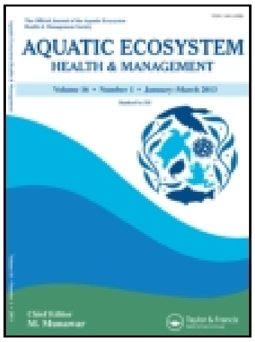

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We present a modelling analysis of the management practices that could lead to significant reduction of phosphorus export from the Bay of Quinte watershed and an evaluation of the overall uncertainty associated with the assessment of the Beneficial Use Impairment Eutrophication and Undesirable Algae. *Our work highlights the internal recycling as one of the key drivers of phosphorus dynamics in the Bay. The flow from the Trent River is the predominant driver of the upper Bay dynamics until the main stem of the middle area however, the sediments in the same segment release a significant amount of phosphorus and the corresponding fluxes are likely amplified by the macrophyte and dreissenid activity. From a management standpoint, the presence of a significant positive feedback loop in the upper Bay suggests that the anticipated benefits of additional reductions of the exogenous point and non-point loading may not be realized within a reasonable time frame (i.e. 5—10 years). Our analysis of nutrient loading scenarios shows that the restoration pace of the Bay could be slow, even if the riverine total phosphorus concentrations reach levels significantly lower than their contemporary values, <25 μg* TP *l^{-1}. We believe that the on-going management decisions, monitoring, and modelling should also explicitly consider the role and broader ramifications of internal phosphorus loading into the system. The anticipated lessons from such a multi-faceted exercise are a unique aspect of the Bay of Quinte ecosystem because of the long history of research and monitoring data. This study can produce*

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transferable knowledge to other systems worldwide, experiencing similar hysteresis patterns associated with internal nutrient loading.

Keywords: eutrophication, phosphorus modelling, internal loading, watershed management, water quality criteria, sediment dynamics

Introduction

A rigorous analysis of decision problems in water quality management requires specification of (i) a finite set of alternative management actions, including any constraints on their use; (ii) an objective function for evaluating the alternative management strategies; (iii) predictive models of system dynamics formulated in terms of quantities relevant to management objectives; and (iv) a monitoring program to follow system evolution and responses to management (Walters, 1986). The objective function specifies the value of alternative management actions and usually accounts for social benefits and costs, as well as conditional constraints. The predictive models must realistically reproduce the relevant behaviors of aquatic ecosystems, which often involve complex non-linear dynamics and are characterized by spatial, temporal, and organizational heterogeneity (Arhonditsis et al., 2007). Perhaps, even greater challenges are posed by the uncertainty in the predictions of management outcomes. This uncertainty may stem from incomplete control of management actions, errors in measurement and sampling, environmental variability, or incomplete knowledge of system behaviour. Failure to recognize and account for these sources of uncertainty can severely affect management performance, and in some cases, has led to catastrophic environmental and economic losses (Reckhow et al., 2005). The currently popular notion of adaptive management implementation is specifically designed to accommodate the dynamics of uncertainty in both the environmental policy making process as well as model development (Dorazio and Johnson, 2003).

The Bay of Quinte, a Z-shaped embayment at the northeastern end of Lake Ontario, represents a characteristic case, where scientific uncertainty underlies the current management efforts to integrate environmental concerns with socioeconomic values. This uncertainty exists despite one of the longest continuing research and monitoring programs of any site in the Great Lakes. The Bay of Quinte has a long history of eutrophication problems resulting in frequent and spatially extensive algal blooms, predominance of toxic cyanobacteria, and hypolimnetic oxygen depletion (Minns et al., 2011). Thus, it was one of the 43 degraded sites around the Great Lakes designated by the International Joint Commission as Areas of Concern (*AOC*s) in 1986[1]. Following the *AOC* designation, the Bay of Quinte Remedial Action Plan (*RAP*) was formulated through a wide variety of government, private sector, and community participants to provide the framework for actions aimed at restoring the system. In this regard, all the restoration efforts in the Bay were founded upon an "ecosystem" management approach, which was selected as a pragmatic means for addressing the effects of a suite of tightly intertwined stressors related to eutrophication. One of the critical questions arising from the management efforts in the Bay of Quinte area is to identify the optimal water quality criteria that can impartially represent the prevailing conditions in the system. Recent empirical evidence suggested that the historical target of a seasonal average *TP* concentration of 30 μg l^{-1} was not representative of the actual temporal variability in the system nor did it reflect the water quality conditions (e.g.

[1]Areas of Concern are sites on the Great Lakes system where environmental quality is significantly degraded and beneficial uses are impaired. In the Bay of Quinte, there are 9 beneficial use impairments: Degraded Fish and Wildlife Populations, Degradation of Benthos, Eutrophication or Undesirable Algae, Restrictions on Drinking Water Consumption or Taste and Odor Problems, Beach Closings, Degradation of Aesthetics, Degradation of Phytoplankton and Zooplankton Populations, Loss of Fish and Wildlife Habitat, Restrictions on Fish and Wildlife Consumption (impaired for fish consumption), while further assessment is required for the beneficial use "Fish Tumors or Other Deformities."

toxic algal blooms) in inshore areas of high public exposure, such as beaches (Kim et al., 2013; Zhang et al., 2013). In this regard, Zhang et al. (2013) asserted that one of the contemporary challenges in the Bay of Quinte is the establishment of eutrophication delisting objectives that will be framed upon: (i) a finer temporal scale, such as monthly or even daily snapshots from samplings that cover the entire growing season; (ii) the need to accommodate the considerable spatial variability in the system; (iii) the importance of identifying a numerical value that is both scientifically sound and achievable; (iv) the pragmatic view that the criteria setting process should explicitly accommodate the natural variability of the system or the substantial uncertainty characterizing the existing exogenous loading estimates by permitting a realistic frequency of goal violations; and (v) the fact that all management decisions should effectively balance between environmental concerns and socioeconomic values. This balance reflects how all citizens, businesses, industries, and the resource management agencies view the potential of the Bay of Quinte to be a symbol of an environmentally sustainable community.

In this study, we present a modelling analysis of the management practices that would lead to significant reduction of phosphorus export from the Bay of Quinte watershed and an evaluation of the overall uncertainty associated with the assessment of the Beneficial Use Impairment *Eutrophication and Undesirable Algae*. Our analysis is based on a network of models that connects the watershed processes with the dynamics of the Bay of Quinte, using the *SPARROW* non-linear regression strategy along with a mathematical model that aims to reproduce the phosphorus dynamics in the system. First, we present an exploratory analysis of the landscape characteristics, land cover patterns, and phosphorus export spatial variability. We then examine the impact of various exogenous phosphorus loading sources relative to the role of dreissenids and macrophytes on the eutrophication processes in the receiving waterbody. Our study undertakes an analysis of management scenarios in the Bay of Quinte watershed and subsequently attempts to shed light on critical aspects of the system functioning that invite further investigation and will likely determine our predictive capacity to assess compliance with the most sensible delisting water quality targets.

Materials and methods

Watershed modelling

Prior to the *SPARROW* application, we used a novel classification technique, Self-Organizing Maps (*SOM*), to gain insights into the physiographical features and land-use patterns in the Bay of Quinte watershed, and to subsequently associate them with the phosphorus non-point source loading. *SOM* is a neural network technique known to provide a powerful means for extracting information from complex multi-dimensional data and map it onto a reduced dimensional space (Kohonen, 1997). Being particularly convenient in visual understanding, *SOM* has been widely applied to pattern recognition of various learning problems (Chon et al., 1996). In the present application, we used eighteen classification variables, such as the landscape slope, saturated soil hydraulic conductivity, soil bulk density, and areal fractions for different land use types (lakes, ponds, alvars, bogs, coniferous swamps, deciduous swamps, fens, marshes, deciduous forests, coniferous forests, cutovers, mining areas, urban lands, pastures, and croplands) in 73 gauged and 137 ungauged subwatersheds. Thus, a total of 210 spatial units were distributed on 2-dimensional hexagonal maps, and then clustered in different groups according to their similarities. We used the *SOM* Toolbox developed by Helsinki University of Technology (Vesanto et al., 2000).

