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Trace metal levels in sediments deposited in urban stormwater management facilities

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Abstract Characteristics of solids recovered from stormwater best management practice (BMP) facilities, including stormwater ponds, constructed wetlands, an infiltration basin, a biofilter, a stormwater treatment clarifier, and three-chamber oil and grit separators were described with respect to their metal chemistry. The reported trace metal concentrations in BMP sediments were assessed against the Ontario Sediment Quality Guidelines. Between 80 to 100% of all samples were marginally-to-intermediately polluted by Cd, Cr, Cu, Fe, Pb, Mn, Ni and Zn. Severe pollution of sediments was noted for Cr (122 μg/g), Cu (151 and 196 μg/g), Mn (1,259 and 1,433 μg/g), and Zn (1,116 μg/g), at several facilities studied, and even higher levels of metals were reported in the literature for certain oil and grit separators. With respect to individual BMPs, the severe pollution was found in sediments from oil and grit separators (for Cd, Cr, Cu, Pb and Zn), the stormwater clarifier sludge (Cu, Mn and Zn), a biofilter (Cu and Mn), an industrial area stormwater pond (Cu only), and a commercial/residential pond (Cr only). Finally, the chemical pollution of pond sediment triggered toxicity testing at some of the facilities studied, and sediment toxicity was confirmed at several sites.

Keywords Best management practices; sediment; sediment quality guidelines; stormwater management; trace metals

Introduction

Management and control of solids is one of the primary tasks of stormwater management arising from the need to mitigate impacts of suspended solids and sediment on the operation of drainage systems and water and habitat quality in receiving waters (MOE, 2003). Sources of solids in urban areas are numerous and include soil erosion, attrition/corrosion of pavements and other surfaces, vehicular traffic, atmospheric deposition, vegetation, litter, spills, and street sanding (Sartor and Boyd, 1972). In wet weather, surface runoff scours solids deposited on urban surfaces and transports them to the drainage system, and/or directly to the receiving waters. Solids accumulations are best controlled by source controls, but depending on the success of such measures, significant quantities of solids do enter stormwater and are transported to, or deposit in, various components of the drainage system. The presence of solids and sediment in the drainage system causes concerns about physical effects on system operation (blockage of inlets and sewers; clogging of such stormwater BMPs as infiltration facilities and filters; reduction of active storage of wetlands and ponds, etc.), and the water quality and aesthetic impacts. Among the water quality impacts, the most common problem is the transport of pollutants, including pathogens. Association of pollutants with urban solids was reported by many authors, referring to street surface residue (Stone and Marsalek, 1996), deposits in sewers, and accumulations in various BMPs, including ponds (Marsalek *et al.*, 1997b), wetlands (Bishop *et al.*, 2000), filters (Mothersill *et al.*, 2000), and oil and grit separators (Schueler and Shepp, 1993). The occurrence of solids deposits and accumulations affects stormwater BMPs in two ways: (a) the need to mitigate adverse impacts on BMP operation by implementation of more complex and costly treatment trains, and (b) degradation of

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habitat functions of BMPs by accumulation of contaminated sediment, with a further risk of release of mobile pollutant fractions (Bishop *et al.*, 2000; vanLoon *et al.*, 2000). The issues of BMP sediment contamination by heavy metals and the need to account for such environmental risks by proper maintenance are discussed for various types of BMP facilities, including ponds, constructed wetlands, an infiltration basin, a biofilter, a stormwater clarifier and three-chamber oil and grit separators.

Sources of data: BMP facilities analysed

The description of the stormwater BMPs studied, or BMPs for which data were adopted from the literature, is limited to basic characteristics, with references to more detailed information presented elsewhere. The selection of the BMPs discussed herein follows from an overview of numerous studies of BMPs, including graduate thesis projects and BMP assessment studies.

