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Metals and PAHs adsorbed to street particles

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Abstract

Particles were collected from 18 different city streets adjacent to five different landuses in the City of Santa Monica, California. Landuses were classified as industrial, roads, multifamily residential, commercial and single family residential. Particles were collected using a vacuum cleaner with a 0.1-μm filter and a rotating brush head. Particles were first sized into six fractions from 43–2200 μm using two sets of sieves. Representative samples of the four size fractions smaller than 841 μm from each landuse were separately digested to extract metals and polynuclear aromatic hydrocarbons (PAHs). Smaller particles had higher solid-phase concentrations, but not as high as the ratios of their specific surface areas, assuming spherical shape. Relative PAHs concentrations were higher on small particles than were metal concentrations. Single-family residential areas were the lowest in metals and PAHs, with only a few exceptions. The greatest mass of pollutants was associated with the particles in the 100–250 μm range.

Keywords: Stormwater; Heavy metals; PAHs; Street; Particles

Introduction

It has long been known that certain pollutants in stormwater, such as polynuclear aromatic hydrocarbons (PAHs) and many metals, tend to partition onto the solid phase. As a result, solid-phase concentrations are often much higher than liquid-phase or soluble concentrations. Best management practices (BMPs) are frequently selected to remove suspended solids in stormwater, in the hope that other more harmful pollutants are removed. This is based upon the assumption that insuring particle removal also insures removal of heavy metals and hydrocarbons. Unfortunately, there are only a few studies that document the concentration of pollutants on particles as a function of size (Viklander, 1998; Liebens, 2001), and even fewer show pollutants as a function of land use (Liebens, 2001; Lee et al., 2002). In order to better define this relationship, and to justify expenditures on BMPs, a study of particle-phase metals and PAHs was conducted.

The study was performed as one part of a series of ongoing, larger investigations funded by the Santa Monica Bay Restoration Project (SMBRP) (Stenstrom and Strecker, 1993; Wong et al., 1997). The SMBRP was one of a number of projects in the US National Estuary Program. A high priority of the SMBRP was to develop methods and assist local governments in reducing stormwater pollutants to the Bay. The completion of secondary treatment at two major wastewater treatment plants (Hyperion, operated by the City of Los Angeles, and the Joint Water Pollution Control Facility, operated by the County Sanitation Districts of Los Angeles County; each about $1.5 \times 10^6\,m^3$/day) reduced many pollutants to levels below that contributed by nonpoint

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sources (Wong et al., 1997). Therefore, future improvements in Bay water quality for many pollutants are more likely to occur through stormwater pollution reduction than enhancements to secondary treatment plants.

Most cities that are in the Santa Monica Bay watershed practice some type of street sweeping. The frequency of sweeping varies with location and landuse, but is usually no more than once per week. Street sweepers play an important role in removing litter and debris, but are less efficient in removing fine particulates. Sartor and Boyd (1972) reported removal efficiencies of less than 50% for particles between 63 and 600 μm (1 μm = 10^{-6} m). Pitt (1979) identified the need for improved sweeping technologies, and suggested improvements based upon assumed particulate-phase pollutant concentrations. German and Svensson (2002) measured metals in sweep sediments and reported that the 125–250 μm fraction was highest in metal masses. Sutherland (2003) and Birch and Scollen (2003) have both reported the highest mass of metals in the less than 62 μm fraction, which suggests that existing sweeping technologies cannot remove particles with the greatest metal concentrations. Newer technologies are reported to have much higher efficiency (Alter, 1995) and may be useful BMPs for stormwater pollutant control.

The objective of this study was to determine the mass of particles that exist on urban streets and the mass of metals and PAHs associated with different size fractions. The results will assist cities and others who are evaluating the potential of BMPs for reducing heavy metals or PAH emissions.

Materials and methods

Sampling locations

All 18 sites for particle collection were within the City of Santa Monica. The City of Santa Monica sweeps their streets weekly, although sweeping was suspended for 1 week prior to particle collection for this study. All particles were collected from paved streets adjacent to the indicated landuses, and all sites had curbs. Generally, collection occurred in strips along the curbs, extending 3–4 m into the street. Sartor and Boyd (1972) reported that the particles are mainly within 1 m of the curb. Table 1 shows the sites.

