The effect of drawdown on suspended solids and phosphorus export from Columbia Lake, Waterloo, Canada

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Abstract:

This study examines the effect of drawdown on the timing and magnitude of suspended solids and associated phosphorus export from a 12 ha reservoir located in an urbanized watershed in southern Ontario, Canada. Water level in Columbia Lake was lowered by 1·15 m over a 2-week period in November 2001. The total phosphorus (TP) concentrations ranged from 63 to 486 µg L^{-1} in Columbia Lake and 71 to 373 µg L^{-1} at its outflow. All samples exceeded the Provincial Water Quality Objective of 30 µg TP L^{-1}. Outflow concentrations of suspended solids and TP increased significantly with decreasing lake level and were attributed to the resuspension of cohesive bottom sediments that occurred at a critical threshold lake level (0·65 m below summer level). Suspended solids at the outflow consisted of flocculated cohesive materials with a median diameter (D_{50}) of *c.* 5 µm. Particulate organic carbon accounted for 8·5% of the suspended solids export by mass. A total mass of 18·5 t of suspended solids and 62·6 kg TP was exported from Columbia Lake, which represents a significant pulse of sediment-associated P to downstream environments each autumn during drawdown. The downstream impacts of this release can be minimized if the water level in Columbia Lake is lowered no more than 0·5 m below summer levels. Copyright © 2004 John Wiley & Sons, Ltd.

KEY WORDS   reservoir; drawdown; suspended solids; phosphorus

INTRODUCTION

River regulation is a common means of flood protection and flow management that alters natural hydrological processes, suspended solids transport, river ecology and downstream geomorphology (Petts, 1984; Church, 1995; Morris and Fan, 1998). Owing to a reduction in flow velocities, coarser fractions of suspended solids from river inflows deposit rapidly in reservoirs but finer fractions remain suspended in the water column for longer periods and are often present in outflow waters (Striegl, 1987; Marsalek *et al.*, 1997). The accumulation of sediment in reservoirs can represent a significant pool of nutrients and associated contaminants (Kristensen *et al.*, 1992; Sondergaard *et al.*, 1992) that influence nutrient cycling and the ecology of downstream environments (Palmer and O'Keefe, 1990). The resuspension of bottom sediment in reservoirs depends on hydrodynamics, benthic biology and sediment properties (e.g. particle density, grain size, degree of consolidation) but variability in these characteristics makes accurate prediction of sediment resuspension difficult (Bedford and Abdelerham, 1987; Luettich *et al.*, 1990; Bengtsson and Hellstrom, 1992; Brassard and Morris, 1997). During the release of water for flood control, resuspended particulate matter and associated pollutants are exported from reservoirs to downstream environments (Petts, 1984; Jansson and Erlinsson,

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2000) and the impact of these fine-grained materials on biodiversity and water quality can be significant in aquatic systems (Wood and Armitage, 1997).

Knowledge of the source, transport and fate of suspended solids is important for reservoir management because many pollutants of concern have environmental pathways that are primarily or exclusively associated with sediment and biological substrates (Reuter and Perdue, 1977; Horowitz, 1991). Approximately 75% of the tributary phosphorus (P) load to the lower Great Lakes is transported in association with suspended solids (Logan, 1987) that are predominantly <63 μm (Stone and Saunderson, 1992). The speciation and fate of sediment-bound P in aquatic systems is related to particle size through its influence on P sorption (Santiago and Thomas, 1992). The chemical composition and mineralogy of suspended solids <13 μm were found to strongly control sorption of inorganic P in two Lake Erie tributaries (Stone and Mudroch, 1989). Deposits of these fine-grained materials in streams are significant for the short-term storage of P (Droppo and Stone, 1994). During periods of high discharge, fine-grained deposits are eroded and transported downstream to receiving water bodies in a series of resuspension and deposition events (Stone and Droppo, 1994). The release of P from cohesive sediment of fluvial origin is an important source of bioavailable P to Lake Erie (Mayer and Manning, 1989; Stone and English, 1993) where algal blooms persist in near-shore environments during the autumn (Rosa, 1987; Nichols *et al.*, 2001). Many rivers in southern Ontario are regulated and during autumn drawdown, the release of sediment-associated P from impoundments across Ontario will increase the nutrient flux to the Great Lakes. Currently, there are no regulations in Ontario to control the water quality of impoundment outflows. Information on the rates and magnitudes of suspended solids and associated P export from impoundments is required to manage the health of receiving waters.

There is considerable knowledge about the transport of suspended solids and phosphorus in unregulated rivers but much less is known about the impact of drawdown on particulate and associated chemical export from reservoirs. This study examines the effect of drawdown on suspended solids and phosphorus export from a 12 ha reservoir (Columbia Lake) in an urbanized watershed in southern Ontario, Canada. The *in situ* particle size characteristics of suspended solids at the inflow, outflow and within Columbia Lake are determined by conventional optical microscopy (COM) and image analysis and related to their provenance. Concentrations of dissolved and total organic carbon are measured to determine the particulate organic fraction of suspended solids at the study sites. Implications of the study for watershed management are discussed.

SITE DESCRIPTION

The Grand River drains an area of 6800 km² in southern Ontario and is the largest Canadian tributary flowing into Lake Erie (Figure 1). It accounts for 68% of the mean annual discharge and 54% of the total Canadian suspended solids load to Lake Erie (Ongley, 1976). The Grand River is the most significant tributary source of phosphorus to the eastern basin of Lake Erie (Rosa, 1987; Mayer and Delos Reyes, 1996) and bioavailable particulate phosphorus forms at the Lake Erie–Grand River confluence have a significant effect on water quality in the near-shore zone of the lake (Mayer and Manning, 1989). The flow of the Grand River is regulated by seven multipurpose reservoirs and 25 smaller dams operated by the Grand River Conservation Authority (Figure 1), including an additional 100 privately owned dams. Water levels in many of the reservoirs are lowered slowly near the end of summer to minimize water quality impacts. However, water levels in most of the smaller dams are lowered in the autumn.