The *SPARROW* model was implemented to estimate nutrient loads, yields, and deliveries at landscape and regional scales (McMahon et al., 2003). The model uses a hybrid empirical/process-based approach designed to be applied to a network of water quality monitoring stations. *SPARROW* consists of a two-level hierarchical spatial structure. Watersheds are first divided into subwatersheds, each of which drains to a water quality monitoring station, and then each subwatershed is disaggregated into reach catchments draining to a particular stream segment (Schwarz et al., 2006). *SPARROW* considers two basic processes: (i) the source processes, represented by export coefficients, accounting for the constituent mobilization;

(ii) the sink processes introduced by delivery factors, predicting how landscape attributes modulate the delivery of the mobilized constituent to streams, and attenuation coefficients, predicting the amount of the delivered constituent remaining in transit per length of stream or per reservoir (see parameter definitions in Table 1). In particular, the governing *SPARROW* equation can be expressed as:

$$MAL_i = \left\{ \sum_{n=1}^{N} \sum_{j=1}^{J_i} \beta_n S_{n,j} e^{(-\alpha Z_j)} H_{i,j}^S H_{i,j}^R \right\} \varepsilon_i$$

where the subscripts i and j refer to subwatersheds and reach catchments, respectively; MAL_i refers to the mean annual total phosphorus load measured at the monitoring station of the subwatershed i in metric tonnes per year; n, N refers to the source index, N is the total number of sources (diffuse and point sources) and n is an index for each source; J_i refers to the number of reaches in subwatershed i; β_n refers to the estimated source coefficient for source n with units metric tonnes per unit area (km^2) and year; $S_{n,j}$ refers to the quantity (area in km^2 or number of septic tanks) of source n in reach j. In the Bay of Quinte application, we explicitly considered the export of phosphorus from forested areas, pastures, urban sites, septic tanks as well as five crop types, i.e. wheat, oat, corn, alfalfa and fallow land areas. The parameter α refers to the vector of land to water delivery

Table 1. Posteriors estimates of all the *SPARROW* parameters.

Parameter	Unit	Mean	S.D.	Parameter description
Delivery coefficient (α)	hr cm^{-1}	0.172	0.063	It takes approximately 10 min for P to be transmitted for 1 cm.
TP export coefficient from forest areas (β_1)	tons km^{-2} yr^{-1}	0.018	0.006	18 kg of *TP* per km^2 are released from forested areas on an annual basis.
TP export coefficient from pasture areas (β_2)	tons km^{-2} yr^{-1}	0.040	0.020	40 kg of *TP* per km^2 are released from pasture areas on an annual basis.
TP export coefficient from urban areas (β_3)	tons km^{-2} yr^{-1}	0.126	0.087	126 kg of *TP* per km^2 are released from urban areas on an annual basis.
TP export coefficient from septic tanks (β_4)	tons tank^{-1} yr^{-1}	0.001	0.001	1 kg of *TP* is released from septic tanks on an annual basis.
TP export coefficient from wheat-cultivated areas (β_{5wheat})	tons km^{-2} yr^{-1}	0.076	0.032	76 kg of *TP* per km^2 are released from wheat-cultivated areas on an annual basis.
TP export coefficient from oat-cultivated areas (β_{5oat})	tons km^{-2} yr^{-1}	0.127	0.065	127 kg of *TP* per km^2 are released from oat-cultivated areas on an annual basis.
TP export coefficient from corn-cultivated areas (β_{5corn})	tons km^{-2} yr^{-1}	0.044	0.026	44 kg of *TP* per km^2 are released from corn-cultivated areas on an annual basis.
TP export coefficient from alfalfa-cultivated areas ($\beta_{5alfalfa}$)	tons km^{-2} yr^{-1}	0.030	0.011	30 kg of *TP* per km^2 are released from alfalfa-cultivated areas on an annual basis.
TP export coefficient from fallow land areas ($\beta_{5fallow}$)	tons km^{-2} yr^{-1}	0.072	0.038	72 kg of *TP* per km^2 are released from fallow lands on an annual basis.
1st order settling rate in lakes (*kr*)	m yr^{-1}	4.980	1.551	*TP* settles with an average rate of 4.98 m per year in the lakes.
1st order attenuation rate for small streams (ks_1)	km^{-1}	0.037	0.022	3.7% of *TP* per kilometer is attenuated in small streams.
1st order attenuation rate for large streams (ks_2)	km^{-1}	0.011	0.007	1.1% of *TP* per kilometer is attenuated in large streams.

coefficients, Z_j is a vector of the land-surface characteristics associated with drainage to reach j. Exploratory analysis prior to the *SPARROW* application showed that the vertical hydraulic conductivity was the optimal surrogate variable to characterize Z_j in the Bay of Quinte watershed. $H^S_{i,j}$ represents the fraction of nutrient mass originating in reach j remaining at the monitoring station of the subwatershed i as a function of first order loss processes in streams; $H^R_{i,j}$ refers to the fraction of nutrient mass originating in reach j remaining at station i as a function of first order loss processes in lakes and reservoirs; and ε_i refers to a random multiplicative error term assumed to be independently and identically distributed across all subwatersheds.

First order loss processes in streams include loss to sediments and biota, and are expressed as:

$$H^S_{i,j} = \exp(-k_s L_{i,j})$$

where k_s refers to the first order loss coefficient for streams (km^{-1}), and $L_{i,j}$ refers to the stream length in kilometers between reach i and station j. Our study explicitly characterizes the attenuation processes in low and high flow streams, using the flow level of 1 m^3 s^{-1} as a cutoff point. First order loss processes operating in lakes and reservoirs are limited to loss to sediment, which is expressed as

$$H^R_{i,j} = \prod_l \exp(-k_r q_l^{-1})$$

where l refers to any lakes or reservoirs between reach i and station j, k_r. refers to the first order loss coefficient or settling velocity (m year^{-1}), q_l refers to the aerial hydraulic loading of the lake/reservoir (m year^{-1}).

Bayesian parameter estimation was also used to address several critical issues related to the *SPARROW* applications, such the uncertainty of calibration data, the importance of informative prior parameter distributions in assisting model calibration, and the implications of the covariance of model parameters on the inference drawn and the posterior patterns derived (see Equation 12 in Wellen et al., 2014). The phosphorus loading estimates in our calibration dataset were based on total phosphorus concentrations and flow data from 73 and 48 monitoring sites in the Bay of Quinte watershed, respectively. The development of a regression model ($r^2 > 0.94$) that connected the annual average flows with the corresponding catchment areas enabled the calculation of the annual *TP* loads in sites, where the flow data were not available. Further information about the methodological protocol used to derive the loading estimates and the associated errors can be found in Wellen et al. (2014) and Kim et al. (2014a,b submitted).

Phosphorus modelling for the receiving waterbody

The basis of the present study is the *TP* mass-balance model for the Bay of Quinte, originally developed by Minns and Moore (2004) and recently modified by Kim et al. (2013). Improvements in the mechanistic foundation of that model involved the explicit representation of macrophyte dynamics; the role of dreissenids in the system; improved spatial resolution; and several processes related to the fate and transport of phosphorus in the sediments along with the interplay between water column and sediments, such as particulate sedimentation dependent upon the standing algal biomass, sediment resuspension, sorption/desorption in the sediment particles, and organic matter decomposition. Schematic illustration of the modelled processes in the receiving waterbody is provided in Figure 1, while the basic conceptual design, the mathematical formulations, and the forcing functions used are described in detail in Kim et al. (2013). The *TP* concentrations in the calibration dataset were generated as time-weighted monthly means of data provided by the Project Quinte members (2011) in their annual monitoring report. Monthly mean nutrient concentrations for the Lake Ontario outlet basin were also provided by the Department of Fisheries and Oceans' Long-term Bio-monitoring (Bioindex) Program (Johannsson et al., 1998).

