Environmental Science & Technology

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Lake Huron's Phosphorus Contributions to the St. Clair–Detroit River Great Lakes Connecting Channel

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Cite This: https://dx.doi.org/10.1021/acs.est.0c00383

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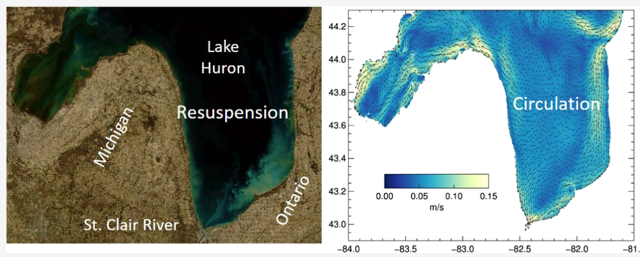

ABSTRACT: The United States and Canada called for a 40% load reduction of total phosphorus from 2008 levels entering the western and central basins of Lake Erie to achieve a 6000 MTA target and help reduce its central basin hypoxia. The Detroit River is a significant source of total phosphorus to Lake Erie; it in turn has been reported to receive up to 58% of its load from Lake Huron when accounting for resuspended sediment loads previously unmonitored at the lake outlet. Key open questions are where does this additional load originate, what drives its variability, and how often does it occur. We used a hydrodynamic model, satellite images of resuspension events and ice cover, wave hindcasts, and continuous turbidity measurements at the outlet of Lake Huron to determine where in Lake Huron the undetected load originates and what drives its variability. We show that the additional sediment load, and likely phosphorus, is from wave-induced Lake Huron sediment resuspension, primarily within 30 km of the southeastern shore. When the flow is from southwest or down the center of the lake, the resuspended sediment is not detected at Canada's sampling station at the head of the St. Clair River.

INTRODUCTION

In response to Lake Erie's re-eutrophication,[1] and based on an ensemble of nine models[2] and public comment, the United States and Canada lowered phosphorus loading targets.[3] One of those targets is to reduce the total phosphorus (TP) load to the lake's western and central basins by 40% compared to 2008 to reduce hypoxia in the central basin. Because the Detroit and Maumee rivers contribute, respectively, 41 and 48% of the TP load to the western basin, and 25 and 29% to the whole lake,[2,4] they have drawn significant attention. The Maumee is the primary driver of harmful algal blooms in Erie's western basin; the Detroit River's high flow but low P concentration tends to dilute or deflect those blooms. However, the Detroit River, along with the Maumee, is a key driver of central basin hypoxia.[2]

Because over 85% of the Maumee River load comes from agriculture, its assessments and action plans focus on those practices. Several studies offered pathways to the reduction goal[5−7] and showed that all successful pathways require large-scale implementation of multiple practices. For example, one pathway targeted 50% of the highest P-loss cropland with a combination of subsurface fertilizer application, winter cover crops, and buffer strips.

The 19,040 km^2 Detroit River watershed is far more complex. It is binational, with 40% of its land in the United States and 60% in Canada, and consists of 49% cropland, 21% urban land, 13% forest, 7% grassland, and 7% water, and the TP loads from point and nonpoint sources are approximately equal.[8] Overall, 79% of the watershed's agricultural land is in Canada and 83% of the urban land is in the United States. While point and nonpoint sources are roughly equal across the watershed, point sources make up 63% of the U.S. contribution, whereas nonpoint sources make up 83% of the Canadian contribution. Five of the six major subwatersheds pass through the 1 115 km^2, 3.8 m deep Lake St. Clair before entering Lake Erie.[9−11] Adding to the challenge of further contributing to the reduction target, the largest point source, the Great Lakes Water Authority (GLWA) Water Resource Recovery Facility (WRRF) (formerly called the Detroit Wastewater Treatment Plant), which discharges to the Detroit River upstream of Lake Erie, has already reduced its load by over 50% compared to 2008.

