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Assessing urban stormwater toxicity: methodology evolution from point observations to longitudinal profiling

Lee Grapentine, Quintin Rochfort and Jiri Marsalek

ABSTRACT

The quality of aquatic habitat in a stormwater management facility located in Toronto, Ontario, was assessed by examining ecotoxicological responses of benthic invertebrates exposed to sediment and water from this system. Besides residential stormwater, the facility receives highway runoff contaminated with trace metals, polycyclic aromatic hydrocarbons (PAHs), and road salt. The combined flow passes through two extended detention ponds (in series) and a vegetated outlet channel. Toxicity of surficial sediment collected from 14 longitudinally arrayed locations was assessed based on 10 acute and chronic endpoints from laboratory tests with four benthic organisms. Greatest overall toxicity was observed in sediment from sites in the upstream pond, where mortality to amphipods and mayflies reached up to 100%. Downstream pond sediment was less toxic on average than the upstream pond sediment, but not the outlet channel sediment where untreated stormwater discharges provided additional sources of contamination. Macroinvertebrate communities in sediment cores were depauperate and dominated by oligochaetes and chironomids, with minimum densities and diversity at the deeper central pond sites. While sediment toxicity was associated with high concentrations of trace metals and high-molecular weight PAHs, benthic community impoverishment appeared related to high water column salinity.

Key words | benthic invertebrates, ecotoxicity, sediment, stormwater management ponds

Lee Grapentine
Quintin Rochfort
Jiri Marsalek (corresponding author)
Water Science and Technology Branch,
Environment Canada,
Burlington, Ontario,
Canada L7R 4A6
E-mail: *Lee.Grapentine@ecv.gc.ca*;
Quintin.Rochfort@ec.gc.ca;
Jiri.Marsalek@ec.gc.ca

INTRODUCTION

Urban stormwater runoff has been recognised as one of the major causes of environmental impacts on receiving waters, with respect to the hydrological regime, sediment regime, physical habitat structure, thermal modifications, and chemical inputs affecting water quality. During the past 25 years, the research in this field addressed stormwater quality and its characterisation with respect to chemistry and microbiology and a vast number of such studies were published (e.g., Duncan 1999). At the same time, the number of chemical substances detected in urban stormwater also grew, with the current estimates in the range from 600 to 900 substances. Under these circumstances, it is becoming ever more challenging to select proper analysis protocols for studies of stormwater quality, while striving to include all the constituents of potential importance and keeping analytical costs under control. This dilemma led to the adoption of biomonitoring in urban runoff quality studies, with a focus on ecotoxicity.

Toxicity testing is not without complications of its own considering the multitude of tests, test organisms and endpoints, media tested and methods of data interpretations described in the literature (Burton *et al.* 2000). With respect to the exposure and typical toxicant concentrations, there is interest in acute toxicity and chronic toxicity, both of which may be relevant to urban stormwater quality assessment. Acute toxicity was reported primarily for highway runoff

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(Marsalek *et al.* 1999*a*,*b*), but other less polluted sources of stormwater may be causing just chronic effects. Toxicity testing of various sources of stormwater, including runoff from highways with various traffic densities, commercial areas, and mixed land use residential areas produced valuable results with respect to assessing priorities for controlling runoff pollution from various types of urban land use. However, it did not reflect well actual conditions in receiving waters resulting from intermittent exposures of biota to stormwater discharges of various levels of pollution, and their mixing and transport in receiving waters. Consequently, the authors modified their toxicity assessment methodology by adopting a sediment quality triad approach (Chapman 1990), in which the sediment chemistry and toxicity data are supplemented by in-situ assessments of benthic invertebrate communities. In the early applications, the triad approach was applied at paired sites, typically located upstream and downstream of stormwater outfalls (Rochfort *et al.* 2000; Grapentine *et al.* 2004). This approach provided more realistic results in terms of toxicity measurement and in-situ assessment of impacts on benthic organisms, which are important indicators of general stream "health" and represent a major source of energy for fish. However, the "discrete" site approach provides spatially limited information, and consequently the authors further extended their methodology by conducting multiple site/multiple source investigations along longitudinal reaches through receiving stream/stormwater management systems, as demonstrated here in the study of the Terraview-Willowfield Stormwater Management Park in Toronto, Canada. The purpose of the study was to assess habitat conditions in the regenerated habitat of the facility, and to evaluate the efficacy of its stormwater quality enhancement, which was judged based on the degree to which water and sediment quality improved from upstream to downstream in the facility.

