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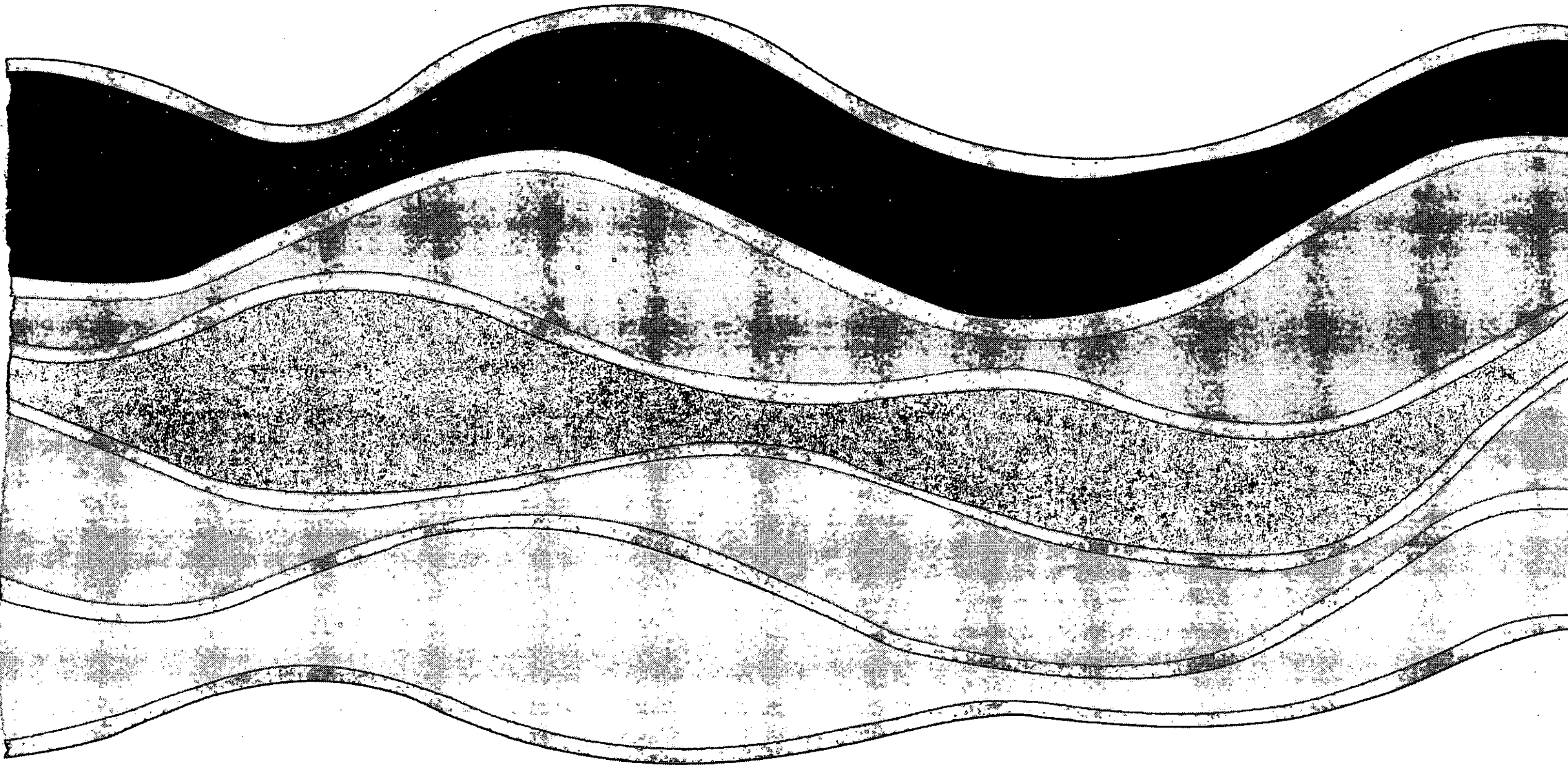

SUSTAINABILITY OF STORMWATER PONDS: ADDRESSING THE SEDIMENT ISSUES

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NWRI Contribution No. 98-017

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Management Perspective

Concerns about urban nonpoint source pollution led to the development of stormwater best management practices (BMPs) which serve to protect receiving waters against physical, chemical and biological impacts of stormwater discharges. Among the BMPs used in the Great Lakes Region, stormwater management ponds are particularly common and hundreds of such facilities have been built. While the environmental benefits of well-designed stormwater ponds are widely recognized, these benefits are sustainable only if ponds are kept fully operational by proper maintenance. As discussed in the paper that follows, many issues of the sustainability of pond performance concern pond sediments and their accumulation, physical, chemical and toxicological properties, and eventual removal and disposal.

This paper should be of interest to designers, environmental planners and managers dealing with control of stormwater pollution.

Sommaire à l'intention de la direction

Des préoccupations relatives à la pollution diffuse urbaine ont conduit à l'élaboration de meilleures pratiques de gestion des eaux pluviales, dont la raison d'être est la protection des eaux réceptrices contre les effets physiques, chimiques et biologiques des rejets d'eaux pluviales. Dans la région des Grands Lacs, l'installation de bassins de retenue des eaux pluviales est une solution particulièrement populaire, des centaines de ces installations ayant été construites. Les avantages écologiques que procurent des bassins bien conçus sont connus de tous, mais ils ne sont durables que dans la mesure où un bon entretien assure leur fonctionnement optimal. Comme on le voit dans cet article, de nombreuses questions ayant trait au maintien de l'efficacité des bassins portent sur les sédiments, leur accumulation, leurs propriétés physico-chimiques et leur toxicité, ainsi que leur enlèvement et leur élimination éventuels.

Cet article s'adresse aux concepteurs, aux urbanistes en environnement et aux gestionnaires concernés par la lutte contre la pollution par les eaux pluviales.

Abstract

Stormwater management ponds facilitate removal of solids from stormwater by settling, which leads to sediment accumulation in ponds. These accumulations comprise sand (20%), silt (35%) and clay (45%), with bulk densities ranging from 1,400 to 2,200 kg·m^{-3}. Sediment deposition rates observed at a number of ponds ranged from 1 to 4 cm·yr^{-1}. Erodibility testing of these materials indicates that they behave like cohesive sediments, which are more resistant to erosion than noncohesive materials, and this resistance further increases with sediment consolidation during dry weather. The need for sediment removal is defined with respect to preservation of pond storage, without considerations of ecological risks associated with excessive pond contamination. The current knowledge of sediment processes in ponds indicates that sediment removals once every 20–25 years might be acceptable, and this frequency can be reduced by overdesigning the pond sediment storage. Sediments from the five ponds studied were marginally polluted, with some exceptions caused mostly by industrial sources. Only a small percentage of samples were heavily polluted and would require special considerations in sediment management and disposal. Similar findings were confirmed by the ecotoxicological testing of pond sediments. The methods of sediment removal depend on facility design for maintenance operations and include bulldozing and bucket or hydraulic dredging. Depending on the chemical composition of the sediment removed, it may be reused in urban areas (e.g., in residential fills), with or without treatment, or it may have to be disposed in controlled areas. Finally, it appears that the main challenge in proper management of pond sediment is the provision of funding and creation of awareness of ecological risks arising from poorly maintained stormwater ponds.

Keywords

Stormwater ponds, pond bottom sediments, sediment chemistry, sediment ecotoxicology, sediment removal and disposal.

