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Wind-Driven Sediment Resuspension in the World's Fourth Largest Lake Contributes Substantial Phosphorus Load to the 11th Largest Lake

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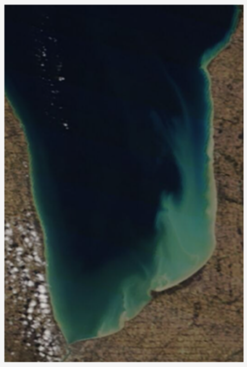
ABSTRACT: Capturing precipitation-based episodes is a longstanding issue for estimating tributary loads; however, wind-driven resuspension in Lake Huron creates similar uncertainties in its estimated load to Lake Erie. Recent suggestions that the phosphorus load from Lake Huron is underestimated because sampling frequencies miss contributions from resuspension events are speculative because they did not include direct load measurements, address all resuspension regions, or assess the potential bioavailability of the load. We address these shortcomings by evaluating Lake Huron's nearshore regions, characterizing the biological availability of the load, and providing direct comparisons of load estimates with and without the resuspended load. We show that total phosphorus concentrations in Lake Huron and the St. Clair River are higher during resuspension events and that bioavailability of that material is comparable to that reported elsewhere. New load estimates, based on continuous turbidity measurements converted to phosphorus through P-turbidity relationships, were almost 90% higher than traditional load estimates, providing empirical evidence for the significantly underestimated previous load. This confirmation is important because if the Lake Huron load is not decreased, reductions from other sources would be needed to meet the overall reduction targets set by the binational Great Lakes Water Quality Agreement.



KEYWORDS: *resuspension, phosphorus, Great Lakes, loadings, turbidity, Lake Huron, Lake Erie*

INTRODUCTION

The importance of capturing precipitation-based episodes has long been an issue for estimating tributary loads.[1−7] Those precipitation-based episodes are challenging due to changes in both discharge volume and concentration. However, in their phosphorus (P) mass balance of the St. Clair and Detroit River system that connects lakes Huron and Erie, Scavia et al.[8,9] suggested that wind-driven resuspension in southern Lake Huron creates similar uncertainties. They suggested that the load from Lake Huron is significantly underestimated because sampling at intermittent frequency misses contributions of P from resuspension events. To our knowledge, this was the first time a direct connection was made between wind-driven sediment resuspension in one lake driving nutrient loads to another.

This finding is also important because, in response to Lake Erie's re-eutrophication,[10] the United States and Canada revised P loading targets[11] based on public input and science synthesized in a multimodel effort.[12] The new targets include reducing P loads by 40% from their 2008 levels to reduce harmful algal blooms and hypoxia—two key Lake Erie issues.[13−15] Phosphorus concentrations in the Detroit River are much lower than for other tributaries, but the immense discharge contributes 25% of the total phosphorus (TP) load to the lake.[12,16] While mixing patterns and the low concentration mean that the Detroit River load may be less important for driving harmful algal blooms in the lake's western basin, it is a key factor driving hypoxia in the central basin.[10,12,17]

These results have broader implications because estimates of nutrient fluxes leaving lakes are needed for constructing the mass balances that are used to determine internal recycling, retention, and loads to downstream systems. Modeling and mass balance studies often assume nutrient outflows are a product of discharge and open-lake or overall average concentrations, whereas nearshore productivity and resuspended sediment may add substantially to the nutrient outflow, potentially biasing mass balance inferences and underestimating the load to downstream systems.

Understanding the sources and potential controls of these loads is critical. For example, Scavia et al.[8] suggested that if the Lake Huron P load cannot be decreased, and further reduction from the system's major water treatment plant (WTP) is not considered because it has already met its target, then other watershed sources will need to decline by 72% to meet an overall 40% reduction target—a significant challenge that needs additional evaluation. Scavia et al.[18] subsequently used a hydrodynamic model, satellite images of resuspension events and ice cover, wave hindcasts, and continuous turbidity

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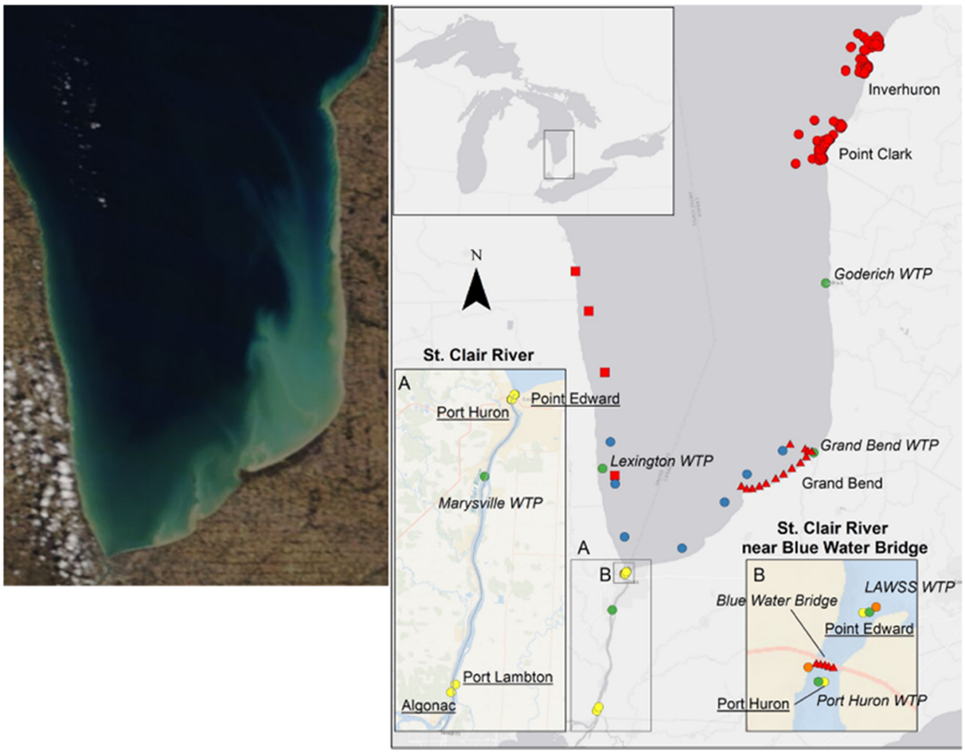

Figure 1. Study region and data locations. Left: true-color image. Terra/MODIS from NASA Worldview at https://tinyurl.com/3e8vfu4w. Right: archived lake samples (red dots), water treatment plant intakes (green), operational modeled currents (blue), monitoring stations (yellow), and EPA NCCA stations (red squares). New lake and river samples (red triangles) and sensors (orange).

measurements at the outlet of Lake Huron to provide evidence that this additional P load, in the form of sediment transport, is from wave-induced resuspended Lake Huron sediment, primarily within 30 km of the Ontario nearshore. They also suggested that the additional load increased over time as ice cover decreased due to climate warming. However, that assessment did not measure the resuspended load directly, did not address potential resuspension from the Michigan nearshore, and did not assess the biological availability of the resuspended particulate phosphorus.