Kingston stormwater pond

The Kingston (Ontario, Canada) Pond is an on-line stormwater management pond, which was built in 1982 to reduce peak stormwater flows from a shopping mall. The two-cell pond consists of a permanent wet pond (area 5,200 m^2 and 1.2 m average depth) and a dry pond (area 5,000 m^2) that floods during larger storm events. Figure 1 shows the pond layout and the location of instrumentation and weirs at the inlets and outlet. Research findings on the Kingston Pond performance and processes were presented elsewhere (Anderson *et al.*, 2002; Van Buren *et al.*, 1997); only the basic findings concerning sediment issues are summarised herein. Marsalek *et al.* (1997b) reported that pond bottom sediments had accumulated at an average rate of 0.02 m/year and comprised gravel, sand, silt and clay; the gravel and sand accumulated only by the inlet whereas the silt and clay were spread throughout the pond and represented up to 45% and 54% of the total sediment respectively. Marsalek (1997) estimated the volume of the inlet sand spit at 150 m^3, and the corresponding sediment mass at 160 t, accumulated over 15 years. The water content of the sediment (by volume) ranged from 48% by the inlet to 75% at the outlet. Anderson *et al.* (2002) noted a disadvantage of on-stream stormwater ponds built on urbanizing catchments – such ponds accumulate sediment at relatively high rates and will require more frequent sediment removal than off-line facilities.

Stormwater wet pond 1

The pond WP1 consists of two irregularly shaped cells in series with a total storage of 68,000 m^3. The upstream cell (with a surface area of 1,750 m^2) is fed by three sewers draining two residential communities and a business park. Flow travels from the upstream cell into the downstream cell (surface area of 3,000 m^2) through three culverts. Sediment samples were collected in the downstream cell (vanLoon *et al.*, 2000).

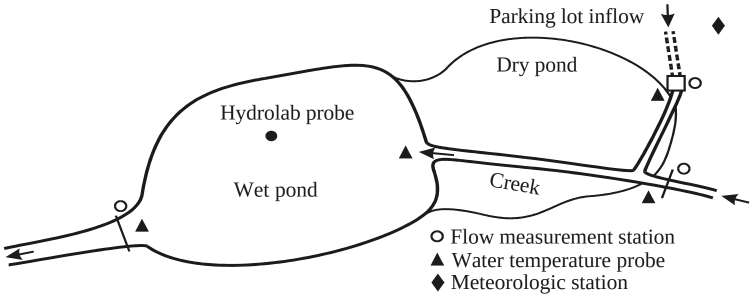

Figure 1 Kingston stormwater management pond

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Stormwater wet pond 2

The pond WP2 consists of two elongated rectangular pond cells, in-series, each with dimensions of about 400 m × 25.5 m (length × width), and a total pond storage of 23,000 m^3. The pond serves principally a residential area, with additional input from about half a dozen agricultural drains. The facility is operated in batch mode and retains stormwater for up to 72 hours (vanLoon *et al.*, 2000).

Harding Park pond

A relatively small pond (surface area = 0.7 ha; volume = 3,000 m^3, comprising 1,000 m^3 permanent pool storage and 2,000 m^3 active storage; maximum depth = 1.5 m) receiving stormwater runoff from a residential area of 16.8 ha in north-east Toronto (Ontario, Canada). The pond consists of three cells – a sediment forebay, a quiescent settling permanent pool and a wetland (Bishop *et al.*, 2000).

Col. S. Smith reservoir

The CSS pond serves a catchment of 340 ha, with industrial, commercial, residential and transportation land uses. It receives runoff from a major multilane divided highway with traffic densities over 100,000 vehicles/day. The pond is of a rectangular shape (38 m × 75 m, length x width), with a surface area of about 0.28 ha and average depth of 2.4 m (nominal volume of 7,000 m^3) (Mayer *et al.*, 1996).

Constructed wetlands

The chemistry of sediments from constructed wetlands serving for stormwater management was reported by Bishop *et al.* (2000). To extend the discussion of BMP sediment quality, the data reported for four constructed wetlands in Guelph (Ontario, Canada) were included here. These wetlands serve to control stormwater from residential areas, and their surface areas range from 2,500 to 7,700 m^2, and depths from 0.2 to 0.7 m. All four facilities yielded similar concentrations for individual metals, which were described by average values for the whole set.