Results and discussion

Land use patterns and phosphorus trends in the Bay of Quinte watershed

The Canadian Shield separates the northern and southern Bay of Quinte watershed into two seemingly distinct sub-basins. In the northern part,

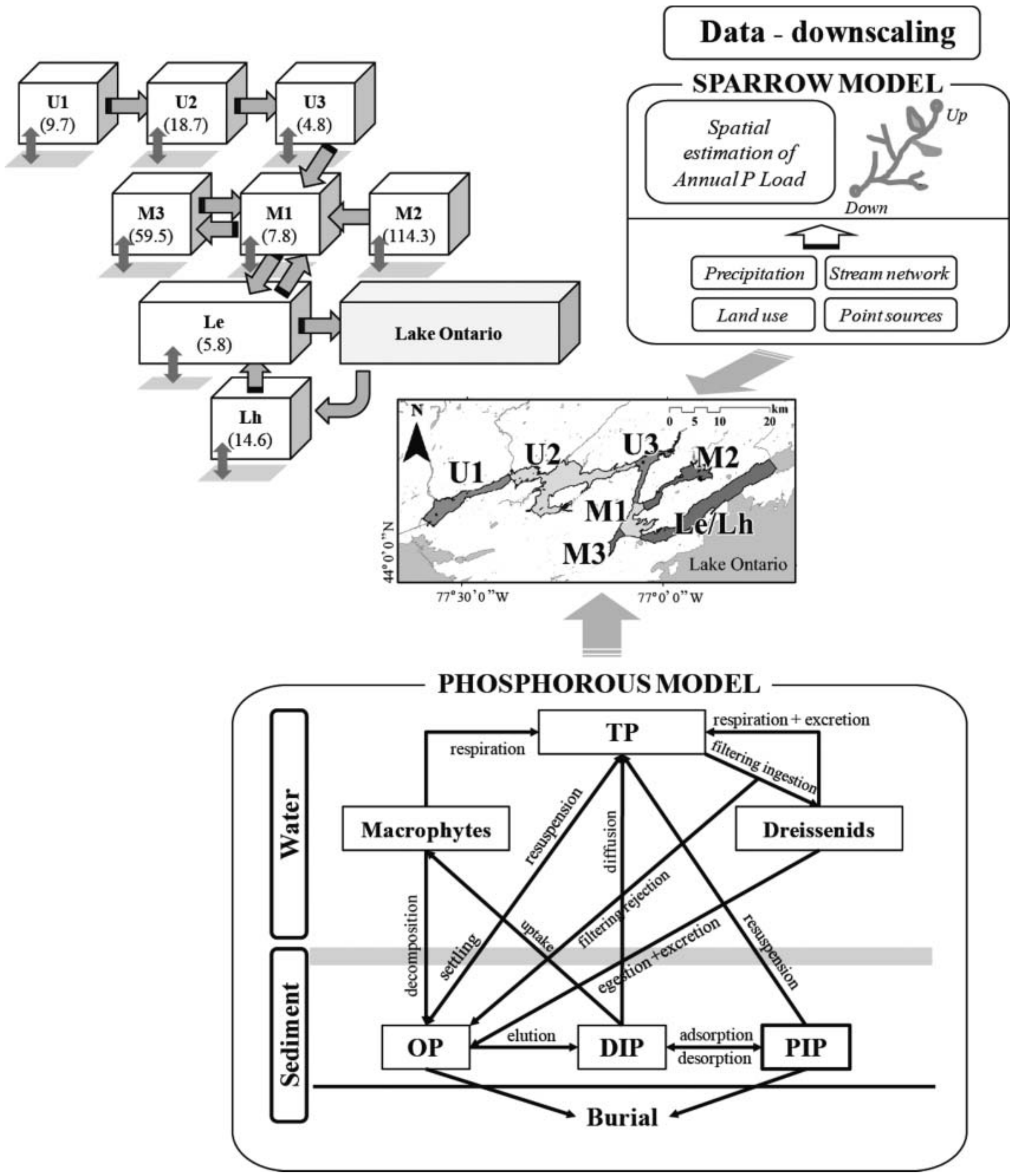

Figure 1. Conceptual diagram of the integrated phosphorus modelling framework for the Bay of Quinte. The spatial segmentation of the model for the receiving waterbody consists of the following compartments: (*U1*) the segment that extends from the mouth of Trent River until the city of Belleville; (*U2*) the segment that begins from the mouth of Moira River and comprises the Big Bay, Muscote Bay, and North Point Bay; (*U3*) the area influenced by the inflows of Napanee River, extending until the outlet of Hay Bay. In the middle Bay, there are three segments corresponding to the main stem (*M1*) and the two adjacent embayments: Hay Bay (*M2*), and Picton Bay (*M3*). The lower segment of the Bay, representing the transitional area to Lake Ontario, was separated into the epilimnetic (*Le*) and hypolimnetic (*Lh*) compartments. Numbers in parentheses correspond to the average flushing rate of each segment.

forested areas with coniferous and deciduous trees represent the most predominant land cover, while croplands occupy a large portion of the lower catchment, particularly in the vicinity of lakes and the Bay of Quinte itself (Figure 2a). Lakes, pastures, and wetlands are sparsely distributed in the southern part of the basin, while the urban landscape mainly corresponds to the cities of Peterborough, Trenton, Belleville and other smaller towns. Based on the spatial heterogeneity of the eighteen classification variables, *SOM* delineated six spatial clusters in the Bay of Quinte watershed with fairly distinct land-use patterns (Figure 2b). Coniferous and deciduous coverage along with pastures and croplands dominate the landscape in cluster 1. It is also interesting to note that different types of wetlands, such as fen (≈10%), coniferous swamp (≈8%), and alvar (≈0.4%) have their highest areal fraction values in the same cluster. In cluster 2, the average landscape slope is steep and the soil bulk density is high. The areal fractions of forests as well as mining and logging sites are also high. In cluster 3, most of the subwatersheds are located in the vicinity of the Bay of Quinte, where crops occupy ≈75% of the area. Not surprisingly, the annual *TP* yield per area and average *TP* concentrations are the highest (528 kg km^{-2} yr^{-1} and 103 μg l^{-1}) in these same regions. In cluster 4, soil hydraulic conductivity is significantly higher, deciduous swamp are more abundant relative to the rest watershed, cropland coverage is the second highest (≈41%), and thus the net *TP* export is high. In cluster 5, urban land represents ≈74% of the land-use coverage and net *TP* export and yield are the second highest (3.72 tonnes yr^{-1} and 209 kg km^{-2} yr^{-1}), which is further accentuated by the increased point source loading (2.44 tonnes yr^{-1}). In cluster 6, pasture and cropland approximately correspond to 60% of the area, and these subwatersheds are mainly located adjacent to the Bay of Quinte.

The goodness-of-fit between the observed and predicted *TP* loading values from *SPARROW* model was excellent in the logarithmic scale ($r^2 > 0.95$), although there were four sites with error greater than 10 tonnes yr^{-1} when the *SPARROW* predictions were back-transformed in the original scale (Figure 3). The posterior parameter values offered interesting insights (and/or testable hypotheses) into the patterns of phosphorus export and delivery in the Bay of Quinte watershed (Table 1). The main findings from the *SPARROW* modelling exercise were as follows: (i) urban areas are characterized by a fairly high areal phosphorus export with a mean estimate of 126 kg of TP per km^2 on an annual basis; (ii) the contribution of phosphorus from agricultural land uses can vary considerably among the various crop types (30–127 *TP* kg per km^2), but is generally lower than the impact of urban sites. This finding appears to contradict the popular notion that rates nutrient export of urban lands below that of agricultural lands due to lower anthropogenic nutrient subsidies, such as fertilizer implementation (Moore, 2004; Soldat and Petrovic, 2008; Soldat et al., 2009). Nonetheless, other studies in the region of Southern Ontario have found urban total phosphorus export rates to be comparable (or even higher) than agricultural total phosphorus export rates (Winter and Duthie, 2000; Wellen et al., 2014); (iii) the crop-specific export coefficient values were on par with those typically reported in the literature (Harmel et al., 2008), although the confounding effects of the uncertainty associated with the delineation of the areal coverage of the various crop types may be responsible for some counterintuitive results (e.g. $\beta_{5oat} > \beta_{5corn}$); (iv) the attenuation rate in low flow streams (3.7% of *TP* per kilometer) appears to be distinctly greater than in those with high flow (1.1% of *TP* per kilometer), reflecting a tighter coupling between the streambed and water column in the former streams that allows the biotic (uptake) and abiotic (settling) processes to exert control on the nutrient load en route to the receiving waterbody (Basu et al., 2011); and (v) fallow areas are responsible for approximately 70 kg of *TP* per km^2 on an annual basis.

