Sediment and nutrient transport dynamics in an urban stormwater impoundment

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Abstract Urban impoundments are water storage measures designed to reduce flooding and provide flow augmentation. Their ability to enhance water quality varies greatly from site to site, due to differences in the quality of runoff, climate, design characteristics and mode of operation. Water quality in urban impoundments and downstream environments is often negatively impacted due to the excessive accumulation of sediments and associated pollutants. To mitigate the adverse impacts of urban development and improper reservoir design on water quality, there have been an increasing number of rehabilitation and redesign efforts in North America to improve water quality. While these engineering projects often focus on modelling water quality and redesigning impoundments to improve water quality, few studies have evaluated the water quality performance of impoundments that have been redesigned to enhance water quality. In the present study, sediment and associated nutrient transport dynamics resulting from redesign of an urban impoundment (Columbia Lake, Ontario, Canada) were studied during both pre- (2003–2004) and post-redesign periods (2006–2007). Hydrometric and water quality data collected at the inlet and outlet of Columbia Lake were used to determine pre- and post-design total phosphorus (TP) and suspended sediment (SS) loads as well as changes in treatment performance resulting from impoundment redesign. Mean outflow pre-design TP concentrations decreased from 116 ± 6 μg L^{-1} to 44 ± 3 μg L^{-1} and mean SS concentrations decreased from 67 ± 5 mg L^{-1} to 16 ± 0.8 mg L^{-1} during the post-design period. The net internal P loading rate decreased significantly after the reservoir was reconfigured. Factors influencing the observed decrease in post-design TP and SS fluxes include the removal of lake-bottom sediment, reconfigured bathymetry and naturalization of the shoreline.

Keywords reservoir design; stormwater impoundment; phosphorus; suspended sediment; water quality; rehabilitation

INTRODUCTION

Urban impoundments are designed to reduce post-development peak discharge rates, reduce the risk of flooding (Van Buren, 1997; OMEE, 2003) and provide flow augmentation (Shammaa *et al.*, 2002; Shantz *et al.*, 2004). Because of sediment accumulations and associated nutrients/ contaminants, the water quality of urban impoundments and downstream environments is often problematic (Van Buren *et al.*, 1997; Fridl & Wuest, 2002). The literature reports considerable variation in treatment performance due to differences in stormwater characteristics and climate as well as impoundment design, size, shape and mode of operation (Van Buren *et al.*, 1997; Alaoui Mhamdi *et al.*, 2007).

Despite the increasing number of rehabilitation and redesign efforts in North America to improve the water quality of urban impoundments, few studies have systematically evaluated improvements in water quality both before and after an impoundment has been redesigned. This is primarily due to the fact that pre- and post-design monitoring data are often not available and subsequently few studies have been conducted to assess and compare the treatment performance (water quality improvement) of various impoundment designs (Strecker *et al.*, 2001). The effectiveness of some measures that prolong water retention and regulate flow circuits has been reported (Paul *et al.*, 1998; Shammaa *et al.*, 2002) but few studies have been conducted to investigate how bottom sediment dredging and changes in bathymetry affect treatment performance (Kleeberg & Kohl, 1999). Various water quality models are used to describe the hydrological and ecological functions of impoundments (Teeter *et al.*, 2001). However, site-specific data are still required, in order to further develop and validate water quality models to predict the long-term performance of impoundments.

In this paper, a mass balance approach is used to determine changes in the pre- and post-design water quality conditions of an urban impoundment (Columbia Lake) in Waterloo, Ontario, Canada. The objective of this study is to evaluate the effectiveness of the Columbia Lake redesign to improve the water quality (total phosphorus and suspended sediment) of the impoundment and downstream reaches. The implications of the study for reservoir design and management are discussed.

MATERIALS AND METHODS

Site description

Columbia Lake is a 12-ha urban impoundment located in a small (74 km^2) subwatershed of the central Grand River watershed in Ontario, Canada. Initially built in 1967 for flood control and recreation, Columbia Lake has a mean depth of 1 m (Barton *et al.*, 2000). Land use above Columbia Lake is predominantly agriculture (cash crops and pasture land). Woodlots and wetlands are located in the northwestern portion of the watershed.