Infiltration basin (IB)

The basin was constructed in an abandoned sand pit, with a capacity of 6,500 m^3. Soils in the basin area are sandy to great depths and underlain with clay. The basin substrate is formed by slightly alkaline crushed stone, forming a 0.3 m layer over 1.25 m of sand. The sand is separated from native soils by a non-woven filter cloth. The facility is equipped with sub-drains. Roadways and other impervious areas form about 25% of the contributing area, another 25% are industrial lands, and the remaining 50% is divided among undeveloped land, a golf course, commercial and other land uses (vanLoon *et al.*, 2000).

Stormwater biofilter

The biofilter was installed at the Kingston Pond outlet and used to polish the pond effluent. It was formed by filling a polyethylene tank (1 m × 1 m × 1 m) with inert expanded schist media, with a nominal diameter of 3–6 mm. When hydraulic losses increased over a threshold, the filter was backwashed. Samples of solids captured by the filter were collected by removing samples of media after three years of operation (Mothersill *et al.*, 2000).

Etobicoke stormwater clarifier

Stormwater treatment by constant high-rate clarification was studied in Etobicoke (Toronto-area, Ontario, Canada) at a site upstream of the Col. S. Smith Reservoir.

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The clarifier was fed with a submersible pump from a 2.5 m diameter storm sewer draining an area of about 300 ha, comprising industrial, commercial, and residential land. The rectangular clarifier was 3 m long, 1.4 m wide and 2 m deep. Stormwater at this site was found to be polluted, with typical concentrations falling between the mean and the 90th percentile of the US NURP data (Wood *et al.*, 2004).

Three-chamber oil and grit separators

Oil and grit separators (OGSs) were developed for control of contaminated sediments and free oil spills at inlets to storm sewers. The original designs used in Maryland comprised three chambers, serving for sediment settling and oil retention. These designs were susceptible to sediment washout and were later replaced by manhole-type designs. The chemistry of sediments retained in OGSs was reported by Schueler and Shepp (1993) and included here as average data for 19 facilities.

Results and discussion

Metal burdens in BMP sediments were analyzed for up to 10 metals and inorganics, which are commonly listed in sediment quality guidelines (e.g. MOEE, 1992) and are of interest in environmental studies. Specifically, this list contains the three most ubiquitous anthropogenic metals, Cu, Pb and Zn, which are known to occur in urban areas at high concentrations and may exert toxic effects, and consequently, they are included on the US EPA list of 129 Priority Pollutants. All three were detected in at least 91% of all NURP runoff samples (US EPA, 1983). The next group of five chemicals, As, Cd, Cr, Hg and Ni, are included in the US EPA Priority list, but their occurrences in urban areas are significantly less frequent (except for Hg, in $>40\%$ of samples) (US EPA, 1983). Finally, Fe and Mn are included in the Ontario guidelines for assessing sediment quality (MOEE, 1992).

The Ontario sediment quality guidelines (MOEE, 1992), described by the Lowest Effect Level (LEL) and the Severe Effect Level (SEL), and metal concentrations in BMP sediments are presented in Table 1. For brevity, As, Hg and Fe concentrations were omitted; in the case of As and Hg, no data exceeded the corresponding LELs of 6 and 0.2 μg/g, respectively, and in the case of Fe, limited data ranged from 1.8 to 3.0% (LEL = 2%, SEL = 4%).