To address these shortcomings, we evaluated P concentrations in Lake Huron and the St. Clair River during resuspension events, measured its potential biological availability, and show that using high-frequency turbidity measurements as a predictor of daily TP concentration substantially improves estimates of daily and annual loads of TP from Lake Huron to the St. Clair River.

METHODS

Study Site. Lake Huron, the second largest Laurentian Great Lake and fifth largest freshwater lake in the world, is oligotrophic based on biological, chemical, and physical characteristics of its open waters. This oligotrophic state has often led to assumptions that its P load to the St. Clair River and Lake Erie was low.[16,19] However, some of the lake's embayments and nearshore regions are more productive, and the load was shown to be 2−3 times higher than offshore estimates based on measurements at two monitoring stations near the lake outflow.[8,20]

The St. Clair River is a connecting channel flowing 64 km from Lake Huron to Lake St. Clair, forming an international boundary between the United States and Canada. The river drops almost 1.5 m from the elevation of Lake Huron to that of Lake St. Clair in a relatively straight, poorly mixed channel.[21,22] It receives inputs from Lake Huron and the Pine, Black, and Belle rivers from the U.S. watershed,[8] as well as direct discharges from point and nonpoint sources from both sides of the river. Its annual average discharge of 5200 m^3/s is 35% of the Mississippi River discharge at Baton Rouge, more than twice that of the Missouri River, and it contributes substantial water and nutrients to Lake Erie via the Detroit River.

Data. As described below, our analysis includes both archived and new data from Lake Huron and the St. Clair River (Figure 1). These include lake and river water samples from monitoring and research sites, intakes from water treatment plants (WTPs), deployed sensors, a stream gauge, and output from an operational hydrodynamic model.

Sample Collection and Analysis. We conducted repeated sampling of southern Lake Huron and the St. Clair River from March to October 2021. Some of this sampling was triggered by southern Lake Huron resuspension events identified in daily MODIS true-color images from NASA's Worldview website (https://worldview.earthdata.nasa.gov/). Sampling generally occurred within 1−2 days of the onset of resuspension events that each typically lasted 3−4 days.

Lake Sampling. Lake Huron was sampled eight times between March 25 and October 27, 2021. Temperature, pH, turbidity, dissolved oxygen, conductivity, and total dissolved solids were recorded at 1 m depth intervals with the YSI Professional Digital Sampling System (ProDSS). For events on March 25, April 14, and April 26, water samples and measurements were taken along a transect perpendicular to the shore from Grand Bend, Ontario, through the resuspension area at stations 7.5, 3, and 1 km from shore (Figure 1). For events on May 28, June 17, September 3, September 28, and October 27, water samples and measurements were taken

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along a transect 1 km offshore and parallel to the shore south of the Grand Bend water treatment plant with stations at the 14, 12, 10, 8, 6, 5, 4, 2, and 1 km (Figure 1). Turbidity was generally uniform in the vertical profile, so most samples were from 0 to 1 m depth. Lake water was collected with a Beta Plus 2.2L Horizontal Van Dorn bottle, poured into 100 mL amber glass bottles with sulfuric acid for total phosphorus, 100 mL amber bottles without preservative for dissolved phosphorus, 60 mL high-density polyethylene (HDPE) bottles without preservative for dissolved reactive P (DRP), and four 500 mL HDPE bottles without preservative for total suspended solids (TSS), and transported to the laboratory the same day.

River Sampling. To capture material exported from southern Lake Huron via the St. Clair River, samples were taken six times between April 26 and October 27, 2021, along a cross-channel transect just downstream of the Blue Water Bridge (BWB) and at two deployed particle sensors near the BWB and Point Edward sites. Samples collected in the BWB cross section were made using the equal discharge increment (EDI) method.[23] A discharge measurement was made at the sampled cross section and sampling locations were determined such that each sampling interval contained an equal amount of incremental discharge.

Initially, each EDI bin was sampled using a Federal Interagency Sedimentation Program (FISP)-approved sampler, the P-6. Five equal-spaced, 1 L samples were collected from the vertical profile within each equal discharge and composited for depth-averaged samples. Because P is associated with the fine particles that are likely well mixed vertically, subsequent sampling was done with a nonisokinetic pump sampler. Three to 5 L were collected in each EDI bin from approximately 2 m below the water surface. The added efficiency of pump sampling allowed an increase in the spatial resolution of the samples from 5 to 10 EDI bins. Samples were also collected near the in situ particle sensor locations from approximately 4−5 m depth with the pump sampler or Kemmler water sampler.

In Situ Particle Sensors. Acoustic backscatter devices, LISST-ABS particle profilers, were deployed on the Michigan side of the river just south of the Blue Water Bridge (42.99815, −82.4256) starting March 12, 2021, and off of Point Edward, Ontario (43.00334, −82.4179), in the vicinity of the Lambton Areas Water Service System (LAWSS) water treatment plant (WTP) intake starting October 7, 2021.

