Transient storage and release of sediment and phosphorus in a small urban impoundment

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Abstract A mass balance approach was used to quantify concentrations and loads of suspended solids and phosphorus (P) at the inflow and outflow of Laurel Pond, a small river impoundment in an urbanized watershed in Waterloo, Ontario, Canada, over a range of hydrological conditions. During baseflow and higher magnitude flow conditions, Laurel Pond was a sink for both sediment and P. However, 8.4 t of sediment and 8.6 kg of P were released from Laurel Pond during drawdown. Concentrations of sediment and P were positively correlated but inversely related to pond depth. A threshold water level was observed in the pond, below which the majority of sediment and P were released. During the Laurel Pond drawdown, 94% of suspended solids and 100% of TP measurements at the pond outflow exceeded Ontario Provincial Water Quality Objectives of 25 mg L^{-1} and 30 µg L^{-1}, respectively.

Key words urban impoundments; sediment; phosphorus; drawdown

INTRODUCTION

Phosphorus supply and mobility are critical drivers of biological activity in aquatic systems and management programmes at watershed scale are required to reduce the eutrophication impacts of urban and agricultural land use on aquatic systems (Withers & Jarvie, 2008). Excessive additions of phosphorus (P) to the lower Laurentian Great Lakes are of concern (Correll, 1998; Coops *et al*., 2003) and management strategies have been implemented to reduce nutrient inputs from sewage inputs and diffuse agricultural sources (IJC, 1980; Rosa, 1987). Management programmes have reduced nutrient loading to the Great Lakes but there is still concern regarding the annual autumn release of water from reservoirs which increases the flux of sediment and P to Lake Erie (Shantz *et al*. 2004).

Rivers are impounded to manage high water levels, reduce the risk of flooding and to augment river discharge during periods of low flow (McGilligan & Nislow, 2005). However, despite these benefits, dams reduce river connectivity longitudinally and laterally by altering the frequency and duration of overbank flow events (Cooke *et al*., 1986). The flow regime in impounded rivers is markedly different from pre-impoundment conditions (Batello *et al*., 2004) and many reservoirs experience high sedimentation rates which decrease water storage volumes and lower reservoir performance (Annandale, 1987).

Water levels are lowered in reservoirs as a flood control measure and to increase water storage capacity by flushing deposited sediments downstream (Morris & Fan, 1998). During this process, bottom sediments are scoured along the length of the reservoir (Wang *et al*., 2007) and sediment and associated P fluxes increase (Correll, 1998; Shantz *et al*., 2004). Drawdown changes turbulence patterns, oxygen availability and temperature and this, in turn, can adversely impact downstream water quality and biotic communities (Ahearn *et al*., 2005).

By understanding processes that control discharge, sedimentation and sediment associated P transport, improvements to reservoir management and pollution mitigation practices can be identified. This study examines spatial and temporal patterns and processes of suspended solids and associated P transfer in a small urban impoundment to quantify the transient storage or release of sediments and nutrients to downstream environments. A mass balance approach is used to quantify concentrations and loads at the inflow and outflow of an impoundment over a range of hydrologic conditions (i.e. baseflow, upstream reservoir release, subsequent drawdown of the impoundment) that occur every autumn, as part of a flood prevention management programme.

METHODS

The Grand River is the largest (6800 km^2) Canadian tributary of Lake Erie and contributes 68% of the mean annual discharge and 54% of the total Canadian suspended solids load to this lake (Ongley, 1976). It is the most significant tributary source of P to the eastern basin of Lake Erie (Rosa, 1987). Discharge in the Grand River is regulated by seven multipurpose reservoirs, 25 smaller dams operated by the Grand River Conservation Authority and approximately 100 privately owned dams (Shantz *et al*., 2004). Reservoir water levels are slowly lowered near the end of summer for flood protection but water levels in smaller dams are lowered in the autumn.

Laurel Creek is a heavily impounded tributary of the Grand River. This study was conducted to examine the effect of water release from upstream reservoirs and impoundments on the sediment and phosphorus transport dynamics of an urban impoundment (Laurel Pond, area 8963 m^2, volume 4781 m^3) located on Laurel Creek in Waterloo, Ontario (UTM N 4812784 E 536864). As part of flood protection and flow management practice, a multi-pond system in Laurel Creek is sequentially drained annually each autumn and the sequence of impoundment drawdown from first to last is Laurel Creek Reservoir, Columbia Lake, Laurel Pond and finally the Health Services Pond.