Prior to its redesign, Columbia Lake was characterized as a shallow impoundment with extremely low habitat diversity, poor substrate quality, high deposition rates of nutrient-rich sediment and degraded benthic communities (Shantz *et al.*, 2004). In 2002, a study was conducted to assess the impacts of Columbia Lake Reservoir on Laurel Creek (Stantec Consulting Ltd, 2004). The study led to the development of a rehabilitation plan to preserve the functions and environmental features within surrounding Reserve Lands and to improve the water quality and aquatic habitat of the Laurel Creek and Columbia Lake. Accordingly, the plan included changing the configuration of Columbia Lake by dredging to reconfigure the lake's bathymetry, removing nutrient-rich sediments and changing the shoreline configuration to diversify and enhance habitat and wildlife opportunities. Lake bathymetry was reconfigured to create variable depths and an undulating naturalized shoreline to enhance in-lake and near-shore habitats. The lake bottom was redesigned to create five habitat zones in a gradient from the outer perimeter to the central part of the lake. The design considerations also included changing lake bottom topography (slopes and depths), creating a beach with sandy flat areas, wetland shallows, a littoral shelf and a deep water zone. Bottom sediments were removed to decrease internal phosphorus loading. Geese and carp control methods were used to minimize bioturbation and the shoreline was reconfigured and naturalized to diversify shoreline habitats (Stantec Consulting Ltd, 2004). The pre- and post-design attributes of Columbia Lake are presented in Table 1. After the redesign, the average retention time of Columbia Lake increased from 13 days to 41 days

Table 1 Physical characteristics of Columbia Lake for pre- and post-design conditions.

Condition	Volume (m^3)	Surface area (m^2)	Depth
Pre-design	127 000	152 000	No more than 1 m on average
Post-design	125 000	95 000	Variable depths from 0 to 3.5 m or more

Hydrometric and water quality analysis

Changes in sediment and associated nutrient transport dynamics resulting from redesign of Columbia Lake were studied from May to the end of August for both pre- (2003–2004) and post-design periods (2006–2007). Hydrometric and water quality data were collected at the inlet and outlet of Columbia Lake to determine pre- and post-design total phosphorus (TP) and suspended sediment (SS) loads as well as changes in treatment performance. Instantaneous discharge was measured using the velocity–area method twice weekly, at both the inflow and the outflow. Suspended solids concentrations were determined gravimetrically. Total phosphorus (TP) concentrations were measured with a Technicon Auto-Analyser II and NAP analysis software using the stannous chloride-ammonium molybdate procedure (Environment Canada, 1987). The particle size characteristics of suspended solids were determined by image analysis techniques as described by DeBoer & Stone (1999).

Statistical analysis

Statistical analysis of inflow and outflow water quality data for pre- and post-design periods was conducted using SPSS software (Version 15.0, SPSS® Inc). The Shapiro-Wilk test ($p = 0.05$) was used to determine if data were normally distributed. Because the data were not normally distributed, nonparametric Kruskal-Wallis tests followed by Bonferroni multiple comparison tests in Univariate Analysis of Variance were used to compare temporal differences in concentrations and loads of total phosphorus and suspended solids between the pre- and post-design periods. Monthly changes in the concentrations and loads of TP and SS were examined by multiple comparison tests (Post Hoc Tests: Bonferroni) in Univariate Analysis of Variance. The confidence level was set at 95%.

RESULTS AND DISCUSSION

Comparison of pre- and post-design TP concentrations and loads

Temporal variation in total phosphorus concentrations at the inflow and outflow of Columbia Lake during the pre- and post-design periods is shown in Fig. 1. With the exception of TP levels measured on Julian Day 231, 233 and 238 in 2003, inflow TP concentrations during the post-design period were similar to pre-design levels. Pre-design outflow TP levels ranged from 10–300 μg L^{-1} compared to a range of 10–160 μg L^{-1} for post-design levels. Post-design outflow TP concentrations and loads were significantly lower than for the pre-design period (Table 2).

