Heavy metal contamination of sediments in stormwater management systems: the effect of land use, particle size, and age

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Abstract Sediments from stormwater retention ponds, roadside swales and street sweepings have to be disposed of or reused periodically. Information on their pollution is needed to establish reuse and disposal regulations and to schedule clean out and street-sweeping activities. This study examines the heavy metal contamination in these sediments and the factors that affect this contamination. Results show that the particle size distribution of the sediments depends on differential erosion processes of natural soils, land use, and technical limitations of street sweepers. Pond and swale sediments are more polluted with heavy metals than natural soils, but street sweepings are not. This can be explained by the high clay contents of sediments in ponds and swales and the very low clay content of sweepings. Land use is an important factor for the heavy metal pollution of ponds and swales, but does not considerably affect heavy metals in street sweepings. Within a given type of land use, heavy metal concentrations in pond sediments increase with age.

Keywords Heavy metals · Retention ponds · Soil contamination · Stormwater · Street sweepings

Introduction

Under the terms of the National Pollutant Discharge Elimination System (NPDES) and the 1987 Clean Water Act Amendments, local government and industrial dischargers must obtain a permit to discharge surface runoff into US waters. Cities and counties, to obtain these permits, have been mandated to map and control their surface runoff and to provide systems to reduce the non-point source pollutants in these waters. For most local government this has led to increased implementation of stormwater management systems such as roadside swales, buffer strips, retention ponds, and street sweeping. Most of the systems now require maintenance to keep them functional. Maintenance includes periodic removal of accumulated residual materials to keep ponds permeable and swales open (Marsalek and others 1992). Currently, the extracted materials are stockpiled, disposed, or reused. Reuse, and even stockpiling, may not be legal usage (FDEP 1998) as these materials may contain elevated levels of pollution. Conversely, because pollutants can vary with land use (Wigington and others 1983; Field and O'Shea 1994; Yun and others 2000) some of the materials may be safe enough for reuses such as land application, roadside stabilization, and construction fill. The question then is what pollutants are to be found in these materials and what factors affect their concentrations.

Numerous studies of the pollution of stormwater management systems exist but many focus on the quality of the water that is released, gradually or during flood events, and the water that infiltrates (Hampson 1986; Yousef and others 1986; Stanley 1996; Fukui 1997). Studies that examine pollutants in sediments in these systems often do so to assess the potential for the transfer of pollutants to the water (Wigington and others 1983; Nightingale 1987; Fernandez and Hutchinson 1993), or to biota (Baker and Yousef 1995; Wenholz and Crunkilton 1995). Few studies examine the pollution of sediments in stormwater management systems to evaluate potential handling and disposal options although the sediments may exceed the volume of municipal wastewater sludge (Field and O'Shea 1994). Yousef and others (1991) studied pollution of sediments in wet retention/detention ponds near major roads in Florida to help formulate maintenance guidelines. Metal concentrations were higher near the top of the accumulated sediments than in the underlying original material, but declined rapidly with depth. In general, metal concentrations in accumulated bottom sediments were much lower than regulatory levels that define hazardous waste. Based on observed metal concentrations and a predictive empirical model for sediment accumulation rates Yousef and others (1991) concluded that the optimal average clean out cycle for the studied ponds was 25 years. Marsalek and Marsalek (1997) characterized bottom sediments

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from an on-stream stormwater pond to help plan pond maintenance and sediment removal and disposal. The sediments contained elevated levels of heavy metals, most of which were in potentially mobile forms. Based on Canadian guidelines, the sediments could not be reused in urban areas nor readily disposed of at municipal landfills. Cox and others (1998) examined residuals from a wide array of stormwater management systems and land uses in Florida. Traffic-related metals (Cr, Pb, Zn) were found at virtually all sites but, generally, heavy metal concentrations did not exceed screening level criteria. The residuals were contaminated with a variety of organic and inorganic pollutants but could not be characterized as hazardous waste. Results did not show significant differences between land-use categories.

A memorandum from the Florida Department of Environmental Protection (FDEP) to County Solid Waste Directors dated 28 April 1998, states that additional characterization data for sediments from stormwater management systems and street sweepings are needed before firm decisions about their reuse and disposal in Florida can be made. The memorandum states that until such data are available reuse of the materials can not be authorized and that the extracted materials have to be disposed of in landfills.

To help provide information on pollution of sediments from stormwater management systems this study generates new data on heavy metal concentrations in sediments from retention ponds, street sweepings, and roadside swales. It also examines the effect of land use, particle size, age of the retention pond, and frequency of street sweeping on the heavy metal concentrations. This type of data facilitates regulatory decision making regarding acceptable reuse and disposal options for the sediments, and can be used by local entities to schedule pond and street-cleaning activities. The data are compared with pollution background levels of the natural soils in the study area and are interpreted in light of the very sandy nature of the natural soils. This study is different from many other related studies (Wigington and others 1983; Nightingale 1987; Yousef and others 1991; Fernandez and Hutchinson 1993) because it examines more stormwater management systems and more heavy metals with the same methods, thus making comparisons and conclusions more robust.

