources of street sediment. Once on the road, all these sediments become polluted by heavy metals originating mainly from car tires, brakes, and engines (Kupiainen et al., 2011). Loose sediment on streets and sidewalks, and in the gutter, is usually substantially enriched in heavy metals.

The sampling and analysis (especially chemically) of street, gutter and sidewalk sediment is not new. Analysis of street sediment has been performed for decades although most studies were carried out after the year 2000. Reviews and lists of studies can be found in, among others, the works by Garnaud (1999), Bris et al. (1999), Tamrakar and Shakya (2011), Shabbaj et al. (2018) and Zglobicki et al. (2018). Detailed samplings of an entire city are very rare however. The sampled cities are usually metropoles, and too large for a detailed sampling (e.g. Paris: Bris et al., 1999; Kathmandu: Tamrakar and Shakya, 2011; Mersin: Arslan and Gizir, 2006; Jeddah: Shabbaj et al., 2018; and many more), or the aim of the study is to compare cities by sampling a limited number of strategic locations (e.g. Amato et al., 2011; Wang et al., 1998; and others). Zhang et al. (2014) performed a sampling of a large part of the city of Xi'an, but their samples included, besides road sediment, also building construction dust, cement samples (from construction sites) and fresh soil sediment collected during excavations at construction sites. Deocampo et al. (2012) sampled two portions of the city of Atlanta, but studied only the distribution of lead; not of other heavy metals.

This study describes the analysis of street sediment in the city of Leuven, Belgium. The whole historic (medieval) city was sampled in detail. This was possible because its surface area is rather small. The city center forms an almost perfect circle with a diameter of only 2.4 km (Fig. 1). Its surface area is only 4.5 km^2. In addition, the city has many streets because of it medieval origin. There is considerable variation in traffic density: there are pedestrian zones, streets with limited traffic, streets with much traffic, and the ring road forming the border of the city has very intense traffic. Clear differences in pollution of street sediment can therefore be expected over the city because traffic has been determined to be the most important factor causing pollution of street sediment (Robra, 2010).

A total of 77 locations were sampled, distributed over the whole city. We only sampled the central (medieval) city itself, without the suburbs of Heverlee, Kessel-Lo and Wilsele. This article describes and discusses the results for a large number of heavy metals, reconstructs the origin of the polluting elements, and investigates the relationship between traffic density and the degree of pollution of the road sediment. A health risk analysis was also performed, but these results will be presented in a separate study.

2. Procedure

2.1 Sampling

Leuven is a historic, early medieval city. The road pattern is therefore typical radial-concentric, with an almost perfectly circular ring road following the trajectory of the second medieval city wall (14th century). Several streets in the center also follow the trajectory of the first city wall (12th century). The large number of streets on a limited surface, and the great variation in traffic density, make the town an ideal place for a detailed sampling. Currently there is no more heavy industry in Leuven or its surroundings. Landuse near the city mainly consists, apart from rural land, of private habitation, research buildings and tertiary sector shops. The only industrial complex is a brewery but it does not release heavy metals into the atmosphere. This means that traffic is the major factor causing pollution of road sediment in the city. Renovation works are currently being carried out in several parts of the town, but these do not release heavy metals although they locally result in denser heavy traffic. Leuven has about 30,000 permanent inhabitants in the central town itself plus another 60,000 inhabitants in the suburbs of Heverlee, Kessel-Lo and Wilsele-Dorp. From late September to early July an additional 40,000 students live in the agglomeration, many of them in the medieval city center itself.

A total of 77 locations were sampled (Fig. 1). When selecting the sampling sites we made sure to cover the whole city center and to include both pedestrian zones, streets with little traffic, streets with much traffic and streets with very busy traffic. We also made sure to include enough (and a comparable amount of) sampling locations for each of these four traffic classes. We avoided sampling large open spaces such as parks and squares because in these areas there is more wind and the local pollution source is less easy to determine, which makes it difficult to investigate a possible correlation between traffic emissions and the pollution of street sediment. . We also opted for sampling the road surface itself and not the gutter or the sidewalk. We avoided sampling the gutter because it serves as a transport channel for water and sediment washed away upstream, sometimes far away from the sampling area. This is especially important in the western part of Leuven, where the city has been built on the western slope of the Dijle valley and where many steep slopes and roads occur. We also opted for not sampling the sidewalk because previous studies have shown that the sediment on sidewalks is often quite coarse (substantially coarser than on the road itself, see for example Artières, 1987) and also because the sidewalk is located farther away from the traffic than the road surface itself, resulting in less resuspension of loose sediment on it compared to the road surface.

