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COMPREHENSIVE STORMWATER POND MONITORING

W. Edgar Watt* and Jiri Maršálek**

** Department of Civil Engineering, Queen's University, Kingston, Ontario K7L 3N6, Canada*
*** National Water Research Institute, Burlington, Ontario L7R 4A6, Canada*

ABSTRACT

Stormwater management ponds are widely used to control urban stormwater pollution. An understanding of the relevant biological, chemical and physical processes in such ponds requires a comprehensive monitoring program. Such a program is described for a 0.52 ha pond near Kingston, Ontario. In addition to continuous measurement and discrete sampling of pond inflow, storage and outflow to define the overall mass balances of water, sediment and chemicals, the program includes special process-related surveys and investigations. These include analyses of bottom sediment cores, suspended sediment and submergent plants as well as modelling/measurement of the velocity field and sediment transport. This comprehensive monitoring program is presented as an example of what should be implemented in many climatic regions before transfer of data on pond performance can be justified.

KEYWORDS

Stormwater management, stormwater ponds, pond processes, field monitoring.

INTRODUCTION

Recent advances in the understanding of urban stormwater pollution indicate that the cumulative impacts of increased flows, erosion, and discharges of pollutants (solids, nutrients, heavy metals, hydrocarbons, bacteria and toxicants) have resulted in severe degradation of urban receiving waters (U.S. EPA, 1983). Consequently, the attitude toward stormwater pollution has changed and the need for its control has been promulgated in government policies (Bowen *et al.*, 1993). To implement such policies, many stormwater management practices have been proposed and their applications reported (Urbonas, 1993). Among such practices, stormwater management ponds seem to be the most widely used (Schueler, 1987).

The literature on actual performance of stormwater management ponds is not very extensive and often represents "grey" literature not subject to a rigorous peer scrutiny. Quite often, such performance is reported on a short-term basis, expressed in gross terms integrating removals by several processes, and because the ponds are typically built in conjunction with natural depressions, the reported performance may depend on the specific geometry of the facility studied.

To improve the understanding of the role of stormwater ponds in control of stormwater quality and mitigation of its impacts on the receiving waters, comprehensive monitoring of such facilities is required, with a clear focus on water, sediment and pollutant mass balances, and identification of sources, sinks, and transport and transformation processes. This approach then creates well defined and fairly extensive demands on pond monitoring. Basic facets of such a monitoring program are presented in the following discussion and illustrated by samples of results collected at a stormwater pond near Kingston, Ontario.

FACILITY DESCRIPTION

The monitored facility is described in terms of its layout and functions, installed instrumentation and equipment or procedures used in special surveys.

Pond Layout and Functions

The study site is an on-line stormwater management pond on the west branch of the Little Cataraqui Creek in Kingston Township; it was constructed in 1982 to reduce stormwater peak flows from the 12.6 ha parking lot of the Cataraqui Town Centre shopping mall (Watt and Paine, 1993). The upstream drainage area (4.1 km^2) is predominantly undeveloped. The two-stage pond consists of a permanent wet pond (area = 0.52 ha) and a dry pond which floods when the water level in the wet pond exceeds the normal water level by 0.2 m. Fig.1 displays the pond layout and sites of upstream inflow, parking lot inflow, pond outflow and the location of instrumentation and flow measuring weirs.