Turbidity, Suspended Solids, and Phosphorus Fractions. Total suspended solids (TSS) were determined by filtering through a weighed standard glass fiber filter with the residue retained dried at 104 ± 1 °C for a minimum of 4 h or until a constant weight was achieved. Turbidity was measured using a turbidimeter (Hach 2100 AN) and US EPA method 180.1.[24]

TP was determined colorimetrically after acid persulfate digestion using procedures adapted from APHA method 4500-P.[25] Total dissolved P (TDP) was determined with procedures adapted from APHA Method 4500-P colorimetrically after persulfate digestion of a sample filtered through a 0.45 or 0.2 μm filter, or determined as the difference between TP and PP. PP was collected onto combusted and acid-rinsed Whatman GF/F filters or determined as the difference between TP and TDP. TP, TDP, and PP were digested with 25 g/L potassium persulfate at 121 °C for 30 min. All P fractions were measured using Seal Analytical method G-297-03 on a Seal Analytical AA3 auto-analyzer or on an Aquakem 200.

Bioavailable particulate phosphorus (BioP) was determined following Baker et al.[26] using procedures adapted from National Center for Water Quality Research Heidelberg University, Method 365.1. Particles retained on a 0.45 μm cellulose acetate filter or glass fiber filter (Whatman GF/F) were extracted with sodium hydroxide and refiltered with a 0.45 μm filter. Extracts were neutralized and analyzed according to APHA 4500-P. The P concentration in the 50 mL extract was converted to sample BioP concentration by multiplying by 50 and dividing by the volume of the original water sample sampled. The potentially bioavailable fraction of PP was calculated by dividing the BioP concentration by the PP concentration from the same water sample.

Archived Data Sources. To augment our collections, we assembled archived data from a number of locations in southern Lake Huron and the St. Clair River (Figure 1), primarily from 2009 to 2021, although some phosphorus records start in 1998.

Turbidity. Hourly and/or daily turbidity measurements were provided directly from the WTPs at the Goderich, Grand Bend, and LAWSS plants in Ontario and the Lexington plant in Michigan. Other Michigan WTP data were provided by Environmental Consulting and Technology, Inc. and Healthy Urban Waters at Wayne State University for the Port Huron and Marysville WTPs. Turbidity from individual grab samples was from Howell et al.[27,28] for the Inverhuron and Point Clark sites, from Environment and Climate Change Canada (ECCC, tinyurl.com/ydbm2kgq) for the Point Edward and Port Lambton sites, and from the Michigan Department of Environment, Great Lakes, and Energy (EGLE, tinyurl.com/5ypywf5d) for Port Huron and Algonac.

Phosphorus and Suspended Solids. TP, TDP, and TSS were from Howell et al.[27] for Inverhuron and Point Clark, ECCC and the Great Lakes Intake Program (GLIP, https://tinyurl.com/2p893adj) for the Point Edward and Port Lambton sites, EGLE for the Port Huron and Algonac sites, and EPAs' Great Lakes National Program Office (EPA's Great Lakes National Program Office, S. Telford) for the National Coastal Condition Assessment sites in the Michigan nearshore waters of Lake Huron.

Hydrodynamics. Lake Huron currents were downloaded from the National Oceanic and Atmospheric Administration's operational Great Lakes Coastal Forecasting System[29] that has undergone extensive skill assessments and verifications.[29,30]

Satellite Imagery. A 2016−2018 time series of true-color (RGB) MODIS images with 500 m spatial resolution was used to observe sediment resuspension in southern Lake Huron.[8,14] Each image was classified by visual inspection separately for the Michigan and Ontario shores as to whether resuspended sediment was visible in a region extending roughly 40 km north of the outlet. Images with no visible sediment were also recorded.

Discharge. Daily discharge for 2009−2021 at Port Huron was downloaded from the National Water Information System (https://waterdata.usgs.gov/nwis/) for USGS station 04159130. Values before 2009 were based on water balances.[8]

Load Estimates. *Traditional Loads.* Traditional load estimates (hereafter, GAM-based) used the Generalized Additive Model[31] (R package "mgcv") as done in Scavia et al.[8] to approximate daily TP concentrations as a function of time based on discrete observations of TP concentrations at the Canadian (Point Edward, Port Lambton) and U.S. (Port Huron, Algonac) stations. Concentrations higher than the

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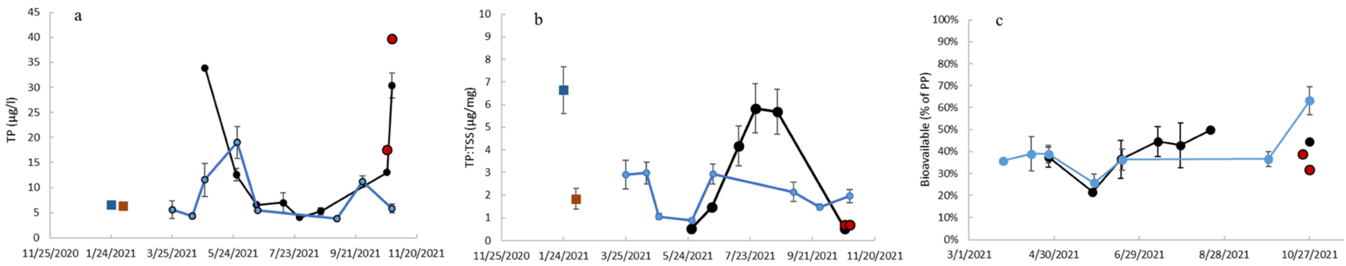

Figure 2. Mean ± SE for total P (TP, μg/L (a)), TP:TSS (μg/mg (b)), and bioavailable P (% of PP (c)) for Grand Bend (blue), St. Clair River (black), Point Edward ABS (red), and from the 2018−2019 Point Edward (blue box) and Port Huron (red box) monitoring stations.