Study area

Samples were collected from Escambia County, Florida, mainly within the limits of the City of Pensacola in the south of the county (Fig. 1). Escambia County is in the extreme western Panhandle of Florida and extends from the Gulf of Mexico north to the Alabama–Florida line. The county lies in the coastal plain province and is underlain by unconsolidated sands, silts, and clays. The upland hills in the north of the county are covered with clay-rich soils whereas sandy soils occur on the flat coastal plain in the south.

Escambia County has a humid, warm, temperate climate. Summers are long and warm, and winters are short and mild. The average summer temperature in Pensacola is 27 °C, the average winter temperature is 13 °C. The annual rainfall is fairly high, nearly 157 cm on average. Rainfall is well distributed throughout the year with a peak in July and August and it often falls as heavy afternoon thunderstorms. The land use in the county is mainly agricultural in the north and commercial and residential in the south. The principal crops are cotton, corn, and soybeans. The City of Pensacola has grown by 33% in the last 20 years. Most new residential developments are medium density, single-unit neighborhoods.

Methods

Site selection

To select sampling sites, a GIS map of retention ponds and sweeping routes that are managed by the City of Pensacola and Escambia County was compiled from digital and hardcopy maps and written records. Future schedules for street sweeping and pond cleaning were entered manually into a GIS database. A general land-use/land-cover map with four broad categories, residential, commercial, agricultural, and other, was created from on-line information. Potential sampling sites were identified by overlying the map of the ponds and sweeping routes on the land-use/land-cover map. The potential sampling sites were then ranked by the perceived ease of access and distance from other land-use categories. Final selection of the ponds and sweeping routes was carried out during a field visit. Because no systematic information on the location of swales was available, potential sampling sites for swales were identified during a windshield survey and sites were ultimately chosen so as to have an adequate number of samples from the various land-use/land-cover categories.

Fieldwork

Sediment samples from retention ponds were acquired in one of two ways. If sediments from a pre-selected pond were being extracted by city or county crews a sample of the sediments that had been piled up on-site for loading on trucks was collected. Extraction and piling up of the material in part homogenized the sediments, but at least four subsamples from different locations in the pile were collected. Because of the relatively limited number of ponds that was cleaned by the city and county during this study, additional ponds were sampled manually. For those ponds a custom-built PVC piston corer was used to collect at least four subsamples in different locations in the pond. In all cases there was a clear break in texture and color between the accumulated sediments, which were sampled, and the original pond bottom.

Street-sweeping samples were collected directly from the hoppers of street sweepers owned by the City of Pensacola and Escambia County. All sweepers were of the rotary brush type and the brushes and other elements of the