It has recently been estimated[8] that 58% of the TP load entering the Detroit River system comes from Lake Huron, much higher than earlier estimates. Using measured TP concentrations at the outlet of Lake Huron, Burniston et al.[12] estimated its load to be almost 3 times the previous estimates that were based on TP concentrations in the ultraoligotrophic Lake Huron.[4,13] They also showed that TP concentrations, especially particulate P, downstream in the St. Clair River were

Received: January 19, 2020
Revised: March 31, 2020
Accepted: April 9, 2020
Published: April 9, 2020

higher than upstream where Lake Huron enters, and that difference has increased over time. Because the concentration differences were not due to additional lateral loads to the river,[8,14] it has been suggested that the difference originates from episodic sediment resuspension in Lake Huron that is not captured at the upstream St. Clair River monitoring station. Accounting for this additional source, these recent estimates also showed that Lake Huron loads have increased over time[8,14] and currently are almost twice again as high as those of Burniston et al.[12]

Field studies conducted in 2008[15] showed that the flow into the St. Clair River carried sand and finer material entrained from Lake Huron's shoreline. Duane[16] had previously suggested that 0.25−2.64 mm diameter material is entrained by wave action, and more recent shear stress analysis[15] showed that particles up to 0.2−0.4 cm could be entrained in Lake Huron near the entrance to the St. Clair River. However, those studies focused primarily on the movement of sand size and larger material and from regions close to the outlet.

Over 30 years ago, Mortimer[17] pointed further north to Lake Huron's Ontario nearshore region as a potential significant source of sediment for Lake St. Clair and Lake Erie. Scavia et al.[8,14] suggested that this wave-induced resuspended sediment carried additional P and that it was often missed by the Canadian monitoring program that samples semimonthly to monthly at a fixed point intake at the outlet of Lake Huron. They showed that increases since 1998 paralleled climate-driven decreases in ice cover and increases in wave heights. Nicholls[18] also showed that January−May average TP concentrations at that monitoring station were highly correlated with percent ice cover and secondarily with water levels. However, he speculated that the higher P concentrations were due to sediment resuspended in Saginaw Bay, Michigan, and transported south along the Michigan shoreline.

Key open questions are where does this sediment load originate, what drives its variability, and how often do significant resuspension events occur. A full understanding of the potential impact of this newly identified load requires a better understanding of its sources and dynamics, as well as the bioavailability of its P content. Herein, we show that high-turbidity events at the Lake Huron outlet monitoring station may be missed when water quality samples are taken, and we use a hydrodynamic model, wind hindcasts, and satellite images of ice cover and resuspension events to explore the sources, dynamics, and timing of this unexpected and potentially important source.

■ MATERIALS AND METHODS

Study Site. We focus on southern Lake Huron (Figure 1), including the Point Edward monitoring site that has been used to estimate the lake's load to the St. Clair River.[12] Lake Huron is the second largest Laurentian Great Lake and the fifth largest freshwater lake in the world, with a surface area of 59 590 km^2, of which 23 580 km^2 lies in Michigan and 36 010 km^2 lies in Ontario. It contains 3540 km^3 of water at low water datum and is about 330 km from east to west and 295 km from north to south, with a maximum depth of about 230 m and an average depth of about 60 m. Lake Huron comprises four interconnected water bodies: the Main Lake, Saginaw Bay, the North Channel, and Georgian Bay (Figure 1). Major inflows come from Lake Superior via the St. Marys River and Lake Michigan via the Straits of Mackinac, and it discharges at

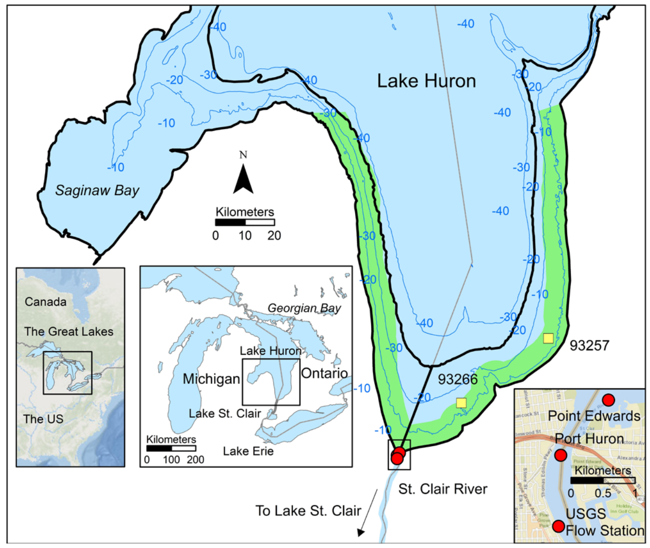

Figure 1. Study area, including depth contours, the buffer zone used to distinguish moderate vs large resuspension (green zone), the 30 m contour used for categorizing 15-day traces of source water for the Point Edward monitoring station (black line), wave station locations (yellow squares), and flow and monitoring station locations (red dots).