Résumé

Les bassins de retenue des eaux pluviales facilitent l'extraction, par décantation, des matières solides transportées par ces eaux; il y a donc accumulation de sédiments dans ces bassins. Ces sédiments sont composés à 20 % de sable, à 35 % de limon et à 45 % d'argile, dont la masse volumique est comprise entre 1400 et 2200 $kg.m^{-3}$. Le taux de décantation observé se situe entre 1 et 4 $cm.an^{-1}$. Les essais pour mesurer l'érosion de ces matériaux indiquent qu'ils se comportent comme des sédiments cohésifs, plus résistants à l'érosion que les substrats non cohésifs. Cette résistance s'élève davantage, en période de sécheresse, avec leur consolidation. La nécessité d'enlever ces sédiments est définie en fonction du potentiel d'emmagasinage du bassin, abstraction faite des risques écologiques associés à une contamination excessive de ces bassins. Dans l'état actuel des connaissances dansa ce domaine, on juge qu'il serait acceptable de nettoyer les bassins aux 20 ou 25 ans; il est possible d'allonger cet intervalle en surdimensionnant les bassins. Les sédiments des cinq bassins étudiés étaient marginalement pollués, les quelques exceptions étant surtout attribuables à des sources industrielles. Un petit pourcentage seulement des échantillons était fortement pollué et nécessiterait la tenue d'essais écotoxicologiques spéciaux sur ces sédiments. Les méthodes d'enlèvement des sédiments dépendent de la conception des installations en fonction des opérations d'entretien; il peut s'agir de l'emploi de bulldozers ou du dragage hydraulique ou au godet. Selon leur composition chimique, les sédiments extraits peuvent être réutilisés en contexte urbain (comme matériau de remblai en milieu résidentiel, par exemple), avec ou sans traitement, ou il faut peut-être les éliminer dans des sites contrôlés. Enfin, il semble que le financement et que la sensibilisation aux risques écologiques associés à des bassins pluviaux mal entretenus soient les principaux défis sur le plan de la gestion de ces sédiments.

Mots-clés

Bassins de retenue d'eaux pluviales, sédiments de bassins, chimie des sédiments, écotoxicité des sédiments, enlèvement et élimination des sédiments.

Introduction

Stormwater ponds were introduced into urban stormwater management on a large scale during the 1970s as management measures offering many benefits including reduced runoff peaks and risk of downstream flooding, lower capital drainage costs, and recharge of groundwater (APWA 1981). Furthermore, attractively landscaped ponds provided general environmental amenities, enhanced the attractiveness of adjacent urban developments and increased real estate values (Baxter et al. 1985). Consequently, well-designed stormwater ponds were readily accepted by the public and regulatory agencies, and adopted in new developments by developers. However, not all pond designs, and certainly not the early ones, were effective in mitigating all adverse impacts of urban development on receiving waters. In fact, some ponds developed for flood control only and often poorly maintained have been found to impact adversely on the environment (Jones and Jones 1984).

During the last 10–15 years, experience with design and operation of stormwater ponds has grown tremendously and served to improve pond design procedures documented in many stormwater management planning and design manuals (e.g., U.S. EPA 1983; Schueler 1987; MOEE 1994). These documents suggest that stormwater ponds, designed according to the recent guidelines for water quality control, are particularly effective in removal of such pollutants as suspended solids and associated heavy metals, phosphorus, and hydrocarbons. For suspended solids, removal rates as high as 90% were reported (U.S. EPA 1983; Brown and Schueler 1997; Liang and Thompson 1997).

At the same time, extreme variability in reported pond removals of suspended solids and associated constituents should be recognized, as documented in a recently compiled database on pollutant removal performance of stormwater best management practices (Brown and Schueler 1997). According to this database which contains raw performance data (i.e., without scrutiny of the data reported by others), removal of suspended solids varied from -33% (i.e., more SS left the pond than entered) to 99% in 43 stormwater ponds monitored. Obviously some of these data are artefacts produced by inadequate monitoring and data processing, which is borne out by the fact that these removals were calculated on the basis of 5–38 samples or events. In any case, these data indicate that the issue of proper and rigorous monitoring and assessment of best management practices (BMPs) cannot be overemphasized. Notwithstanding these data uncertainties, it also appears that our knowledge of BMP performance or their inherent limitations prevent us from attaining high levels of performance under difficult conditions.

Regardless of the actual pollutant removals, stormwater ponds do accumulate sediments with associated pollutants, and once these accumulations have exceeded some critical volume, they will interfere with pond performance in flow and water quality control and undermine the sustainability of such facilities. While the issue of sustainability of BMPs involves a number of considerations, including the pollutant removal, operation and maintenance aspects, and in-pond ecosystem development, the discussion in this paper is restricted to the impacts of pond sediment and the related maintenance aspects. Finally, to assist pond operators in planning pond maintenance and sediment removal in particular, the process of sediment settling is examined, data on pond sediment characteristics are presented, and some guidance for sediment removal and disposal is offered.

Sediment Settling in Stormwater Ponds

Among the physical processes occurring in ponds, the two most important ones are hydraulic transport and settling. Hydraulic processes control pond inflow, storage, and outflow to the receiving waters, and internal circulation which affects practically all other physical, chemical and biological processes in the pond. Both pond outflow and internal hydraulics have implications for the protection of downstream waters. Poorly controlled outflow may lead to erosion in the downstream channel, large sediment inputs to receiving waters, and destruction of aquatic life habitat (Booth 1990). Consequently, the magnitude and distribution of pond outflows must be achieved by properly designed outlet control devices (Schueler 1987).

In-pond flow circulation may produce short-circuiting currents, fast flows and dead zones, which all reduce stormwater hydraulic residence times in the pond (Shaw et al. 1997), impede effective setting, and thereby contribute to higher discharges of pollutants to the receiving waters. Thus, the knowledge of internal circulation (the velocity field) is required to describe the sediment and chemical transport in ponds, and where needed, to mitigate unfavourable conditions by retrofitted structures (e.g., baffles; Matthews et al. 1997). Without the knowledge of internal flow field, expedient (over)simplifying assumptions have to be made, e.g., by assuming plug flow or fully mixed flow, and field observations indicate that these assumptions do not reflect well the actual conditions.

Settling is undoubtedly the most important process for enhancing water quality in stormwater ponds (Whipple 1979), and removes not only suspended solids, but also the associated hydrophobic pollutants. Thus, ponds efficiently removing suspended solids are also likely to remove total phosphorus, heavy metals, trace organic contaminants, and particulate associated hydrocarbons (Schueler 1987). Field experience indicates that settling in ponds (or similar facilities) is a complex process (Chocat 1997) encompassing such sub-processes as particle transport by advection and turbulent diffusion, with concomitant particle aggregation (also referred to as flocculation; Marsalek et al. 1998) and break up by turbulence (Lau and Krishnappan 1997), and the resulting sediment deposition and scouring.

Since mathematical descriptions of suspended solids settling are not as yet well developed, the current practical approaches (Driscoll 1986; MOEE 1994) adopt much simpler conceptual models, e.g., by treating stormwater ponds as ideal settling basins (Fair and Gayer 1954). However, the inherent simplifying assumptions are far reaching and hardly describe the conditions found in actual stormwater ponds: (a) within the settling zone of the pond, sedimentation takes place exactly as in a quiescent container of equal depth, (b) the flow is steady, and, upon entering the settling zone, the concentration of suspended particles of each size is uniform throughout the cross-section at right angles to flow, and (c) a particle that enters the sludge zone stays removed (Fair and Gayer 1954). Furthermore, in such basins, the inflow is uniformly distributed along the upstream edge of a rectangular basin. With these assumptions and using pioneering work conducted in the early 1900s (Hazen 1904), effects of in-pond hydraulics on settling are described by a single "perturbation" parameter and may contribute to reduced efficiency of stormwater settling (Fair and Gayer 1954). On the contrary, in real facilities, stormwater ponds have irregular shapes and multiple point inflows and/or outflows, settling zone conditions are impacted by eddies and turbulence caused by flow circulation and wind, flow during storms is unsteady, lateral mixing and dispersion are not uniform, and the risk of particle resuspension during storm flows can not be discarded (Matthews et al. 1997; Shaw et al. 1997).