Road sediment was collected using a plastic brush and a plastic dustpan, similar to most road dust studies (Yongming et al., 2006; Shabbaj et al., 2018; Zglobicki et al., 2018). We recognize that this can result in a loss of some fine dust (Amato et al., 2011). However, the goal of this study was not to determine the absolute amount of sediment on the roads, as this can vary greatly over even short distances (see, for example, Deocampo et al., 2012). For optimal sampling, collecting the sediment by dry vacuuming (e.g. Butler et al., 1992; Amato et al., 2011) or wet vacuuming (e.g. Bris et al., 1999) is recommended. We had no permission in this study to use these techniques in the streets of Leuven.

Sweeping was performed at about 1 m from the sidewalk. This can be considered the area where most car tires are in contact with the street surface and, thus, where most street dust contamination can be expected to occur. Both sides of the road were sampled, each over a length of 10 m. After each sampling the brush and dustpan were carefully cleaned to avoid cross-contamination of the samples. Before sampling, possible street sweep actions by city services were carefully checked on each sampling location because comparing cleaned with uncleaned streets will give an incorrect picture of the spatial distribution of the contamination, and there is also a risk of cross-contamination.

After collection, the sediment was stored in clean, closed plastic bags. Samplings were carried out in the first week of July 2018, after a 3-week long dry spell.

2.2 Sediment analysis

2.2.1 Grain size

There is inconsistency in the literature with regard to the size of sediment analyzed in street sediment studies. Very different size fractions have been used, varying from very fine (<10 µm, for example Amato et al., 2011) to very coarse (<2 mm, for example El-Hasan et al., 2006). Because the concentration of heavy metals may substantially vary with particle size (Sutherland et al., 2012) direct comparisons between studies are often very difficult. In this study we opted for analyzing the fraction <60 µm for several reasons. First, these particles are easily (re)suspended and may remain airborne for long time periods (Shilton et al., 2005; Soltani et al., 2015). Second, heavy metal concentrations generally decrease with increasing particle size (Fergusson and Ryan, 1984; Sutherland et al., 2012). Third, small particles have been proven to cause the largest threat to human health (Zhou et al., 2003; Liu et al., 2014). As a consequence many studies on street sediment focus on the particles smaller than 63 µm (Saeedi et al., 2012; Shabbaj et al., 2018). Sieving was done in two steps: the collected sediment was first sieved at 125 µm to remove impurities such as leaves, branches, rocks, glass, etc.; then the remaining sediment was sieved at 60 µm. Plastic sieves were used to avoid any contamination of the samples.

2.2.2 Geochemical analysis

For each sample a total of 100 mg was transferred to a glass tube and 1 ml of 65% HNO_3 solution was added, followed by 3 ml of 37% HCl solution. The samples were left to dissolve for one night. The next day the tubes were heated on a hot plate for 3 hours to ensure all metals were fully dissolved. The plate was first heated to 90 °C; after 30 min the temperature was increased to 120 °C, and then the temperature was increased by 20 °C every 30 min ending with a 30-min period at 200 °C. The tubes were then left to cool down, after which the solutions were diluted to 20 ml with ultrapure Milli-Q water. The tubes were then thoroughly shaken to ensure a homogeneous solution. Samples were then left to allow for settling of the insoluble particles. Finally 7 ml of the solution was transferred to small plastic flasks using a pipette. Flasks were stored in a fridge until analysis.

Inductively coupled plasma-optical emission spectrometry (ICP-OES) was used to determine the concentration of the following elements: As, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, S, Sb, V, and Zn. The instrument used was a Agilent Varian 720 ES analyzer with a detection limit varying between 1 and 100 ppb (Agilent, 2012). For quality control and assessment each batch of samples also contained two reagent blank samples, two reference materials, and at least two duplicates for each sample. BCR-143R (Sewage sludge amended soil) and QCM-31 standard material were used as standard reference materials.

2.3 Quantification of pollution

Several indices have been used in the literature to quantify the pollution of urban street sediment. The most frequently used ones are the Enrichment Factor (EF), the Geoaccumulation Index (Igeo), and the Pollution Index (PI). They are also used in the present study.