Laurel Creek is a small (74 km²) tributary in the central Grand River basin and its land use varies from highly developed commercial and residential areas in the lower sections of the watershed to agricultural fields, woodlots and wetlands in upstream areas (GRCA, 1993). The main branch of Laurel Creek has one multipurpose reservoir (Laurel Creek Reservoir) and two smaller downstream impoundments (Columbia Lake and Silver Lake). Laurel Creek Reservoir provides flood protection and is typically drained in the autumn two weeks before Columbia Lake. Columbia and Silver Lake are less significant for flood control and are used mainly for recreation (GRCA, 1993). Columbia Lake was constructed in 1967 and is located approximately
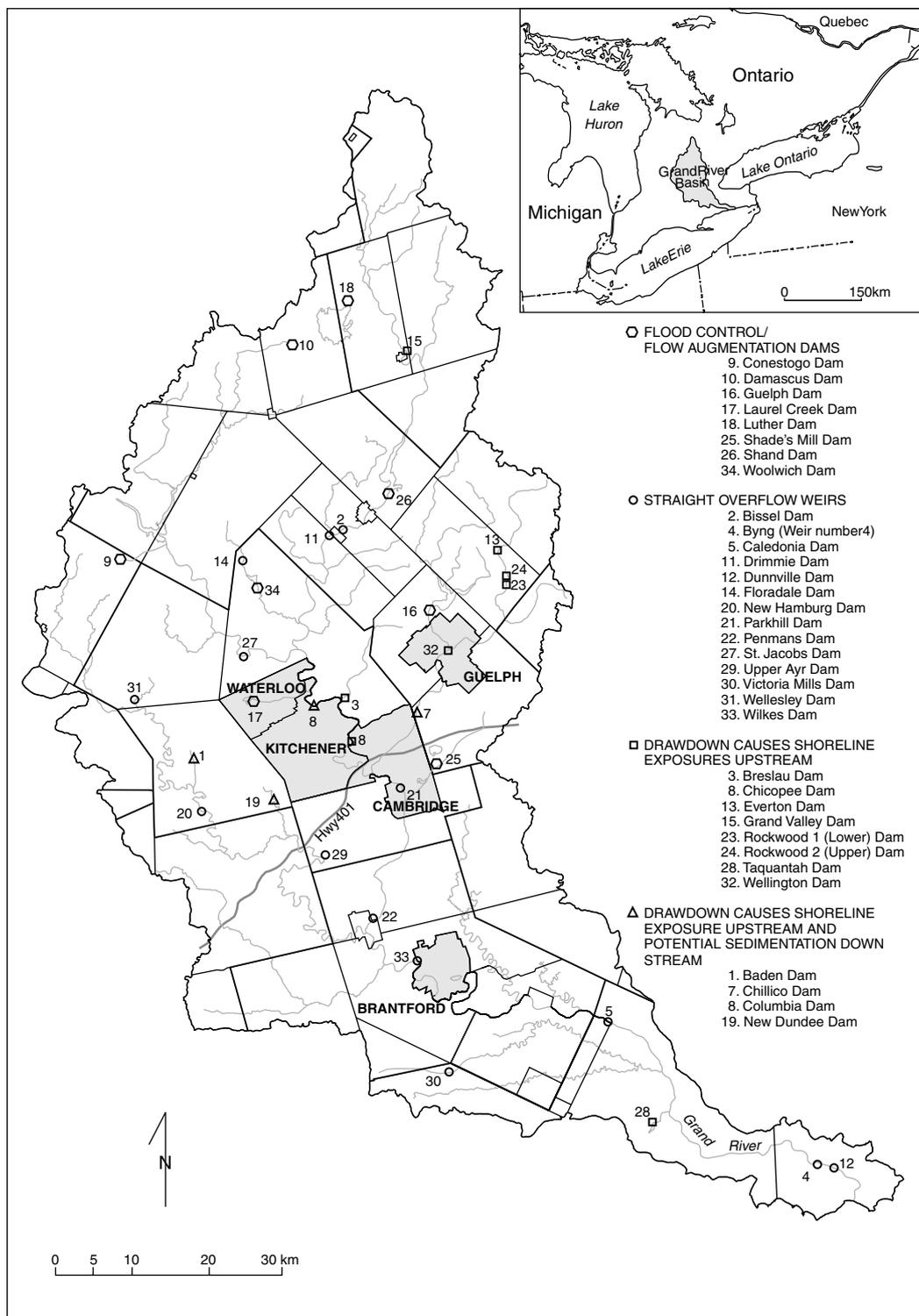
Figure 1. Grand River watershed dam locations