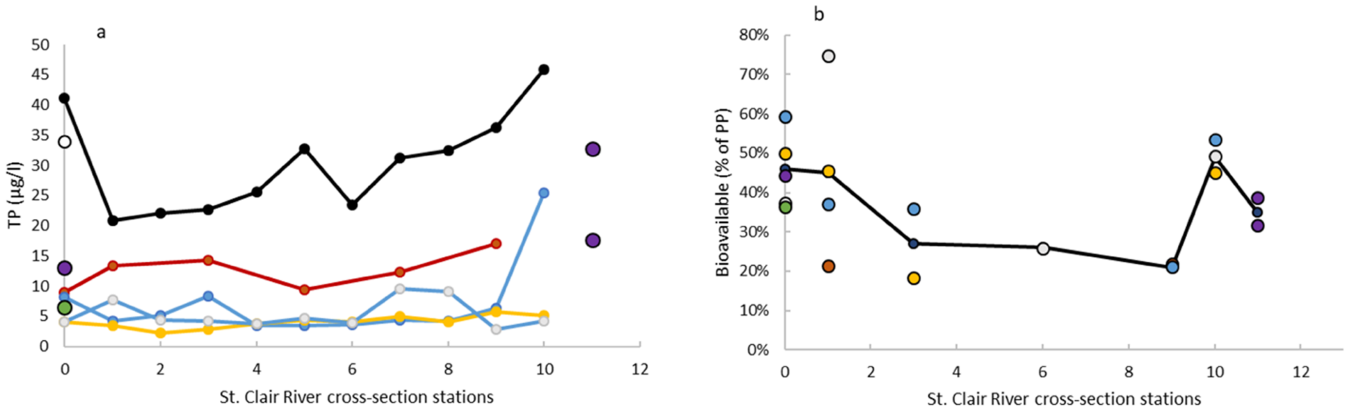

Figure 3. Total P (μg/L (a)) and bioavailable P (% of PP (b)) along the St. Clair River cross section. Michigan shore (0), Ontario shore (10), and ABS sensor Point Edward location (11) for individual dates (4/26, white; 5/27, red; 6/16, green; 7/12, blue; 7/28, yellow; 8/18, gray; 10/27 and 10/27, black; 10/22 and 10/27 ABS, purple). Bioavailable P mean (b) (black line).

mean plus three standard deviations for each site, representing less than 3.3% of the observations, were removed as outliers. GAM models are generalized linear models in which the response variable depends linearly on unknown smooth functions of some predictor variables that, in our case, allow one to estimate a continuous concentration time series for use with daily flow measurements to estimate daily loads. We used the following formula to construct the GAM model:

$$\mathrm{TP} = \mathrm{intercept} + s(\mathrm{Julian}) + \mathrm{error}$$

where TP is the total phosphorus concentration, Julian is the number of days since January 1, 1985, and s is the smoothing function. When applying the smoothing function, we used the default setting from the mgcv R package. For each model fitting, the dimension of the basis, which controls the variations in the model fit, is estimated by the program. We then used the functions from the mgcv R package to evaluate if the basis dimension is too low or if it needed to be increased. The Restricted Maximum Likelihood (REML) method was used to estimate the smoothing parameters.

Modeled daily TP concentration and associated standard errors (SE) were multiplied by daily discharge measured at Port Huron to estimate daily loads and then summed to annual loads in metric tons per year (MTA). Other methods, such as WRTDS and LOADEST, are not as appropriate for estimating loads in the St. Clair River because P concentrations are not correlated with flow in this connecting channel.[32,33] However, estimates using WRTDS were similar to using the GAM model.

Turbidity- and TSS-Based Loads. Daily turbidity-based load estimates were determined by converting daily WTP turbidity to PP via PP−turbidity regressions. TSS-based load estimates were determined by converting daily TSS measurements from the LISST sensor to TP via TP−TSS regressions. Both regressions were done in Excel on log-transformed data. Modeled daily TP concentrations and associated standard errors were multiplied by daily discharge and summed to annual loads.

■ RESULTS

Characterizing Phosphorus. Sampling was triggered by resuspension that occurred mainly in early spring and fall. Phosphorus concentrations during those times were higher than those typically reported for the open waters of Lake Huron (e.g., 2.3 μg/L)[34] and higher than the 2018−2019 averages from observations at Point Edward and Port Huron (6.5 and 6.3 μg/L, respectively, Figure 2a and Table S1). The P content of suspended solids (TP/TSS) varied seasonally, especially in the St. Clair River (Figure 2b), and was intermediate between the Port Huron and Point Edward 2018−2019 averages. The bioavailable fraction of PP (Figure 2c) was fairly consistent throughout the year at both the Grand Bend and St. Clair River stations. On average, 39 (±9)% of PP was biologically available, which is comparable to the Maumee River that drains a highly agricultural watershed into the western basin of Lake Erie (30 ± 7%, summarized in Bertani et al.[35]).

TP was variable across the river channel in 2021. April and October concentrations were elevated and tended to be higher along both shores (Figure 3a). Bioavailability as a fraction of PP also tended to be higher along the two shores (Figure 3b).

Traditional Load Estimates. We updated the GAM-based traditional TP load estimates from Lake Huron based on updated samples at the upstream Point Edward and Port

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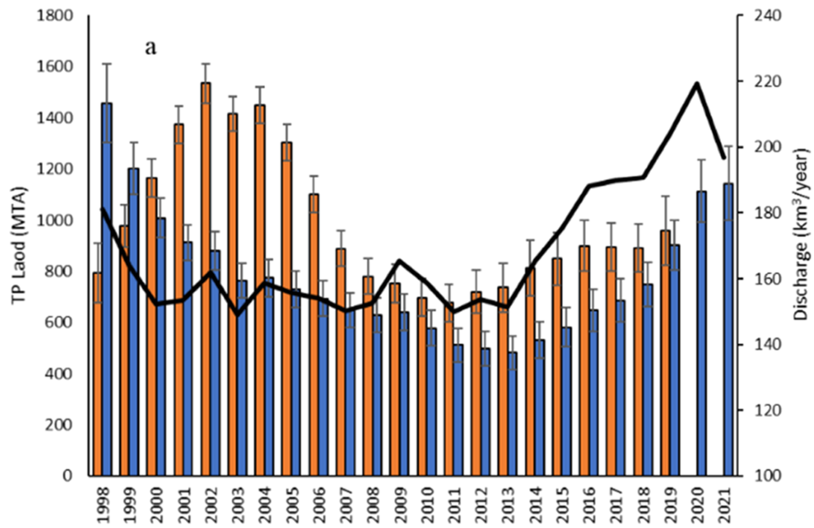

Figure 4. Traditional GAM-based annual load estimates (MTA ± SE) for upstream stations at Point Edward (orange) and Port Huron (blue) and annual discharge (km^3/year) at Port Huron.