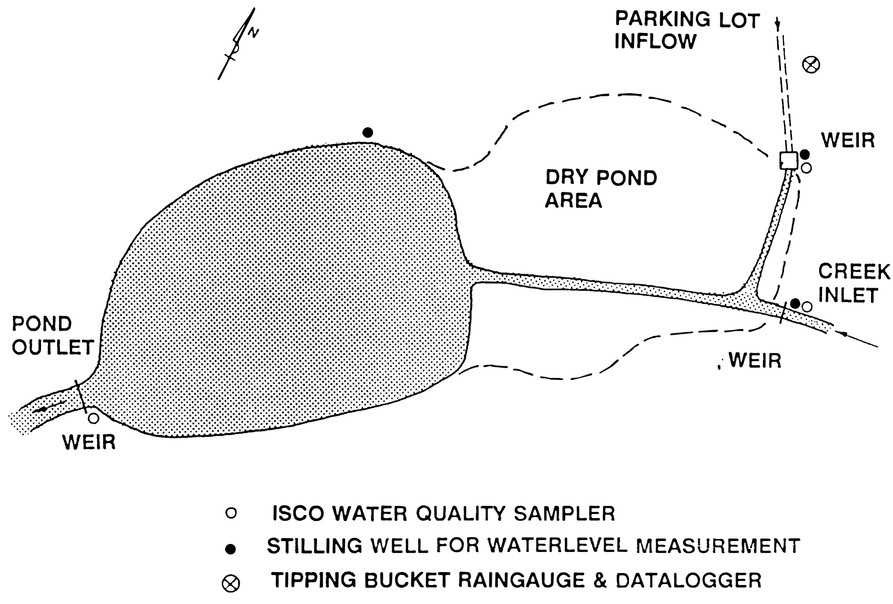

Fig.1. Kingston Township Stormwater Management Pond

Processes Monitored

To evaluate the pond performance, the mass balances of water, sediment and chemicals are of interest. For water mass balance, pond and contributing area hydrology, and hydraulic transport through the pond need to be addressed. For sediment mass balance, the sediment regime (input and output, comprising transport through or scouring and washout of sediment) is of interest, and for chemical balances, chemical sources, partitioning (i.e. among the liquid phase, solid phase, biota and atmosphere), transport and transformations are of interest. Furthermore, as this partitioning is affected by environmental conditions, such conditions (particularly dissolved oxygen and pH levels) also need to be measured.

Instrumentation

Pond instrumentation was designed and installed to continuously measure rainfall, inflow, outflow and pond water level with water quality sampled on an event basis. Rainfall is measured using a 0.2 mm tipping bucket rain gauge located 3 m above the ground level. Upstream inflow, parking lot inflow and pond outflow are measured by calibrated weirs. The data from the rain gauge and all three weirs are recorded by a datalogger.

Automated water quality sampling is performed using 24-bottle ISCO water quality samplers (Models 2700 & 3700). The sampling program is initiated by a liquid level activator when the water level at each of the measurement structures reaches a predetermined threshold. Once the samplers are initiated, samples are collected at the parking lot inflow, upstream inflow and pond outflow at 30, 45 and 45 minute intervals, respectively. These intervals were selected to obtain representative samples during typical short period rainfall events. In addition to automatic sampling, weekly baseflow samples are collected at the pond inlet and outlet. Enhanced manual sample collection is also performed as necessary during long rainfall events or at times of equipment failure.

Following each event, samples are submitted to an analytical laboratory and analyzed for metals (Cu, Pb, Zn), solids (TSS, TDS), nutrients (various forms of N and P), COD, oil and grease, phenols, sulphate and chloride. Separate samples are also collected and analyzed for indicator bacteria.

Special Surveys

Continuous monitoring has been supplemented by special surveys. These included bottom sediment surveys (the collected core samples were analyzed for particle size and chemistry), dye tracing (to verify a hydrodynamic model and flow patterns), drogue surveys (to identify flow currents), sampling of suspended particulate by centrifuging and manual collection (to identify the chemistry of particulate and floc properties), and sampling of submergent plants (to identify chemistry). Other work has been done in conjunction with treatment facilities downstream from the pond, but it is not covered in the discussion presented herein.

RESULTS AND DISCUSSION

The presentation of results follows the outline of the processes monitored - it starts with pond hydrology, followed by hydraulics, sediment regime, chemical regime, and biomonitoring.

Hydrology

Pond hydrology has been monitored for over three years and, during that period, a good understanding of the pond and the contributing area hydrology has been developed. From these measurements, a water balance has been developed on an annual basis and on seasonal basis in the following form:

$$I + P = O + E + S \quad (1)$$

where I is the inflow volume, P is the precipitation over the pond surface, O is the outflow volume, E is the evaporation, and S is the volume of seepage through pond walls and bottom (all in m^3).

The hydrology of the contributing catchment has also been studied is some detail. For this purpose, it is useful to examine separately the partly developed contributing creek catchment (4.1 km^2) and the fully impervious shopping plaza catchment (0.126 km^2). The basic hydrologic characteristics of these two contributing areas are summarized in Table 1.

