Performance Assessment of a Pond-Wetland Stormwater Management Facility - Markham, Ontario

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PERFORMANCE ASSESSMENT OF A POND-WETLAND STORMWATER MANAGEMENT FACILITY - MARKHAM, ONTARIO

a report prepared by:

STORMWATER ASSESSMENT MONITORING
AND PERFORMANCE (SWAMP) PROGRAM

for

Great Lakes Sustainability Fund of the Government of Canada
Ontario Ministry of Environment and Energy
Toronto and Region Conservation Authority
Municipal Engineers Association of Ontario
Town of Markham

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THE SWAMP PROGRAM

The Stormwater Assessment Monitoring and Performance (SWAMP) Program is an initiative of the Government of Canada's Great Lakes Sustainability Fund, the Ontario Ministry of Environment and Energy, the Toronto and Region Conservation Authority, and the Municipal Engineer's Association. A number of individual municipalities and other owner/operator agencies have also participated in the SWAMP studies.

During the mid to late 1980s, the Great Lakes Basin experienced rapid urban growth. Stormwater runoff associated with this growth is a major contributor to the degradation of water quality and the destruction of fish habitats. In response to these environmental concerns, a variety of stormwater management technologies have been developed to mitigate the impacts of urbanization on the natural environment. These technologies have been studied, designed and constructed on the basis of computer models and pilot-scale testing, but have not undergone extensive field-level evaluation in southern Ontario. The SWAMP Program was designed to address this need.

The SWAMP Program's objectives are:

* to monitor and evaluate the effectiveness of new or innovative stormwater management technologies; and
* to disseminate study results and recommendations within the stormwater management industry.

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Additional information concerning SWAMP and the sponsoring agencies is included in Appendix A.

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- the Government of Canada's Great Lakes Sustainability Fund,
- the Ontario Ministry of Environment and Energy,
- the Toronto and Region Conservation Authority,
- the Municipal Engineers Association of Ontario.

Funding support for this project was provided by the Great Lakes 2000 Cleanup Fund (superseded by the Great Lakes Sustainability Fund), the Ontario Ministry of Environment and Energy (OMOEE) and the Town of Markham. The OMOEE also provided office facilities and logistic support for the SWAMP program. The Laboratory Services Branch of the OMOEE provided laboratory analyses. Administrative support to the SWAMP program was provided by the Toronto and Region Conservation Authority. Staff at the Town of Markham provided permission to conduct the monitoring study and assisted with the installation and operation of monitoring equipment.

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EXECUTIVE SUMMARY

Background and Objectives

In 1998, a multi-party agreement among the participating agencies of the Stormwater Assessment Monitoring and Performance (SWAMP) program[1] was established to monitor a stormwater pond-wetland demonstration facility located on the Upper Morningside Tributary of the Rouge River watershed in Markham, Ontario. The facility, known as the Markham Best Management Practice Demonstration Project (or Markham BMP), consists of a sediment forebay, wet pond and wetland that treats stormwater runoff from a 600 hectare, predominantly residential drainage basin. The pond-wetland system replaces a smaller water quantity stormwater dry pond and was selected from among four alternatives based on an ecosystem approach. Selection of the BMP design was based on an ecosystem approach, with goals and objectives determined as an integrated subset of management plans for the Morningside Tributary sub-watershed and the Rouge River watershed. A twelve-month baseline monitoring program of environmental conditions prior to construction of the facility[2] forms the backdrop of this study.

The overall objective of this study was to assess the performance of the Markham BMP against the original design goals and targets identified for the facility. Within this general context, the specific aims were to:

- evaluate the function of the system in terms of contaminant removal, runoff control, temperature impacts, and sediment dynamics;
- assess seasonal variations in stormwater quality and facility function;
- assess potential impacts of the facility on channel morphology and, indirectly, on aquatic habitat within the Morningside Tributary;
- document aquatic plant regeneration patterns in the wetland;
- estimate sediment accumulation rates and dredging requirements for the facility, and
- suggest recommendations for system improvement and/or further research.

This study provides one of the first comprehensive assessments of pollutant removal and flow attenuation by a large, centralized multi-cell pond-wetland facility located within a temperate climate region. As a

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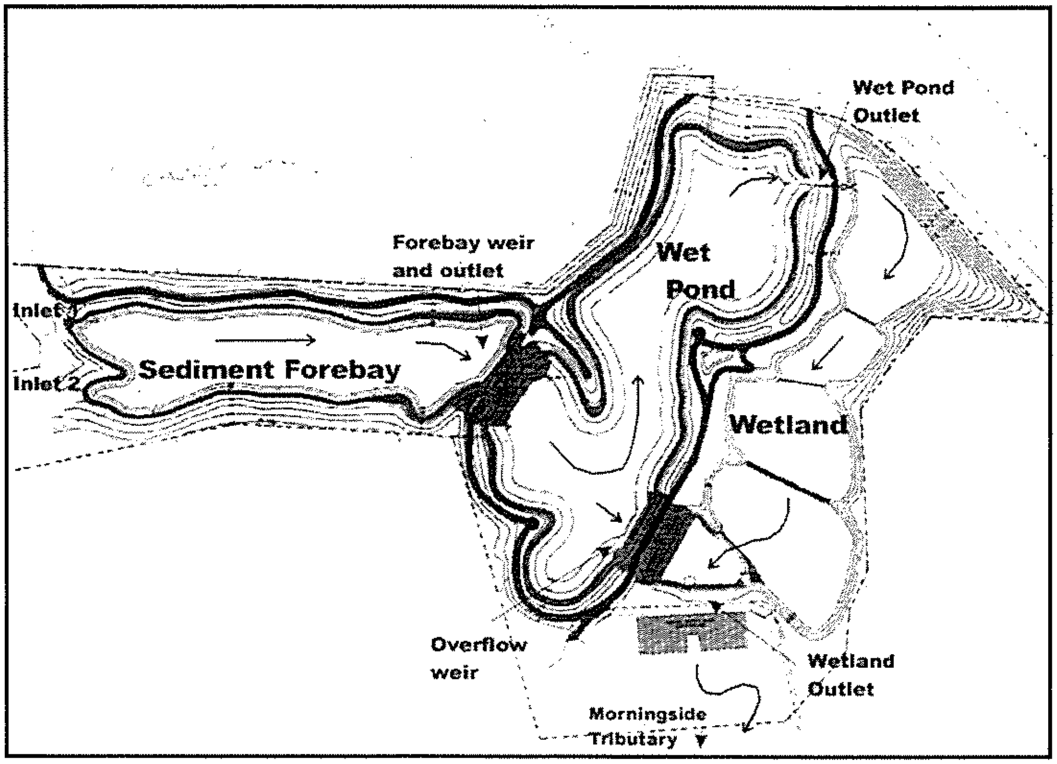
[1] The participating agencies are Government of Canada's Great Lakes Sustainability Fund, Ministry of Environment and Energy, Toronto and Region Conservation Authority, Municipal Engineer's Association and the Town of Markham.

[2] Beak Consultants Ltd and Aquafor Beech, Ltd. 1997. *Best Management Practices Environmental Resource Management Demonstration Project, Town of Markham, Phase II and III report.* Brampton, Ontario.

demonstration project, it is hoped that the results of this study will help guide the planning, design and retrofit of similar stormwater management facilities in Ontario.

Study Area and Facility Design

The 600 hectare drainage basin for the Markham BMP comprises 28% of the Morningside subwatershed. At the time of the study, approximately 67% of the drainage basin was developed (90% residential, 10% industrial). The catchment was expected to be fully developed within 5 to 10 years. The topography of the area is characterized by gently rolling hills with predominantly silty-sand soils. A fish and benthic invertebrate survey conducted by Beak and Aquafor Beech in 1992/3 in the Morningside Tributary downstream of the facility indicated generally degraded aquatic habitat consisting predominantly of tolerant warmwater communities with relatively low diversity.



Adapted from: Beak Consultants Ltd and Aquafor Beech, Ltd. 1997. *Best Management Practices Environmental Resource Management Demonstration Project, Town of Markham, Phase II and III Report.* Brampton, Ontario.

Figure 1: Markham BMP

The multi-cell on-line Markham BMP (Figure 1) was designed to perform several functions, including stormwater treatment, base-flow augmentation, flood protection and downstream erosion control. These functions are partly provided through extended detention storage above the 73,000 m^3 permanent pool for events with less than 25 mm of rain. By design, over three-quarters of the total extended detention volume for the 25 mm event was to drain within the first 24 hours, with the remainder draining over a period of 3 to 6 days. Total storage volume (permanent pool + extended detention) is 151,000 m^3, representing a volume-to-catchment area ratio of 252 m^3 per hectare, and a storage area-to-catchment ratio of 1.2%. Runoff volumes exceeding the extended storage capacity of the forebay and wet pond bypass the wetland and overflow directly from the wet pond to the wetland outlet.

A distributed runoff control structure at the wet pond outlet, consisting of a reverse slope feed pipe, inlet chamber and proportional weir, was designed to reduce the frequency of flows exceeding bankfull rates and augment flows during dry weather. The storage volume, length-to-width ratio, extended detention depth and drawdown time exceed the OMOEE's 'Level I' fisheries protection guidelines for this type of facility, but the maximum pond depth is 1.2 m deeper than the 3 m recommended limit.

Monitoring Program

Data were collected from November 1998 to December 1999 and from April to June 2000. The monitoring set-up consisted of continuous flow loggers, temperature probes and auto-samplers at the two inlets and at the outlets of the forebay, wet pond and wetland. Grab samples were taken at the inlets and wetland outlet during dry weather. Precipitation was determined using a tipping bucket rain gauge located within the drainage basin, approximately 1 km west of the facility. A total of 129 samples were collected, representing 30 rainfall events from November 1998 to December 1999. Water quality samples were preserved and submitted to the Ministry of Environment and Energy Lab in Toronto for analysis immediately following sample collection. Samples were analyzed for a wide range of chemical and physical parameters. Subsequent data analysis included calculations for flow balances, peak flow reduction, hydraulic detention times, flow duration, peak-to peak lag times, mean sample concentrations, contaminant loading rates and load-based removal efficiencies. Statistical analyses of water quality results were performed using a program developed by the OMOEE for stormwater constituent analysis.

Study Findings

Hydrology

At the level of development in 1999, the retrofitted Markham BMP met or exceeded the hydrologic design targets and objectives described in the environmental study report for the project[3]. Flood peaks were reduced by more than 80% for all storms, outlet peak flows were consistently below estimated bankfull rates (0.5 to 1.3 m^3/s) in the downstream tributary, storm flows were released gradually over a 3 to 10 day period, and hydraulic detention times (as calculated from inlet and outlet hydrograph centroids) averaged 31 hours. Peak

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[3] Beak Consultants Ltd and Aquafor Beech, Ltd. 1997. *Best Management Practices Environmental Resource Management Demonstration Project, Town of Markham, Phase II and III Report.* Brampton, Ontario.

flows during large storms were also consistently less than the two year pre-development rate, estimated at 4.9 m^3/s.

The hydraulic residence time was estimated to be 87 hours, or 3.6 days, based on plug flow conditions (*i.e.* no mixing, no short circuiting), the mean influent flow rate (0.27 m^3/s) and an estimate of the average pond volume during an event (85,000 m^3). Dead zones, short-circuiting, internal mixing and other factors would typically reduce this value. The hydraulic residence time was not measured by tracer tests as part of this study.

The runoff coefficient, or fraction of rainfall converted to storm runoff, averaged 0.16. This is slightly lower than expected for 1999 levels of catchment imperviousness (estimated at 24%), and may be attributed in part to mandatory roof drainage disconnection requirements for new development in Markham. Although several large rain events (> 25 mm) were recorded during the study period, few generated sufficient runoff volumes to cause overflow across the wet pond spillway. Hence, the hydrodynamics of this flow path could not be characterized.

During dry weather, the wet pond distributed runoff control structure helped to augment baseflow, but summer basseflow rates averaged only 6 L/s. During one long dry period, flow rates in the upper 100 m of the downstream tributary slowed to a trickle. As stormflow volumes increase with urbanization, higher average inter-event water levels are expected to further augment baseflow rates.

Water quality

Composite samples collected at five monitoring stations within the facility were analyzed for a large suite of parameters including suspended solids, metals, nutrients, chloride, herbicides, Polynuclear Aromatic Hydrocarbons (PAHs), phenols, bacteria and particle size. This report provides statistical summaries for individual parameters and assesses load and concentration-based contaminant removal efficiencies of the facility. Results are interpreted and discussed with reference to the original water quality targets for the facility, Provincial Water Quality Objectives (PWQOs), baseline conditions and other studies of stormwater ponds and wetlands.

Major conclusions from the analysis of the water quality data were as follows:

- Influent concentrations of several contaminants had very low detection frequencies, including arsenic, selenium, mercury, 9 herbicides, 7 phenols and 22 PAHs. Lead, cobalt and mercury were detected more frequently at the inlet, but were almost never detected at the outlet of the facility.

- Overall load-based removal efficiencies during the summer/fall period for selected constituents are presented in Table 1. Winter average concentration-based removal rates were less than summer removal rates for all constituents except TSS, total ammonia, *E.coli*, *F.streptococcus*, cadmium, nickel, lead, manganese, zinc and titanium.

- The majority of pollutants settled out in the forebay and wet pond (Table 1). The wetland showed slightly higher removal than the wet pond for several pollutants and was particularly effective in removing dissolved pollutants such as nitrate and phosphate.

Table 1: Overall load-based removal efficiencies (%) for selected constituents during the summer/fall period

	Forebay	**Wet pond**	**Wetland**
TSS	79	92	95
copper	75	84	85
zinc	83	87	87
chromium	63	80	84
nickel	67	65	62
ammonia (NH_3+NH_4)	28	44	22
TKN	53	48	55
total phosphorus	76	83	87
phosphate	61	76	89
E.coli	51	97	79
F. streptococcus	90	99	99

Note: Removal efficiencies represent cumulative load-based removal up to the outlet of each cell (forebay, wet pond and wetland). Thus, numbers in the wetland column represent overall removal for the entire facility.

- During wet weather, removal efficiencies for sand, silt and clay sized particles were estimated at 100%, 96% and 84%, respectively. Size selective removal of suspended particulates resulted in a decrease in the median particle size as water travelled through the facility. The median size of the average influent particle size distribution was 3.8 µm, compared to a median size of approximately 2.0 µm at the forebay, wet pond and wetland outlets. By volume, particles less than 4 µm (clay) accounted for 53% and 78% of the influent and wetland effluent particle size distributions, respectively.

- During the summer/fall monitoring period (May to November), mean wet weather effluent concentrations of copper, total phosphorus and *E.coli* were above Provincial Water Quality Objectives/Guidelines for these constituents. Based on limited sampling during dry weather, mean concentrations of chromium, iron and total phosphorus exceeded Ontario guidelines.

- The mean effluent temperature from May to July, 2000 was 4.1°C higher than the influent temperature. The maximum effluent temperature was 23.6°C, which is below the 26°C maximum target for the facility, but above the 21°C threshold for coldwater fisheries habitat.

- The retrofitted Markham BMP was significantly more effective than the original pond in terms of contaminant removal and peak flow attenuation, despite significantly increased catchment impervious cover in 1999.

Downstream channel adjustments

The Markham BMP was intended to prevent channel enlargement and erosion by attenuating peak flows and extending stormflow drawdown times. To evaluate progress towards this goal, morphological changes within the Morningside tributary north of Steeles Avenue were assessed through erosion pin measurements and channel cross section surveys in 1996, 1998/1999 and, as part of this study, in August 2000. In general, changes in channel morphology since 1996 were modest relative to urban streams without stormwater control. A small decrease in channel area due to sediment deposition (up to 20 cm) was observed at cross sections 100 and 160 m downstream of the facility. Further downstream, at 250 and 500 m, the channel was slightly larger relative to 1996 elevations due to bed erosion of up to 25 cm. Changes since 1999 were more significant than between 1998 and 1999, probably due to a series of large storms in April and May 2000, two of which overtopped the spillway, causing major erosion of the overflow berm between the pond and wetland, and considerable sediment transport downstream. Unlike other large storms, the volume and force of the overflows were sufficient to remove armour stones (approximately 10-40 cm in diameter) and erosion cloth installed to prevent scour of the overflow channel.

Wetland Vegetation Assessment

The sediments and associated seedbank from the former marsh were used in the construction of the new wetland as a means of promoting rapid post-construction establishment of plants. A survey of wetland plants indicated that this strategy was reasonably successful. A community of plants very similar to what previously existed at the former marsh had naturally re-established itself only two years after construction. The species composition was dominated by common cattails (85-90%) and reed canary grass (8-13%), with several other wetland plants forming a minor part of the vegetation community.

Operation and Maintenance

Acceptable performance levels at the Markham BMP can only be sustained if the facility is adequately maintained. Regular inspections are required for sediment accumulation, weir blockage, bank and spillway erosion, vegetation health and the occurrence of industrial spills. Sediment removal is the most costly maintenance activity. Sediment accumulation rates were estimated from flow volume and TSS data collected in 1999, and were based on the assumption that the catchment will be fully developed in 2005. At ultimate development levels, sediment accumulation rates are estimated at 15.2, 5.5 and 0.2 mm/yr in the forebay, wet pond and wetland, respectively. At these rates, the forebay, wet pond and wetland will require sediment removal roughly 21, 54 and 193 years from the time the facility became operational in 1997.

Conclusions and Recommendations

The facility met or exceeded most of the original design targets and objectives, demonstrating that significant improvement in performance can be achieved by retrofitting small single-subdivision catchment water quantity stormwater ponds to much larger and more cost-effective centralized pond-wetland treatment systems as development within the catchment increases. Observed improvements in performance can be mostly attributed to an increased storage area-to-catchment ratio and the innovative distributed runoff control structure at the wet pond outlet, which minimized the frequency of bankfull flow rates in the downstream channel and prolonged the release of stored water after an event. The wetland on the end of the treatment train also contributed to the success of the facility by improving system performance, particularly with respect to dissolved constituents.

Recommendations for system improvement, maintenance and further research are as follows.

- Erosion cloth lining the spillway was seriously damaged during a large storm event in April 2000. The cloth protects underlying soils from transport downstream during overflow events, and should be repaired so as not to endanger the health of aquatic communities within the downstream tributary.

- Bypass flow from the wetpond was discharged to the downstream portion of the wetland. As indicated above, this geometry can lead to erosion within the wetland. Future designs should, therefore, allow bypass flow around the wetland directly into the downstream channel.

- The drawdown time of the wetpond runoff control structure often exceeded the average interevent period (approximately 72 hours in Ontario). Thus, the active storage capacity available for a subsequent event would have been limited, increasing the likelihood of bypass flow. To enhance the design of future facilities, further consideration should be given to weir designs and pond hydraulics such that an optimum balance is achieved among storage, detention time, and baseflow augmentation in the downstream channel.

- The wetland outlet structure accumulated coarse bedload sediment during low flow periods. A low concrete barrier elevating the outlet structure above the wetland bed would help to trap the sediment, while sustaining a permanent pool of water in the upstream wetland cells. The permanent pool would enhance water quality functions of the wetland by increasing the bottom-to-water contact ratio.

- Estimates of sediment accumulation rates provided in this report were based on several assumptions and should not be relied upon to determine dredging requirements. For this reason, direct measurements of sediment accumulation in each of the cells and around outfalls and intake pipes are recommended at 5 year intervals.

- Drawing upon earlier studies, this report documents changes in performance of the Markham pond/wetland at different stages of development. As the catchment becomes increasingly urbanized, continued monitoring will be required to verify whether the hydrological and water quality performance of the facility continue to meet the original design targets and objectives.

- Direct assessment of urban runoff impacts on aquatic biota was beyond the scope of this study. Shifts in aquatic health often occur very gradually and therefore require long term monitoring of appropriate biological and habitat indicators. The existence of this and earlier studies on the water quality, geomorphology and health of the Morningside tributary make the Markham site well suited for long-term aquatic habitat monitoring.

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1.0 INTRODUCTION

1.1 Background

Urban stormwater runoff often results in adverse impacts to watercourses and receiving waters. These impacts may be manifested in the form of higher downstream flooding risks, enhanced channel erosion, lower baseflow and increased pollutant loads relative to less developed areas (USEPA, 1999). Stormwater was identified by the Toronto and Region Remedial Action Plan (1999) as the most significant local source of contaminants to Toronto's waterfront. If permitted to enter receiving waters untreated, stormwater contaminants can disrupt aquatic ecosystem functions, harm wildlife and limit recreational use of waterways. Actions are currently underway to enhance beneficial uses and prevent further degradation of Toronto's watersheds through rehabilitation projects and implementation of Best Management Practices (BMPs) (Toronto and Region RAP, 1999).

When maintained appropriately, wet detention ponds and constructed wetlands are among the most effective BMPs for stormwater pollutant removal and flood peak attenuation (*e.g.* OMOEE, 1994a; Brown and Schueler, 1997), while providing ancillary benefits in terms of recreation and aesthetics (see Appendix B for a glossary of terms). The permanent pool in the pond or wetland promotes quiescent conditions required for settling of particles and associated pollutants, whereas vegetation and microbial populations in the rooting zone remove contaminants through filtration, plant uptake and bio-chemical degradation. Removal efficiencies for suspended solids and associated contaminants exhibit a wide range depending on facility design, outlet control, influent characteristics and base-flow concentrations (Tsihrintzis and Hamid, 1997), but are typically above 50% for appropriately designed facilities (Mudgway et. al., 1997; Brown and Schueler, 1997; USEPA, 1983). Removal of highly mobile dissolved constituents is generally lower and more seasonally variable (*e.g.* Loucks, 1989; Martin, 1988).

The Markham Best Management Practice Demonstration facility, or Markham BMP, consists of a sediment forebay, wet pond and wetland and is a unique example of a centralized facility treating stormwater runoff from a drainage area several times larger than the typical single-subdivision stormwater pond found in Ontario. Centralized facilities provide opportunities for cost savings by eliminating the need to construct several smaller ponds and facilitating long-term operation and maintenance activities (Wisner and Arishenkoff, 1997).

The Markham BMP was jointly commissioned as a demonstration project by the Town of Markham, the Ontario Ministry of Environment and Energy and the Government of Canada's Great Lakes 2000 Cleanup Fund (superceded by the Great Lakes Sustainability Fund). Selection of the BMP design was based on an ecosystem approach, with goals and objectives determined as an integrated subset of management plans for the Morningside Tributary sub-watershed and the Rouge River watershed (Beak and Aquafor Beech, 1993).

The project was undertaken in six phases, as follows:

Phase I: develop project approach; select an appropriate site among four alternatives
Phase II: monitor baseline environmental conditions; determine goals, objectives and design targets
Phase III: select and prepare pre-design of BMP(s); define maintenance requirements and costs
Phase IV: prepare detailed design of the preferred BMP(s)
Phase V: construct BMP(s)
Phase VI: assess the performance of the completed BMP(s) through detailed monitoring

The monitoring study completes Phase VI of the project and provides one of the first comprehensive assessments of pollutant removal and flow attenuation by a large, centralized multi-cell pond-wetland facility located within a temperate climate region.

1.2 Study objectives

The overall goal of the study was to assess the water quality and runoff control functions of the Markham BMP within the context of its original design targets and objectives. Specifically, this study was designed to:

- evaluate the function of the Markham BMP in terms of contaminant removal, runoff control, temperature impacts, and sediment dynamics;
- assess seasonal variations in stormwater quality and facility function;
- assess potential impacts of the Markham BMP on channel morphology and, indirectly, on aquatic habitat within the Upper Morningside Tributary;
- document aquatic plant regeneration patterns in the wetland;
- estimate sediment accumulation rates and dredging requirements for the BMP; and
- suggest recommendations for system improvement and further research.

As a demonstration project, it is hoped that the results of this study will help guide the planning, design and retrofit of similar stormwater management facilities in Ontario.

1.0 STUDY SITE

2.1 Location and drainage area

The study area is located in the Town of Markham, Region of York, on the Upper Morningside Tributary of the Rouge River watershed. The total area covers approximately 880 hectares (40% of the Morningside Tributary subwatershed area) and is roughly bounded by 14th Avenue to the north, Steeles Avenue to the south, Brimley road to the west and Parkview golf course to the east (Figure 2.1). Several intermittent streams once drained from west to east across the study area, then south towards Steeles Avenue, but with increased urbanization, these were enclosed and directed through concrete channels into two on-line stormwater facilities (Beak and Aquafor Beech, 1997).

The Markham BMP is the larger of the two facilities (Figure 2.2), covering 9.1 hectares (including banks and berms). It is a retrofit of a smaller stormwater pond (referred to in this and previous reports as the North pond) constructed in 1983, and has a drainage area of approximately 600 hectares, representing 28% of the Morningside subwatershed (Badelt, 1999). The smaller dry pond south of the Markham BMP (see 'South pond' in Figure 2.1) receives runoff from the lower 280 hectares of the study area and was constructed when land use was predominantly agricultural. The South pond is undersized for the current level of urbanization and, consequently, no longer provides adequate stormwater control (Badelt, 1999). The South pond was not evaluated as part of the present study.

2.2 Land use changes

Construction for commercial and residential land uses was ongoing during the monitoring period (Nov. 1998 to Dec. 1999), but on average approximately 67% (90% residential, 10% industrial) of the drainage area for the Markham BMP was partly or fully developed. This represents a significant increase from 20% urban land use in 1979, and 34% in 1993 (Badelt, 1999). Within 5 to 10 years the drainage area is expected to be fully developed except for residential park lands and zones designated by the Town of Markham as Areas of Local Environmental Significance (ALES) along the valley reach downstream of the facility (Figure 2.1). Impervious cover under fully developed conditions is estimated at 40% (Badelt, 1999).

2.3 Climate

The mean annual precipitation (1951-1980) for the Toronto area is 800 mm, 17% of which falls as snow. Mean monthly precipitation values for the winter/spring period (December to April) and the summer/fall period (May to November) are 66 and 68 mm, respectively (Toronto Bloor AES station, as cited in Beak and Aquafor Beach, 1997). Average daily temperature for the region is 12.8°C, ranging from –4.6°C in January to 22.0°C in July. Mean maximum daily temperatures for the two hottest months, July and August, are 26.7 and 25.6°C, respectively.

2.4 Topography, Soils and Groundwater

The topography is characterized by gently rolling lands. Soils consist of Millikan and Woburn loams composed of silty-sand glacial till materials. The study area is located within a groundwater recharge area with water tables slightly below the creek elevation (Beak and Aquafor Beech, 1993).

2.5 Aquatic and Terrestrial Resources

A baseline aquatic survey conducted by Beak and Aquafor Beech in 1992/93 revealed that the aquatic resource in the upper Morningside tributary had degraded from a coldwater community of high diversity to a tolerant warmwater community consisting of 5 fish species or less. The shift was attributed to high water temperatures, low baseflow rates and decreased channel stability associated with increased urbanization. A transition to coolwater and coldwater communities was observed in the middle and lower reaches of the Morningside tributary south of Steeles. Benthic invertebrate surveys revealed similar degradation of aquatic habitat in the upper reach of the tributary. No evidence of chronic toxicity was found.

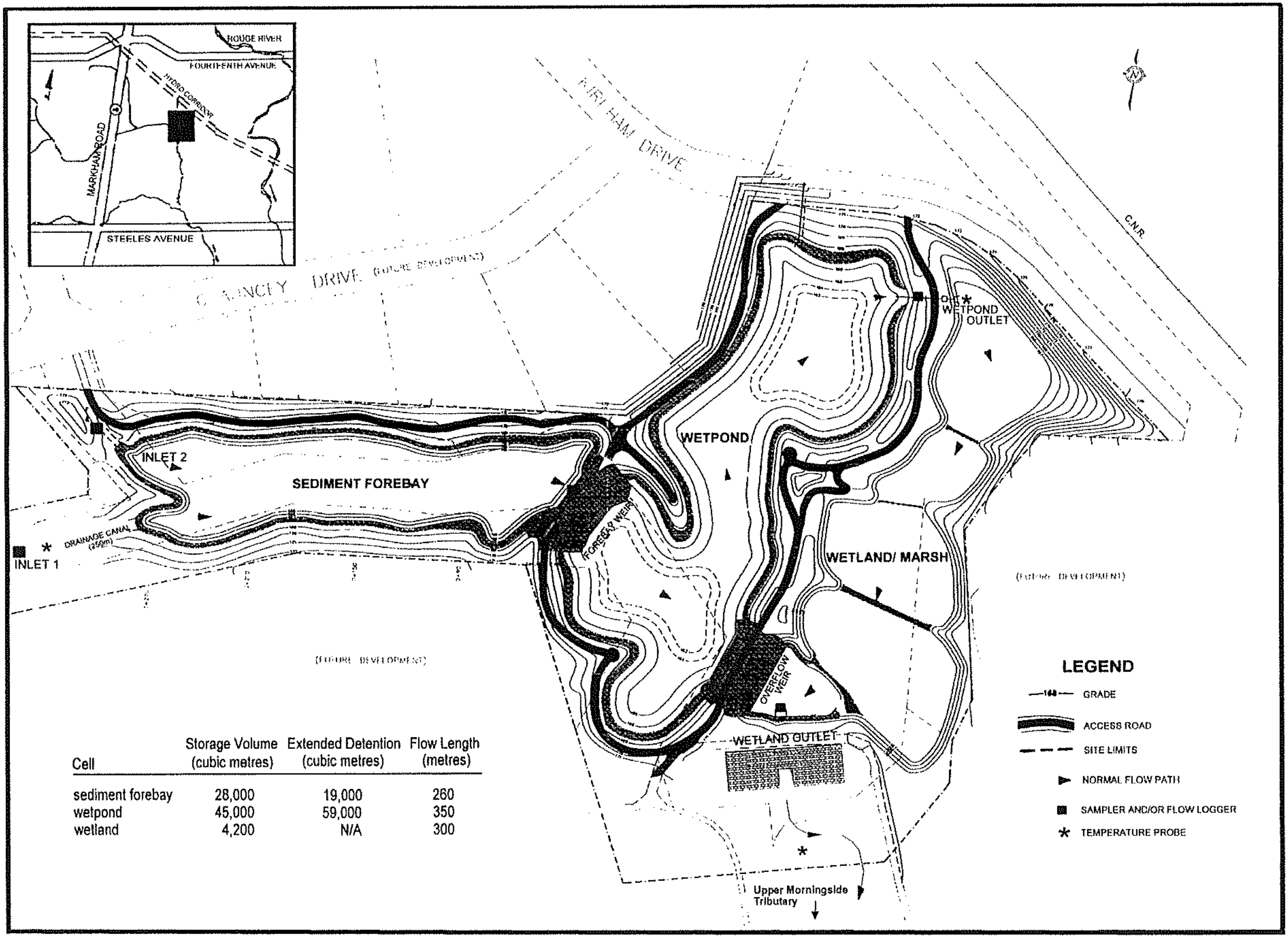
The stream reach downstream of the Markham BMP and north of Steeles is designated by the Town of Markham as a Locally Significant Area. The baseline study reported high wildlife diversity associated with wetlands and forested areas near the former pond (Beak and Aquafor Beech, 1993). Although not specifically identified as a project objective, wetland construction helped to maintain or enhance wildlife diversity in the area. During the study period, deer, beaver, racoon and several bird species, including great blue herons, barn swallows and blue jays, were observed in the area.

2.6 Facility design and operation

The multi-cell on-line Markham BMP (Figure 2.2) was designed to perform several functions, including stormwater treatment, base-flow augmentation, flood protection and downstream erosion control. These functions are partly provided through extended detention above the 73,000 cubic metre permanent pool for rainfall depths less than 25 mm (4 hour Chicago distribution). By design, over three-quarters of the total extended detention volume for the 25 mm event was to drain within the first 24 hours, with the remainder draining over a period of 3 to 6 days. The average depths of the pond and forebay with extended detention are both approximately 3.8 m. Total storage volume (permanent pool and extended detention storage) is 151,000 cubic metres, representing a volume to catchment area ratio of 252 m^3 per hectare and a storage area to catchment ratio of 1.2%.

As shown in Figure 2.2, stormwater enters the facility through two inlets at the west end of the sediment forebay. The south inlet (inlet 1) flows along a 250 m vegetated channel before discharging into the forebay. A submerged weir separates the forebay and wet pond. Flow exits the wet pond through a 'distributed runoff control' structure consisting of a reverse slope feed pipe, inlet chamber and proportional weir, as shown in

Figure 2.1: Study area in 1999, showing the location of the Markham BMP, Rouge River, the Morningside Tributary, and other stormwater ponds (blue thatch), within the drainage basin.



Cell	Storage Volume (cubic metres)	Extended Detention (cubic metres)	Flow Length (metres)
sediment forebay	28,000	19,000	260
wetpond	45,000	59,000	350
wetland	4,200	N/A	300

Figure 2.2: Study site and location of monitoring equipment (adapted from Beak and Aquafor Beech, 1997)

Figure 2.3. The reverse slope pipe draws cool water from deep within the pond to reduce temperature impacts and minimize contamination from floating debris and Light Non-Aqueous Phase Liquids (LNAPLs) such as oil and grease. Baseflow is augmented through a small orifice plate connected to a perforated inlet control riser pipe. The proportional weir above the orifice plate is sized to limit the frequency of flows exceeding bankfull rates, estimated at between 0.52 m^3/s and and 1.3 m^3/s (Badelt, 1999; Beak and Aquafor Beech, 1997). For events larger than 25 mm over 4 hours (approximately 2 year return frequency), stormwater bypasses the wetland and spills from the wet pond directly over a wide overflow weir to the wetland outlet (Figure 2.2).

The water treatment function of the pond and sediment forebay occurs primarily through the permanent pool (varying from 2.2 to 4.2 m in depth), which provides quiescent conditions necessary for particles and associated contaminants to settle out. The pond's irregular shape and depth (length:width ratio = 5:1) enhances settling by extending the flow path, promoting plug flow conditions and preventing short circuiting. The wetland provides additional polishing of effluent through sedimentation, biological uptake, plant filtration and microbial transformation of contaminants. The four cells within the wetland (low and high marsh areas) allow for varying water depths and greater plant biodiversity, enhancing the wetland's value as wildlife habitat.

Major design features of the Markham BMP are compared to OMOEE (1994a) water quality design guidelines in Table 2.1. In addition to water quality enhancement and baseflow augmentation, the facility was designed to control peak discharge rates to pre-development levels for the 2 to 100 year storm events. Hence the extended detention volume and drawdown time are well above recommended levels set by the OMOEE for water quality enhancement. The permanent pool volume and length-to-width ratio also meet the guidelines, but the maximum pond depth exceeds the 3 m OMOEE guideline by 1.2 m. The maximum depth guideline was intended to prevent the formation of anoxic conditions in bottom sediments, which may cause resuspension of some pollutants (OMOEE, 1994a), especially during warm summer periods when thermal stratification and biochemical activity is highest.

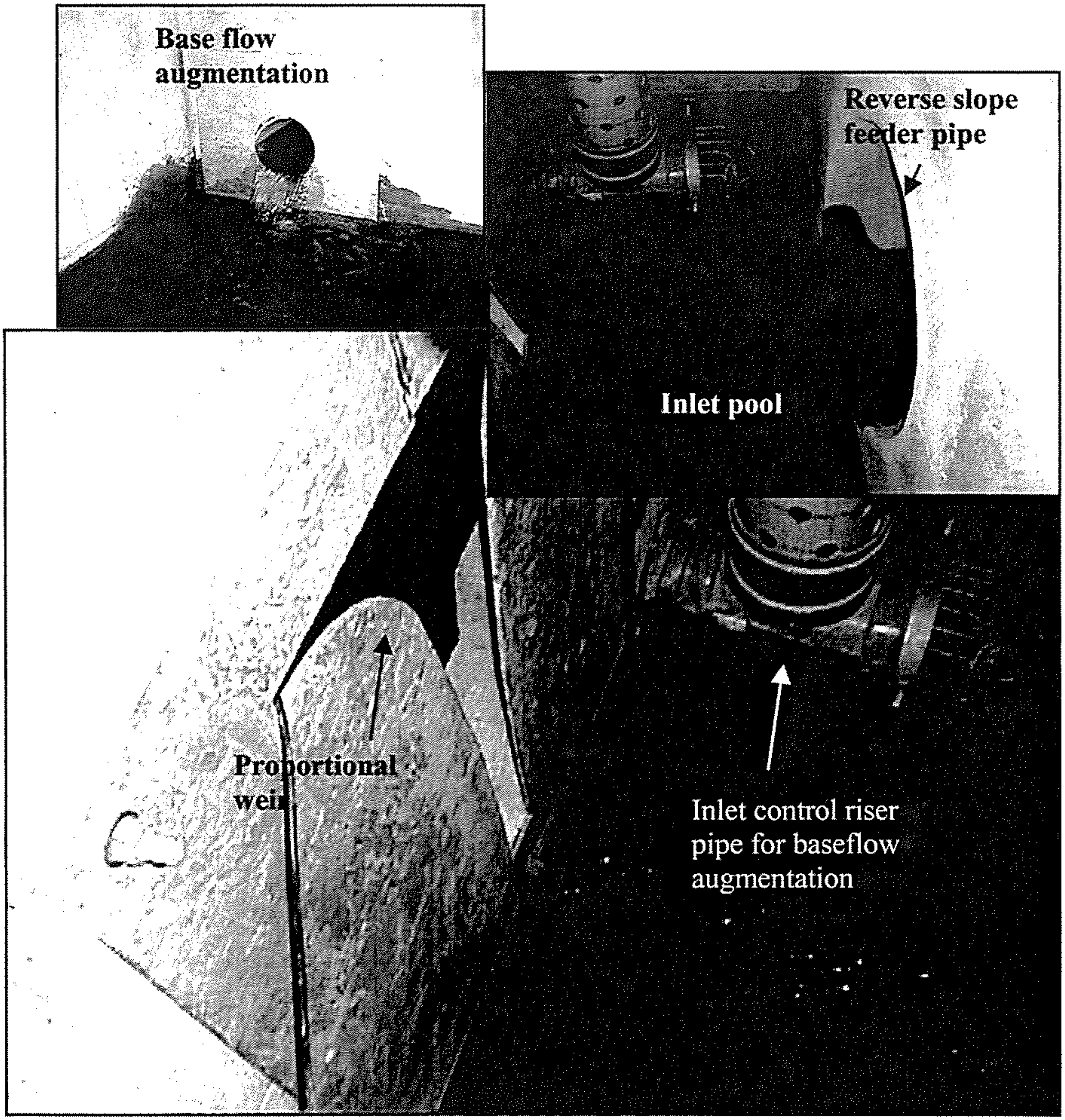


Figure 2.3: The wet pond outlet distributed runoff control structure.