Stream discharge and stage were measured at the inflow and outflow of Laurel Pond from Julian day 292 to 320 (2009) using a Swoffer Current Velocity meter (Model 2100) and pressure transducers (Solinst Levelogger Gold Series 3001). Rating curves were created from the inflow and outflow data. Precipitation data were obtained from the University of Waterloo meteorological station. ISCO auto-samplers were deployed at the inflow and outflow of Laurel Pond to collect water samples. Additional surface water grab-samples were collected in duplicate in acid washed, pre-rinsed 100-mL polyethylene bottles for TP and soluble reactive phosphorus (SRP) analysis then refrigerated at 4°C in the laboratory within 2 h of collection. Water samples were filtered through 45 μm Millipore filters and SRP concentrations were determined according to the stannous chloride–ammonium molybdate procedure (Environment Canada, 1979). After potassium persulphate digestion, TP concentrations were determined using the stannous chloride–ammonium molybdate procedure. Suspended solids concentrations were determined gravimetrically according to Standard Methods no. 2540–D (APHA, 1992). Discharge and water quality data (suspended solids, SRP, TP concentrations) were used to calculate event mean concentrations (EMCs) and sediment, TP and SRP loads.

RESULTS AND DISCUSSION

Sediment concentrations and loads

Temporal changes in discharge and suspended solids (SS) concentrations at the inflow of Laurel Pond during the sequential release of water from Laurel Creek Reservoir, Columbia Lake and Laurel Pond are shown in Figs 1, 2 and 3, respectively. Sediment loads, EMCs and the percentage of samples exceeding the 25 mg L^{-1} Ontario Provincial Water Quality Objectives (PWQO) at the inflow and outflow of Laurel Pond are summarized in Table 1. Prior to the Laurel Creek Reservoir drawdown, average SS concentrations were 12 ± 6 mg L^{-1} at the inflow and 10 ± 6 mg L^{-1} at the outflow of Laurel Pond. Discharge at the Laurel Pond inflow increased from 0.2 to 3 m^3 s^{-1} during drawdown of the Laurel Creek Reservoir (Fig. 1) and SS concentrations initially increased from 12 to 63 mg L^{-1}, but then decreased to an average of 20 mg L^{-1} for the remainder of the flow event (Fig. 1). A second increase in SS concentration was observed at the Laurel Pond inflow when water was released from Columbia Lake (Fig. 2). During the drawdown of Columbia Lake and Laurel Pond, the SS EMCs at the Laurel Pond inflow were 11 and 8 mg L^{-1}, respectively (Table 1) while the EMCs at the outflow were 10 and 337 mg L^{-1}, respectively (Table 1). During Laurel Pond drawdown, the maximum outflow concentration was 910 mg L^{-1} but the average inflow concentration was 11 mg L^{-1} (Fig. 3).