its southern end through the St. Clair River into Lake St. Clair, which in turn discharges through the Detroit River into Lake Erie. In addition to flows from Lake Superior and Lake Michigan, Lake Huron receives water and nutrients from its own 134,000 km^2 watershed that is roughly 30% in Canada and 70% in the United States. The majority of the lake's nearshore waters are of high quality, but areas along the southeast shore and Saginaw Bay experience episodic algal blooms.[19] Invasive zebra and quagga mussels have been associated with the decline in open-lake nutrient levels and increased water clarity since the mid-1990s,[20] and nutrient concentrations there remain very low.

Satellite Imagery. A three year (2016−2018) time series of true-color (RGB) MODIS images with 500 m spatial resolution was used to observe the occurrences of sediment resuspension in southern Lake Huron. MODIS was chosen over other satellite data for its high temporal resolution; images are collected twice daily. The time series was filtered using Google Earth Engine to remove images with more than 60% cloud cover within the area of interest and then manually filtered separately for the Ontario and Michigan shores to remove additional cloudy and unusable images. After filtering, there were 131, 135, and 110 usable images for the Ontario region and 130, 99, and 82 usable images for the Michigan region in 2016, 2017, and 2018, respectively.

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 (Figures 1 and 2). Based on a qualitative review of all images, we classified sediment visible within 8 km of the shore as moderate resuspension and the sediment that extended further than 8 km from the shore as large resuspension. Images with no visible sediment were also recorded. If a single day had two MODIS images with different sediment classifications, the smaller category was used.

Waves. Deep-water wave characteristics for 2016 and 2017 were downloaded from the U.S. Army Corps of Engineers

https://dx.doi.org/10.1021/acs.est.0c00383
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Figure 2. MODIS images of sediment resuspension in southern Lake Huron. Coded as none (left), moderate (center) when the sediment is inside the buffer line (white), and large (right) when extending offshore of the buffer line.

Wave Information Study (WIS) website (http://wis.usace.army.mil/, retrieved on 12-7-2019; station 93266; latitude: 43.16, longitude: −82.16, depth: 59 m; and station 93257; latitude: 43.36, longitude: −81.8, depth: 66 m; Figure 1). In addition to accessing significant wave height and wave period, we estimated the depth at which waves greater than 1 m would be influenced by the bottom for each day in 2016 and 2017 (2018 wave data were not yet available). At depths equal to half the wavelength, waves become transitional and are influenced by the bottom, and that depth can be estimated as $gT^2/4\pi$, where g is the acceleration due to gravity (9.81) and T is the mean wave period (s).[21] We assumed that waves with these characteristics have the potential to resuspend sediment from that point shoreward (SI).

Phosphorus. As described more fully by Burniston et al.,[12] Environment and Climate Change Canada (ECCC) operates a water quality monitoring program on the St. Clair River. The upstream sampling station at Point Edward (43.0048° N, −82.4155° W; Figure 1) is situated in Lake Huron near its outlet, just north of Sarnia, ON. Monitoring equipment is located within the municipal Lambton Area Water Supply Service (LAWSS) facility. Nutrient and major ion samples are collected from a 19 mm polyethylene water intake that extends 100 m into the lake at a depth of approximately 15 m below the surface. Samples were collected every 2 weeks until March 2012 and then every 4 weeks until March 2017 when it returned to every 2 weeks. Since 2014, these samples have been collected automatically using a Teledyne ISCO 5800 refrigerated sampler. Once filled, the sample bottles are capped and transported to the Canada Center for Inland Waters (CCIWs) in Burlington, ON, where they are analyzed by ECCC's National Laboratory for Environmental Testing (NLET) using NLET Method 01-1191. The whole water samples are transferred to a 125 mL flint glass bottle and preserved with sulfuric acid to a pH of <2. The sample is shaken, a 10 mL aliquot is poured in a glass digestion tube, and a mixture of sulfuric acid/persulfate is added. The sample is then digested in an autoclave for 30 min at 121 °C. The digest is analyzed in a continuous segmented flow analyzer (CFA), where the orthophosphate is reacted in an acid medium with ammonium molybdate and potassium antimonyl tartrate to form antimony-phosphomolybdate acid. This is then reduced with ascorbic acid to form the molybdenum blue complex. The absorption of radiation by the complex is proportional to TP concentration in the sample and is determined by the CFA colorimeter at an 880 nm wavelength. Quantification is achieved by calibration of the colorimeter with known solutions of phosphorus standards spread across the analytical range.