Collections were performed in April. The time of year is important, because Los Angeles has distinct wet and dry periods. Average annual rainfall is approximately 380 mm, and falls primarily in the months of December, January and February. Therefore an April collection represents the beginning of the dry period. Runoff shows a seasonal flush, with the first heavy rain (usually between October and December) producing disproportionally greater masses of pollutants and litter to the Bay (Lee et al., 2004; Kim et al., 2004).

Table 1
Sampling sites

Landuse	Sample location	Street side	AADT*	Area sampled (m^2)	Total sediment mass (g)
Industrial	1700 block of 22nd	East side	n/a	38	
Industrial	1600 block of 19th	West side	n/a	29	
Industrial	1700 block of Berkeley	East side	n/a	17	1393
MFR	2700 block of Kansas	North side	n/a	36	
MFR	2500 block 28th St	E/W side	5.8	28	
MFR	2300 block of Oak	North side	n/a	31	1124
Roads	Cloverfield N. of Michigan	West side	26.7	25	
Roads	3300 block of Pico	South side	26.9	33	
Roads	2500 block of Lincoln	West side	50.8	17	1146
SFR	1300 block of Pacific	North side	n/a	21	
SFR	900 block of Yale St.	East side	n/a	19	
SFR	300 block of 16th St.	East side	n/a	22	1597
Commercial-1+	800 block of Pico	North side	19	42	1440
Commercial-2	1400 block of 2nd St.	East side	22.2	28	
Commercial-2	200 block of Broadway	North side	10.1	24	1424
Commercial-3	300 block of Arizona	North side	10.1	33	
Commercial-3	Main b/t Bay and Pico	East side	15.9	26	
Commercial-3	1600 block of Montana	North side	18	52	626

*Annual average daily traffic (in thousands); n/a = not available.
+Six commercial sites were used to form three samples, due to insufficient sample mass.

Sites were selected that were adjacent to well-defined landuses. Single-family residential (SFR), multi-family residential (MFR), commercial, industrial and roads were selected. These landuses have been used in storm-water models of this area (Wong et al., 1997). Commercial areas generally were composed of shops, restaurants, banks, etc. Industrial areas should be considered light industrial, in that no heavy industries were present. One site contained a concrete mixing and distribution facility; others representing industries included a power distribution facility, automobile repair facilities, and a wholesale chemical distribution facility. The roads landuses were major intersections with gasoline stations nearby. All sites were paved. Table 1 also shows the traffic (average daily traffic, thousand vehicles/day) at these locations. The single- and multi-family residential sites, as well as the industrial site, had very little traffic and are reported as "n/a" in Table 1.

Vacuuming technique

Particles were collected with a Royal Model 4150 vacuum cleaner, which was equipped with a 230 mm wide rotating brush with 6 mm long bristles. The brush rotated in contact with the pavement. The cleaner was equipped with a filter bag that retains particles of 0.1 μm and larger. The bag was upstream of the motor and fan blades, and a new bag was used at each location. This instrument is similar to vacuum cleaners used in previous studies (Sartor and Boyd, 1972). The cleaner was moved in strips parallel to the street curb to collect particles. Generally two passes were needed to remove all material, which was determined by visually observing the pavement. After collection, the material in the bag was transferred to a plastic sample bag (food grade), labeled, sealed and stored at 4 °C. Material too large to be collected by the vacuum cleaner was picked up and placed in the sample bag. Multiple bags were needed at some sites.

Particles sieving

Upon return to the laboratory, the particles and collected material were manually mixed and two subsamples were created from a portion of the total sample. Care was taken to insure that representative subsamples were obtained. One subsample was used for metals analysis and the other for PAH analysis. Samples were allowed to air dry; oven drying was not performed for fear of changing particle size. Moisture content of the air-dried samples was less than 20%.

Sieves were constructed to fractionate the samples without contaminating them. Polyester and stainless steel screens were purchased in six sizes with openings from 43 to 2200 μm. Sizes were selected to correspond to well-known sieve sizes (e.g., Tyler screen meshes), with the smallest size approximately corresponding to 325 mesh. Frames approximately 15 cm square were constructed of aluminum or wood. The wooden frames were equipped with polyester screens and the aluminum frames were equipped with stainless steel screens. In this way samples for PAH analysis were handled in all metal or glass containers, and samples for metal analysis were handled in non-metal, non-glass containers. Each fraction was then weighed and stored in appropriate containers (polypropylene for metals and glass for PAHs) at 4 °C. The masses of recovered sieved solids were within 3% of the original mass.