2 km downstream of the Laurel Creek Reservoir. Columbia Lake, has a surface area of approximately 12 ha and maximum depth of 2·8 m (City of Waterloo, 1995). The 2001 drawdown of Laurel Creek Reservoir occurred from 15 October to 31 October. Columbia Lake was subsequently drained from 5 to 19 November and is hereafter referred to in this paper as the drawdown period. Sample locations at the inflow and outflow of Columbia Lake are shown in Figure 2. The stream reach between Beaver Creek Road and Columbia Lake has extensive riparian buffers and stream banks are well vegetated. The inflow site was chosen because it was accessible, useful to characterize the outflow from Laurel Creek Reservoir and sediment inputs from uplands to Laurel Creek along this reach are negligible.
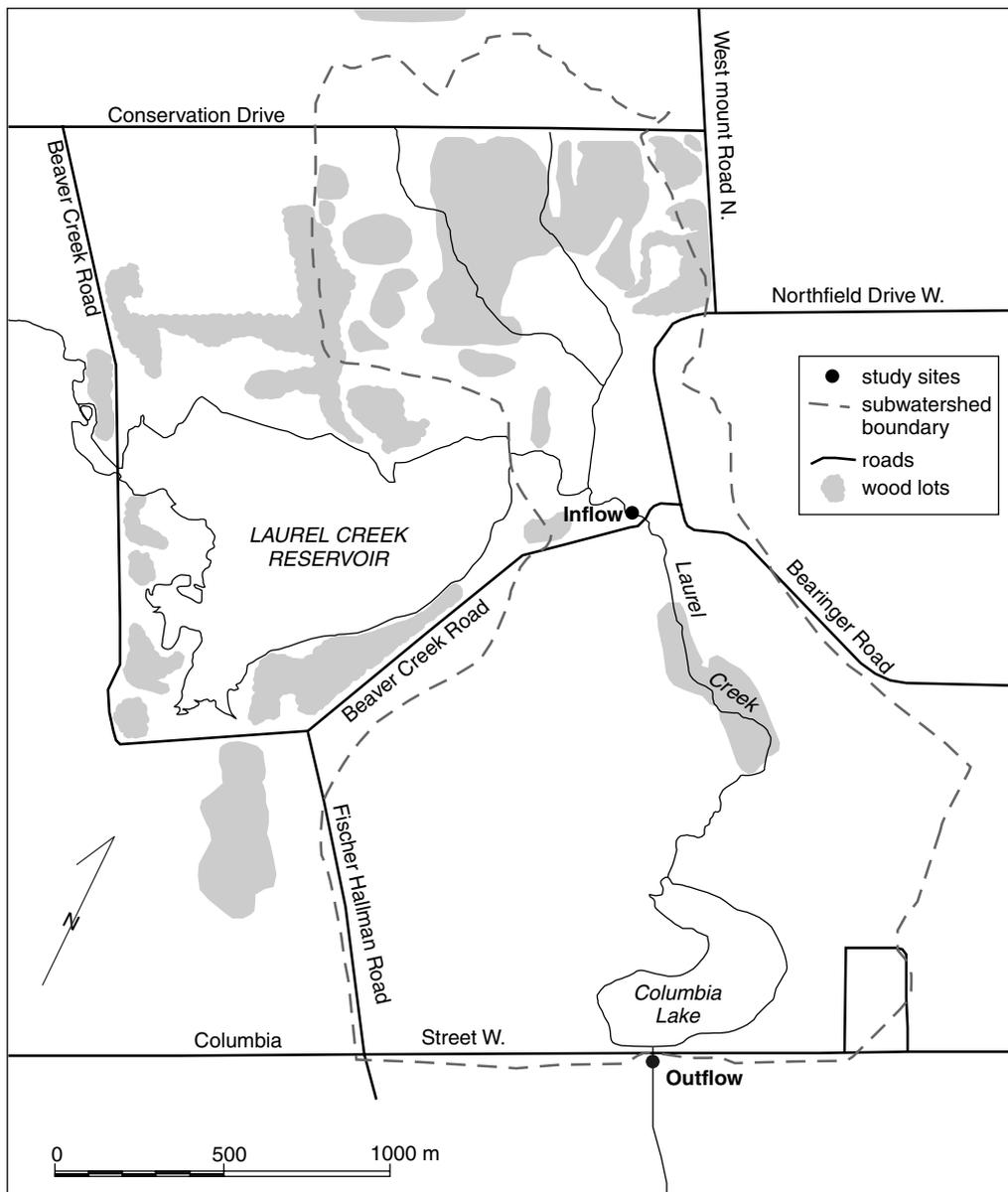

Figure 2. Study Area

METHODS

Discharge and water quality parameters were sampled before (pre-drawdown) and during the drawdown period. Pre-drawdown discharge and water samples for suspended solids (SS) and total phosphorus (TP) were collected twice weekly at the inflow and outflow of Columbia Lake in August 2001 as part of the Laurel Creek Water Quality Monitoring Programme (M. Stone, unpublished data). During drawdown, water samples were collected twice daily at the inflow, outflow and within Columbia Lake and analysed for suspended solids, total phosphorus, soluble reactive phosphorus, dissolved organic carbon and particulate organic carbon, dissolved oxygen, temperature and total dissolved solids.

Instantaneous discharge at the inflow and outflow was determined with an Ott propeller-type current meter using the velocity–area method (Dingman, 1994). Lake levels were recorded before and during drawdown from a permanent staff-gauge. Suspended solids were collected with a USGS DH48 depth-integrating suspended sediment sampler and solids concentrations were determined gravimetrically according to Standard Methods No. 2540–D (APHA, 1992).

The *in situ* particle size characteristics of suspended solids were determined by the method of DeBoer and Stone (1998). The method allows for the direct sampling and observation/measurement of solids collected on 0·45 μm Millipore HA filters. During analysis, filters are rendered (semi) transparent by applying three drops of Stephens Scientific low viscosity immersion oil to distinguish particles from the background. Particles are sized to a lower resolution of 2 μm (10× objective) using conventional optical microscopy (COM) with a Zeiss Axiovert 100 microscope connected to a Northern Exposure™ image analysis system.

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 0·45 μm Millipore filters and SRP concentrations determined according to the stannous chloride–ammonium molybdate procedure (Environment Canada, 1979) using a Technicon Auto-analyser II linked to a computer running NAP™ analysis software. After potassium persulphate digestion, samples were filtered through 0·45 μm Millipore filters and TP concentrations determined using the stannous chloride–ammonium molybdate procedure (Environment Canada, 1979).