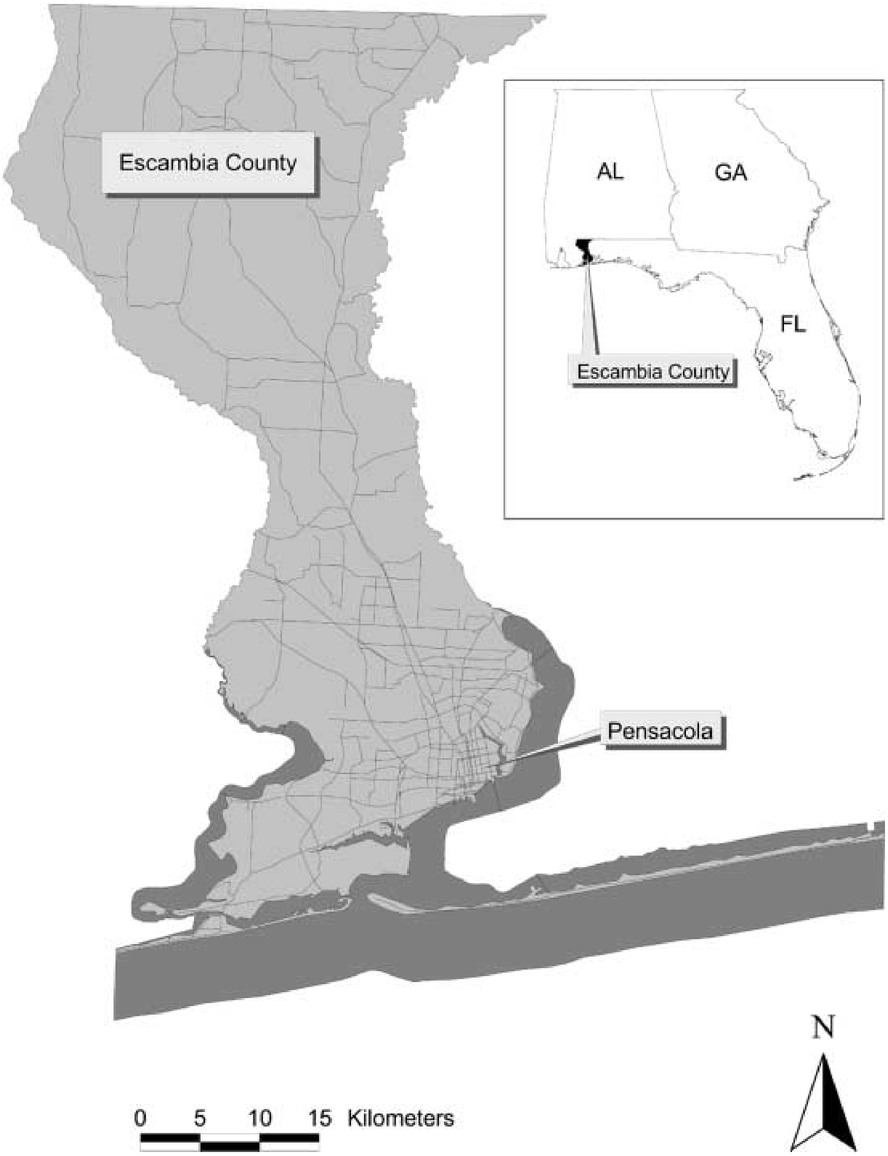

Fig. 1
Location of study area

collection system were in good condition. On each sampling day one of the two entities was contacted early in the morning and a meeting between the field crew and project personnel was arranged. Each sample was composed of at least four aliquots taken with a stainless steel trowel from different places in the hopper.

At swale sampling sites grass and weeds in the thalweg were removed with a shovel. A thin layer of soil, approximately 1 cm thick, was removed from the top with a stainless steel trowel and the sample was then taken with the stainless trowel up to a depth of 5 cm or up to a clear change in texture, whichever was shallower. At least three subsamples were taken at each swale site.

Samples for background values from natural soils were collected near eight of the sampled retention ponds. These control sites were chosen close to the ponds in wooded areas where human disturbance was minimal. Grass and weeds were removed with a stainless steel trowel. The sample was then taken with the stainless trowel up to a depth of 5 cm or up to a clear change in texture, whichever was shallower. At least three subsamples were taken slightly apart at each site.

Laboratory analysis

Samples collected in the field were mixed and further homogenized in lab, and split with stainless-steel sample splitters into aliquots for the various analyses. For grain size determination, air dried aliquots were manually crushed with mortar and pestle. Analyses were performed by dry, Ro-tap, sieving for the sand fractions (2–0.063 mm) and by the pipette method for clays (procedure 3A1 of Soil Survey Laboratory Staff 1992). Samples were analyzed for aluminum, arsenic, barium, beryllium, cadmium, copper, chromium, lead, mercury, nickel, silver, and zinc. Mercury was determined by USEPA Method 245.5 for cold vapor atomic absorption spectrometry (USEPA 1983). For all other metal determinations the samples were digested according to USEPA method SW-846-3050B (USEPA 1996). Per the method, arsenic, cadmium, chromium, and lead were prepared for graphite furnace atomic absorption spectrometry (GFAAS). The other metals were prepared for flame atomic absorption spectrometry (FLAAS). The digestates were then analyzed according to USEPA Method 3111 for FLAAS (Eaton and others 1995), or Method 200.9 for GFAAS (USEPA 1991).

A principal component analysis was run on the heavy metal data to reduce the number of variables. A *t*-test for equality of means was performed on the scores for the first component to evaluate the influence of land use and the differences between stormwater management systems and background values. The proper *t*-test was selected after running an *F*-test for equality of variances. The α=0.05 criterion was used to evaluate the statistical significance of the tests.

Results and discussion

General

A total of 24 ponds were sampled in residential and commercial areas. Only one retention pond managed by local government is in the agricultural part of the study area and its data are not included in this study. All sampled ponds are dry retention ponds in which stormwater runoff infiltrates, in principle, in the 2–3 days following a rainfall event. Some of the ponds have decreased infiltration rates and stay wet for 1–2 weeks after heavy rainfall. Bottom sediments had not been extracted from any of the sampled ponds since construction of the ponds. Seventeen street-sweeping routes were sampled. They were all from residential and commercial areas because in agricultural areas roads are unpaved or paved but bordered by a swale rather than a curb and gutter that can be swept. A total of 22 swales, all grassed, were sampled. Residential land use is not represented in the swale data set because suitable sites could not be identified in residential neighborhoods. The swales in commercial areas are all in high traffic zones.

Streets are swept on a regular basis by the City of Pensacola and Escambia County. The City of Pensacola interrupts its schedule one day a week to sweep sections that are perceived to need more frequent sweeping. These sections include the downtown area and some commercial sections. All other sections are swept approximately every 6–8 weeks. The county interrupts its regular schedule when it is requested to sweep a certain section. Request usually come from businesses, which means that commercial sections are swept more often than residential sections. In the county's normal schedule a section is swept every 8–10 weeks. A precise schedule can not be adhered to because of mechanical problems with sweepers and inclement weather conditions.

Only eight control sites could be sampled because the surroundings of most ponds had obviously been disturbed. The selected control sites are located within 100 m of a pond and do not receive residential or commercial runoff. They can be expected to receive some airborne pollutants. It is assumed that the samples represent background values for the whole study area. This may or may not be valid depending on the variability of the natural soils in the area. However, more reliable and detailed background data on soil pollution are not available for the study area.