Table 2.1: Markham BMP design features as compared to OMOEE (1994a) design guidelines

Design feature	Design Objective	OMOEE guidelines (1994a)	Markham BMP
Permanent Pool Depth (m)	minimize resuspension; avoid anoxic conditions	1-2 (average); 3 (max.)	2.2 to 4.2
Permanent Pool Volume (m^3/ha)	provision of 'Level I' fisheries protection	112*	129$^{\xi}$, 122†; 75‡
Extended Detention Depth (m)	storage and flow control	1 to 1.5	1.6
Extended Detention Volume (m^3/ha)	provision of 'Level I' fisheries protection	40	130†; 98‡
Drawdown Time (days)$^{++}$	suspended solids settling	1	3 to 6
Length-to-Width Ratio	minimize short circuiting	at least 3:1	5:1
Near Shore Slope	safety	at least 5:1	7:1
Gradated Planting Strategy	safety, aesthetics, recreational amenity, shading for temperature control	five zones – aquatic to upland	Grassed berms; natural regeneration

* based on 'Level I' fisheries protection and 40% surface imperviousness.

$^{\xi}$ forebay, pond, and wetland; †forebay and pond; ‡pond only

$^{++}$The OMOEE 'detention time' guideline for erosion control is 24 hours for a 4 hour, 25 mm storm. The SWMP manual suggests using a drawdown equation to meet the detention time guideline. Hence, the term 'drawdown time' is used in Table 2.1.

3.0 STUDY APPROACH

Data were collected from November 1998 to December 1999 and from April to June 2000. The monitoring protocol was designed to provide data on seasonal and intra/inter-event variations in measured parameters and facilitate comparison of results with the baseline monitoring study.

3.1 Rain

Precipitation was determined using a tipping bucket rain gauge, installed within the Markham BMP drainage basin at St. Vincent School, approximately 1 km west of the facility. Data were collected in real time and downloaded at bi-weekly intervals. Another rain gauge located at Markham Road and 16th Avenue, less than 1 km north east of the study area, was used as a back-up in case of equipment malfunction.

3.2 Runoff

Discharge rates were logged continuously at 5 minute intervals in each of the two inlet storm sewers and at the wet pond outlet with flow loggers and area-velocity probes (Figure 2.2). Area-velocity probes contain two transducers that emit and receive ultrasonic waves. Average velocity measurements are based on the shift in ultrasonic wave frequency caused by reflection of the waves off suspended particles in the flow stream. A pressure transducer inside the same probe measures depth allowing for a simple conversion to area based on channel dimensions. The flow loggers provided accurate flow velocities for water depths above 50 mm. Baseflow below this depth was determined manually with a current meter at regular intervals during the study period.

At the wetland outlet, discharge rates were estimated from a stage-discharge relationship ($R^2 = 0.91$) and continuous water level data (5 minute intervals) collected during the study period. The stage-discharge relationship was developed from manual measurements of water depth (stage), channel width, and velocity using a current meter. Manual measurements were taken over discharge rates ranging from 20 to 476 L/s. Over 95% of effluent storm discharge rates observed during the monitoring period fell within this range.

3.3 Water quality

3.3.1 Temperature

Temperature was monitored at 10-minute intervals from April to July 2000 using Ryan Temperature Monitors (RTM)™. The units were installed near the outfall of inlet 1, at the wet pond outlet and in a small pool downstream of the wetland outlet. At all locations, temperature probes were submerged 50 cm below the dry weather water surface.

3.3.2 Water quality sampling

Composite water samples were collected at the two inlets, and at the sediment forebay, wet pond and wetland outlets using ISCO 3700™ automated wastewater samplers. Samplers were programmed to start collecting when the water level rose above a set level, then collect 24 samples at 5 minute intervals (120 minute duration) at the two inlets and at 10 minute intervals (240 minute duration) at the forebay and wet pond outlets. The wetland sampler was set to begin 24 hours after the start of the storm, and sample at one hour intervals (24 hour duration).

Composite samples collected in this manner were considered to be an approximate measure of the mean concentration of the period over which the samples were collected, rather than the mean concentration of the entire event, commonly referred to as the Event Mean Concentration. Since stormflow exited the facility over a period of several days, the tail end of the hydrograph (after 48 hours) was not sampled. This, and the non-flow proportioned nature of sampling, are important points that should be borne in mind when interpreting the results.

Composite samples were also collected in the winter during snowmelt events and grab samples were collected during dry weather at the two inlets and wetland outlet. Since grab samples are collected at a single point in time, these data should be interpreted with caution.

A total of 129 samples were collected, representing 30 rainfall events from Nov 16, 1998 to Dec 5, 1999. No samples were collected from the forebay and pond during the winter period.

Water quality samples were preserved (metals and nutrients) and submitted to the Ministry of Environment and Energy Lab in Toronto. Analyses were conducted following principles outlined in *Standard Methods* (Eaton *et al.*, 1995) for metals, nutrients (P and N), bacteria, organics and general chemistry (*e.g.* pH, conductivity, alkalinity). Particle size analysis of suspended solids was undertaken using an optical laser light diffraction method and results were reported by size class in percent by volume. Appendix C summarizes the analytical procedures used in this study.

3.3.3 Statistical Methods

Statistical analysis of water quality results was performed using a software package developed by the Ministry of Environment and Energy for use in stormwater constituent analysis (Maunder *et al.*, 1995). The package used probability distribution estimation (PDE) techniques to generate the mean, standard deviation and 95% confidence intervals for data sets containing left censored data (*i.e.* data at or below the limit detectable by lab analytical equipment). These techniques (*e.g.* Maximum likelihood estimation) generate values for data below the detection limit based on the log-normal probability distribution of the non-censored data. In instances where PDE techniques could not be used, left censored data were assigned a value equal to half the detection limit (Maunder *et al.*, 1995). These methods were particularly useful in generating statistics for organics, heavy metals and other constituents typically found at very low concentrations in stormwater.

Overall load-based removal efficiency (*LE*), which requires both the runoff volume (V) and the concentration of constituents (C), was calculated for single events during the summer/fall using the following equation:

$$LE = \frac{(V^i \text{ x } C^i) - (V^o \text{ x } C^o)}{V^i \text{ x } C^i} \text{ x } 100\% \qquad (3.1)$$

where i = inlet
o = outlet

Performance over the summer/fall period (May to November) was calculated based on the sum of loads at the inlet and outlet, as follows:

$$SLE = \frac{\sum_{j=1}^{m} \left[V_j^i \text{ x } C_j^i - V_j^o \text{ x } C_j^o \right]}{\sum_{j=1}^{m} \left[V_j^i \text{ x } C_j^i \right]} \text{ x } 100\% \qquad (3.2)$$

where: m = number of events

At the forebay monitoring station, where flow was not measured, flow volumes for each event were assumed to be equal to the inlet flow volume less 40% of the measured loss or gain in flow volume from the inlet and wet pond outlet (based on the ratio of the forebay to wet pond surface area). The loss or gain of runoff volume across the pond system results from net exfiltration/infiltration, from evaporation and direct precipitation, and also reflects instrument errors.

During the winter/spring period (December 1 to April 31) and during dry weather, concentration-based removal efficiency (*CE*) was determined from composite and grab sample concentrations (C), respectively.

$$CE = \frac{(C^i - C^o)}{C^i} \text{ x } 100\% \qquad (3.3)$$

The seasonal average was calculated as,

$$Average\ CE = \frac{1}{m} \left[\sum_{j=1}^{m} \frac{C_j^i - C_j^o}{C_j^i} \right] \text{ x } 100\% \qquad (3.4)$$

This method of calculating removal efficiencies assumes a good volumetric water balance in the facility, which is probably valid in the winter, when losses through evaporation and infiltration are generally low. A detailed discussion of methods for estimating efficiency in pond systems is provided in Appendix B.

4.0 WATER QUANTITY ANALYSIS

A hydrological summary for the summer/fall period is presented in Table 4.1. The summary represents 55% of storms monitored during the summer/fall season for which rainfall was greater than 5 mm. Other storms were omitted from the analysis because of missing or unreliable data at one or more of the monitoring stations. Winter flow data were available only at the two inlets. The selected storms include 5 large storms (>25 mm), 3 medium sized storms (10 to 25 mm) and 3 small storms (5 to 10 mm). Terms and concepts used in this chapter are defined and explained in Appendix B.

4.1 Rainfall

Rainfall within the study area from May to November 1999 (485 mm) was very close to the 30-year average (1951-1980) recorded at the Toronto-Bloor meteorological station (472 mm) over the same period (Figure 4.1). The highest rainfall depths were recorded in June (88 mm) and September (93 mm), both of which were higher than the 30-year average for these months (Figure 4.1). Precipitation data during the winter (December to April, 1999) at Markham were not available. The annual 30-year average is 328 mm, 38% of which falls as snow (Beak and Aquafor Beech, 1997)

4.2 Runoff Coefficients

The storm runoff coefficient (Table 4.1) is the ratio of runoff volume (stormwater pond influent) to rainfall volume, and represents the proportion of rainfall converted to surface runoff over the course of an event. Runoff coefficients averaged 0.16 at both inlets. These coefficients are on the lower end of the range reported for other developed catchments in the United States with a similar level (20 to 25%) of imperviousness (Schueler, 1994). The relatively low coefficients in this study may be in part explained by the presence of several dry ponds within the catchment (Figure 2.1), as well as mandatory roof drainage disconnection requirements for new development in Markham (Wisner and Arishenkoff, 1997).

As a further check on data collected during this study, runoff coefficients were calculated using stream gauge data collected in the Morningside Tributary at Steeles Avenue, approximately 1 km downstream of the study site (data from Badelt, 1999). This station received flow from the entire study area (880 ha.), which includes the South pond catchment (Figure 2.1). Flow data from this station and a rain gauge located 1 km north of the study site (at Markham Road and 16th Avenue) indicated runoff coefficients of 0.15, 0.13 and 0.16 for large storms on August 24th, 1998, October 6th, 1998 and April 22, 1999, respectively. The average of these coefficients is marginally lower than the 0.16 average estimate for the Markham BMP catchment in 1999, possibly due to the less developed nature of the catchment in 1998. Stream gauging data at Steeles Avenue were not available during the summer/fall of 1999.

Table 4.1: Summary of hydrologic statistics for selected rain events

Storm Date	Precipitation				Flow Volume (m^3)					Volumetric Balance (%)*		Runoff Coefficient[++]		
Summer/fall 1999	Rain (mm)	Interevent Duration (hr.)	Rainfall duration (hr.)	Average Intensity (mm/hr)	Inlet 1	Inlet 2	Inlet total	Pond Outlet	Wetland Outlet	Pond Outlet	Wetland Outlet	Inlet 1	Inlet 2	Total Inlet
8-May	8.4	363	10.1	0.8	3244	3767	7011	6837	6920	7.5	8.8	0.10	0.22	0.14
18-May	10.9	227	9.0	1.2	6301	3831	10132	9726	7749	8.5	27.6	0.14	0.18	0.15
24-May	20.2	118	22.0	0.9	15391	5648	21039	25133	26320	-14.4	-17.3	0.17	0.19	0.17
1-Jun	25.8	129	17.1	1.5	22527	11474	34001	34617	37025	1.6	-3.4	0.22	0.22	0.22
7-Jun	9.3	115	1.0	9.3	5358	1145	6503	6863	8200	1.0	-14.7	0.14	0.06	0.12
24-Jun	45.5	248	19.0	2.4	38233	11774	50007	58488	55711	-12.2	-4.8	0.21	0.13	0.18
3-Jul	12.3	115	4.2	2.9	4925	2492	7417	7160	8074	10.3	2.3	0.10	0.10	0.1
3-Aug	63.4	75	43.0	1.5	31056	15581	46637	48442	48038	2.3	5.8	0.12	0.12	0.12
6-Sep	29.0	290	19.0	1.5	21214	16642	37856	36834	33756	6.0	15.3	0.18	0.28	0.22
13-Sep	9.0	99	7.0	1.3	3573	1437	5010	4807	6499	11.4	-15.4	0.08	0.08	0.09
13-Oct	39.0	110	12.0	3.2	52825	17962	70787	63946	72509	11.6	1.0	0.33	0.23	0.3
average	24.8	171.7	14.9	2.4	18604	8341	26945	27532	28255	3.1	0.5	0.16	0.16	0.16

*accounts for direct rain input to the forebay/pond (4.64 ha) and forebay/pond/wetland (6.92 ha).

[++] based on catchment areas for inlet 1 and 2 of 400 and 200 hectares, respectively

Storm Date	Detention Time (hrs)		Peak Flow (m^3/s)				Peak-to-Peak Lag Time (hr.)[+]				Duration of Flow (hr.)			
Summer/fall 1999	Pond Outlet	Wetland Outlet	Inlet 1	Inlet 2	Pond Outlet	Wetland Outlet	Inlet 1	Inlet 2	Pond Outlet	Wetland Outlet	Inlet 1	Inlet 2	Pond Outlet	Wetland Outlet
8-May	28.0	28.6	0.44	0.21	0.04	0.04	5.5	5.4	10.9	12.7	26.4	39.6	138	88
18-May	31.7	29.6	0.48	0.18	0.06	0.05	0.9	0.9	17.1	21.8	19.5	22.2	123	92
24-May	54.8	53.0	0.35	0.14	0.11	0.11	1.3	1.3	10.0	10.5	21.2	27.5	188	152
1-Jun	39.2	42.0	3.13	0.41	0.17	0.15	0.2	0.3	3.7	4.4	6.6	22.7	142	138
7-Jun	25.0	26.7	2.79	0.47	0.07	0.07	0.4	0.4	6.4	9.6	4.6	5	74	72
24-Jun	28.9	32.4	7.90	0.75	0.34	0.28	0.5	0.6	3.3	3.7	64.4	87.2	156	150
3-Jul	16.8	18.2	2.48	0.25	0.07	0.07	0.3	0.2	6.5	7.6	1.7	12.4	81	79
3-Aug	21.3	24.6	4.25	0.22	0.24	0.20	0.8	0.8	16.7	18.7	19.1	132.4	250	244
6-Sep	30.1	31.0	2.08	0.59	0.14	0.12	0.2	0.3	14.1	14.6	26.7	107.7	157	151
13-Sep	22.7	24.7	0.81	0.13	0.04	0.06	1.7	1.4	6.9	10.1	18.1	20.9	86	76
13-Oct	17.7	26.7	4.97	0.47	0.41	0.40	0.8	0.5	8.9	10.5	34.7	176.8	197	190
average	28.7	30.7	2.70	0.35	0.15	0.14	1.1	1.1	9.5	11.3	22.1	59.5	144.7	130.2

[+] Defined as the time delay between the rainfall and hydrograph peaks.

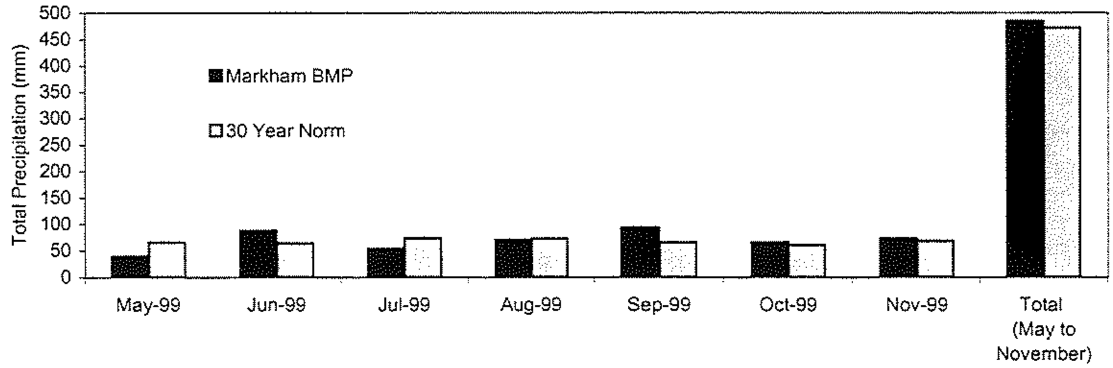


Figure 4.1: Monthly rainfall at the Markham BMP during the summer/fall (May to November, 1999) compared to 30-year normals (1951-1980) from the Toronto Bloor meteorological station

4.3 Flow and Storage Volumes

The average inflow to the wet pond for selected storms listed in Table 4.1 was 28,255 m^3, representing 36% of the total extended detention volume (78,000 m^3) and 39% of the permanent pool storage (73,000 m^3) in the wet pond and forebay. Under plug flow conditions (*i.e.* no mixing of influent and pond water; no short circuiting), very few storms would have produced flow volumes sufficient to displace the permanent pool volume. Therefore, water volumes exiting the wet pond mostly represent treated water from previous events, rather than new event water. As will be discussed in Chapter 5, this observation has important implications for effluent water quality and system performance.

Overflow across the wet pond bypass spillway was not measured during the flow monitoring period. However, based on the average runoff coefficient (0.16), only short duration storms with rainfall greater than 76 mm would have generated flow volumes in excess of the extended detention volume. Two events of this magnitude occurred in May 2000, after the flow monitoring equipment had been removed, causing significant damage to the spillway channel. As urban development within the catchment expands, these overflow events are expected to become more frequent.

4.4 Peak Flow Attenuation

Hydrographs in Figure 4.2 visually depict the capacity of the system to attenuate storm peaks and slow the release of water to the downstream channel. Inlet flood peaks were reduced by over 80% at the wet pond and wetland outlets (Table 4.1). Peak flows during large storms were also below the 2-year (25 mm, 4 hour duration) pre-development peak flow rates, estimated at 4.9 m^3/s (Beak and Aquafor Beech, 1997). Wetland outlet peak flows were always below the 1.3 m^3/s bankfull estimate suggested by Beak and Aquafor Beech (1993) and only once exceeded the more conservative 0.5 m^3/s estimate provided by Badelt (1999) for the Upper Morningside tributary.[1] Bankfull flow occurs every 1 to 2 years in natural channels and is considered to be the dominant channel forming flow (MNR, 1994). Prolonging the duration of flows through effluent throttling at the wet pond outlet (see Section 2.6) is the primary means by which these larger more destructive flows were avoided. Flow durations at the wet pond outlet averaged 6.0 days, compared to an average of only 0.9 and 2.5 days at the two inlets (Table 4.1 and Figure 4.2).

By design, the wetland was to support a permanent pool depth of 0.3 m (volume = 4200 m^3), but observed water depths in all but the first cell were negligible, even during medium-sized storm events (10-20 mm of rain). During larger storm events, flow was more evenly distributed over the entire wetland, and water depths ranged from approximately 1 m in the first cell to 0.2 m in the fourth. As flow volumes increase with development, water levels in the wetland are expected to rise. Low antecedent water levels in the wetland likely explain the long time lag between peak flows at the wet pond and wetland during the May 18th and September 6th storms (Figure 4.2).

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[1] The event with wetland peak flow exceeding 0.5m^3/s was not one of the selected events included in Table 4.1 because reliable flow measurements were not available at one or more stations.

4.5 Baseflow

During dry weather, total flow from the two inlets was approximately 45 L/s. This is slightly higher than the 40 L/s reported in the 1993 baseline study. Influent baseflow originates mostly from groundwater seepage through sewer pipe cracks and joints. At the wetland outlet, water drained from the facility for up to 10 days following an event, after which effluent baseflow declined to an average of 6 L/s during the summer months. During one dry period in 1998, flow in the upper reach of the Morningside tributary ceased altogether. As urbanization within the catchment increases, the average duration of stormflow exiting the wet pond is expected to rise due to higher stormflow volumes and higher average water levels in the pond. These longer durations will result in higher low flow rates (*i.e.* enhanced baseflow augmentation) and a permanent pool of water in the wetland. Higher and less sporadic baseflow rates will prevent damage to aquatic habitat caused by ephemeral flow conditions in the downstream tributary.

4.6 Volumetric Flow Balance

The flow balance across the pond/wetland system averaged 0.5% and ranged from –15.4 to 27.6%. At the pond outlet, the average volumetric balance was 3.1%, with a range between –14.4 to 11.6%. In general, a positive volumetric balance implies that the quantity of water entering the pond through groundwater discharge exceeds the quantity of water lost by evaporation and groundwater recharge. However, flow balance is also affected by instrument errors. Since groundwater recharge/discharge and evaporation were probably relatively insignificant components of the water balance, flow balances greater than ±10% probably reflect inaccuracies in flow measurements, especially at the two inlets, where stormflow response times were very rapid. Other studies of stormwater ponds in Ontario (SWAMP, 2002a; Liang and Thompson, 1996), report summer/fall water losses of between 5 and 15% due to infiltration and evaporation.

4.7 Hydraulic Detention and Residence Times

The hydraulic detention time, calculated as the time difference between the inlet and outlet hydrograph centroids, is a measure of the throttling effect of the outlet structure by which the bulk of fluid is held back or detained within the pond (see discussion in Appendix B). The detention time averaged 29 and 31 hours from the inlet to the pond and wetland outlets, respectively (Table 4.1). By comparison, the time lag between the inlet and wetland outlet peaks averaged 10 hours, and ranged widely between 4 and 21 hours.

The hydraulic residence time (a.k.a. retention time) of different elements of fluid is typically determined through the use of tracers. In this study, tracer tests were not undertaken; therefore, the residence time could not be determined. However, a crude estimate may be provided by assuming steady state flow, an average pond volume and plug-flow conditions (i.e. no mixing, no short circuiting). Based on a mean influent flow rate for the storms presented in Table 4.1 of 0.27 m^3/s and an average pond volume of approximately 85,000 m^3, the hydraulic residence time is 87 hours (3.6 days). Dead zones in the pond, short-circuiting, internal mixing and other factors would typically reduce this value. Also, since most storms occur over less than 4

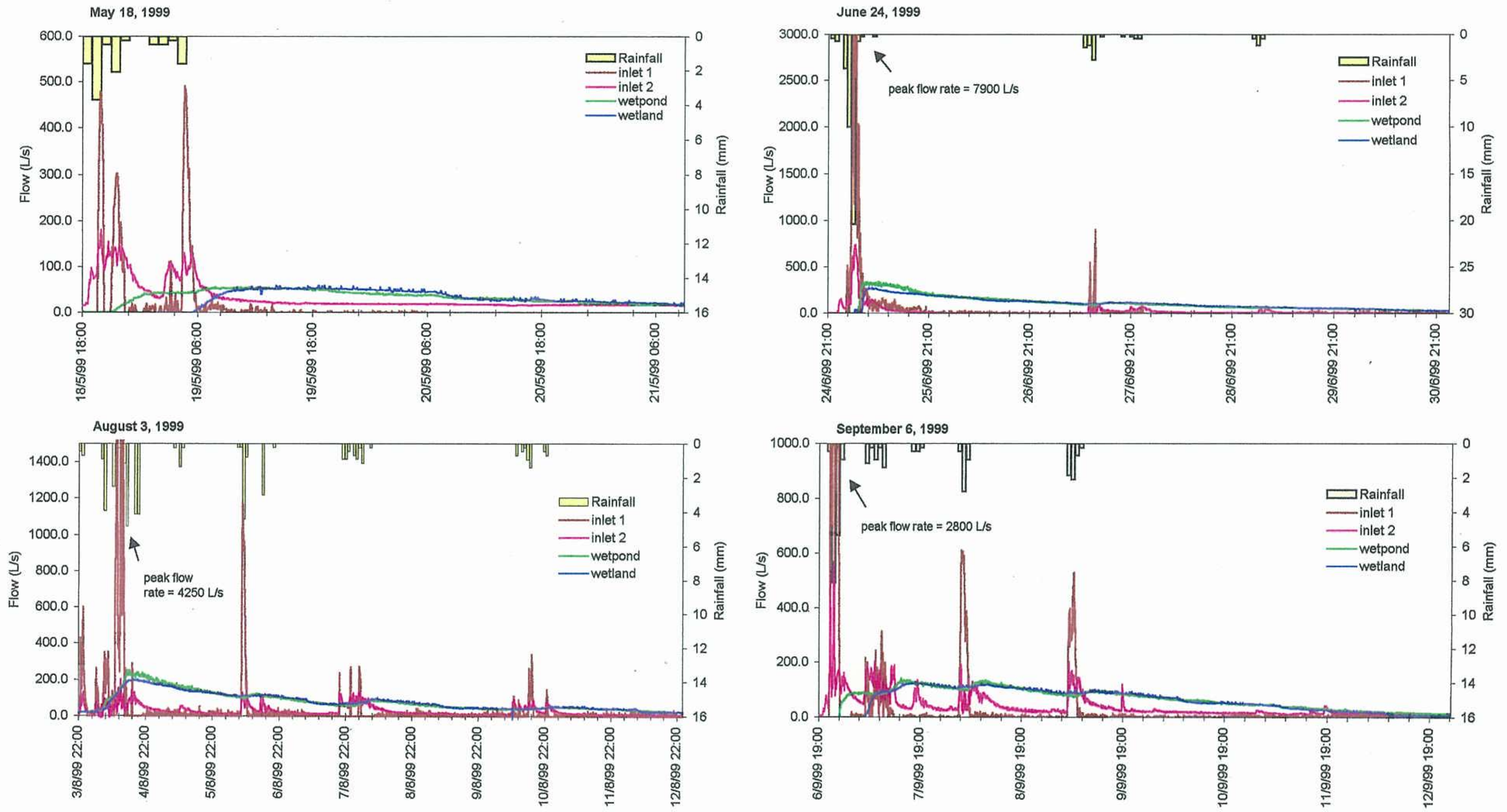


Figure 4.2: Hydrographs and rainfall hyetographs for storms on May 18, June 24, August 3 and September 6, 1999. Note difference in horizontal and vertical scales.

days, all or a portion of the influent runoff will remain in the pond during interevent periods. The long residence times are an important factor for the attainment of runoff quality improvements.

4.8 Changes in hydrologic conditions: 1992/3 to 1999

Hydrologic monitoring data collected by Beak and Aquafor Beech (1993) at the former 'North' pond from September 1992 to August 1993 provide a baseline against which the retrofit facility can be compared. In 1992, only 34% of the catchment was developed, compared to 67% during the 1999 study.

Table 4.2 summarizes hydrologic statistics from the baseline study (Beak and Aquafor Beech, 1993). The high runoff coefficient (average = 0.33) relative to the present study (average = 0.16) suggests that the earlier data were likely overestimated. Typical runoff coefficients for urban residential catchments with less than 20% impervious cover rarely exceed 0.20 (Schueler, 1994). Further, runoff coefficients from an independent flow measurement at Steeles Avenue in 1998 and 1999, approximately one km downstream of the study site, were consistently below 0.17 (Badelt, 1999).

Table 4.2: Baseline hydrologic summary for selected events (1992/3) (Beak and Aquafor Beech, 1993)

Event date	**Rainfall**			**Runoff (Discharge from North Pond)**				
	Depth (mm)	**Duration (hr)**	**Time-to-Peak (hr)**	**Volume (m^3)**	**Duration (hr)**	**Peak flow (m^3/s)**	**Runoff Coef.**	**Peak-to-Peak Lag Time (hr)***
Sep 22/92	21.6	5.5	4.0	52200	64.0	1.52	0.40	2.0
Sep 27/92	3.6	7.5	0.5	3330	32.5	0.11	0.10	2.0
Oct 9/ 92	10.7	6.5	4.0	6660	38.0	0.45	0.10	1.0
Oct 20/92	12.5	17	3.0	41640	140.5	0.49	0.48	6.0
Nov 2/92	28.7	20	18.5	64260	53.5	1.30	0.37	2.0
Nov 12/92	31.3	13.5	9.0	111420	83.0	1.70	0.59	5.5
Nov 22/92	17.0	17.5	9.5	57720	53.5	1.09	0.57	2.0
May 31/93	12.2	7.5	5.5	3600	10.5	0.29	0.05	1.0
Average	**17.2**	**11.9**	**6.8**	**42604**	**59.4**	**0.87**	**0.33**	**2.7**

* defined as the time delay between the rainfall and hydrograph peaks

A comparison of data sets indicates that peak flows were approximately 4 times higher at the former pond (1992/3) outlet for similar sized storms, causing bankfull flow (maximum 1.3 m^3/s) to be reached or exceeded for storms with rainfall greater than 21 mm. These differences may reflect differences in outlet control at the current and former ponds.

As expected, flow control at the wet pond outlet resulted in significantly longer outflow durations than the former pond. The duration of outflow for 20 to 30 mm storms ranged from 5.7 to 7.6 days at the Markham BMP, compared to 2.2 to 2.7 days at the former pond. The time lag from peak rainfall to peak runoff at the outlet also differed significantly, averaging 11.3 and 2.7 hours at the Markham BMP and former pond, respectively. Baseline data on hydraulic detention times were not available, but a comparison of flow duration data sets suggest that detention times were significantly longer at the Markham BMP.

5.0 WATER QUALITY ANALYSIS

Wet weather concentrations and 95% confidence limits are presented in Figures 5.1 (a and b) and 5.2 for the summer/fall (May to November) and winter/spring (December to April) seasons, respectively. Table 5.1 presents mean concentrations and compares them to the City of Toronto wet (Maunder et. al, 1995) and dry (Snodgrass and D'Andrea, 1993) weather discharge studies, and Provincial Water Quality Objectives (PWQOs). A more detailed summary of water quality statistics (means, standard deviations, 95% confidence limits, etc.) can be found in Appendix D. Figures 5.3 and 5.4 show wet weather removal efficiencies for the summer and winter seasons, respectively. Removal efficiencies for individual events are provided in Appendix E. These results are interpreted and discussed below with reference to the original water quality targets for the facility, Provincial Water Quality Objectives (PWQOs), baseline conditions and other studies of stormwater ponds and wetlands.

5.1 Frequency of detection

Detection frequencies of effluent samples are presented in Table 5.2. This table lists several parameters analyzed in this study with very low detection frequencies (<10% detection), especially in the Polyaromatic Hydrocarbon (PAH), herbicide and phenol groups. With the exception of lead, cobalt and molybdenum, these parameters also had very low detection frequencies at the two inlets. Detection limits for organic parameters are provided in Appendix C and for all other parameters in Appendix D.

5.2 Total Suspended Solids

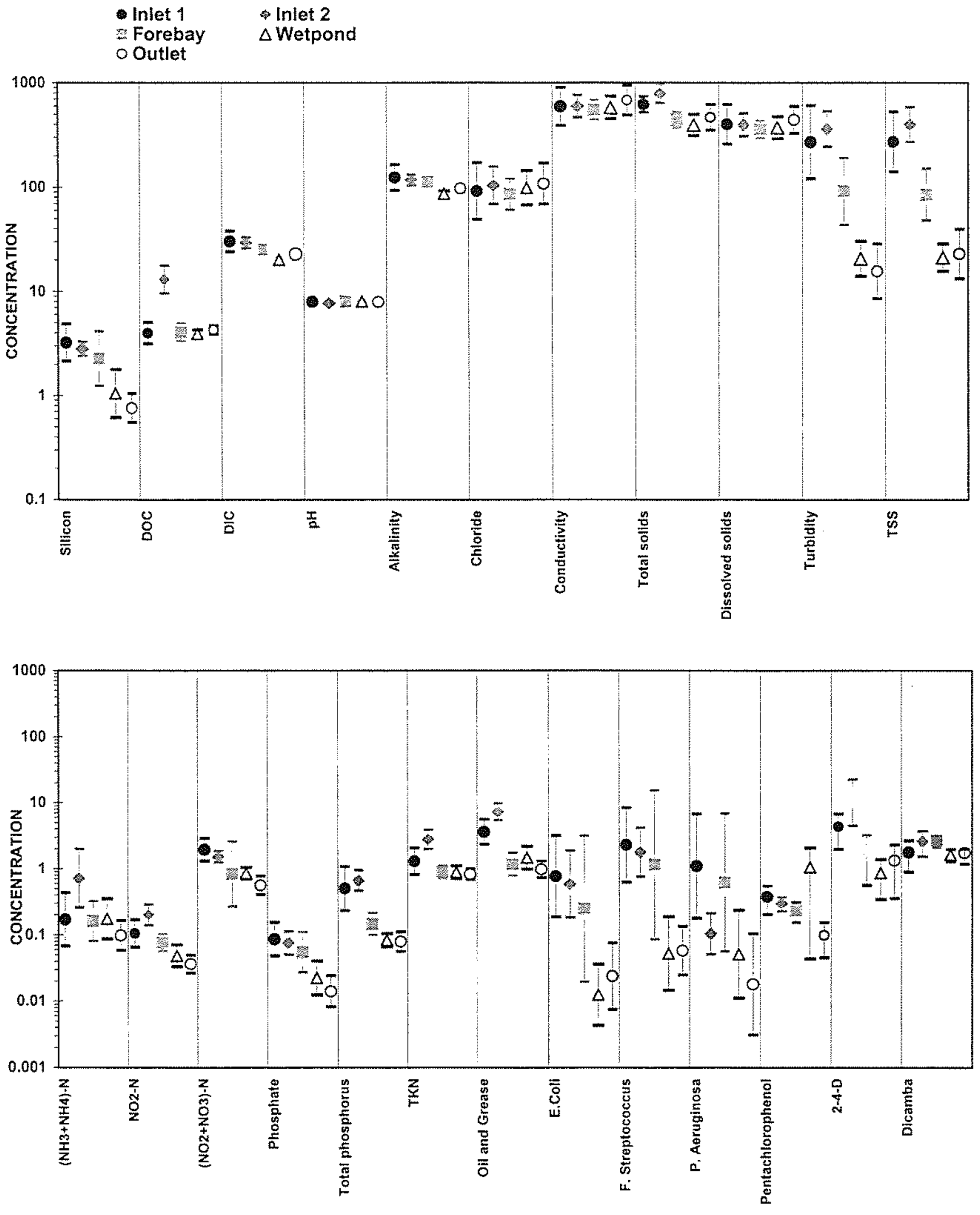
Insoluble particles and other solid materials that become suspended in water are, in terms of total mass, the largest source of water pollution. Suspended particulate matter clouds the water, reduces the ability of some organisms to find food, inhibits photosynthesis by aquatic plants, disrupts aquatic food webs, and carries heavy metals, pesticides, bacteria and other harmful substances. Once deposited, bottom sediment can destroy feeding and spawning grounds of fish and fills lakes, artificial reservoirs, stream channels and harbours. Due to the close relationship between total suspended solids (TSS) and various stormwater pollutants, TSS concentration has often been used as an indicator of stream health.