Interesting temporal trends were also found about the relative contribution of the different point and non-point sources to the total phosphorus loading in the Bay of Quinte (Figure 4). The inflows from Trent River represented less than 50% of the total loading discharged into the system before the reduction of phosphorus in detergents and the upgrades at the local wastewater treatment plants in the 1970s, but the relative contribution of the Trent River to total loading has gradually increased up to 70% over the last decade. By contrast, the proportion of phosphorus loading associated with the point sources was reduced from 21% to 3%, while the relative contribution of the rest of the tributaries has remained essentially unaltered over the time period

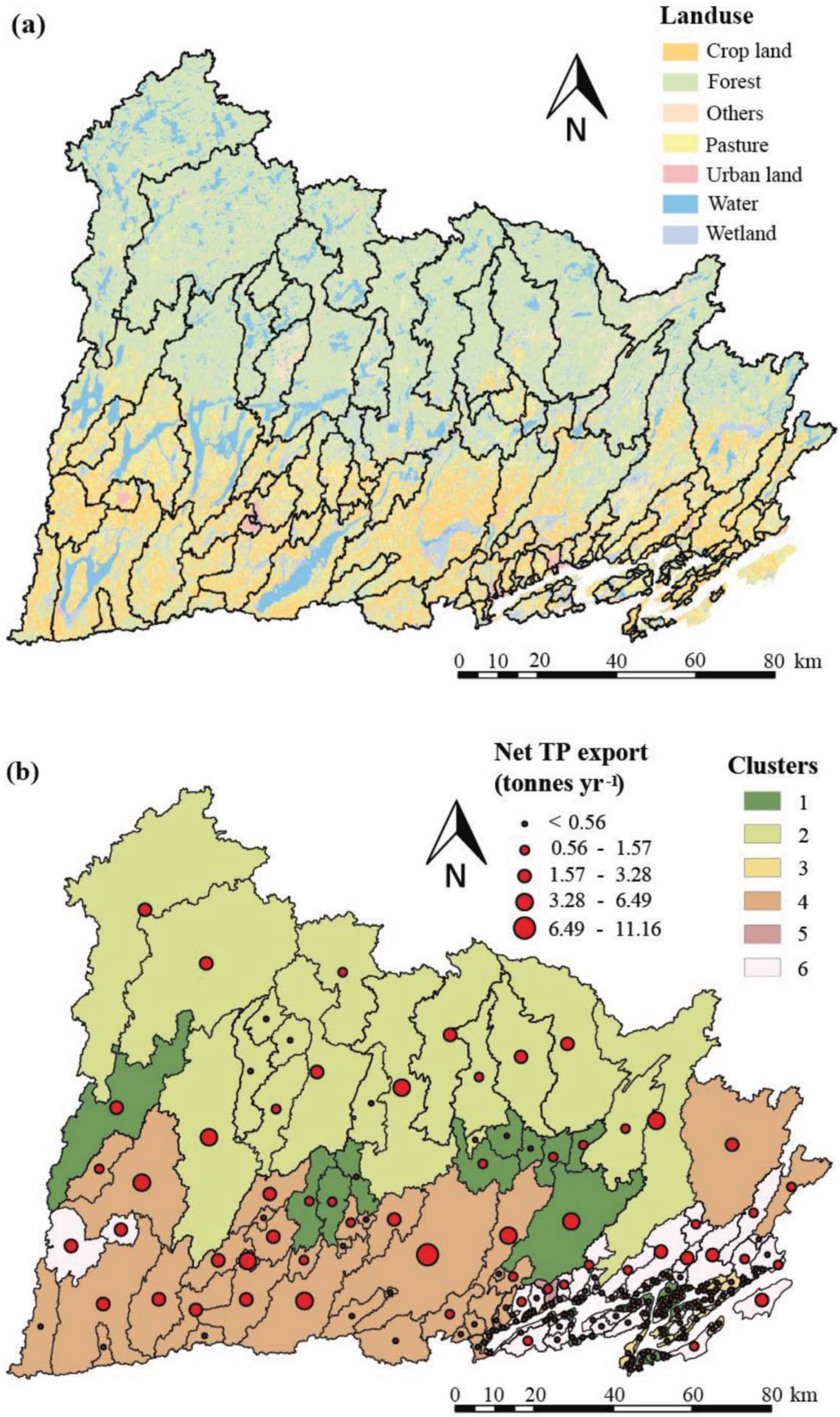

Figure 2. Map of Bay of Quinte watershed: (a) land use types and (b) classification based on artificial neural networks and associated phosphorus export per subwatershed.

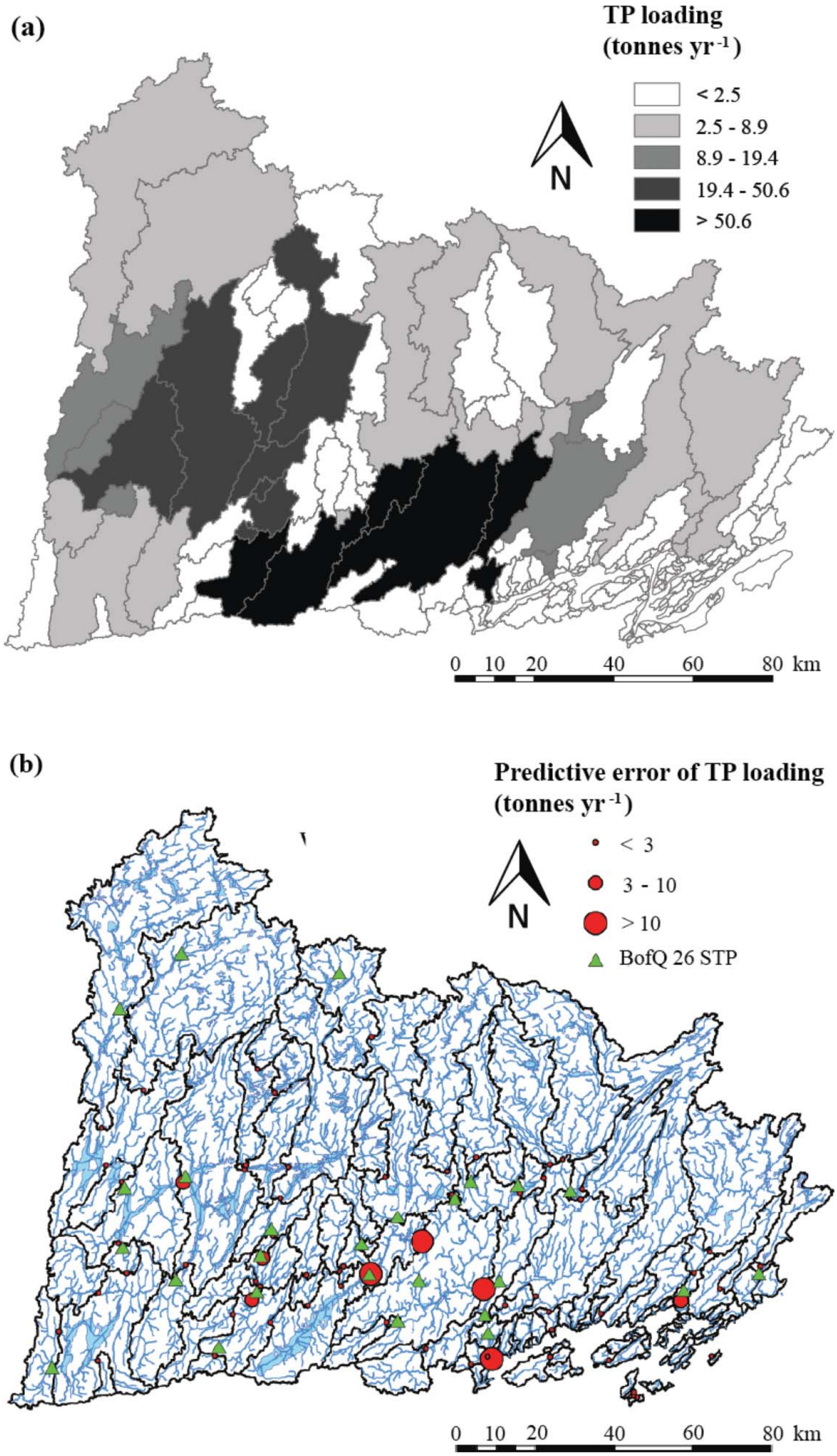

Figure 3. (a) Mean TP loading predictions and (b) associated errors of the *SPARROW* model application in the Bay of Quinte watershed. Triangles (green) indicate the locations of 26 sewage treatment plants.