Particle size data

Ponds

The proportions of the various particle size fractions vary widely in the pond sediments (Table 1). Sand content can be as high as 85% and as low as 25%. Clay content ranges from less than 5 to 35%. Sand is the dominant fraction in all but one sample. This dominance of sand is related to the high sand content of natural soils in the area. The pond sediments have less sand but more clay and silt in commercial areas than in residential areas (Table 1). For sand, this difference between the two types of land use is statistically significant, for silt, it is borderline significant (*P*=0.07), while for clay, it is not statistically significant. This suggests that land use affects the particle size distribution of sediments in retention ponds to some degree. This contention is supported by the absence of a statistically significant difference in age of the ponds in the two types of land use (Table 1) and between the particle size distribution of natural soils in the two types of land use (α=0.05). The influence of land use on the particle size distribution of the sediments may be related to the inability of rotary brush street sweepers to pick up fine materials (i.e., clay and silt; Young and others 1996; Kidwell-Ross 1998; Brinkmann and others 1999). Commercial streets are swept more often than residential streets, and sand is more often removed from commercial streets. Consequently, sediments washed into retention ponds in commercial areas are more often enriched in silt and clay. Clay and silt content are higher and sand content is lower in retention ponds than in natural soils (Tables 1 and 2). This observation holds when ponds are compared with their corresponding control site and for all ponds in general. Most of the streets in the drainage basins of the ponds are swept regularly and the observation may be

Table 1
Particle size distribution for pond sediments (%) and age of ponds (year). **P* value for *t*-test for equality of means

	All ponds			Residential n=16	Commercial n=8	Resid. vs. comm.
	Minimum	Maximum	Mean	Mean	Mean	*P**
Sand	25.7	85.0	65.1	70.7	54.6	0.05
Silt	5.9	50.5	20.1	16.6	26.6	0.07
Clay	4.6	34.9	14.8	12.7	18.8	0.19
Age	4.0	22.0	11.3	10.5	12.7	0.32

Table 2
Particle size distribution (%) at control sites. *P value for *t*-test for equality of means

	Control sites *n*=8			Control sites vs. ponds	Control sites vs. swales	Control sites vs. sweepings
	Minimum	Maximum	Mean	*P**	*P**	*P**
Sand	81.6	91.1	87.1	0.00	0.00	0.00
Silt	5.7	9.9	8.6	0.00	0.00	0.00
Clay	3.0	9.0	4.2	0.00	0.00	0.01

Table 3
Particle size distribution (%) for swale sediments. *P value for *t*-test for equality of means

	All			Commercial	Agricultural	Commercial vs. agricultural
	Minimum	Maximum	Mean	*n*=6 Mean	*n*=16 Mean	*P**
Sand	31.7	93.2	67.3	72.9	64.8	0.30
Silt	2.5	42.6	18.7	17.7	19.2	0.76
Clay	3.7	25.7	14.0	9.4	16.0	0.02

related to the preferential removal of coarse materials by street sweepers. If the initial particle size distribution in sediments on streets is similar to that of natural soils, and coarse materials are removed selectively by the sweepers, only the fine materials, i.e., clay and silt, are available for transport to retention ponds.

Swales

As is the case for pond sediments, particle size fractions for swale sediments vary widely (Table 3). Sand content varies between about 32 and 93% and clay content ranges from just under 4 to 26%. Sand is the dominant fraction in all swale samples because of the high sand content of the natural soils in the area. Comparison of swale sediments with the control sites shows that clay and silt contents are higher and sand content is lower in swales (Tables 2 and 3). This can be explained by the preferential transportation of fine particles into the swales by erosion of natural soils whereas coarser particles are deposited in grassed field borders and on the edges of swales.

The swale sediments have more clay and silt, but less sand in agricultural areas than in commercial areas (Table 3). The difference between the two land-use classes is statistically significant for clay but not for silt and sand (Table 3). However, larger land-use related differences in particle size distribution become evident when swales in the two types of agricultural land use are compared. Swales near cotton fields have much less sand and more silt and clay than swales near pastures (Table 4). These observations indicate that land use influences the particle size distribution of swale sediments, especially clay content. This can be explained by higher rates of erosion in agricultural areas as compared with commercial areas, and in cotton fields as compared with pastures, and thus by the increased effect of preferential transportation of fine particles by runoff. High levels of preferential transportation of fine particles in agricultural areas, and in cotton fields in particular, and subsequent deposition in swales, is consistent with clay contents that are much higher in these swales than in natural soils in the area (Tables 2 and 4).

Table 4
Particle size distribution for swale sediments as a function of agricultural land use (%).*P value for *t*-test for equality of means

	Cotton[a] *n*=7	Pasture[a] *n*=5	*P**
Sand	54.6	80.6	0.00
Silt	25.8	9.7	0.00
Clay	19.6	9.6	0.00

[a] Swales from other agricultural land use are not included because *n* values are too low

Sweepings

The particle size distribution of street sweepings is uniform (Table 5). Sand content is very high and never drops below 91%. Clay and silt content are very low in all sweeping samples, clay content never exceeds 3%. Differences between residential and commercial land use are very small and statistically not significant (Table 5). This uniformity is most likely caused by the use of rotary brush street sweepers that pick up coarse materials only, regardless of the particle size of the source materials.