Enrichment Factor (*EF*)

This factor compares the concentration of a heavy metal in the street sediment sample to the background value in local unpolluted soil (Yongming et al., 2006; Saeedi et al., 2012). It is defined as $EF = \frac{C/C_{ref}}{B/B_{ref}}$, where C and C_{ref} are the measured concentrations of the heavy metal and a reference element in the street sample and B and B_{ref} the concentrations of the heavy metal and the reference element in local unpolluted soil. In this study Mn was used as the reference element since its concentration in the street sediment was close to the background value in the local soil. Mn has also been used as a reference element in other studies (Saeedi et al., 2012).

Geoaccumulation Index (I_{geo})

This index, introduced by Müller (1969), compares heavy metal concentrations in urban soils to background concentrations in local unpolluted soils. It is defined as $I_{geo} = log_2\ (C/1.5B)$, where C is the measured concentration in the street sample and B the background value in the unpolluted soil. The factor 1.5 minimizes the effect of possible variations in the background value (Sutherland, 2000).

Pollution Index (PI)

This index, defined as $PI = C/B$ (Lu et al., 2009), is the ratio of the heavy metal concentration in street sediment (C) to the background value in unpolluted soil (B). To assess the integrated pollution level of all heavy metals present in street sediment the Integrated Pollution Index (IPI) can be used: $IPI = (PI_1 + PI_2 + PI_3 + \cdots + PI_n)/n$, where $PI_1$is the Pollution Index for heavy metal 1, PI_2 the Pollution Index for heavy metal 2, etc. and n is the number of heavy metals considered.

Table 1 shows the degree of pollution for each of the contamination indices used.

3. Results

3.*1 Elemental concentrations*

Table 2 gives an overview of the statistics for the 13 chemical elements analyzed in Leuven. Recall that 77 locations were sampled in total. Background values for Flanders (last column on the right) are from Tariku et al. (2005) and Tariku et al. (2006). For Co, Fe, Mn, S, Sb and V no data were provided by these authors; for these elements background values for European soils (Salminen et al., 2006) were used. The table shows that substantially elevated concentrations occur in the street sediment in Leuven for several elements, although comparable concentrations have been measured in other cities (Table 3). Note that to eliminate the effect of particle size, only studies that investigated a similar particle size fraction as in Leuven are shown in Table 3. No data are given in the table for As, S and Sb since many street sediment studies do not consider these elements.

Table 4 shows that, in Leuven, highest enrichment (strongest pollution) was measured for Cu, Sb, Pb and Zn. For Cu and Zn the concentrations in Leuven clearly exceed those in most of the other cities in Table 3. Moderate enrichment was measured for Cd, Cr, Ni and S. The other elements (As, Co, Fe, Mn and V) showed concentrations close to the background value in unpolluted soil. The Integrated Pollution Index (IPI) for Leuven is 8.15, which classifies Leuven, on average over its surface area, as a "very highly polluted" city (Table 1).

3.2 Multivariate analysis

Principal Component Analysis (PCA) and Cluster Analysis (CA) were used to group the elements in distinct classes based on their intensity of contamination. Fig. 2 shows the PCA loadings in a 3D-plot, for all 13 elements analyzed in this study. A total of 4 groups can be selected: S, Co, Mn and V (group 1), As and Fe (group 2), Pb, Ni, Zn and Cd (group 3; note that Cd is located somewhat eccentric in this group), and Sb, Cu and Cr (group 4). Cluster analysis based on Ward's (1963) clustering method allows to separate Cd from group 3 so that 5 groups were finally retained, as shown in Fig. 3.

3.3 Source identification

Heavy metals that belong to a same group (as defined before) can be expected to have a similar source. The lowest degree of contamination was found for S, Co, Mn and V (group 1) and As and Fe (group 2). Analysis of the pollution indices for these elements (Table 4) shows that the concentration of these elements in Leuven street sediment is similar to the concentration in uncontaminated soil, which suggests that their source is natural soil. The elements in groups 3, 4 and 5, on the other hand, are clearly enriched, suggesting that these elements can be associated with one or more types of vehicle traffic emissions (Sutherland, 2000; Sternbeck et al., 2002; Duong and Lee, 2011). For Cd (group 5), likely sources are combustion engines and motor oils (Sutherland, 2000). Brake wear is a major pathway for Cu and Sb emissions (Sternbeck et al., 2002; Adachi and Tainosho, 2004; Lijima et al., 2007); therefore group 4 (Cu, Sb and Cr) is likely associated with brake wear. Zn and Pb are often associated with tire wear (Apeagyei et al., 2011; Duong and Lee, 2011; Sutherland, 2000); therefore tire wear is a likely source for the enhanced concentration of the elements of group 3 (Zn, Pb and Ni). Pb has also been related to historic contamination caused by leaded gasoline (De Miguel et al., 1997; Charlesworth et al., 2003) but leaded gasoline has already been forbidden in Belgium since the year 2000.