Only the smallest four fractions were analyzed for PAHs and metals. The larger fractions were not analyzed because they are better removed by existing street sweepers, and are not needed to evaluate new sweeper technology to remove PAHs and metals.

Analytical methods

PAHs were analyzed by extracting 10 g of each particle fraction using a Soxhlet extractor with 150 ml dichloromethane for 12 h using Standard Method 8540 (EPA, 1999). The extracts were evaporated to 3 ml using a rotary evaporator and cleaned up using silica gel chromatography before analysis by GC-MS. The GC-MS system was a Finnigan 4000 Quadrapole mass spectrometer with a Finnigan 9610 gas chromatograph. A splitless injector (at 290 °C) was used for sample injection onto a 30 m × 0.25 mm i.d. DB-5ms capillary column (J&W Scientific). The GC temperature program was an initial hold of 30 °C for 4 min, 30°–300° at 6 °C/min and 300 °C for 30 min. Mass spectral data were collected by using a scan range of 35–500 amu and a scan rate of 1 scan/s. Mass spectra were compared to commercially available standards.

Samples for metals analysis were prepared by digesting 0.5 g in 10 ml concentrated nitric acid for 10 min using a microwave unit (CEM Corp., Mathews, NC). After cooling, the digested samples were filtered, diluted to 50 ml and analyzed using an inductively coupled plasma atomic emission (ICP-AE) spectrophotometer. This procedure is essentially the same as SW Method 3051 (US Environmental Protection Agency (US EPA) Appropriate blanks and standards were used to insure quality control.

Results and discussion

Fig. 1 shows the results of size fractionation. Most landuses showed similar trends, with the 250–841 and 100–250 μm fractions being most abundant. The smallest fraction (<43 μm) showed the greatest abundance in industrial and SFR areas. The reasons for this are unknown; there are no obvious features that might cause the occurrence of small particles. The difference between

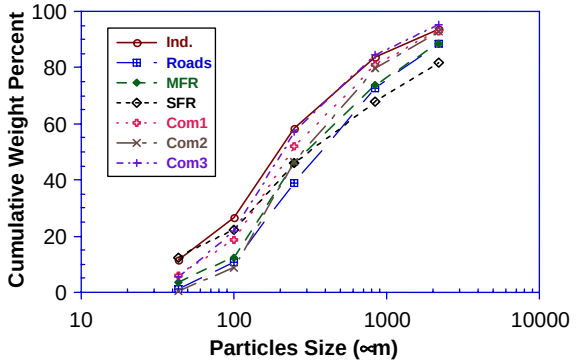

Fig. 1. Size fractionation results as a function of particle size for various landuses (landuse categories: Ind. = industrial; Roads = streets; MFR = multi-family residential; SFR = single-family residential; Com.1, Com.2, Com.3 = three different commercial areas).

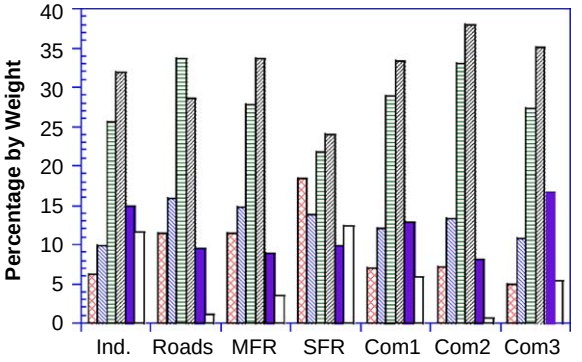

Fig. 2. Size fractionation results as a function of landuse (particle size fractions: ▩ >2200 μm; ▨ 841–2200 μm; ▤ 250–841 μm; ▨ 100–250 μm; ■ 43–100 μm; □ <43 μm; landuse categories: Ind. = industrial; Roads = streets; MFR = multi-family residential; SFR = single-family residential; Com.1, Com.2, Com.3 = three different commercial areas).

the maximum value and 100% for each landuse is the percentage of material greater than 2200 μm. Fig. 2 shows the size fractionations plotted as a function of particle size. The abundance of the 250–841 and 100–250 μm fractions is more obvious in this figure. The particles from SFR areas were the most evenly distributed among the land uses. The range is narrower than Viklander's (1998) findings for particle size distribution of street sediments collected from both residential and city center areas in Lulea, Sweden. Her results showed that approximately 10% of collected sediments from both landuses were less than 75 μm size, and more than 50% were greater than 2000 μm. The particles collected in this study were numerous in the middle size ranges.