TABLE 1 Hydrologic Characteristics of Sub-Catchments Contributing Flow to the Kingston Stormwater Management Pond

	Parking Lot	Creek	Pond
Basin Area (km^2)	0.126	4.086	4.212
Rainfall Depth (mm)	560	560	560
Runoff Depth (mm)	400	80	75
Loss (mm)	160	480	485

Pond Hydraulics

Flow patterns in the pond are of primary interest when assessing transport of pollutants through the pond. To establish these patterns, computer simulations of flow were undertaken and attempts were made to verify the simulated flow distribution. Flow simulations were done by means of commercial software PHOENICS which provides a solution of St.Venant's equations in three dimensions (PHOENICS, 1993). Many simulation runs were executed and this work is still progressing. An example of model output, showing the velocity field in the pond, is given in Fig.2.

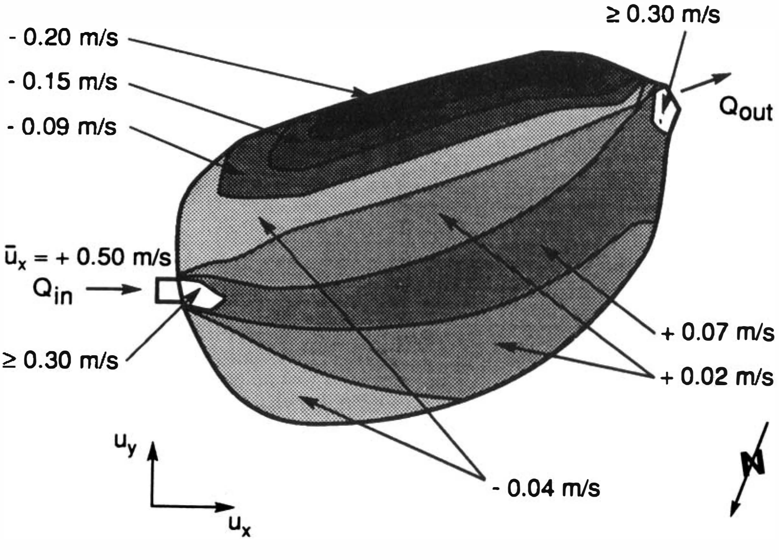

Fig.2. Simulated Surface Velocity Distribution in the Pond Studied

In the case depicted in Fig.2, a typical pond inflow (v = 0.50 m/s, Q = 0.525 m^3/s) was considered with unstratified flow and no wind shear stress on the surface (densimetric and surficial wind stress issues will be addressed later). The velocity vectors indicate that the flow entering the pond continues in the direction of the inflow channel and the main transfer of mass occurs along the north shore. Along the south shore, a large recirculation zone with a counterclockwise eddy develops. Flow particles carried by the main current may spend about 50 minutes in the pond.

Early attempts to verify the simulated flow distribution were only partly successful. Two types of field measurements were conducted - current surveys by drogues and dye tracing. For the first measurement, a current drogue was designed. It consisted of an upright PVC rod (20 mm in diameter) with two perpendicular vanes attached at the lower end and a geodetic target (reflector) attached at the top end. Flotation of this drogue was ensured by a plastic bottle positioned along the rod and, by keeping this bottle partially submerged, the flotation of the drogue could be adjusted. These drogues were released close to the inlet during a very low flow (i.e. corresponding to the baseflow) through the pond and tracked by a geodetic instrument. It was noticed that for these very low flow velocities, the forces exerted by wind on the tracking target and the drogue rod exceeded those of currents on the submerged vanes and the drogues moved in the direction of the wind. Refined drogue designs are contemplated for the next field season.

Dye tracing was conducted during the same period. A slug of rhodamine B was released and partly mixed across the creek cross-section about 40 m upstream of the pond. A set of five cross-sections, uniformly dividing the distance between the inlet and outlet, was established in the pond and the dye was traced along these cross-sections. The movement of the dye cloud confirmed the simulated flow distribution - the highest concentrations moved fairly quickly toward the north shore and followed it toward the outlet. More detailed testing is planned next field season.

Sediment Transport

Sedimentation is probably the most important process enhancing water quality in stormwater ponds (Marsalek *et al.*, 1992). The reported field data on sedimentation indicate significant removals of solids and associated pollutants (U.S. EPA 1983). However, the sedimentation in ponds is still not fully understood.