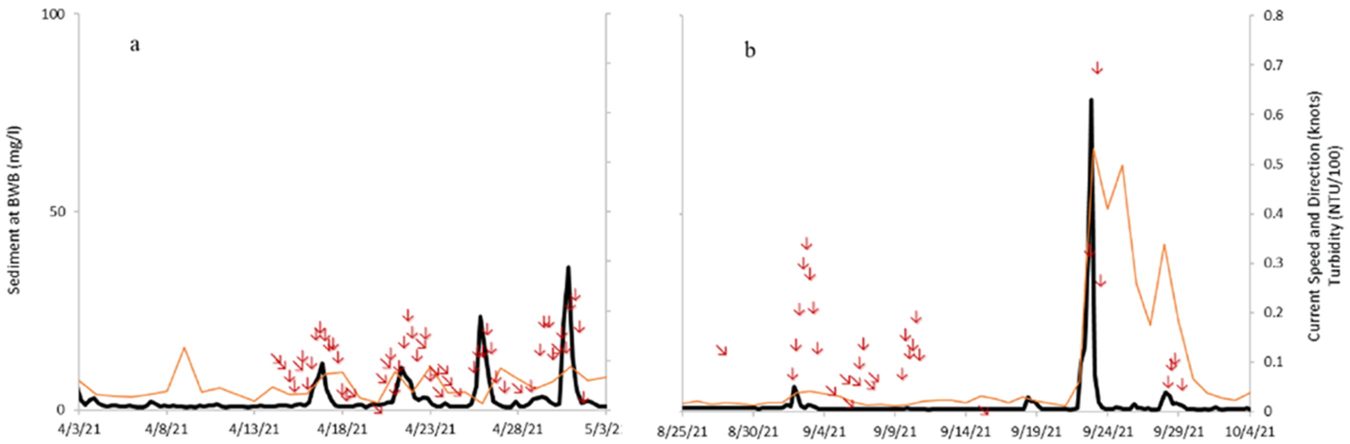

Figure 5. Daily average TSS (mg/L) at the Michigan LISST sensor (black line), turbidity (NTU/100) at the Lexington WTP, and current speed (knots) and direction (arrows) in Lake Huron near Lexington for 4/3/21−5/3/21 (a) and 8/5/21−10/4/21 (b). Current speeds and arrows are only displayed when currents come from the north or northwest.

Huron stations. Point Edward loads increased in the early 2000s, decreased, and then rose gradually in the latter half of the decade (Figure 4). Port Huron loads were lower than Point Edward, declined through 2013, and then rose gradually. These estimates are lower than those reported in Scavia et al.[8] because we augmented the original Point Edward data with GLIP data from the same site. For example, they reported a 2013−2016 average load of 976 MTA, compared to our new estimates of 662 MTA for the same period. A substantial portion of the increased load in the latter half of the decade appears driven by increased discharge. Between 2013 and 2019, discharge and load increased by 35 and 53% respectively.

Turbidity- and TSS-Based TP Load Estimates. *Lake Huron Resuspension and Turbidity.* Resuspension in the Ontario and Michigan nearshore regions, documented with MODIS satellite images for 2016−2018,[14] was reflected in turbidity measurements at the Goderich and Grand Bend WTPs in Ontario and at the Lexington WTP in Michigan (Figure S1). This allows use of WTP intake data to identify resuspension, avoiding the impact of clouds on images during the times of the year most susceptible to resuspension. Turbidity measurements at these relatively deep-water intakes also confirm that these satellite-based images, when they are available, were not only surface features.

We calculated the average number of days per year with turbidity greater than twice the 2016−2021 mean for each of the WTPs as an indication that these are relatively frequent events along both sides of the lake (Figure S2). The number of days with turbidity above twice the long-term mean for Goderich and Grand Bend WTPs in Ontario was 52 and 50 days/year, and 24 days/year for the Lexington WTP in Michigan. The greater frequency of resuspension in the Ontario nearshore region is consistent with the analysis of MODIS images in 2010, 2011, and 2016−2018[8,14] that showed consistently larger and more frequent events in Ontario.

The fact that elevated turbidity at the Point Edward and Marysville river intakes corresponded to these events (Figure S3) also suggests the resuspended material moved into the river. The lower frequencies in the rivers (Port Huron, 29 days/year; LAWSS, 35 days/year; Marysville, 22 days/year) are likely because lake currents are not always favorable for transporting the resuspended material to the river.[14] For example, currents were not from the north or northwest