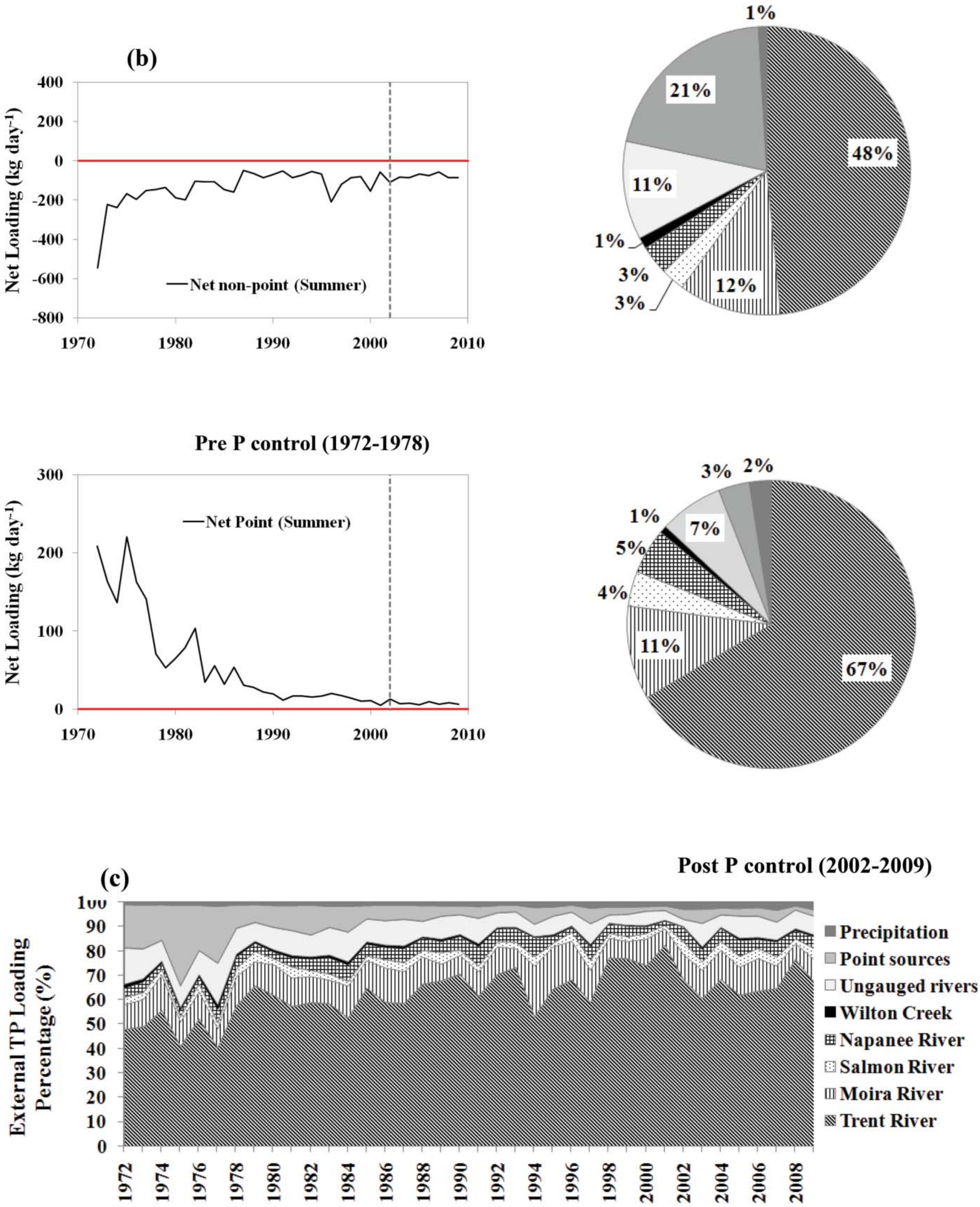

Figure 4. Temporal trends of exogenous TP loading in the Bay of Quinte during the study period (1972–2009): (a) net non-point (upper panel) and point (lower panel) sources of phosphorus loadings into the Upper Bay ($= \text{Flows}_{\text{exogenous}} \times [\text{TP}_{\text{exogenous}} - \text{TP}_{\text{Upper Bay}}]$); (b) comparison between the pre- (1972–1978) and post-control (2002–2009) periods; (c) relative contribution from the different loading sources over time (modified from Kim et al., 2013).

examined. We also calculated the net loading[2] from both point and non-point sources to weigh the different transport of phosphorus due to the variability in the corresponding flow regimes (Johnson and Owen, 1971; Minns et al., 2004). During the earlier years of the study period, our analysis showed that the computed total seasonal *P* loads would always indicate the river loads were greater than point source loading, sometimes much more so when river flows are higher in the upper Bay of Quinte. However, the net loading values clearly suggest that the point sources always have a positive sign, while the river net loads were mostly negative. Net river loads were negative when point source loads were higher, because the point source inputs elevated *TP* concentrations in the system far above the river levels. Hence, when point source loads were high, river inputs actually displaced some of the excess loading. In recent years, both point source loadings and ambient concentrations in the Bay have significantly declined; the river net loads still remain negative, but their absolute values have decreased. The impact of the point loading on the prevailing conditions in the Bay of Quinte has been reduced. It is important to note though that the ambient *TP* concentrations towards the end of summer (August-September) still rise to levels well above the 30 μg l^{-1} target. Because this period coincides with the time when the river flows decline to their lowest annual values, we believe that this recurring pattern is indicative of the role of internal nutrient sources (e.g. sediment reflux) in the system.

Phosphorus dynamics in the Bay of Quinte: Evaluation of the role of exogenous loading relative to internal recycling

The *SPARROW* model was subsequently integrated with the Kim et al. (2013) phosphorus model. The downscaling of the annual nutrient loading predictions to daily inputs was based on a Monte Carlo algorithm, which was designed to generate the probability distributions of the annual average *TP* concentrations in the different tributaries, while accounting for the *SPARROW* structural and parametric uncertainty as well as the observed flow variability. The ratios between simulated and long-term average *TP* concentrations (2002–2012) were then used as (stochastic) weights for adjusting the tributary-specific rating curves (Zhang et al., 2013), and thus used to obtain daily estimates of tributary phosphorus loads from the contemporaneous flows. The model was then calibrated to match the observed monthly *TP* patterns in the upper, middle, and lower segments of the Bay during the 2002–2009 period (Kim et al., 2013). The model demonstrated satisfactory ability to fit the monthly *TP* levels in the Bay of Quinte, and was able to reproduce the end-of-summer increase of the ambient *TP* levels in the upper segment, even in years (e.g. 2005) when the corresponding concentrations were greater than 60 μg l^{-1}. The model also faithfully depicted the spatial gradients in the system, with distinctly higher *TP* levels in the upper segment relative to those experienced in the middle/lower Bay (Kim et al., 2013, 2014c submitted).

We also used the model to draw inference on the spatial variability of the various external and internal *TP* flux rates in the Bay of Quinte (Figure 5 and Table 2). The net *TP* contributions (sources or sinks) represent the mass of phosphorus associated with the various compartments (water column, sediments, macrophytes, dreissenids) throughout the growing season (May-October) averaged over the 2002–2009 period. In the U_1 segment, the phosphorus budget is predominantly driven by the external sources (phosphorus loading: 158.6 kg day^{-1}) and sinks (outflows: 152.2 kg day^{-1}). Our model suggests that the sediments (resuspension and diffusion from the sediments to water column minus particle settling) act as a net source of phosphorus in this segment (57.9 kg day^{-1}). Dreissenids subtract approximately 65.9 kg day^{-1} from the water column (particle filtration minus respiration) and subsequently deposit 62.4 kg day^{-1} via their excretion and particle rejection. Likewise, the U_2 segment receives 205.8 kg day^{-1} from exogenous sources, including the upstream inflows, and transports downstream 190.0 kg day^{-1}. The net contribution of the

[2]The net loading accommodates the idea that two equal total loads with opposite pairs of flow and concentration, high flow with low concentration or low flow with high concentration, could potentially have a very different effect on the trophic state of the system, and is simply calculated by multiplying the inflows from a particular source with the difference between the inflow and outflow concentrations (Johnson and Owen, 1971).