Water samples for both dissolved organic carbon (DOC) and total organic carbon (TOC) analyses were collected in 10-mL, evacuated glass serum vials. The vials were pre-rinsed with sample and air bubbles removed (Wangersky, 1995). The samples were stored in the dark at 4 °C and acidified with 10% HNO_3 according to the methods of Otson *et al*. (1979). Prior to analysis, DOC samples were filtered through a 0·45 μm glass-fibre filter. Both DOC (filtered) and TOC (unfiltered) were analysed on a Dorhmann DC 190 high-temperature total carbon analyser with a platinum catalyst according to the methods of APHA (1992). The concentration of particulate organic carbon (POC) was calculated as the difference between TOC and DOC. Lake-bottom sediments were collected from three locations in the reservoir using a Ponar sediment sampler (Mudroch and Azcue, 1995). The samples were combined into a composite sample and oven dried at 80 °C for 48 h. Prior to analysis, the dried composite sample was coned and quartered into eight 10-g samples (Grimshaw, 1989). The organic composition of Columbia Lake bottom sediments was estimated by loss on ignition (Bengtsson and Enell, 1986).

Dissolved oxygen and water temperature were measured with a YSI portable dissolved oxygen/temperature meter (Model 55/12) and electrical conductivity was measured using an ORION Model 126 conductivity meter. Atmospheric conditions including air temperature, precipitation and wind speed and direction were measured at the University of Waterloo weather station located approximately 25 m west of Columbia Lake.

RESULTS

Flow

Results of the study for pre-drawdown and drawdown conditions are summarized in Table I. The coefficient of variation (CV), expressed as a percentage, is the standard deviation divided by the mean times 100. The

Table I. Summary of water quality and flow data

| | Inflow | | | | | | | | Columbia Lake | | | | Outflow | | | | | | | |
| | Pre-drawdown | | | | Drawdown | | | | Drawdown | | | | Pre-drawdown | | | | Drawdown | | | |
	Mean	CV %	Median	n	Mean	CV %	Median	n	Mean	CV%	Median	n	Mean	CV%	Median	n	Mean	CV%	Median	n
Q (m^3 s^{-1})	0·02	39	0·02	8	0·19	21	0·19	6					0·02	110	0·01	8	0·37	77	0·24	21
Temperature	19·3	6	19·9	8	8·7	22	7·9	7	7·1	30	6·7	14	22·5	4	22·5	8	7·1	36	6·9	19
DO (mg L^{-1})	5·6	15·7	5·7	8	8	9	8	7	8	10	8	16	5	7	5	8	9	24	9	20
SRP (µg L^{-1})					12	35	12	7	7	72	6	13					9	59	9	19
SRP load (g h^{-1})					9	14	9	6									11	77	8	19
TP (µg L^{-1})	33	50	34	8	417	41	371	7	183	63	130	13	85	24	90	8	173	56	128	19
TP load (g h^{-1})	3	80	2	8	292	54	279	6					5	131	4	8	225	105	139	19
TDS (mg L^{-1})					630	5·6	641	7	560	31	610	12					650	11	619	19
TDS load					429	25	388	6									819	72	540	19
DOC (mg L^{-1})					5·57	10·78	5·43	6	5·74	3	5·82	7					5·34	42	5·93	15
POC (mg L^{-1})					3·74	10·48	3·78	6	3·83	29	3·34	7					4·31	53	3·73	15
SS (mg L^{-1})	15	72	12	8	96	43	94	6	200	52	143	12	41	123	40·3	8	51	123	27	20
SS load (kg h^{-1})	1·2	1·2	0·5	8	344	43	339	6					2·6	144	1·2	8	102	181	23	20

average pre-drawdown discharge at the inflow and outflow of Columbia Lake was similar (C. 0·02 m s^{-1}). During drawdown, the lake level was lowered a total of 1·15 m and periodic increases in the discharge at the outflow resulted from removal of logs in the dam (Figure 3). The average outflow discharge (0·37 m s^{-1}) was approximately twice the inflow discharge (0·19 m s^{-1}) (Table I).

Suspended solids

Concentrations of suspended solids for the pre-drawdown period averaged 15 mg L^{-1} at the inflow and 41 mg L^{-1} at the outflow. During this period, no general trends in the data were observed as a function of discharge or sample location. Temporal patterns of suspended solids concentrations at the three study sites during drawdown are shown in Figure 4. Solids concentrations at the inflow ranged from 41 to 149 mg L^{-1} and inputs to the lake remained relatively constant during drawdown. The average suspended solids concentration was 95 mg L^{-1} at the inflow and 51 mg L^{-1} at the outflow (Table I). Throughout the drawdown period, $\log_{10}$ suspended solids concentrations at both Columbia Lake and the outflow were significantly related to decreasing
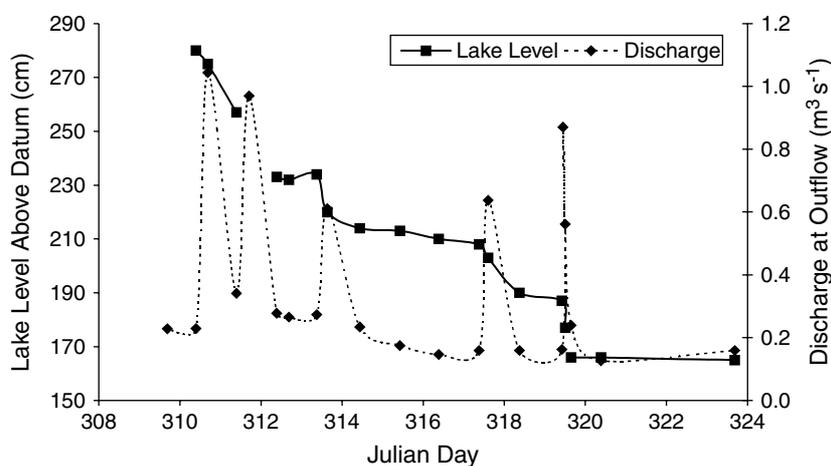