To bypass the complexities of theoretical approaches, the treatability of stormwater by settling is commonly estimated empirically by testing stormwater samples in settling columns (Randall et al. 1982). Laboratory settleability tests indicate removals of suspended solids in the range from 70 to 90%, total phosphorus 50%, lead 65 to 85%, zinc 30 to 45%, and copper about 40%, for settling times ranging from 24 to 40 hours (Whipple and Hunter 1981; Randall et al. 1982). Furthermore, flocculent settling of stormwater can be reproduced in settling columns. While the settling tests approximate some basic aspects of stormwater testing, they do deviate from field conditions in one important aspect – they produce quiescent settling without any disturbances typical for field conditions. Consequently, settling in ponds produces somewhat lower removals (U.S. EPA 1983; Van Buren et al. 1997), because of disturbance of quiescent settling by velocity fields and turbulence generated by in-pond flow circulation, or wind driven waves and currents.

Settling in ponds depends on a number of factors – the pond size relative to the design runoff volume, the frequency of runoff events, flow conditions in the pond, and physico-chemical characteristics of local runoff and its particulates. The pond size, drawdown characteristics and the local runoff regime can be used to optimize the capture volume of runoff in the pond (Urbonas et al. 1990). Slow drawdown is needed to achieve long detention times (12–40 hours) and effective settling; even longer detention times may be implemented in extended detention ponds (Schueler 1987). With reference to flow conditions, effective sedimentation in stormwater ponds is achieved by inducing good mixing of the influent at the pond inlet, uniform flow velocity distribution in the pond favouring quiescent settling, and prevention of short circuiting and sediment re-suspension by high flow velocities or secondary currents. The attainment of such conditions imposes a number of conditions on pond geometry, particularly the length to width ratio, overall layout, depth, and orientation with respect to prevailing winds.

In terms of runoff characterization, sedimentation is particularly effective in removing solids, heavy metals (mostly lead and copper), phosphorus, hydrocarbons, and some other toxic substances. However, it is ineffective in removal of dissolved pollutants (e.g., dissolved forms of nutrients; Hey 1982; Randall et al. 1982). For preliminary sizing of ponds in specific climates, design charts (U.S.EPA 1983) indicate that removals of suspended solids from 60 to 80% could be achieved in ponds with surface areas representing from 0.001 to 0.005 of the contributing catchment area.

Finally, a rigorous discussion of stormwater settling must include two important factors – (a) the nature of solids transported by stormwater, and (b) ambiguity in describing pond performance (or that of any other settling device) by percent removal of solids. Both factors are further addressed below.

Urban stormwater conveys large quantities of solids, including sand, silt and clay, which enter ponds in three forms, as the bed load, or suspended and dissolved loads. The bed load consists of sand ($D > 62\ \mu m$), and the suspended load consists of silt ($4\ \mu m < D < 62\ \mu m$) and clay ($D < 4\ \mu m$). Sand entering ponds settles quickly by the inlet (Marsalek et al. 1997) and forms a delta which gradually grows and encroaches deeper into the pond, unless it is restrained within the sediment forebay. For an on-stream pond in Kingston, with most of the trapped sediment originating from the upstream urbanizing catchment rather than an adjacent shopping plaza, Marsalek (1997) estimated that about one sixth of the total annual mass of solids (i.e., bed load and suspended solids) deposited in the form of sand delta deposits in the pond.

It should be further recognized that bed load transport of sandy materials is generally not detected by automatic water samplers with sampler intakes above the bottom (to avoid clogging) and sampling line velocities inadequate to lift sand particles, with high settling velocities, from channel bottom into elevated sampling bottles. However, in sizing the pond sediment storage, it is advisable to consider this unmonitored influx of sand from the catchment. Besides natural sources, abrasion of solid surfaces (streets, roofs) and winter road maintenance are other important sources of sand in urban catchments.

With respect to percent solids removal, this measure of settling efficiency of any solid separation device (a pond, or a grit separator) is ambiguous and inadequate without specifying the nature of solids entering the device. Sandy particles can be removed with almost 100% efficiency by any facility/device even with very short hydraulic residence times in the order of minutes. On the other hand, fine clays or much larger flocs of low density (Marsalek et al. 1998) may require days to settle. Thus, in stormwater ponds, there are some residual (non-treatable) suspended solids concentrations, which are attributable to very fine particulates kept in suspension by naturally occurring turbulence (inflow, wind). For example, in Technical Note 75 (Center for Watershed Protection 1996), such "irreducible" suspended solids concentrations are defined as 20–40 $mg{\cdot}L^{-1}$. Another inadequacy of percent removal is the fact that for high incoming concentrations, even substantial removals (60–70%) may leave residual concentrations which are still too high.

Thus, stormwater ponds serve as settling basins which accumulate significant quantities of sediment, depending on catchment sources and pond effectiveness in solids removal. Once the sediment accumulations in the pond exceed some critical value, they will interfere with pond performance and will have to be removed to keep ponds fully operational and minimize impacts on downstream receiving waters, or contaminant uptake by biota in the pond.

Characteristics of Pond Sediments

For planning pond maintenance, sediment removal and disposal, or an assessment of the contamination status of ponds, it is required to know the characteristics of the accumulated sediments. The characteristics of interest include physical characteristics (including particle sizes, density, erodibility), and sediment chemistry and ecotoxicity (for disposal considerations, or contamination status assessment).

Physical Characteristics

Particle sizes of sediments accumulated in stormwater ponds vary extensively and depend on upstream sediment sources and the pond design. In general, sediment size distribution also varies within the pond, with coarser particles settling close to the inlet and finer particles settling throughout the pond. To retain coarser particles (fine gravel and coarse sand) close to the inlet and to simplify their removal, recent pond designs incorporate sediment traps (forebays) capturing such materials (MOEE 1994).

Typical size distributions of pond sediments can be obtained from data obtained at five stormwater ponds; four located in the Toronto area (Fig. 1) and one in Kingston (an on-stream facility; Fig. 2). In the Toronto area, sediment samples were collected in Colonel Sam Smith Reservoir (Etobicoke), Tapscott Reservoir (Scarborough), Heritage Estates Pond (Richmond Hill), and Unionville Reservoir (Markham). The Kingston Pond is an on-stream facility which was described in detail elsewhere (Van Buren et al. 1997). Average sizes (number of samples > 50) of sediments from these five ponds are listed in Table 1.

The data in Table 1 indicate that majority of the materials deposited in the ponds studied, outside of the inlet (or forebay) area, fall into the silt and clay classes. The observed material size distributions have some implications for sediment erodibility (susceptibility to resuspension and washout), bulk density (fine materials with high water require special consideration in removal and disposal), reuse, and sediment pollution (smaller particles generally contain higher concentrations of contaminants).

Sediment particle size distribution also affects its in situ density. The bulk density of silt and clay deposits with high water content can be as low as 1,400–1,600 kg·m^{-3}, but material densities in sandy deltas can be as high as 2,200 kg·m^{-3} (Marsalek et al. 1997). Such densities are important in estimating the depth of sediment deposits and the water volume displaced by the sediment and the resulting loss of storage. In other words, fine-grained solids deposited in the pond may occupy a volume up to 60% larger than an equal mass of sandy particles.