Estimates of efficiency of stormwater sedimentation are obtained by testing stormwater samples in settling columns. However, field tests in ponds indicate lower efficiencies, because of the dynamic nature of settling in field conditions and erroneous estimates of settling times derived from simplifying assumptions. It follows from Fig.2 that the actual residence times of most of the flow entering the pond are much shorter than typically assumed in computations, even at low flows. Referring to the flow conditions in the pond, effective sedimentation is achieved by inducing good mixing of the influent at the pond inlet, a uniform flow velocity distribution in the pond (which favours quiescent settling), and prevention of short-circuiting and sediment resuspension by high flow velocities or secondary currents (Ellis, 1989; Hvitved-Jacobsen, 1990). Following these recommendations and referring to the results in Fig.2, further improvements of flow patterns in this pond are planned by implementing remedial measures comprising installations of an inlet skimmer and flow baffles.

Sediment surveys in the studied facility focused on two types of sediment - benthic sediment deposited on the bottom and suspended particulate transported through the facility. A detailed survey of the benthic sediment was undertaken. The pond bottom was discretized into a square grid and two types of samples were collected in each grid square - core samples and surficial samples.

Core samples indicated that the thickness of bottom sediment varied from 0.15 to 0.2 m. This layer of sediment was accumulated over a 10-year period, with an average rate of accretion of about 0.02 m/year. Sediment cores were sliced into 3 or 4 layers and individual layers were analyzed for particle size distribution and chemical composition, mostly characterized by metals. A typical particle size distribution in a sediment core is shown in Table 2.

TABLE 2 Particle Size Distribution in a Central Pond Core

Layer	Clay(%)	Silt(%)	Sand(%)	Gravel(%)
0-3 cm (top)	63	34	3	0
3-8 cm	57	43	1	0
8-13 cm	57	42	1	0
13-18 cm (bottom)	66	22	5	7

The size distributions are fairly consistent, indicating that the benthic sediment comprises mostly silt (35%) and clay (61%). Some coarser materials were found in the bottom layer (possibly remnants of construction activities) and, to a lesser degree, in the top layer.

Sediment entering and/or passing through the pond is subject to grading by hydraulic transport. Such grading can be detected from particle size analysis performed on samples collected upstream from, in, and downstream from the pond. Such data are shown in Fig.3.