Turbidity. In addition to phosphorus and other water quality parameters, ECCC initiated continuous (hourly) monitoring of turbidity at Point Edward in 2016. Drawing from the same intake, the flow is fed continuously to a YSI EXO2 multiparameter sonde equipped with an optical EXO turbidity smart sensor. Sensors are calibrated and deployed on an 8 week basis, and separate, dedicated quality control sondes are used onsite and in the lab to check sensors against standards and determine fouling and calibration drift. The turbidity data for 2016−2018 are presented for the first time here.

Hydrodynamic Model and Water Traces. To assess the origins and pathways of water that passes the monitoring station, backward-in-time trajectories were examined using a three-dimensional hydrodynamic model and a Lagrangian particle model. The hydrodynamic model is based on the National Oceanic and Atmospheric Administration (NOAA) Lake Michigan-Huron Operational Forecast System (LMHOFS[22−24]). LMHOFS is built on the finite volume community ocean model (FVCOM[25]), which is a three-dimensional primitive equation oceanographic model that solves the integral form of the equations of motion with an unstructured horizontal grid and a σ-level (σ= 21), terrain-following, vertical coordinate system with 21 uniformly distributed vertical layers. The LMHOFS model has an unstructured grid that ranges in horizontal resolution from 200 m in the nearshore to 2500 m offshore, and uses hourly meteorology from the NOAA High-Resolution Rapid Refresh (HRRR[26]) to produce hourly simulations of currents, water temperature, and water level using a computational time step of 10 s. The boundary condition at the head of the St. Clair River, which is the outlet of the model, is prescribed as hourly outflow provided by a USGS streamflow gage located in the river (USGS station 04159130; Figure 1). Available coastal water level stations were used for the validation of predicted water level fluctuations and assessed using National Ocean Service (NOS) skill assessment criteria before implementation into NOAA operations (https://tidesandcurrents.noaa.gov/ofs/lmhofs/lmhofs.html).

The modeled hourly currents are supplied to the FVCOM's Lagrangian particle model, which allows for a reverse-current backward trajectory. Horizontal diffusion in the neutrally-buoyant particle model is prescribed by grid-size-dependent Smagorinsky parameterization, and vertical diffusion includes a random-walk methodology. The particle model has been applied successfully with a similar configuration in the Lake Erie HAB Tracker.[27] For the period 2016−2018, particles were released at the location of the Point Edward station, at a depth of 15 m, at a rate of 10 particles/h. Particles were tracked backwards in time for 60 days, and the results were compiled for each day (240 particles, hourly locations for a duration of 60 days). We compared 5-, 10-, 15-, and 30-day traces and found only modest differences in results (Figure S1). We used 15-day traces because, given average long-shore currents of 0.01−0.04 m/s (Figure S2), those traces would typically cover 13−50 km, roughly over half way through our study area.