Sand content is higher and clay content is lower in sweepings than in natural soils in the study area (Tables 2 and 5). This clearly shows that, compared with the local natural soils, street sweepings are enriched in sand and depleted in clay. These observations show again that rotary brush street sweepers are more efficient at picking up coarse materials than fine materials (Young and others 1996; Kidwell-Ross 1998; Brinkman and others 1999).

Table 5
Particle size distribution for street sweepings (%).*P value for *t*-test for equality of means

	All			Residential	Commercial	Commercial vs. agricultural
	Minimum	Maximum	Mean	*n*=11 Mean	*n*=6 Mean	*P**
Sand	91.0	97.4	95.2	95.4	94.8	0.60
Silt	1.1	7.8	3.3	3.2	3.6	0.64
Clay	0.7	2.9	1.5	1.5	1.6	0.71

Heavy metal data

Ponds

Concentrations for all heavy metals are higher in pond sediments than at the control sites (Tables 6 and 7). A principal component analysis of the heavy metal concentrations for the ponds and control sites returned a first principal component (PC1) that explains 53% of the variance in the data set. A *t*-test on the scores on PC1 indicates that ponds are statistically more polluted with heavy metals than control sites (*P*=0.00). This strongly suggests that stormwater runoff in the study area carries elevated levels of heavy metals. Clay content is also much higher in the ponds than at the control sites (Tables 1 and 2). The correlation coefficient between scores on PC1 and clay content is 0.7 (*P*=0.00). This is consistent with the generally accepted idea that concentrations of heavy metals are directly related to clay content (Haster and James 1994; Sansalone and Buchberger 1997; Singh and others 1999).

Pond sediments have consistently higher concentrations of heavy metals in commercial areas than in residential areas (Table 6). A principal component analysis run on the heavy metal concentrations for just the ponds returned a PC1 that explains 60% of the variance in the data set. A *t*-test on the scores for PC1 indicates that commercial ponds are statistically more polluted with heavy metals than residential ponds (*P*=0.04). A difference in clay content between these two land-use categories exists (Table 1), as does a small difference in age (Table 1), and in principle these factors could cause the dissimilar heavy metal concentrations. The differences in clay content and age are, however, not statistically significant (Table 1). Consequently, in addition to clay content, land use is one of the principle factors that affects heavy metal pollution of these sediments. The effect of land use has been described for urban environments (Wigington and others 1983), but a broader comparison of various types of land use did not find a coherent variation (Cox and others 1998).

Old ponds have higher concentrations of heavy metals than young ponds from the same land-use category (Table 8). The only exception are beryllium and mercury concentrations in residential ponds. This suggests that there is an influence of pond age on heavy metal levels within each of the land-use categories. Some studies of sediments from urban stormwater ponds (Marshall Macklin Monaghan 1992; Fernandez and Hutchinson

Table 7
Heavy metal concentrations at control sites (mg/kg)

	Minimum	Maximum	Mean
Aluminum	2,853	15,175	5,429
Arsenic	1.08	5.23	1.80
Barium	14.18	29.01	18.94
Beryllium	0.39	1.61	0.97
Cadmium	0.09	0.63	0.42
Chromium	3.78	18.53	11.72
Copper	2.53	13.80	8.12
Lead	6.30	21.46	68.38
Mercury	0.0477	0.1344	0.0798
Nickel	3.19	7.60	7.26
Silver	0.04	0.59	0.42
Zinc	5.63	52.94	112.13

Table 6
Heavy metal concentrations for pond sediments (mg/kg). *bdl* Below detection limit

	All			Residential	Commercial
	Minimum	Maximum	Mean	Mean	Mean
Aluminum	2,442	39,413	18,882	16,421	23,498
Arsenic	1.78	7.47	3.82	3.56	4.32
Barium	9.33	81.10	31.82	26.83	41.18
Beryllium	0.41	4.75	1.69	1.67	1.73
Cadmium	bdl	3.13	0.64	0.38	1.15
Chromium	0.22	55.04	17.13	14.27	22.48
Copper	bdl	54.54	16.73	11.04	27.41
Lead	5.34	776.97	59.73	15.68	142.31
Mercury	0.0092	0.3945	0.1108	0.0768	0.1717
Nickel	1.85	23.78	9.80	7.87	13.42
Silver	bdl	2.59	0.74	0.56	1.11
Zinc	0.27	621.55	114.21	39.73	253.85

Table 8
Mean heavy metal concentrations for pond sediments as a function of land use and pond age (mg/kg)

	Residential		Commercial	
	Young[a] 4–5 years *n*=3	Old[a] 9–12 years *n*=9	Young[a] 5–10 years *n*=3	Old[a] 15–19 years *n*=4
Aluminum	14,702	18,482	18,991	26,202
Arsenic	2.92	4.04	4.16	4.41
Barium	26.49	29.64	36.08	44.24
Beryllium	2.36	1.63	1.56	1.84
Cadmium	0.17	0.51	0.77	1.38
Chromium	11.15	15.86	16.34	26.16
Copper	7.60	12.74	15.48	34.56
Lead	11.48	15.55	45.90	200.16
Mercury	0.0913	0.0744	0.1129	0.2070
Nickel	6.58	7.85	11.57	14.54
Silver	0.50	0.59	0.65	1.39
Zinc	29.21	41.73	137.41	323.72