Table 1 Sediment quality guidelines and metal concentrations in BMP sediment

Guideline or BMP Type	Constituent concentration [μg/g]						
	Cd	Cr	Cu	Mn	Ni	Pb	Zn
MOE-LEL (sediment quality guideline)	0.6	26	16	460	16	31	120
MOE-SEL (sediment quality guideline)	10	110	110	1,100	75	250	820
Kingston Pond (outlet)(Kingston)	1.4	**122**	80	485	34	149	406
WP1 (pond) (Ottawa area)	0.46	42	28	–	25	20	127
WP2 (pond) (Ottawa area)	0.53	31	22	–	15	22	95
Harding Park pond (Toronto)	< 1	24	37	484	24	24	117
Col. Sam Smith pond (Toronto)	4.2	45	**151**	693	–	202	610
Constructed wetlands (average)(Guelph)[1]	0.07	16	39	–	11	45	397
Infiltration basin (Ottawa area)	1.9	55	86	–	28	107	514
KP biofilter (Kingston)[2]	1.0	49	73	**1,433**	43	82	352
Stormwater clarifier (Toronto)[3]	1.7	61	**196**	**1,259**	–	200	**1,116**
Three-chamber OGS (average)(USA)[4]	**19.4**	**300**	**346**	–	–	**599**	**2,100**

[1] Constructed wetlands = average of four facilities, data from Bishop *et al.* (2000); [2] KP biofilter = biofilter used to polish effluent from the Kingston Pond; [3] Stormwater clarifier = a clarifier operated upstream of the Col. S. Smith pond; [4] Three-chamber Oil Grit Separators (average) = average of 19 facilities sampled by Schueler and Shepp (1993)

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Environmental significance of observed data

The presence of high concentrations of heavy metals creates an environmental hazard, but the actual risk is difficult to assess without assessing the mobility and bioavailability of such burdens (Mikkelsen *et al.*, 2001). There are a number of sediment quality guidelines that help assess the degree of sediment pollution. In this study, the Ontario aquatic sediment quality guidelines (see Table 1) were adopted as the most appropriate for most of the locations studied. These guidelines serve as triggers, which if exceeded, initiate further action including biotesting. Further discussion of potential ecotoxicological risks of sediment from various BMPs follows and focuses on individual BMPs, chemical levels, metal speciation, and toxicological data.

Comparison of individual BMPs

Among the sites studied by the authors, two stand out in terms of metal concentrations – the stormwater clarifier and Col. S. Smith pond, both located on the same sewer trunk and collecting sediment from the same sources. Undoubtedly, this catchment produces fairly polluted stormwater and sediments (Wood *et al.*, 2004) significantly exceeding the level of pollution for the US NURP median site (US EPA, 1983). The runoff from the area drained appears to be heavily polluted by highway runoff and possibly by older *in situ* deposits arising from industrial operations in this catchment. However, the metal concentrations in the clarifier sludge are generally lower than those reported for highway runoff sediment by Marsalek *et al.* (1997a): Cu = 314, Ni = 56, Pb = 402, and Zn = 997 μg/g, and much lower than the fine fraction of such sediment ($< 45\,\mu$m), Cu = 737, Ni = 126, Pb = 527, and Zn = 1,634 μg/g. The quality of highway runoff sediments is fairly similar to that of sediments collected by Schueler and Shepp (1993) from oil and grit separators: Cd = 19.4, Cr = 300, Cu = 346, Pb = 599, and Zn = 2,100 μg/g (average of 19 sites, with various land use). Such data exceed the Ontario SELs by about three times, and reflect the nature of the trapped sediments – sediments associated with road runoff, with high content of volatile solids (5–45%) and presence of hydrocarbons. The lowest metal concentrations were observed for three residential ponds, WP1, WP2 (vanLoon *et al.*, 2000) and the Harding Park Pond, and four constructed wetlands (Bishop *et al.*, 2000).

In the overall assessment of Ontario data, only 8.1% (six cases) of site mean concentrations listed in Table 1 exceeded the SEL, with two thirds of those originating in the Etobicoke catchment. Exceedances of Cu, Zn and Mn limits were consistent with the pollution sources in the areas studied, including highway runoff. Among the remaining sites, only the outlet concentrations of Cr in the Kingston Pond exceeded the SEL, but those elevated concentrations were affected by the local geology and represented largely non-bioavailable Cr, as documented by the high residual Cr fraction at this site, up to 60% (Marsalek *et al.*, 1997b). The last exceedance of the SEL was observed for Mn in the biofilter sediment. There is a possibility that the filter medium retained the finest Mn enhanced sediments, with Mn concentrations about twice those found in the pond sediment. The remaining metal concentrations were typically significantly below the SEL, but greater than the LEL.