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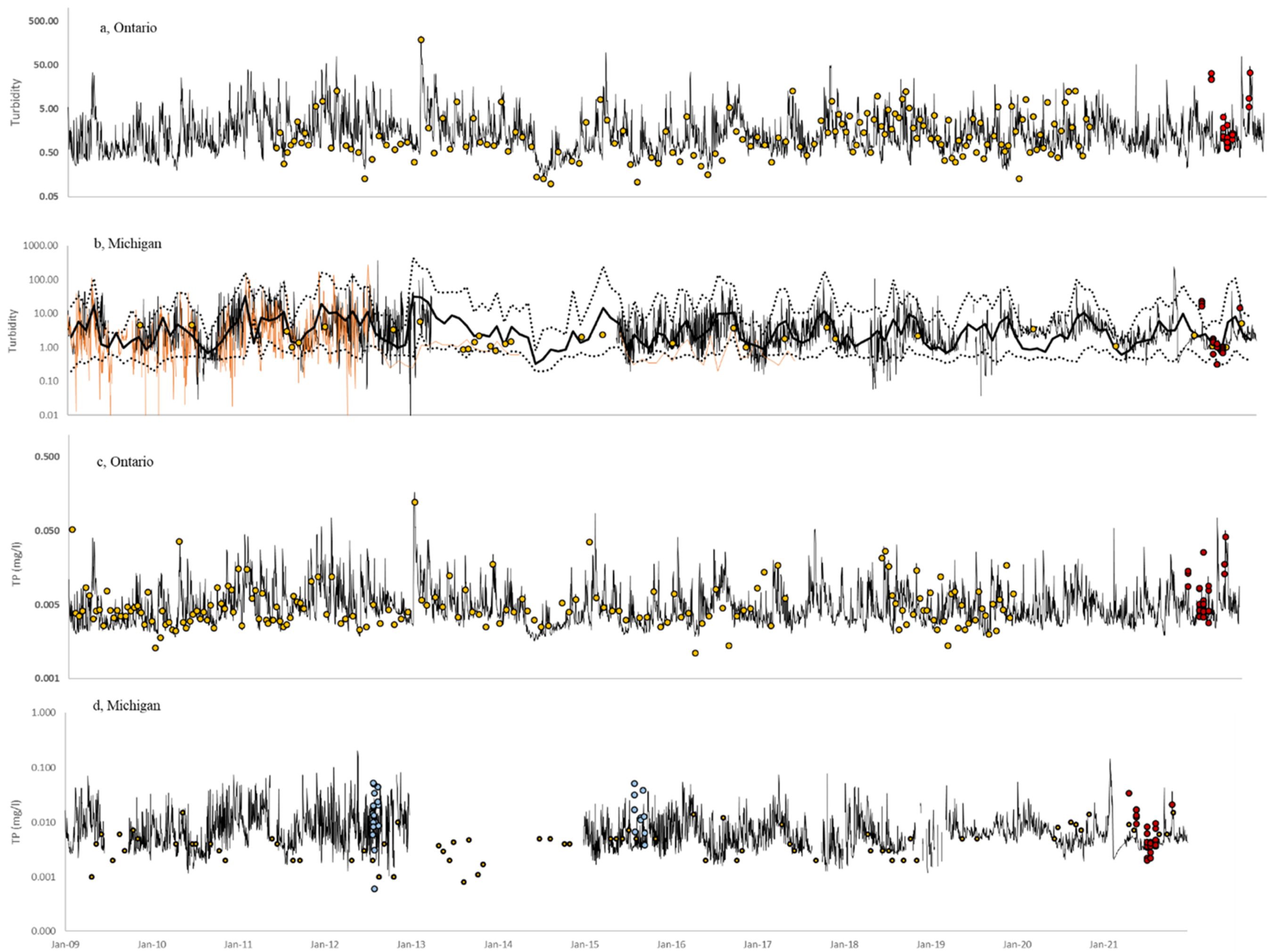

Figure 6. Water treatment plant and sample turbidity (a, b) and TP (c, d) in the river. (a) Ontario: LAWSS WTP (black line), Point Edward samples (orange dots), and St. Clair River samples (red dots). (b) Michigan: Port Huron WTP daily (orange line), monthly mean (black line), and monthly minimum and maximum (dotted line), Marysville WTP (black line), Port Huron samples (orange dots), and St. Clair River samples (red dots). (c) Ontario: TP from LAWSS WTP (black line), Point Edward samples (orange dots), and St. Clair River samples (red dots). (d) Michigan: TP from Marysville WTP (black line), Port Huron samples (orange dots), St. Clair River samples (red dots), TP from Michigan nearshore Lake Huron (blue dots). Shown in log scale to emphasize variability at the low end.

around the time of the Lexington turbidity pulse on 4/9/2021, so there was no TSS pulse detected at the Michigan sensor (Figure 5a). Currents were favorable for pulses later that month. Another example shows the TSS sensor reacting to the initial phase of the Lexington turbidity pulse on 9/22/2021, but as the current direction shifted away from the north or northwest, the sensor pulse declined (Figure 5b).

St. Clair River Turbidity. We compared WTP turbidity with turbidity measured in water samples to ensure they were consistent. Comparisons on the Ontario side of the river matched well (r = 0.89, n = 30), including some of the relatively high turbidity events at both the Point Edward and BWB stations (Figure 6a). WTP turbidity also captures the less frequent Port Huron discrete samples. However, daily records at Port Huron are not available after 2011. So, for additional comparisons, we include the monthly mean, minimum, and maximum values from that station (Figure 6b). The correlation between turbidity at the Marysville WTP, the site we used for load estimation 10 km downstream from Port Huron, and turbidity sampled at Port Huron is 0.74 (n = 20).

Phosphorus Regressions. Robertson et al.[36] developed regression equations to estimate constituent loads based on flow, season, and a number of surrogate measures for 30 tributaries to the Great Lakes. They showed strong correlations between TP concentration and turbidity, as have others,[27] and their best overall model for TP included ln(flow), season, and turbidity. Because there are no strong relationships between TP concentration and flow or season in the St. Clair River and to use data more relevant to our study site, we developed new PP and TP regressions using data from Inverhuron, Point Clark, Point Edward, Port Lambton, Port Huron, Algonac, and our collections at Grand Bend and the St. Clair River (Figure 1).

The best fits (Figure S5) were log(PP) = 0.75 log(turbidity) − 2.51 (R^2 = of 0.81, n = 350) and log(TP) = 0.62 log(TSS) − 2.41 (R^2 = 0.78, n = 381). The predicted P concentration when TSS and turbidity are very low (1.0 mg/L or 1 NTU) are 0.0028 (95% CI: 0.0026−0.0030) and 0.0039 (95% CI: 0.0037−0.0042), roughly comparable to average TDP measured at Inverhuron (0.0029) and Point Clark (0.0039) and Point Edward (0.0025). Retransformation biases were very

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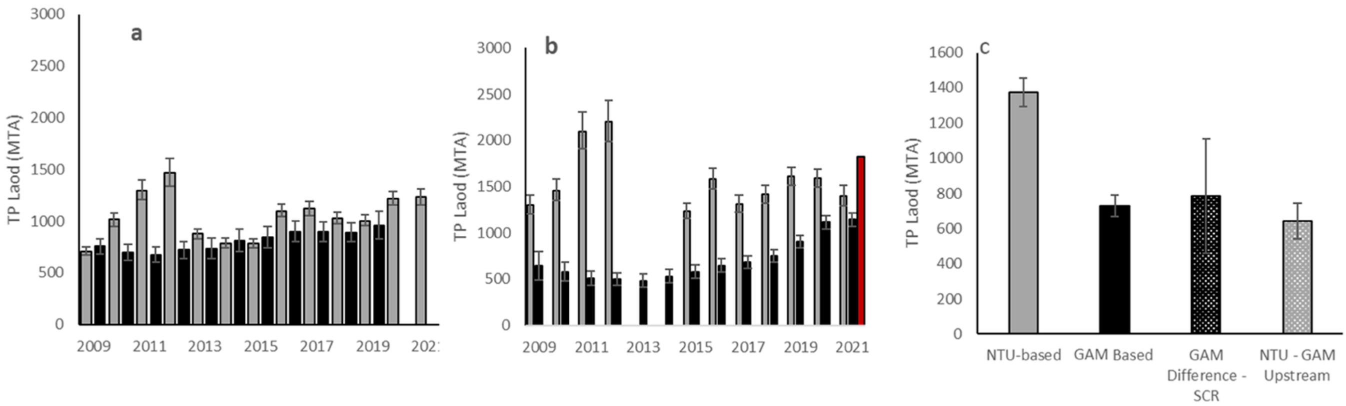