The distribution of particles in this study is coarser than particles measured in stormwater. The reasons for this are not fully understood, but may relate to the ability of stormwater to consistently mobilize larger particles. Sansalone et al. (1998) reported that 30% of the mass of particles transported in highway runoff were greater that 1000 μm and noted that the sampling method can influence the collection of large particles. They have criticized collection methods that involve subsampling, which may tend to lose larger particles. Morquecho and Pitt (2003) found a much larger fraction of smaller particles. Other work in our laboratory from highways also found a larger proportion of smaller particles (Li et al., 2005). There exists some controversy over the collection methods and transport of particles larger than 400 μm.

Metals concentrations

Table 2 and Figs. 3 and 4 show the metals results by size fraction and landuse. The table reports metals per unit area of street (μg/m^2), and have been calculated to show the mass of metal that could be collected by a street sweeper or other device. Three examples of each landuse type were selected and combined to broaden the coverage. Six commercial sites were selected and later combined to three sites because it was expected that there would be greater variability among sites, since commercial landuse definition is very broad. Fig. 3 shows solid-phase concentrations (mg/g) as a function of landuse. Copper, zinc, chromium, lead, cadmium and nickel are reported. We analyzed for other metals, but the metals shown are of the most concern for the Santa Monica Bay watershed; other metal concentrations will be reported later. Only one of the commercial land uses is shown in Fig. 3 for brevity.

The variation of concentrations as a function of particle size is not as great as anticipated. If metals were uniformly adsorbed to particle surfaces, the concentrations would be greatest on the smallest particles, which have the greatest specific surface areas. The ratio of the specific surface areas of spherical particles is proportional to the square of the diameter divided by the cube of the diameter (surface area divided by volume). The ratio of specific surface areas for the smallest to largest sizes fractions (using the average diameter of the indicated ranges) is 25:7.6:3.1:1. If contaminant attachment were strictly proportional to surface area, the concentrations would match these ratios. The concentrations are more uniform among size fractions, with size fraction 100–250 μm often being as high or higher in concentration than the smallest fraction. With a few exceptions, the ratios of concentrations on the smallest particles (<43 μm) were no more than 3 times as large as the concentrations on the largest particles (250–841 μm). Sansalone and Christina (2004) suggest that particles are not spherical, which might explain our findings. Particles from SFR landuses tended to have the lowest metals concentrations, as might be expected. Commercial landuses generally were highest, except for nickel.

Table 2
Mass of metals per unit area of street surface

Metals (mg/m^2) and size fraction (μm)		Landuse						
		Industrial	Roads	Multi-family	Single-family	Commercial		
						Area 1	Area 2	Area 3
Cu	<841	2.682	2.628	0.559	0.701	5.770	4.960	1.559
	250–841	1.301	1.247	0.130	0.075	0.370	0.877	0.534
	100–250	0.745	1.028	0.279	0.193	3.759	3.241	0.577
	43–100	0.376	0.319	0.102	0.176	1.163	0.769	0.346
	<43	0.260	0.034	0.048	0.257	0.478	0.082	0.102
Ni	<841	3.925	0.291	0.365	0.461	1.137	0.667	0.177
	250–841	0.147	0.036	0.133	0.052	0.150	0.155	0.017
	100–250	2.715	0.179	0.117	0.143	0.501	0.387	0.101
	43–100	0.752	0.066	0.085	0.103	0.313	0.112	0.042
	<43	0.311	0.010	0.030	0.163	0.173	0.013	0.017
Zn	<841	6.436	4.212	3.924	3.679	28.383	18.722	3.022
	250–841	1.170	0.764	0.874	0.384	4.694	4.476	0.427
	100–250	2.502	2.191	2.226	1.261	11.389	10.350	1.373
	43–100	1.504	1.108	0.577	0.775	4.919	3.514	0.943
	<43	1.260	0.149	0.247	1.259	2.381	0.382	0.279
Cr	<841	0.420	0.327	0.239	0.371	1.485	0.848	0.197
	250–841	0.061	0.068	0.050	0.040	0.529	0.201	0.021
	100–250	0.170	0.170	0.138	0.137	0.592	0.491	0.101
	43–100	0.108	0.082	0.037	0.083	0.268	0.143	0.051
	<43	0.081	0.007	0.014	0.111	0.096	0.013	0.024
Pb	<841	2.813	1.641	1.244	1.485	8.246	3.605	0.881
	250–841	0.477	0.234	0.223	0.195	2.796	0.731	0.214
	100–250	1.437	0.939	0.728	0.516	3.417	2.195	0.398
	43–100	0.501	0.415	0.203	0.258	1.341	0.615	0.202
	<43	0.398	0.053	0.090	0.516	0.692	0.064	0.067
Cd	<841	0.033	0.017	0.018	0.018	0.108	0.044	0.008
	250–841	0.006	0.002	0.004	0.002	0.009	0.011	0.001
	100–250	0.010	0.008	0.010	0.006	0.071	0.023	0.003
	43–100	0.012	0.006	0.003	0.005	0.021	0.009	0.003
	<43	0.005	0.001	0.001	0.005	0.007	0.001	0.001