The Ontario provincial water quality objective (PWQO) for TP is 30 μg L^{-1} (OMEE, 1994). Water quality targets for Laurel Creek set by the City of Waterloo recommend that TP concentrations downstream of Laurel Creek Reservoir should not exceed 80 μg L^{-1}. For the pre-design period, 18% and 0% of the TP concentrations met the PWQO at the inflow and outflow, respectively, and about 28% of outflow TP concentrations met the City of Waterloo target. For the

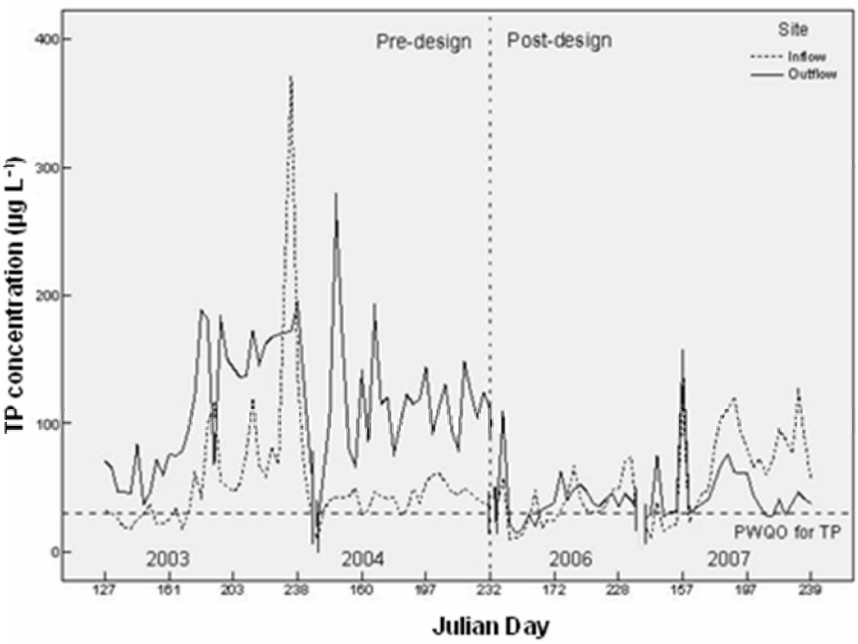

Fig. 1 Change in TP concentrations at the inflow and outflow during pre and post-design periods.

Table 2 Statistical comparisons of TP concentrations and loads at the inflow and outflow during the pre- and post-design periods (Kruskal Wallis Tests).

	TP concentrations	TP loads
Inflow between the pre- and post-design periods	P = 0.965	**P = 0.0001**
Outflow between the pre- and post-design periods	**P = 0.0001**	**P = 0.0001**
Pre-design between the inflow and outflow	**P = 0.0001**	**P = 0.0001**
Post-design between the inflow and outflow	P = 0.291	P = 0.823

P values in bold denote statistically significant differences.