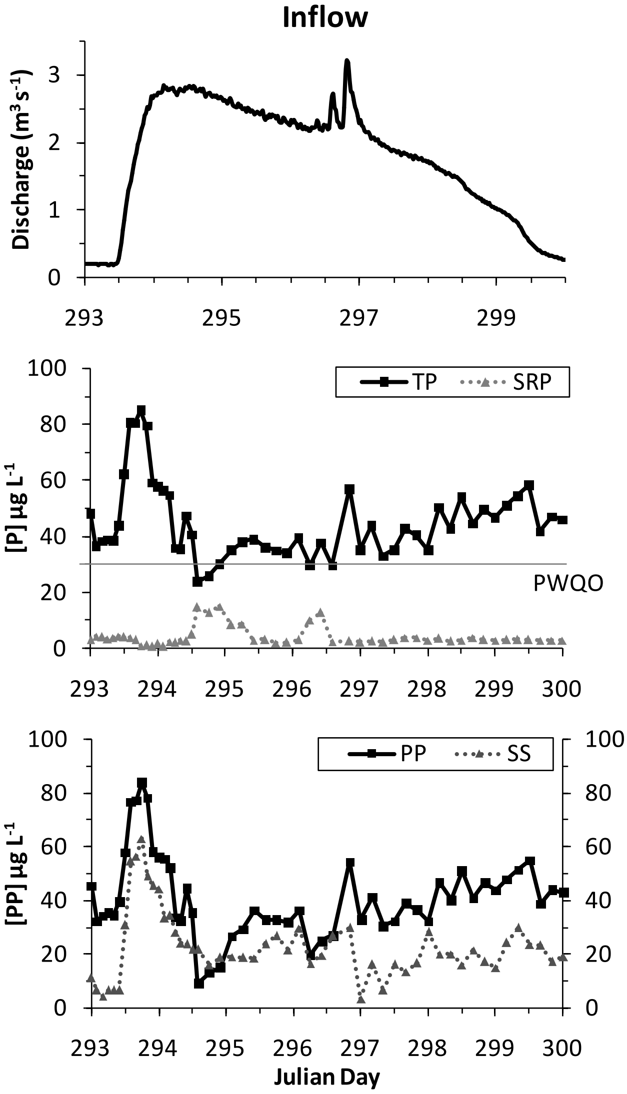

Fig. 1 Temporal variation in phosphorus (TP, PP, SRP) and suspended solids (SS) concentrations at the Laurel Pond inflow during the Laurel Creek Reservoir drawdown.

During a low flow period that preceded the Laurel Reservoir drawdown, the average SS load measured at the inflow and outflow of Laurel Pond was 12 ± 6 kg h^{-1} and 9 ± 5 kg h^{-1}, respectively. Maximum sediment loads at the Laurel Pond inflow varied in response to fluctuating water levels from upstream reservoir release; Laurel Reservoir drawdown (466 kg h^{-1}), Health Services Pond drawdown (299 kg h^{-1}) and rainfall event (78 kg h^{-1}) that occurred during flow rates of 1.96, 0.75, 0.23 m^3 s^{-1}, respectively. Sediment loads at the outflow during the Laurel Pond drawdown ranged from 33 to 1711 kg h^{-1}. The total mass of sediment exported from the pond was 8.4 t and 94% of the suspended solids measurements during this period exceeded the SS PWQO (Table 1).

Phosphorus concentration and loads

During the drawdown of the Laurel Creek Reservoir, total phosphorus (TP) concentrations at the inflow of Laurel Pond increased from 40 to 90 µg L^{-1}. The mean TP concentration was 46 ± 14 µg L^{-1} and the majority of observations exceeded the PWQO of 30 µg L^{-1}. Total phosphorus and SS concentrations were highly correlated (r^2 = 0.91). PP comprised the majority of measured TP (Fig. 3). The TP EMCs at the inflow and outflow of Laurel Pond during Columbia Lake drawdown