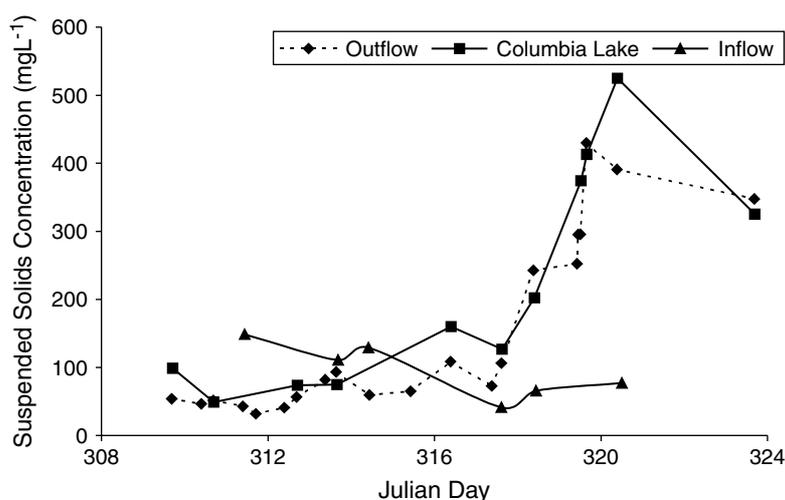Figure 3. Lake level change and outflow discharge during drawdown

Figure 4. Variability in suspended solids concentration during drawdown

water level in the lake ($r^2 = -0.894$ and -0.841, $p = 0.01$), respectively. Suspended solids concentrations in Columbia Lake and its outflow increased markedly after the water level reached a point 0.65 m below the pre-drawdown level (Figure 5). At the outlflow, the average suspended solids load was 102 kg h^{-1} and a maximum load of 805 kg h^{-1} was recorded on Julian Day 319. A total sediment mass of 18.5 t was exported from Columbia Lake over a period of 14 days.

The *in situ* particle size distributions of suspended solids collected at the study sites before, during and after (7, 15, and 16 November) drawdown are shown in Figure 6. At the inflow, the median diameter (D_{50}) of suspended solids remained relatively constant (*C*. 5.6 μm) over the drawdown period. With the exception of a few larger individual particles, all of the solids at this site were <63 μm in diameter. The particle size distribution of suspended solids in Columbia Lake varied over time. The D_{50} changed from 4.5 on 7 November to 8.7 μm on 15 November and 5.1 μm on 16 November. At the outflow, the <4 μm fraction decreased from 43% of the number of particles in suspension on 7 November to 28% on 15 November. On this day, the D_{50} in the lake and outflow was 5.1 μm but the proportion of finer particles (<20 μm) was higher in the lake. Representative COM micrographs of suspended solids collected at the study sites before, during and after drawdown are shown in Figure 7. Before drawdown, solids at the inflow were typically larger, more flocculated and contained plant debris (Figure 7, 1A). The lack of these larger organic materials in the water column of Columbia Lake and its outflow on 7 November (Figure 7, 2A and 3A) indicates that they settle quickly upon entering the lake. During drawdown, suspended solids concentrations increased in the lake and larger organic materials were present in the water column (Figure 7, 2B). The larger flocculated materials at the outflow (Figure 7, 3B) on 15 November result from transient flow conditions and highly turbulent discharge caused by declining lake level, which increased resuspension of bottom sediments. At the end of the drawdown period, larger but less flocculated materials remained in the water column of Columbia Lake and its outflow (Figure 7, 2C and 3C).

During drawdown, POC represented 3.9, 8.5 and 1.9% of the suspended solids concentration by mass for the inflow, outflow and Columbia Lake, respectively. Outflow POC concentrations showed little variability until the final day of drawdown when POC concentrations increased nearly three times to 9.7 mg L^{-1}. The POC concentrations returned to 4.73 mg L^{-1} one day after the final logs were removed. Throughout the drawdown, POC was greater in the outflow than in the reservoir and the inflow. The POC was not significantly related with discharge or lake level. The organic matter content of bottom sediments determined by loss on ignition tests was 8.4% ± 0.27, which is similar to the 8.5% POC at the outflow.
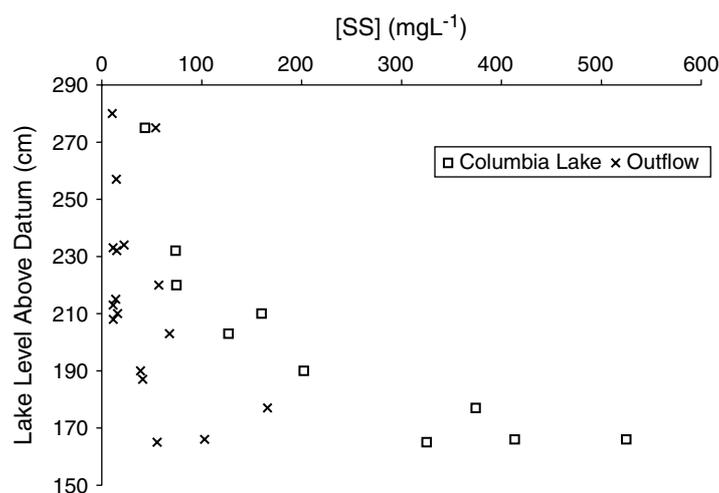