The data shown in Table 2 showing the mass of metals per unit area of paved surface are plotted in Fig. 4 to show the percentage of metal mass as a function of particle size. The averages are mass-weighed averaged. The mass is a function of both solid-phase concentration as well as particle abundance. The percentage of metal mass for combined landuses and SFR are shown. The masses are greatest in the 100–250 μm size fraction for combined landuses. The average mass contained in this size fraction is 47.7%, with copper the lowest at 44.5% and chromium the highest at 48.0%. The average mass contained in the smallest fraction (<43 μm) for combined landuses is 11.1%, with copper the lowest at 10.3% and chromium the highest at 12.1%. Metals from SFR landuse show a different trend than the other landuses, in that the smallest size fraction is a larger proportion of the total mass. The contribution of the smallest fraction was lowest for cadmium at 27.7% and highest for copper at 36.4%. The reason for the greater mass in the smallest size fraction for SFR results from the greater abundance of small particles. Fig. 2 shows that SFR landuse has the greatest fraction of particles in the <43 μm size.

The 100–250 μm size fraction is clearly the most important size fraction for all landuses except SFR, where the three smaller size fractions are roughly equal in importance. In an absolute sense, SFR has the lowest contribution of metals compared to the other landuses

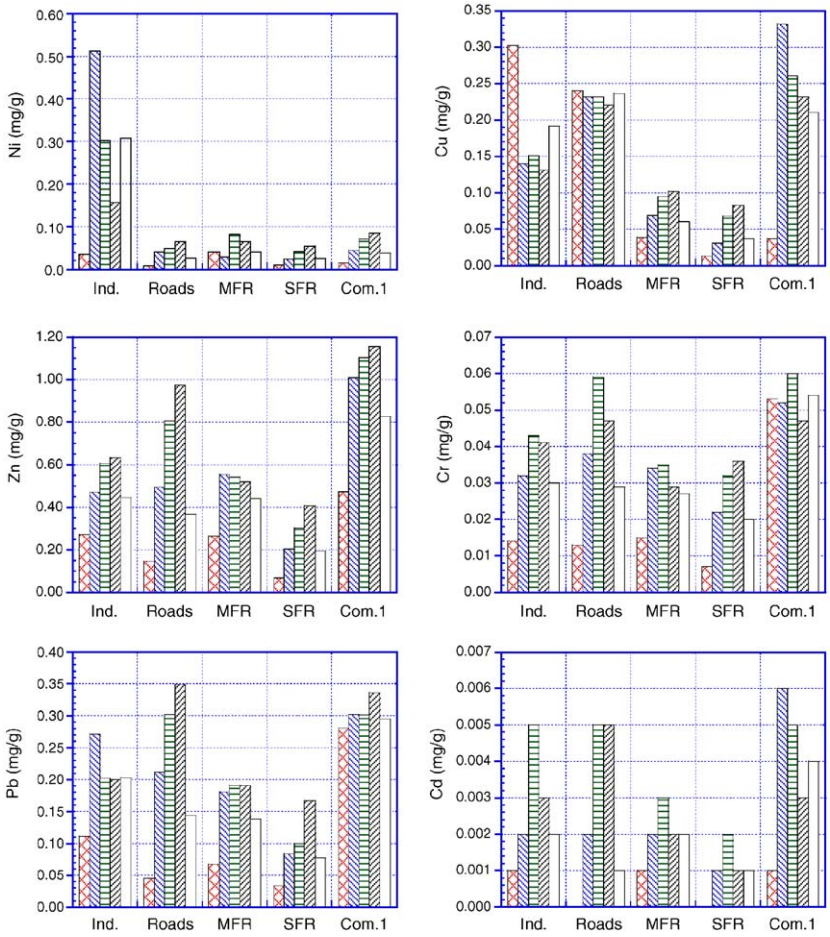

Fig. 3. Metals concentrations (mg metal/g particle) as a function of landuse (particle size fractions: ▩ 250–841 μm; ▧ 100–250 μm; ▤ 43–100 μm; ▨ <43 μm; □ average; landuse categories: Ind. = industrial; Roads = streets; MFR = multi-family residential; SFR = single-family residential; Com.1 = commercial areas).