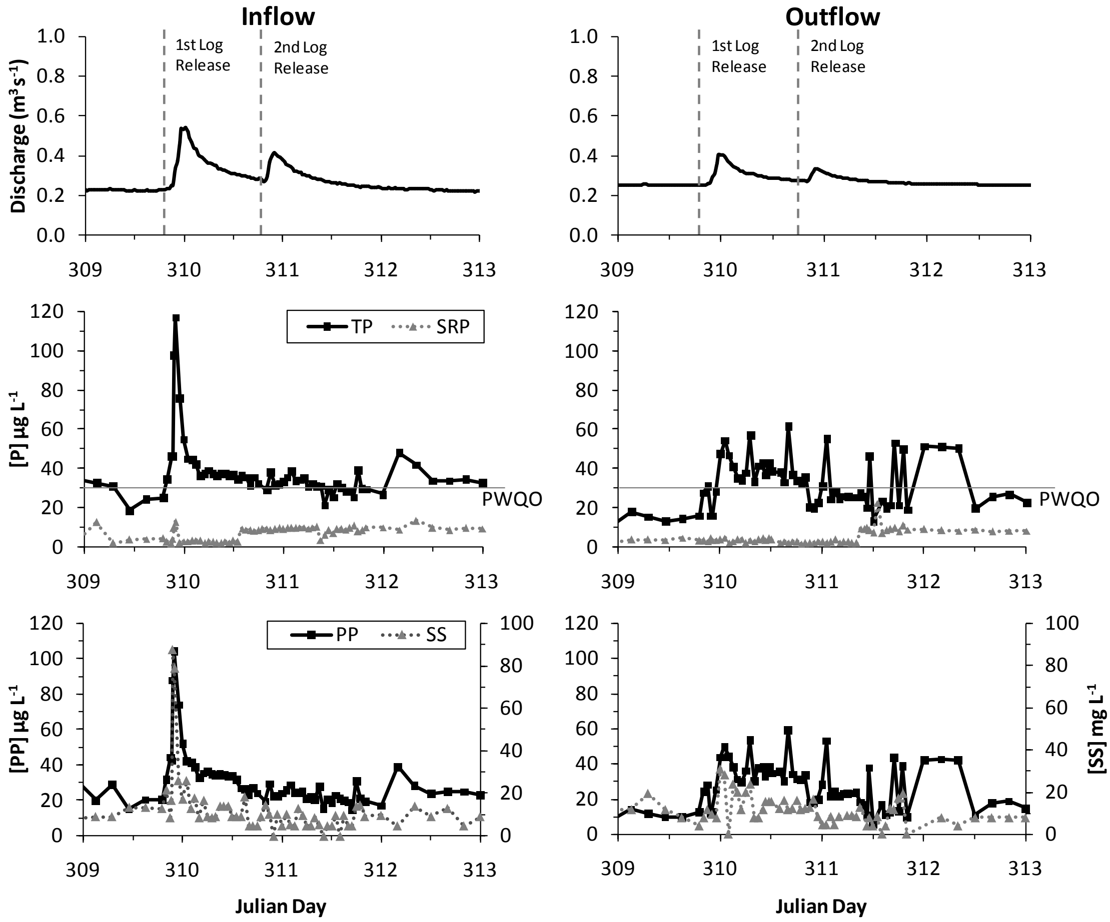

Fig. 2 Temporal variation in phosphorus (TP, PP, SRP) and suspended solids (SS) concentrations at the inflow and outflow of Laurel Pond during the Columbia Lake drawdown.

were 38 and 36 µg L^{-1}, respectively (Table 2). The average SRP concentration at the Laurel Pond inflow was 5 µg L^{-1}. The TP loads calculated at the inflow and outflow during this 63-hour event were 2.67 and 2.35 kg, respectively. There was a decrease in the number of samples that exceeded the TP PWQO at the outflow. The drawdown of Laurel Pond followed by the Health Services Pond drawdown produced dramatic changes in TP concentrations at the Laurel Pond outflow compared to the inflow (Fig. 3). The TP EMC at the outflow for the two events was 247 and 91 µg L^{-1} compared to 36 and 23 µg L^{-1} at the inflow (Table 2). The TP PWQO was exceeded 100% and 89% at the outflow of Laurel Pond during its drawdown and the subsequent drawdown of the Health Services Pond. During these two events, a total of 8.6 kg of P was exported from Laurel Pond.

Table 1 Summary of sediment loads, EMCs and % of observations exceeding PWQOs.

Event (h)	Inflow TSS load (kg)	EMC[5] (mg L^{-1})	Exceed PWQO[6] (%)	n	Outflow TSS load (kg)	EMC[5] (mg L^{-1})	Exceed PWQO[6] (%)	n	Storage (In – Out)[7] (kg)
BF[1] (212)	2222	12	4	54	1790	12	0	43	432
CLD[2] (63)	817	11	8	53	653	10	4	49	164
LPD[3] (24)	101	8	0	11	8462	337	94	36	–8361
HSD[4] (4)	93	22	31	16	624	163	100	21	–531

1 Baseflow; 2 Columbia Lake Drawdown; 3 Laurel Pond Drawdown; 4 Health Services Pond Drawdown; 5 Event Mean Concentration; 6 Percent of samples that exceeded the Provincial Water Quality Objective of a TSS concentration of 25 mg L^{-1}; 7 Storage was calculated by subtracting the amount of sediment (kg) leaving the pond at the outflow from the amount of sediment entering the pond at the inflow.