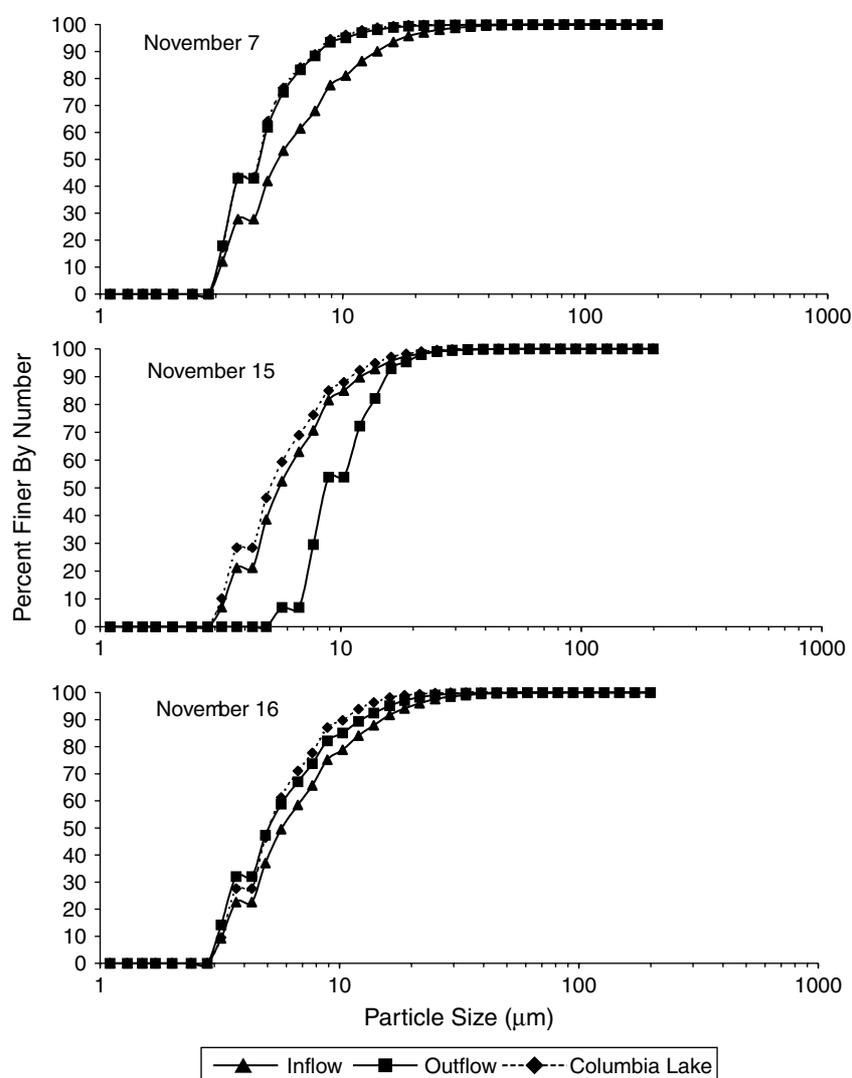Figure 5. Lake level change and suspended solids concentration in Columbia Lake and its outflow

Figure 6. Changes in the particle size distribution of suspended solids during drawdown

Phosphorus

Temporal variability in total phosphorus concentrations at the three study sites is shown in Figure 8 and a summary of phosphorus (TP, SRP) concentrations and loads for pre-drawdown and drawdown periods is presented in Table I. Inflow TP concentrations ranged from 233 to 647 $\mu g\ L^{-1}$ during the drawdown owing to the availability and transport of P-enriched solids from Laurel Creek reservoir to Columbia Lake (Figure 8). Increases in TP concentration at the inflow on Julian Day 319 are associated with the erosion of P-enriched river-bed sediments as the river adjusted to declining water levels in Columbia Lake. Total phosphorus concentrations in Columbia Lake and its outflow increased over the study period as a function of declining lake level (Figures 8 and 9).