[a] Some ponds are not included because their age could not be determined, age brackets are based on natural break points in distribution of ages

1993) also have found an influence of pond age, which seems reasonable because older ages represent longer accumulation times for the heavy metals, but other studies have been inconclusive (Nightingale 1987). In the present study, the difference between PC1 scores for old and new ponds is statistically not significant for either of the land uses (*P*=0.19 for residential, *P*=0.20 for commercial). For the commercial ponds there is a strong positive correlation between the age of the ponds and PC1 (*r*=0.8), but for the residential ponds there is only a weak correlation between age and PC1 (*r*=0.2). Thus, statistical tests do not fully support the notion that there is an influence of pond age on heavy metal levels within each of the land-use categories. This lack of statistical significance of the tests may be, at least in part, because of the relatively low values for *n*. For the commercial ponds there is also a difference in clay content that potentially could explain the dissimilar concentrations for old and young ponds, but this difference in clay content is not statistically significant (Table 9).

Swales

Concentrations for all heavy metals, except beryllium and mercury, are higher in swale sediments than at the control sites (Tables 10 and 7). A principal component analysis of the heavy metal concentrations for the swales and control sites returned a PC1 that explains 62% of the variance in the data. A *t*-test on the scores for PC1 indicates that swales are statistically more polluted than control sites (*P*=0.00). As did the results for retention ponds, this strongly suggests that stormwater runoff in the study area transports substantial amounts of heavy metals. Clay content is also much higher in the swales than at the control sites (Tables 2 and 3). The correlation coefficient between scores on PC1 and clay content is 0.5 (*P*=0.00). This is again consistent with the generally accepted notion that concentrations of heavy metals in stormwater management systems are directly related to clay content (Haster and James 1994; Sansalone and Buchberger 1997; Singh and others 1999).

No systematic differences exist between the heavy metal concentrations in sediments from swales in commercial and in agricultural areas (Table 10). In commercial areas concentrations are higher for barium, beryllium, cadmium, chromium, copper, lead, nickel, silver, and zinc. The differences for copper, lead, and zinc are statistically significant (Table 10). In agricultural areas concentrations are higher for aluminum, arsenic, and mercury but none of these differences is statistically significant. A *t*-test on PC1, which explained 61% of the variance in the swale data, was consistent with these observations and failed to show a statistically significant difference between swales from agricultural and commercial areas (*P*=0.10).

Although heavy metal concentrations in commercial and agricultural swales are comparable, some of the observed differences make sense. Lead and zinc for instance, are associated with transportation, and there clearly is more traffic in commercial areas. Similarly, mercury and arsenic, which are used in pesticides, are known to be associated with agricultural activities. Higher levels of aluminum in agricultural areas are harder to explain. Clay content is higher in swales in agricultural areas but apparently does not lead to higher heavy metal concentrations (Table 3 and 10). This is contradictory to the finding that, here and in other studies, there is a direct relationship between heavy metal concentrations and clay content. A possible, but unverified, explanation is that production of heavy metals is so much lower in agricultural areas than in commercial areas that it leads to relatively low concentrations of heavy metals in the swale sediments, in spite of the high clay content of the swales.

Table 9
Particle size distribution for pond sediments as a function of land use and pond age (%).**P* value for *t*-test for equality of means

	All		Residential			Commercial		
	All ages	*r*[a]	Young[b] 4–5 years *n*=3	Old[b] 9–12 years *n*=9	*P**	Young[b] 5–10 years *n*=3	Old[b] 15–19 years *n*=4	*P**
Sand	65.1	–0.2	68.1	68.1	0.99	65.7	48.0	0.16
Silt	20.1	0.1	18.4	17.8	0.92	19.7	30.7	0.21
Clay	14.8	0.3	13.5	14.0	0.89	14.6	21.4	0.46

[a] Correlation coefficient between particle size fraction and age
[b] Some ponds are not included because their age could not be determined

Table 10
Heavy metal concentrations for roadside swales (mg/kg). *P for t-test for equality of means, printed in bold when difference is significant at $\alpha=0.05$. *bdl* Below detection level

	All			Commercial	Agricultural	Commercial vs. agricultural
	Minimum	Maximum	Mean	$n=6$	$n=16$	P^*
Aluminum	5,173	55,158	19,837	15,032	21,638	0.19
Arsenic	1.58	17.68	5.59	4.60	5.95	0.33
Barium	14.75	163.27	47.60	53.95	45.22	0.71
Beryllium	bdl	2.63	0.84	1.35	0.70	0.19
Cadmium	0.12	4.12	0.93	1.69	0.64	0.15
Chromium	2.17	43.47	15.48	24.53	12.08	0.10
Copper	2.07	49.59	14.09	27.10	9.21	**0.02**
Lead	19.80	189.47	68.27	121.10	48.46	**0.01**
Mercury	0.0261	0.1818	0.0689	0.0644	0.0706	0.67
Nickel	2.06	23.35	11.10	12.46	10.59	0.61
Silver	bdl	2.44	1.01	1.42	0.85	0.07
Zinc	16.25	565.24	101.05	268.39	38.29	**0.03**