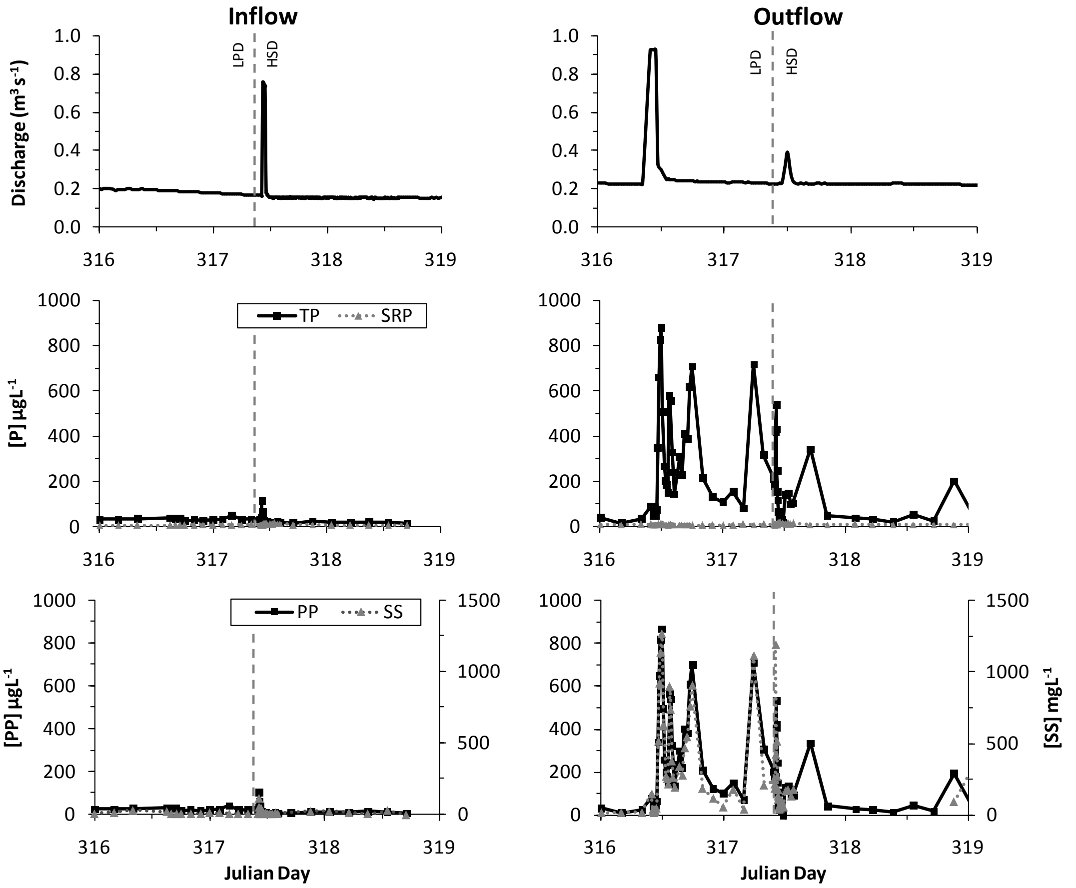

Fig. 3 Temporal variation in phosphorus (TP, PP, SRP) and suspended solids concentrations at the inflow and outflow of Laurel Pond during the Laurel Pond and subsequent Health Services Pond drawdown.

Table 2 Summary of phosphorus loads, EMCs and % of observations exceeding PWQOs.

Event (h)	Inflow TP load (kg)	EMC[5] ($mg L^{-1}$)	Exceed PWQO[6] (%)	n	Outflow TP load (kg)	EMC[5] ($mg L^{-1}$)	Exceed PWQO[6] (%)	n	Storage (In – Out)[7] (kg)
BF[1] (212)	5.97	33	72	54	4.95	27	25	44	1.03
CLD[2] (63)	2.67	38	81	52	2.35	36	58	52	0.32
LPD[3] (24)	0.56	36	82	11	7.00	247	100	36	–6.44
HSD[4] (31)	0.43	23	28	25	2.54	91	89	35	–2.11
Total	9.63				16.84				–7.21

1 Baseflow; 2 Columbia Lake Drawdown; 3 Laurel Pond Drawdown; 4 Health Services Pond Drawdown; 5 Event Mean Concentration; 6 Percent of samples that exceeded the Provincial Water Quality Objective of 30 mg L^{-1} TP; 7 Storage was calculated by subtracting outflow P values (kg) from inflow P values (kg).

During the Laurel Pond drawdown, SS and P concentrations were positively correlated but inversely related to pond depth. Below a threshold water level (45 cm), the majority of sediment was eroded and exported from Laurel Pond. Using the pond bathymetry and hydrodynamic data from this study, the critical bed shear stress for variable water levels in Laurel Pond was estimated using a two dimensional flow and sediment transport modelling system (TABS-MD with SMS user interface). The model output indicated that bed shear stress in Laurel Pond during water release from both the Laurel Creek Reservoir and Columbia Lake was ~0.02 Pa. However, when water was released from Laurel Pond the water level decreased below 45 cm and the shear stress quickly increased to ~0.15 Pa. Several recent studies conducted in laboratory flumes have advanced knowledge regarding the erosive behavior of cohesive sediment and reported the critical shear stress for its erosion and deposition (e.g. Stone *et al*., 2008). These studies suggest that the critical shear stress for deposition of cohesive sediment is ~0.05 Pa, and ~0.12 Pa for erosion. The model output and field data indicate that a minimum water depth of 45 cm is required to minimize P and SS export from Laurel Pond.

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