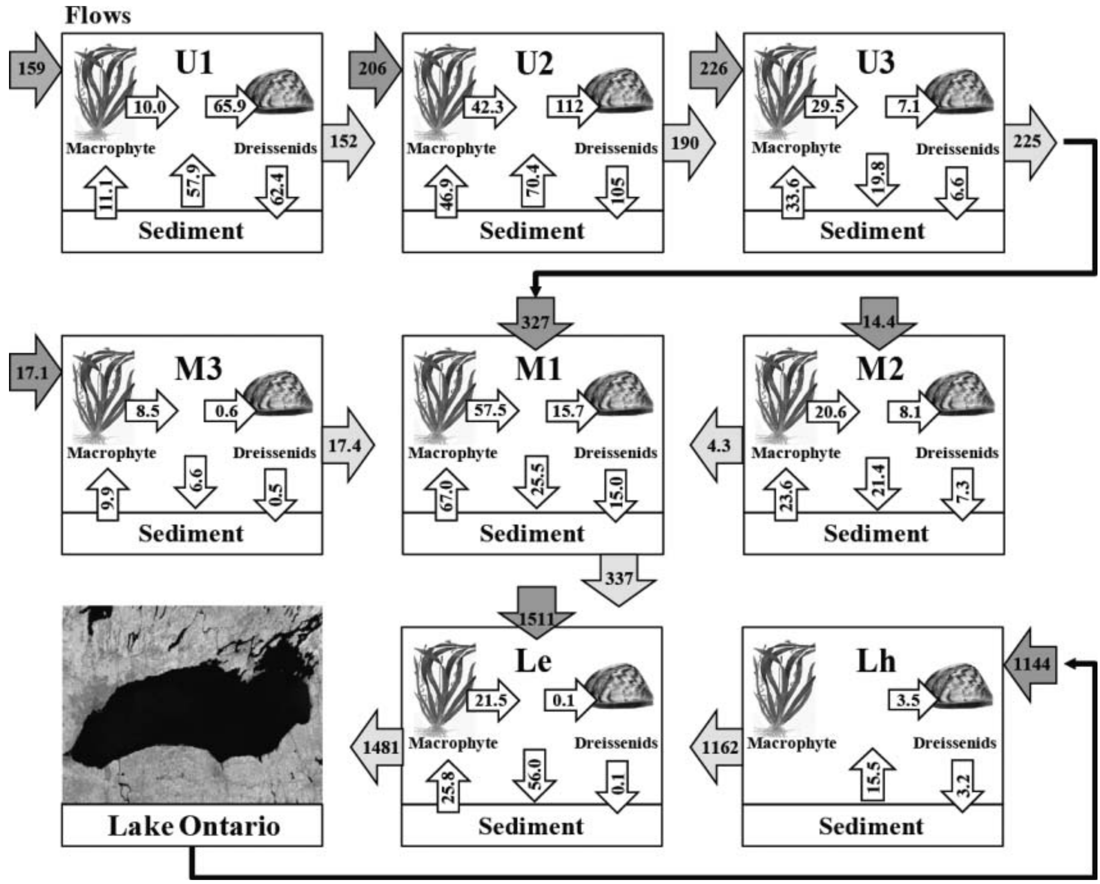

Figure 5. Spatial variability of the various external and internal TP flux rates (kg day^{-1}) in the Bay of Quinte. Arrow directions indicate the net contribution (sources or sinks) of the various compartments (water column, sediments, macrophytes, dreissenids). Dark gray arrows show the TP inflows in a spatial segment, while the light-gray arrows depict the corresponding outflows.

sediments accounts for 70.4 kg day^{-1}, while dreissenids on average reduce the ambient *TP* levels by 111.8 kg day^{-1}. The main differences between the two segments in the upper Bay are the *TP* fluxes related to macrophyte *P* intake from the sediments and respiration that can reach the levels of 46.9 and 42.3 kg day^{-1} relative to the fluxes of 11.1 and 10.0 kg day^{-1} in the U_1 segment. Likewise, the macrophyte intake from the sediments minus the amount of P regerenerated from the decomposition of the dead plant tissues varies between 35–65 kg day^{-1} in segments U_3 and M_1, while the subsequent release of their metabolic by-products is approximately responsible for 19–26 kg day^{-1}. Interestingly, the settling of particulate *P* dominates over the resuspension and diffusion from the sediments to the water column with the corresponding net fluxes ranging between 25–35 kg day^{-1}. In Hay Bay (M_2), the fluxes mediated by the macrophytes and dreissenids primarily modulate the *TP* dynamics and the same pattern appears to hold true in Picton Bay (M_3). In the lower Bay of Quinte (L_e and L_h), the model postulates a significant pathway (>1100 kg *P* day^{-1}) through which the inflowing water masses from Lake Ontario well up from the hypolimnion to the epilimnion and are subsequently exported from the system. In the same area, the internal biotic sources (macrophytes) similarly represent an important vector of phosphorus transport.

Relative to the present loading conditions, we evaluated a number of management scenarios intended to reduce the exogenous levels of phosphorus entering the system. For the sake of brevity, we here present the predicted *TP* levels along with the broader implications for ecosystem functioning of a scenario related to the reduction of the contribution of the agricultural

Table 2. Estimation of TP flux rates from different components of the Bay of Quinte model.

	Net TP flux (kg day^{-1})						
Site	*Water–Sed*	*Water–Macro*	*Water–Zebra*	*Sed– Zebra*	*Sed – Macro*	*Water in*	*Water out*
			Present loading conditions				
U1	57.9	10.0	65.9	62.4	11.1	158.6	152.2
U2	70.4	42.3	111.8	105.5	46.9	205.8	190.0
U3	–19.8	29.5	7.1	6.6	33.6	226.3	225.5
M1	–25.5	57.5	15.7	15.0	67.0	326.9	337.4
M2	–21.4	**20.6**	**8.1**	**7.3**	**23.6**	14.4	4.3
M3	–6.6	8.5	0.6	0.5	9.9	17.1	17.4
Le	–56.0	21.5	0.1	0.1	25.8	1510.6	1480.8
Lh	15.5	0.0	3.5	3.2	0.0	1144.0	1162.5
			Reduced loading conditions				
U1	63.6	10.0	58.1	55.4	11.1	130.3	137.3
U2	76.2	42.3	105.3	99.6	46.9	185.8	180.5
U3	–17.8	29.5	6.5	6.1	33.6	209.9	211.4
M1	–24.0	57.5	14.8	14.2	67.0	309.5	321.3
M2	–19.9	20.6	7.3	6.6	23.6	12.3	4.0
M3	–6.3	8.5	0.5	0.5	9.9	16.2	16.6
Le	–54.7	21.5	0.1	0.1	25.8	1487.7	1457.0
Lh	15.7	0.0	3.4	3.2	0.0	1142.0	1158.7

Water–Sed: resuspension and diffusion from the sediments to water column − particle settling; *Water–Macro*: macrophyte respiration; *Water–Zebra*: respiration and 0.4 × excretion of dreissenids − particle filtration of dreissenids; *Sed–Zebra*: 0.6 × excretion, egestion and rejection from dreissenids; *Sed–Macro*: macrophyte mortality − macrophyte intake from sediment; *Water in*: upstream inflow and external loading; *Water out*: downstream outflow.