Settling is the primary mechanism for removal of TSS in stormwater ponds, although physical and biochemical flocculation can also be important between rainfall events or during long residence times within ponds. At the Markham BMP, wet weather load-based removal efficiencies for suspended solids during the summer/fall period were 78, 91 and 95% at the forebay, wet pond and wetland monitoring stations (Figure 5.3). At the wetland outlet, only one of the nine events monitored displayed removal below 95%. During the winter/spring, the concentration-based removal efficiency was 98%, despite the formation of an ice layer, which can reduce storage volume and performance during cold weather (Oberts, 1994). These removal

Table 5.1 : Inlet and outlet composite sample concentrations during wet and dry weather

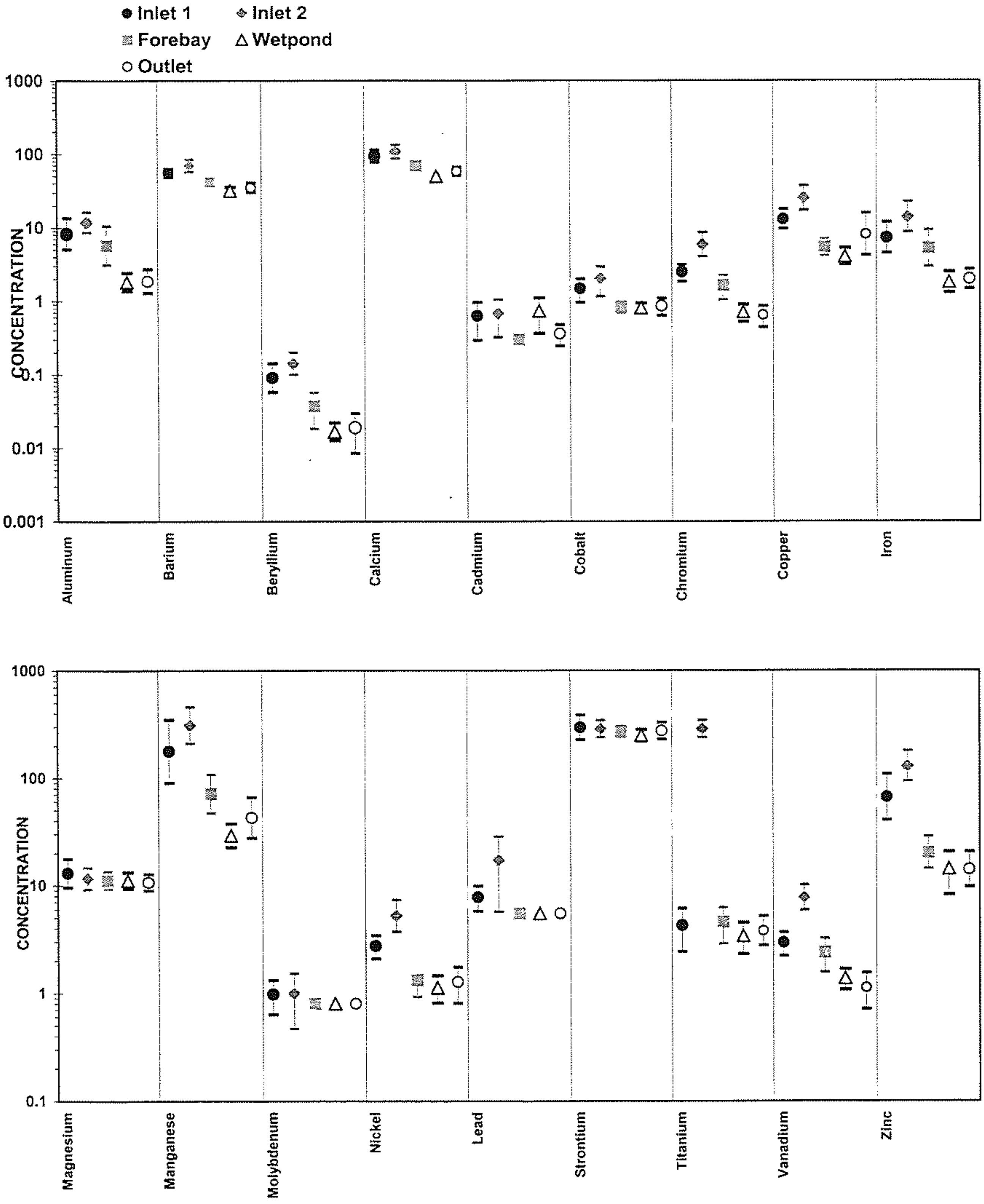
		Wet Weather Concentrations						Dry weather Conc.				
		Winter/spring		Summer/fall				Four seasons		MTWWS**	MTDWS**	PWQOs
Parameter	**Units**	**Inlet**	**Outlet**	**Inlet**	**Forebay**	**Wetpond**	**Outlet**	**Inlet**	**Outlet**			
General Chemistry												
Oil and Grease	mg/l	6.5	0.9	4.8	1.2	1.5	1.0	1.4	0.7	4.1	-	-
Suspended Solids	mg/l	291.2	7.1	313.7	85.2	21.1	23.0	86.9	10.1	238	15.7	-
Solids; total	mg/l	1587.5	764.6	675.4	440.0	393.7	465.7	968.9	487.7	-	-	-
Solids; dissolved	mg/l	1405.2	760.8	398.4	358.3	371.7	442.9	843.2	473.1	-	-	-
Silicon	mg/l	2.8	1.3	3.1	2.3	1.0	0.8	4.0	0.8	-	-	-
Carbon; diss. org.	mg/l	5.2	3.0	7.0	4.1	3.9	4.3	2.3	2.7	-	-	-
Carbon; diss. inorg.	mg/l	29.0	24.4	29.9	25.3	20.1	22.9	38.3	24.3	-	-	-
Alkalinity	mg/l	123.1	104.1	121.3	112.1	86.6	97.4	163.3	105.0	97.5	-	-
Conductivity	mg/l	2415.8	1241.2	593.5	550.1	578.6	679.7	1321.1	788.0	-	-	-
pH	none	8.0	8.1	7.9	8.0	8.0	7.9	8.1	8.1	-	-	6.5 to 8.5
Chloride	mg/l	612.1	325.5	95.6	85.4	98.5	107.9	269.9	121.6	-	-	-
Turbidity	FTU	196.9	9.6	300.6	91.5	20.6	15.6	86.4	11.1	-	-	-
Metals												
Aluminum	µg/l	1030.8	115.4	942.6	572.2	182.1	187.1	387.8	209.0	1,400	168.0	-
Barium	µg/l	64.2	37.2	60.0	41.7	31.9	35.0	60.1	32.0	41	-	-
Beryllium	µg/l	0.10	0.04	0.11	0.04	0.01	0.02	0.05	0.02	0.13	-	1,100
Cadmium	µg/l	**1.01**	0.39	**0.64**	0.30	**0.70**	0.36	**0.57**	0.40	0.94	2.50	0.5
Cobalt	µg/l	**1.48**	<dl	**1.67**	0.83	0.81	0.86	<dl	<dl	-	-	0.9
Chromium	µg/l	**6.21**	0.68	**3.63**	**1.64**	0.71	0.65	**1.66**	**1.40**	7.00	8.50	1.0*
Copper	µg/l	**19.5**	3.7	**17.1**	**5.4**	4.1	**8.2**	**7.0**	3.6	45.0	36.0	5
Iron	µg/l	**1216.7**	107.7	**951.1**	**525.8**	181.2	199.5	**348.2**	173.0	2830.0	62.0	300
Manganese	µg/l	184.1	14.1	118.9	71.5	29.2	42.8	52.0	15.0	160.0	112.5	-
Mercury	µg/l	0.02	<dl	0.02	<dl	<dl	<dl	<dl	<dl	0.04	0.08	0.2
Nickel	µg/l	3.71	1.02	3.61	1.33	1.13	1.27	<dl	<dl	10.00	6.50	25
Lead	µg/l	**23.5**	<dl	**10.9**	<dl	<dl	<dl	<dl	<dl	57.00	14.50	5
Strontium	µg/l	349.0	332.3	293.2	269.7	249.7	275.2	409.4	256.0	-	-	-
Titanium	µg/l	12.0	2.1	5.4	4.6	3.4	3.8	6.1	4.8	-	-	-
Vanadium	µg/l	5.2	1.1	4.5	2.4	1.4	1.1	1.8	0.8	-	-	6
Zinc	µg/l	**110.5**	7.0	**87.2**	**20.1**	14.3	14.1	**24.9**	9.0	150.0	49.5	20
Calcium	mg/l	98.3	63.9	98.2	69.1	50.1	58.1	113.2	57.8	-	-	-
Magnesium	mg/l	11.8	13.9	12.2	11.2	11.1	12.1	14.4	8.6	-	-	-
Bacteria												
E. Coli	c./100 ml	**1750.1**	10.1	**7047.8**	**2499.9**	**124.3**	**236.9**	**385.2**	26.5	409,000	310,150	100
F. Streptococcus	c./100 ml	3429.9	9.6	21121.6	11484.8	520.5	578.8	1353.2	62.4	122,000	-	-
P. Aeruginosa	c./100 ml	25.4	2.7	7683.1	6228.7	513.4	179.7	22.0	6.3	988.0	-	-
Nutrients												
Nitrogen; ammonia	mg/l	0.25	0.06	0.35	0.16	0.17	0.10	0.02	0.05	0.08	-	-
Nitrogen; nitrite	mg/l	0.10	0.03	0.14	0.08	0.05	0.04	0.03	0.04	0.14	-	-
Nitrogen; nitrates	mg/l	1.84	0.92	1.80	0.83	0.85	0.56	2.20	1.17	1.96	2.62	-
Phosphate	mg/l	0.05	0.01	0.08	0.05	0.02	0.01	0.02	0.01	-	-	-
Phosphorus; total	mg/l	**0.37**	**0.04**	**0.55**	**0.15**	**0.08**	**0.08**	**0.11**	**0.07**	0.82	0.15	0.03
Nitrogen; TKN	mg/l	1.71	0.66	1.79	0.89	0.88	0.82	0.65	0.70	4.11	0.66	-
Organics												
Pentachlorophenol	ηg/l	21.2	12.0	35.0	23.2	105.3	9.9	-	-	-	48.40	500
Dicamba	ηg/l	27.3	53.0	198.2	255.0	162.0	159.1	-	-	-	-	200,000
2,4-D	ηg/l	684.9	148.0	741.8	189.0	86.3	133.3	-	-	-	70.30	4,000

*1.0 ug/L for hexavalent Chromium; 100 ug/L for trivalent Chromium. **Metro Toronto Wet Weather Study (Metropolitan Toronto Waterfront Wet Weather Outfall Study, Maunder *et. al*, 1995); Metro Toronto Dry Weather Study ('Dry Weather discharges to the Metropolitan Toronto Waterfront', Snodgrass and D'Andrea, 1993) - concentrations are average of fall and winter.
<dl : mean concentration was below the laboratory analytical detection limit (dl). Note: shaded values represent concentrations above Provincial Water Quality Objectives (PWQOs).



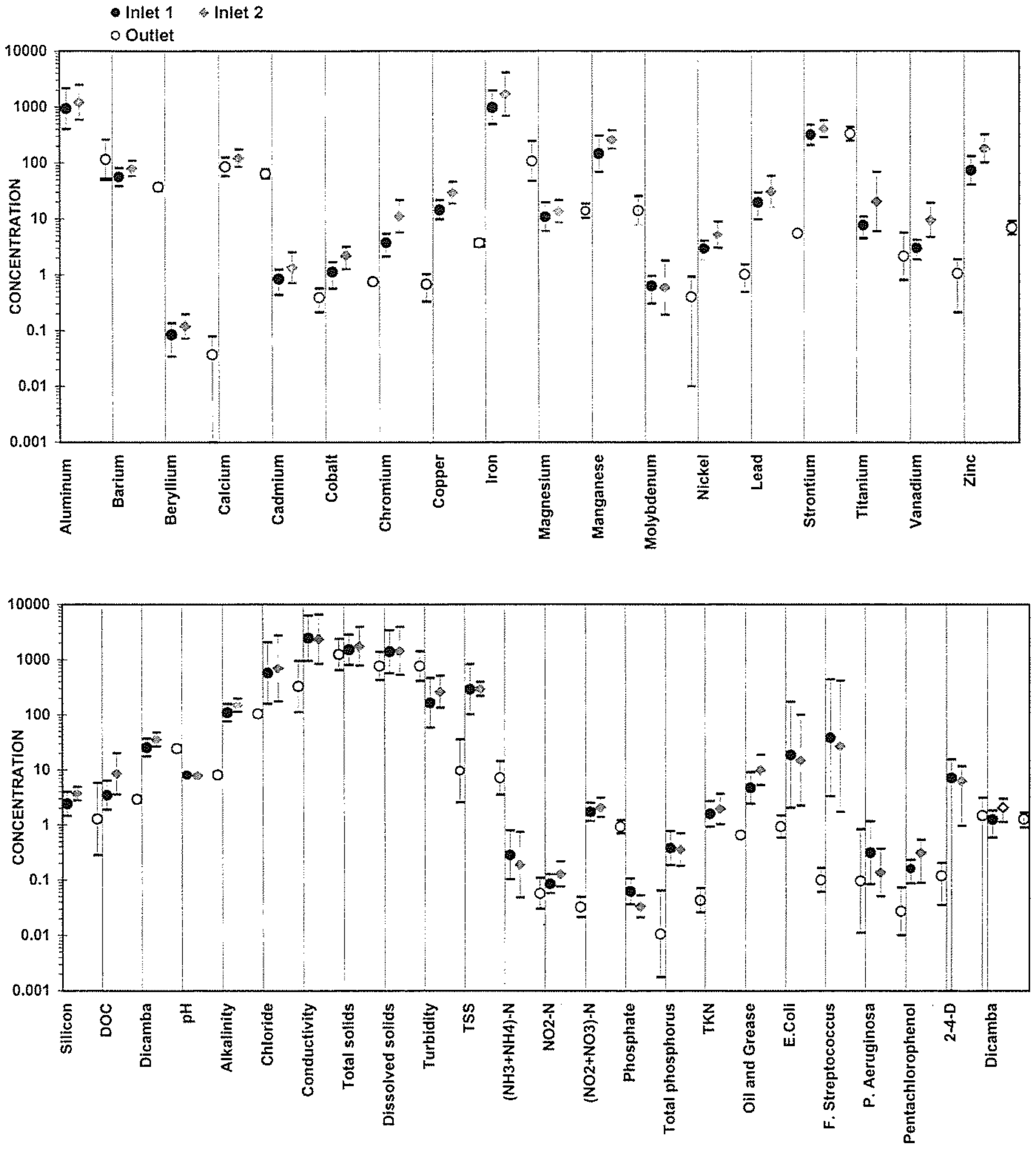
Note: all concentrations are in mg/L except conductivity (µS/cm), turbidity (FTU), pH (no units), bacteria (c./100ml x 10^{-2}) and organics (ηg/L x 10^{-2}). This graph is intended to show relative differences in mean concentrations and confidence intervals among monitoring stations. For numerical values and additional statistical data, see Table 5.1 and Appendix D.

Figure 5.1a : Mean **wet weather** sample concentrations and 95% confidence intervals for general chemistry, nutrient and organic constituents over the **summer/fall period (May to November)**.



Note: All concentrations are in µg/L except for calcium and magnesium (mg/L), aluminum and iron (mg/L x 10^{-2}). Concentrations of lead, molybdenum and cadmium were below detection limits at one or more monitoring stations. This graph is intended to show relative differences in mean concentrations and confidence intervals among monitoring stations. For numerical values and additional statistical data, see Table 5.1 and Appendix D.

Figure 5.1b: Mean **wet weather** sample concentrations and 95% confidence intervals for metals over the **summer/fall period (May to November)**.



Note: All metal concentrations are in μg/L except for calcium and magnesium (mg/L). All other concentrations (lower chart) are in mg/L except for pH (no units), alkalinity (mg/l as $CaCO_3$), conductivity (μS/cm), turbidity (FTU), bacteria (c./100mL x 10^{-2}) and organics (ηg/L x 10^{-2}). This graph is intended to show relative differences in mean concentrations and confidence intervals among monitoring stations. For numerical values and additional statistical data, see Table 5.1 and Appendix D.

Figure 5.2: Mean **wet weather** sample concentrations and 95% confidence intervals during the **winter/spring period (December to April).**

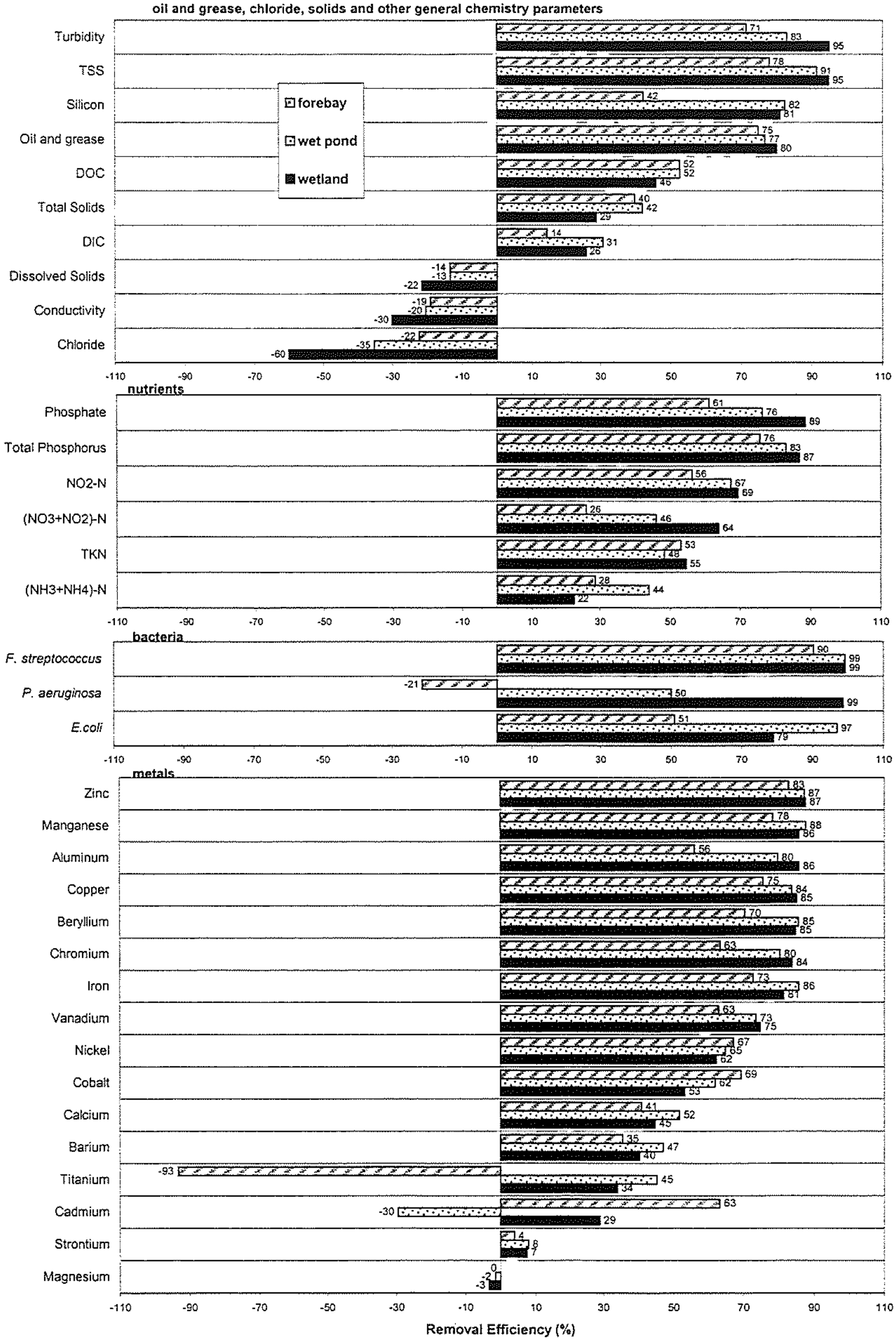


Figure 5.3 : Overall load-based removal efficiencies at the forebay, wetpond and wetland monitoring stations over the summer/fall period (May to November,1999).

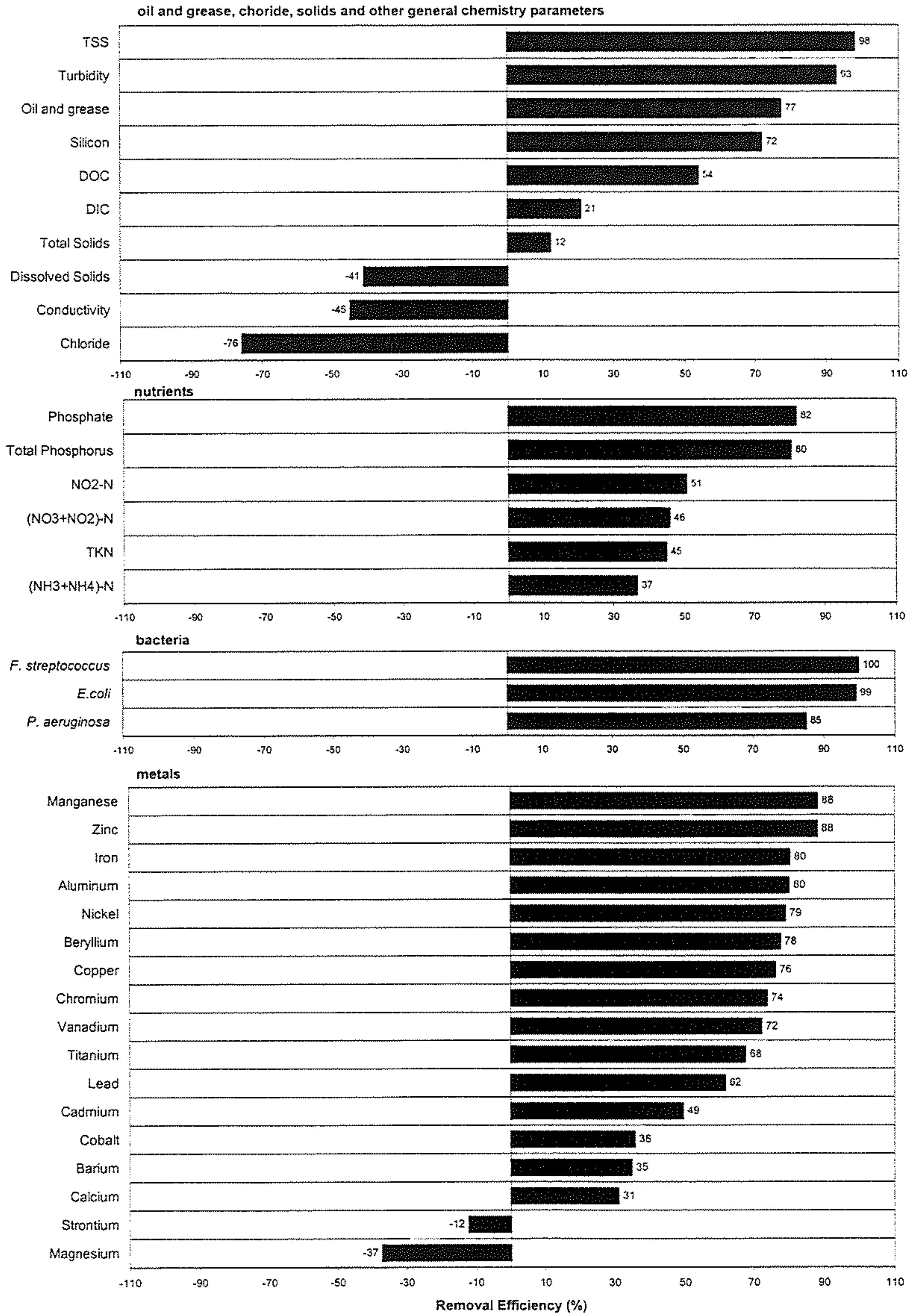


Figure 5.4: Mean concentration-based removal efficiencies for the winter/spring period (December 1998 to April 1999).

efficiencies are well above the 80% recommended in the SWM Practices Planning and Design Manual (OMOEE, 1994a) for 'level 1' fish habitat. Most studies of detention ponds and wetlands report removal efficiencies for TSS between 60 and 85% (Brown and Schueler, 1997, Martin, 1988).

TSS Effluent concentrations during dry and wet weather (Figure 5.5) were considerably below the 150 mg/L maximum target level for aquatic health in the Morningside Tributary (Beak and Aquafor Beech, 1997). The average effluent concentration was only 23 mg/L, compared to 271 and 398 mg/L at the two inlets.

Table 5.2: Effluent sample concentration detection frequencies

Inorganics	**Organics**
Detected in 75% or more	
100% Aluminum	100% Oil and grease
100% Barium	76% Dicamba
100% Copper	
100% Iron	
100% Manganese	
100% Strontium	
100% Titanium	
100% Zinc	
100% Chloride	
100% Calcium	
100% Magnesium	
Detected in 50% to 74%	
50% Vanadium	none
Detected in 25 to 49%	
28% Beryllium	29% Pentachlorophenol
39% Nickel	29% 2,4-D
Detected in 10% to 24%	
17% Cadmium	none
17% Chromium	
Detected in < 10%	
< 2% Arsenic	< 2% 22 Poly-Aromatic Hydrocarbons (PAHs)*
6% Cobalt	
< 2% Lead	< 2% 7 phenols*
< 2% Mercury	< 2% 10 herbicides/pesticides*
< 2% Molybdenum	
< 2% Selenium	

*See Appendix C for full list of organics, detection limits and respective PWQOs.
Note: phosphorus, nitrogen and bacteria sample concentrations had 100% detection frequencies

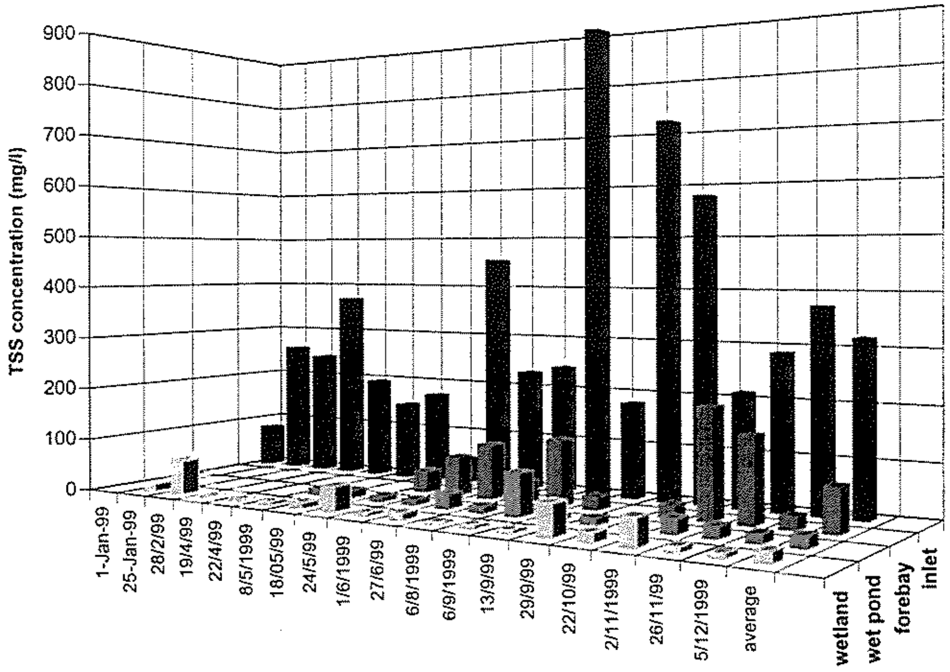


Figure 5.5: Average and individual event TSS concentrations from January to December, 1999.

5.3 Particle size analysis

The size distribution of suspended solids affects water quality and aquatic ecosystem health in two ways. The first is through the inverse relationship between particle size and the concentration and bio-availability of sediment bound pollutants (*eg:* Greb and Bannerman, 1997; Forstner and Wittmann, 1983). In general, small particles have higher surface-to-volume ratios than large particles and, consequently, adsorb contaminants more readily. This is particularly true of clays, which have a crystalline structure characterized by plates or flakes with external and internal surfaces (Brady, 1984). In a study of runoff from 20 watersheds in Oklahoma and Texas, Sharpley *et al.* (1992) observed that the fraction of clay sized particles in runoff samples was a more important determinant of particulate phosphorus bioavailability than was sediment concentration.

The second effect of particle size on aquatic health relates to its influence on the substrate of streambeds, to which benthic invertebrates are very sensitive. Several studies have shown higher invertebrate density as substrate particle size increases (Waters, 1995). This phenomenon is primarily a function of substrate heterogeneity, and the shelter, food and protection this environment offers bottom dwelling organisms. Early investigations downstream of the original pond in Markham indicated a general degradation of benthos from a diverse mix of immature insect larvae and nymphs (*e.g. Plecoptera, Coleoptera, Trichoptera*, etc...) on gravel and pebble substrates prior to urbanization, to the dominance of sludge worms (*tubificid oligochaetes*) on silt and clays following development (Beak and Aquafor Beech, 1993). An increase in the proportion of clay and silt sized particles in the Markham BMP effluent could further exacerbate this situation.

Average particle size distributions (PSD) at each of the four monitoring stations during dry and wet weather are presented in Figures 5.6 to 5.8. Particle size distributions for individual events are provided in Appendix F. Like other stormwater facilities in southern Ontario (SWAMP, 2002a), fine particles dominated the PSD, with all but one percent of particles smaller than 62 µm (silt and clay sized). During the summer/fall, the average median particle sizes were 3.8 µm at the inlet (weighted average of the two inlet sample locations) compared to approximately 2.0 µm at the forebay, wet pond and wetland outlets. In contrast, baseline median particle sizes of influent and effluent particle size distributions from the former pond (1992/3) were 6.8 and 3.6 µm, respectively (Beak and Aquafor Beech, 1997). During dry weather, median particle sizes at the Markham BMP ranged from 2.6 µm at inlet 1 to 0.85 µm at the wet pond outlet. The median particle size increased by 0.65 µm from the wet pond to the wetland.

Table 5.3: Wet weather total suspended solids concentrations and removal efficiencies for sand, silt and clay particle size classes.

	Wet weather average conc. (mg/l)				**Removal efficiency (%) from inlet to:**		
Particle size classes	**Inlet***	**Forebay**	**Wet pond**	**Wetland**	**Forebay**	**Wet pond**	**Wetland**
Sand (999 – 62 µm)	6.9	0.03	0.02	0	99.6	99.7	100
Silt (3.8 - 62 µm)	210.1	40.8	6.9	8.8	80.5	96.7	95.8
Clay⁺ (1.69 – 3.7 µm)	86.2	44.3	14.3	14.2	48.6	83.4	83.6
Total (mg/l)	303.2	85.2	21.2	23.0			
Average (%)					76.2	93.3	93.1

*represents a weighted average of inlet 1 (0.678) and inlet 2 (0.333)

+ The lower particle size threshold for laboratory measurement of TSS concentrations is 1.5 µm. Hence, the concentration of solids below this size threshold could not be calculated. This omitted size fraction (0.17 to 1.68 µm) accounts for, on average, 30, 43,43 and 46% of the total volume of particles at the inlet, forebay, wet pond and wetland monitoring stations, respectively.

Table 5.3 summarizes TSS concentrations and removal efficiencies for particle sizes in the fine sand, silt and clay groups using the relative volumetric concentrations provided by the particle size analysis procedure. The analysis assumes negligible density differences among size categories.[2] Concentrations for clay particle sizes less than 1.5 µm could not be evaluated because laboratory analysis of TSS excludes particles less than 1.5 µm[3]. By volume, particles less than 4 µm (clay) and larger than the lower threshold of the particle size instrument (0.17µm) accounted for 53% and 78% of the influent and wetland effluent particle size distribu-

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[2] The particle size analysis method used in this study does not provide particle counts. Hence, actual particle volume is unknown and particle density could not be calculated.

[3] Approximate pore size of a standard glass fibre filter used for TSS analysis

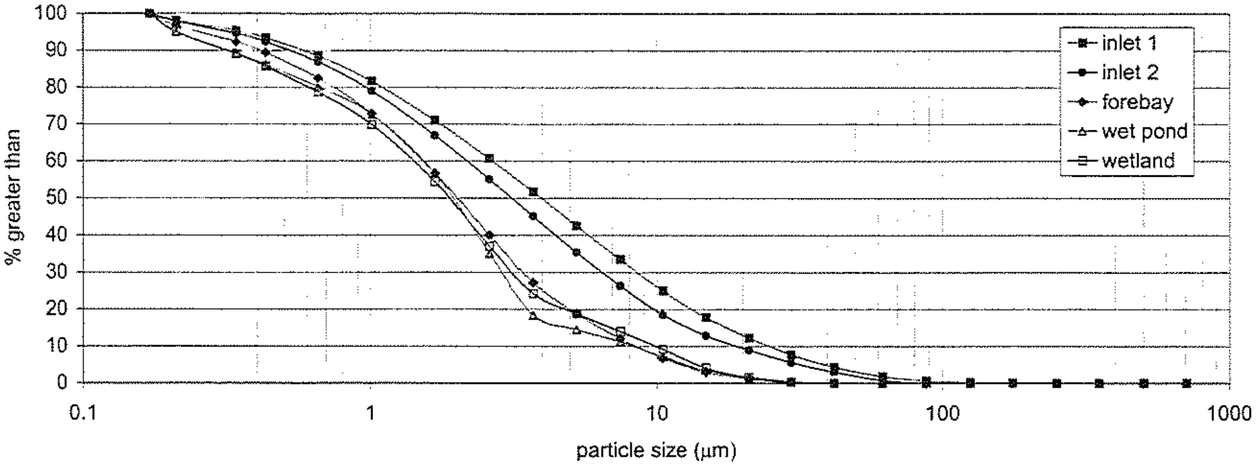


Figure 5.6: Average particle size distributions during the summer/fall (May to November)

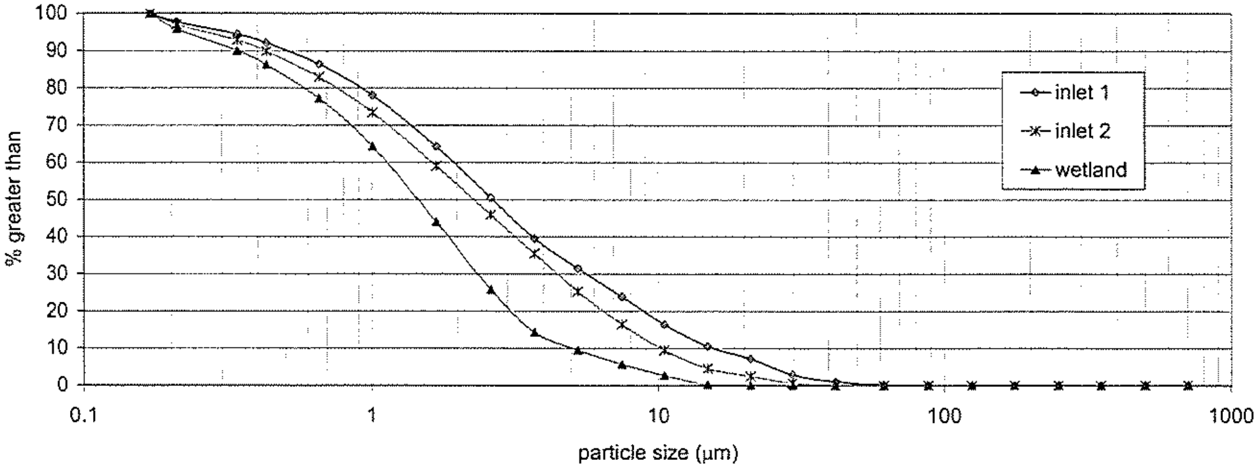


Figure 5.7: Average particle size distributions during the winter/spring (December to April)

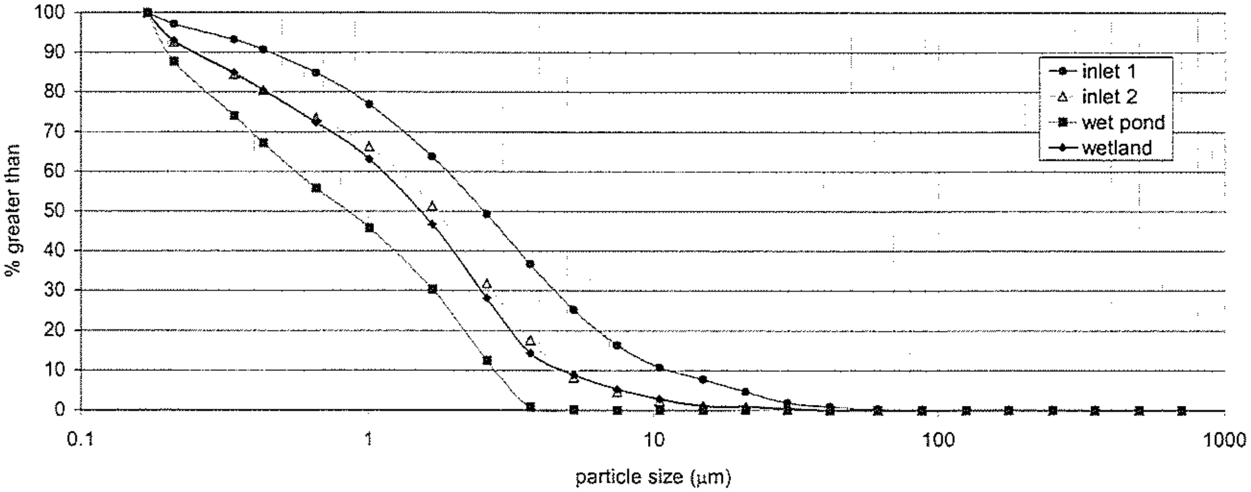


Figure 5.8: Average particle size distributions during dry weather (January to December, 1999)

tions, respectively. During wet weather, the system was effective in removing close to 100% of sand (>62μm), 96% of silt (3.8 μm to 62 μm), and 84% of clay (1.69 to 3.7 μm) sized particles.

5.4 General Chemistry

Chemical parameters such as alkalinity, pH, and water hardness influence the solubility and bio-toxicity of some contaminants, particularly heavy metals (Ellis et. al., 1987). pH and associated alkalinity levels are influenced primarily by photosynthetic algae, atmospheric inputs of carbon, and the minerals and soils within the drainage basin. Mean influent and effluent pH levels were between 7.9 and 8.1, which is within the 6.5 to 8.5 range stipulated by Provincial Water Quality Objectives (OMOEE, 1994b) for protection of aquatic habitat and healthy recreational use of waterways. Mean alkalinity concentrations, which act as a buffer for pH, averaged 120 and 100 mg/L as $CaCO_3$ at the inlet and outlet, respectively. Alkalinity is imparted mostly by the bicarbonate component of the water supply, and is therefore strongly correlated with dissolved inorganic carbon levels (R^2=0.93).

Total Hardness (TH) of the water was 291.1 and 202.1 mg/L as $CaCO_3$ at the inlet and outlet respectively. Carbonate hardness (as determined from alkalinity concentrations) comprised 41 and 49% of total hardness at the inlet and outlet. Hard water has been found to reduce the solubility and increase the threshold at which some heavy metals become toxic (Munger et. al, 1995; Boulay and Edwards, 2000).

5.5 Chloride, Conductivity and Total Dissolved Solids

As observed in other studies of stormwater ponds in Ontario (*e.g.* SWAMP, 2002a; 2002b), chloride concentrations displayed distinct seasonal patterns (Figure 5.9) and were closely correlated with dissolved solids and conductivity ($R^2 > 0.98$). In the winter, when roadway de-icing compounds were applied, influent chloride concentrations rose above 1500 mg/L, while effluent concentrations remained below 400 mg/L. In contrast, spring (May to June) influent and effluent concentrations averaged 130 and 186 mg/L respectively, as chloride stored during the winter was gradually flushed out of the system. The lowest influent and effluent chloride concentrations were recorded during the fall period.

Winter storage of chloride in the pond is enhanced by ice cover, thermal stratification, and the slow release of chloride rich stormwater during snow melt events and dry weather, all of which promote relatively quiescent conditions in the pond. Spring turnover and more intense storm flows during the spring-summer period break up the stratified winter chloride layer, resulting in chloride export from the facility (SWAMP, 2002b). There are no provincial guidelines in Ontario pertaining to chloride in surface waters, but studies (*e.g.* Environment Canada, 2000) have shown that prolonged exposure to chloride concentrations above 250 mg/L can be harmful to certain species of fish, zooplankton and benthic invertebrates.

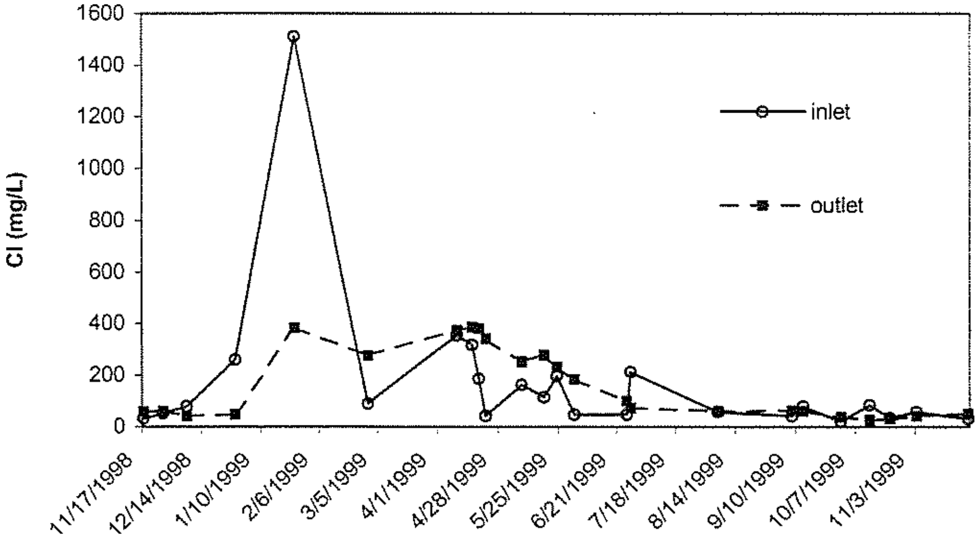


Figure 5.9: Wet weather influent and effluent chloride concentrations from November 1998 to November 1999.