STUDY AREA

The Terraview-Willowfield Stormwater Management Park (TWSMP) is a multi-feature facility dividing runoff from 39 ha of urban land (30 ha residential land, 9 ha 16-lane freeway) into two treatment trains: (a) a surface water train comprising a sediment forebay, two stormwater management ponds, and connecting and outlet channels, with the main runoff entry at the upstream end and additional inflows through five storm sewer outlets distributed along the connecting channel between both ponds and the concrete-lined outlet channel immediately below the second pond (see Figure 1), and (b) a subsurface stormwater treatment train featuring an underground exfiltration vault. Only the surface train, providing aquatic habitat, is addressed here.

METHODS

Surficial sediment quality was assessed by collecting samples longitudinally through the TWSMP from the sediment forebay and into the outlet channel about 260 m downstream of Willowfield Pond. In each of 2003 and 2004, 41 sediment cores were collected and analysed for selected trace metals and polycyclic aromatic hydrocarbons (PAHs), which represent the two major groups of pollutants in highway runoff feeding into the TWSMP (Burton & Pitt 2002).

Sediment toxicity and benthic community structure were assessed in 2003 at 14 points along the longitudinal profile. Toxicity of petite-Ponar grab-collected sediment was evaluated in laboratory tests involving four benthic invertebrate species and 10 endpoints: midge (*Chironomus riparius*) 10-day survival and growth, amphipod (*Hyalella azteca*) 28-day survival and growth, mayfly (*Hexagenia* spp.) 21-day survival and growth, and oligochaete worm (*Tubifex tubifex*) 28-day survival and reproduction (three endpoints). Replicate sediment samples were collected from five points and tested to estimate within-site variability in toxicity. Methods are further described in Reynoldson *et al.* (2000). For the benthic community analyses, macroinvertebrates were sorted from sediment cores and identified to genus or species level using a low-power stereo microscope and, for chironomids and oligochaetes, a high-power microscope. Poriferans, nematodes, copepods and cladocerans were excluded.

In 2003 and 2004, water column profiles of temperature, pH, conductivity, and dissolved oxygen were obtained

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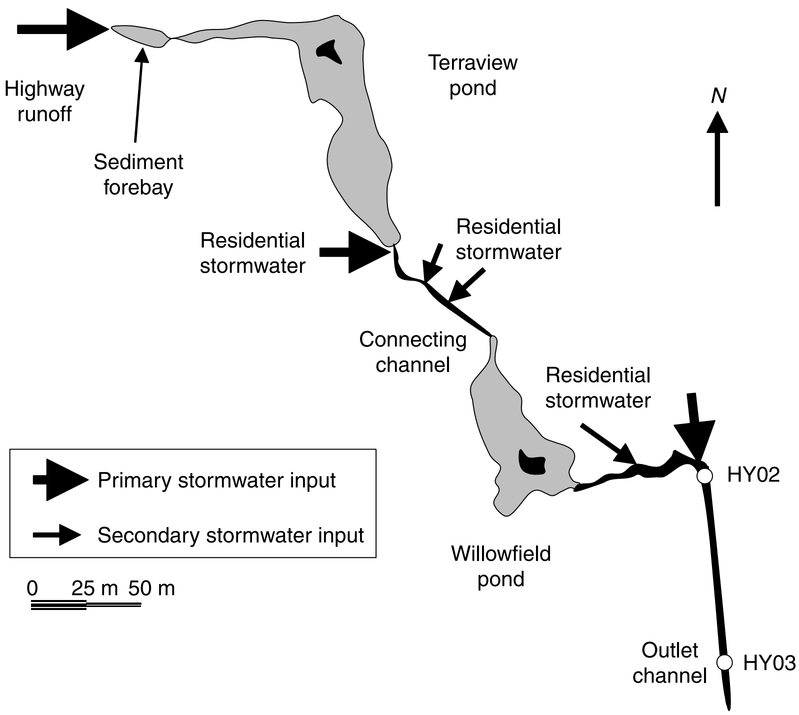