A schematic overview of these potential sources is shown in Fig. 3. One should realize that pinpointing one particular source for each group is difficult as street sediment can be (and usually is) contaminated by a variety of processes; but the distinction between the natural and anthropogenic sources (groups 1 and 2 versus groups 3, 4 and 5) is obvious from the data collected.

3.4 Spatial distribution

The spatial distribution of pollution for the most enriched elements (Cu, Sb, Pb and Zn) is shown in Fig. 4. For Cu and Sb the highest contamination is found on the ring road and the busy traffic circulation loops. This could be expected since Cu and Sb are associated with brake wear. For Zn and Pb, however, the highest contamination occurs in the city center, in the pedestrian zone where no traffic is allowed except for buses and taxis. One would expect that for these elements, which are most likely associated with tire wear, concentrations would be highest where the traffic volume is also highest, such as on the ring road. A possible explanation is that the current pattern still reflects the historic accumulation of these elements at the time traffic was still allowed in the current pedestrian zones. Many streets in these zones are quite narrow and behave like street canyons, hampering the evacuation of pollution. Several of them are also covered with cobblestones and the space between the stones is filled with soil material; it could thus be that these surfaces still contain much more historic contamination than other streets with more (and faster) traffic where the surface material is more likely to be moved or resuspended by traffic movements.

4. Discussion

The spatial pollution pattern for especially Zn and Pb shows that the strongest pollution of urban street sediment does not necessarily occur in the zones with the highest traffic density. The question can therefore be asked whether or not the contamination of urban street can be considered a reliable tool to quantify the current trafic density and reverse. As suggested by Fig. 4, the role of historic pollution should not be neglected and could even become dominant.

To additionally test the hypothesis that the unexpected preferential concentration of Zn and Pb in the pedestrian area is a result of historic accumulation we compared the concentrations with information on the current traffic density and pollution. For the latter we used data collected by the project CurieuzeNeuzen Vlaanderen (De Craemer et al., 2020; Weichenthal et al., 2020). In that project, airborne NO_2 concentrations were measured at 20,000 locations all over Flanders (the northern part of Belgium). NO_2 is a very good proxy to quantify traffic pollution (Vlaamse Milieumaatschappij, 2017). Road transport is the largest contributor to NO_x (NO and NO_2) pollution, ahead of the energy, commercial, institutional and household sectors (Degraeuwe et al., 2019). The CurieuzeNeuzen field campaign took place from April 28, 2018 to May 26, 2018, very close to the period where the Leuven street sediment samples were collected. Technical information on the CurieuzeNeuzen project and the analysis methods used can be found in Meysman et al. (submitted). In the area where our street samples were collected, NO_2 was measured at a total of 114 locations. Several of these coincided with places where our street sediment samples were collected. Others did not because of logistic or other reasons. For the latter spots we estimated the NO_2 concentrations based on the data of neighboring measuring points, in the same (where possible) or in comparable adjacent streets, and a careful check of the local traffic intensity during field observations. In 8% of the cases the samplings for street sediment and NO_2 could be performed at exactly the same place, and in 53% of the cases the points were less than 100 m from each other, many of them even less than 50 m. The average distance between a sediment sampling point and the corresponding NO_2 sampling point was 116 m. For several neighborhoods we could also use information collected by the projects Straatvinken (http://www.straatvinken.be) and Straten Vol Leuven (http://stratenvolleuven.be). Straatvinken counts traffic movements in Leuven, and Straten Vol Leuven performed measurements of black carbon emitted by traffic in the city and some of its suburbs.

If our hypothesis that the unexpected high concentrations of Zn and Pb in the pedestrian area results from historic accumulation is correct, then no correlation should be seen between the Zn and Pb concentrations and the NO_2 concentrations since both are mainly produced by traffic. To make the analysis more complete and check whether the chemical composition of urban street sediment can be considered a good indicator for traffic density at all we extended the analysis to Cu and Sb, which are produced by car brakes, and to Cd, which occurs in car exhaust and in motor oil.