5.6 Nutrients

Excess nutrients such as nitrogen (N) and phosphorus (P) originate mainly from lawns, gardens, agricultural fields, animal waste and atmospheric sources (Jansson et. al., 1994). Nutrients cause eutrophication of surface waters by stimulating algal and aquatic plant growth, which deplete oxygen levels as they decompose resulting in fish kills and restrictions on recreational use of waterways. Phosphorus is the limiting nutrient for plant growth in most inland waters, whereas nitrogen is often more limiting in estuaries (Sharpley *et. al.*, 1994). In the United States, inorganic nutrient concentration thresholds beyond which excess aquatic plant growth occurs are 0.3 mg/l for nitrogen and 0.01 mg/l for phosphorus (Daniel et al., 1994).

5.6.1 Phosphorus

Dry and wet weather samples were analyzed for total phosphorus (TP) and reactive ortho-phosphate (OP). Total phosphorus includes organic and inorganic species, most of which are insoluble, and not available for plant uptake, as well as soluble and insoluble ortho-phosphates. Most of the dissolved phosphorus is comprised of ortho-phosphate, considered to be immediately available for algal growth (*i.e.* bioavailable) (Daniel *et. al.*, 1994). Although not investigated as part of this study, from 10 to 90% of phosphorus associated with sediment runoff (particulate phosphorus) is also bioavailable, depending on land use and watershed management factors (Sharpley *et al.*, 1992). Fine clay sized sediments in particular contain more sorbed phosphorus and less primary mineral phosphorus because of the larger surface-to-volume ratio relative to coarse sized soil particles.

Phosphorus is adsorbed by sediment within minutes to hours of contact and is therefore removed effectively by settling of suspended solids (Sharpley *et al.*, 1992). Summer/fall TP removal efficiencies observed from the inlet to the forebay, wet pond and wetland were 76%, 83% and 87%, respectively. During the winter/spring period, 80% of TP was removed. Although these removal rates are higher than usual for this type of facility (*e.g*: Oberts and Osgood, 1991), the effluent concentration for TP (0.07 mg/L) still exceeded the provincial guideline of 0.03 mg/L intended to prevent excessive plant growth in rivers and streams (OMOEE, 1994b).

Strong correlations between TP and TSS concentrations in influent (R^2=0.74) and effluent (R^2=0.80) samples suggest that much of the TP was suspended and, hence, settling was the primary phosphorus removal mechanism. Filtration, plant uptake, microbial degradation and adsorption were also probably important processes in the wetland, due to the greater abundance of plants and higher water-to-bottom contact ratios during storm events.

The dissolved phosphorus fraction (orthophosphate) is usually less effectively removed in stormwater ponds because sediment adsorption is required before settling can occur (Oberts and Osgood, 1991; Brown and Schueler, 1997). However, in this study, the summer/fall removal efficiency for phosphate (89%) was similar to that of TP (87%). Orthophosphate removal during the winter/spring period (82%) was only marginally lower than during the summer/fall. Plant senescence and nutrient release from dead plants has been reported to reduce phosphate removal efficiency during the cold season (Richardson, 1985).

5.6.2 Nitrogen

Unlike phosphorus, only approximately 10 to 20% of nitrogen is transported in particulate form (Vought *et al*, 1994). Removal depends on the transformation and cycling of nitrogen from organic nitrogen to ammonium (NH_4^+) through mineralization, followed by nitrification of ammonium to nitrite (NO_2^-) and nitrate (NO_3^-), and finally denitrification of nitrate and nitrite to nitrogen gas products (N_2 or N_2O) (Cirmo and McDonnell, 1997). Chemical speciation and cycling of nitrogen in detention ponds depends on residence time, temperature, substrate and prevailing biogeochemical conditions. The complex, site specific nature of these processes partly explains the large variation in nitrogen removal efficiencies reported in the literature.

In this study, samples were analyzed for ammonia (NH_3-N + NH_4-N), nitrite, nitrate (as Nitrogen) and total Kjeldahl nitrogen (TKN). Organic nitrogen (TKN minus ammonia) is readily mineralized to ammonium in wetlands and ponds and may also be deposited within the facility by birds and other wildlife (Kadlec and Knight, 1996). Un-ionized ammonia was always below the PWQO (OMOEE, 1994b) limit established for this constituent.

Removal rates for ammonia during the summer/fall and winter/spring periods were only 22 and 37%, respectively. The large resident waterfowl population in the pond may partly account for the poor removal efficiency rates for ammonia. During the summer/fall, higher removal efficiencies at the wet pond outlet (44%), relative to the wetland (22%) suggests that the wetland may have been a source of ammonia. Use of the wetland by wildlife may partly explain this result. Usually wetland plants would be expected to enhance ammonia removal. However, in a study of nutrient removal in wastewater wetlands, Gersberg *et. al.* (1986) indicated that cattails (the dominant plant species in the Markham wetland) were significantly less effective than reeds and bulrushes in removal of ammonia. The authors attributed this phenomenon to lower rates of nitrification in the shallower and less oxidizing cattail rooting zone.

Wet weather removal during the cold season was 51% for nitrite and 46% for nitrate, compared to 64 and 69% in the summer/fall. Both influent and effluent nitrate concentrations were well below the 10 mg/L Ontario drinking water limit. Unlike ammonia, summer/fall nitrate removal efficiencies increased from 26% at the forebay weir, to 46% at the pond outlet and 64% at the wetland outlet. Nitrates are denitrified to nitrous oxide (N_2O) or molecular nitrogen (N_2) by heterotrophic bacteria that preferentially use oxygen, nitrate and other constituents as electron acceptors to obtain energy. Since these bacteria gain more energy from using O_2 than NO_3, denitrification occurs mainly in O_2 limiting environments of bottom sediments (Korom, 1992). Elevated dissolved oxygen levels during cold weather may account for the lower winter removal rates of nitrite and nitrate. Several studies (*e.g.* Kachka and Turner, 1996; Jansson *et. al.,* 1994) have identified nitrification and denitrification as the primary nitrogen removal mechanisms in wetlands.

5.7 Metals

Most metals in urban stormwater are associated with automobile use, wind-blown dusts, roof runoff and road surface materials (Campbell, 1994). Ellis and Revitt (1991; as cited by Scholes *et. al.,* 1998) estimate that roadways, while typically covering less than 10% of urban catchments, contribute from 35 to 75% of heavy metals in runoff. Zinc, copper and lead are the most frequently detected metals in urban stormwater runoff (USEPA, 1983; Marselek and Schroeter, 1988). Iron and manganese are found at high concentrations in rocks, minerals and soils, and typically increase very little with urbanization (Waters, 1995).

Heavy metals have a strong affinity to sediments and can accumulate in benthic organisms, phytoplankton, and fish (Wanielista and Yousef, 1993; Campbell, 1994). Wilbur and Hunter (1980) found that easily extracted metals in urban sediment comprised about 21% of the total concentration. Soluble portions of total lead, copper and zinc concentrations in highway runoff have been estimated to range from 1-10%, 20-40% and 30-50%, respectively (Ellis et al., 1987). Cadmium is found mostly in soluble form, but usually at very low concentrations. Chromium is relatively insoluble in its more common form as CrIII, but highly soluble and toxic as CrVI. Hard water and high pH (as found in the Markham wet pond) significantly reduces the solubility of most heavy metals (Ellis et. al., 1987).

In this study, concentrations and removal efficiencies of 19 metals (not including calcium and magnesium) were determined. Wet weather removal during the summer/fall season was above 50% for all metals except barium, cadmium, strontium, and titanium. Efficiencies above 75% were observed for aluminum, beryllium, copper, chromium, iron, manganese, and zinc. At the wetland outlet, several metals were below analytical detection limits (selenium, arsenic, mercury, molybdenum, lead) or had low detection frequencies (nickel, chromium, cadmium, beryllium and cobalt). Overall, influent metal concentrations were low relative to wet and dry weather metal concentrations at the Toronto waterfront (Table 5.1). Among the metals, only mean outlet concentrations of copper exceeded Ontario objective levels (OMOEE,1994b). In the relatively alkaline, high pH waters of the Markham BMP, insoluble hydrated copper carbonate was likely the dominant form of this element (Kadlec and Knight, 1996).

In the winter/spring, average removal for copper, chromium, cadmium, lead, nickel, and zinc was 71% compared to 65% during the summer/fall. This 6% difference between seasons may simply represent natural variations among events, rather than seasonal differences in concentrations, although metal solubility would be greater at higher temperatures. Cold season concentrations of all metals for which PWQOs (OMOEE, 1994b) have been identified were below recommended levels.

5.8 Organics

Samples were analyzed for 22 Poly-Aromatic Hydrocarbons (PAHs), seven phenols, and 10 herbicides/pesticides, several of which are designated as priority pollutants in the Great Lakes ecosystem (Maunder *et al.*, 1995). A list of these parameters with corresponding detection limits and PWQOs are provided in Appendix C. Note that for several organics analyzed, PWQOs are below the analytical detection limit, rendering it impossible to evaluate whether the stormwater effluent at the Markham BMP was risk free with respect to these parameters.

Most organic compounds settle out with suspended solids or are volatilized or metabolized by microbes and plants. Only three organic compounds were found at concentrations above their respective detection limits: pentachlorophenol, dicamba and 2-4-D. Pentachlorophenol originates primarily from wood preservatives, whereas dicamba and 2-4-D are two of the more commonly used water soluble components of commercial weedkillers. These herbicides can find their way into stormwater sewers through surface runoff, soil leaching, drift and deposition during application, or by inappropriate cleaning and disposal of pesticide applicators near storm sewers and roadside gutters (Schueler, 1995). Effluent concentrations of dicamba were above the detection limit most frequently (76%) followed by pentachlorophenol (29%) and 2-4-D (29%). Mean concentrations for dicamba, pentachlorophenol, and 2-4-D fell from 143, 30, and 702 ηg/L at the inlet to 128, 10 and 138 ηg/l at the outlet, respectively. All mean concentrations were significantly below PWQOs (OMOEE, 1994b) for these contaminants (Table 5.1).

Oil and grease contain various hydrocarbon compounds toxic to aquatic life and benthic organisms at low concentrations. These are lighter than water but strongly adsorbed by sediments and are therefore subject to settling (MWCG, 1987). The removal efficiency for oil and grease was 77% in the winter/spring and 80% in the summer/fall. These statistics compare favourably to a pond/wetland stormwater facility in nearby Harding Park, where oil and grease were reduced by only 37% in the summer/fall and 6% in the winter/spring

(SWAMP, 2002a). The forebay accounted for 75% of total summer/fall removal within the facility. Removal at the pond outlet was only marginally higher at 77%, despite the reverse flow pipe, which was designed to reduce intake of buoyant contaminants by drawing water from below the permanent pool elevation. A similar pattern was observed for pentachlorophenol, which is also lighter than water. This result may simply reflect the tendency for greater removal with higher initial loads. Since the concentrations were reduced significantly at the forebay, little additional removal could be expected in the wet pond.

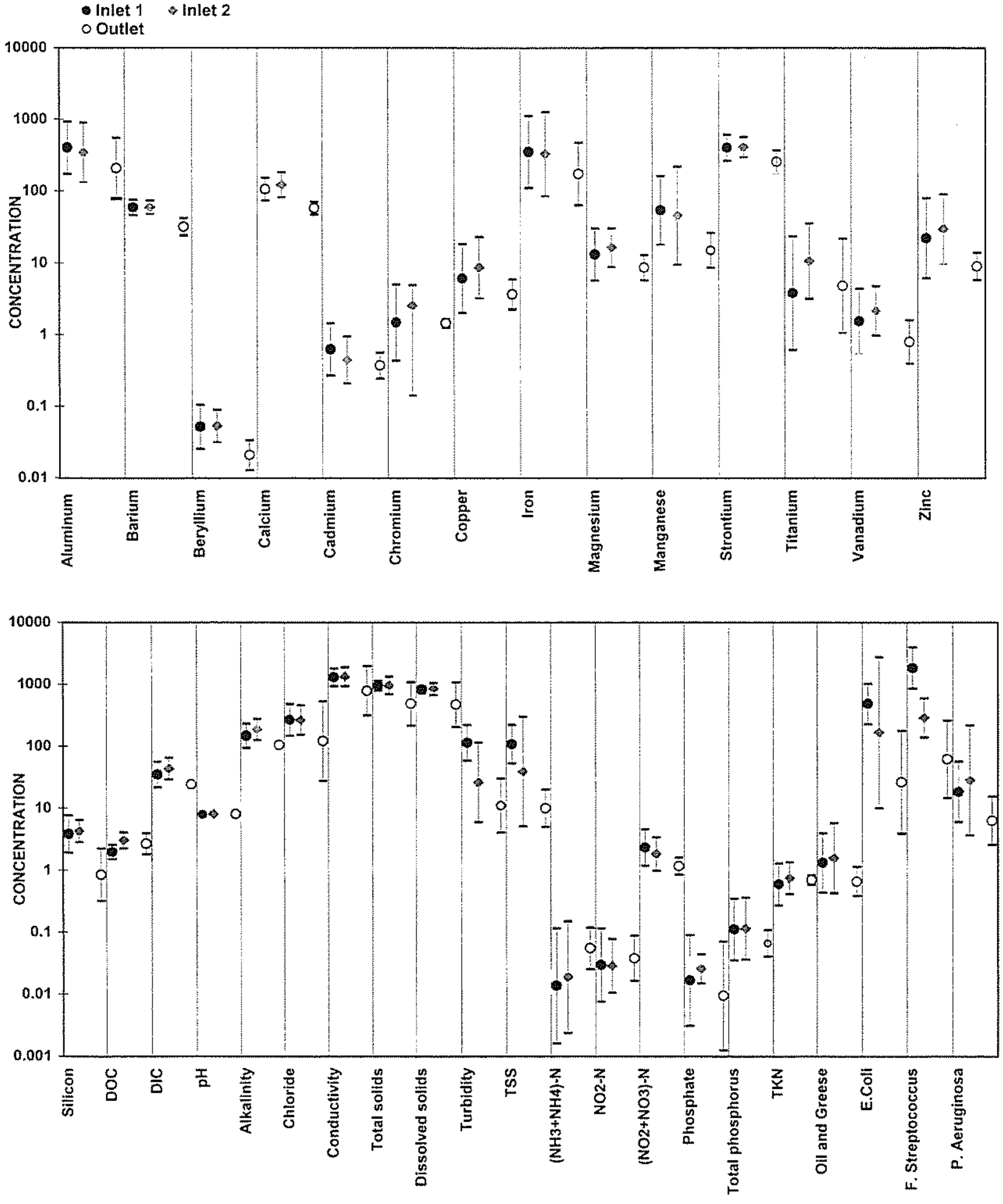
5.9 Bacteria

The *Escherichia Coli* and *Fecal Streptococcus* groups of bacteria indicate the presence of fecal wastes and other harmful bacteria. *Pseudonamas auerognosa* is one of several bacterial pathogens found in stormwater that poses a risk to public health. *E. Coli* may be removed through sedimentation, predation, and natural die-off due to prolonged exposure to sunlight and other physical, chemical and biological conditions (Kachka and Turner, 1996). At the Markham BMP, bacterial pollutants originate primarily from non-human sources, such as dogs, raccoons and the large resident waterfowl community living for periods of the year in or near the facility.

Removal efficiencies during the summer/fall for *E.coli, F. streptococcus* and *P. auerognosa* were 79, 99 and 99%, respectively. Bacteria concentrations were significantly lower during the colder winter/spring period, but removal rates still exceeded 84%. Average effluent concentrations were less than 11 c./100 mL for all bacterial parameters in the cold season, compared to mean effluent concentrations of 180c./100 mL for *Pseudonamas auerognosa*, 237 c./100 mL for *E. Coli* and 579 c./100 mL for *F. streptococcus* during the summer/fall. Despite good removal rates, the average concentration for *E.Coli* during wet weather exceeded the PWQO for this indicator by 137 c./100 mL.

5.10 Dry weather performance

Dry weather average concentrations and removal efficiencies are summarized in Figures 5.10 and 5.11. Results are compared with average wet weather concentrations at the Markham BMP, PWQOs (OMOEE, 1994b) and Toronto waterfront discharge concentrations (Snodgrass and D'Andrea, 1993; Maunder *et al.*, 1995) in Table 5.1.



Note: All metal concentrations are in µg/L except for Calcium and Magnesium (mg/L). All other concentrations (lower chart) are in mg/L except for pH (no units), Conductivity (µS/cm), Turbidity (FTU), bacteria (counts/100mL) and organics (ηg/L). Cobalt, Lead, Nickel and Molybdenum concentrations were below analytical detection limits. For numerical values and additional statistical data, see Table 5.1 and Appendix D.

Figure 5.10: Mean dry weather concentrations and 95% confidence intervals (n=4) for the entire monitoring period (**November 1, 1998 to December 13, 1999**).

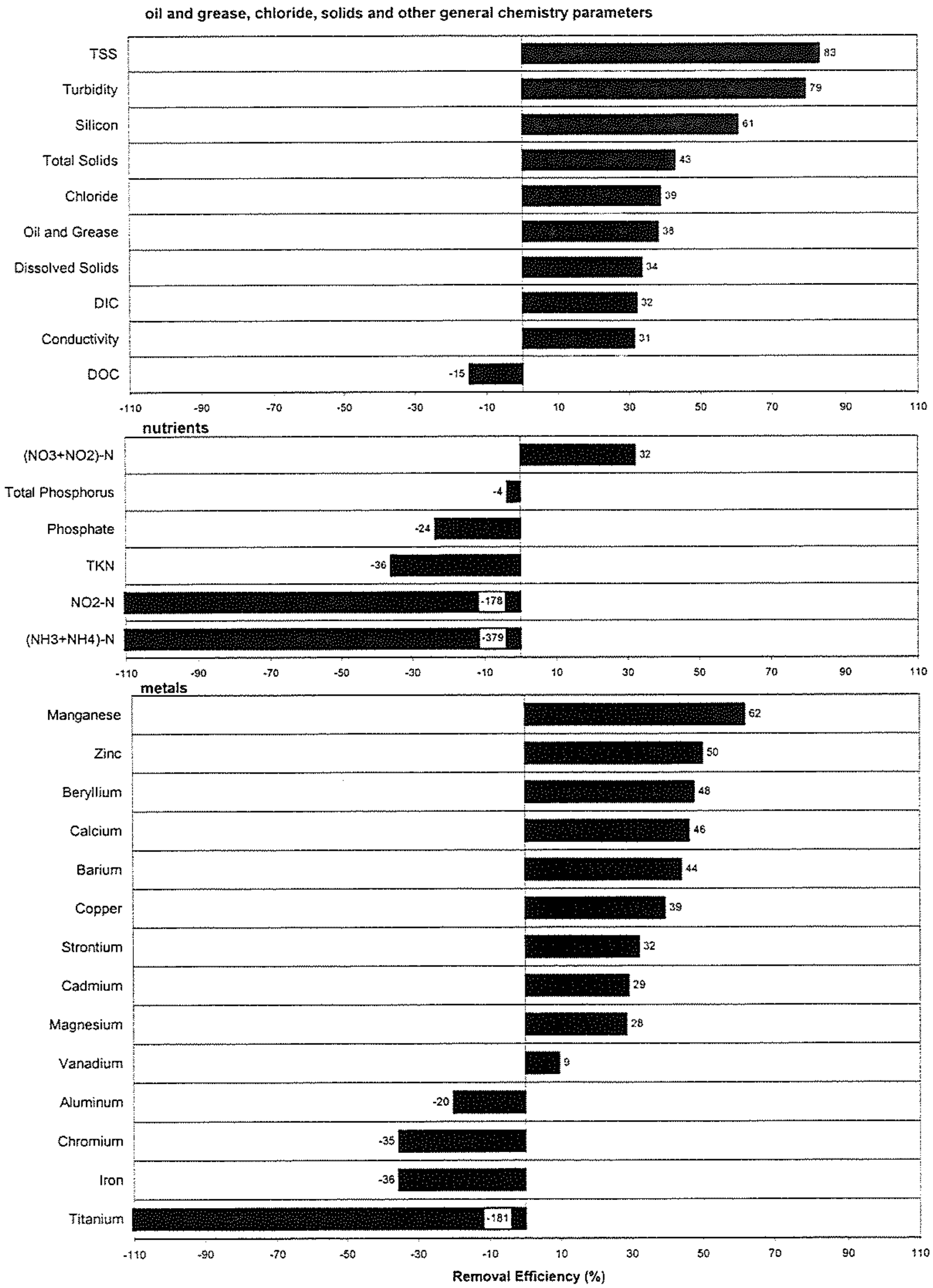


Figure 5.11 : Concentration-based removal efficiencies during **dry weather** (January to December, 1999)

Despite relatively low influent concentrations, dry weather removal efficiencies for most metals and general chemistry parameters exceeded 25%. Total phosphorus, phosphate, TKN, nitrite, ammonia, aluminum, chromium, iron and titanium increased in concentration from the inlet to the outlet. Dry weather average effluent concentrations for most constituents were similar to, or lower than wet weather average effluent concentrations. Dry weather effluent concentrations for TP and iron exceeded PWQOs (OMOEE, 1994b) for these constituents. Only two dry weather effluent samples were analyzed for bacteria, and neither of these were taken in the summer when bacteria concentrations are high.

5.11 Changes in Water Quality: 1992/93 to 1999

As previously mentioned, baseline water quality data were collected from September 1992 to August 1993. The difference between the two periods represents an increase in urbanization from approximately 34% in 1992/93 to 67% in 1999.

Table 5.4: Influent wet and dry weather concentrations at the former 'North pond' (1992/3) and the Markham BMP (1998/99).

		Wet Weather Concentrations				**Dry Weather Concentrations**				
		North pond[+]	**Markham wet pond/wetland**			**North pond**	**Markham wet pond/wetland**			
Parameter	**Units**	**Inlet (n=11)**	**Inlet 1 (n=24)**	**Inlet 2 (n=23)**	**Weighted Average**	**Inlet (n=4)**	**Inlet 1 (n=4)**	**Inlet 2 (n=4)**	**Weighted Average**	**PWQOs**
Copper	µg/L	14	13.5	26.4	17.8	1	6.1	8.6	7.0	5
Nickel	µg/L	5	2.8	5.4	3.7	1	<1.5	<1.5	<1.5	25
Lead	µg/L	11	12.3	20.7	15.1	4	<11	<11	<11	5
Zinc	µg/L	69	68.6	142.6	93.3	1	22.2	29.7	24.9	20
Iron	µg/L	1673	809	1450	1022	30	352	329	348.1	300
Cadmium	µg/L	0.4	0.7	0.9	0.8	0.1	0.6	0.4	0.54	0.5
Chromium	µg/L	4	3.0	7.2	4.4	0	1.5	2.0	1.7	1.0
E. coli	c./100 ml	4084	5198*	4141*	4845.2	147	486.2*	167*	385.1	100
Total Solids	mg/L	809.9	896.8	988.8	927.5	895	956	963	968.6	-
TSS	mg/L	301.9	269.0	366.4	301.4	4.7	108.9	39.5	87.0	-
Total Phosphorus	mg/L	0.68	0.44	0.58	0.49	0.01	0.11	0.11	0.11	0.03
Phosphate	mg/L	0.04	0.08	0.06	0.07	0.002	0.02	0.03	0.02	-
Nitrogen (TKN)	mg/L	1.88	1.40	2.53	1.77	0.33	0.6	0.7	0.6	-
Ammonia	mg/L	0.05	0.23	0.48	0.31	0.003	0.14	0.02	0.10	-
Nitrate + nitrite	mg/L	0.99	1.84	1.66	1.78	3.39	2.3	1.8	2.2	-
Nitrite	mg/L	0.074	0.10	0.18	0.12	0.01	0.03	0.03	0.03	-
Conductivity	µS/cm	503	1097.8	927.1	1040.9	1224	1298.8	1322.9	1320.7	-
Chloride	mg/L	54.2	200.7	200.4	200.6	188.1	267.6	235.8	259.9	-

* wet weather: n = 3; Dry weather: n=3 at inlet 1 and n=2 at inlet 2.

[+] flow proportionate samples

5.11.1 Influent Concentrations

Table 5.4 compares stormwater influent concentrations at the original pond (Beak and Aquafor Beech, 1993) to influent concentrations at the retrofitted Markham BMP. Wet weather influent concentrations in 1998/99 were higher than in 1992/93 for all parameters except nickel, iron, total phosphorus and Total Kjedhal nitrogen. Despite increased imperviousness in 1999, average influent concentrations of total suspended solids were similar at the original and retrofit facilities.

The dry weather water quality data set consisted of only 4 samples at the North pond and Markham BMP, and therefore should be interpreted with caution. Mean influent concentrations during dry weather in 1999 were higher than in 1992/93 for all parameters. Relatively high concentrations of heavy metals and chloride suggest that dry weather flows may not enter the facility exclusively from groundwater sources, which generally contain these constituents only at very low concentrations (Freeze and Cherry, 1979).

Table 5.5: Wet and dry weather average effluent concentrations at the former North pond (1992/3) and the Markham BMP (1998/9)

		Wet Weather Average Effluent Concentrations		**Dry Weather Average Effluent Concentrations**		
Parameter	**Units**	**North pond (n=11)**	**Markham BMP (n=18)**	**North pond (n=4)**	**Markham BMP (n=6)**	**PWQOs***
Copper	µg/L	10	6.3	1	3.6	5
Nickel	µg/L	3	1.2	1	<dl	25
Lead	µg/L	8	<dl	5	<dl	5
Zinc	µg/L	36	11.6	2	9.0	20
Iron	µg/L	1503	174	71	173	0.3
Cadmium	µg/L	<dl	0.4	<dl	0.4	0.5
Chromium	µg/L	4	0.65	<dl	1.4	1.0^{++}
E. coli	c./100ml	1276	175^{+}	177	26^{+}	100
Total Solids	mg/L	578	553	868	488	-
TSS	mg/L	193.2	17.4	9.5	10.1	-
Total Phosphorus	mg/L	0.34	0.07	0.013	0.07	0.03
Phosphate	mg/L	0.02	0.02	0.003	0.009	-
Nitrogen (TKN)	mg/L	1.66	0.77	0.44	0.07	-
Ammonia	mg/L	0.032	0.08	0.02	0.05	-
Nitrate + Nitrite	mg/L	1.60	0.69	3.09	1.17	-
Nitrite	mg/L	0.07	0.03	0.017	0.04	-
Conductivity	µS/cm	722	852	1230	788	-
Chloride	mg/L	96.4	175.7	184.2	121.6	-

$^{+}$: wet weather sample size is 10 and dry weather sample size is 2.
*: (OMOEE, 1994b); $^{++}$: 1.0 µg/l for CrVI and 100 µg/l for CrIII

5.11.2 *Effluent concentrations and performance*

Mean effluent concentrations and concentration-based removal efficiencies at the original pond and the Markham pond/wetland retrofit are compared in Table 5.5 and Figures 5.12 and 5.13. Removal of TSS during wet weather was 36% at the original facility compared to 94% at the newer one. Also, most effluent concentrations were significantly lower at the Markham BMP. Average wet weather removal efficiency for nutrients, metals and bacteria was 16, 38, and 69% in 1992/3, compared to 71, 73 and 96% in 1999.

At the Markham BMP, only cadmium had lower wet and dry weather removal efficiencies than the original pond. However, this was of little concern since effluent concentrations of cadmium at both sites were below the PWQO for this constituent. With the exception of ammonia, all nutrients (phosphorus and nitrogen species) had lower wet weather effluent concentrations after the retrofit. During dry weather, despite better removal, only total solids, *E.coli*, TKN, nitrate, conductivity and chloride had lower effluent concentrations at the Markham retrofit facility.

5.12 Temperature Analysis

Since most water entering the Upper Morningside tributary flowed first through the Markham facility, the impact on water temperatures was a significant consideration in selecting and designing the retrofit pond-wetland system. Even minor changes in stream temperature can harm aquatic organisms and macroinvertebrate species adapted to cool and cold water conditions downstream of stormwater facilities (Schueler, 2000a). Temperature change in receiving waters is an unavoidable by-product of urbanization, especially if ponds are used to treat stormwater. Reduced baseflow, removal of vegetation and high runoff from paved surfaces are among the most important modifying impacts. As traps for incoming solar radiation, pond treatment systems typically result in temperature increases from 2 to 10°C (Liang and Thompson, 1996; SWAMP, 2002a). Two features were built into the design of the Markham BMP to minimize temperature impacts:

(i) a reverse slope feed pipe at the wet pond outlet, drawing cooler water from deep within the pond;
(ii) tree planting along the pond and forebay banks to intercept solar radiation and provide shading.

The second of these had not been completed at the time of the study.

A summary of temperature data collected from April 28 to July 7, 2000 are presented in Table 5.6. The pond-wetland system caused average and maximum temperatures to rise to 17.2 and 23.6°C, representing an increase of 4.9 and 3.1°C, respectively. This compares to a maximum of 24°C and a mean inlet to outlet increase of 2°C observed during the 1992/93 baseline study (Beak and Aquafor Beech, 1993). The observed maximum up to July 7 was below the 26°C specified target level for the facility, but well above the 21°C coldwater fishery threshold level, indicating that the tributary north of Steeles would only be suitable for warm water fish species.

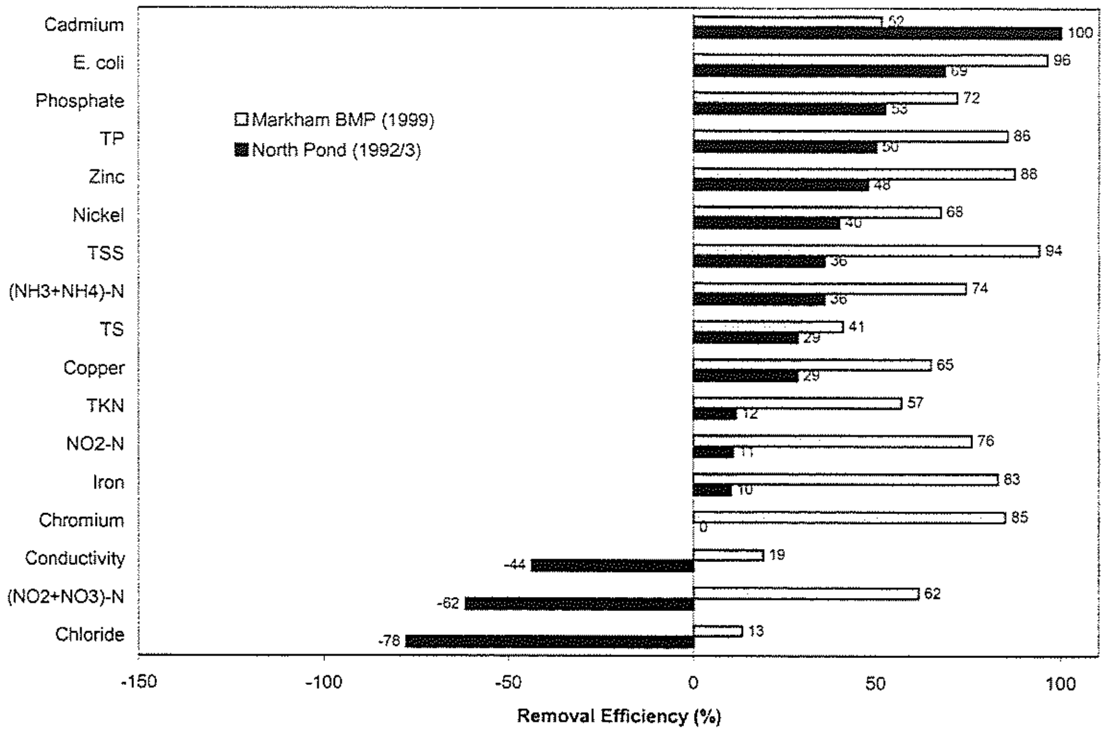
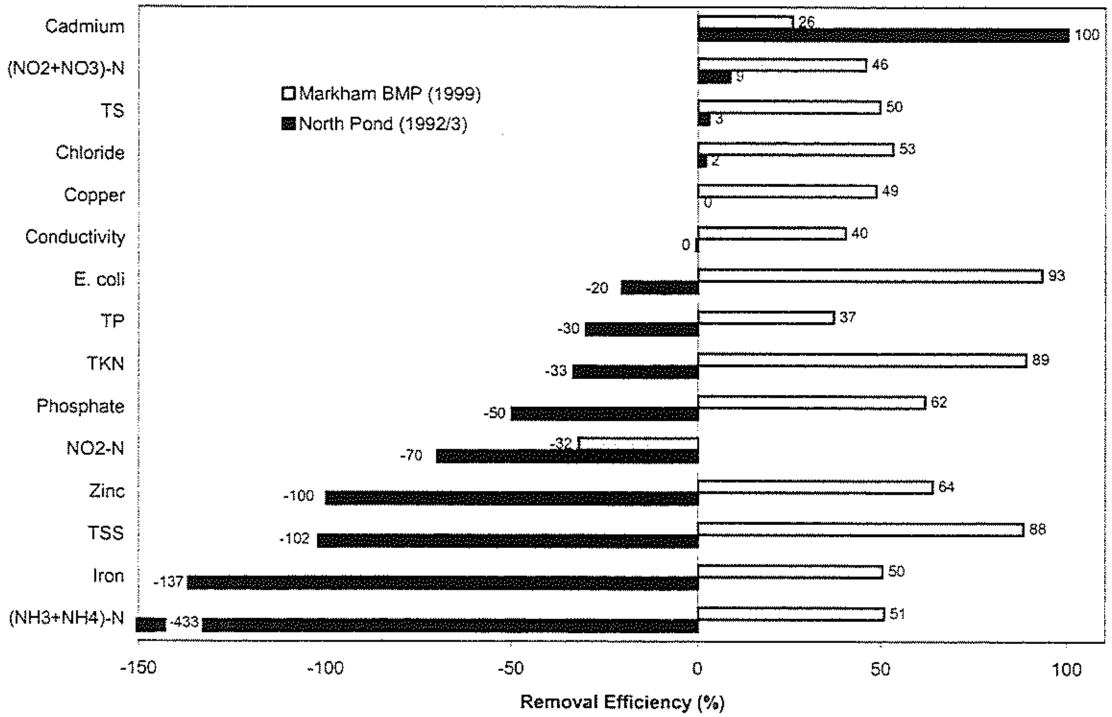


Figure 5.12: Wet weather concentration-based removal efficiencies at the Markham BMP (1998/9) and the former North pond (1992/93)



Note: dry and wet weather removal efficiencies at both facilities were calculated from the geomean of the influent and effluent concentrations.

Figure 5.13: Dry weather mean concentration-based removal efficiencies at the Markham BMP (1998/9) and the former North pond (1992/93)

Undisturbed headwater streams in Ontario typically have daytime summer temperatures below 18°C, and maximums below 20°C (Beak and Aquafor Beech, 1997).

Table 5.6: Summary of temperature statistics at the inlet, wet pond and wetland monitoring stations from April 28 to July 7, 2000.

	Temperature (°C)				time > 21 °C (hours) *
	Mean	**Median**	**Minimum**	**Maximum**	
Inlet 1	12.3	12	8.8	20.5	0
Wet pond outlet	17.8	18.3	12	23.7	313
Wetland outlet	17.2	17.6	9.5	23.6	195
Increase	4.9	5.6	0.7	3.1	195

Note: 21 °C represents the approximate limit for coldwater fisheries habitat

The reverse slope feed pipe that draws cool water into the wet pond outlet structure from deep within the pond appears not to have had only a minor (if any) effect on reducing the temperature of the pond effluent. In fact, the wet pond outlet had slightly higher temperatures than the much shallower wetland, although in general the diurnal pattern of temperature fluctuations was similar at the two sites (Figure 5.14). Partial shading from vegetation at the wetland monitoring location may partly account for the slightly lower temperatures observed there.

The temperatures at the inlet increased by 6 to 7°C in response to warmer surface runoff during rain events, but fell rapidly following the storm as flow became increasingly dominated by groundwater sources. Consequently, the temperature of greatest frequency at the inlet was between 11 and 12°C, compared to maximum temperature frequencies of 20 to 21°C and 19 to 20°C at the wet pond and wetland outlets, respectively (Figure 5.15).