Figure 1 | Layout of the Terraview-Willowfield Stormwater Management Park (TWSMP) in Toronto, Canada.

at 10–11 longitudinally-spaced sites in the TWSMP using a Hydro-Lab multi-probe.

Data analyses were aimed at determining if sediment quality in the TWSMP (a) differed from that expected for ponds and streams not exposed to stormwater discharges and (b) changed in relation to longitudinal location within the facility. For the first objective, contaminant concentrations in sediment were compared to Canadian Sediment Quality Guidelines (CSQG) (CCME 1999), toxicity results for the TWSMP samples were compared to those for uncontaminated laboratory control sediment, and benthic communities were compared to those from minimally disturbed streams and ponds in the Toronto region. For the second objective, conditions were examined from upstream to downstream for discernable patterns.

RESULTS AND DISCUSSION

Contaminant concentrations and distribution

Among trace metals, relatively infrequent exceedances of the CSQG Probable Effect Level (PEL) were observed, and only such cases are displayed in Table 1. Concentrations of Cu, Pb and Zn in the TWSMP were, however, several times greater than those reported by Casey *et al.* (2006) for 13 highway and residential stormwater ponds in Maryland, USA. At all the other sites, concentrations were below the PEL. For trace metals, most of the exceedances occurred in the upstream pond or downstream at sites HY02 and HY03 (located in the concrete-lined channel below the pond). PAH PELs were exceeded at several sites in both ponds. Heavier PAHs were highest in Terraview pond, whereas light PAHs were highest in the downstream Willowfield pond. Overall, there was a weak trend of decreasing contaminant concentrations with distance downstream in the TWSMP. By the outlet of Willowfield pond, most contaminants were below the PEL thresholds. The contaminant data in Table 1 suggest that toxicity could be encountered in both ponds.

Sediment toxicity

Sediment toxicity, particularly mortality, was highest at the upstream sites in Terraview pond, low or absent in

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Table 1 | Summary of trace metal and PAH concentrations exceeding PEL at the 41 sites sampled in 2003. " < " indicates that the site did not exceed the PEL

	Constituent concentrations (μg/g)						
Sampling area	**Cr**	**Cu**	**Pb**	**Zn**	**PE***	**FL†**	**PY‡**
PEL	90	197	91	315	0.52	2.36	0.88
T§-Forebay	182	<	<	370	2.44	2.44	1.94
T-Inlet	112	206	129	768	2.71	3.37	2.86
T-Mid-pond	<	<	<	<	<	<	<
T-Deep Mid-pond	<	<	<	<	2.39	<	1.48
T-Outlet	<	<	<	<	0.78	<	<
W‖-Inlet	<	<	<	373	1.39	3.03	2.45
W-Mid-pond	<	<	<	351	0.71	1.82	1.55
W-Outlet	<	<	<	<	<	<	<
HY¶02	<	<	212	354	10.1	13.7	10.8
HY03	94.8	<	168	688	4.43	9.58	7.78

*PE = phenanthrene.
†FL = fluoranthene.
‡PY = pyrene.
§T–Terraview pond.
‖W–Willowfield pond.
¶HY–Hydro corridor sites downstream of ponds.