Erosion of non-cohesive sediment is traditionally determined by using the Shields curve, indicating the inception of sediment motion as a function of sediment characteristics and flow properties. Recent experiments conducted at the National Water Research Institute in Burlington, Ontario indicate that fine-grained sediments from stormwater ponds (i.e., the silt and clay materials collected from the Kingston pond) behave like cohesive materials (Lau and Krishnappan 1997). Such materials have higher erosion resistance, but once the erosion is initiated, large quantities of deposited material erode at fast rates. Furthermore, it was noted that the erodibility of this sediment depended on its consolidation. During the period of consolidation, biological processes increase the material cohesiveness and resistance to erosion. Such consolidation would take place during dry weather periods, when there is practically no inflow to the pond and the accumulated sediments are not disturbed. Thus, pond sediments with a significant percentage of fines behave like cohesive materials, with greater resistance to scouring, and this resistance further increases with deposit age.

Chemical Characteristics

The sediment chemistry is important for assessing the risk of chemical releases from deposits (to the water column or biota) and for determining the acceptable means of disposal of the sediment removed from ponds. Relatively clean materials can be reused in municipal operations (antiskid materials, residential fill) to reduce the disposal costs. While the assessment of sediment contamination is a complex task best accomplished by combined chemical, toxicity, and biological community assessments, for less contaminated materials (usually including those from residential stormwater ponds), simple chemical screening may be sufficient (MOEE 1992). In this screening, pollutant concentrations in the sediment are compared against three levels of contamination given in the MOEE guidelines, the No Effect Level (NEL), the Lowest Effect Level (LEL), and the Severe Effect Level (SEL), defined as:

(1) The No Effect Level (NEL) – at this level, no chemical transfer into the food chain is expected. There are practically no restrictions on disposal of such sediment.

(2) The Lowest Effect Level (LEL) – this level of contamination has practically no effect on the majority of sediment dwelling organisms. The sediment is considered to be marginally polluted. There are some restrictions on disposal of such sediment.

(3) The Severe Effect Level (SEL) – the sediment is heavily polluted and likely to affect the health of sediment dwelling organisms. Special management plans may be required for disposal of such sediment, or it may have to be removed from the water body.

Specific pollutant concentrations, corresponding to the above three levels, were developed for a number of chemicals and recommended as sediment quality guidelines (MOEE 1992). The selected guidelines for metals, nutrients and total polynuclear aromatic hydrocarbons (16 U.S. EPA PAHs) are listed in Table 2, together with some results from the five ponds studied. The LEL and SEL concentrations are listed in columns two and three, followed by (geometric) mean concentrations measured in 80 samples from four Toronto ponds (i.e., 20 samples from each pond), mean concentrations (N=5) in the Kingston pond sediment (Marsalek et al. 1997), frequencies of LEL exceedance (for all four Toronto ponds and two residential ponds, Heritage and Unionville, respectively), and frequencies of SEL exceedance, again for four ponds and two residential ponds, respectively. Additional guidelines are available for about 20 organic compounds (or groups of compounds) and five additional parameters; in the latter case, no effect levels are specified.

The chemistry of sediments from the four Toronto ponds indicates that up to 98% of all samples exceeded LELs with respect to at least one of the guideline chemicals (metals, nutrients and PAHs), and should be considered as "marginally to significantly polluted". Less than 17% of all samples exceeded SELs; all of these samples originated in a pond serving a catchment with some industrial land use. These sediments displayed a significant level of contamination and would require further toxicity assessment by bioassays. The data from the Kingston Pond were similar to those for the residential ponds, with one exception, higher levels of chromium (Cr), in several cases even exceeding SELs. It was suggested by Marsalek et al. (1997) that a true assessment of the significance of these concentrations would require determination of Cr speciation and its mobility. High residual Cr fractions (40–60%) were noted in this sediment and suggested that much of the reported Cr burden was of natural origin.

With respect to the remaining 21 organic compounds specified in the MOEE guidelines (basically older-type organochlorine pesticides, plus mirex and PCBs), it was noted that most sediment data were below the detection limits, with relatively few exceptional values exceeding LELs. With respect to SELs, the observed data were at least two orders of magnitude lower than the corresponding SELs. It can be concluded that the risk of pond sediment contamination by these 21 organic compounds is extremely low and, in the absence of site specific sources, does not cause environmental concerns.

The total chemical concentrations do not indicate chemical mobility, bioavailability and ease of entry into the food chain. Such characteristics are sometimes studied in the case of metals by conducting sequential sample analysis, comprising a series of five extraction procedures releasing metals bound by various bonds (Tessier et al. 1979). The sequential extraction releases five operationally defined geochemical phases: (1) exchangeable cations, (2) carbonates, (3) iron and manganese oxides, (4) organic matter, and (5) residual phase. The results reported in the literature (Stone and Marsalek 1996) indicate that metal fractions in relatively mobile phases (1) and (2) are relatively low in stormwater sediment. However, under certain ambient conditions (e.g., oxygenated or reduced conditions and various pH levels), metals may be released from the accumulated sediment.

The potential release of chemicals from pond sediments depends on chemical characteristics of pond water, and metal speciation in sediment. Field studies at one facility indicated that 90% of Pb, 80% of Zn, 70% of Cu and 40% of Cr were in potentially mobile fractions and could be released by significant changes in the ambient water pH, oxygen levels and ionic composition (Marsalek et al. 1997). Relatively clean or detoxified sediment can be reused in municipal operations.

Sediment Ecotoxicity

Abundance of chemicals in sediments does not necessarily indicate the sediment toxicity, which depends strongly on chemical bioavailability. Such issues are better studied by various methods of biotesting and biomonitoring. Many such procedures are still in the developmental stage, and while they may be useful and effective in detecting toxicants in sediments, their application in control of contaminated sediment disposal has not been yet widely established or accepted. With reference to the ponds studied, bottom sediments, suspended particulates, and their extracts were subjected to a battery of bioassay tests to determine the toxicant/genotoxicant presence. Details of such procedures and their results were reported elsewhere by Dutka et al. (1994a; 1994b). Only a brief summary of results follows.

The bottom sediments were collected from 5 sites within each of the Toronto area four ponds using an Ekman dredge. Suspended particulates were collected by centrifuging water at various locations in individual ponds. These samples were further processed as required in three types of bioassays tests applied – direct sediment testing (minimum processing), tests applied to pore water (obtained by centrifuging sediment samples) and sediment extracts (obtained by solvent extraction). In each of these media, a number of tests were applied.

All the samples collected from the four ponds contained some concentrations of bioavailable toxic chemicals, with the Unionville pond having the greatest concentrations of genotoxicants/promutagens. The spatial distribution of chemicals within each pond appeared to be random. Suspended particulates appeared to have greater toxicant concentrations than the bottom sediments.

The most sensitive bioassays were *Daphnia magna* acute toxicity test, Direct Sediment Toxicity Testing Procedure (DSTTP; Kwan 1991), SOS-Chromotest+S9 (i.e., with the addition of S9, the rat liver homogenate), and the forward electron transport assay using beef heart submitochondrial particles (SMP). Because the MetPAD tests indicated absence of bioavailable metals, but the presence of pesticides was indicated by the competitive immunoassay test for triazine, one could speculate that the sediment toxicity was caused by other chemicals than toxic metals, possibly pesticides. This hypothesis is somewhat supported by the positive toxic responses from a residential area pond in Unionville. It will be desirable to continue the testing described in this study to assess the significance of toxic responses reported.

Sediment toxicity was investigated at Kingston stormwater pond using a battery of toxicity tests, including DSTTP, sediment chromotest and Microtox solid phase. Kingston samples also underwent solid phase nematode testing. In the urban creek upstream of the Kingston pond, samples were either non-toxic, or, where impacted by urban drainage, showed moderate toxicity. Sediment collected at the two pond inlets (creek weir and storm weir) was moderately toxic. All samples within the pond were moderately to severely toxic. Below the pond weir and progressively further downstream, sample toxicity was greatly reduced, and it would appear that the majority of the toxic sediment is retained within the stormwater pond.