One can also speculate that the apparent contradiction is caused by differences in clay mineralogy. The effect of clay mineralogy on cation exchange capacity and adsorption of heavy metals has long been recognized (Bittell and Miller 1974), and has been discussed in the context of pollution of stormwater ponds (Nightingale 1987; Fernandez and Hutchinson 1993). The agricultural part of the study area is underlain by old and highly weathered soils. The dominant type of clay mineral in those soils are low activity 1:1 clays that have low cation exchange capacities. The effect of clay content on heavy metal concentration may, therefore, be smaller in those agricultural areas than in commercial areas, which are located on younger and less weathered soils that presumably have higher cation exchange capacities.

A comparison of the two types of agricultural land use shows large and systematic differences (Table 11). Swales near cotton fields have higher concentrations for all heavy metals, except beryllium, than swales near pastures. Differences are most pronounced for aluminum, barium, copper, and nickel, and the majority of the differences is statistically significant (Table 11). A t-test on scores for PC1 was consistent with these observations and showed a statistically significant difference between swales near cotton fields and swales near pastures ($P=0.01$). This suggests that a very specific influence of the type of agricultural land use on heavy metal concentrations in swales exist. However, clay content is also highest in swales near cotton fields and can potentially explain the observed differences (Table 4). Because it was argued above that clay content is affected by land use, land use is ultimately the dominant factor.

Table 11
Mean heavy metal concentrations for roadside swales as a function of agricultural land use (mg/kg). *P for t-test for equality of means, printed in bold when difference is significant at $\alpha=0.05$

	Cotton $n=7$	Pasture $n=5$	Cotton vs. pasture P^*
Aluminum	26,607	10,734	**0.01**
Arsenic	6.57	2.91	**0.02**
Barium	49.39	21.01	**0.05**
Beryllium	0.43	1.03	**0.02**
Cadmium	0.78	0.36	**0.01**
Chromium	14.95	9.39	0.32
Copper	12.36	4.58	**0.03**
Lead	59.50	32.93	**0.01**
Mercury	0.0773	0.0465	**0.02**
Nickel	13.47	5.22	**0.01**
Silver	0.87	0.48	0.25
Zinc	46.66	25.53	**0.03**

Sweepings

Concentrations for many heavy metals are lower in street sweepings than at the control sites (Tables 7 and 12). Arsenic, barium, cadmium, copper, and silver are higher at the control sites. A t-test on the scores for PC1, which explains 31% of the variance in the data set, indicates that there is a statistically significant difference between street sweepings and control sites ($P=0.00$). The value of this statistical test obviously has to be qualified because of the low variance explained by PC1. Clay content is more than 50% lower in the sweepings than at the control sites (Tables 3 and 4) and can account for the generally lower concentrations. As shown above, rotary brush sweepers are inefficient in collecting fine materials. The lower concentrations of heavy metals in sweepings can, therefore, be ascribed to the ineffectiveness of the street sweepers in picking up clay particles.

Street sweepings from residential areas have higher concentrations for most of the heavy metals than sweepings from commercial areas (Table 12). The only statistically significant difference is for beryllium. Sweepings from commercial areas have higher concentrations for chromium, mercury, and zinc, but none of these differences is statistically significant (Table 12). A t-test for equality of means on the first principle component, which explains 45% of the variance in the data set, fails to show a statistical difference between residential and commercial areas ($P=0.69$). These observations indicate that some differences in heavy metal pollution in street sweepings from residential and commercial areas exist, but they are not large, systematic or statistically significant. This similarity in concentrations is consistent with equal clay contents for

Table 12
Heavy metal concentrations for street sweepings (mg/kg). *P for *t*-test for equality of means, printed in bold when significant at α=0.05. *bdl* Below detection limit

	All			Residential	Commercial	Resid. vs. commer.
	Minimum	Maximum	Mean	Mean	Mean	*P**
				n=11	*n*=6	
Aluminum	1,278	17,312	4,252	4,837	3,181	0.30
Arsenic	bdl	13.30	1.96	2.5	1.03	0.36
Barium	6.31	85.91	27.35	29.6	23.22	0.54
Beryllium	bdl	1.799	0.63	0.77	0.28	**0.04**
Cadmium	bdl	1.37	0.50	0.70	0.29	0.10
Chromium	1.26	21.06	9.70	9.57	9.95	0.91
Copper	2.43	43.53	9.62	10.19	8.60	0.70
Lead	5.24	94.12	19.68	19.86	19.33	0.95
Mercury	0.0006	0.0502	0.0188	0.0135	0.0286	0.08
Nickel	0.88	13.93	6.20	6.42	5.81	0.73
Silver	bdl	1.30	0.73	0.81	0.59	0.39
Zinc	6.77	108.19	38.48	28.95	55.94	0.11

the two land-use categories (Table 5), whereas the slight difference (i.e., seemingly lower concentrations in commercial areas) can be explained by a higher frequency of sweeping in commercial areas.