Figure 7. Load estimates (MTA ± SE) for Point Edward (a) and Port Huron (b). Traditional GAM estimates (black bars), NTU-based estimates (gray bars), TSS-based estimates (red bar); (c) 2009−2012 and 2015−2019 averages (±SE) for turbidity-based (gray) and GAM-based (black) upstream loads, GAM-based differences between upstream and downstream minus St. Clair River direct loads (black stippled), and difference between turbidity-based and GAM-based upstream loads (gray stippled).

small, resulting in 3.5% and 2.7% increases in TP concentrations for the turbidity and TSS models, respectively.

Daily TP Estimates. Total river load estimates are determined by averaging loads calculated with phosphorus concentrations on the Ontario and Michigan sides of the river. When estimating TP from WTP turbidity and the PP regression model, a value of 0.001 mg/L was added to account for total dissolved P and to better match observations. These TP estimates are correlated strongly with the wide range of TP measurements (min = 0.0002, max = 0.126 mg/L) at Point Edward for 2009−2019 (r = 0.74, n = 422), as well as in the St. Clair River in 2021, catching many instances with high concentrations (Figure 6c). To be consistent across the entire time period of analysis, we use only Marysville data to represent concentrations on the Michigan side of the river for Michigan load calculations. However, because Marysville turbidity tended to be higher than Port Huron, we scaled the Marysville data by a factor of 0.8 to obtain a better match, particularly at the lower concentrations. The WTP-based concentrations captured many of the higher and lower measured concentrations (Figure 6d), but the relatively sparse measurements at Port Huron, with a much smaller range (min = 0.008, max = 0.015 mg/L), resulted in low correlation (r = 0.07, n = 75). To expand the qualitative assessment, we included additional data from Lake Huron's Michigan nearshore region in 2012 and 2015, and in the St. Clair River in 2021 (Figure 6d).

TP estimates based on daily averaged TSS from the Michigan-side sensor and the TP-TSS regression were higher than those measured in the river. To achieve a better match with this short period of record, we scaled the sensor TSS measurements by a factor of 0.5 (Figure S6). Because the TSS sensor was not deployed until March 12, our 2021 annual load estimate from this sensor represents March 12, 2021, to March 11, 2022.

Comparing Turbidity-Based, TSS-Based, and Traditional Load Estimates. The turbidity-based and TSS-based annual load estimates are generally higher than those estimated by the more traditional GAM method (Figure 7a,b). This supports the claim that traditional load estimates fail to account for at least some of the resuspension events.[8,14] The difference between GAM- and turbidity-based loads at Port Huron is larger than that at Point Edward because turbidity from resuspension events is more likely to be missed by the relatively sparse sampling at Port Huron. Between 1997 and 2019, there were on average 7.3 samples per year at Port Huron, compared to 60.4 samples per year at Point Edward. To further demonstrate this, we compared turbidity-based estimates for Point Edward with GAM-based estimates using subsets of TP measurements. Monte Carlo analysis resulted in the mean of 100 cases decreasing and the distribution of loads increasing as the number of samples dropped from 90% of the full set to 10% (Figure S7).

Averaged over 2009−2012 and 2015−2021, the updated GAM-based load estimate is 730 (SE = 101) MTA and the turbidity-based load is 1372 (SE = 81) MTA (Figure 7c). This turbidity-based load is almost 90% higher than the GAM-based load. To explore the impact of resuspension explicitly, we recalculated the turbidity-based load, after capping turbidity values at just below their respective long-term averages to mimic reduced resuspension. The result is an average load of 755 MTA, closer to the GAM-based load of 730 MTA. This is further evidence that resuspension is driving a substantial part of the total load.

Accounting for the Additional Load. Burniston et al.[20] noted that downstream TP concentrations (Port Lambton) were higher than those upstream at Point Edward and that the biggest difference was in the particulate fraction. Scavia et al.[8,14] suggested that some of this upstream/downstream difference could be the result of the resuspended load being missed at the upstream location, but detected downstream due to mixing during the 8−10 h river travel time between the two stations.

We can test this assumption. The difference between turbidity-based and GAM-based upstream loads is one measure of the load missed with infrequent upstream sampling. After correcting for direct river inputs[8] that we updated with Canadian industrial point sources (ECCC, personal communication), the difference between GAM-based traditional downstream and upstream estimates is another measure of the missed load. Subtracting the direct river inputs (206 MTA) from the GAM-based downstream/upstream difference (990 MTA) suggests that the downstream load is 784 (±326) MTA higher than the upstream estimate. The difference between the turbidity-based and GAM-based upstream loads (643 ± 101 MTA, Figure 7c) suggests that the missed resuspension-based load could account for 82% downstream−upstream load difference.

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DISCUSSION

Total phosphorus concentrations in Lake Huron's nearshore and the St. Clair River are higher during resuspension events than those typically measured in monitoring programs (Figure 2). Importantly, the fraction of particulate phosphorus that is potentially bioavailable during resuspension events is comparable to those reported for the Maumee River, a highly agricultural watershed that drains into Lake Erie's western basin. Although the P concentrations in the St. Clair River are much lower than in the Maumee River, and additional inputs and losses of P occur between Lake St. Clair and Lake Erie,[8] these results show that the resuspension-driven component of the Lake Huron load is important for mass balances and estimates of the impactful load to Lake Erie.