Stormwater Pond Operation and Maintenance

One of the main concerns the public raises in connection with stormwater ponds is proper operation and maintenance. Typical concerns include: maintaining a static water level, system flow blockage, sedimentation and infilling, trash and debris collection, algae and nuisance weed control, shoreline protection, insect control and structural stability of inlet/outlet controls. All of these concerns are first considered in the design stage and later addressed by regular inspections, maintenance and corrective actions requiring adequate access to all points in the facility by maintenance vehicles.

To alleviate the above concerns, MOEE has developed detailed schedules for stormwater management practices operation and maintenance activities (MOEE 1994). The list of such activities, for wet and dry ponds, includes inspections, grass cutting, weed control, upland vegetation replanting, shoreline fringe and flood fringe replanting, aquatic vegetation replanting, removal of accumulated sediments, outlet valve adjustment, and trash removal. The discussion presented below focuses on sediment removal.

Pond Sediment Removal

Sediment accumulation rates

Sedimentation occurs in practically all water impoundments, both man-made and natural. Sedimentation rates are generally calculated from the thickness of accumulated sediment divided by the age of the pond, assuming zero initial storage. In lakes, sedimentation rates are generally in the order of $\mathrm{mm \cdot yr^{-1}}$; in stormwater ponds, such rates are about one order of magnitude higher. The actually measured data reported in the literature range from $1\ \mathrm{cm \cdot yr^{-1}}$ to $4\ \mathrm{cm \cdot yr^{-1}}$ (Yousef et al. 1994). Generally, the deposition rate depends on the age of pond, size and characteristics of the drainage area, surface area and volume of the detention pond, percent imperviousness of drainage area, and sediment sources.

For pond design and maintenance planning, it is desirable to estimate sediment deposition rates for specific facilities. One such estimate was $0.3\ \mathrm{cm \cdot yr^{-1}}$, produced by Liang and Thompson (1997) for the Heritage Estates Pond. This estimate was produced by runoff modelling with a calibrated model, and it is not obvious whether this estimate includes sand export from the catchment and a correction for water content of the deposited material. The latter information would require knowledge of particle size distributions not available in modelled results.

As stated earlier, the bulk density of deposited material may be relatively low, 1200–1400 $\mathrm{kg \cdot m^{-3}}$ (MOEE 1994), indicating that much of the sediment volume is occupied by water. In situ sediment densities have to be considered when calculating the volume of accumulated sediment from loading calculations.

Planning sediment removal

With respect to sediment removal, two aspects are of interest; when to remove sediment from an existing facility, and what frequencies of subsequent removals can be expected. In accord with the current practices, sediment removal is addressed here only in connection with sediment impacts on pond storage and the associated pond performance in pollutant removal. A different argument could be made with respect to pond contamination, impacts on biota, downstream waters, and risk of contaminant releases. While the first aspect (pond treatment performance) can be addressed quantitatively and produces guidance for planning sediment removal, the facility contamination aspects do not allow such quantification, but should be considered in periodic pond sediment surveys.

Initial sediment removal

The sediment accumulating in ponds reduces the operational storage volume and, ultimately, the effectiveness of the pond in sediment removal. Recognizing that sediment removal may be a rather costly operation, it is required to develop a good rational for identifying when this operation becomes necessary. Theoretically, it would be possible to undertake a cost-benefit analysis of this problem (costs of sediment removal vs. benefits arising from restored pond performance), but because of inherent complexity and environmental constraints, in the current practice, operational guidance was derived from experience. In particular, two criteria were found in the literature stating that the sediment should be removed when:

(a) The design total suspended solids (TSS) removal efficiency was reduced by 5% (MOEE 1994)
(b) The design storage was reduced by 10% (Florida; Yousef et al. 1994)

A general comparison of both criteria is not possible, but some appreciation of their relationship can be obtained by examining the charts indicating the TSS removal, R_{TSS}, as a function of the pond volume, V; $R_{TSS} = f(V)$ (U.S. EPA 1983). In that case, the slope of such curves can be determined as $S = \Delta R_{TSS} / \Delta V$, and when $S = 0.5$, both criteria describe identical conditions. As a numerical example, one of the NURP pond design charts (U.S. EPA 1983) for the North-East USA was used and the value of $S = 0.5$ was found for $R_{TSS} = 63\%$. Thus in a pond designed according to this chart for removal of 63% of suspended solids, both criteria would produce identical results. For smaller R_{TSS}, the TSS removal condition would control sediment removal, and for $R_{TSS} > 63\%$, the volume preservation condition would control sediment removal.

In terms of practicality of these criteria, the first one, based on storage volume, is much easier to implement. It requires repeated surveys of sediment deposits, with the first one done after say five years of pond operation, and the following ones at similar or shorter time intervals. It should be noted that if sediments are being washed out of the pond, there will not be any increases in accumulations. Such deficiencies would be, however, detected by routine pond monitoring as recommended in the MOEE manual (MOEE 1994). The criterion based on the TSS removal is more difficult to implement. For guidance, the MOEE manual suggests that sediment should be removed once every 10 years (under review).

For the existing facilities, the frequency of sediment removal can be determined for accumulation rates and the storage volume preservation condition; probably in the range from once every 10 to 15 years. The period recommended in the MOEE manual is once every 10 years (pending revisions); the values reported from Florida would indicate removal periods as long as 25 years. It should be noted that ponds are sometimes oversized (in terms of design storage) and this extra space is reserved for sediment accumulation. Under such conditions, the frequency of sediment removal could be significantly reduced. Removal periods between 15 and 25 years are probably realistic for most facilities.

Sediment Removal Methods

The methods used in sediment removal depend on pond design and any design allowances made for this operation, including equipment access, sediment forebays with hard (concrete) bottoms and on-site sediment storage/processing facilities. Typical methods include the use of front-loaders and bulldozers, bucket dredging and hydraulic dredging. Each of these procedures has some advantages and disadvantages, depending on local conditions.

The least expensive method may be sediment removal by front-loaders or bulldozers, which is particularly acceptable where the sediment storage area (e.g., a sediment trap, a forebay) with a hard bottom can be dewatered, the heavy equipment placed in this area, and sediment removed. Without the benefit of a hard bottom, this method may cause considerable environmental damage and therefore be recommended as the last resort (Yousef et al. 1994). To cope with high water content of dredged sediment, this operation should be performed in late fall, with the onset of freezing temperatures. Other methods of sediment dewatering or solidifying its consistency have been also used (wooden mulch or similar materials).

Bucket dredging is less expensive than hydraulic dredging, but its main disadvantages include the placement of dredged material on shoreline (unless removed immediately), damage to the aquatic environment, turbidity problems caused by sediment dropping from the bucket into water, and difficulties with removal precision – overcutting or undercutting is unavoidable. Among the advantages of hydraulic dredging, one could name low resuspension of solids during operation, the feasibility of sediment discharge through a pipe to a nearby containment site, protection of shoreline against damage, and quiet operation. The costs are sometimes higher, but may be offset by all the above listed benefits. In some regions, there are private companies specializing in sediment removal, and this eliminates the need for pond operators to acquire special equipment.