To synthesise the BMP sediment pollution data, a pollution index was introduced, relating individual metal concentrations to the corresponding SEL, and characterising each BMP by an average index value. Further simplification was possible by grouping all residential pond data together. BMP sediment pollution index values are shown in Figure 2.

The data in Figure 2 indicate that the least polluted sediments are found in residential ponds and constructed wetlands with low input of road runoff. Increased inputs of

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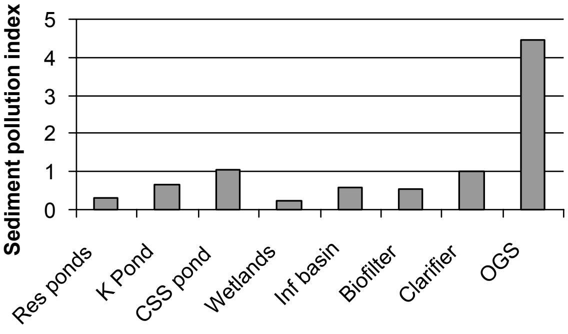

Figure 2 Sediment pollution index (SPI) for various BMPs (SPI $= \Sigma\ (C_i/SEL_i)/n$, $i = 1-n$)

polluted sediments from road/highway runoff (or similar sources) are reflected in lower quality of sediments in ponds or "treatment" devices processing stormwater (biofilter, clarifier, OGS separators).

While sediment chemistry data may indicate relatively high burdens, such loads represent environmental risks only if bioavailable, or susceptible to transformations which would make them bioavailable. To address the issues of bioavailability, various approaches are used, starting with speciation of metal fractions using sequential analysis, followed by biotesting either *in situ*, or in the laboratory. Some experience with such approaches is reviewed below.

Sequential analysis proposed by Tessier *et al.* (1979) leads to determination of five particular metal fractions operationally defined as exchangeable (Fraction 1), bound to carbonate (Fraction 2), bound to iron and manganese oxides (Fraction 3), bound to organic matter (Fraction 4), and residual (Fraction 5). Using this procedure, sediment samples from seven sites were analysed and the results are summarised in Table 2.

The data in Table 2 indicate large differences in speciation of metals in BMP sediments. The most potentially mobile is Cd, followed by Cu and Pb. The least potentially mobile (and bioavailable) is Cr. It appears from Table 2 that for most metals, the oxidizing and reducing conditions would be most critical with respect to release of metals from sediments, and this indicates the importance of maintaining a stable oxygen regime in stormwater management ponds. Another way of studying bioavailability of accumulated trace metals in pond sediments is by studying metal uptake by caged freshwater mussels. Anderson *et al.* (2004) found no correlation between total metals in pond sediments and the accumulated burden in the mussels. Results also suggested that Pb was a possible concern due to bioavailability, Ni, Cr and Cd did not appear to be in bioavailable forms, and Cu had some limited bioavailability. It was suggested that this type of evaluation tool also be considered by managers in determining operation and maintenance for BMP facilities.

Table 2 Sequential analysis results for sediment samples from seven sites

Source	Sediment fractions [%] (mean of seven sites)				
	Cd	Cr	Cu	Pb	Zn
Fraction 1	12.0	0.7	1.2	1.8	0.3
Fraction 2	38.5	1.2	3.5	14.7	15.8
Fraction 3	25.3	7.7	15.0	43.2	19.5
Fraction 4	12.5	23.3	53.5	22.3	28.8
Fraction 5	11.8	67.5	26.3	26.3	35.8

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Sediment particle size affected the sediment chemistry, with fine particles (silt and clay) by the Kingston pond outlet (line 5 in Table 1) containing up to four times higher concentrations of metals than sandy particles by the inlet (Marsalek *et al.*, 1997b). The presence of organic carbon would be particularly important for Cu, which seems to have a significant fraction bound to organic matter. For Kingston pond sediment, organic carbon varied from 3.8% in bottom sediment to 5.8% in suspended particulate (Marsalek *et al.*, 1997b); much higher levels were noted in the stormwater clarifier (Wood *et al.*, 2004), with VSS representing on average 26% of TSS. Also, the OGS data in Table 1 indicate that sediments with higher organic content contain higher metal levels (Schueler and Shepp, 1993).