(see Table 2). The implication of these results is that BMPs for removing particles from streets should be able to capture particles as small as 100 μm.

It is possible to estimate the metals in stormwater if one assumes that the collected particles compose the particulates in stormwater. For example, if typical TSS concentrations ranged from 50 to 250 mg/l, the particulate copper concentration for roads landuse would be 45–225 μg/l. As a comparison, Han et al. (2004) report median highway runoff concentrations of particulate copper and TSS as 27 μm/l and 67.7 mg/l, respectively, which is approximately 44% of what is expected from the particles reported in this paper.

PAHs results

Table 3 shows the PAH fractionation results by individual PAHs. The table shows the results as mass per unit area of pavement. SFR had lower concentrations than the other landuses. Surprisingly, MFR showed concentrations similar to the other landuses. The lower molecular weight PAHs, such as naphthalene, were detected much less frequently, even though they are thought to be produced in greater masses. Naphthalene is more volatile than the other PAHs and is probably lost to the atmosphere. No consistent pattern between the particle size and PAHs of lower molecular weight (such as biphenyl and acenaphthene) was detected. The amount of higher molecular weight PAHs (such as chrysene and benz[a]anthracene) generally increases as the particle size decreases.

Fig. 5 shows the total PAH results as solid-phase concentrations (unit mass of PAH per unit particle mass, μ/g). With the exception of industrial landuse, the PAHs were more concentrated on the smaller particles, and the ratios of small particle concentrations to large particle concentrations were in some cases 10 times or more. The ratios were not as great as the ratios of the hypothetical

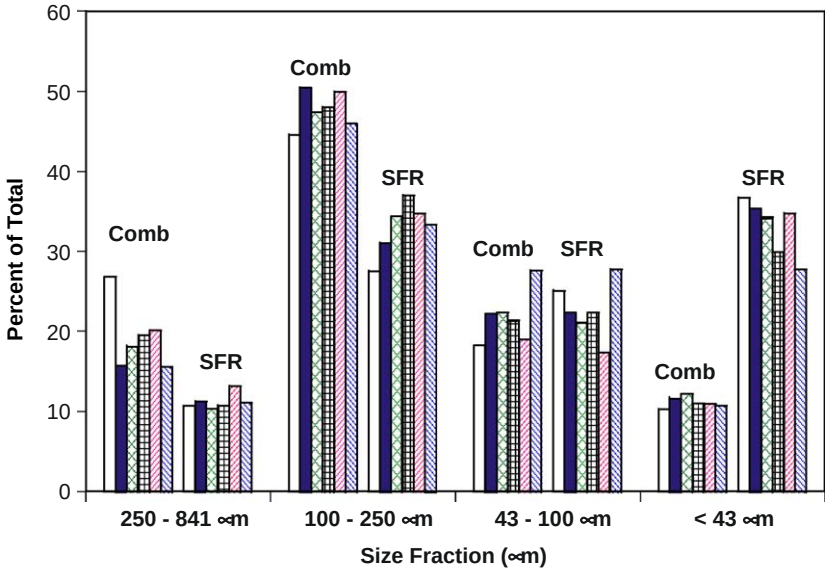

Fig. 4. Metal mass on each particle size fraction as a percentage of the total metal mass for combined (Comb) and single-family residential landuse (SFR) (□ Cu; ■ Ni; ⊠ Zn; ▦ Cr; ▨ Pb; ▧ Cd).