Disposal of Dredged Material

Proper disposal of the dredged material is usually the most difficult task in pond sediment removal. The basic consideration concerns the sediment quality and determination whether the material can be reused in municipal operations, either in residential fills or for winter street sanding. For reuse in residential fills, sediment quality criteria are available (MOEE 1992), and conceivably, some sandy materials from residential ponds would meet these criteria. For example, when comparing the quality of the Kingston pond sand and gravel deposit by the inlet (Marsalek et al. 1997) against these criteria, among the ten metals listed, the only one not meeting the criteria was chromium (observed level 66 $\mu g \cdot g^{-1}$, criterion value 62 $\mu g \cdot g^{-1}$). There may also be an opportunity for improving the sediment quality, for example by bioleaching. Anderson et al. (1998) tested the leaching of Kingston Pond sediment by naturally occurring acidophilic bacteria and reported average metal solubilization (equivalent to removal) efficiencies for five heavy metals – Cr, 13%; Cu, 64%; Fe, 6%; Pb 71%; and Zn, 98%. With these efficiencies, it is believed that most of residential pond sediments could be treated to comply with residential fill criteria and thereby reused in municipal operations.

For disposal of contaminated sediment, three types of scenarios may be encountered – lack of local disposal sites, the available disposal sites may be inadequate (in terms of size, or contaminant containment), and adequate disposal sites are available. The first case involves sediment transport to proper sites and this increases the overall costs. Where inadequate containment sites are available, they have to be upgraded by constructing embankments or barriers and creating a sufficient storage which would contain the dredged material with the associated water, per one dredging cycle. When the space is filled, the depth of the dredged material in the containment area should not exceed 0.9 m.

When planning the containment area, it should be designed to receive and dewater the dredged material as quickly as possible. The supernatant water must be of acceptable quality to be discharged into the local receiving waters; another possibility is to discharge it into sanitary sewers for proper treatment. Furthermore, the containment area should be designed to enhance the feasibility of sediment reuse. By enhancing the reuse possibilities, the search for containment areas is simplified and more of such sites become potentially available. Therefore, to optimize the disposal of dredged materials in a given containment area, a focus should be made on improving the engineering properties of the material, as well as the underlying soil.

Summary

Stormwater sediments accumulate in urban stormwater ponds at rates typically ranging from 1 to 4 $cm \cdot yr^{-1}$. The particle size distributions in sediment deposits vary and indicate presence of sand (20%), silt (35%) and clay (45%). Such variations are reflected in the in situ bulk density of sediment deposits ranging from 1,400 to 2,200 $kg \cdot m^{-3}$. Erodibility testing of these materials indicates that they behave like cohesive sediments and are more resistant to erosion than noncohesive materials. This resistance further increases with sediment consolidation during dry weather. The need for sediment removal is defined either by reduction in pond sediment removal effectiveness (e.g., by 5%), or by reduction in pond volume (e.g., by 10%). Neither of these criteria reflect the ecological risks arising from excessive pond contamination. With respect to preservation of pond storage, the earlier recommendations to remove accumulated sediments every 10 years were probably conservative; less frequent removals (up to once every 20–25 years) might be acceptable. This frequency can be reduced by overdesigning the sediment storage space in the pond. Sediments from the five ponds studied were marginally polluted, with some exceptions caused mostly by industrial sources. Only a small percentage of samples was heavily polluted and would require special considerations in sediment management and disposal. Similar findings were confirmed by the ecotoxicological testing of pond sediments, with selected bioassays showing some toxicity at practically all facilities, but significant improvements in downstream areas. The methods of sediment removal depend on facility design for maintenance operations and include bulldozing and bucket or hydraulic dredging.

Depending on the chemical composition of the sediment removed, it may be reused in urban areas (e.g., in residential fills), with or without treatment, or it may have to be disposed in controlled areas. It appears that the main challenge in proper management of pond sediment is the provision of funding and creation of awareness of ecological risks arising from poorly maintained stormwater ponds.

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References

American Public Works Association (APWA). 1981. Survey of stormwater detention. Unpublished report, APWA, Chicago.

Anderson, B.C., A.T.F. Brown, W.E. Watt, and J. Marsalek. 1998. Biological leaching of trace metals from stormwater sediments: influential variables and continuous reactor operation. Accepted for presentation at IAWQ Biennial, Vancouver, June 1998.

Baxter, E.H., Mulamoottil, G. and D. Gregor. 1985. A study of residential stormwater impoundments: perceptions and policy implications. Water Resour. Bull. 21:83-88.

Booth, D.B. 1990. Stream-channel incision following drainage basin urbanization. Water Resour. Bull. 26:407-417.

Brown, W. and Schueler, T. 1997. National pollutant removal performance database for stormwater BMPs. Center for Watershed Protection, Silver Spring, Md., August.

Center for Watershed Protection. 1997. Technical Note 75: Irreducible pollutant concentrations discharged from urban BMPs, Watershed Protection Techniques 2(2):369-372.

Chocat, B. (Coordinator) 1997. Encyclopédie de l'hydrologie urbain et de l'assainissement. Lavoisier TEC & DOC, Paris, ISBN: 2-7430-0126-7.

Driscoll, E.D. 1986. Detention and retention controls for urban runoff, p. 381-365. In: B. Urbonas and L.A. Roesner (eds.), Urban Runoff Quality - Impact and Quality Enhancement Technology, Proc. Eng. Found. Conf., ASCE, New York, NY.

Dutka, B.J., J. Marsalek, A. Jurkovic, K.K. Kwan and R. MacInnis. 1994a. Ecotoxicological study of stormwater ponds under winter conditions. Zeitschrift fur angewande Zoologie 80(1):25-41.

Dutka, B.J., J. Marsalek, A. Jurkovic, R. MacInnis and K.K. Kwan. 1994b. A seasonal ecotoxicology study of stormwater ponds. Zeitschrift fur angewande Zoologie 80(2):361-381.

Fair, G.M. and J.C. Gayer. 1954. Water supply and wastewater disposal. John Wiley & Sons, Inc., New York.

Hazen, A. 1904. On sedimentation. Trans. ASCE 53:53-61.

Hey, D.L. 1982. Lake Ellyn and urban stormwater treatment, p. 220-235. In: W. DeGroot (ed.), Stormwater Detention facilities, Proc. Eng. Found. Conf., ASCE, New York, NY.

Jones, J.E. and D.E. Jones. 1984. Essential urban detention ponding considerations. J. Water Resour. Plan. Manage. 110:418-433.

Kwan, K.K. 1991. Direct sediment toxicity testing procedure (DSTTP). NWRI Contribution No. 91-90, National Water Research Institute, Burlington, Ontario.

Lau, Y.L and Krishnappan, B.G. 1997. Measurement of size distributions of settling flocs. NWRI Publication No. 97-223, National Water Research Institute, Environment Canada, CCIW, Burlington, Ontario, Canada.

Liang, W.Y. and M.K. Thompson. 1997. Performance assessment of an off-line stormwater management pond. Ontario Ministry of Environment and Energy and The Metropolitan Toronto and Region Conservation Authority, Toronto.

Marsalek, J., W.E. Watt, B.C. Anderson and C. Jaskot. 1997. Physical and chemical characteristics of sediment from a stormwater management pond. Water Qual. Res. J. Canada 32(1):89-100.

Marsalek, J, B.G. Krishnappan, W.E. Watt and B.C. Anderson. 1998. Size Distribution of Suspended Sediments in an On-Stream Stormwater Management Pond. Submitted to Novatech 98, Lyon, France.

Marsalek, P.M. 1997. Special characteristics of an on-stream stormwater pond: winter regime and accumulation of sediment and associated contaminants. M.Sc. thesis, Queen's University, Kingston, Ontario.

Matthews, R.R., W.E. Watt, J. Marsalek, B.C. Anderson and A.A. Crowder. 1997. Extending retention times in a stormwater pond with retrofitted baffles. Water Qual. Res. J. Canada 32(1):73-87.

Ministry of Environment and Energy (MOEE). 1992. Guidelines for Protection and Management of Aquatic Sediment Quality in Ontario. MOEE, Toronto, Ontario.