Besides trace metals, other chemicals in BMP sediment are also of interest in connection with toxicological considerations. Earlier research indicated two major groups of potential toxicants – hydrocarbons (particularly polycyclic aromatic hydrocarbons, PAHs) and pesticides. For the Kingston Pond, Marsalek *et al.* (2002) reported total PAH concentrations of 16.37 μg/g, well below the SEL level in Ontario guidelines (specified as 10,000 μg/g of organic carbon). Dutka *et al.* (1994) studied sediment toxicity in four Toronto area ponds, and found incidences of sediment toxicity, which appeared related to pesticides (triazine, metolachlor) in late spring sampling. Without specialized TIE (Toxicity Identification Evaluation) analysis, it appears impossible to clearly identify the sources of toxicity. Most likely, the synergistic effect of various chemicals, and the ambient BMP conditions, lead to sediment toxicity and the development of chemical protocols should focus on known sources of toxicants in the areas studied.

Sediment toxicity testing was reported for the Kingston Pond (Marsalek *et al.*, 1999) and five Toronto ponds (Dutka *et al.*, 1994; Mayer *et al.*, 1997; Rochfort *et al.*, 2000). A variety of bioassays were employed in these tests, including the well known Microtox™ solid phase test, the direct solid-phase SOS-chromotest (for genotoxicants), *Panagrellus redivivus* (nematode), and benthic toxicity tests (*H. azteca*, *C. riparius*, *Hexagenia* spp., *T. tubifex*; Rochfort *et al.*, 2002). Such tests indicate the overall toxicity of sediments, without identification of causal constituents. In all studies, some toxic effects were noted. In the Kingston Pond, Microtox™ test results indicated toxicity in pond flow sources – an upstream creek and runoff from a commercial plaza, strong toxicity of sediments in the pond, and no toxicity in the creek downstream of the pond (Marsalek *et al.*, 1999). Even higher toxicity was indicated by Microtox™ for sediments in the Rouge River Pond (Toronto), receiving runoff from a major multi-lane divided highway (Marsalek *et al.*, 1999). In four Toronto ponds (including Col. S. Smith reservoir), sediment solvent extracts showed toxic responses, suggesting presence of organic toxicants/genotoxicants. The highest incidence of responses was found in the Col. S. Smith pond (Mayer *et al.*, 1997), and on a seasonal basis, in spring. The Dutka *et al.* (1994) study also showed the presence of toxicants and genotoxicants in sediments, indicating the presence of bioavailable toxicants and promutagens, with no seasonal patterns. Finally, benthic toxicity testing indicated no toxicity in the Harding Pond (residential pond), but toxicity indications in the receiving creek, both upstream and downstream of the pond outlet, and therefore attributable to other sources (Rochfort *et al.*, 2000).

Conclusions

Stormwater BMP treatment trains are designed to immobilize suspended solids and sediment in various train elements to protect downstream BMPs and drainage elements against clogging and the downstream waters against pollution. These designs lead to accumulation of solids in BMPs, including ponds, wetlands, biofilters, infiltration basins, and oil and grit separators. Such solids are fairly polluted by metals and inorganics, as

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indicated by the data reported in this study, and by other chemicals, as reported in the literature. The highest concentrations of heavy metals were found in two facilities serving an area with industrial land and a highway corridor. Identification of chemicals exerting toxic effects remains a challenge and, consequently, direct toxicity testing may be more effective. Circumstantial evidence points to highway runoff sediment as a major contributor to BMP sediment toxicity. Guidelines for operation and maintenance of BMPs neglect the ecotoxicological risks associated with contaminated BMP sediments and should be amended to account for, and to minimise, such risks.

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