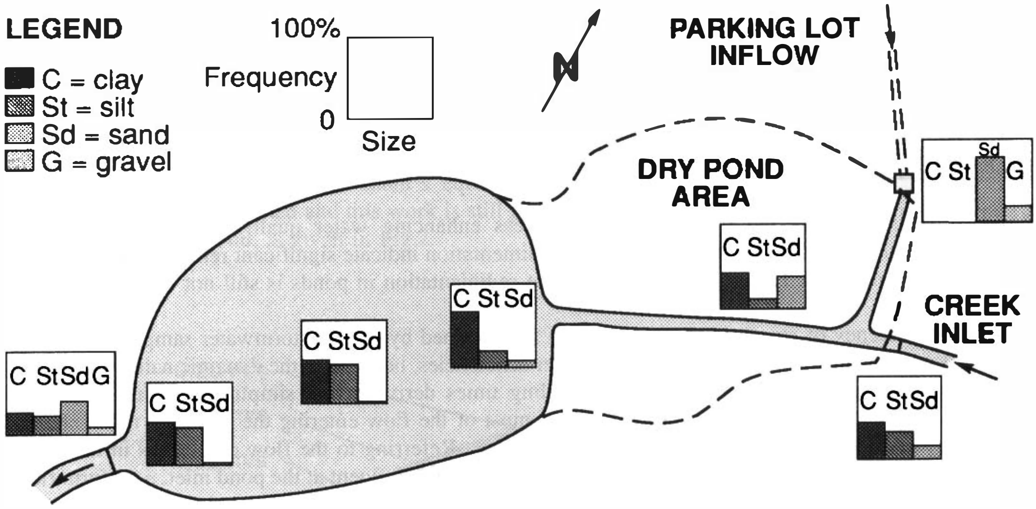

Fig.3. Particle Size Distribution of Sediments from the Study Area

The data in Fig.3 indicate that sediment in the creek upstream from the pond is well graded, with good representation of sand, silt and clay. In the drain conveying the shopping plaza runoff to the pond, mostly sand and gravel are deposited; finer particles are probably transported with high flows to the pond. Sand from the creek and plaza drainage is partly transported through the dry pond channel and partly deposits there. Consequently, the samples from this channel contain a high percentage of sand (41%). In the pond, close to the inlet, sand deposits rapidly, contributing to sand contents of about 10%. In the middle of the pond and close to the outlet, there is about 1% sand and the rest of the material is silt and clay, with clay dominating in about a 7:4 ratio. In the creek downstream from the pond, a much more uniform grading was observed, with gravel, sand, silt and clay represented. Compared to the distribution upstream from the pond, it would appear that the finer fractions, silt and clay, were somewhat underrepresented downstream of the pond. Obviously much of this material has been retained in the pond.

Even though the benthic pond sediment indicates deposition of significant quantities of fine-grained material in the pond, some suspended particulate passes through the pond, and/or some material may be scoured and resuspended from the pond bottom. Such material is of interest in establishing the pond efficiency in removing pollutants from incoming flow. Consequently, physical and chemical properties of such materials should be investigated.

Samples of suspended particulate were collected from the pond by dipping a short (50 mm) cylinder in the pond water. After slow decantation, the particulate from this sample was photographed under a microscope and its geometrical characteristics were examined. An example of such particulate is shown in Fig.4.

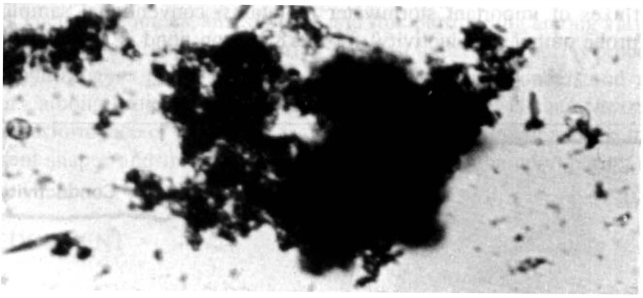

Fig.4. Suspended Particulate from the Pond Studied (Equivalent diameter = 0.15 mm)

Fig.4 reveals that the suspended particulate represents flocculated aggregates combining primary particles. The sizes of such flocs can be appreciable - with an equivalent diameter of about 0.25 mm. Further study of geometrical shapes, physical properties (mostly density) and chemistry of these particles is planned.

Other samples of suspended particulate were collected by centrifuging pond water in various locations. In this case, the collected particles ranged from 0.24 to 62.5 μm in size; obviously flocs were broken by centrifuging and/or the use of chemical dispersants in particle size analysis. In each location, centrifuging had to be conducted for 6-8 hours to obtain sufficient suspended sediment samples (20-50 g). While these samples are adequate for chemical analyses, the physical properties of flocs were altered and no longer describe the settling properties of original particles. Further studies of suspended sediment, using fractal analysis to establish physical and chemical properties of particles, are planned.

Chemical Fluxes

Chemical sources, sinks, fluxes, and flux partitioning among various phases are of interest when establishing mass balances of stormwater ponds. In principle, the chemical mass balance for a specified time interval (e.g. one year) can be written as

$$I_i - O_i = S_i + W_i + A_i + B_i \pm T_i \tag{2}$$

where I is the chemical input, O is the output, S is the chemical bound to the sediment in the pond, W is the chemical mass in pond water, A is the chemical mass volatilized, B is the chemical mass in the biota, T is the chemical mass arising from transformations (either a production with plus sign, or a loss with a minus sign), and the subscript i denotes various chemicals studied.

The range of chemicals studied varies from study to study, but generally several typical groups are considered: solids, nutrients, metals, and some typical toxicants (e.g.PAHs). The significance of individual terms in eq.(2) varies depending on the substance under consideration. For example, for most parameters in the facility studied, the terms W, A B and T are of secondary importance and can be neglected.