Ministry of Environment and Energy (MOEE). 1994. Stormwater Management Practices Planning and Design Manual. MOEE, Toronto, Ontario.

Randall, C.W., K. Ellis, T.J. Grizzard and W.R. Knocke. 1982. Urban runoff pollutant removal by sedimentation, p. 205-219. In W.DeGroot (ed.), Stormwater Detention Facilities, Proc. Eng. Found. Conf., ASCE, New York, NY.

Schueler, T.R. 1987. Controlling Urban Runoff: A Practical Manual for Planning and Designing Urban BMPs. Washington Metropolitan Water Resources Planning Board, Washington, DC.

Shaw, J.K.E., W.E. Watt, J. Marsalek, B.C. Anderson and A.A. Crowder. 1997. Flow pattern characterization in an urban stormwater detention pond and implications for water quality. Water Qual. Res. J. Canada 32(1):53-71.

Stone, M. and J. Marsalek. 1996. Trace metal composition and speciation in street sediment: Sault Ste. Marie, Canada. Water Air Soil Pollut. 87: 149-169.

Tessier, A., P.G.C. Campbell, and M. Bisson. 1979. Sequential extraction procedure for the speciation of particulate trace metals. Anal. Chem. 51(7):844.

U.S. Environmental Protection Agency (EPA). 1983. Results of the Nationwide Urban Runoff Program Volume I - Final Report. Water Planning Division, U.S. EPA, Washington, DC.

Urbonas, B., C.Y. Guo and L.S.Tucker. 1990. Optimization of stormwater quality capture volume, p. 94-110. In: H.C. Torno (ed.), Urban Stormwater Quality Enhancement – Source Control, Retrofitting and Combined Sewer Technology, Proc. Eng. Found. Conf., ASCE, New York, NY.

Van Buren, M.A., Watt, W.E. and Marsalek, J. 1997. Removal of urban stormwater constituents by an on-stream pond. J. Environ. Plan. Mgmt. 40(1):5-18.

Whipple, W. 1979. Dual-Purpose detention basins. J.Water Res.Plng. Mgmt. Div. ASCE 105:403-412.

Whipple, W. and J.V. Hunter. 1981. Settleability of urban runoff pollution. J. Water Pollut. Control Fed. 53:1726-1731.

Yousef, Y.A., T. Hvitved-Jacobsen, J. Sloat and W. Lindeman. 1994. Sediment accumulation in detention or retention ponds. Sci. Tot. Env. 146/147:451-456.

Table 1. Average particle size distributions in five stormwater ponds

Facility	**Gravel**	**Sand**	**Silt**	**Clay**
Four Toronto Ponds	–	20%	33%	47%
Kingston Pond – inlet[1]	29%	70.6%	0.2%	0.2%
Kingston Pond – centre[1]	–	5.4%	40.6%	54%

[1] After Marsalek et al. 1997

Table 2. Provincial Sediment Quality Guidelines for metals and nutrients (in $\mu g \cdot g^{-1}$ (ppm); MOEE 1992) and observed data

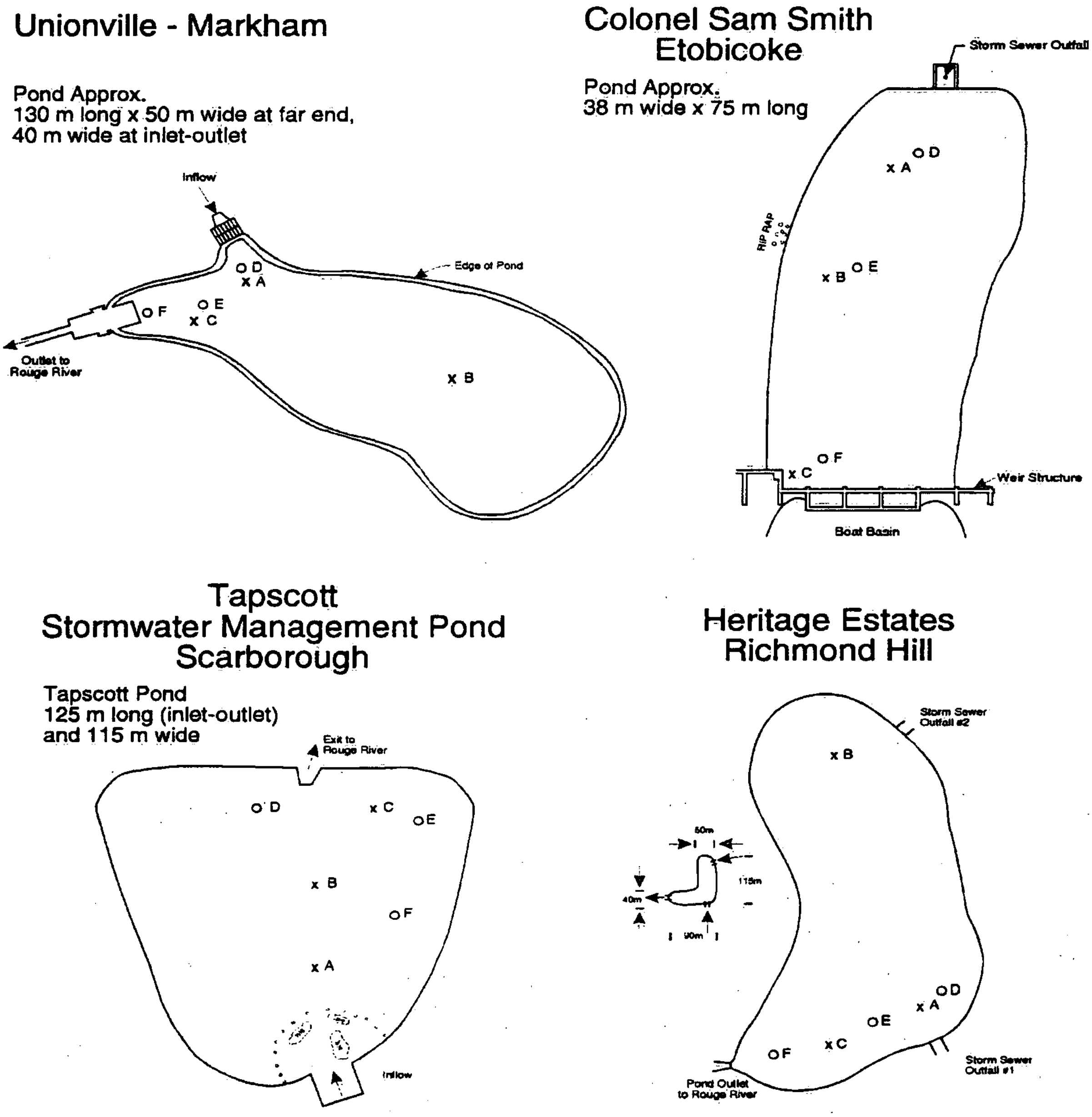
	MOEE Guidelines		Observed Data					
	Lowest Effect Level	Severe Effect Level	Mean Concentration ($\mu g \cdot g^{-1}$)		Frequency of exceeding LEL		Frequency of exceeding SEL	
Metals								
Arsenic	6	33	3.3[1]	2[2]	1.3[3]	0[4]	0[3]	0[4]
Cadmium	0.6	10	1.2	1.4	57.5	45	0	0
Chromium	26	110	48.0	122	88.8	25	1.3	0
Copper	16	110	71.6	80	95	90	17.5	0
Iron (%)	2	4	2.5	3.02	83.8	75	0	0
Lead	31	250	76.4	149	55.0	55.0	6.3	0
Manganese	460	1100	667	485	91.3	87.5	3.8	0
Mercury	0.2	2	0.1	0.066	3.8	0	2.5	0
Nickel	16	75	30.4	34	90.0	82.5	1.3	0
Zinc	120	820	252	406	86.3	72.5	2.5	0
Nutrients								
TOC(%)	1	10	3.0	–	96.3	92.5	0	0
TKN	550	4800	1873	–	91.3	85.0	0	0
TP	600	2000	756	–	92.5	90.0	0	0
Organic Compounds								
Total PAHs	2	11000	11.0	–	97.5	95	0	0