The pre-drawdown mean TP concentration was 33 $\mu g\ L^{-1}$ at the inflow and 85 $\mu g\ L^{-1}$ at the outflow but during drawdown, mean TP levels increased an order of magnitude to 417 $\mu g\ L^{-1}$ at the inflow and approximately doubled to 173 $\mu g\ L^{-1}$ at the outflow (Table 1). Dissolved phosphorus (SRP) represented
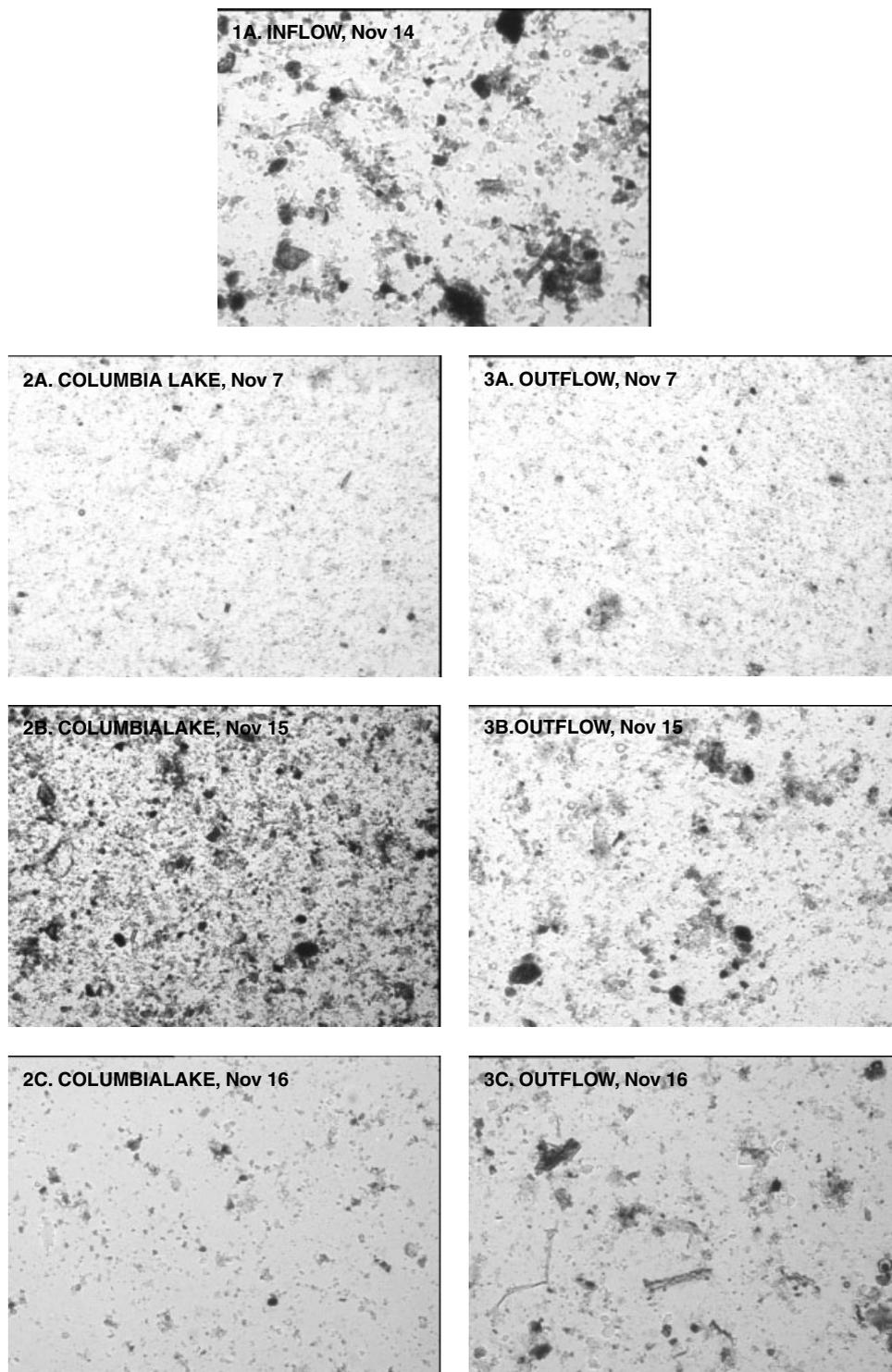
Figure 7. Conventional optical microscopy micrographs of suspended solids at the inflow, Columbia Lake and its outflow during drawdown. Each micrograph is 625 μm × 475 μm
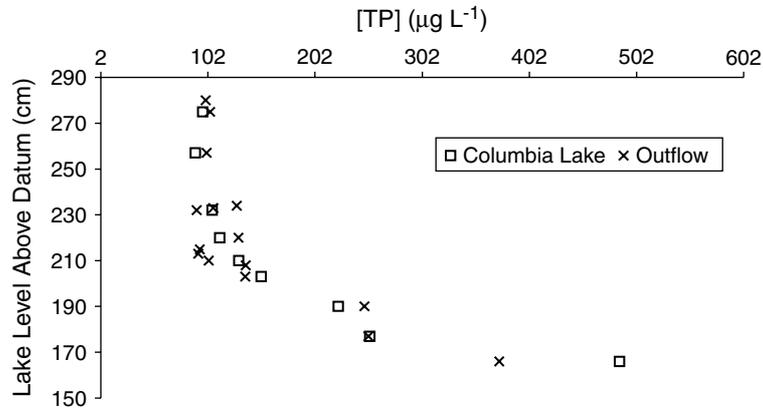
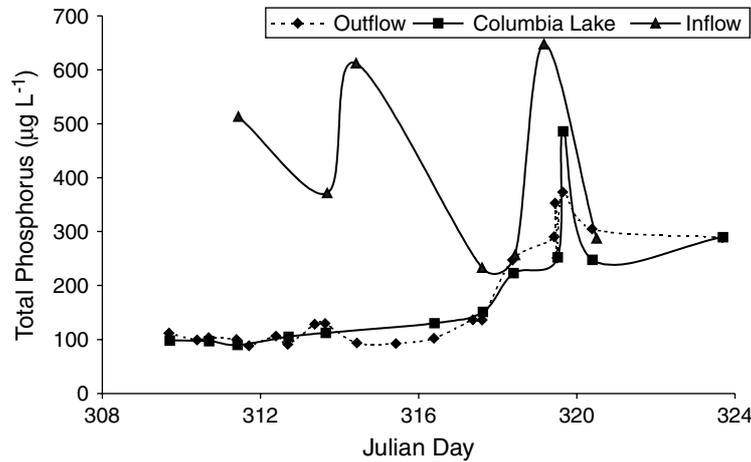Figure 8. Variability in total phosphorus concentrations during drawdown

Figure 9. Lake level change and total phosphorus concentration in Columbia Lake and its outflow

about 5% of the TP concentration and 1·3% of the total dissolved solids in Columbia Lake and its outflow. The average TP load at the outlet of Columbia Lake was 182 g h^{-1} and the maximum load of 507 g h^{-1} was recorded on Julian Day 319. A TP mass of 62·6 kg was exported from Columbia Lake over a period of 14 days

DISCUSSION

Export characteristics—pre-drawdown

During the pre-drawdown period, concentrations of suspended solids and total phosphorus were significantly higher at the outflow than the inflow of Columbia Lake ($p < 0.007$) (Table I). In shallow reservoirs, bottom shear stresses from wind turbulence resuspend benthic sediment into the water column (Douglas and Rippey, 2000). The data show that before drawdown, Columbia Lake is a net exporter of solids and phosphorus owing to constant resuspension of bottom sediments from wave action and bioturbation by carp and ducks (M. Stone, unpublished data). Other studies have shown that bottom sediments in reservoirs can represent a large source of particulate P that can be resuspended into the water column (Sondergaard *et al*., 1992). In

the study of a eutrophic reservoir, Perkins and Underwood (2001) reported that internal phosphorus loading increased when physical conditions facilitate the resuspension of cohesive bottom sediment. The magnitude of suspended solids and phosphorus export from Columbia Lake is similar to a small storm-water retention pond in Kingston, Ontario (Anderson *et al*., 1996). The concentrations of suspended solids are comparable to a study by Striegl (1987) in a small Illinois urban watershed. The TP levels at the Columbia Lake outflow are similar to the range reported by Bodo (1988) for selected Great Lakes tributaries.