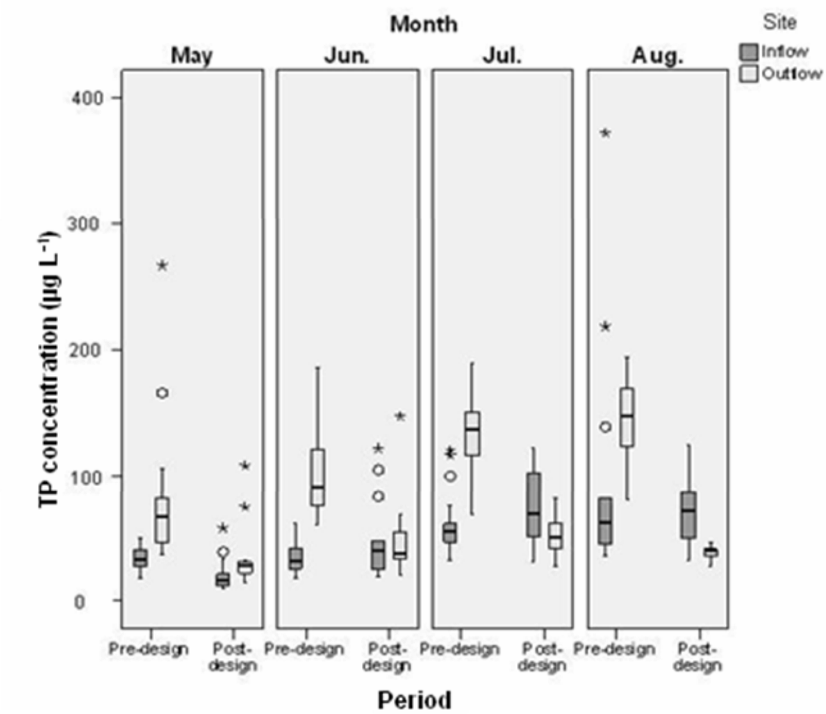

Fig. 2 Comparison of monthly TP inflow and outflow concentrations during for the pre- and post-design periods (* = the extreme, ° = outlier)

post-design period, outflow TP concentrations decreased dramatically. While the post-design inflow (29%) and outflow (25%) TP concentrations continued to exceed the PWQO, 94% of the outflow levels were below 80 μg L^{-1}.

Monthly TP concentrations at the inflow and outflow for pre- and post-design periods are presented in Fig. 2. During the pre-design period, significant differences were only observed for outflow TP concentrations in May and July, and in May and August. The average TP concentration in May was about 50 μg L^{-1} lower than for July and August. The monthly average internal TP loads gradually decreased from 64 to 4 g h^{-1}. In 2003 and 2004, Columbia Lake consistently acted as a TP source but the data show that Columbia Lake became a TP sink after it was reconfigured. Strong post-design correlations between TP loads and SS loads (log-transformed) at the inflow and outflow ($r = 0.794$ and 0.915, $p = 0.0001$) demonstrate that physical processes (sedimentation/re-suspension) play an important role in decreasing the flux of TP to downstream environments. This observation is consistent with the results of other studies (Van Buren, 1997; Teodoru & Wehrli, 2005; Alaoui Mhamdi *et al.*, 2007).

Comparison of pre- and post-design SS concentrations and loads

Suspended solids concentrations at the outflow of Columbia Lake (Fig. 3) decreased significantly (Table 3) during the post-design period. Before the lake reconstruction, Columbia Lake was a

Table 3 Statistical comparisons of SS concentrations and loads at the inflow and outflow during pre- and post-design periods (Kruskal Wallis Tests, p = 0.0001).

	SS concentrations	SS loads
Inflow between the pre- and post-design periods	**P = 0.0001**	**P = 0.0001**
Outflow between the pre- and post-design periods	**P = 0.0001**	**P = 0.0001**
Pre-design between the inflow and outflow	**P = 0.0001**	**P = 0.0001**
Post-design between the inflow and outflow	**P = 0.0001**	**P = 0.004**

P values in bold denote statistically significant differences.