Table 3
Mass of PAHs per unit area of street surface

Metals (μg/m^2) for different size fraction (μm)		Landuse						
		Industrial	Roads	Multi-family	Single-family	Commercial		
						Area 1	Area 2	Area 3
Naphthalene			0.029		0.022	0.542	0.115	
	<841							
	250–841					0.290	0.048	
	100–250					0.112	0.041	
	43–100		0.025			0.104	0.020	
	<43		0.004		0.022	0.036	0.006	
2-Methyl naphthalene			0.003		0.033	0.147		0.036
	<841							
	250–841					0.099		0.021
	100–250							0.012
	43–100					0.007		
	<43		0.003		0.033	0.041		0.003
1-Methyl naphthalene			0.002		0.022	0.039		0.022
	<841							
	250–841					0.039		0.017
	100–250							
	43–100							
	<43		0.002		0.022			0.005
Bipheny		0.079	0.013		0.185			0.141
	<841							
	250–841							0.055
	100–250							0.070
	43–100							
	<43	0.079	0.013		0.185			0.016

Table 3 (*continued*)

Metals ($\mu g/m^2$) for different size fraction (μm)		Landuse						
		Industrial	Roads	Multi-family	Single-family	Commercial		
Acenaphthene		0.013	0.002			0.013		0.104
	<841							
	250–841	0.003				0.013		0.069
	100–250	0.010						0.029
	43–100							
	<43		0.002					0.006
Fluorene		0.947	0.183	0.32		1.978	1.636	0.134
	<841							
	250–841	0.011				0.402	0.542	0.072
	100–250	0.612		0.225		1.106	0.800	0.052
	43–100	0.324	0.181	0.091		0.429	0.291	
	<43		0.002	0.004		0.041	0.003	0.010
Dibenzothiophene		0.692	0.425	0.71	0.662	1.445	1.247	0.186
	<841							
	250–841	0.007	0.294	0.469	0.308	0.276	0.390	0.100
	100–250	0.425		0.157	0.184	0.787	0.621	
	43–100	0.220	0.127	0.068	0.137	0.305	0.230	0.062
	<43	0.040	0.004	0.016	0.033	0.077	0.006	0.024
Phenanthrene		2.529	0.636	0.947	0.789	4.852	2.486	5.342
	<841							
	250–841	0.072	0.261	0.312	0.034	0.790	0.599	4.191
	100–250	1.867	0.011	0.297	0.220	2.212	1.214	
	43–100	0.590	0.296	0.134	0.111	0.914	0.578	0.871
	<43	0.338	0.035	0.120	0.185	0.444	0.071	0.057
Anthracene		1.293	0.806	1.293	0.306	2.391	2.106	0.013
	<841							
	250–841	0.020	0.571	0.885		0.494	0.694	
	100–250	0.851		0.285	0.306	1.331	1.021	
	43–100	0.422	0.232	0.117		0.519	0.383	
	<43		0.003	0.006		0.047	0.008	0.013
Fluoranthene		5.067	0.453	0.569	0.598	4.443	2.418	2.398
	<841							
	250–841	0.115	0.016			0.652	0.400	
	100–250	3.330		0.157		1.744	1.255	1.312
	43–100	0.682	0.308	0.091		0.838	0.619	0.812
	<43	0.940	0.129	0.321	0.598	1.209	0.144	0.274
Pyrene		5.389	1.012	1.073	0.74	9.189	7.645	2.405
	<841							
	250–841	0.103	0.277			1.191	1.474	
	100–250	3.122		0.325		4.181	3.987	1.219
	43–100	0.688	0.610	0.235		1.738	1.886	0.896
	<43	1.476	0.125	0.513	0.740	2.079	0.298	0.290
Benz[a]anthracene			1.249	0.388	0.575	1.94	3.561	0.464
	<841							
	250–841		0.514		0.197	0.448	0.580	0.083
	100–250			0.225	0.130	0.769	2.359	0.187
	43–100		0.610	0.073	0.085	0.450	0.547	0.154
	<43		0.125	0.090	0.163	0.273	0.075	0.040
Chrysene/triphenylene		2.845	0.462	0.545	1.066	4.87	5.854	2.08
	<841							
	250–841	0.047				0.704	0.970	0.673
	100–250	1.421		0.084	0.054	1.500	3.670	0.589
	43–100	0.324	0.362	0.116		1.108	1.017	0.617
	<43	1.053	0.100	0.345	1.012	1.558	0.197	0.201

Table 3 (*continued*)

Metals (μg/m^2) for different size fraction (μm)		Landuse						
		Industrial	Roads	Multi-family	Single-family	Commercial		
Benzo(e)pyrene		4.81	5.044	1.983	1.139	10.562	8.886	0.942
	<841							
	250–841	0.046	1.819			2.087	1.940	0.166
	100–250	2.811	2.040	1.277		4.818	3.752	0.332
	43–100	1.278	1.128	0.456	0.671	2.798	3.062	0.329
	<43	0.675	0.057	0.250	0.468	0.859	0.132	0.115
Benzo(a)pyrene		5.059	4.907	1.481	0.919	6.849	0.071	0.431
	<841							
	250–841	0.061	1.819			1.606		0.072
	100–250	3.278	2.309	0.992		4.799		0.181
	43–100	1.382	0.744	0.369	0.734			0.121
	<43	0.338	0.035	0.120	0.185	0.444	0.071	0.057

Missing values are less than 0.002 μg/m^2.