For each day, we calculated the percent of 15-day traces that fell within each of the three regions—outside the 30 m depth contour (Center), inside that contour in Canada (Ontario), or inside the contour in the United States (Michigan) (Figure 1)—by calculating the total length of traces in each region

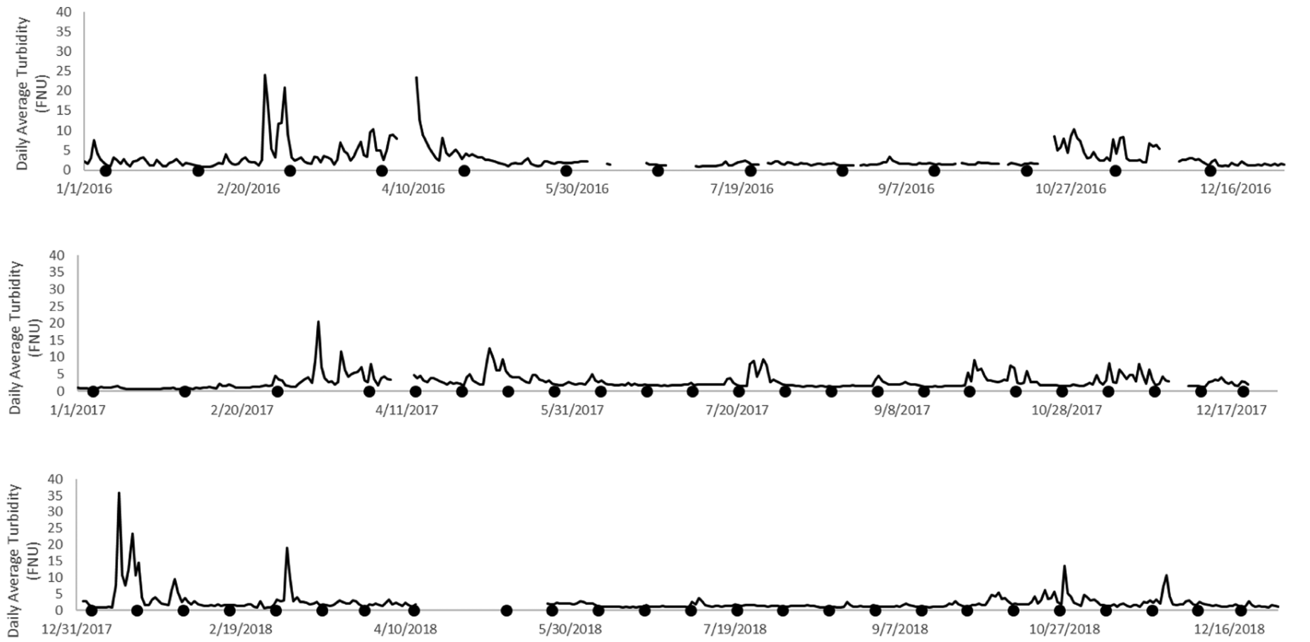

Figure 3. Daily averaged (line) turbidity at the Point Edward sampling station. Large dots on the *x*-axis are phosphorus sampling times, demonstrating the significant number of events missed in the phosphorus sampling program.