The correlations are shown in Fig. 5. The IPI values in the graphs are for the combination of the metals in question (Cu and Sb, Zn and Pb, and Cd). For the three types of car pollution we checked the correlations for the entire city center and for the pedestrian and car-allowed area separately. Out of these nine tests, seven did not show any correlation (slope of the regression line not significantly different from zero). The two remaining cases are (1) brake pollution, all areas (significant at the 0.05 level but not at the 0.01 level), and (2) combustion / motor oil pollution in the pedestrian area (significant at the 0.01 level). The latter relationship may look a little strange since we are talking of the pedestrian area, but recall that in Leuven buses and taxis are still allowed in this zone. We conclude that the preferential concentration of Zn and Pb in the pedestrian zone of the city of Leuven is not related to the current traffic, and because there are no other important sources for these two elements (there are, and have been, no Zn or Pb related industries or manufacturing activities in what is now the pedestrian zone in Leuven) the preferential concentration in the pedestrian zone can only be the result of historic accumulation of these elements at times where cars were still allowed in this zone.

5. Conclusions

The results show that, at least for the city of Leuven, both the spatial and the quantitative pollution patterns of street sediment generally did not match with the pattern of NO_2 concentration. Since it is well known that in sediments the concentrations of chemical elements are the highest in the finest particle fractions and our study considered the fraction <60 µm, which is the finest fraction in street sediment, we consider it likely that our conclusions will also apply to other cities worldwide although explicit confirmation by future studies will be necessary.

In Leuven the highest enrichment (strongest pollution) was measured for Cu, Sb, Pb and Zn. For Cu and Zn the concentrations in Leuven exceed those in most of the other cities investigated in the literature. Moderate enrichment was measured for Cd, Cr, Ni and S. The other elements (As, Co, Fe, Mn and V) showed concentrations close to the background value in unpolluted soil. The Integrated Pollution Index (IPI) for Leuven is 8.15, which, according to the criteria proposed by Wan et al. (2016a) and Chen et al. (2005), classifies Leuven, on average over its surface area, as a "very highly polluted" city.

For Cu and Sb the highest contamination is found on the ring road and the busy traffic circulation loops. For Zn and Pb the highest contamination occurs in the city center, in the pedestrian zone where no traffic is allowed except for buses and taxis. We hypothesize that this is a result of historic accumulation of these elements at the time traffic was still allowed in this zone. Many streets in this zone are quite narrow and behave like street canyons, hampering the evacuation of pollution. Several of them are also covered with cobblestones and the space between the stones is filled with soil material; it could thus be that these surfaces still contain much more historic contamination than other streets with more (and faster) traffic where the surface material is more likely to be moved or resuspended by traffic movements.

This study shows that measurements of current pollution by traffic are not sufficient to determine the health risk because much exposure to toxic substances may be caused by resuspension, by traffic or by wind, of substances that have accumulated in the city over time, sometimes decades ago, when regulations were much less stringent then today. Adequate environmental management should consider such aspects.

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Credit Author Statement

Gunnar Bergman: Methodology, Formal Analysis, Investigation, Writing

Dirk Goossens: Conceptualization, Methodology, Formal Analysis, Investigation, Writing, Supervision

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Figure captions

Fig. 1: City of Leuven with location of the 77 sampling sites. The suburbs of Heverlee, Kessel-Lo and Wilsele-Dorp were not sampled and are therefore not shown.

Fig. 2: 3D plot of PCA loadings, for the 13 chemical elements investigated

Fig. 3: Cluster dendrogram using Ward's (1963) hierarchical clustering method, for the 13 chemical elements investigated. The 5 identified groups are indicated by the colored boxes; the most likely source for each group appears below each box. Height in the ordinate is a measure for the dissimilarity between clusters, calculated by minimizing the within-cluster error sum of squares.

Fig. 4: Spatial distribution of the enrichment factor for Cu, Sb, Zn and Pb

Fig. 5: Relationship between airborne NO_2 concentration and the concentration of the analyzed chemical elements that can be related to traffic. NO_2 data are from the CurieuzeNeuzen Vlaanderen project, Universiteit Antwerpen.

Table captions

Table 1: Contamination indices used in this study

Table 2: Elemental concentrations (mg/kg) in the street sediment in Leuven

Table 3: Average elemental concentrations (mg/kg) in street sediment of different cities around the world. Only studies that investigated a similar particle size (PS) to that analyzed in Leuven are shown. Numbers in italic are the standard deviations for the Leuven data.

Table 4: Mean values for Leuven of the contamination indices used in this study. Numbers in italic are the standard deviations.