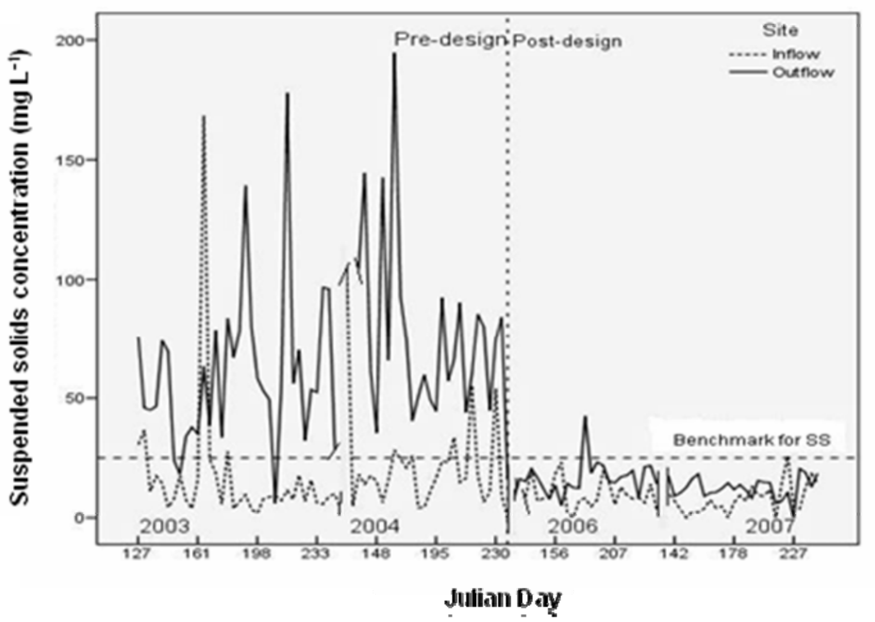

Fig. 3 Change in suspended solids concentrations at the inflow and outflow during pre- and post-design periods.

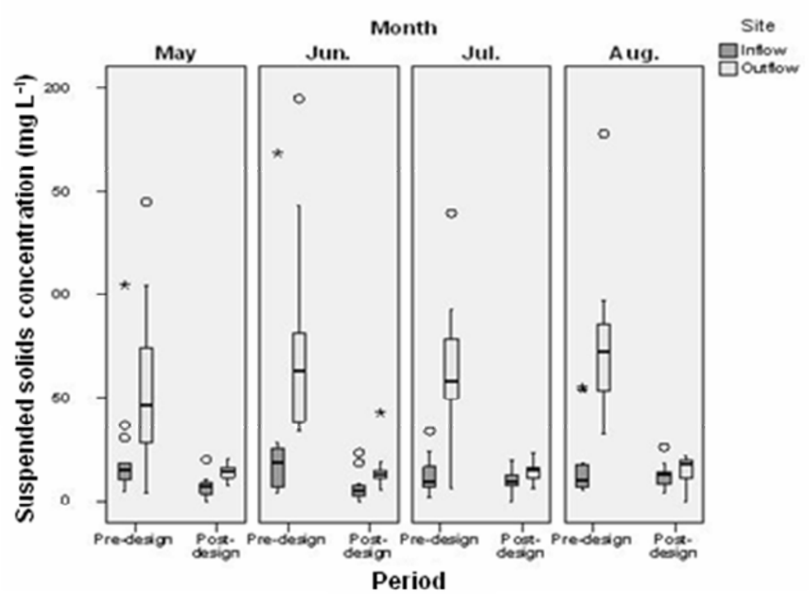

Fig. 4 Change in the monthly suspended solids concentrations at the inflow and outflow during pre- and post-design periods (∗ = extreme values, ○ = outlier).