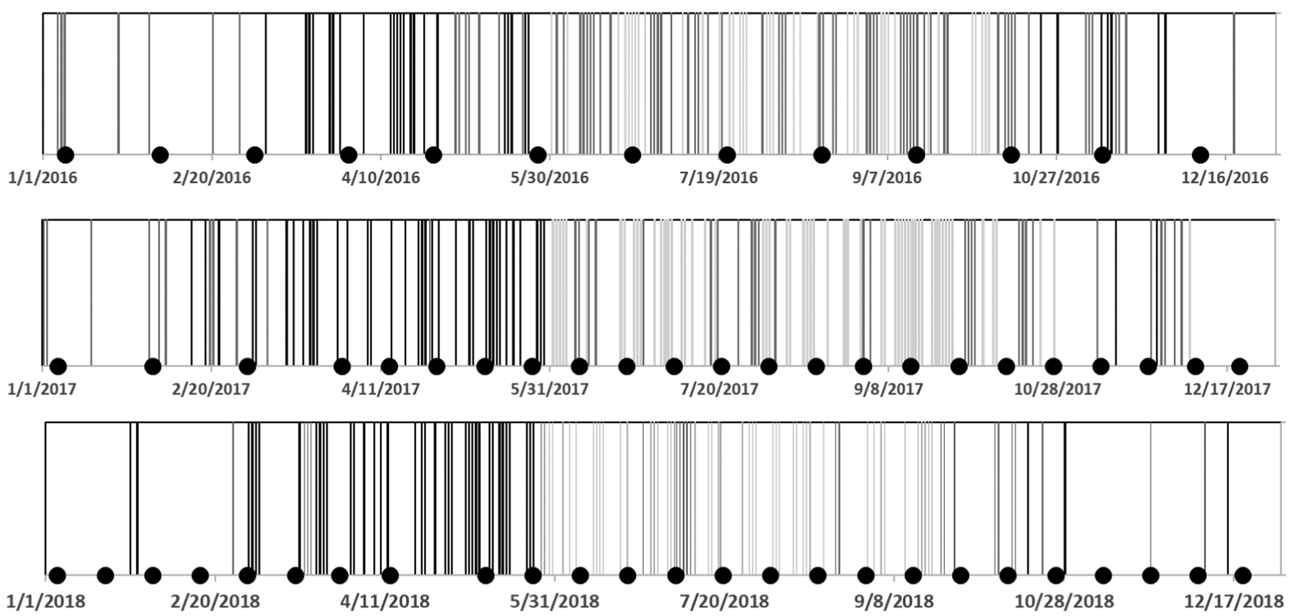

Figure 4. Classification of resuspension events (2016–2018). Large (dark lines), moderate (medium lines), and no (light lines) resuspension. White space represents times with no usable images. Dots represent sampling times at Point Edward.

divided by the total length of all traces. To reduce noise in these observations, we used 7-day moving averages.

Ice Coverage. We analyzed the daily ice concentration in the 30 km Michigan and Ontario nearshore zones in 2016, 2017, and 2018 to evaluate the potential for ice dampening of resuspension events. We used a concentration threshold of 40%, above which we assumed ice was sufficiently present to have an effect. Ice data were from the U.S. National Ice Center (NIC); U.S. National Ice Center: Naval Ice Center (www.natice.noaa.gov/products/great_lakes.html, accessed 1/5/2020). The NIC produces daily gridded ice analysis charts through a binational coordination with the Canadian Ice Center. The charts are derived from a variety of data sources, including AVHRR, Radarsat-2, Geostationary Operational and Environmental Satellites (GOESs), Envisat, and the Moderate Resolution Imaging Spectroradiometer (MODIS), and are output on a 1.8 km grid.

RESULTS AND DISCUSSION

Turbidity at Point Edward. Turbidity varied hourly, daily, seasonally, and across the 3 years. While there were a few gaps in coverage, it is clear that large peaks, reflecting the passage of suspended solids and likely particulate P, occurred in late winter, early spring, and late fall in 2016 (Figure 3). In 2018, there were peaks in fall and early winter and almost none throughout much of the rest of the year. Peaks were more

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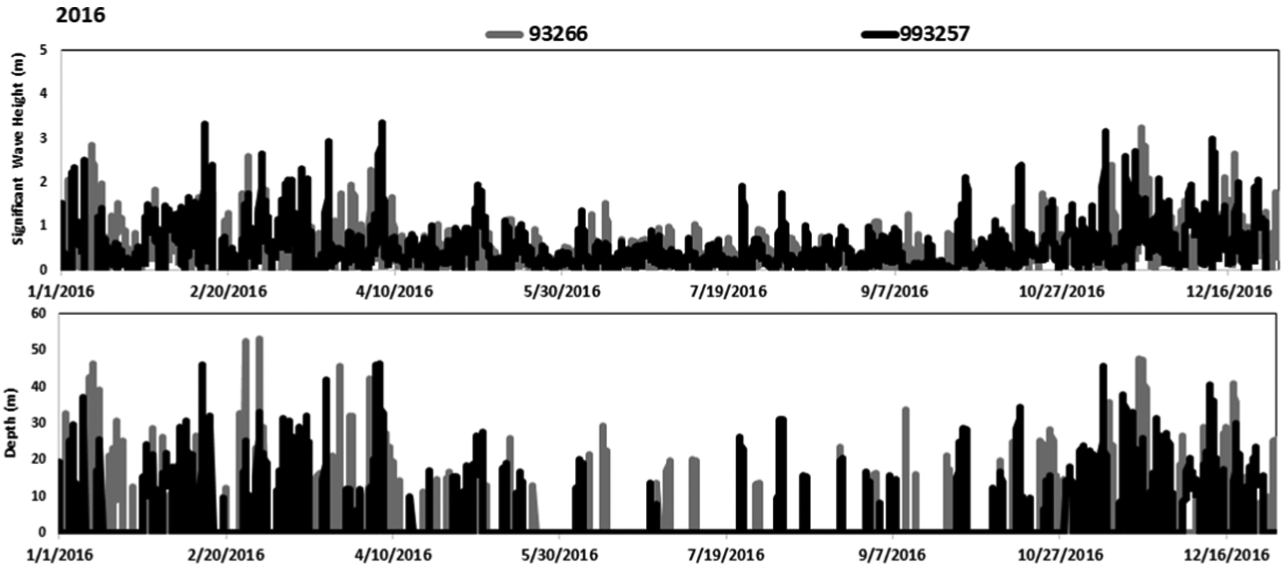