Willowfield pond, and elevated again in the outlet channel (Figure 2). In the *Chironomus* tests, 50% of 14 test sites had a lower survival than laboratory control sediment, but growth at nearly all sites was as good as, or better than, in control sediment. These test results suggest nutrient enrichment in the TWSMP system. *Hexagenia* showed a somewhat lower survival, with 57% of sites indicating a lower survival than laboratory control sediment. Growth was significantly impaired, with just one site equalling the control sediment and 93% of sites being significantly below. There was a strong improvement in *Hexagenia* growth from upstream to downstream, until the two lower channel sites (Figure 2B). For *Hyalella*, 71% of sites showed survival rates comparable to those in control sediment; 29% were below. With respect to growth, 11 sites showed impaired growth compared to control sediment, and three were comparable. Finally, *Tubifex tubifex*, known to be tolerant of urban pollution, had 100% survival at all 14 sites. Two of the three *Tubifex* reproduction endpoints (number of cocoons and number of young per adult) showed impairment in the upper sites, but generally increased to control levels throughout the facility (Figure 2C). Hatching success in the pond sediment was similar to that for control sediment and not affected by location in the TWSMP, except for an elevated response in the sample from the site near the outlet of Willowfield pond.

Among the Terraview and Willowfield samples, toxicity was usually associated with higher concentrations of trace metals and the high-molecular weight PAHs in sediments, which were deposited mainly in the upstream pond. Elevated toxicity noted in the outlet channel was likely due to inputs of untreated runoff directly from several fairly impervious residential areas. Results from toxicity tests conducted on samples collected in 2004 from the TWSMP confirmed the 2003 spatial pattern of toxicity.

Benthic macroinvertebrate communities

Macroinvertebrate communities in the sediment cores were highly dominated by oligochaete worms and chironomid flies (Figure 3A). All of the 10 most abundant taxa are members of these two groups, which contain numerous pollution-tolerant species. Taxa considered sensitive to pollution (Clements & Newman 2002), such as amphipods, mayflies (Ephemeroptera), caddisflies (Trichoptera), and stoneflies (Plecoptera) were absent. Walsh *et al.* (2005) noted a similar species shift, from those sensitive to urban pollution towards those tolerant of urban pollution, in urban streams impacted by wet-weather discharges in Australia.

In general, the sediment communities within the ponds were depauperate, with lowest densities and taxon richness in the mid-pond samples, some of which were completely devoid of macroinvertebrates (Figure 3B). Communities from other ponds and streams sampled in the Southern Ontario region, including sites exposed to urban runoff, typically had invertebrate densities and taxon richness several fold to an order of magnitude greater than the Terraview-Willowfield system (Rochfort *et al.* 2000). The absence of macroinvertebrates in the mid-pond samples could be due to poor water quality rather than sediment contamination. Highly elevated salinity in deeper parts of the ponds was indicated by conductivity measurements of 1,000–5,000 $\mu S\,cm^{-1}$ (chloride levels > 1,000 mg/L). Differences in sediment benthic communities among sites in the TWSMP were not related to contaminant concentrations.