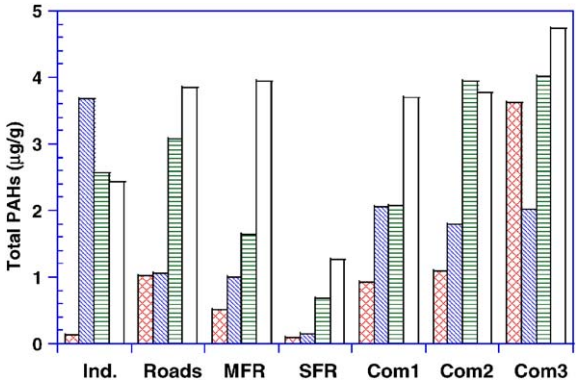

Fig. 5. Total PAHs concentrations based upon solid-phase concentrations (μg PAH/g particle) for different particle size fractions as a function of landuse (particle size fractions: ▩ 250–841 μm; ▧ 100–250 μm; ▤ 43–100 μm; □ <43 μm; landuse categories: Ind. = industrial; Roads = streets; MFR = multi-family residential; SFR = single-family residential; Com.1, Com.2, Com.3 = three different commercial areas).

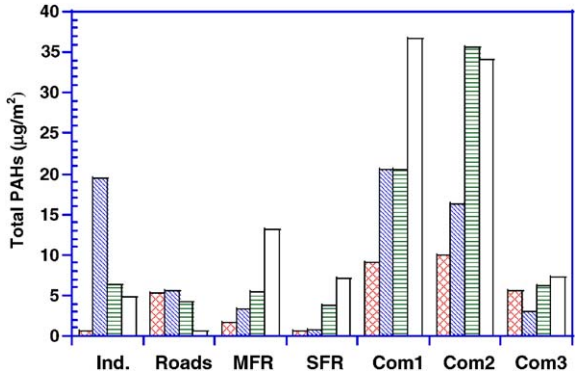

Fig. 6. Total PAH mass per unit area of road (μg/m^2) as a function of landuse for different particle sizes (particle size fractions: ▩ 250–841 μm; ▧ 100–250 μm; ▤ 43–100 μm; □ <43 μm; landuse categories: Ind. = industrial; Roads = streets; MFR = multi-family residential; SFR = single-family residential; Com.1, Com.2, Com.3 = three different commercial areas).

spherical particle specific surface areas, but were greater than the concentration ratios observed for metals. Fig. 6 shows the total PAHs plotted as PAH mass per unit area of streets or roads. The PAHs on the smaller particles are a larger portion of the total mass than observed for the metals. The small particles are more important for two commercial landuses and SFR, but for roads and industrial the 100–250 μm fraction was most important.

Conclusions

This paper has reported PAHs and metals found on street particles as solid-phase concentrations and as mass per unit area of pavement. Both are important contaminants in stormwater. The results confirm earlier research, and the general belief, supported by adsorption theory, that smaller particles have higher contaminant concentrations. The distribution is not as great as the ratios of the specific particle surface areas, assuming spherical particles. This might result because the smaller particles may be composed of different material than the larger particles, and the particles are not necessarily spherical.

Commercial, roads and industrial landuses had higher concentrations of both metals and PAHs than residential landuses. Nickel was the only exception, which was clearly greater in industrial landuse. Higher molecular weight PAHs were generally more abundant than lower

weight PAHs. Single-family residential had the lowest concentrations of various pollutants. The data provide quantitative evidence for prioritizing BMPs application to industrial and commercial landuses.

The abundance of the various particle sizes changes the relative contribution of particles to total mass load. For metals, the 100–250 μm fraction was most important. For PAHs particle sizes smaller than 100 μm were the most important, except for roads and industrial landuses.

The data presented here can be used, in the absence of site-specific test results, to estimate the potential performance of BMPs in removing metals and PAHs by TSS removal. The cost of providing a better BMP that removes smaller particles can be compared to the benefits of greater contaminant removals. The data should be useful in planning for total mass daily limits (TMDLs).

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