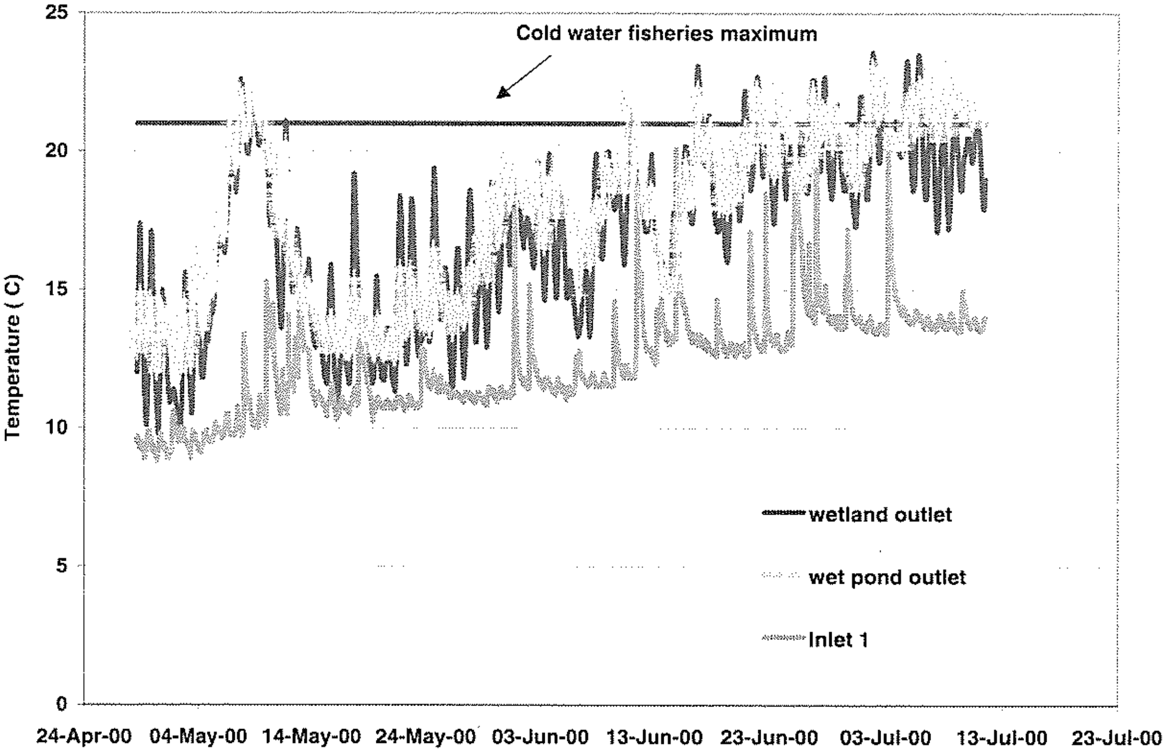


Figure 5.14: Variations in temperature at inlet 1, the wet pond outlet and the wetland outlet from April to July, 2000.

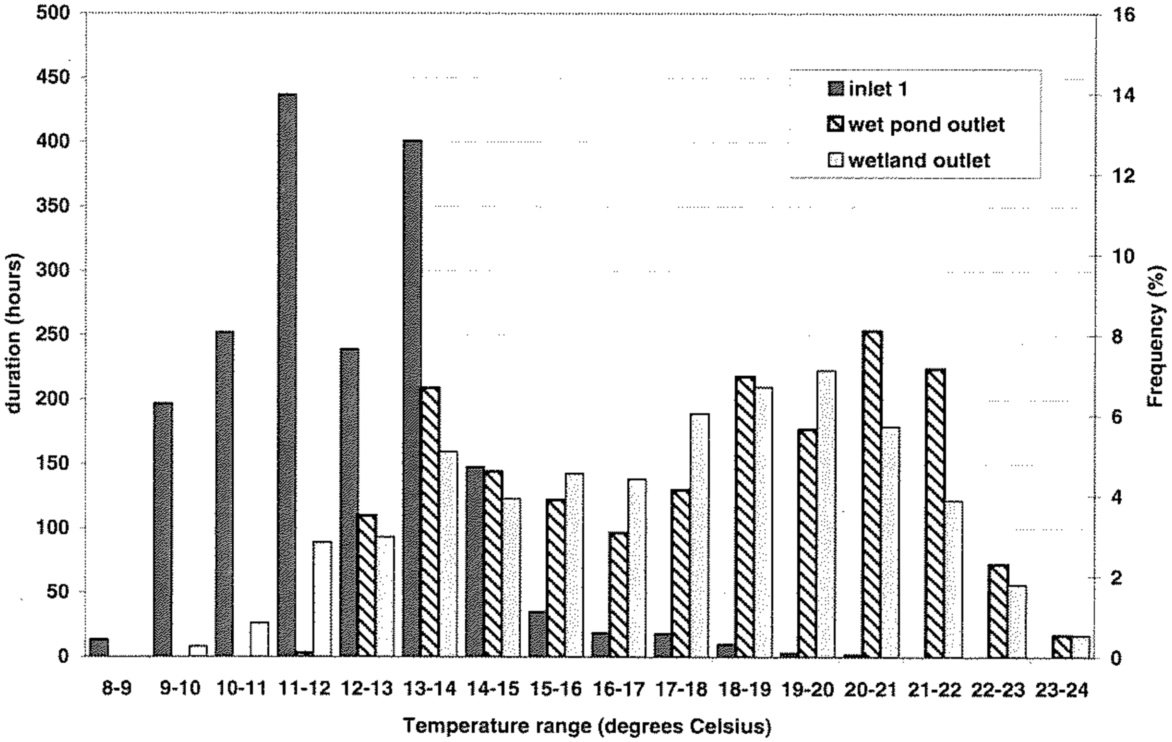


Figure 5.15: The duration and frequency of temperature ranges at inlet 1, the wet pond outlet and the wetland outlet from April to July, 2000.

6.0 WETLAND VEGETATION ASSESSMENT

Establishment of vegetation in the newly constructed wetland was to be promoted through: (i) use of sediments, and the associated seedbank, from the former marsh, and (ii) planting of seedlings to enhance diversity (Beak and Aquafor Beech, 1993). Varying water depths within the wetland (low and high marsh areas) were intended to enhance biological diversity and provide better treatment. Although the seedling planting program was never implemented, by August 1998 (one year after construction) plants had partly recolonized the surface, and by fall 1999, a dense mat of mature vegetation had been established. The vegetation survey conducted in July 2000 provides a general indication of the diversity and abundance of the plant community that eventually established at the site.

Major plant species in the wetland and their estimated abundance are listed in Table 6.1. Common cattail (*Typha latifolia)* and isolated patches of Reed Canary Grass (*Phalaris arundinacea)* dominated the site, with other species located primarily on the low rock outcrops separating the cells. In deeper water around the fringe of the pool in the first wetland cell, Floating-leaved Pondweed (*Potamogeton natans*) was abundant. Submergent wetland species were also present, but these were not identified in the short survey conducted as part of this study.

***Table 6.1*:** List of plants found in the Markham BMP wetland

Common Name	Scientific Name	Estimated Abundance
Common cattail	*Typha latifolia*	85 – 90%
Reed Canary Grass	*Phalaris arundinacea*	10-15%
Floating-Leaved Pondweed	*Potamogeton natans*	<5%
Rice Cut Grass	*Leersia orzoides*	<2%
Field Horsetail	*Equisetum arvense*	<1%
Wild Mint	*Mentha arvensis*	<2%
Climbing Nightshade	*Solanum dulcamara*	<1%
Soft Rush	*Juncus effusus*	<2%
Water Horehound	*Lycopus americanus*	<1%
Asters	*Aster sp.*	<2%
Patience Dock	*Rumex patientia*	<1%
Couch Grass	*Agropyron repens*	<1%
Grass	*Bromus sp.*	<1%
Rugel's Plantain	*Plantago rugelii*	<1%
Wild Cucumber	*Echinocystis lobata*	<1%
Canada Thistle	*Cirsium arvense*	<1%
Grass	*Calamagrostis sp.*	<1%
Sour Dock or Curled Dock	*Rumex crispus*	<1%
Timothy	*Phleum pratense*	<1%

A more detailed survey in 1992/3 (Beak and Aquafor Beech, 1993) reported the presence of similar plant species, indicating that re-vegetation patterns at the site reflect the plant diversity maintained within the sediments of the former marsh. As in July 2000, Common Cattails (*Typha latifolia*) and patches of Reed

Canary Grass (*Phalaris arundinacea*) dominated the site in 1992, with other species such as Wild Cucumber (*Echinocystis lobata*), Spotted Jewelweed *(Impatens capensis)* and Floating-leaved Pondweed forming a minor part of the vegetation community at the former marsh. If the survey in 2000 had been as comprehensive as the baseline survey, other less abundant species present in 1992, such as beggar ticks (*Bidens frondosa*), may also have been found in the plant inventory.

Cattails (*Typha spp.*) are one of the most frequently used plants in wetlands for wastewater treatment (Gersberg *et. al.*, 1986). They have a high tolerance to pollutants and are able to thrive under conditions of widely fluctuating water levels. Since pollutant uptake occurs mostly in the root zone, they present little risk to wildlife. Unfortunately, these aggressive colonizers tend to dominate their environment, preventing successful establishment of other plant species. Higher plant diversity would promote greater resilience to disturbance, support a more varied microbial population, and provide a more favourable habitat structure for wildlife.

The other dominant plant observed at the site, Reed Canary Grass (*Phalaris arundinacea*), is considered an invasive species that provides poor wildlife habitat and tends to form a monoculture once established. For this reason, it is not usually recommended for planting in constructed wetlands. In terms of treatment, however, this species is recognized to have high nitrogen removal capacity, even at temperatures below which plant growth occurs.

Wetland plants became well established within only two years of construction. This period is similar to the time period required for full colonization of a small stormwater wetland in Richmond Hill (SWAMP, 2002a). At the Richmond Hill site, terrestrial and meadow marsh type plants were introduced through a planting program, but aquatic plants were left to colonize naturally. Rapid natural establishment at these sites suggests that a planting plan may not be required if the primary goal is plant coverage, rather than diversity.

7.0 CHANNEL ADJUSTMENTS IN THE MORNINGSIDE TRIBUTARY

Hydrological changes accompanying urban development are known to have appreciable effects on stream channel stability and geometry (Schueler, 2000b). The concept of an "enlargement ratio", defined as the ratio of a stream cross section area before and after disturbance, is commonly employed to assess these changes. For alluvial streams, MacRae and D'Andrea (1999) estimate an 'ultimate' enlargement ratio of 4.0 for catchments with 40% impervious cover. In this context, 'ultimate' refers to the stream channel area after it has re-established equilibrium in response to the hydrological conditions imposed upon it, a process which may occur 50 to 75 years after the onset of development (Schueler, 2000b).

The Markham BMP was intended to prevent channel enlargement and erosion by attenuating peak flows and extending stormflow drawdown times. To evaluate progress towards this goal, morphological changes within the Morningside tributary north of Steeles Avenue were assessed with erosion pins and channel cross section surveys, first in 1996 (Beak and Aquafor Beech, 1997), and again in May 1998 and 1999 (Badelt, 1999) after construction was complete. The most recent measurements in August 2000 provide evidence of change since May 1999, during which one very large storm in April 2000 overtopped the spillway causing erosion within the wetland and considerable sediment transport downstream. Unlike other large storms, the volume and force of the April overflow was sufficient to remove armour stones (approximately 10 to 40 cm in diameter) and erosion cloth installed to prevent scour of the overflow channel. This storm was followed by other large storms in late April and May.

Results of the August survey are compared with previous surveys in Figure 7.1. The four cross sections were located 100, 160, 250 and 500 m downstream of the facility, respectively. Deposition of sediment occurred in a straight portion of the channel at cross section #1, where stormflow overtopped the bank. In 1999, the west bank was approximately 20 cm lower than the east bank, but in 2000 the west and east bank elevations were similar. The significant change in channel shape is likely associated with flows from the large storm events in April and May 2000. At cross section #2, 160 m downstream of the facility, and also on a straight portion of the channel, there was some deposition of sediment on the banks, but little change in bed depth since 1999. Channel bed erosion of up to 15 cm since 1999 was observed at cross section #3, which is located on a sharp bend in the channel. The channel shape at cross section #4 changed very little from 1999, but was up to 25 cm lower than in 1996.

Erosion pin measurements taken in 1992, 1993, 1999 and 2000 are presented in Table 7.1. The erosion pins were located 130 m (E1) and 750 m (E2) downstream of the Markham BMP outlet. The channel pins indicated decreased bed elevation by 21.0 and 3.6 cm at the 130 and 750 m downstream, respectively. The mid-bank and toe pins at the upstream station could not be found in 2000. The length of the toe bank pin at the downstream station decreased slightly from 53 to 51 cm. The erosion pin and cross section data suggest that, since 1998, channel impacts from pond outflows appear to be mostly

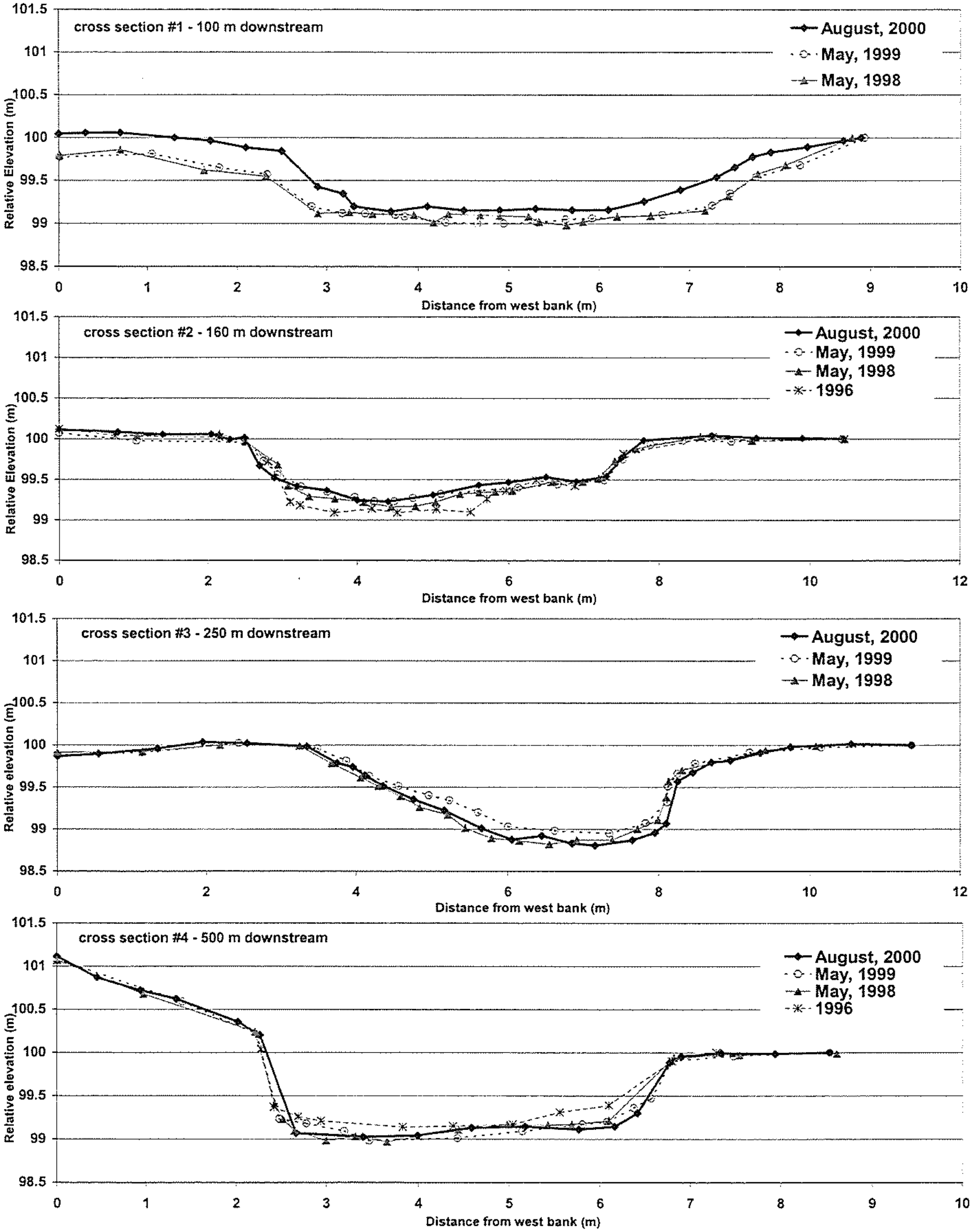


Figure 7.1: Cross sections of the Upper Morningside Tributary downstream of the Markham BMP.

limited to the upper reaches of the channel, with deposition occurring within the first 100 m, followed by a combination of scour and deposition between 120 and 200 m, and mostly bed scour further downstream. Enlargement ratios were less than 1.2 at all cross sections, which is considerably less than would be expected from a developed catchment without stormwater controls.

Table 7.1: Erosion pin measurements in 1992, 1993, 1999 and 2000

Station*	Date	Duration (yrs)	Pin exposure (cm)			Change (cm)		
			1	**2**	**3**	**1**	**2**	**3**
	Oct., 1992	0	6	6	4	0	0	0
E1	Oct., 1993	1	19	20	33	13	14	29
	May, 1999	6.5	>75	>75	27	>56	>55	-6
	Aug., 2000	7.7	-	-	48	-	-	21
	Oct., 1992	0	5	5	5	0	0	0
E2	Oct., 1993	1	8	21	4	3	16	-1
	May, 1999	6.5	14	53	0	6	32	-4
	Aug., 2000	7.7	14	51	3.6	0	-2	3.6

1 – mid-bank, 2- bank toe, 3 – stream bed

* E1 and E2 are located approximately 130 and 750 m downstream of the wetland outlet

8.0 OPERATION AND MAINTENANCE CONSIDERATIONS

Acceptable performance levels for pond and wetland treatment systems can only be sustained if facilities are adequately maintained. Declining performance of SWM facilities over time has often been attributed to insufficient maintenance. In particular, regular inspections are required for:

- sediment accumulation
- outlet/inlet weir blockage by ice or debris
- bank and spillway erosion
- health of shoreline and wetland vegetation, and
- occurrence of industrial or oil spills

Details on the method and frequency of inspection in each case are provided by the SWMP Planning and Design Manual (OMOEE, 1994a).

Sediment removal is the most costly maintenance activity for stormwater ponds. Removal frequency requirements depend on rainfall, sediment loads, and the distribution of sediment loads in each of the cells. The SWMP Planning and Design Manual suggests removal of sediment when TSS removal rates decline by 5%. Under fully developed conditions this translates into a storage volume reduction of approximately 25 m^3/ha (OMOEE, 1994a), or a decrease in permanent pool storage of 19%.

At the Markham facility, annual loading rates were estimated from runoff volume and TSS concentration data collected from January to December 1999. Average annual TSS concentrations were substituted for actual concentrations when data were not available. Missing or unreliable flow data at the forebay, wet pond and wetland were estimated from inlet flow data assuming a loss in volume due to evapotranspiration and groundwater recharge of 2.4% in the forebay and pond, and 2% in the wetland.

Dry and wet weather flow volumes and sediment concentrations in 1999 are shown in Table 8.1. Assuming a wet sediment bulk density of 1230 kg/m^3 (OMOEE, 1994a), the total mass of sediment loading to each cell converts to sediment accumulation rates of 10.6, 3.9 and 0.1 mm/yr in the forebay, wet pond and wetland, respectively (Table 8.2). These rates are expected to increase with further increases in catchment impervious cover. During and after construction of the facility, when 50% of the catchment had been developed (1997 to 1998), imperviousness cover was estimated at 16% (Badelt, 1999). This level increased to approximately 24% in 1999, and is expected to increase further to 29% in 2000, and 40% in 2005, when the catchment is fully developed (Badelt, 1999; L. Arishenkoff, pers. comm. 2000).

***Table 8.1*:** Estimated total suspended solids load at each of the monitoring stations for 1999

Monitoring Station	**Flow volume (m^3)**			**Mean TSS Concentration (mg/L)**		**Total Load (kg)**
	Wet weather	**Dry weather**	**Total**	**Wet weather**	**Dry weather**	
Inlet 1	606889.8	878731.9	1485621.7	259.4	108.2	265908.3
Inlet 2	209182.8	439300.1	648482.9	364.2	111.9	149480.8
Total influent	816072.6	1318032.0	2134104.6	289.1	109.4	424313.8
Forebay	806241.1	719938.4	1526179.4	70.6	76.2	137159.7
Wet pond	796409.6	121844.7	918254.3	21.5	22.5	21451.3
Wetland	778164.2	117158.4	895322.6	19.7	19.3	19855.1

***Table 8.2*:** Current and projected sediment accumulation rates and storage volume change as impervious cover increases from 16% in 1998 to 40% in 2025.

	Year	**Forebay**	**Wet pond**	**Wetland**
Sediment Accumulation (mm/yr)	1998	8.1	2.9	0.1
	1999	10.6	3.9	0.1
	2000	12.1	4.4	0.1
	2005	15.2	5.5	0.2
Permanent Pool Storage Volume (m^3)	1997	28000	45000	4200
	1998	27858	44915	4198
	1999	27673	44804	4195
	2000	27461	44676	4192
	2005	26269	43961	4173
	2025	20961	40774	4090
Permanent Pool Storage Volume Reduction since 1997 (%)	1998	0.5	0.2	0.1
	1999	1.2	0.4	0.1
	2000	1.9	0.7	0.2
	2005	6.2	2.3	0.6
	2025	25.1	9.4	2.6
Sediment removal interval (yrs)*	-	21	54	193

*Based on a 19% reduction of the original permanent pool volume (see text for rationale)

Sediment accumulation rates were calculated based on the following assumptions:

- rainfall during 1999 approximates the 30 year normals for the area (rainfall recorded at Markham from May to December 1999 satisfies this condition);
- additional runoff from new development enters at the upstream end of the forebay;

- TSS concentrations remain constant at 1999 levels; and
- flow volumes increase in proportion to the impervious level–storage volume relationship provided in the Ontario Ministry of Environment and Energy (1994a) Stormwater Practices and Planning Manual.

If these assumptions hold true, sediment accumulation rates will increase to a maximum of 15.2, 5.5 and 0.2 mm/yr in the forebay, wet pond and wetland by 2005. This increase represents a total reduction in storage volume by 2025 (28 years after construction) of 25.1, 9.4 and 2.6% in the three cells, respectively (Table 7.2). If the sediment removal interval is based on a 19% reduction in permanent storage (as suggested above) then the forebay and wet pond will require sediment removal after approximately 21 and 54 years, whereas the wetland will almost never need to be dredged. Note, however, that sediment accumulation estimates do not incorporate mass and volume loss caused by decomposition of the organic fraction of TSS, nor do they consider the propensity of vegetation in the wetland to die and accumulate in the form of peat. Hence actual accumulation rates may differ slightly from what is suggested here.

The overall intent of these calculations is to provide a rough estimate of sediment accumulation under specified conditions as a general maintenance guide. Direct measurements of sediment accumulation should be performed at regular intervals once fully developed conditions have been reached. Other factors, such as the distance between the reverse slope pipe connected to the wet pond outlet structure and the bottom of the pond, the distribution of the sediment within the pond, and the location and relative volume of flow from additional inlets connected to the facility, should also be considered when determining sediment removal intervals.

9.0 CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

The Markham BMP monitoring study was conducted in 1998/99, at a catchment impervious level of approximately 24%. Once the entire catchment is developed in 5 to 10 years, roughly 40% of the drainage basin will be impervious, and peak flow rates and contaminant loads are expected to increase further. Bearing this in mind, the major findings of this study were as follows:

1. The facility met or exceeded design targets with respect to storm runoff control. Influent peak flows were reduced by greater than 80% for all storms, and effluent discharge never exceeded the target bankfull rate of 1.3 m^3/s. Peak flows were also less than the two year pre-development peak flow rate (roughly 25 mm over 4 hours), estimated at 4.9 m^3/s. During monitored rain events, hydraulic detention times ranged from 18 to 53 hours (mean: 31 hours) and outflow was distributed over a period of 3 to 10 days.

2. Although effluent baseflow rates were often above the 13 L/s minimum target for the facility, the summer average was approximately 6 L/s and flow in the upper 100 m of the Morningside tributary slowed to a trickle during long interevent periods.

3. The runoff coefficient for the partly developed 600 hectare catchment averaged 0.16, which is lower than expected for estimated levels of catchment imperviousness (24%). Mandatory downspout disconnection for new development and the presence of several dry ponds within the catchment are suggested as possible explanations for the low coefficient.

4. Overall, contaminant removal efficiencies were impressive. Total suspended solids removal efficiencies frequently exceeded 90% and facility effluent concentrations were consistently below the 150 mg/L target for fisheries protection downstream of the facility. Summer/fall removal efficiencies for nutrients, bacteria and metals averaged 64, 92 and 64%, respectively. Wet weather mean effluent concentrations for copper, *E.coli* and total phosphorus exceeded their respective Provincial Water Quality Objectives (PWQOs). Based on a limited data during dry weather, PWQO exceedances were noted for chromium, iron and total phosphorus.

5. Pollutant loading data for individual cells indicated that most contaminants settled out in the forebay and, to a lesser extent, the wet pond. Removal efficiencies measured at the wetland outlet differed only marginally from those measured at the wet pond outlet for most pollutants. Low contaminant loads to the wetland enhanced its value as wildlife habitat.

6. Although the winter composite sample data set was small (n=5), study results indicated that average concentration-based removal efficiencies during the winter were higher than concentration and load-based

efficiencies during the growing season for TSS, *E.coli*, *F.streptococcus*, cadmium, nickel, lead, manganese, zinc and titanium.

7. During wet weather, removal efficiencies for sand, silt and clay sized particles were estimated at 100%, 96% and 84%, respectively. The median size of the average influent particle size distribution was 3.8 µm, compared to approximately 2.0 µm at the forebay, wet pond and wetland outlets. By volume, particles less than 4 µm (clay) accounted for 53% and 78% of the influent and wetland effluent particle size distributions, respectively.

8. The maximum temperature recorded at the outlet from April to July, 2000 was 23.6°C, which is below the 26°C maximum target for the facility, but above the 21°C limit for coldwater fisheries habitat. The mean and maximum effluent temperatures over the same period were 4.1 and 3.1°C greater than influent temperatures, respectively.

9. Comparison of water quality data sets from the Markham BMP (1998/9) with the 1992/93 baseline study of the former 'North Pond' indicated significant improvement in contaminant removal and substantially lower wet weather effluent concentrations for most constituents. Peak flows were also attenuated more effectively by the retrofitted Markham BMP.

10. Comparative cross sectional surveys in the channel downstream of the facility indicated relatively minor channel adjustments between 1996 and 2000. The channel area decreased in size at cross sections 100 and 160 m downstream of the facility. However, further downstream, at 250 and 500 m, bed and bank erosion resulted in a larger channel relative to 1996 elevations. Between 1999 and 2000, significant sediment deposition in the upper channel section was likely associated with a series of large storms in April and May 2000, at least two of which overtopped the spillway, causing major erosion within the wetland and considerable sediment transport downstream

11. The wetland plant survey showed that preserving the pre-existing seedbank by using soil from the former marsh in construction of the Markham wetland may have contributed to successful re-establishment of similar species. Although seedlings were not artificially introduced, new plants started to emerge only one year after construction and a good vegetation cover naturally regenerated after two years. Cattails covered 85-90% of the total wetland area, limiting the establishment of other plant species.

12. Based on 1999 TSS loading data, sediment accumulation rates in the forebay, wet pond and wetland were estimated at 10.6, 3.9 and 0.1 mm/yr, respectively. By 2005, when the drainage basin is expected to be fully developed, these accumulation rates are expected to increase to approximately 15.2, 5.5 and 0.2 mm/yr. Based on these estimates, the forebay, wet pond and wetland will require sediment removal roughly 21, 54 and 193 years from the time the facility became operational in 1997.

9.2 Recommendations

Recommendations for system improvement and further research are listed below.

1. Erosion cloth lining the spillway was seriously damaged during a large storm event in April 2000. The cloth protects underlying soils from transport downstream during overflow events, and should be repaired so as not to endanger the health of aquatic communities within the downstream tributary.

2. Bypass flow from the wetpond was discharged to the downstream portion of the wetland. As indicated above, this geometry can lead to erosion within the wetland. Future designs should, therefore, allow bypass flow around the wetland directly into the downstream channel.

3. The drawdown time of the wetpond runoff control structure often exceeded the average interevent period (approximately 72 hours in Ontario). Thus, the active storage capacity available for a subsequent event would have been limited, increasing the likelihood of bypass flow. To enhance the design of future facilities, further consideration should be given to weir designs and pond hydraulics such that an optimum balance is achieved among storage, detention time, and baseflow augmentation in the downstream channel.

4. The wetland outlet structure accumulated coarse bedload sediment during low flow periods. A low concrete barrier elevating the outlet structure above the wetland bed would help to trap the sediment, while sustaining a permanent pool of water in the upstream wetland cells. The permanent pool would enhance water quality functions of the wetland by increasing the bottom-to-water contact ratio.

5. Estimates of sediment accumulation rates provided in this report were based on several assumptions and should not be relied upon to determine dredging requirements. For this reason, direct measurements of sediment accumulation in each of the cells and around outfalls and intake pipes are recommended at 5 year intervals.

6. Drawing upon earlier studies, this report documents changes in performance of the Markham pond/wetland at different stages of development. As the catchment becomes increasingly urbanized, continued monitoring will be required to verify whether the hydrological and water quality performance of the facility continue to meet the original design targets and objectives.

7. Direct assessment of urban runoff impacts on aquatic biota was beyond the scope of this study. Shifts in aquatic health often occur very gradually and therefore require long term monitoring of appropriate biological and habitat indicators. The existence of this and earlier studies on the water quality, geomorphology and health of the Morningside tributary make the Markham site well suited for long-term aquatic habitat monitoring.

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APPENDIX A

Historical Context of the SWAMP Program

HISTORICAL CONTEXT OF THE SWAMP PROGRAM

Over the past 15 years, the Great Lakes Basin experienced rapid urban growth. Stormwater runoff associated with this growth has been identified as a major contributor to the degradation of water quality and the destruction of fish habitats. In response to these concerns, a variety of stormwater management programs have been developed in the Great Lakes basin.

A number of complementary programs have been established at the international, national, provincial and municipal levels to protect the Great Lakes ecosystem. The SWAMP program and the study that is the subject of this report are parts of the overall effort.

International Joint Commission

The International Joint Commission (IJC) prevents and resolves disputes between the United States of America and Canada under the Boundary Waters Treaty of 1909. The IJC pursues the common good of both countries as an independent and objective advisor of the two governments.

In particular, the IJC rules upon applications for approval of projects affecting boundary or transboundary waters and may regulate the operation of these projects; it assists the two countries in the protection of the transboundary environment. Among the responsibilities of the IJC is the implementation of the Great Lakes Water Quality Agreement.

Great Lakes Water Quality Agreement

The first Great Lakes Water Quality Agreement (GLWQA) between Canada and the United States was signed in 1972 in recognition of the urgent need to improve environmental conditions in the Great Lakes. The focus of the agreement was to improve water quality through pollution control programs. Objectives included the reduction of nuisance conditions and control of toxic substances. Specific numerical targets were included for the reduction of phosphorus loadings.

The Great Lakes Water Quality Agreement was amended in 1978 to include the objective of controlling persistent toxic substances. The new agreement also incorporated the ecosystem approach to environmental management.

In 1987, the Canadian and U.S. governments signed a protocol that identified local Areas of Concern (AOC's) where beneficial uses of the ecosystem had been significantly degraded. Remedial Action Plans (RAP's) were to be prepared by various levels of government for the AOC's. The plans would contain strategies to clean up problem areas in the Great Lakes region. In addition, the 1987 protocol included annexes addressing specific subjects such as non-point contaminant sources and contaminated sediments.

In total, 43 Areas of Concern were identified throughout the Great Lakes basin. Of the total, 17 AOC's were in Canada.

Great Lakes Sustainability Fund

The Canadian federal government's commitment to the Great Lakes ecosystem was initially managed through the Great Lakes Action Plan (GLAP). In 1990, the Great Lakes Cleanup Fund (GLCuF) was created to provide support for environmental projects designed to benefit the Great Lakes basin ecosystem.

In 1994, GLAP was replaced by the Great Lakes 2000 Program. GLCuF was extended and renamed the Great Lakes 2000 Cleanup Fund. In 2000, the Great Lakes Basin 2020 Action Plan was introduced in addition to the successor to the GLCuF, the Great Lakes Sustainability Fund (GLSF). The new plan and fund place priority on the restoration of environmental quality in Canada's remaining 16 Areas of Concern.

The GLSF supports the implementation of remedial actions falling within federal responsibilities that will lead to the restoration of beneficial uses in the Canadian Great Lakes Areas of Concern. The five-year, $30 million GLSF builds on past successes and is administered by Environment Canada on behalf of eight Government of Canada departments.

To restore these beneficial uses in the Great Lakes Areas of Concern, joint Canada-Ontario teams work in consultation with local Public Advisory Committees to develop Remedial Action Plans (RAPs) aimed at eliminating or reducing the major sources of contamination in these areas. When all beneficial uses in an AOC have been restored, the area is delisted. The RAPs have had some important successes. Collingwood Harbour was delisted in 1994, and Spanish Harbour was designated an Area of Recovery in 1999.

Canada – Ontario Agreement

Canada and Ontario have had Great Lakes environmental agreements in effect since 1971. The latest version of the Canada-Ontario Agreement Respecting the Great Lakes Basin Ecosystem (COA) was signed in June, 2002. The agreement provides the framework for systematic and strategic coordination of shared federal and provincial responsibilities for environmental management in the Great Lakes basin. The main objectives are to restore degraded areas, to prevent and control pollution, and to conserve and protect human and ecosystem health.

Ontario Ministry of Environment and Energy

The Ontario Ministry of Environment and Energy (OMOEE) manages a number of programs that contribute to the protection and clean-up of the Great Lakes basin. The Provincial Water Protection Fund assists municipalities to address water and sewage treatment problems and to undertake related studies. The Ontario

Great Lakes Renewal Foundation, established in 1998, provides seed money to support local projects that include habitat restoration and stormwater management. The OMOEE works in partnership with federal and state agencies and municipal governments to achieve numerous environmental goals; the Great Lakes Remedial Action Plans have been a prominent example of such work.

Toronto and Region Conservation Authority

The Toronto and Region Conservation Authority (TRCA) is one of 38 conservation authorities in Ontario that develop and implement programs for the management of water and natural resources on a watershed basis. Conservation authorities are created and given their mandate under the Conservation Authorities Act and involve a partnership of the municipalilties within a watershed and the Province of Ontario. The TRCA jurisdiction includes nine watersheds in the Toronto Region.

The TRCA and the Waterfront Regeneration Trust are the local coordinating agencies for the Toronto and Region Remedial Action Plan. The two agencies help the provincial and federal governments fulfill their obligations under the Great Lakes Water Quality Agreement and Canada-Ontario Agreement. The TRCA's general RAP role is to focus implementation activities on an individual watershed basis and provide technical expertise to its implementation partners. Stormwater management and the remediation of combined sewer overflows are integral to the restoration of the Toronto and Region Area of Concern.

SWAMP

In 1995, the Storm Water Assessment Monitoring and Performance Program (SWAMP) was created as a cooperative initiative of agencies interested in monitoring and evaluating the performance of various stormwater management technologies. The SWAMP program acts as a vehicle whereby federal, provincial, municipal and other interested agencies can pool their resources in support of shared research interests.

The objective of SWAMP is to collect data and report on the performance of stormwater treatment facilities. SWAMP is supported by the Great Lakes Sustainability Fund, the Ontario Ministry of Environment and Energy, the Toronto and Region Conservation Authority, the Municipal Engineers Association, a number of individual municipalities in Great Lakes Areas of Concern, and other owner/operator agencies.

A variety of stormwater management technologies have been developed to mitigate the impacts of urbanization on the natural environment. Prior to the creation of SWAMP, these technologies had been studied using computer models and pilot-scale testing, but had not undergone extensive field-level evaluation in southern Ontario.

The objectives of the SWAMP Program are:

- to monitor and evaluate the effectiveness of new or innovative stormwater management technologies,
- to disseminate study results and recommendations within the stormwater management community.

Technologies that have been addressed by the SWAMP program include:

- wet ponds and constructed wetlands,
- underground storage tanks,
- flow balancing systems,
- oil and grit separators,
- conveyance exfiltration systems.

A number of people have been part of the SWAMP team since the inception of the program. In alphabetical order, the staff members have been:

David Averill	Program Coordinator [July 2001 to present]
David Fellowes	
Rene Gagnon	
Dajana Grgic	
Weng Liang	Program Coordinator [1995 to 2000]
Serge Ristic	
Derek Smith	
Sheldon Smith	
William Snodgrass	Program Coordinator [December 2000 to June 2001]
Michael Thompson	
Tim Van Seters	

In addition, several student employees contributed to the success of the projects. Staff of the Ontario Ministry of Environment and Energy, Standards Development Branch, provided administrative and facility support. In addition, Standards Development Branch staff have contributed their technical expertise through informal advice and review of draft reports.