land uses, urban storm water, and point sources by 20%, 50%, and 60%, respectively (Figure 6). The latter reduction aimed to evaluate the effects of a "phosphorus load cap" that stipulates a total phosphorus effluent concentration of 0.1 mg l^{-1} in the local sewage treatment plants. Importantly, after the consideration of the deposition of biogenic material (e.g. production of pseudo-feces by dreissenids, decomposition of the dead macrophyte tissues), the simulated scenario does not reach the "threshold load" for rapid system recovery at which the flux downward equals the flux upward from anoxic sediments (Table 2; see net *TP* exchange between water column and sediments in segments U_3, M_1, M_2, M_3). In fact, the sediment reflux in the inner segments of the upper Bay (U_1 and U_2) is predicted to increase under the reduced nutrient loading scenario, as the increased vertical gradient (i.e. decreased ambient levels relative to stable sediment phosphorus content) will likely shape the transient dynamics by intensifying the diffusive exchanges. Nonetheless, our predictions suggest that the maximum *TP* concentrations in the upper Bay will be lower than 40 μg l^{-1} across a wide range of flow conditions, when the flow-weighted *TP* concentration approximately falls below the level of 20 μg l^{-1} (black dotted line). Interestingly, our simulations also suggest that the maximum ambient *TP* levels will be further reduced by 5–20% (or 1–5 μg l^{-1}), when the same reduced loading conditions prevail for about 5–10 years (Kim et al., 2014c submitted). The reduction of the *TP* concentrations is even more distinct, if we consider the fact that the increased sequestration into the algal cells is likely to decrease the dissolved to particulate phosphorus ratio in the water column, which in turn implies that a greater portion of phosphorus could be subject to sedimentation

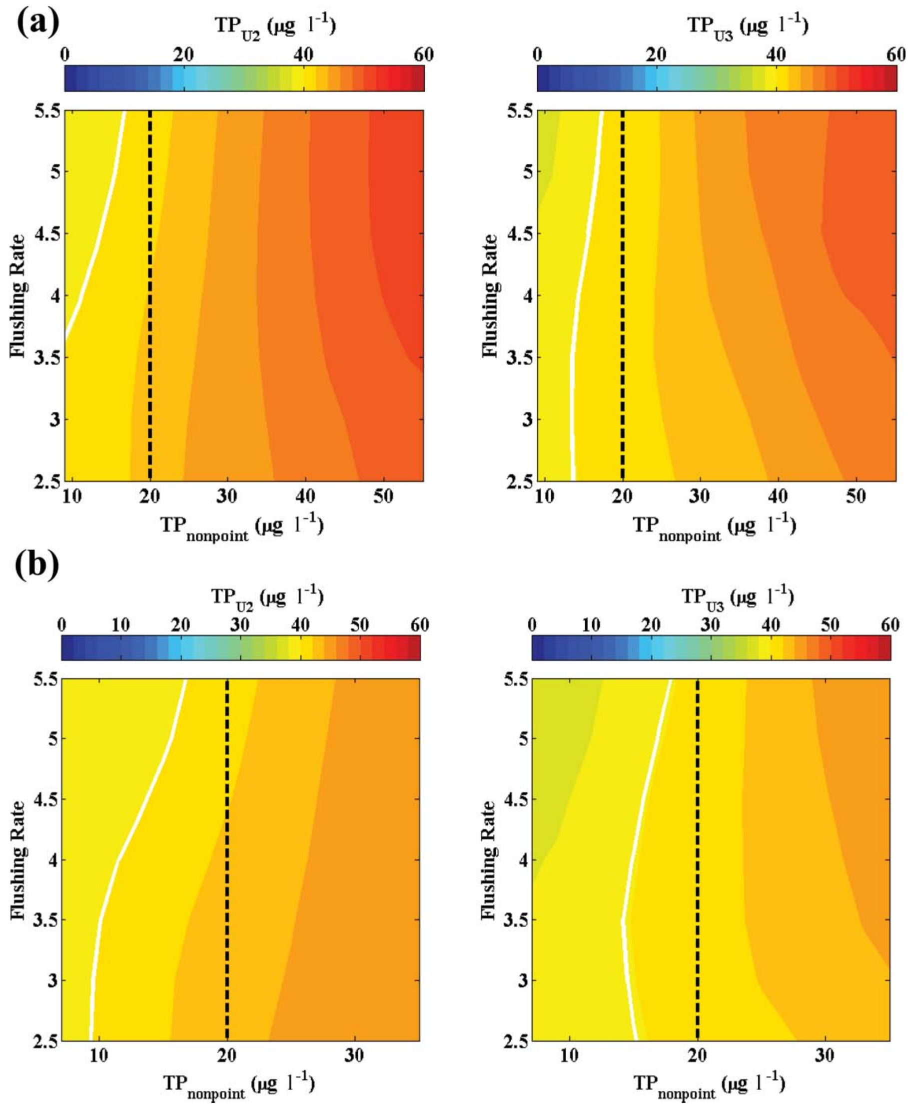

Figure 6. Simulated maximum *TP* concentrations during the growing season (May-October) in the Bay of Quinte. Upper (a) panels refer to the predictions associated with the reference environmental conditions; and lower (b) panels represent the predictions of a *TP* loading reduction scenario (60% point sources, 20% non-point sources, and 50% urban storm water). The first eleven years (2002–2012) were based on real meteorological and nutrient loading conditions, while the final (12^{th}) year was forced with a wide range of combinations of *TP* riverine concentrations and flows that were generated from the mean (± error) predictions of the *SPARROW* model. The white contour line corresponds to the proposed targeted level of 40 μg *TP* l^{-1}. The flushing rates express the frequency (number of times) of water renewal in the upper Bay during the growing season. The black dotted line represents a threshold level of 20 μg l^{-1} for the flow-weighted *TP* concentration in all the major tributaries in the upper Bay of Quinte.

and/or dreissenid infiltration. It is also important to note though that these predictions refer to spatially average *TP* values, contingent upon the coarse resolution of the model, and do not necessarily reflect the conditions that may be experienced in the areas adjacent to the major tributaries.

Synthesis and conclusions

Significant progress has been made with the reduction of both point and non-point loading discharges in the Bay of Quinte over the last four decades. However, Kim et al. (2013) recently underscored the challenges of the current management efforts to further improve the water quality conditions, as the sediments in the upper middle Bay area act as a net source of phosphorus and the corresponding fluxes are likely magnified by the macrophyte and dreissenid activity. The presence of a feedback loop in the system suggests that the emergence of hysteresis patterns may compromise the efficiency of additional external loading reductions (Scheffer et al., 2001; Minns et al., 2004; Gudimov et al., 2011). While the Bay of Quinte morphology minimizes the likelihood of regime shifts to occur (Seifried, 2002), the contribution of internal nutrient loading could significantly protract the realization of an improved state. (Zhang et al., 2013). Similar to Kim et al.'s (2013) projections, the present modelling analysis provides evidence that the restoration pace of the Bay could be slow, even if the riverine average *TP* concentrations reach levels significantly lower than their current values, $<25\ \mu g\ TP\ l^{-1}$.

Because of the skepticism arising from the projected limited system response to the nutrient loading scenarios examined, we caution that there is considerable uncertainty regarding the characterization of the phosphorus cycle and the assumptions made about the sedimentation rates or the nutrient subsidies from dreissenids, macrophytes, and sediment diagenesis. In particular, Manning (1996) reported that a significant portion of the riverine fine-grained assemblage of phosphate-oxides-organic matter is transported through the upper Bay and deposits downstream in the middle and lower segments. As a result, his estimates of the phosphorus sedimentation rate were significantly lower than those assigned by Minns et al. (2004) and Kim et al. (2013) to reproduce the observed *TP* concentrations in the water column. Nonetheless, counter to the Minns et al.'s (2004) characterization of the sediments, Kim et al. (2013) (and the present model) assumed a significantly lower permanent loss of phosphorus mass from the system through the sediment burial. This feature along with the explicit consideration of the recycling mediated by dreissenids and macrophytes resulted in a strong feedback loop in our modelling exercise relative to the Manning's (1996) and Minns et al.'s (2004) estimates that appears to profoundly modulate the capacity of the management scenarios examined to shape the dynamics of phosphorus in the Bay. In this regard, one of the compelling research questions in the system involves the delineation of the sediment *TP* profiles and the improvement of our quantitative understanding of the mechanisms of phosphorus mobilization in the sediments. The on-going determination of the *TP* fractionation in the sediment profiles and the characterization of the diagenesis processes are likely to shed light on the plausibility of the hypotheses proposed from our modelling work (Dittrich et al., unpublished data).