These results have implications beyond the interconnected Great Lakes because, in general, estimates of nutrient fluxes leaving lakes are needed to construct mass balances used in determining internal recycling, retention, and loads to downstream systems. These efforts often assume that nutrient outflows are a product of discharge and open-lake or overall average concentrations, whereas resuspended sediment may add substantially to overall nutrient outflow, potentially biasing mass balance inferences and underestimating the load to downstream systems.

After confirming that WTP intake turbidity converted to TP concentration from regression equations tracked concentrations in water samples, we modeled annual turbidity-based loads to the St. Clair River and showed that they were almost 90% higher than traditional estimates based on relatively infrequent sampling for TP concentration. Capping turbidity to just below their long-term means, simulating reduced resuspension, resulted in loads similar to the traditional estimates. Based on our load calculations, the difference between turbidity- and GAM-based upstream loads could account for much of the upstream−downstream difference in GAM-based loads.

Satellite-based images of resuspension in Lake Huron were reflected in turbidity measurements at water treatment plant intakes in both Ontario and Michigan waters, indicating that these events are not simply surface features. Based on turbidity measurements, resuspension events are frequent, occurring over 50 days per year along the Ontario shore and 24 days per year along the Michigan shore, and reflected in the river between 22 and 35 days per year.

Based on 2013−2016 averages, Scavia et al.[8] calculated that accounting for Lake Huron's additional resuspension load suggests the need for a much higher load reduction from other sources than was previously thought. Increased discharge and loads between 2010 and 2021 further increased the significance of that load. These results are important because, if the Lake Huron load cannot be decreased and reductions from the major water treatment systems are not considered because they have already met reduction targets, it will require additional reductions from other sources to meet the overall reduction targets set by the binational Great Lakes Water Quality Agreement.[11] Based on P mass balances for the St. Clair and Detroit rivers, Scavia et al.[8,14] estimated that other sources would need to decline by 70% or more to meet the overall 40% reduction goal. Canada and the United States should consider this as they adaptively manage their relevant domestic action plans.[37,38]

Monitoring Implications. Nutrient fluxes leaving lakes are required for constructing mass balances to determine internal recycling, retention, and loads to downstream systems. In most cases, they are based on the assumption that the nutrient concentration leaving the lake can be represented by open-lake or average concentrations. However, those assumptions can be biased low when more localized and episodic events like wind-driven sediment resuspension occur with sufficient frequency. While the impact of resuspension events will vary from system to system, they are likely not predictable, especially for larger systems. This is because not only do winds have to be strong enough and in the right direction to suspend sediment, but currents must be flowing in the right direction to move that material toward the lake outlet. So, it is unlikely that resuspension forecasts could be developed to trigger the sampling required in both US and Canadian waters to catch both base flow and events. As such, turbidity-based load estimates are likely more reliable and efficient. We provide the following suggestions for estimating the P load to the St. Clair River from Lake Huron-based turbidity and TSS sensors.

Sensor Types. Optical turbidity sensors are widely used as a surrogate for sediment and P load estimates; however, they are known to preferentially detect sediment from the smaller end of the grain size spectrum. Newer acoustic sensors sense a wider portion of the grain size spectrum. An acoustic sensor, a LISST-ABS, manufactured by Sequoia Scientific was installed at the Port Huron site in this study. The LISST-ABS outputs TSS concentration directly, whereas turbidity sensors output turbidity units (NTU or FNU). In either case, P concentrations are available only through a rigorous sampling program to build statistical relationships between P and turbidity or TSS. In our case, strong relationships were developed (R^2 = 0.81 for turbidity and 0.78 for TSS) with large sample sizes (n = 350, 381, respectively). However, because the LISST sensor includes larger grain sizes not generally associated with P, sensor TSS values had to be scaled by a fact of 0.5 before using them to estimate field phosphorus observations.

Sensor Locations and Sampling Frequency. Deployed sensors can record turbidity at many time scales, and we found that daily averages captured most significant events. However, these point observations can complicate interpretation in large systems with complex dynamics. For example, unless the river is well mixed, it is possible for resuspended material to bypass the sensors. Flow at the outlet of our system appears to be well mixed vertically, but minimal lateral mixing suggests the need for at least two sensors, preferably in the head of the river just downstream of the outlet. The current Canadian turbidity sensor that records hourly at Point Edward is located at the WTP intake in Lake Huron proper. An installation in the river, near the Blue Water Bridge would likely be more representative of river conditions. The US turbidity and TSS sensors are located near Port Huron. However, because the Port Huron WTP reports turbidity as monthly means, we relied on daily measurements from a downstream WTP at Marysville. Daily reports from Port Huron would be preferred. To meet the goal of developing a surrogate for nutrient monitoring, additional sensors deployed between the U.S. and Canadian shores should be installed—at least experimentally—to test if additional ones in the cross section are needed.

Phosphorus Concentration Estimates. Predicting phosphorus concentrations as a function of turbidity or TSS requires site-specific information because the phosphorus

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fractions in the resuspended material depend on a wide range of variables, including the characteristics of the overlying algal production, the proportion of autochthonous vs allochthonous material, and the relative proportions of particulate and dissolved phosphorus fractions. While the relationships between phosphorus and turbidity or TSS are generally strong on log−log scales, substantial variability requires large sample sizes. In our case, data were assembled from locations in Lake Huron and the St. Clair River, but more reliable regressions would rely on samples only from the head of the river.

Load Calculation. Estimating loads from daily turbidity and discharge avoids uncertainties associated with smoothing and interpolation methods like GAM, LOADEST, and WRTDS. With daily estimates of discharge and turbidity, and the regression results, load estimates are simple summations of the product of daily discharge and concentration. Because turbidity and discharge are generally measured with relatively low uncertainty, it is only regression uncertainty that needs to be considered.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.2c02820.

> Time series of satellite images of resuspension and turbidity; frequency of resuspension events; lake and river WTP turbidity time series; turbidity, TSS, and current speed and direction time series; phosphorus and turbidity/TSS regressions; TP concentrations and TSS sensor estimates; and lake and river phosphorus measurements (PDF)

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Notes

The authors declare no competing financial interest.

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