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APPENDIX B

Glossary and Fundamental Concepts of Pond Systems

1.0 GLOSSARY

active storage: see 'extended detention storage'.

adsorption: The adhesion of a liquid, gaseous or dissolved substance to a solid, resulting in a higher concentration of the substance (Raven *et al.*, 1992).

alga; *pl.* algae: Traditional term for a series of unrelated groups of photosynthetic eukaryotic organisms lacking multicellular sex organs (except for the charophytes); the 'blue-green algae,' or cyanobacteria, are one of the groups of photosynthetic bacteria (Raven *et al.*, 1992).

average event mean concentration (AEMC): The arithmetic mean of two or more individual storm runoff Event Mean Concentrations.

bankfull stage: Typically defined as the elevation of the active floodplain surface. The bankfull stage corresponds go the bankfull discharge, often considered to be the dominant channel forming discharge and has been shown to occur with a frequency of about 1.5 years (Badelt, 1999).

benthic: Pertaining to occurrence on or in the bottom sediments of wetland and aquatic ecosystems (IWA, 2000).

best management practice (BMP): A device, practice, or method for removing, reducing, retarding, or preventing targeted stormwater runoff constituents, pollutants, and contaminants from reaching receiving waters (ASCE, 1999).

catchment: That area determined by topographic features within which falling rain will contribute to runoff to a particular point under consideration. The area tributary to a lake, stream, sewer or drain. See also drainage area, drainage basin, river basin, catchment area, watershed (James and James, 2000).

drawdown time: During a storm runoff event, the time required for water levels in a pond, retention basin or tank to return to the water level existing prior to the storm event, beginning at the peak level..

emergent macrophytes: A rooted, vascular aquatic plant that grows in periodically or permanently flooded areas and has portions of the plant (stems and leaves) extending through and above the water column (adapted from IWA, 2000).

eutrophic: pertaining to a water body containing a high concentration of dissolved nutrients; often shallow, with periods of oxygen deficiency (Parker, 1989).

evapotranspiration: The combined processes of evaporation from the water or soil surface and transpiration of water by plants (IWA, 2000).

event mean concentration (EMC): The arithmetic mean concentration of an urban pollutant measured during a storm runoff event. The EMC is calculated by flow-weighting either grab samples or consecutive composite concentrations collected over the course of an entire storm event. (James and James, 2000).

extended detention storage: The storage provided by temporarily retaining water within a basin, tank or reservoir. Also called active storage.

flora: Plants (Parker, 1989).

geotextile: A woven or nonwoven fabric manufactured from synthetic fibers or yarns that is designed to serve as a continuous membrane between soil and aggregate in a variety of earth structures.

glacial till: Unsorted and unstratified drift consisting of a heterogeneous mixture of clay, sand, gravel and boulders which is deposited by and underneath a glacier (Parker, 1989).

groundwater recharge: Replenishment of groundwater naturally by precipitation or runoff or artificially by spreading or injection (James and James, 2000).

groundwater table: The upper surface of groundwater, or the surface below which the pores of rock or soil are saturated (James and James, 2000).

heterotroph: an organism that cannon manufacture organic compounds and so must feed on organic materials that have originated in other plants and animals (Raven *et al.*, 1992)

hydraulic detention time: The time delay in a pond or reservoir between the inlet and outlet hydrograph centroids.

hydraulic residence time (or hydraulic retention time): A measure of the average duration over which an element of fluid occupies a given volume or vessel, as estimated from tracer studies with conservative tracers such as lithium or dyes (adapted from IWA, 2000).

hydraulic conductivity: The rate of water flow through a cross section under a unit hydraulic gradient (Parker, 1989).

hydrograph: A graph showing, for a given point on a stream or conduit, the discharge, stage, velocity, available power, or other property of water with respect to time (James and James, 2000)

hyetograph: A graphical representation of the variation in rate of rainfall over time (James and James, 2000).

infiltration rate: The rate at which water enters the soil or other porous material under a given condition (James and James, 2000) (also see hydraulic conductivity and permeability)

lag time: In this study, the time delay between peak rainfall and peak runoff. Lag time is also sometimes calculated as the time delay between the centroid of the rainfall hyetograph and the centroid of the influent runoff hydrograph (see section 2.2 below).

left-censored data: Data sets including pollutant concentrations at or below the laboratory analytical detection limit.

mass balance: An accounting for all identified materials entering, leaving, or accumulating within a defined region.

matric forces: Forces acting on soil water that are independent of gravity but exist due to the attraction of solid surfaces for water, the attraction of water molecules for each other, and a force in the air-water interface due to the polar nature of water (Parker, 1989).

peak discharge: The maximum instantaneous flow at a specific location resulting from a given storm condition (James and James, 2000).

peak-shaving: Reduction of peak discharge rates by providing temporary detention in a BMP. Also called peak flow attenuation (adapted from James and James, 2000).

perched water table: The water table or upper surface of groundwater that is unconfined and separated from an underlying main body of groundwater by an unsaturated zone (Parker, 1989)

performance: A measure of how well a BMP meets its goals for stormwater that the BMP is designed to treat. (ASCE, 1999)

permanent pool volume: A volume of water that is stored permanently in a pond, reservoir or tank, as compared to extended detention volume, which exists only temporarily during storm runoff events.

permeability (of soil): property of soil which governs the rate at which water moves through it (James and James, 2000) (also see infiltration rate and hydraulic conductivity)

plug flow: Flow in which fluid particles are discharged from a tank or pipe in the same order in which they entered it. The particles retain their discrete identities and remain in the tank for a time equal to the theoretical detention time. A flow value used to describe a constant hydrologic condition. Also a sequence of parcels of water. (James and James, 2000)

porosity: The fraction of a solid, as a percent of its total volume, occupied by minute channels or open spaces (Parker, 1989).

recharge basin: A basin excavated in the earth to receive the discharge from streams or storm drains for the purpose of replenishing groundwater supply (James and James, 2000).

regolith: The layer of rock or blanket of unconsolidated rocky debris of any thickness that overlies bedrock and forms the surface of the land (Parker, 1989).

removal efficiency: A percentage reduction in a specific contaminant or constituent of the wastewater or runoff, as measured across a treatment system or an individual treatment unit.

runoff: That part of the precipitation which runs off the surface of a drainage area and reaches a stream or other body of water or a drain or sewer (James and James, 2000).

runoff coefficient: The ratio of the depth of runoff from the drainage basin to the depth of rainfall (James and James, 2000)

transpiration: The transport of water vapour from the soil to the atmosphere through actively growing plants (IWA, 2000).

unsaturated zone: A subsurface zone containing water below atmospheric pressure and air or gases at amospheric pressure (Parker, 1989).

vascular: pertains to any plant tissue or region consisting of or giving rise to conducting tissue *e.g.* xylem, phloem, vascular cambium (Raven et al, 1992).

watercourse: A natural or artificial channel for passage of water (James and James, 2000).

watershed: A topographically defined area drained by a river or a stream or a system of connecting rivers and streams such that all outflow is discharged through a single outlet (James and James, 2000).

zooplankton: microscopic animals that move passively in aquatic ecosystems (Parker, 1989).

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2.0 FUNDAMENTAL CONCEPTS FOR POND SYSTEMS

The purpose of this section of the appendix is to explain the basic principles of stormwater storage pond systems. Material balance principles will be used to derive important relationships and to explain relevant definitions.

2.1 System Definition

Figure B1 illustrates the basic system diagram for a stormwater pond. A fundamental feature of this system is that its operation is not steady-state; the hydraulic and pollutant loadings vary appreciably with time. Storage within the vessel makes the effluent hydrograph differ from that of the influent. Separation of the pollutants, in both suspended and dissolved forms, within the pond can result in both positive and negative removal efficiencies as a function of time and the many mechanisms that control the process. If there is a continuous dry-weather flow through the pond, the effect of storm events is modified by that flow, and vice-versa. In cases without a continuous dry-weather flow (baseflow), operation of the system is completely intermittent and both the storm event and the inter-event quiescent period must be considered.

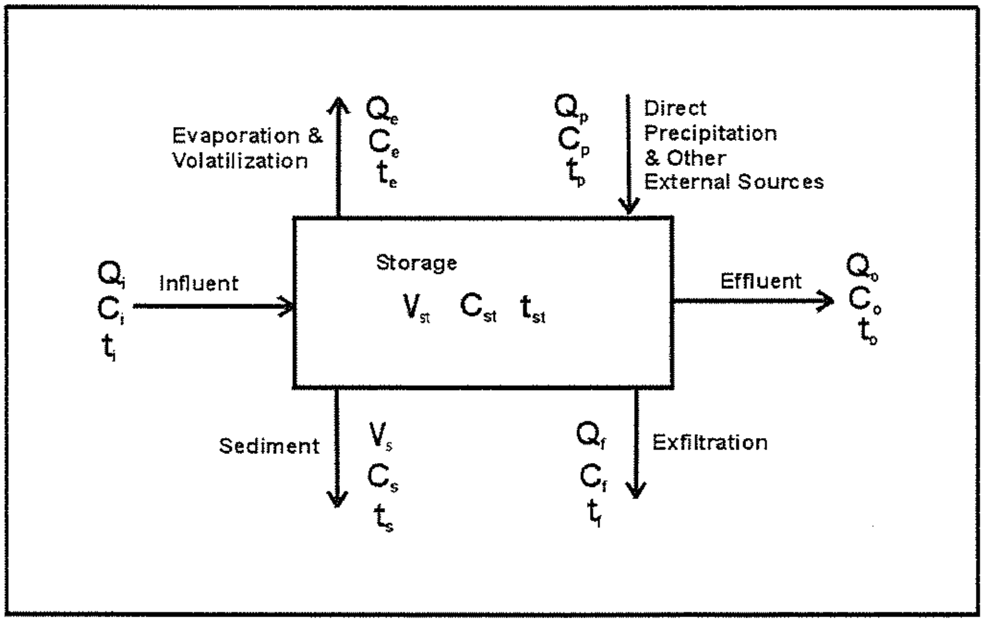

Figure B1: Stormwater Pond Material Balance Diagram

In Figure B1, "Q" represents a flow rate, "C" represents a pollutant concentration and "V" represents a volume. The symbol "t" represents a time period over which the respective flows, concentrations or volumes are being considered, or are of significance. As will be discussed, this time frame is of particular importance in the determination of system performance, particularly in situations that include long inter-event periods (quiescent or low-flow conditions) or emptying of the vessel between events.

Inlet flow (Q_i) and outlet flow (Q_o) are typically represented by time-series graphs called *hydrographs.* Monitoring of the inlet and outlet concentrations may not always continue for the full duration of the respective flows, or for sufficient time to establish complete mass balances. Methods of sampling also vary and can affect the reliability of the resulting performance data.

The volume of water in the pond is typically variable, resulting from the flow-throttling effect of the effluent structure. Concentrations in the pond may be measured only in the more intensive studies. Storage time in the pond has various meanings, as will be discussed.

Exfiltration, through the pond sides or a semi-pervious dam, may be a significant factor in some installations. Conversely, a high water table in the vicinity of the pond may result in infiltration of groundwater into the treatment facility. The quality of infiltration/exfiltration is generally estimated by summing the other flows.

In most stormwater pond studies, losses and gains to and from the atmosphere are seldom considered. These factors are more relevant to lake studies and lake modeling. However, other non-point contributions to the pond can result from waterfowl and other wildlife, including overland drainage from the surrounding area.

The volume and quality of the sediment are important considerations in stormwater ponds. The residence time is governed by decomposition rates and clean-out frequency.

The material balance diagram provides the basis for computing material (mass and volume) balances for the system. An understanding of the dynamics of the system is also necessary to design monitoring programs, and to define parameters representing system performance.

2.2 Quantity Considerations

Stormwater ponds are often designed in accordance with runoff quantity, quality and erosion control objectives. The characteristics relevant to runoff quantity and erosion control will be discussed with reference to actual data from a stormwater storage pond (Figure B2). This example will help to illustrate not only the basic principles but also some of the constraints associated with the analysis of real-world data.

Figure B2a contains the rainfall *hyetograph* and the runoff *hydrograph*. The hyetograph is a plot of rainfall depth versus time; unlike the example in Figure B2a, this data set is often plotted as a bar graph using an inverted y-scale. The hydrograph is a plot of runoff flow rate versus time; in this case, the hydrograph contains the inflow to the stormwater pond. Given the surface area of the catchment, both data sets can be converted to volumes of water, or to a uniform depth of water over the catchment area. The runoff coefficient for the catchment is the ratio of the runoff volume (or depth) to the rainfall volume (or depth); in this case, the value of the runoff coefficient was 0.28. The runoff coefficient is a measure of the ability of the catchment to retain rainfall, such that it percolates into the ground or returns to the atmosphere through evaporation and transpiration, rather than generating runoff. A high value of the runoff coefficient is indicative of a large percentage of impervious surfaces in the catchment. In this example, a little more than one-quarter of the rainfall was measured as runoff.

Various event characteristics related to time and intensity can be extracted from Figure B2a:

- The lag time of the catchment may be expressed as the time delay between the start of the rainfall and the start of runoff at the point of measurement. This quantity may be influenced by the frequency of observation; in the example data set, the rainfall was reported hourly and the runoff was reported every 5 minutes. Lag times also reflect the intensity of the storm, since a light rainfall may be largely contained in depression storage.
- The centroids of the hyetograph and hydrograph may be computed (from the first moment) and used to represent the variables as existing in points of time. This approach is useful in computing inter-event times. The time difference between the centroids also provides an alternative means of characterizing the catchment lag time, one that takes the total volume into consideration and is not biased by the initial rainfall intensity. Baseflow is not included in the calculation of the runoff hydrograph centroid, such that the centroid represents the average runoff conditions independent of the dry-weather flow.
- The durations of both the rainfall event and the runoff are also of interest. Because of the distance over which the runoff must flow, and the resistance to flow created by different surfaces and different paths of flow, the duration of runoff must exceed the duration of rainfall. The duration of the runoff event is measured from the appearance of a flow greater than the baseflow (or dry-weather flow) and ending with the return to baseflow. However, the end of the runoff event may be defined somewhat subjectively because surface and subsurface storage can cause the tails of the runoff curves to persist for long time periods.
- Each curve may be represented by its peak factor: the ratio of the maximum value to the mean. Because of flow attenuation in the catchment, the peak factor for the runoff is expected to be less than that of the rainfall. In some cases, the temporal relationships of the rainfall and runoff peaks may be documented (e.g., a peak-to-peak lag time); however, in events with multiple peaks, the significance of such relationships is not clear. In this case, the peak rainfall and the peak runoff flow were essentially simultaneous, a situation which would not be expected under most (simpler) conditions.
- The base flow, or dry-weather flow, may be different before and after the event. A prolonged dry period before the event would cause a small base flow. The rainfall event would be expected to increase the elevation of the groundwater table, promoting infiltration into the sewer system, and residual surface and subsurface water would enter subgrade drains and other parts of the system slowly. Consequently, the baseflow after the event would be elevated for a considerable time, making estimation of the duration of runoff difficult. The base flow may not return to the initial conditions before the next rainfall event. In the example, the initial and final base flows were smoothed and extended for illustrative purposes; the initial value was 0.025 m^3/s and the final value was 0.050 m^3/s.

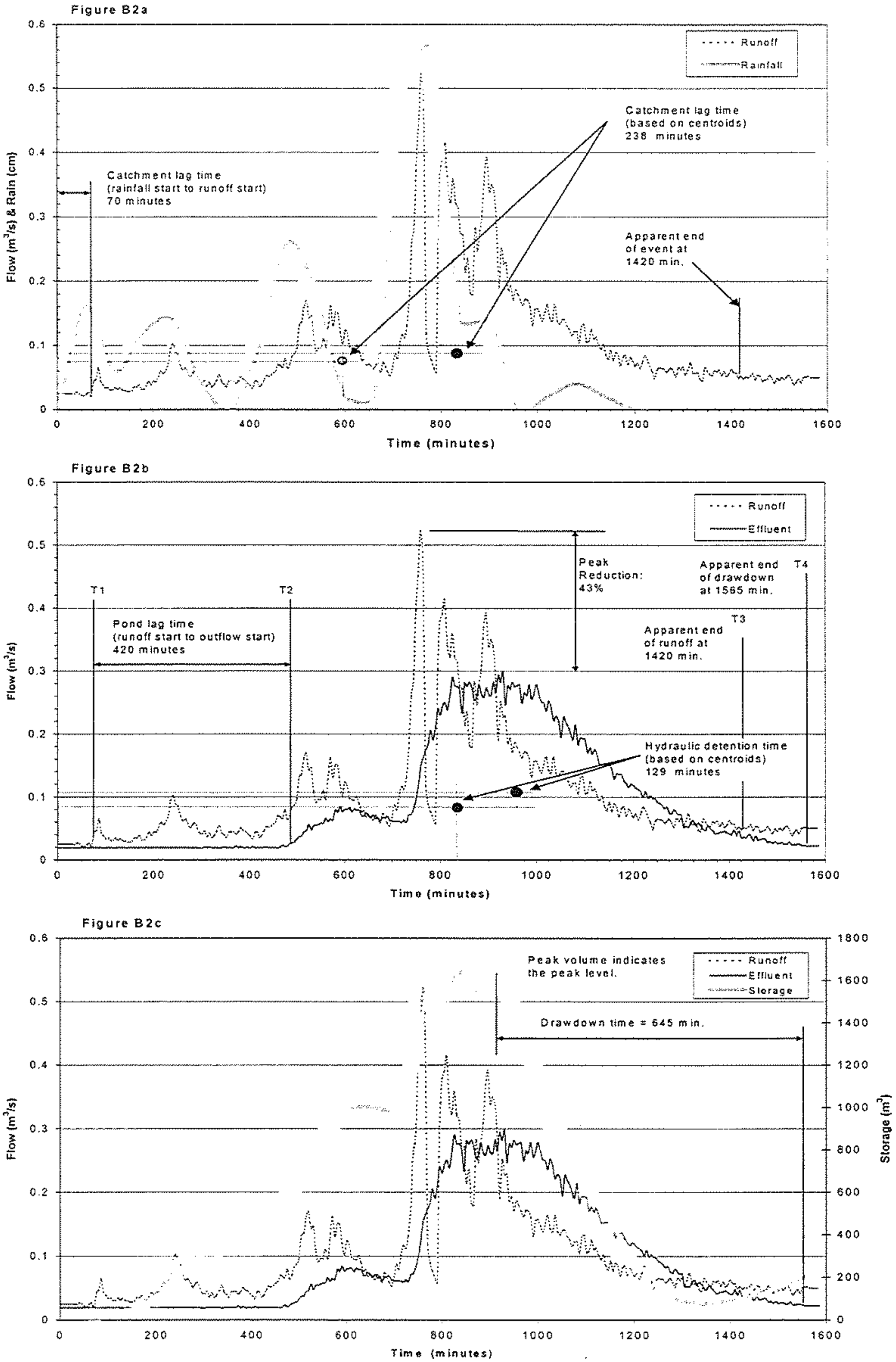

Figure B2: Hydrologic time series graphs for a sample event

Figure B2b contains the runoff hydrograph and the pond effluent hydrograph. Several system characteristics can be determined.

- The lag time of the pond may be expressed as the time delay between the start of the runoff flow (pond influent) and the start of the pond effluent flow. Several factors can influence this variable. In the example, the base effluent flow was often too small to be measured with the installed equipment and some manual extrapolation was employed to adjust the curve[1]. In some cases, a combination of evaporation and exfiltration from the pond can lower the surface of the water below the effluent control structure, producing a storage volume that would otherwise be unavailable and delaying the start of the effluent flow.
- The centroids of the hydrographs may be computed (from the first moment) and used to represent the variables as existing in points of time. The time difference between the centroids is defined as the *hydraulic detention time*, or the average time by which the bulk of fluid is held back or detained by the pond. The hydraulic detention time is determined primarily by the throttling effect of the effluent control structure. It is a measure of the ability of the facility to smooth and extend the runoff hydrograph to reduce its impact on the receiving stream.
- Differences in the durations of the influent and effluent hydrographs are another measure of the flow throttling effect of the facility. Normally, the effluent duration would be expected to exceed the influent duration. However, in this case, the effluent duration was less than that of the influent because of the shapes of the curves and the possible (extra) storage volume. In addition, the effluent was seen to exceed the influent at times, as a result of the irregularity of the rainfall and runoff curves; hence, the pond provided a flow smoothing function as well as attenuation. Also in this case, the average effluent flow was observed to be greater than the average influent flow, as a consequence of uncertainty in the initial conditions.
- Because of flow attenuation in the pond, the peak factor for the effluent is expected to be less than that of the runoff (influent). In some cases, the temporal relationships of the influent and effluent peaks may be documented (e.g., a peak-to-peak lag time); however, in events with multiple peaks, the significance of such relationships is not clear.
- The effluent base flow may be less than the influent base flow because of evaporation and exfiltration losses from the pond. At other sites, groundwater may flow into the pond causing the effluent base flow to exceed that of the influent. Also, the initial and final effluent base flows may be different because of changes in these gain or loss rates and in the influent base flow. In this example, the initial effluent base flow was 0.019 m^3/s and the final value was 0.022 m^3/s. The initial and final evaporation/exfiltration losses were therefore approximately 0.006 m^3/s and 0.028 m^3/s respectively. These estimates were affected by the poor quality of the initial data; if the initial effluent base flow had actually been closer to zero, the losses would have been similar.

Figure B2c contains the active (or dynamic) storage volume of the pond together with the influent and effluent hydrographs. The storage volume is calculated from the two sets of flow data. This graph is particularly useful as a means of testing the volumetric balance of the data set. Any deviation from zero storage at the end of the event indicates inaccuracy in the flow measurements and/or the estimation of other gains or losses. In this case, the evaporation/exfiltration losses were estimated from the initial data alone. Failure to include the final baseflow conditions in the calculation procedure is evident in the upward slope of the storage curve after the event. The overall volumetric error was 9%; if measurement of the small initial outflow had been feasible, the computed error may have been smaller.

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[1] Further examination of the effluent level and flow signals may lead to re-interpretation of the initial flow data. Instrument data will be the subject of discussion in a future report.

The water level in the pond is another variable of interest. Water level measurements provide an independent check on volumetric data, providing that a reasonable stage-storage relationship can be derived for the pond based on its geometry. In the example, the pond level was not measured but survey data resulted in a linear stage-storage relationship over the range of active storage volumes. Hence, the pond level is proportional to the stored volume. Knowledge of the water level also permits the computation of another typical pond parameter:

- The *drawdown time* is defined as the period between the maximum water level and the minimum level (dry-weather or antecedent level) in the pond. A theoretical drawdown curve for a pond may be taken as the stage-discharge relationship of a specific effluent control structure. The theoretical value would be approached in practice only if there was no influent flow at the time that the pond was draining. Because there is typically some inflow during this time, the value of the actual drawdown time is expected to exceed that of the theoretical curve.

2.2.1 Summary – stormwater quantity

Table B1 summarizes the hydraulic characteristics of the pond stormwater event used as an example in Figure B2. The underlying principle for runoff quantity analysis is that the displacement of water is acknowledged. In other words, the emphasis is on bulk water quantities. The actual molecules of water entering the system are not necessarily those exiting the system within the timeframe considered. Hence, these quantity relationships should not be confused with the water quality relationships discussed in the next section.

Table B1: Hydraulic Characteristics – Example Pond Event

Parameter	Rainfall	Runoff - Influent	Pond Effluent
Volume (cubic metres)	32,380	8,950	8,130
Duration (minutes)	1,200	1,350	1,075[1]
Runoff Coefficient		0.28	
Pond Volumetric Error[2] (%)			9
Peak Factor	7.6	5.2	3.3
Peak Reduction			43%
Lag Time (minutes)			
- start-to-start		70	420[1]
- centroid-to-centroid		238	129
- peak-to-peak[3]		n/a	n/a
Pond Drawdown Time (minutes)			645

Notes: [1] Difficulty measuring initial effluent flow reduced the duration and increased the lag time.

[2] Volumes and volumetric error are determined after accounting for baseflow.

[3] Peak-to-peak time intervals can not be adequately defined in a multi-peak event.

2.3 Quality Considerations

Stormwater quality refers to the pollutants in the water. Runoff pollutant concentrations typically vary with time as a result of erosive forces (flow rate) and the duration of runoff events. Consequently, water quality data are often represented by *pollutographs*. Pollutographs are measured by collecting discrete samples at uniform time intervals, and are graphed as time-series data sets.

The fate of pollutants in a pond or other treatment system is determined by the physical, chemical and biological forces to which the pollutants are exposed, and the duration of exposure. Each element of fluid that enters the treatment system has a specific residence time (or retention time) within that system. The *hydraulic residence time* is determined by the pond volume, the flow rate and the flow patterns within the pond. The flow rate and the volume of water within the pond vary as described under the heading of "quantity considerations". The flow patterns are determined by several factors including the geometry of the pond, hydraulic conditions at the inlet and outlet, thermal stratification, density stratification and wind effects.

Because different elements of fluid can take different paths through the pond, a range of residence times exists for each facility. This range is quantified as a residence time distribution, which is measured through the use of an inert tracer material. The tracer is added to the inlet flow at a point in time and concentrations in the outflow are measured as a function of time. The average residence time is measured as the centroid of the residence time distribution curve.

The fate of pollutants in a treatment system may be predicted knowing the hydraulic residence time and a "decay rate" specific to each pollutant. The decay rate is the rate of reaction for substances that are destroyed or transformed within the treatment system, or the settling rate for suspended material that is retained within the system. Reaction rates for specific pollutants depend on many physical, chemical and biological factors. Some pollutants may be both settled and reacted. Some substances may be produced within the pond, for example by photosynthesis. Hence, the residence time of a pollutant is specific to each situation. For inert suspended materials, residence time is determined in part by the frequency of clean-out operations. Inert soluble materials such as chloride may follow the flow paths and leave the ponds in the effluent or the exfiltration flow, but may also be stored for extended periods of time in density layers within the ponds.

No tracer tests were undertaken for the pond used as an example above. Hence, the hydraulic residence times were not determined. A general impression of the hydraulic residence time may be obtained by assuming steady-state flow, an average pond volume and plug-flow conditions (no mixing of influent and pond contents and no short-circuiting of flow). If the average flow were 0.1 m^3/s and the average volume were 7000 m^3 (both consistent with the above example), the hydraulic residence time would be 1,170 minutes (19.4 hr.) under plug-flow conditions. Short-circuiting of flow, internal mixing and other factors would tend to reduce that value, on average. However, since many rainfall/runoff events are shorter than 19 hours, some of the runoff may be expected to reside in the pond for several days (inter-event periods). Also, eddy currents and dead spaces within the ponds can hold elements of water and associated pollutants for extended periods of time and produce long tails on the residence time distribution curves.

2.4 Discussion

Hydraulic detention time and hydraulic residence time (a.k.a. hydraulic retention time) are two distinctly different concepts and are used for different purposes. Detaining, delaying or holding back runoff is an important aspect of hydraulic control – the flattening of runoff hydrographs. Retaining, storing or holding volumes of stormwater is an important aspect of pollution control – the destruction or separation of pollutants. Detention times and residence times can be vastly different within any given system. Figure B3 illustrates extreme conditions that emphasize the choice of appropriate system characteristics.

A long, narrow pond with inlet and outlet structures at either end (Figure B3a) forces the flow to proceed under essentially "plug-flow" conditions, such that each element of flow entering the pond has essentially the same residence time as well as the maximum time permitted by the pond volume and flow rate. The average residence time under such conditions could be measured in days. The water level in the pond, however, responds quickly to inflow. If there is minimal effluent flow throttling, the effluent hydrograph could follow very quickly after the influent hydrograph, resulting in a hydraulic detention time of minutes.

The other extreme case is a long, thin pond with the inlet and outlet structures located very close together (Figure B3b). The pond may be large with good effluent flow throttling, resulting in a long hydraulic detention time. However, elements of the influent flow can proceed quickly from the inlet structure to the outlet structure or, if stored for longer periods of time, would not migrate far from the two structures such that they are discharged before significant treatment can occur. The hydraulic residence time in this case is very short, and much of the volume of the pond is essentially inactive from the perspective of quality control.

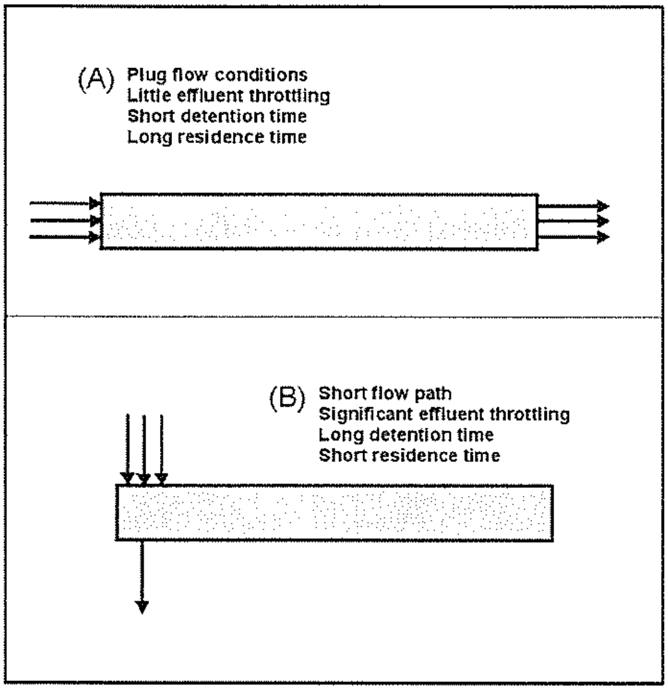

Figure B3: Detention and Residence Time Scenarios

There is a tendency in the stormwater literature to interchange – or at least confuse - hydraulic detention time and hydraulic residence time. Hydraulic detention time may be discussed (incorrectly) in the context of settling rates or treatment efficiency. Assuming that pond geometry guidelines are followed, a reasonable correlation between detention and retention times would likely exist and, by extension, a correlation between detention time and treatment efficiency. However, such correlations do not imply a cause-and-effect relationship, nor can they be used to examine removal mechanisms. Only an extensive review of performance data would indicate whether any such correlations may be reliable, and within what range of system geometry.

2.5 Performance

2.5.1 Volume, mass and concentration

The total volume and total pollutant mass found in any water or wastewater stream may be determined by summation over the appropriate time intervals. For example, with reference to Figures B1 and B2, the influent volume (V_i) and influent pollutant mass (M_i) are calculated as:

$$V_i = \sum_{k=\mathrm{T1}}^{\mathrm{T3}} Q_{i_k} \Delta t_k \qquad \text{(B-1)}$$

$$M_i = \sum_{k=\mathrm{T1}}^{\mathrm{T3}} C_{i_k} Q_{i_k} \Delta t_k \qquad \text{(B-2)}$$

where: Q = flow measured over finite time interval, Δt
C = concentration of a specified pollutant measured over finite time interval, Δt
T1 represents the start of the runoff (influent) flow
T3 represents the end of the runoff (influent) flow

The flow-weighted average influent pollutant concentration ($\overline{C}_i$) may be determined from the total influent mass and the total influent volume:

$$\overline{C}_i = \frac{M_i}{V_i} \qquad \text{(B-3)}$$

Similarly, the volume, mass and a flow-proportioned mean concentration may be calculated for the effluent or any other significant flow.

Ideally, the average pollutant concentration measured at a specific location for one event is determined by integration of continuous data or the summation of multiple flow-weighted discrete observations. However, sampling programs seldom generate sufficient data for a rigorous analysis. The average concentration is often determined from composite samples. Important considerations include whether or not the composite sample was flow-proportioned (flow-weighted) and whether the sampling period included all of the runoff event^2.

Given appreciable temporal variation in most storm events (i.e., in hydrograph and pollutograph shapes), the lack of flow-proportioned samples can result in appreciable error. The worst case scenario consists of simultaneous peaking of the hydrograph and pollutograph, such that high concentrations occur at high flow and a large mass of pollutant is transported during that part of the event. Hence, the type of sampling should be indicated when an average concentration is reported.

An average concentration, measured at a specified location over the duration of one event, is typically called the *event mean concentration* (EMC). Ideally, the type of sampling used to determine the EMC should be indicated:

EMC^{p} = flow-proportioned event mean concentration

EMC^{t} = time-averaged or non-flow-proportioned event mean concentration

2.5.2 Event efficiency – load-based

Load-based efficiency (LE) is defined as the ratio of the mass of a specific pollutant removed to the corresponding influent concentration[3]. This parameter may also be referred to as *mass efficiency*. The *LE* is determined by considering the entire event cycle: the time from the start of the stormwater flow to the end of the effluent drawdown curve. Equation 4 is written using the summation of incremental mass quantities (the product of flow and pollutant concentration over finite observation intervals). Ideally, all sources and destinations of flow and pollutants would be considered; practically, only the influent and effluent are included in the definition of efficiency.

$$LE = \frac{\sum_{k=T1}^{T3} Q_{i_k} C_{i_k} \Delta t_k - \sum_{k=T2}^{T4} Q_{o_k} C_{o_k} \Delta t_k}{\sum_{k=T1}^{T3} Q_{i_k} C_{i_k} \Delta t_k} \qquad \text{(B-4)}$$

Equation B-4 may also be written using the sums of all mass loads entering *(SOL_{in})* and leaving *(SOL_{out})* the facility.

$$LE = \frac{SOL_{in} - SOL_{out}}{SOL_{in}} \qquad \text{(B-5)}$$

In Equation B-5, the summations are assumed to be over the time periods relevant to the influent and effluent.

2.5.3 Event efficiency - concentration-based

In stormwater studies, flow and volume data may not always be available. In such cases, the Event Mean Concentration *(EMC)* is an average concentration that has been obtained without flow-proportioned sampling. Using the *EMC* values, a concentration-based pollutant removal efficiency for a single event may be defined as follows:

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[2] The selection and programming of sampling equipment, as well as other sampling logistics considerations will be the subject of a subsequent report.

[3] In this document, removal efficiency is expressed as a fraction rather than a percentage, primarily to simplify the equations.

$$CE = \frac{EMC_i - EMC_o}{EMC_i} \tag{B-6}$$

$$CE = 1 - \frac{EMC_o}{EMC_i} \tag{B-7}$$

This expression for concentration-based efficiency is the definition of efficiency commonly used for continuous-flow clarifiers with negligible underflow.

2.5.4 Residence time and intermittent operation

There are further complications to be considered when examining effluent samples and calculating removal efficiencies. These considerations are consequences of the long residence times and intermittent operation common to stormwater treatment systems.

Ideally, removal efficiency should be associated with each element (or incremental volume) of suspension that enters the treatment system. Each element of fluid entering the system contains a specific matrix of pollutants that will be removed in accordance with their characteristics, the hydraulic and other conditions in the system, and the time during which the element of fluid resides in the system. Comparison of the characteristics of that element of fluid, as it leaves the system, with its initial characteristics would provide a true measure of treatment efficiency.

Consider a large wet pond treatment system:

- Effluent flow at the start of an event consists primarily of displaced fluid that had been in the pond since the previous event or had accumulated during the intervening dry-weather period. The long residence times for these elements of fluid would probably result in pollutant concentrations equivalent to the non-settleable (non-treatable) residual concentrations.
- As the event progresses, the component of the effluent flow generated by the current event begins to increase. Some influent flow will mix with the pond contents and some elements of the influent may short-circuit to reach the effluent structure before the majority of the flow. The result is measurement in the effluent stream of partly diluted and partly settled current-event influent.
- In moderate-size events, the remainder of the influent fluid elements would reside in the pond until the next event or until they are gradually displaced by dry-weather flow. These elements would be expected to receive the maximum treatment efficiency possible for the specific installation.
- In large events, the total contents of the pond may eventually be exchanged. The effluent would then reflect only the current influent conditions and the treatment efficiency of the pond in continuous (flow-through) operation mode.

Effluent samples are typically collected during each runoff event and only for the duration of the event hydrographs. Effluent quality from that sampling period may be compared directly to the influent quality from the same event to estimate treatment efficiency. The result is a measure of the change in water quality across the pond, and the reduction in pollutant loading during that specific event. However, that procedure ignores the residence time in the system and may introduce significant errors in examining the removal mechanisms and determining the overall environmental loadings from the facility.

Ideally, the least error would result from continuous measurement of influent and effluent during both wet-weather and dry-weather. Short-term efficiency would be best represented by comparison of influent samples to effluent samples with the latter offset by the residence time in the system. However, the residence time could not be measured on a continuous basis because it is a distribution that is influenced by many physical factors, and it is measured by a pulse addition of a tracer. The concept of following elements of fluid through the treatment system may be appropriate to numerical simulation techniques[4].

Inter-event (or dry-weather) flow and pollutant loading are often not considered. Low flows and small concentrations may be difficult to measure, and differential concentrations (removals) may not be significant numbers. However, the long dry-weather time periods can conceptually result in large volumes and pollutant masses.

Practically, composite samples are collected for each event and few - if any - samples are collected between events. Hence, the data analysis options are: (1) compare the effluent data to the influent data of the same event, (2) compare the effluent data to the influent data of the previous event, or (3) calculate efficiency based only on long time periods considering the total influent and effluent masses (long-term mass efficiency). The latter option will provide the best estimate of system efficiency.

2.5.5 Long-term efficiency - load-based

Load-based efficiency calculations provide the most accurate method of determining long-term efficiency. In this procedure, the summations are made over the full time frame of interest (several events, a season, a year or several years).

The sum-of-loads concept may be expressed in terms of *EMC* values and event volumes *(V)*. Hence, the efficiency ratio based on mass load for a single event is:

$$LE_{emc} = 1 - \frac{EMC_o \times V_o}{EMC_i \times V_i} \qquad \text{(B-8)}$$

An average efficiency ratio could be calculated for several events:

$$ALE_{emc} = \frac{\sum_{j=1}^{m} LE_j}{m} \qquad \text{(B-9)}$$

where: m represents the number of events.

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[4] Numerical simulation of stormwater ponds will be the subject of a subsequent report.

However, a simple average of efficiencies gives equal importance (weight) to each event, regardless of event size. A better estimate of long-term efficiency is obtained by totaling the mass quantities over the time period of interest:

$$SLE_{emc} = 1 - \frac{\sum_{j=1}^{m} EMC_{o_j} \times V_{o_j}}{\sum_{j=1}^{m} EMC_{i_j} \times V_{i_j}} \quad \text{(B-10)}$$

Table B2 contains an example of the extent to which averaging of event performance can distort the estimate of long-term efficiency. In this hypothetical example, one large event, one small event and two moderate-sized events each have reasonable TSS removal efficiencies. A simple average of the four efficiencies, however, does not adequately represent actual system performance.

These definitions of efficiency are not as rigorous as those derived from material balance principles. The difference is that the composite samples that are used to determine the *EMC* values were not necessarily flow-proportioned. However, from a practical perspective (given current sampling practice), mass loading based on *EMC* values and averaged over as large a variety of events as possible is the best feasible method of representing stormwater pond performance.

Table B2: Hypothetical Data Set - Effect of Averaging Performance Data

Event No.	Volume	*EMC* in	*EMC* out	% Rem.	Mass in	Mass out
1	2,000	125	50	60	250,000	100,000
2	500	110	15	86	55,000	7,500
3	10,000	165	120	27	1,650,000	1,200,000
4	1,500	115	30	74	172,500	45,000
ALE				62		
Total					2,127,500	1,352,500
SLE				36		

2.5.6 Long-term efficiency – concentration-based

Flow and volume data are not always available; consequently, pollutant mass can not be determined. In such cases, an average event mean concentration *(AEMC)* may be calculated for several events, for example over one year or a runoff season.

$$AEMC = \frac{\sum_{j=1}^{m} EMC_j}{m} \tag{B-11}$$

where: m represents the number of events.