There are two major differences between the system conceptualization postulated by Kim et al. (2013) and the present study. First, counter to the Kim et al. (2013) calibration strategy, we downplay here the direct release of phosphorus in the water column due to macrophyte respiration. Instead, greater weight is placed on the indirect pathway through which the dead plant tissues are subject to microbial decomposition in the sediments and phosphorus is subsequently released into the water column through diffusive exchanges in the sediment-water column interface. The latter conduit can be an important source of nutrients, as the macrophytes demonstrate high capacity of luxury uptake and thus tend to accumulate nutrients in concentrations higher than their physiological requirements (Bini et al., 2010). Second, the *SPARROW* application showed the use of the Wilton Creek equivalents[3] approach likely underestimates the levels of phosphorus export from the ungauged catchments (Kim et al., 2014b submitted), and thus rendered support to our concerns that the role of the nutrient recycling may have been overstated somewhat in our earlier work (Kim et al., 2013). This finding is particularly relevant to the middle sections of the system, such as the Hay Bay area (*M2*), where the nutrient regeneration processes were originally predicted to overwhelmingly dominate the *TP* budget (Kim et al., 2013). The greater reliance of inshore waters in the upper-middle Bay of Quinte upon external nutrient subsidies attests to the benefits of optimizing the management practices in the corresponding catchments. In particular, both our *SOM* and *SPARROW* analysis highlighted the urban

[3]The Wilton Creek equivalent approach, originally introduced Minns et al. (1986), assumes that the daily load from an un-gauged subwatershed equals the daily load from Wilton Creek weighted by the ratio of the area of the ungauged site to the Wilton Creek area.

areas adjacent to the Bay as major phosphorus contributors per unit area, and thus a more effective stormwater management and point source loading control could ameliorate the prevailing local water quality conditions. Interestingly, our analysis still predicts a co-dependence between macrophyte and dreissenid activity in Hay Bay (*M2*) (Kim et al., 2013; see also bold numbers in Table 2), suggesting that the magnitude of the macrophyte "nutrient pump effect" and the associated stimulation of algal growth can potentially induce significant variations in the amount of particles filtered/ingested by the dreissenids as well as in their excretion/pseudofeces production rates (Vanderploeg et al., 2001).

In a recent paper, Zhang et al. (2013) argued against the historical delisting criterion of a seasonal average *TP* concentration lower than 30 μg l^{-1}, asserting that it is neither a reflection of the considerable intra-annual variability in the upper Bay nor representative of the water quality conditions in nearshore areas of high public exposure (e.g. beaches). It is would seem very unlikely that a single-value water quality standard monitored in a few offshore sampling stations can capture the entire range of dynamics in the system (e.g. the extremes seen in the nearshore sites) or the magnitude of the end-of-summer *TP* peaks. Responding to these skeptical views, the Bay of Quinte *RAP* considers adopting the pragmatic stance that the delisting objectives should revolve around extreme (and not average) values of variables of management interest and must explicitly accommodate all the sources of uncertainty (insufficient information, lack of knowledge, and natural variability) by permitting a realistic frequency of standard violations. Namely, the critical threshold level was set at a value of 40 μg *TP* l^{-1}, which cannot be exceeded more than 10–15% in both time and space. Under the assumption that the *TP* concentrations in the Bay of Quinte follow a log-normal distribution and that *TP* values $<$15 μg l^{-1} are likely to occur only 10% of the time during the growing season, then 10–15% exceedances of the 40 μg *TP* l^{-1} level are approximately equivalent to a targeted seasonal average of 25–28 μg *TP* l^{-1}. Thus, the replacement of the historical paradigm (binary assessment) with a probabilistic approach to water quality criteria does not intend to make the delisting of AOCs easier, but rather it offers a more comprehensive method to track the prevailing conditions in the Bay.

Bearing in mind that the *TP* targeted levels merely represent a "means to an end" and not "the end itself", the actual question that the local stakeholders should ponder is to what extent the anticipated benefits from a more efficient external phosphorus loading control could also be capitalized as a significant decrease of the algal bloom frequency? With respect to the total phytoplankton biovolume, Nicholls et al. (2002) showed that it declined after the control of phosphorus in the 1970s, but did not change significantly after the establishment of dreissenids in the system. Moreover, Nicholls and Carney (2011) asserted that the arrival of Dreissenid Mussels may be associated with both desirable (e.g. *Aphanizomenon* and *Oscillatoria* decline) and undesirable (e.g. *Microcystis* increase) changes in the integrity of the Bay of Quinte ecosystem. Importantly, the post-Dreissena increase of the cyanophyte *Microcystis* has had significant implications for the aesthetics and other beneficial uses in the Bay, through the formation of "scums" on the water surface (Jacoby et al., 2000) as well as due to the fact that some strains of *Microcystis* are toxin producers (Vanderploeg et al., 2001). Some of these structural changes in the phytoplankton community composition could stem directly from the feeding selectivity of dreissenids or indirectly from the improvements in the transparency of the water column (Blukacz-Richards and Koops, 2012), but the role of the feedback loop associated with their nutrient recycling activity could conceivably be another important factor. On positive note, according to the predictions of a non-linear quantile regression model (Carvalho et al., 2013), the current average *TP* concentrations (30–40 μg l^{-1}) represent the area where the algal biovolume vs *TP* relationship is characterized by a steep slope and thus any further improvements in the ambient nutrient levels are likely to induce more favourable quantitative and qualitative changes in phytoplankton (Figure 7). Nonetheless, existing empirical evidence from the system is indicative of a weak correlation between chlorophyll *a* and cyanobacterial toxin concentrations (Watson et al., 2011), suggesting that a complex interplay among physical, chemical, and biological factors may drive the spatiotemporal abundance and composition patterns of the algal assemblages in the Bay of Quinte (Nicholls et al., 2002). In a system like

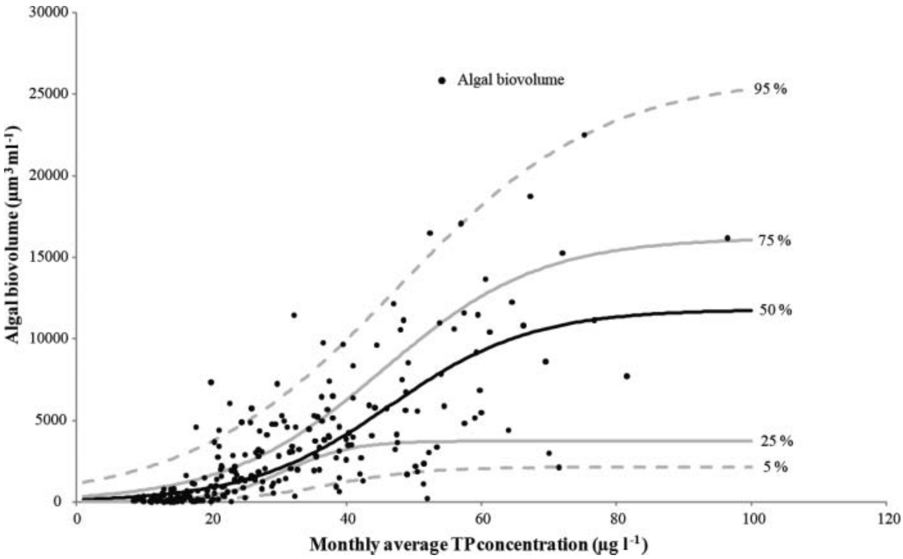

Figure 7. Quantile regression model for total phytoplankton biovolume against monthly average TP concentration in the Bay of Quinte.

the Bay of Quinte, where the severity of eutrophication phenomena is driven by both external and internal loading, there will inevitably be some uncertainty in the overall assessment of the Beneficial Use Impairment *Eutrophication and Undesirable Algae*. It is our belief though that the recent shift in the focus of the Bay of Quinte *RAP* activities (management decisions, monitoring, and modelling) on extreme states (>40 μg *TP* l^{-1}, toxic algal blooms) offers a more sensible way to evaluate the actual progress over time. Recognizing that it is practically impossible to eliminate these events in the foreseeable future, the robust assessment of their frequency of occurrence and the effective communication of the actual trends to the end-users (stakeholders and public) should be essential steps of the local management efforts.

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