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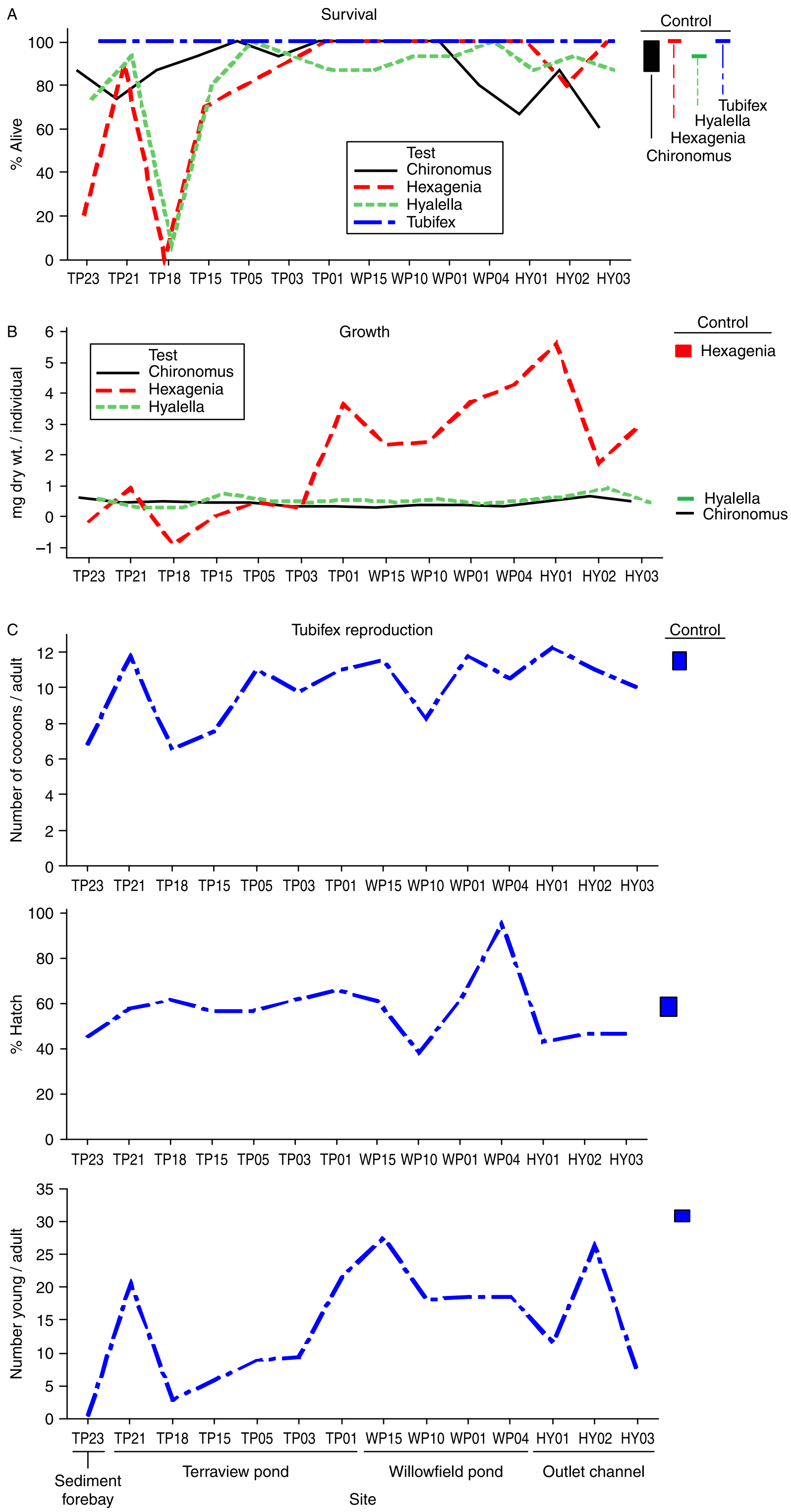

Figure 2 | Toxicity of sediments from the TWSMP to four benthic invertebrates. Responses for 10 endpoints (four survival, three growth, three reproduction) are shown in relation to sampling sites, which are ordered from upstream to downstream. Ranges of responses to laboratory control sediment for the endpoints are shown by heights of the boxes on the right margin of each panel.