Similarly, long-term *average efficiency (ACE)* can be calculated from *AEMC* values:

$$ACE^{*} = \frac{AEMC_i - AEMC_o}{AEMC_i} \tag{B-12}$$

$$ACE^{*} = 1 - \frac{AEMC_o}{AEMC_i} \tag{B-13}$$

Alternatively, individual efficiencies can be averaged. Numerically, averaging the concentrations over a season and calculating a seasonal efficiency based on averages is not the same as calculating individual *EMC*-based efficiencies and averaging them $(ACE^{*} \quad ACE^{\#})$.

$$ACE^{\#} = \frac{\sum_{j=1}^{m} CE_j}{m} \tag{B-14}$$

APPENDIX C

Analytical Procedures and List of Organic Parameters Analyzed

Table C1: OMOEE Analytical Procedures Employed in the Markham Pond-Wetland Study

Method Number	Product Number	Constituent	Procedure	Comments
E3016A	CL3016	Chloride	Colourimetry following two-stage reaction with mercuric thiocyanate and ferric iron	interferences from bromide, iodide, sulphide, cyanide, thiosulphate
E3060B	HG3060	Mercury	Cold vapour flameless atomic adsorption spectrophotometry (CV-FAAS) at 253.7 nm following acid digestion and reduction with stannus chloride solution	method is suitable for "clean" waters
E3089A	ASSE3089	Arsenic, Selenium	Flameless atomic adsorption spectroscopy (FAAS) following acid digestion and hydride generation	
E3119A	CPA3119	Chlorophenols and phenoxyacid herbicides	Solid phase extraction (SPE) using pre-conditioned C_{18} cartridges followed by elutriation with solvent, treatment with diazomethane and analysis gas chromatography with electron capture detectors (GC-ECD)	16 compounds
E3120B	OCS3120	Organochlorine pesticides (OC's), polychlorinated biphenols (PCB's) and other chlorinated organic compounds	GC-ECD following solvent extraction and clean-up with Florisil™	38 compounds
E3265A	PAH3265	Acid/base and neutral compounds	In-situ acetylation and liquid/liquid extraction with dichloromethane, followed by drying with sodium sulphate, concentration and analysis by gas chromatography with a mass selective detector (GC-MSD) with single ion monitoring (SIM) data capture	a wide range of organic compounds including phenolics and PAH's
E3289A	PHALCO 3289	Conductivity, pH, Alkalinity	Automated system using electrodes in a constant temperature bath for conductivity, a calibrated potentiometric system for pH and titration for TFE alkalinity (to an end-point of pH 4.5)	Supernatant or filtrate is analyzed. Gran alkalinity by special request only
E3311A	TURB3311	Turbidity	Measurement of light scattering at 90° ±30° by nephelometry calibrated to Formazin turbidity standards	
E3328A	PART3328	Particle size	Optical – laser light diffraction (Coulter LS130 Particle Size Analyzer)	0.1to 900 μm in 27 size channels. Reported as % by volume (no count data)

E3334A	ID3334 SXT3334	Organic Solvent Extractable Matter (liquid-liquid or liquid-solid extraction)	Diffuse reflectance infrared Fourier transform spectroscopy (DR-IR) after extraction with dichloromethane	3 major groups: non-volatile petroleum hydrocarbons, cooking oils, soaps and detergents (Presence of humic acid detected in several samples).
E3364A	DISNUT 3364	Dissolved nutrients: ammonia + ammonium nitrite nitrate + nitrite phosphate	Simultaneous, automated analysis of one aliquot of sample: - ammonia by conversion to indophenol blue with sodium nitroprusside as a catalyst - nitrite by colourimetric method after reaction with sulphanilamide and N(1-napthyl) ethylenediamine dihydrochloride - nitrate + nitrite by colourimetric method following conversion of nitrate to nitrite - phosphorus, as orthophosphate, by colourimetric method folowing reaction with ascorbic acid	
E3188B	TSD3188	Total, Suspended and Dissolved Solids	Suspended solids are determined as the material removed from suspension by a 1.5 to 2.0 µm glass fibre filter, after drying at 103° ±2°C. Disssolved solids is the material that remains in solution after suspended solids are filtered out, as determined by evaporating to dryness at 103±2 C. Total solids is the sum of suspended and dissolved solids.	
E3367A	TOTNUT 3367	Total nutrients: total P TKN	Total P: digestion in sulphuric acid, mercuric oxice, potassium sulphate media followed by reduction with ascorbic acid – measured a orthophosphate Total Kjeldahl Nitrogen: digestion with Kjeldahl's reagent, neutralization and analysis for ammonia species by colourimetry	
E3370A	DCSI3370	Silicon: reactive silicate Dissolved organic carbon Dissolved inorganic carbon	Molybdate reactive silicates: dissolved reactive silicate ions are measured throught he formation of molybdenum heteropoly blue complex Dissolved inorganic carbon (+ carbon dioxide) are measured by acidifying the sample supernatant, extracting the CO_2 through a dialysis membrane and reacting it with phenolphthalein and colourimetric measurement Organic carbon is measured in the sample supernatant by acidification followed by nitrogen flushing to remove inorganic carbon and UV digestion in an acid-persulphate medium. The resulting CO_2 is analyzed as above.	

E3371A	ECFSPS 3371	*Escherichia coli* *Fecal streptococcus* *Pseudomonas aeruginosa*	Membrane filtration procedures are used to recover and enumerate several bacteria or bacterial groups. The culture media, incubation temperatures and incubation periods are specific to each bacterial analyte.	
E3386A	MET3386	Metals	Inductively coupled plasma (ICP) following ultrasonic nebulizer	Digestion is not used.

***Table C2*: Analytical Detection Limits and PWQOs for Herbicides and PAHs analyzed in this study**

Polynuclear Aromatic Hydrocarbons	**Reporting Method Detection Limit (µg/L)**	**PWQO Limit (µg/L)**
Napthalene	1.6	7.0
2-methylnaphthalene	2.2	2.0
1-methylnaphthalene	3.2	2.0
2-chloronaphthalene	1.8	0.2
Acenaphthylene	1.4	--
Fluorene	1.7	0.2
Phenanthrene	0.4	0.03
Anthracene	1.2	0.0008
Fluoranthene	0.4	0.0008
Pyrene	0.4	--
Benzo(a)anthracene	0.5	0.0004
Chrysene	0.3	0.0001
Benzo(b)fluoranthene	0.7	--
Benzo(k)fluoranthene	0.7	0.0002
Benzo(a)pyrene	0.6	--
Dibenzo(a,h)anthracene	1.3	0.002
Benzo(g,h,i)perylene	0.7	0.00002
1-chloronaphthalene	2.5	0.1
Perylene	1.5	0.00007
Indole	1.9	--
5-nitroacenaphthene	4.3	--
Biphenyl	0.6	0.2
Herbicides and Pesticides		
2,4-dichlorophenol	2.0	0.2
2,4,6-trichlorophenol	0.02	18.0
2,4,5-trichlorophenol	0.1	18.0
2,3,4-trichlorophenol	0.1	18.0
2,3,4,5-tetrachlorophenol	0.02	1.0
2,3,4,6-tetrachlorophenol	0.02	1.0
Pentachlorophenol	0.01	0.5
Silvex	0.02	--
Bromoxynil	0.05	--
Picloram	0.1	--
Dicamba	0.05	200.0
2,4-D-propionic acid	0.1	--
2,4-D	0.1	4.0
2,4,5-T	0.05	--
2,4-DB	0.2	--
Dinoseb	0.02	--
Diclofop-methyl	0.1	--

APPENDIX D

Water Quality Statistics

Table D1 : Inlets during wet weather - entire monitoring period (November 16, 1998 to December 5, 1999).

			Inlet 1								Inlet 2							
Parameter	Unit	RMDL*	N	% > D.L.	MIN	MAX	MEAN	SD	95%CI-LL	95%CI-UL	N	% > D.L.	MIN	MAX	MEAN	SD	95%CI-LL	95%CI-UL
Oil and grease	mg/L	2.5	24	100	1.0	14.0	4.0	0.80	2.8	5.5	23	100	1.5	16.0	7.9	0.58	6.2	10.1
Suspended Solids	mg/L	2.5	24	100	11.0	725.0	269.0	1.23	160.0	452.3	23	100	79.0	1780.0	366.4	0.65	276.9	484.7
Solids; total	mg/L	2.5	24	100	324.0	3430.0	896.8	0.62	689.5	1166.4	23	100	390.0	5900.0	988.8	0.56	775.0	1261.6
Solids; dissolved	mg/L	4	24	100	80	3420	684	1.02	445	1053	23	100	110	5690	598	0.76	431	829
Aluminum	µg/L	3	24	100	56	2190	848	0.94	569	1262	23	100	297	3210	1175	0.62	899	1535
Barium	µg/L	0.3	24	100	24.6	82.6	55.4	0.34	48.0	63.9	23	100	33.7	181.0	72.4	0.36	62.0	84.6
Beryllium	µg/L	0.02	24	1	0.01	0.24	0.09	0.07	0.06	0.11	23	100	0.03	0.57	0.13	0.62	0.10	0.18
Cadmium	µg/L	0.6	24	63	0.18	2.87	0.70	0.64	0.44	0.96	22	50	0.30	3.05	0.86	0.85	0.51	1.22
Cobalt	µg/L	1.5	24	33	0.75	3.70	1.35	0.97	0.96	1.73	23	64	0.75	8.35	2.08	1.69	1.38	2.79
Chromium	µg/L	1	24	88	0.5	9.0	3.0	1.91	2.2	3.7	23	100	1.1	21.2	7.2	0.76	5.2	10.1
Copper	µg/L	0.6	24	100	3.6	33.4	13.5	0.53	10.8	16.9	23	100	5.6	133.0	26.4	0.69	19.6	35.6
Iron	µg/L	100	24	100	84.6	2110.0	808.8	0.87	559.0	1170.2	23	100	297.0	14500.0	1450.0	0.90	981.7	2141.8
Manganese	µg/L	0.1	24	100	5.8	330.0	161.3	1.11	101.0	257.6	23	100	58.7	1760.0	295.0	0.67	220.6	394.6
Molybdenum	µg/L	1.6	10	10	0.8	1.9	0.9	0.33	0.7	1.1	22	31	0.8	2.0	1.1	0.50	0.8	1.4
Nickel	µg/L	1.5	24	88	0.8	6.2	2.8	1.43	2.3	3.4	23	95	0.8	25.0	5.4	4.83	3.4	7.4
Lead	µg/L	11	24	46	5.5	56.6	12.3	1.96	7.8	16.8	22	68	5.5	105.0	20.7	2.33	10.7	30.7
Strontium	µg/L	0.3	24	100	124	609	303	0.49	246	372	23	100	103	663	319	0.38	270	376
Titanium	µg/L	0.3	24	92	0.2	15.5	5.6	4.41	3.8	7.3	22	95	0.2	45.3	10.4	11.57	5.6	15.3
Vanadium	µg/L	0.9	24	92	0.5	6.5	3.0	1.55	2.4	3.6	23	100	2.6	24.6	8.1	0.55	6.4	10.3
Zinc	µg/L	0.6	24	100	6.3	196.0	68.6	0.84	48.2	97.7	23	100	46.0	667.0	142.6	0.63	108.6	187.3
Silicon; reactive silicate	mg/L	0.002	24	100	0.8	6.9	2.9	0.70	2.1	3.9	23	100	1.1	5.8	3.0	0.32	2.6	3.5
Escherichia Coli	c/100mL	4	13	100	10	16000	5198	1.75	1800	15008	13	100	140	14300	4141	1.45	1722	9955
Fecal Streptococcus	c/100mL	4	13	100	50	33000	14750	1.65	5458	39862	13	100	420	95000	14680	1.37	6400	33671
P. Aeruginosa	c/100mL	4	13	100	4	15000	5632	2.52	1227	25860	13	100	10	3300	1634	1.93	510	5238
Carbon; diss. organic	mg/L	0.1	24	100	0.8	7.7	3.8	0.60	3.0	4.9	23	100	1.9	28.5	11.9	0.69	8.9	16.1
Carbon; diss. inorg.	mg/L	0.2	24	100	12.2	53.8	28.4	0.44	23.5	34.2	23	100	19.6	55.6	30.9	0.26	27.7	34.6
Alkalinity; fixed endpt.	mg/L	0.2	24	100	45.0	232.0	117.6	0.49	95.8	144.5	23	100	64.0	234.0	125.3	0.26	112.0	140.1
Conductivity	µS/cm	1	24	100	124	5920	1098	1.05	705	1710	23	100	169	9800	927	0.77	665	1293
pH	none	0.1	24	100	7.7	8.8	8.0	0.03	7.9	8.1	23	100	7.3	8.1	7.7	0.03	7.7	7.8
Chloride	mg/L	0.2	23	100	7.8	1800.0	200.7	1.40	109.5	367.6	23	100	11.4	3540.0	200.4	1.11	123.9	324.1
Calcium	mg/L	0.04	24	100	39.5	150.0	90.7	0.40	76.6	107.4	23	100	49.8	319.0	111.1	0.39	93.7	131.8
Magnesium	mg/L	0.01	24	100	3.5	33.1	12.2	0.64	9.3	16.0	23	100	3.0	29.0	11.4	0.46	9.3	13.9
Turbidity	FTU	0.01	24	100	2.0	489.0	218.2	1.40	120.7	394.3	23	100	70.2	2000.0	331.1	0.72	242.2	452.5
Nitrogen; ammonia	mg/L	0.002	24	92	0.00	0.96	0.23	0.21	0.11	0.44	23	100	0.00	1.13	0.48	1.80	0.22	1.05
Nitrogen; nitrite	mg/L	0.001	24	100	0.01	0.27	0.10	0.73	0.07	0.13	23	100	0.04	0.54	0.18	0.66	0.14	0.24
Nitrogen; nitrates	mg/L	0.005	24	100	0.40	3.96	1.84	0.63	1.41	2.40	23	100	0.59	3.90	1.66	0.41	1.39	1.98
Phosphorus; phosphate	mg/L	0.0005	24	100	0.01	0.68	0.08	0.92	0.05	0.11	23	100	0.01	0.25	0.06	0.75	0.05	0.09
Phosphorus; total	mg/L	0.002	24	100	0.01	1.40	0.44	1.21	0.26	0.74	23	100	0.08	2.33	0.58	0.72	0.42	0.79
Nitrogen; total Kjeldahl	mg/L	0.02	24	100	0.20	5.20	1.40	0.80	1.00	1.95	23	100	0.52	6.56	2.53	0.65	1.91	3.35
Mercury	µg/L	0.02	24	33	0.01	0.04	0.02	0.01	0.01	0.02	22	45	0.01	0.08	0.02	0.02	0.02	0.03
Pentachlorophenol	ηg/L	10	24	71	5	120	30	2.68	18	41	22	100	12	76	30	1.69	23	37
Dicamba	ηg/L	50	24	54	25	700	121	2.92	59	183	22	59	25	780	208	3.69	114	301
2,4-D	ηg/L	100	24	75	50	4000	540	3.59	197	883	22	82	50	6500	1190	4.01	473	1906

* RMDL: Reporting Method Detection Limit

***Table D2*:** Outlet during wet weather - entire monitoring period (November 16, 1998 to December 5, 1999).

Parameter	Unit	RMDL*	N	% > DL	MIN	MAX	MEAN	SD	95%CI-LL	95%CI-UL
Oil and grease	mg/L	2.5	18	100	0.5	1.5	1.0	0.43	0.8	1.2
Suspended Solids	mg/L	2.5	19	100	3.5	88.0	17.4	0.94	11.1	27.5
Solids; total	mg/L	2.5	19	100	220.0	986.0	552.8	0.53	428.6	713.0
Solids; dissolved	mg/L	4	19	100	192	982	535	0.56	409	701
Aluminum	µg/L	3	19	100	49	530	165	0.71	117	232
Barium	µg/L	0.3	19	100	24.2	51.1	35.6	0.22	32.0	39.7
Beryllium	µg/L	0.020	18	28	0.01	0.12	0.02	0.03	0.01	0.04
Cadmium	µg/L	0.6	18	17	0.30	1.01	0.37	0.20	0.27	0.46
Cobalt	µg/L	1.5	18	6	0.75	2.22	0.83	0.35	0.67	0.99
Chromium	µg/L	1	18	17	0.5	1.7	0.7	0.37	0.5	0.8
Copper	µg/L	0.6	19	100	1.5	57.7	6.3	0.90	4.1	9.7
Iron	µg/L	100	19	100	39.4	479.0	174.1	0.69	124.8	243.1
Manganese	µg/L	0.1	19	100	7.8	164.0	33.5	0.82	22.6	49.6
Molybdenum	µg/L	1.600	18	0	all data below the detection limit					
Nickel	µg/L	1.5	19	39	0.8	3.7	1.2	0.79	0.8	1.6
Lead	µg/L	11	18	0	all data below the detection limit					
Strontium	µg/L	0.3	19	100	181	396	293	0.30	254	338
Titanium	µg/L	0.3	19	100	0.6	7.1	3.4	0.77	2.3	4.9
Vanadium	µg/L	0.9	18	50	0.5	2.7	1.1	0.79	0.7	1.5
Zinc	µg/L	0.6	19	100	4.9	60.4	11.6	0.58	8.8	15.4
Silicon; reactive silicate	mg/L	0.002	18	100	0.0	2.1	0.9	0.90	0.6	1.4
Escherichia Coli	c/100mL	4	10	100	8	490	175	1.55	58	529
Fecal Streptococcus	c/100mL	4	10	100	4	1100	667	2.14	145	3076
Pseudomonas Aeruginosa	c/100mL	4	10	100	2	780	97	1.96	24	396
Carbon; dissolved organic	mg/L	0.1	18	100	2.4	5.3	3.8	0.22	3.4	4.3
Carbon; dissolved inorganic	mg/L	0.2	18	100	17.8	30.0	23.4	0.12	22.0	24.9
Alkalinity; total fixed endpt	mg/L	0.2	18	100	78.5	125.0	99.6	0.12	93.8	105.7
Conductivity	µS/cm	1	18	100	295	1560	852	0.60	633	1147
pH	none	0.1	18	100	7.6	8.3	8.0	0.02	7.9	8.0
Chloride	mg/L	0.2	18	100	30.2	387.0	175.7	0.91	111.6	276.7
Calcium	mg/L	0.04	19	100	44.0	85.2	59.9	0.20	54.4	65.9
Magnesium	mg/L	0.01	19	100	6.8	18.5	12.7	0.32	10.8	14.8
Turbidity	FTU	0.01	18	100	1.9	93.0	13.8	1.10	8.0	23.9
Nitrogen; ammonia	mg/L	0.002	18	100	0.01	0.19	0.08	0.75	0.06	0.12
Nitrogen; nitrite	mg/L	0.001	18	100	0.01	0.07	0.03	0.45	0.03	0.04
Nitrogen; nitrates	mg/L	0.005	18	100	0.22	1.28	0.69	0.51	0.53	0.89
Phosphorus; phosphate	mg/L	0.0005	18	100	0.00	0.06	0.02	1.34	0.01	0.03
Phosphorus; total	mg/L	0.002	19	100	0.03	0.26	0.07	0.59	0.05	0.09
Nitrogen; total Kjeldahl	mg/L	0.02	19	100	0.52	1.60	0.77	0.27	0.67	0.87
Mercury	µg/L	0.02	17	0	all data below the detection limit					
Pentachlorophenol	ηg/L	10	17	29	5	34	11	2.08	6	15
Dicamba	ηg/L	50	17	76	25	260	128	2.37	90	166
2,4-D	ηg/L	100	17	29	50	540	138	2.47	57	218

*RMDL: Reporting Method Detection Limit

Table D3: Inlets during wet weather - summer/fall period (November 1 to November 30, 1998; May 1, 1999 to November 31,1999) .

							Inlet 1								Inlet 2			
Parameter	Unit	RMDL*	N	%>D.L.	MIN	MAX	MEAN	SD	95%CI-LL	95%CI-UL	N	%>D.L.	MIN	MAX	MEAN	SD	95%CI-LL	95%CI-UL
Oil and grease	mg/L	2.5	15	100	1.0	13.0	3.6	0.78	2.3	5.6	17	100	1.5	15.0	7.3	0.57	5.4	9.7
Suspended Solids	mg/L	2.5	15	100	13.0	725.0	271.4	1.19	140.4	524.5	17	100	79.0	1780.0	398.4	0.74	272.0	583.4
Solids; total	mg/L	2.5	15	100	344.0	976.0	620.4	0.32	519.6	740.9	17	100	390.0	2250.0	785.4	0.40	639.7	964.3
Solids; dissolved	mg/L	4	15	100	80	962	400	0.79	258	619	17	100	110	662	395	0.50	306	510
Aluminum	µg/L	3	15	100	56	1870	826	0.88	508	1343	17	100	297	3210	1177	0.62	857	1616
Barium	µg/L	0.3	15	100	36.2	82.6	55.0	0.23	48.6	62.3	17	100	33.7	181.0	69.9	0.38	57.6	84.8
Beryllium	µg/L	0.02	15	100	0.02	0.20	0.09	0.81	0.06	0.14	17	100	0.03	0.57	0.14	0.68	0.10	0.20
Cadmium	µg/L	0.6	15	67	0.30	2.87	0.63	0.66	0.29	0.96	17	35	0.30	2.85	0.68	0.75	0.32	1.04
Cobalt	µg/L	1.5	15	40	0.75	3.70	1.48	1.04	0.96	2.01	17	1	0.75	8.35	2.05	1.86	1.17	2.93
Chromium	µg/L	1	15	93	0.5	4.9	2.5	1.29	1.8	3.1	17	100	1.1	17.3	5.9	0.73	4.0	8.6
Copper	µg/L	0.6	15	100	3.6	33.4	13.1	0.55	9.6	17.7	17	100	5.6	133.0	25.3	0.75	17.2	37.1
Iron	µg/L	100	15	100	84.6	2070.0	730.1	0.87	449.8	1185.2	17	100	297.0	14500.0	1393.7	0.93	862.9	2251.1
Manganese	µg/L	0.1	15	100	5.8	330.0	177.7	1.22	90.5	348.9	17	100	0.1	2.0	1.1	1.07	0.4	2.6
Molybdenum	µg/L	1.6	6	17	0.8	1.9	1.0	0.43	0.6	1.3	9	24	0.8	2.0	1.3	0.55	0.9	1.6
Nickel	µg/L	1.5	15	87	0.8	5.1	2.7	1.31	2.1	3.4	17	94	0.8	25.0	5.4	5.39	2.8	7.9
Lead	µg/L	11	15	27	5.5	15.4	7.8	1.52	5.8	9.8	17	59	5.5	105.0	17.2	2.24	5.9	28.5
Strontium	µg/L	0.3	15	100	160	609	296	0.48	228	386	17	100	103	618	287	0.36	239	345
Titanium	µg/L	0.3	15	93	0.2	14.2	4.3	3.63	2.4	6.1	17	94	0.2	21.8	7.7	6.44	4.6	10.7
Vanadium	µg/L	0.9	15	93	0.5	6.5	2.9	1.45	2.2	3.7	17	100	2.8	24.6	7.7	0.52	5.9	10.1
Zinc	µg/L	0.6	15	100	6.3	149.0	66.3	0.89	40.5	108.7	17	100	46.0	667.0	129.1	0.64	93.0	179.2
Silicon; reactive silicate	mg/L	0.002	15	100	0.8	6.9	3.2	0.74	2.1	4.9	17	100	1.1	4.1	2.8	0.31	2.4	3.3
Escherichia Coli	c/100mL	4	10	100	10	16000	7636	1.98	1852	31480	10	100	140	14300	5869	1.63	1831	18810
Fecal Streptococcus	c/100mL	4	10	100	50	33000	22866	1.81	6243	83748	10	100	2680	95000	17628	1.20	7493	41473
P. Aeruginosa	c/100mL	4	10	100	4	15000	11001	2.53	1799	67262	10	100	180	3300	1037	1.00	506	2122
Carbon; diss. organic	mg/L	0.1	15	100	1.6	7.7	4.0	0.43	3.1	5.1	17	100	4.9	28.5	13.0	0.59	9.6	17.6
Carbon; diss. inorg.	mg/L	0.2	15	100	14.8	52.4	30.3	0.41	24.1	38.0	17	100	19.6	39.4	29.2	0.23	25.9	33.0
Alkalinity; fixed endpt.	mg/L	0.2	15	100	45.0	226.0	123.5	0.51	93.1	163.8	17	100	64.0	164.0	116.9	0.23	103.7	131.7
Conductivity	µS/cm	1	15	100	124	1360	592	0.76	388	904	17	100	169	869	596	0.48	465	762
pH	none	0.1	15	100	7.7	8.3	8.0	0.02	7.9	8.1	17	100	7.3	8.1	7.7	0.03	7.6	7.8
Chloride	mg/L	0.2	15	100	7.8	265.0	91.4	1.13	48.9	170.9	17	100	11.4	168.0	103.9	0.80	68.8	156.9
Calcium	mg/L	0.04	15	100	47.1	150.0	93.7	0.34	77.6	113.1	17	100	49.8	319.0	107.4	0.41	86.8	132.9
Magnesium	mg/L	0.01	15	100	6.5	33.1	13.0	0.55	9.6	17.6	17	100	3.0	24.2	10.6	0.45	8.4	13.4
Turbidity	FTU	0.01	15	100	2.0	489.0	270.0	1.46	120.4	605.5	17	100	84.6	2000.0	361.9	0.76	244.8	535.0
Nitrogen; ammonia	mg/L	0.002	15	100	0.00	0.96	0.17	1.67	0.07	0.43	17	100	0.00	1.13	0.71	1.99	0.26	1.98
Nitrogen; nitrite	mg/L	0.001	15	100	0.01	0.27	0.11	0.85	0.07	0.17	17	100	0.04	0.54	0.20	0.70	0.14	0.29
Nitrogen; nitrates	mg/L	0.005	15	100	0.40	3.96	1.94	0.72	1.30	2.89	17	100	0.59	2.68	1.52	0.40	1.24	1.86
Phosphorus; phosphate	mg/L	0.0005	15	100	0.01	0.68	0.09	1.06	0.05	0.16	17	100	0.02	0.25	0.08	0.78	0.05	0.11
Phosphorus; total	mg/L	0.002	15	100	0.01	1.40	0.50	1.38	0.23	1.07	17	100	0.15	2.33	0.66	0.70	0.46	0.95
Nitrogen; total Kjeldahl	mg/L	0.02	15	100	0.20	3.62	1.30	0.85	0.81	2.07	17	100	0.52	6.56	2.77	0.66	1.97	3.89
Mercury	µg/L	0.02	15	13	0.01	0.04	0.01	0.01	0.01	0.02	17	47	0.01	0.08	0.02	0.02	0.01	0.03
Pentachlorophenol	ηg/L	10	15	80	5	120	38	2.60	20	55	17	100	12	60	30	1.60	23	37
Dicamba	ηg/L	50	15	80	25	700	177	2.40	89	265	17	76	25	780	261	3.30	153	370
2,4-D	ηg/L	100	15	73	50	1500	436	2.00	197	675	17	88	50	6500	1355	4.10	448	2262

*RMDL: Reporting Method Detection Limit

***Table D4*:** Forebay during wet weather - summer/fall period (May 1, 1999 to November 30,1999).

Parameter	Unit	RMDL*	N	%>D.L.	MIN	MAX	MEAN	SD	95%CI-LL	95%CI-UL
Oil and grease	mg/L	2.5	10	100	0.5	2.5	1.2	0.56	0.8	1.7
Suspended Solids	mg/L	2.5	11	100	18.0	223.0	85.2	0.85	48.1	151.1
Solids; total	mg/L	2.5	11	100	280.0	624.0	440.0	0.25	371.4	521.4
Solids; dissolved	mg/L	4	11	100	232	584	358	0.29	296	434
Aluminum	µg/L	3	11	100	88	2300	572	0.91	311	1052
Barium	µg/L	0.3	11	100	34.2	56.9	41.7	0.17	37.3	46.6
Beryllium	µg/L	0.02	10	58	0.01	0.12	0.04	0.03	0.02	0.06
Cadmium	µg/L	0.6	11	0		all data below the detection limit				
Cobalt	µg/L	1.5	11	8	0.75	1.59	0.83	0.25	0.68	0.98
Chromium	µg/L	1	11	67	0.5	3.8	1.6	1.02	1.0	2.2
Copper	µg/L	0.6	11	100	2.6	9.1	5.4	0.40	4.1	7.0
Iron	µg/L	100	11	100	108.0	1670.0	525.8	0.86	295.2	936.2
Manganese	µg/L	0.1	11	100	21.1	161.0	71.5	0.61	47.4	107.9
Molybdenum	µg/L	1.6	11	0		all data below the detection limit				
Nickel	µg/L	1.5	11	42	0.8	2.4	1.3	0.69	0.9	1.7
Lead	µg/L	11	11	0		all data below the detection limit				
Strontium	µg/L	0.3	11	100	174	342	270	0.19	238	306
Titanium	µg/L	0.3	11	100	0.4	74.0	4.6	2.88	6.3	24.3
Vanadium	µg/L	0.9	11	92	0.5	6.0	2.4	1.40	1.5	3.2
Zinc	µg/L	0.6	11	100	7.5	31.8	20.1	0.51	14.3	28.4
Silicon; reactive silicate	mg/L	0.002	10	100	0.3	3.8	2.3	0.84	1.2	4.1
Escherichia Coli	c/100mL	4	6	100	10	6400	2500	2.42	197	31761
Fecal Streptococcus	c/100mL	4	6	100	20	11800	11485	2.48	851	154918
P. Aeruginosa	c/100mL	4	6	100	50	16600	6229	2.29	566	68557
Carbon; diss. organic	mg/L	0.1	10	100	3.0	7.5	4.1	0.27	3.4	5.0
Carbon; diss. inorg.	mg/L	0.2	10	100	18.2	31.8	25.3	0.16	22.6	28.3
Alkalinity; fixed endpt.	mg/L	0.2	10	100	82.5	149.0	112.1	0.16	100.2	125.4
Conductivity	µS/cm	1	10	100	358	918	550	0.30	443	683
pH	none	0.1	10	100	7.9	8.2	8.0	0.01	7.9	8.1
Chloride	mg/L	0.2	10	100	41.4	191.0	85.4	0.48	60.5	120.6
Calcium	mg/L	0.04	11	100	48.3	88.6	69.1	0.19	60.7	78.6
Magnesium	mg/L	0.01	11	100	6.3	14.5	11.2	0.28	9.3	13.5
Turbidity	FTU	0.01	10	100	12.4	287.0	91.5	1.03	43.8	191.2
Nitrogen; ammonia	mg/L	0.002	10	100	0.02	0.40	0.16	0.97	0.08	0.32
Nitrogen; nitrite	mg/L	0.001	10	100	0.03	0.14	0.08	0.41	0.06	0.10
Nitrogen; nitrates	mg/L	0.005	10	100	0.01	2.31	0.83	1.58	0.27	2.58
Phosphorus; phosphate	mg/L	0.0005	10	100	0.01	0.13	0.05	0.97	0.03	0.11
Phosphorus; total	mg/L	0.002	10	100	0.06	0.31	0.15	0.53	0.10	0.21
Nitrogen; total Kjeldahl	mg/L	0.02	10	100	0.56	1.34	0.89	0.32	0.71	1.12
Mercury	µg/L	0.02	11	0		all data below the detection limit				
Pentachlorophenol	ηg/L	10	10	82	5	43	23	2.20	15	31
Dicamba	ηg/L	50	10	100	150	380	255	1.30	210	300
2,4-D	ηg/L	100	10	100	100	780	189	2.00	56	322

*RMDL: Reporting Method Detection Limit

Table D5: Wetland and wetpond outlets during wet weather (November 1 to November 31, 1998; May 1, 1999 to November 30,1999).

			Wetpond outlet								Wetland outlet							
Parameter	**Unit**	**RMDL***	**N**	**%>D.L.**	**MIN**	**MAX**	**MEAN**	**SD**	**95%CI-LL**	**95%CI-UL**	**N**	**%>D.L.**	**MIN**	**MAX**	**MEAN**	**SD**	**95%CI-LL**	**95%CI-UL**
Oil and grease	mg/L	2.5	16	100	0.5	7.5	1.5	0.75	1.0	2.2	12	100	0.5	1.5	1.0	0.45	0.7	1.3
Suspended Solids	mg/L	2.5	17	100	9.5	78.0	21.1	0.59	15.6	28.6	13	100	4.5	88.0	23.0	0.90	13.3	39.7
Solids; total	mg/L	2.5	17	100	208.0	798.0	393.7	0.45	312.5	496.0	13	100	220.0	820.0	465.7	0.47	351.1	617.7
Solids; dissolved	mg/L	4	17	100	188	784	372	0.47	291	474	13	100	192	814	443	0.49	329	597
Aluminum	µg/L	3	17	100	55	542	182	0.55	137	241	13	100	53	530	187	0.62	129	272
Barium	µg/L	0.3	17	100	24.2	42.0	31.9	0.19	28.9	35.3	13	100	24.2	51.1	35.0	0.25	30.0	40.7
Beryllium	µg/L	0.02	16	11	0.01	0.04	0.01	0.01	0.01	0.02	12	28	0.01	0.07	0.02	0.02	0.01	0.03
Cadmium	µg/L	0.6	17	28	0.30	3.16	0.70	0.84	0.29	1.11	13	17	0.30	1.01	0.36	0.21	0.24	0.48
Cobalt	µg/L	1.5	17	6	0.75	1.87	0.81	0.26	0.69	0.93	13	6	0.75	2.22	0.86	0.41	0.64	1.09
Chromium	µg/L	1	17	28	0.5	2.0	0.7	0.40	0.5	0.9	13	17	0.5	1.7	0.6	0.38	0.4	0.9
Copper	µg/L	0.6	17	100	1.7	11.7	4.1	0.50	3.1	5.3	13	100	1.5	57.7	8.2	1.09	4.2	15.7
Iron	µg/L	100	17	100	33.1	660.0	181.2	0.62	131.4	249.9	13	100	84.6	479.0	199.5	0.50	147.7	269.4
Manganese	µg/L	0.1	17	100	10.5	73.9	29.2	0.49	22.7	37.6	13	100	14.0	164.0	42.8	0.72	27.7	66.1
Molybdenum	µg/L	1.6	17	0	all data below the detection limit						13	0	all data below the detection limit					
Nickel	µg/L	1.5	17	28	0.8	3.0	1.1	0.69	0.8	1.4	13	39	0.8	3.7	1.3	0.86	0.8	1.7
Lead	µg/L	11	17	0	all data below the detection limit						13	0	all data below the detection limit					
Strontium	µg/L	0.3	17	100	173	367	250	0.24	220	283	13	100	181	384	275	0.30	230	329
Titanium	µg/L	0.3	17	94	0.2	8.5	3.4	2.38	2.3	4.5	13	100	1.2	7.1	3.8	0.52	2.8	5.2
Vanadium	µg/L	0.9	17	83	0.5	2.7	1.4	0.64	1.1	1.7	13	50	0.5	2.6	1.1	0.76	0.7	1.5
Zinc	µg/L	0.6	17	100	3.3	47.2	14.3	2.31	8.2	20.4	13	100	5.2	60.4	14.1	0.62	9.7	20.4
Silicon; reactive silicate	mg/L	0.002	17	83	0.0	1.9	1.0	1.03	0.6	1.8	12	100	0.3	1.4	0.8	0.50	0.5	1.0
Escherichia Coli	:/100ml	4	11	100	4	490	124	1.58	43	360	7	100	20	490	237	1.25	75	752
Fecal Streptococcus	:/100ml	4	11	100	4	1360	521	1.90	145	1866	7	100	100	1100	579	0.91	249	1348
P. Aeruginosa	:/100ml	4	11	100	4	9600	513	2.27	112	2362	7	100	2	780	180	1.90	31	1042
Carbon; diss. organic	mg/L	0.1	17	100	2.7	5.2	3.9	0.18	3.6	4.3	12	100	3.4	5.3	4.3	0.15	3.9	4.7
Carbon; diss. inorg.	mg/L	0.2	17	100	16.4	25.2	20.1	0.11	19.0	21.3	12	100	17.8	26.4	22.9	0.12	21.3	24.6
Alkalinity; fixed endpt.	mg/L	0.2	17	100	73.5	109.0	86.6	0.11	81.8	91.8	12	100	78.5	113.0	97.4	0.11	90.6	104.6
Conductivity	µS/cm	1	17	100	288	1260	579	0.49	450	743	12	100	295	1300	680	0.52	489	945
pH	none	0.1	17	100	7.9	8.2	8.0	0.01	7.9	8.0	12	100	7.6	8.0	7.9	0.02	7.8	8.0
Chloride	mg/L	0.2	17	100	27.6	292.0	98.5	0.74	67.5	143.8	12	100	30.2	279.0	107.9	0.71	68.7	169.3
Calcium	mg/L	0.04	17	100	37.3	64.5	50.1	0.15	46.4	54.1	13	100	44.0	85.2	58.1	0.21	51.2	65.8
Magnesium	mg/L	0.01	17	100	6.2	18.4	11.1	0.34	9.3	13.3	13	100	6.8	18.5	12.1	0.34	9.9	14.8
Turbidity	FTU	0.01	17	100	2.0	42.6	20.6	0.75	14.0	30.3	12	100	3.7	93.0	15.6	0.95	8.5	28.7
Nitrogen; ammonia	mg/L	0.002	17	100	0.00	0.31	0.17	1.36	0.09	0.35	12	100	0.01	0.19	0.10	0.80	0.06	0.16
Nitrogen; nitrite	mg/L	0.001	17	100	0.01	0.11	0.05	0.74	0.03	0.07	12	100	0.01	0.07	0.04	0.49	0.03	0.05
Nitrogen; nitrates	mg/L	0.005	17	100	0.35	1.24	0.85	0.39	0.70	1.04	12	100	0.22	1.18	0.56	0.50	0.41	0.77
Phosphorus; phosphate	mg/L	0.0005	17	100	0.00	0.06	0.02	1.15	0.01	0.04	12	100	0.00	0.06	0.01	0.85	0.01	0.02
Phosphorus; total	mg/L	0.002	17	100	0.02	0.18	0.08	0.45	0.07	0.10	13	100	0.03	0.26	0.08	0.57	0.06	0.11
Nitrogen; total Kjeldahl	mg/L	0.02	17	100	0.24	1.44	0.88	0.43	0.71	1.10	13	100	0.52	1.60	0.82	0.31	0.68	0.99
Mercury	µg/L	0.02	16	0	all data below the detection limit						12	0	all data below the detection limit					
Pentachlorophenol	ηg/L	10	16	63	5	760	105	5.24	4	206	12	29	5	34	10	2.05	5	15
Dicamba	ηg/L	50	16	88	25	230	162	2.04	128	196	12	76	25	260	159	1.96	118	200
2,4-D	ηg/L	100	16	19	50	470	86	1.83	34	138	12	29	50	540	133	2.48	37	230