Chemical fluxes should be monitored at all the inflow and outflow points. Ideally, they would be monitored continuously by water quality probes. Unfortunately, even though continuous probes for a number of chemicals are available, they work only in a laboratory environment and very few parameters can be continuously monitored in the field. In the pond studied, two HYDROLAB SURVEYOR 3 water quality probes were installed, close to the inlet and outlet, respectively. These probes measure continuously temperature, specific conductance, dissolved oxygen, pH and redox. Such parameters are useful for identifying some chemical transformations in the pond. For example, both dissolved oxygen and pH affect chemical exchanges between the sediment and water column (Striegl, 1987; Yousef *et al.*, 1986). However, for determination of fluxes of important stormwater pollutants, conventional sampling is required. An example of the water probe output (conductivity) for the Kingston pond is given in Fig.5.

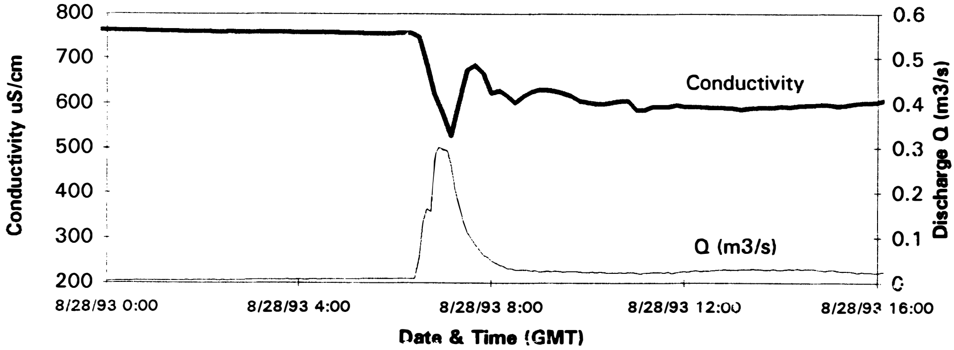

Fig.5. Continuous Flow and Conductivity Records: Dilution of Pond Water by Inflow

In view of the limitations of water quality probes, chemical fluxes are typically monitored by inflow and outflow sampling, and supplemented by special surveys (e.g. of the sediment). In the study discussed, two inflows are recognized - the creek and the shopping plaza storm drain. Sequential samples are collected automatically during wet weather, and manually during dry weather to characterize the baseflow.

High costs of sample analyses do not allow to analyze all the samples collected. Consequently, it is required to approximate the fluxes during unmonitored events by computer simulations. Using the data collected in many events, regression approximations for various constituents were derived as functions of flow or sediment transport. These equations can be applied to unmonitored events to estimate chemical fluxes.

Removals of chemicals from the studied pond by biota were found to be insignificant. There is no significant presence of aquatic plants or other living organisms in the pond. Experiments with submerged pods containing aquatic plants showed sequestration of some chemicals (particularly metals) by these plants, but the quantities observed were not significant. In other installations, however, this component could be much more important and should not be neglected (Ellis, 1989).

Bacteria

Ponds also contain various microorganisms and, from the public health point of view, the interest focuses mostly on indicator bacteria. Any water body in an urban area will attract attention, particularly during the summer months, when children may attempt to wade in the pond and there is some risk of contracting waterborne diseases. Consequently, indicator bacteria were also monitored in the pond, by manually collecting water samples and submitting them for analyses of faecal coliform, *E. coli*, *Pseudomonas aeruginosa* and faecal streptococcus. Early results indicate frequent exceedance of the (Canadian) recreational water quality criterion of 100 *E. coli*/100 ml, but no other conclusions can be drawn at this time.

CONCLUSIONS

Rigorous evaluation of stormwater pond performance requires close monitoring of various processes taking place in ponds and contributing to enhancement of water quality. The list of such processes starts with the pond and contributing catchment hydrological processes, pond hydraulics described by velocity distributions for various discharges, chemical sources, sinks, fluxes and flux partitioning among various phases, including chemical transformations, and occurrence of bacteria. The best understood part is probably that dealing with catchment and pond hydrology. Other aspects are still inadequately understood and their monitoring procedures greatly vary among projects. Unless the pond performance is characterized by such a detailed monitoring, the actual performance of individual facilities is not well known and the transfer of data among the facilities of different shapes and from different climates may not be appropriate.

ACKNOWLEDGEMENT

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