[1] Data from the four Toronto ponds combined

[2] Data from the Kingston Pond (outlet; after Marsalek et al. 1997)

[3] Only for the four Toronto ponds

[4] Only for Toronto residential area ponds



Unionville - Markham

Pond Approx.
130 m long x 50 m wide at far end,
40 m wide at inlet-outlet

Colonel Sam Smith
Etobicoke

Pond Approx.
38 m wide x 75 m long

Tapscott
Stormwater Management Pond
Scarborough

Tapscott Pond
125 m long (inlet-outlet)
and 115 m wide

Heritage Estates
Richmond Hill

Figure 1. Four Toronto area stormwater management ponds.

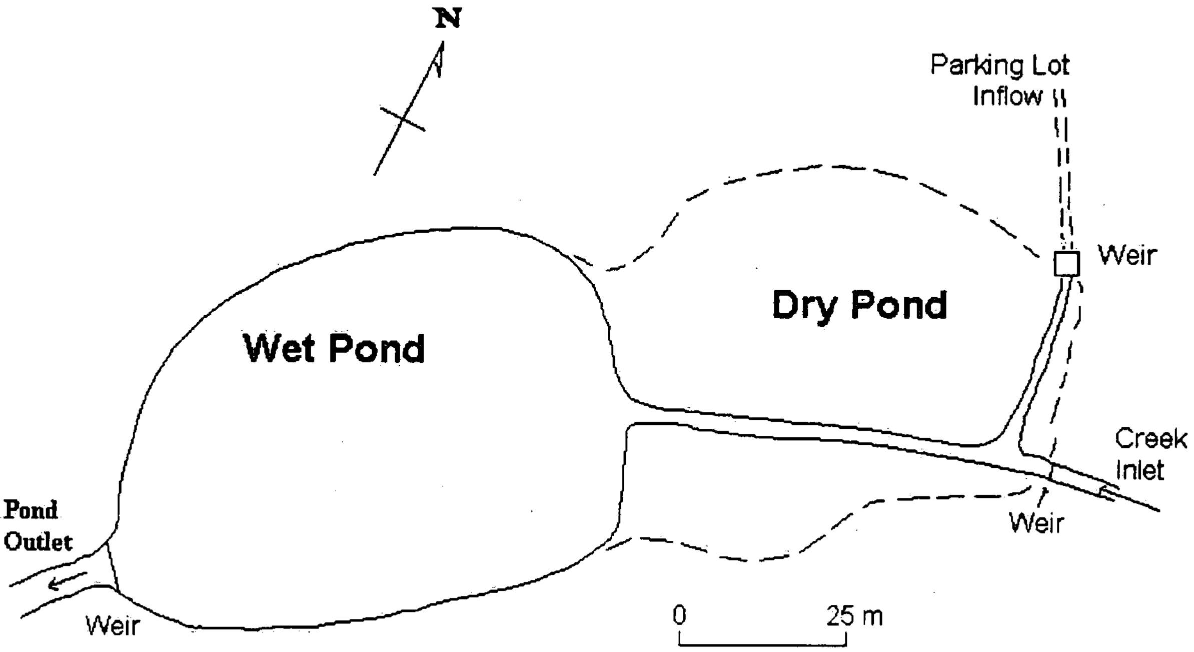
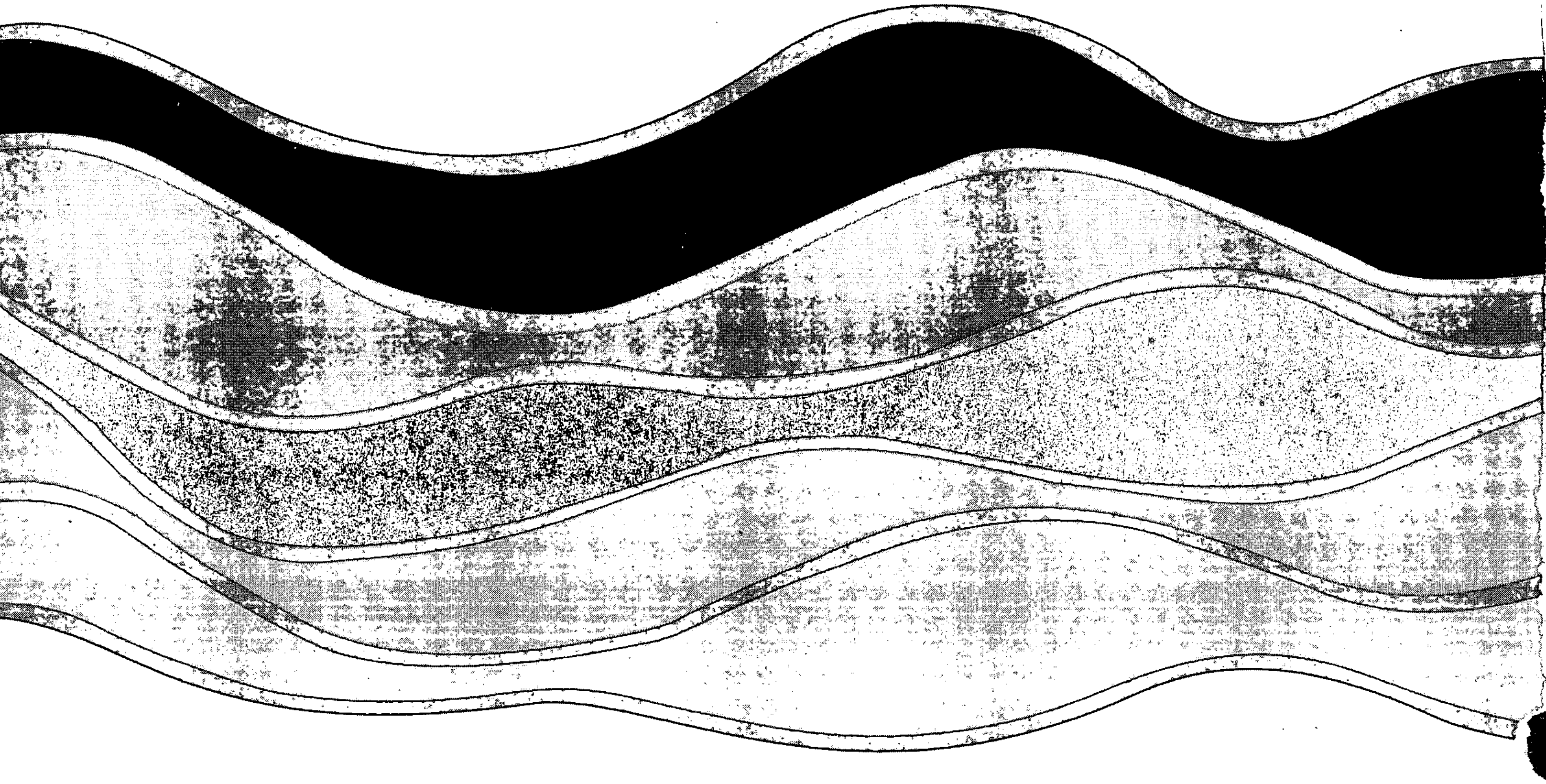


Figure 2. Kingston stormwater management pond.



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