*RMDL: Reporting Method Detection Limit

***Table D6*:** Inlets during wet weather - winter/spring period (December 1, 1998 to April 30, 1999).

			Inlet 1								Inlet 2							
Parameter	Unit	RMDL*	N	% > D.L.	MIN	MAX	MEAN	SD	95%CI-LL	95%CI-UL	N	%>D.L.	MIN	MAX	MEAN	SD	95%CI-LL	95%CI-UL
Oil and grease	mg/L	2.5	9	100	1.0	14.0	4.7	0.85	2.5	9.1	6	100	3.0	16.0	10.0	0.60	5.3	18.8
Suspended Solids	mg/L	2.5	9	100	11.0	428.0	290.1	1.36	101.7	827.5	6	100	213.0	421.0	293.5	0.28	219.0	393.3
Solids; total	mg/L	2.5	9	100	324.0	3430.0	1512.1	0.82	802.5	2849.1	6	100	736.0	5900.0	1738.4	0.77	777.0	3889.1
Solids; dissolved	mg/L	4	9	100	148	3420	1389	1.17	566	3412	6	100	356	5690	1437	0.95	531	3886
Aluminum	µg/L	3	9	100	69	2190	939	1.10	404	2178	6	100	470	1830	1216	0.68	593	2493
Barium	µg/L	0.3	9	100	24.6	82.3	56.4	0.49	38.7	82.1	6	100	49.5	122.0	79.9	0.30	58.2	109.8
Beryllium	µg/L	0.02	9	89	0.01	0.24	0.08	0.08	0.03	0.14	6	100	0.07	0.24	0.12	0.47	0.07	0.20
Cadmium	µg/L	0.6	9	56	0.30	2.02	0.84	0.62	0.43	1.24	6	100	0.55	3.05	1.35	0.61	0.71	2.54
Cobalt	µg/L	1.5	9	22	0.75	3.29	1.12	0.85	0.56	1.68	6	80	0.75	3.53	2.20	1.08	1.25	3.14
Chromium	µg/L	1	9	78	0.5	9.0	3.8	2.54	2.1	5.4	6	100	3.6	21.2	11.1	0.63	5.7	21.6
Copper	µg/L	0.6	9	100	6.4	31.6	14.6	0.52	9.8	21.7	6	100	15.5	52.0	29.5	0.43	18.8	46.3
Iron	µg/L	100	9	100	184.0	2110.0	980.1	0.90	490.9	1956.8	6	100	468.0	3630.0	1690.6	0.86	686.6	4163.0
Manganese	µg/L	0.1	9	100	18.8	318.0	146.3	0.96	69.8	306.8	6	100	156.0	385.0	259.8	0.36	178.1	378.9
Molybdenum	µg/L	1.6	4	0	all data below the detection limit						6	0	all data below the detection limit					
Nickel	µg/L	1.5	9	89	0.8	6.2	3.0	1.68	1.9	4.1	6	100	2.7	8.7	5.2	0.51	3.0	8.9
Lead	µg/L	11	5	78	5.5	56.6	19.8	2.10	9.8	29.8	6	100	12.6	70.8	30.9	0.61	2.0	58.9
Strontium	µg/L	0.3	9	100	124	571	318	0.55	209	484	6	100	258	663	411	0.33	291	580
Titanium	µg/L	0.3	9	89	0.2	15.5	7.7	4.95	4.5	11.0	6	100	2.1	45.3	20.4	1.17	6.0	69.6
Vanadium	µg/L	0.9	9	89	0.5	6.1	3.0	1.79	1.9	4.2	6	100	2.6	15.2	9.6	0.67	4.7	19.4
Zinc	µg/L	0.6	9	100	21.2	196.0	74.3	0.77	41.1	134.5	6	100	88.3	413.0	182.9	0.55	102.8	325.4
Silicon; reactive silicate	mg/L	0.002	9	100	0.8	6.3	2.4	0.65	1.5	4.0	6	100	2.6	5.8	3.7	0.27	2.8	5.0
Escherichia Coli	c/100mL	4	3	100	520	3100	1876	0.89	204	17242	3	100	700	2700	1497	0.76	224	9986
Fecal Streptococcus	c/100mL	4	3	100	760	4400	3808	0.98	333	43552	3	100	420	3500	2673	1.10	172	41604
Pseudomonas Aeruginosa	c/100mL	4	3	100	20	50	31	0.53	8	116	3	100	10	20	14	0.40	5	37
Carbon; dissolved organic	mg/L	0.1	9	100	0.8	7.3	3.5	0.79	1.9	6.4	6	100	1.9	12.0	8.6	0.82	3.6	20.3
Carbon; dissolved inorganic	mg/L	0.2	9	100	12.2	53.8	25.4	0.49	17.5	37.0	6	100	23.4	55.6	36.0	0.28	26.7	48.4
Alkalinity; total fixed endpt.	mg/L	0.2	9	100	55.5	232.0	109.7	0.47	76.4	157.4	6	100	110.0	234.0	149.9	0.27	113.4	198.0
Conductivity	µS/cm	1	9	100	226	5920	2445	1.23	949	6299	6	100	548	9800	2357	0.99	836	6642
pH	none	0.1	9	100	7.8	8.8	8.1	0.04	7.8	8.3	6	100	7.7	8.1	7.9	0.02	7.7	8.1
Chloride	mg/L	0.2	8	100	26.2	1800.0	570.2	1.54	157.2	2068.4	6	100	69.0	3540.0	696.1	1.31	175.5	2760.2
Calcium	mg/L	0.04	9	100	39.5	147.0	86.3	0.49	59.1	125.9	6	100	74.7	209.0	122.5	0.33	86.3	174.0
Magnesium	mg/L	0.01	9	100	3.5	26.8	10.9	0.77	6.0	19.6	6	100	8.2	29.0	13.7	0.44	8.6	21.7
Turbidity	FTU	0.01	9	100	6.0	343.0	164.4	1.36	58.0	466.2	6	100	70.2	485.0	261.9	0.63	135.0	508.0
Nitrogen; ammonia	mg/L	0.002	9	100	0.01	0.47	0.29	1.33	0.10	0.79	6	100	0.02	0.71	0.19	1.30	0.05	0.74
Nitrogen; nitrite	mg/L	0.001	9	100	0.04	0.23	0.09	0.52	0.06	0.13	6	100	0.06	0.24	0.13	0.50	0.08	0.22
Nitrogen; nitrates	mg/L	0.005	9	100	0.66	3.33	1.72	0.50	1.17	2.52	6	100	1.41	3.90	2.07	0.38	1.39	3.10
Phosphorus; phosphate	mg/L	0.0005	9	100	0.02	0.16	0.06	0.70	0.04	0.11	6	100	0.01	0.05	0.03	0.44	0.02	0.05
Phosphorus; total	mg/L	0.002	9	100	0.07	0.94	0.38	0.93	0.19	0.78	6	100	0.08	0.43	0.36	0.65	0.18	0.71
Nitrogen; total Kjeldahl	mg/L	0.02	9	100	0.56	5.20	1.58	0.70	0.92	2.72	6	100	0.54	2.80	1.95	0.61	1.03	3.68
Mercury	µg/L	0.02	9	6	0.01	0.04	0.02	0.01	0.01	0.03	5	60	0.01	0.04	0.02	0.01	0.01	0.04
Pentachlorophenol	ηg/L	10	9	56	5	30	16	2.38	9	23	5	100	14	76	31	25.65	2	54
Dicamba	ηg/L	50	9	11	25	52	28	1.58	22	34	5	0	all data below the detection limit					
2,4-D	ηg/L	100	9	78	50	4000	713	3.32	-129	1556	5	80	50	1500	628	606.77	4	1160

*RMDL: Reporting Method Detection Limit

Table D7 : Wetand outlet during wet weather - winter/spring period (December 1, 1998 to April 30, 1999).

Parameter	Unit	RMDL*	N	%>D.L	MIN	MAX	MEAN	SD	95%CI-LL	95%CI-UL
Oil and Grease	mg/L	2.5	6	100	0.5	1.5	0.9	0.44	0.6	1.5
Suspended Solids	mg/L	2.5	6	100	3.5	18.5	7.1	0.66	3.5	14.3
Solids; total	mg/L	2.5	6	100	274.0	986.0	764.6	0.56	424.2	1378.1
Solids; dissolved	mg/L	4	6	100	256	982	761	0.58	412	1405
Aluminum	µg/L	3	6	100	49	374	115	0.77	51	260
Barium	µg/L	0.3	6	100	30.8	43.0	37.2	0.14	32.0	43.1
Beryllium	µg/L	0.02	6	40	0.01	0.12	0.04	0.05	0.00	0.08
Cadmium	µg/L	0.6	6	20	0.30	0.75	0.39	0.20	0.21	0.57
Cobalt	µg/L	1.5	5	0	all data below the detection limit					
Chromium	µg/L	1	6	20	0.5	1.4	0.7	0.39	0.3	1.0
Copper	µg/L	0.6	6	100	3.0	4.3	3.7	0.12	3.2	4.2
Iron	µg/L	100	6	100	39.4	354.0	107.7	0.78	47.5	244.4
Manganese	µg/L	0.1	6	100	7.8	36.8	14.1	0.56	7.8	25.4
Molybdenum	µg/L	1.600	5	0	all data below the detection limit					
Nickel	µg/L	1.5	6	20	0.8	2.1	1.0	0.60	0.5	1.5
Lead	µg/L	11	5	0	all data below the detection limit					
Strontium	µg/L	0.3	6	100	201	396	332	0.27	251	440
Titanium	µg/L	0.3	6	100	0.6	6.8	2.1	0.93	0.8	5.7
Vanadium	µg/L	0.9	5	40	0.5	2.7	1.1	0.96	0.2	1.9
Zinc	µg/L	0.6	6	100	4.9	9.3	7.0	0.26	5.3	9.2
Silicon; reactive silicate	mg/L	0.002	6	100	0.0	2.1	1.3	1.44	0.3	5.8
Escherichia Coli	c/100mL	4	3	100	8	12	10	0.20	6	17
Fecal Streptococcus	c/100mL	4	3	100	4	18	10	0.87	1	83
Pseudomonas Aeruginosa	c/100mL	4	3	100	2	4	3	0.40	1	7
Carbon; dissolved organic	mg/L	0.1	6	100	2.4	3.3	3.0	0.12	2.6	3.4
Carbon; dissolved inorganic	mg/L	0.2	6	100	20.6	30.0	24.4	0.14	21.2	28.1
Alkalinity; total fixed endpt	mg/L	0.2	6	100	86.0	125.0	104.1	0.13	90.7	119.6
Conductivity	µS/cm	1	6	100	392	1560	1241	0.62	650	2370
pH	none	0.1	6	100	8.0	8.3	8.1	0.02	8.0	8.2
Chloride	mg/L	0.2	6	100	41.8	387.0	325.5	1.02	111.6	949.1
Calcium	mg/L	0.04	6	100	45.1	72.3	63.9	0.18	53.2	76.8
Magnesium	mg/L	0.01	6	100	8.1	16.9	13.9	0.28	10.4	18.7
Turbidity	FTU	0.01	6	100	1.9	54.7	9.6	1.25	2.6	35.8
Nitrogen;ammonia	mg/L	0.002	6	100	0.02	0.12	0.06	0.61	0.03	0.11
Nitrogen;nitrite	mg/L	0.001	6	100	0.02	0.07	0.03	0.40	0.02	0.05
Nitrogen;nitrates	mg/L	0.005	6	100	0.60	1.28	0.92	0.27	0.70	1.22
Phosphorus;phosphate	mg/L	0.0005	6	100	0.00	0.05	0.01	1.72	0.00	0.06
Phosphorus;total	mg/L	0.002	6	100	0.03	0.10	0.04	0.48	0.03	0.07
Nitrogen;total Kjeldahl	mg/L	0.02	6	100	0.56	0.70	0.66	0.08	0.60	0.72
Mercury	µg/L	0.02	5	0	all data below the detection limit					
Pentachlorophenol	ηg/L	10	5	62.5	5	24	12	2.17	4	20
Dicamba	ηg/L	50	5	40	25	110	53	2.22	18	88
2,4-D	ηg/L	100	5	40	50	480	148	2.95	-16	312

*RMDL: Reporting Method Detection Limit

***Table D8*:** Inlets during dry weather - entire monitoring period (November 16, 1998 to December 5, 1999)

			Inlet 1								Inlet 2							
Parameter	**Unit**	**RMDL**	**N**	**% > dl**	**MIN**	**MAX**	**MEAN**	**STD. DEV**	**95%CI -LL**	**95%CI -UL**	**N**	**% > dl**	**MIN**	**MAX**	**MEAN**	**STD. DEV.**	**95%CI -LL**	**95%CI -UL**
Chloride	mg/l	0.2	4	100	137	485	267.6	1.82	148.4	482.4	4	100	190	613	265.8	1.75	153.7	459.5
Suspended Solids	mg/l	2.5	4	100	52.5	286	108.9	2.07	53.4	222.0	4	100	6	421	39.5	7.98	5.2	302.0
Total Solids	mg/l	2.5	4	100	802	1160	956.1	1.21	794.2	1151.0	4	100	710	1290	963	1.40	692	1341
Dissolved Solids	mg/l	4	4	100	724	966	827.9	1.14	730.3	938.5	4	100	704	1170	847	1.26	673	1065
Oil and grease	mg/l	2.5	4	100	0.5	4	1.3	3.08	0.4	4.0	4	100	0.5	6	1.6	3.77	0.4	5.8
Conductivity	µs/S	1	4	100	864	1820	1298.8	1.39	940.1	1794.4	4	100	938	2180	1322.9	1.43	931.7	1878.3
pH	none	0.1	4	100	7.83	7.98	7.9	1.01	7.9	8.0	4	100	7.77	8.34	8.1	1.03	7.9	8.4
Alkalinity	mg/l as $CaCO_3$	0.2	4	100	89	223	148.5	1.59	94.3	234.0	4	100	103	236	188	1.50	127	279
Turbidity	FTU	0.01	4	100	67.7	284	114.6	1.96	59.3	221.4	4	100	5.2	125	26.4	4.53	6.0	115.9
Nitrogen, (NH3+NH4)	mg/l	0.002	4	100	0.001	0.144	0.014	8.82	0.002	0.115	4	100	0.001	0.154	0.019	8.30	0.002	0.150
Nitrogen, nitrite	mg/l	0.001	4	100	0.007	0.122	0.030	4.01	0.008	0.116	4	100	0.011	0.08	0.03	2.76	0.01	0.08
Nitrogen, NO3+NO2	mg/l	0.005	4	100	1.18	4.97	2.3	2.00	1.2	4.6	4	100	0.835	3.9	1.84	1.89	0.99	3.43
Phosphorus, phosphate	mg/l	0.0005	4	100	0.003	0.104	0.017	5.60	0.003	0.090	4	100	0.015	0.051	0.03	1.74	0.01	0.04
Total Phosphorus	mg/l	0.002	4	100	0.026	0.38	0.11	3.22	0.04	0.35	4	100	0.038	0.43	0.11	3.24	0.04	0.36
Nitrogen, total Kjedhal	mg/l	0.02	4	100	0.24	1.6	0.6	2.21	0.3	1.3	4	100	0.44	1.6	0.7	1.83	0.4	1.3
Carbon,diss org.	mg/l	0.1	4	100	1.5	2.8	2.0	1.31	1.5	2.6	4	100	2.2	4.1	3.0	1.36	2.3	4.1
Carbon, diss. inorg.	mg/l	0.2	4	100	20.2	53	35.0	1.63	21.7	56.4	4	100	23.6	56	43.6	1.51	29.1	65.5
Silicon	mg/l	0.002	4	100	1.74	7.24	3.85	2.03	1.92	7.71	4	100	2.3	5.76	4.3	1.52	2.8	6.5
E.coli	c./100ml	4	2	100	260	680	486.2	1.72	229.2	1031.2	3	100	40	700	167	7.57	10	2765
F. streptococcus	c./100ml	4	2	100	990	2800	1854.3	1.74	862.5	3986.5	3	100	200	420	290	1.69	140	600
P. aeruginosa	c./100ml	4	2	100	8	40	18.6	2.24	6.1	56.8	3	100	10	80	28	4.35	4	217
Aluminum	mg/l	3	4	100	170	978	401.6	2.35	173.6	929.5	4	100	133	1090	347	2.65	134	900
Barium	mg/l	0.3	4	100	44.3	74.7	59.3	1.28	46.4	75.8	4	100	50.6	82.6	60	1.25	48	74
Beryllium	mg/l	0.02	4	100	0.0195	0.102	0.1	2.06	0.0	0.1	4	100	0.029	0.0833	0.1	1.71	0.0	0.1
Calcium	mg/l	0.04	4	100	67.8	150	106.5	1.44	74.5	152.3	4	100	79.7	209	123.0	1.50	82.5	183.4
Cadmium	mg/l	0.6	4	50	0.3	1.62	0.6	2.36	0.3	1.4	4	25	0.3	1.4	0.4	2.16	0.2	0.9
Chromium	mg/l	1	4	50	0.5	4.54	1.5	3.50	0.4	5.0	4	75	0.5	6.86	2.0	3.18	0.6	6.1
Copper	mg/l	0.6	4	100	1.84	18.1	6.1	3.10	2.0	18.4	4	100	2.85	20.3	8.6	2.74	3.2	23.1
Iron	mg/l	100	4	100	125	1360	352.0	3.26	110.7	1119.5	4	100	98.4	1600	329	3.97	85	1272
Magnesium	mg/l	0.01	4	100	6.07	30.4	13.2	2.35	5.7	30.4	4	100	6.56	29	16.4	1.89	8.8	30.6
Manganese	mg/l	0.1	4	100	18.1	169	54.3	3.06	18.1	162.6	4	100	6.59	180	45.6	4.98	9.5	219.9
Strontium	mg/l	0.3	4	100	254	602	401.9	1.54	264.0	611.9	4	100	317	663	411.1	1.39	298.2	567.0
Titanium	mg/l	0.3	4	100	0.341	19.5	3.8	6.42	0.6	23.5	4	100	2.26	30.9	10.6	3.43	3.2	35.6
Vanadium	mg/l	0.9	4	100	0.45	4.25	1.5	2.91	0.5	4.4	4	100	0.939	6.08	2.2	2.25	1.0	4.8
Zinc	mg/l	0.6	4	100	6.66	85	22.2	3.70	6.2	80.0	4	100	8.17	88.3	29.7	3.14	9.7	91.0

Note: all sample concentrations of cobalt, lead, nickel, molybdenum, mercury and organics were below analytical detection limits. *RMDL:Reporting Method Detection Limit

Table D9: Wetland outlet during dry weather - entire monitoring period (November 16, 1998 to December 5, 1999)

					Wetland outlet					
Parameter	**Unit**	**RMDL**	**N**	**% > DL**	**MIN**	**MAX**	**MEAN**	**STD. DEV.**	**95%CI -LL**	**95%CI -UL**
Chloride	mg/l	0.2	4	100	25.8	516	121.6	4.51	27.8	532.0
Suspended Solids	mg/l	2.5	4	100	4	22.5	10.1	2.04	5.0	20.2
Total Solids	mg/l	2.5	4	100	204	1080	487.7	2.29	217.0	1096.3
Dissolved Solids	mg/l	4	4	100	192	1060	473.1	2.33	206.1	1086.0
Oil and grease	mg/l	2.5	4	25	0.5	1.5	0.7	1.73	0.4	1.1
Conductivity	µs/S	1	4	100	296	1960	788	2.55	314	1974
pH	none	0.1	4	100	7.92	8.18	8.1	1.02	8.0	8.2
Alkalinity	mg/l as $CaCO_3$	0.2	4	100	98.5	113	105	1.06	99	111
Turbidity	FTU	0.01	4	100	2.66	28.6	11.1	2.79	4.1	30.3
Nitrogen, (NH3+NH4)	mg/l	0.002	4	100	0.018	0.116	0.05	2.20	0.03	0.12
Nitrogen, nitrite	mg/l	0.001	4	100	0.014	0.102	0.04	2.35	0.02	0.09
Nitrogen, NO3+NO2	mg/l	0.005	4	100	0.911	1.84	1.17	1.38	0.85	1.60
Phosphorus, phosphate	mg/l	0.0005	4	100	0.0005	0.041	0.009	7.85	0.001	0.071
Total Phosphorus	mg/l	0.002	4	100	0.032	0.1	0.07	1.65	0.04	0.11
Nitrogen, total Kjedhal	mg/l	0.02	4	100	0.6	0.9	0.7	1.20	0.6	0.8
Carbon,diss org.	mg/l	0.1	4	100	1.6	3.7	2.7	1.49	1.8	3.9
Carbon, diss. inorg.	mg/l	0.2	4	100	22.4	26	24.3	1.06	22.9	25.8
Silicon	mg/l	0.002	4	100	0.26	2.18	0.8	2.70	0.3	2.2
E.coli	c./100ml	4	2	100	10	70	26.5	3.96	3.9	178.1
F. streptococcus	c./100ml	4	2	100	30	130	62.4	2.82	14.8	262.8
P. aeruginosa	c./100ml	4	2	100	4	10	6.3	1.91	2.6	15.5
Aluminum	mg/l	3	4	100	52.8	548	209	2.71	79	554
Barium	mg/l	0.3	4	100	24.2	41	32.0	1.33	24.2	42.2
Beryllium	mg/l	0.02	4	100	0.01	0.03	0.020	1.64	0.013	0.034
Calcium	mg/l	0.04	4	100	45.2	72.3	57.8	1.23	47.2	70.8
Cadmium	mg/l	0.6	4	25	0.3	0.698	0.4	1.53	0.2	0.6
Chromium	mg/l	1	4	100	1.18	1.61	1.4	1.15	1.3	1.7
Copper	mg/l	0.6	4	100	2.52	7.27	3.6	1.63	2.3	5.9
Iron	mg/l	100	4	100	39.4	417	173.0	2.78	63.4	471.7
Magnesium	mg/l	0.01	4	100	5.58	15.2	8.6	1.52	5.7	13.0
Manganese	mg/l	0.1	4	100	10.9	35.1	15.0	1.77	8.6	26.2
Strontium	mg/l	0.3	4	100	164	382	256	1.46	176	372
Titanium	mg/l	0.3	4	100	0.569	21	4.8	4.67	1.1	21.9
Vanadium	mg/l	0.9	4	50	0.45	1.96	0.8	2.04	0.4	1.6
Zinc	mg/l	0.6	4	100	6.31	17.2	9.0	1.56	5.8	13.9

Note: all sample concentrations of cobalt, lead, nickel, molybdenum, mercury and organics were below analytical detection limits. *RMDL:Reporting Method Detection Limit

APPENDIX E

Removal Efficiencies

Table E1 : Load-based removal efficiencies at the forebay outlet for the summer/fall period (May to November, 1999)

Parameter/ Storm Date	**May 24, 1999**	**June 1, 1999**	**June 25, 1999**	**September 6, 1999**	**September 13, 1999**	**October 22, 1999**	**November 26, 1999**	**Overall Load-based Efficiency**
Chloride	0	-17	-46	-36	26	-54		-22
TSS	-6	79	70	89	88	96	48	79
Total Solids	26	43	23	63	50	54	-3	40
Dissolved Solids	27	-22	-32	-41	31	-52	-71	-14
Solvent Extractable	32	82	85	71	54	82		75
Conductivity	17	-22	-49	-42	31	-52		-19
Turbidity	-2	52	46	88	91	95		74
(NH_3+NH_4) - N	-18	-56	58	36	-714	47		28
NO_2-N	0	15	72	64	-12	65		56
(NO_3+NO_2) - N	57	-1	26	-16	53	-59		26
Phosphorus, phosphate	-58	62	41	79	85	85		61
Total Phosphorus	-113	74	66	85	74	89		76
TKN	-82	49	52	73	36	73		53
DOC	28	40	67	46	22	32		52
DIC	43	-3	11	0	34	-35		14
Silicon	66	14	77	-10	46	-77		42
E.coli	-435	59		53	97			51
F. streptococcus	-161	96		57	99			90
P. aeruginosa	-522	70		-80	96			-21
Aluminum	-17	41	50	69	86	80	43	56
Barium	30	29	20	56	49	43	16	35
Beryllium	24	56	60	83	88	94	57	70
Calcium	48	36	28	62	41	26	-13	41
Cadmium	-233	52	100	74	100	45	65	63
Cobalt	2	62	56	87	51	71	43	69
Chromium	53	29	51	86	70	81	45	63
Copper	-8	45	72	91	77	75	54	75
Iron	-3	29	38	86	87	68	33	73
Magnesium	45	-6	-37	7	35	-57	-77	0
Manganese	-32	68	70	89	75	85	49	78
Nickel	43	47	46	85	81	83	41	67
Lead	2	52	53	90	43	2	33	71
Strontium	41	-3	-23	16	33	-42	-59	4
Titanium	-44	-41	-43	-461	62	-29	-126	-93
Vanadium	28	51	52	78	79	49	47	63
Zinc	17	74	78	91	88	92	63	83

***Table E2*:** Load-based removal efficiencies at the wet pond outlet for the summer/fall period (May to November, 1999)

Parameter/ Storm Date	May 8, 1999	May 18, 1999	May 24, 1999	June 1, 1999	June 25, 1999	August 6, 1999	September 6, 1999	September 13, 1999	October 22, 1999	November 2, 1999	November 26, 1999	Overall Load-based Efficiency
Chloride	-81	-144	-32	-180	-42	-22	9	18	35	29	-51	-35
TSS	95	93	76	97	87	95	93	95	97	89	93	92
Total Solids	14	-15	16	17	31	45	74	55	75	50	39	42
Dissolved Solids	-12	-60	13	-126	-33	9	-5	34	21	13	-34	-13
Solvent Extractable	80	86	73	91	55	69	100	70	83	86	37	77
Conductivity	-31	-60	-1	-135	-51	9	-5	34	21	14	-34	-20
Turbidity	94	93	81	5	81	96	97	95	93	87	86	84
(NH_3+NH_4) - N	100	78	67	-87	24	-6132	-46	-468	74	76	-534	44
NO_2-N	87	80	54	-35	86	51	84	65	62	69	40	67
(NO_3+NO_2) - N	53	51	72	-6	48	61	61	80	17	30	-43	46
Phosphorus, phosphate	99	93	75	79	80	86	92	87	88	37	74	76
Total Phosphorus	80	83	30	96	79	72	88	76	87	79	75	83
TKN	72	57	3	87	57	16	69	23	75	12	0	48
DOC	77	71	50	28	69	3	64	16	34	44	24	52
DIC	58	41	55	1	22	35	34	50	20	29	5	31
Silicon	72	87	91	64	86	79	73	80	15	99	66	82
E.coli			93	100		99	96	97		96		97
F. streptococcus			99	100		100	95	100		98		99
P. aeruginosa			97	100		98	-3	100		94		50
Aluminum	85	87	71	89	77	86	79	92	76	71	84	80
Barium	39	28	33	33	35	48	64	59	68	49	50	47
Beryllium	89	88	65	92	71	87	89	88	95	87	93	85
Calcium	54	35	52	38	38	54	77	53	60	42	29	52
Cadmium	-133	-179		-13	7	17	40	32	57	-28	-69	-30
Cobalt	61	53	5	61	58	50	87	52	72	30	45	62
Chromium	76	90	54	87	87	83	90	88	82	57	50	80
Copper	73	81	48	72	78	80	93	85	80	78	68	84
Iron	90	89	81	88	69	78	91	90	61	71	79	86
Magnesium	3	-17	32	-70	-35	14	28	35	32	-16	-28	-2
Manganese	78	87	61	94	78	85	92	83	91	83	91	88
Nickel	69	76	44	75	47	71	79	81	83	29	77	65
Lead	42	64	5	51	54	13	90	44	5	5	35	60
Strontium	8	-7	29	-38	-21	37	35	40	30	-20	-21	8
Titanium	76	62	96	58	21	46	-394	77	-185	64	2	45
Vanadium	94	86	44	60	69	64	84	92	50	71	63	73
Zinc	93	88	78	89	87	93	87	92	93	90	61	87

Table E3: Load-based and mean concentration-based removal efficiencies at the wetland outlet for the summer/fall period (May to November, 1999)

Parameter/ Storm Date	May 8, 1999	May 18, 1999	May 24, 1999	June 1, 1999	June 25, 1999	August 6, 1999	September 13, 1999	October 22, 1999	November 26, 1999	Overall Load-based Efficiency	Average Concentration-based Efficiency
Chloride	-66	-128	-15	-269	-40	-16	20	31	-39	-60	-61
TSS	97	95	-17	98	96	98	97	97	96	95	95
Total Solids	7	-12	18	1	38	48	55	74	45	29	27
Dissolved Solids	-23	-57	20	-170	-27	11	34	17	-23	-22	-19
Solvent Extractable	80	86	61	80	93	38	71	83	69	80	76
Conductivity	-37	-60	7	-165	-44	10	34	17	-23	-30	-27
Turbidity	96	97	30	97	93	99	98	97	95	95	95
(NH_3+NH_4) - N	75	49	61	-210	39		-93	98	-218	22	52
NO_2-N	82	71	55	49	81	28	83	73	66	69	68
(NO_3+NO_2) - N	91	77	80	29	52	77	88	23	-17	64	66
Phosphorus, phosphate	92	81	68	93	91	86	89	94	58	89	89
Total Phosphorus	88	85	41	93	87	83	77	92	82	87	86
TKN	61	48	13	58	70	16	47	69	36	55	50
DOC	66	63	44	12	68	-9	15	28	22	46	36
DIC	32	26	50	-11	23	29	46	6	11	26	26
Silicon	83	83	90	72	82	78	79	37	76	81	78
E.coli			66	97		59	83			79	82
F. streptococcus			51	100		91	97			99	99
P. aeruginosa			99	100		99	71			99	93
Aluminum	87	86	-8	86	89	90	95	80	86	86	84
Barium	30	22	13	23	45	54	59	69		40	40
Beryllium	89	89	-145	91	93	91	89	95		85	84
Calcium	42	30	45	31	47	54	52	58		45	43
Cadmium	67	74	-95	-21	59	18	33	58	-64	29	39
Cobalt	61	54	7	58	59	50	53	72	46	53	52
Chromium	91	91	55	86	87	84	88	82	71	84	83
Copper	85	82	100	85	85	83	86	55	86	85	80
Iron	84	85	25	81	85	80	90	68	81	81	79
Magnesium	-2	-15	34	-100	-19	19	37	30	-14	-3	5
Manganese	54	71	-44	87	90	90	86	94	93	86	81
Nickel	86	76	-30	74	59	72	82	19	78	62	59
Lead	41	65	7	48	55	33	46	7	37	44	39
Strontium	1	-8	24	-65	-5	39	41	28	-10	7	9
Titanium	74	60	33	17	25	48	75		-26	34	34
Vanadium	94	94	-21	88	73	86	81	55	74	75	74
Zinc	91	90	28	90	91	90	92	80	87	87	85

Table E4: Concentration-based removal efficiencies for the winter/spring period (December to April)

Parameter/ Storm Date	**December 7, 1998**	**April 16, 1999**	**April 19, 1999**	**April 22, 1999**	**December 5, 1999**	**Average Concentration-based Removal Efficiency**
Chloride	48	-74	-94	-297	39	-76
TSS	95	99	99	98	99	98
Total Solids	62	-6	6	-74	73	12
Dissolved Solids	28	-43	-45	-185	40	-41
Oil and grease	33	88	92	79	93	77
Conductivity	28	-46	-49	-198	41	-45
Turbidity	69	99	98	98	100	93
(NH_3+NH_4) - N		3	90	86	-33	37
NO_2-N	-63	82	88	62	84	51
(NO_3+NO_2) - N	45	49	70	7	58	46
Phosphorus, phosphate	28	94	96	99	92	82
Total Phosphorus	60	62	96	88	96	80
TKN	30	-30	84	59	81	45
DOC	14	76	58	38	82	54
DIC	16	27	39	-31	53	21
Silicon	48	94	99	52	66	72
E.coli		98	100			99
F. streptococcus		100	100			100
P. aeruginosa		80	90			85
Aluminum	26	89	96	93	98	80
Barium	28	22	46	-3	81	35
Beryllium	48	85	91	89	75	78
Calcium	29	18	52	-14	70	31
Cadmium	0	67	56	43	80	49
Cobalt	0	0	53	36	89	36
Chromium	0	94	95	93	87	74
Copper	41	81	88	80	91	76
Iron	25	85	97	96	97	80
Magnesium	10	-79	4	-168	47	-37
Manganese	58	93	96	94	99	88
Nickel	73	74	82	82	83	79
Lead	0	67	88	71	81	62
Strontium	12	-40	15	-103	55	-12
Titanium	14	85	95	94	49	68
Vanadium	-7	93	94	93	88	72
Zinc	57	94	96	95	98	88

Table E5: Concentration-based removal efficiencies during dry weather

Parameter/ Storm Date	**February 5, 1999**	**April 9, 1999**	**October 19, 1999**	**November 22, 1999**	**Average Concentration-based Removal Efficiency**
Chloride	3	-9	83	78	39
TSS	81	99	79	73	83
Total Solids	8	26	74	64	43
Dissolved Solids	-1	-2	74	64	34
Solvent Extractable	63	88	1	1	38
Conductivity	0	-5	67	64	31
Turbidity	78	99	64	77	79
(NH_3+NH_4) - N	22	-77	-1355	-107	-379
NO_2-N	32	74	-764	-54	-178
(NO_3+NO_2) - N	-71	59	71	69	32
Phosphorus, phosphate	24	99	-199	-20	-24
Total Phosphorus	52	92	-21	-138	-4
TKN	23	60	-48	-179	-36
DOC	9	12	-34	-47	-15
DIC	-12	29	57	55	32
Silicon	-12	85	74	96	61
E.coli			85	98	91
F. streptococcus			82	98	90
P. aeruginosa			81	26	54
Aluminum	79	92	-159	-92	-20
Barium	15	35	63	63	44
Beryllium	69	90	28	3	48
Calcium	12	46	64	63	46
Cadmium	39	75	1	1	29
Chromium	73	62	-218	-58	-35
Copper	55	81	14	7	39
Iron	84	94	-223	-97	-36
Magnesium	-24	-8	76	69	28
Manganese	74	94	35	45	62
Strontium	-1	3	67	60	32
Titanium	77	95	-77	-820	-181
Vanadium	89	88	-112	-28	9
Zinc	71	91	-2	41	50

APPENDIX F

Single Event Particle Size Distributions

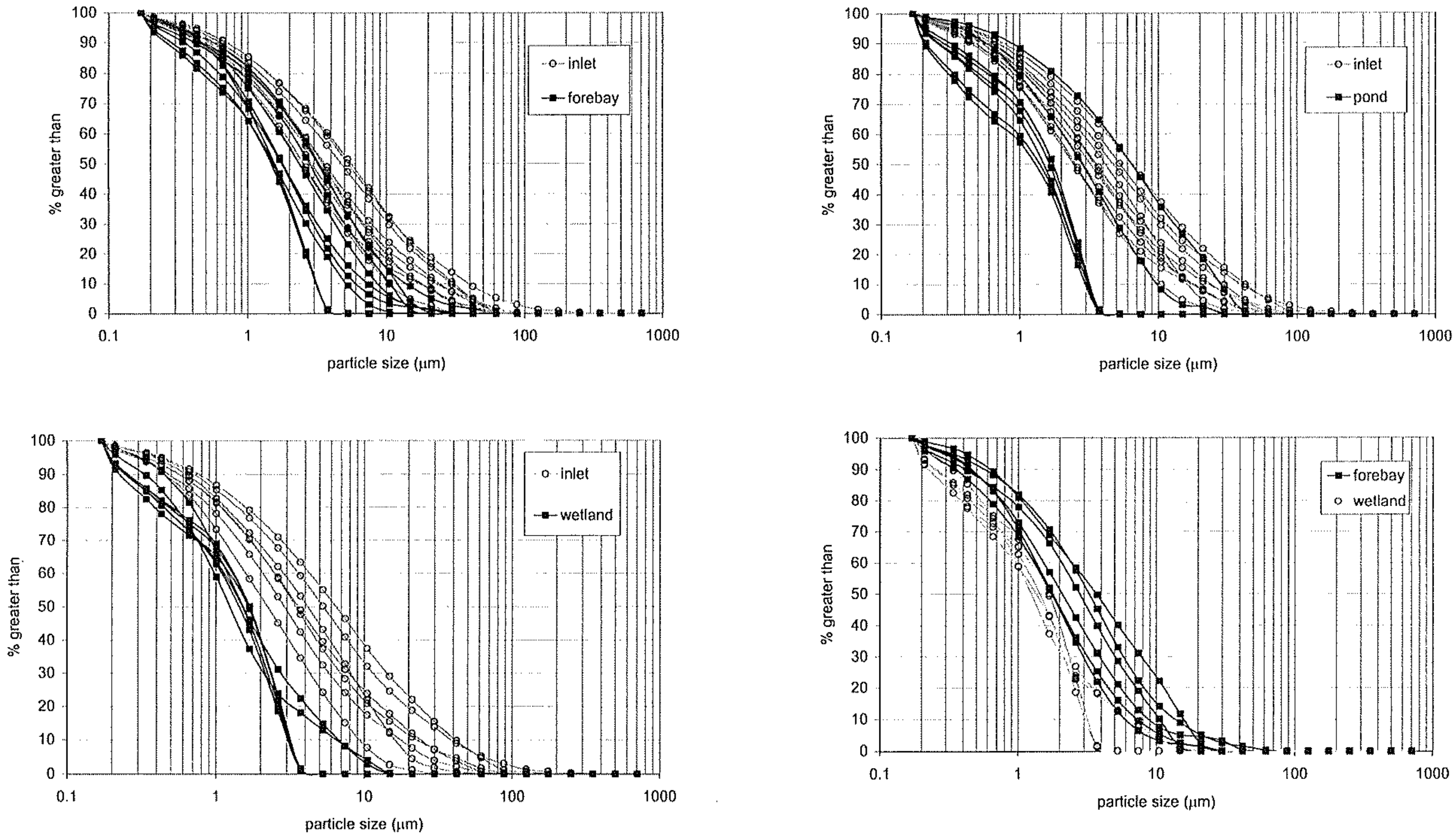

Figure F1: **Individual event particle size distributions of wet weather samples collected during the summer/fall period, 1999.**