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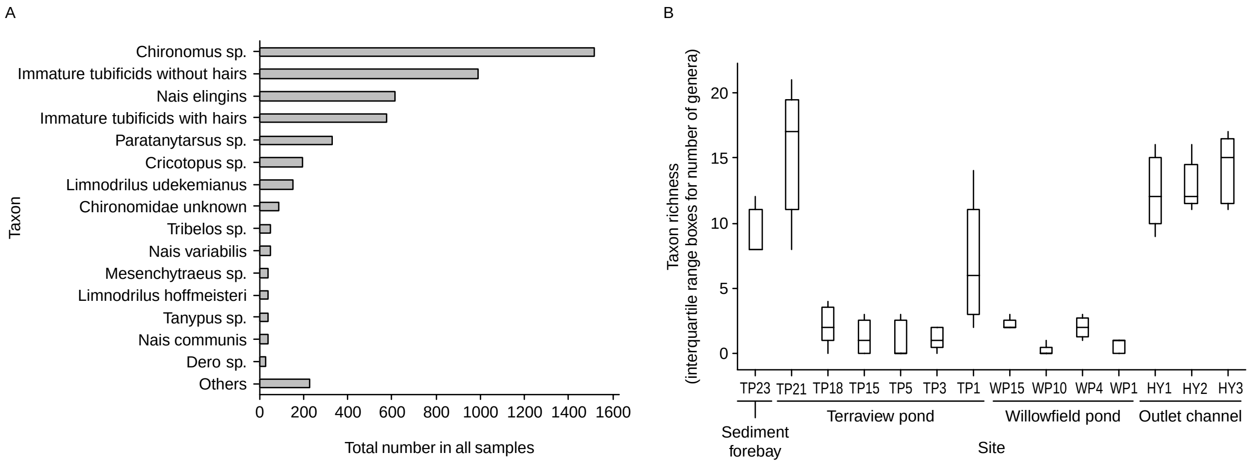

Figure 3 | Macroinvertebrate communities in the TWSMP: (A) organism counts (all sites samples combined) and (B) taxon richness along the main flow path.

CONCLUSIONS

The assessment of urban stormwater toxicity has progressed from the monitoring of point source discharges with a battery of acute tests to the in-stream assessment techniques employed at the TWSMP. Using a combination of information on benthic sediment toxicity, benthic community structure and sediment chemistry of each site allows a full assessment of the habitat conditions in which impairment is evaluated in terms of ecological endpoints, rather than simply chemical levels. The danger of using chemical data alone is that they cannot account for additive sublethal effects, bioavailability of various (unidentified) chemical species, or for substances which were not included in the analyses. Indeed, it can be difficult to predict impacts of bulk concentrations of contaminants accumulated in sediment because a large fraction may not be bioavailable (Luoma & Fisher 1997). The approach applied in this study investigated changes along a longitudinal profile of the ponds and the receiving stream to provide a comprehensive description of habitat quality.

Sediment surveys in the facility indicated contamination by several trace metals and PAHs, most severely in the upstream Terraview Pond and its sediment forebay. Sediment toxicity, based on toxicity tests with four benthic organisms, was also greatest in Terraview pond and generally decreased with distance downstream. High metal and high-molecular weight PAH concentrations were associated with elevated sediment toxicity. Of the four toxicity test organisms, *Hyalella* and *Hexagenia* appeared to be the most sensitive to the pollutants present at the TWSMP. Benthic communities were depauperate showing habitat quality impaired not just by trace metals and PAHs, but also by chloride (from winter road deicing), which accumulated in the deeper parts of the ponds.

Construction of the TWSMP replaced a concrete-lined drainage channel, which provided no protection to the receiving waters downstream. As a stormwater "treatment" facility, the ponds appear at least partially successful in reducing contaminants and toxicity of sediments. Conditions in the outflow channel, though, were almost as degraded as in upper Terraview pond. As restored aquatic habitat, the facility is less successful: sediments at most of the sampled pond sites supported few macroinvertebrates. Further naturalisation of the TWSMP will require control of highway runoff pollutants entering Terraview pond (proposed in the original plan, but not implemented) and management of salinity in the ponds. Such remedial measures should further increase the value of this aesthetically attractive facility serving recreational needs of the local residential neighbourhood.

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