Although the reasons for the differences between land-use categories are not always apparent, it is within expectations that somewhat higher levels of chromium, mercury, and zinc are observed in commercial areas. For example, chromium is used in steel, in plating, and as a pigment in glass; zinc is used as a pigment, in car tires and in industrial applications; and mercury is used in lamps, batteries, and pesticides.

Comparison of heavy metal data for ponds, sweepings, and swales

Of the three stormwater management systems, street sweepings have the lowest concentrations of heavy metals (Tables 6, 10, and 12). This may be because of short accumulation times on streets, about 8 weeks, as compared to the age of ponds and swales (years). However, for many metals concentrations in street sweepings are also lower than concentrations in natural soils (Tables 7 and 12) and differences in accumulation times can not explain this difference. Clay content in street sweepings is an order of magnitude lower than clay contents in ponds and swales (Tables 1, 3, and 5) and about 50% lower than the clay content at control sites (Tables 2 and 5). This enforces the idea that clay content is an important factor in the variability of heavy metal concentrations.

The above observation that sweepings have the lowest concentrations for heavy metals suggests that if streets were not swept, and the less contaminated materials were washed into retention ponds by stormwater runoff, sediments in retention ponds would be diluted and the rate of increase of heavy metal concentrations would be lower. Because environmental regulations that apply to the reuse and disposal of pond sediments are based on concentrations (FDEP 2000; NOAA 2000; ORNL 2000; USEPA Region III 2000), letting the pond sediments be diluted with these less contaminated materials could possibly increase the number of acceptable reuse and disposal options. Obviously, with time more and more contaminants would accumulate in the ponds and contaminant loading (loading is the concentration of the pollutant times the weight of the material the pollutant is in) of the ponds would increase. This is clearly not a desirable effect from an environmental point of view, but loadings do not seem to be regulated for the reuse and disposal options.

The lowest concentrations for most of the heavy metals can be found in street sweepings from commercial areas (Tables 6, 10, and 12). The highest concentrations for most of the heavy metals appear in swales and ponds in this same type of land use. This is consistent with the above contention that sweeping streets remove only the less contaminated coarse materials. Because commercial areas are swept more often, the less contaminated materials are removed more frequently, and the concentration of what is left behind on the streets and washed into retention ponds is increased more often.

Conclusions

The particle size distribution of sediments in retention ponds and swales depends on land use. For ponds, the effect of land use is mainly through its influence on street-sweeping frequency and thus the frequency of selective removal of coarse materials from sediments that will be washed into retention ponds. For swales the effect of land use is through its influence on erosion and the associated preferential transportation of fine particles from natural soils into the swales. The particle size distribution of street sweepings is consistent, does not vary with land use, and is much coarser than the texture of the local natural soils. This is because of the inability of the employed type of street sweeper to pick up small particles.

Sediments from retention ponds and swales are more polluted with heavy metals than natural soils in the area. These elevated levels result from the accumulation of metals transported by stormwater runoff and are bolstered by relatively high amounts of clay in the sediments. Street sweepings have low levels of heavy metal pollution because of their coarse particle size.

Sediments from retention ponds are more polluted with heavy metals in commercial areas than in residential areas. The higher levels of pollution can not be explained by age of the pond or clay content because, in the present study, these factors are not significantly different for the two land-use categories. Land use is, therefore, one of the major factors contributing to the differences in heavy metal concentrations in the sediments. Within each of the two land-use categories heavy metal concentrations increase with pond age. This implies that reuse and disposal options for sediments from stormwater retention ponds will vary with land use and pond age. These factors should be taken into consideration when formulating reuse and disposal guidelines for the sediments or when preparing long-term pond clean out schedules.

Swale sediments are more polluted with heavy metals in commercial areas than in agricultural areas, although the latter have higher clay contents. A possible explanation for this apparent contradiction is that in agricultural areas heavy metal production is low enough to offset the abundance of clay. In the agricultural areas swales near cotton fields have higher concentrations of heavy metals than swales near pastures. These higher levels may be because of land-use related factors, such as the more intense use of pesticides, herbicides, defoliants, and fertilizers on cotton, but also appear to be caused by higher clay content.

Heavy metal concentrations in street sweepings from commercial and residential areas are similar. This lack of variation is probably related to the consistent particle size distribution and the very sandy nature of the sweepings. Slightly lower concentrations are observed in commercial areas where the frequency of sweeping is somewhat higher.

Of the three stormwater management systems studied, street sweepings have the lowest concentrations of heavy metals. These low concentrations are because of the inability of street sweepers to collect the finest street dust, to which most heavy metals are adsorbed. This suggests that if streets were not swept, the less polluted sediments would be washed into ponds, and heavy metal concentrations would increase at a lower rate. From an environmental perspective it is not desirable to stop sweeping streets because pollutant loading in ponds would increase. However, because reuse and disposal regulations for these materials are based on concentrations, and not loading, one could argue that from a regulatory perspective more reuse and disposal options for the retention pond sediments would be available if streets were not swept.

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