Export characteristics—drawdown

Neither suspended solids nor TP concentrations at the outflow correlated well with discharge but were significantly related to lake level ($p = 0.01$), particularly at and greater than lake levels 0.65 m below pre-drawdown conditions (Figure 5). At this threshold water level, minor decreases in lake level resulted in dramatic increases in suspended solids and TP concentrations in Columbia Lake and its outflow. As Columbia Lake water levels decreased, wave action and increased bottom shear from turbulent inflows increasingly influenced the resuspension rate of bottom sediments causing SS and TP concentrations in the water column to increase. In a study on drought-induced decreases in lake level, Matty *et al*. (1987) reported increasing sediment resuspension with declining lake level owing to an increased proportion of bottom sediments susceptible to storm-wave action. Mayer *et al*. (1991) determined that particulate phosphorus (PP) loads in the Niagara River were dependent on SS concentrations related to resuspension of bottom sediments in Lake Erie during storm events. After a 1·2 m decrease in the water level of Columbia Lake, inflowing waters formed a channel that meandered across the exposed lake bottom. Flow in this channel eroded lake bottom sediment further increasing the export of solids from the lake. Despite the increase in TP and SS export during the drawdown period, Columbia Lake was a sink for these pollutants. Mean SS loads at the inflow and outflow were 344 kg h^{-1} and 102 kg h^{-1} respectively, whereas mean TP loads for the same sites were 292 g h^{-1} and 225 g h^{-1} (Table 1).

Droppo and Amos (2001) used an *in situ* annular flume to determine the structure, stability and transformation of cohesive bottom sediments in Hamilton Harbor. They proposed a general three-layer stratigraphical model with surface deposited organic flocs (layer 1) that compress in a collapse zone (layer 2) to form a consolidated bed (layer 3). From the surface layers to the consolidated bed, there is an increase in consolidation and floc density but a decrease in water content. Particle size data from the Columbia Lake study provide indirect evidence for the mechanism of sediment resuspension with decreasing lake level and indicate that materials in the water column are characteristic of solids from bottom layers 1 and 2 of the general model proposed by Droppo and Amos (2001). During drawdown, the D_{50} of suspended solids in Columbia Lake and its outflow increased (Figure 6). Based on visual inspection of COM micrographs, suspended solids in the lake were highly flocculated and organic materials and larger flocs were present in the outflow waters. The presence of larger porous flocs, observed in COM micrographs (Figure 7, 2B), suggest that the materials originated from sediment layers 1 and 2 in Columbia Lake, which is consistent with direct field observations of bottom materials.

The POC concentration at the outflow increased as lake level decreased ($p = 0.005$). Wetzel (1983) observed that annual POC concentrations strongly follow the patterns of lake stratification and the resuspension of settled biofilm-coated suspended solids and decaying organisms. The lowering of Columbia Lake increased the bottom shear stress on lake bottom sediments resulting in the observed relationship between POC and both lake level and suspended solids. Hydrogen bonding with silica surfaces is important from pH 5 to 8 and within this range, silica is negatively charged by loss of protons. Consequently, the particle surface behaves as a weak cation-exchange resin (Thurman, 1985). The pH in Columbia Lake is well within this range and it is hypothesized that the sorption of dissolved organic matter to newly suspended solids can explain this significant relationship. As the concentration of suspended solids increases in the system, the sites available for organic matter sorption also increase, which increases the POC concentration in the system. This observation is consistent with other studies (Meybeck, 1981, 1993).

The present study has implications for water management of the Grand River and its impact on nutrient dynamics in the near-shore zone of the Lake Erie eastern basin. During the study, concentrations of TP and suspended solids at the Columbia Lake outflow exceeded the Ontario Provincial water quality objectives of 30 ug L^{-1} and 50 mg L^{-1}, respectively (OMEE, 1999), which represents a significant pulse of sediment-associated P to downstream reaches. Through a series of subsequent resuspension and deposition events in the river, this particulate P will eventually contribute to the external loading of Lake Erie. In order to minimize sediment and nutrient export to downstream environments, we recommend that winter water levels be lowered no more than 0·6 m below pre-drawdown conditions. The annual autumn release of water from all reservoirs in the Grand River watershed (Figure 1) will add to the solids and phosphorus flux to Lake Erie thus affecting the external nutrient loading to Lake Erie and increasing P concentrations in the near-shore zone. Further study on the structure, composition and mass flux of reservoir sediment via the Grand to the near-shore littoral environment of Lake Erie is required to understand the fate and effects of sediment-associated P exported from watersheds and to determine its relationship to zebra mussel (*Dreissena polymorpha*) driven changes on the cycling of P and organic matter throughout the lake.

CONCLUSIONS

Suspended solids and total phosphorus export from Columbia Lake increased significantly with decreasing lake level. Elevated solids concentrations at the outflow were attributed to the resuspension of cohesive bottom sediments at a threshold lake level, below which, the majority of sediment and phosphorus was exported from Columbia Lake. Suspended solids consisted of flocculated cohesive materials and their potential for the downstream transport of nutrients and other pollutants is relatively high. The systematic release of water from reservoirs in the Grand River will increase the tributary flux of particulate P to Lake Erie and may partially account for the observed increases of TP concentrations in the near-shore zone during autumn.

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