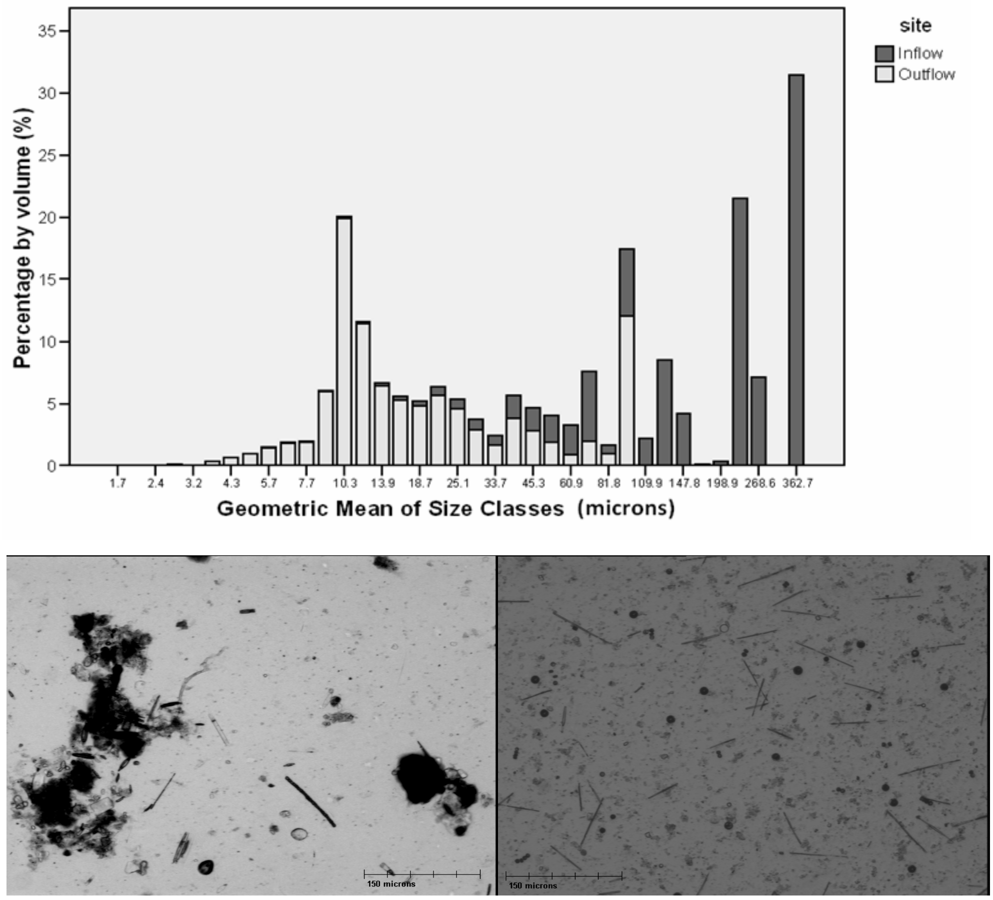

Fig. 5 The size distribution of suspended solids at the lake inflow and outflow and representative micrographs for the inflow (left) and the outflow (right).

source of suspended solids to downstream reaches of Laurel Creek. Outflow suspended solids concentrations and loads decreased by 78% and 88% during the post-design period. The monthly change in suspended solids concentrations at the inflow and outflow of Columbia Lake for pre- and post-design periods is presented in Fig. 4. In the pre-design period, monthly average SS concentrations at the outflow increased slightly from May to August. In the post-design period, there was no significant difference in the suspended solids concentrations by month.

The median diameter (D_{50}) of suspended solids was significantly higher at the inflow than the outflow (p = 0.001). Stone & English (1993) investigated the effect of grain size and sediment geochemistry on phosphorus sorption by river sediment and found that particles <8 μm were important in the sorption and release of phosphorus. In Columbia Lake, particles <8 μm accounted for 40–60% of the solids at the inflow but 80–90% of the particles at the outflow. Representative photomicrographs of suspended solids in Columbia Lake (Fig. 5) show that particles at the inflow were larger and more flocculated than at the outflow. This suggests that the majority of the larger suspended particles (>40 μm) tend to settle on the lake bottom, due to the post-design reduction of flow velocity and increased water retention time in Columbia Lake.

Post-design treatment performance

Previous investigations have shown that properly designed stormwater impoundments can effectively reduce TP and SS loads to downstream environments (Szilagyi *et al.*, 1990; Paul *et al.*, 1998; Shammaa *et al.*, 2002). In the present study, post-design TP and SS internal loading rates were significantly lower than the pre-design period (p = 0.001). Several factors, including the creation of an island, the removal of bottom sediments and changes to the lake bathymetry, caused the decrease in net internal TP and SS loading rates. These measures increased the water retention time (R_T) from the average of 13 days in the pre-design period to 41 days in the post-design period. The littoral shelf, drop-off shelf and deep water zone were covered by coarse (sand to gravel) substrates (Stantec Consulting Ltd, 2004). Changes to the bathymetry and the addition of coarser bottom substrates reduced re-suspension rates.

CONCLUSIONS

The redesign of Columbia Lake had a significant effect on both the reservoir water quality and downstream reaches of Laurel Creek. Post-design outflow concentrations and loads of TP and suspended solids decreased dramatically but still exceeded the Ontario PWQO. A combination of reconfigured reservoir bathymetry and removal of bottom sediments decreased internal TP and suspended solids loadings, by reducing re-suspension rates and the subsequent release of phosphorus to the water column. While maintaining the flood control benefits of reservoirs, their impacts on downstream water quality can be minimized through the use of a range of integrated design measures that promote particle settling and reduce P mobilization.

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