Figure 5. Significant wave heights (top) and estimated depth of bottom influence (bottom) for waves >1 m for 2016 for WIS station 93266 (gray) and 93257 (black).

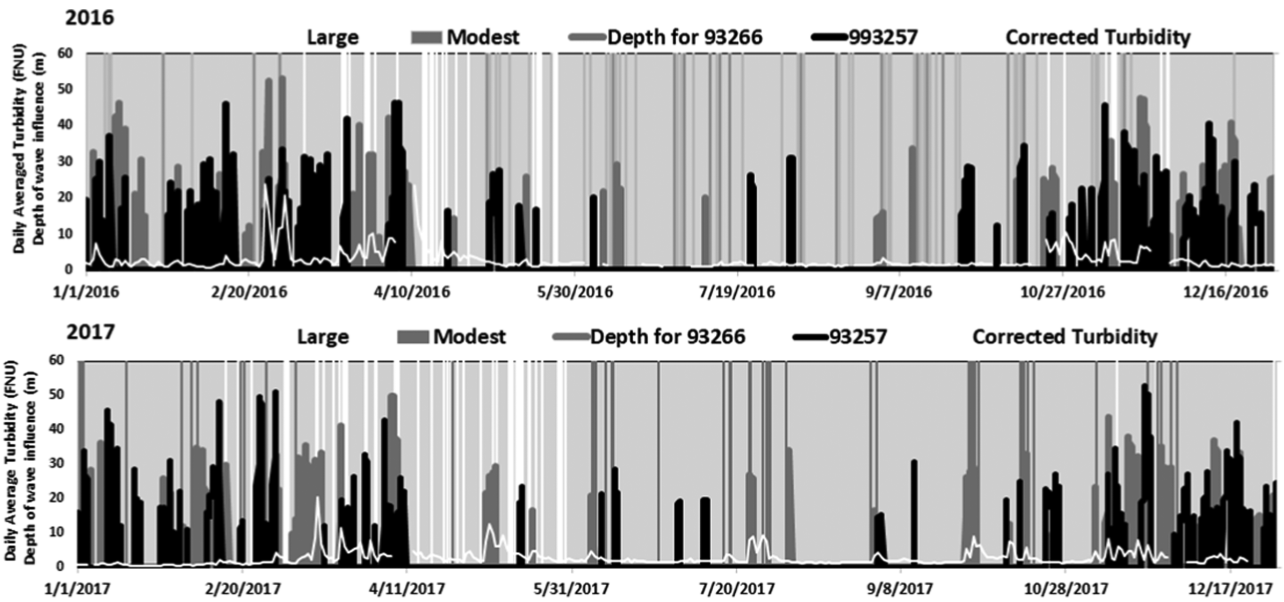

Figure 6. Comparison of turbidity at Point Edward (white line), large (white bars) and moderate (light gray bars) resuspension as determined from satellite analysis, and depths at which waves at Station 93266 (dark gray bars) and 93257 (black bars) reach the bottom for 2016 (top) and 2017 (bottom).

evenly distributed in 2017. By comparing turbidity with P sampling times (Figure 3), it is also clear that several significant high-turbidity events were missed by the P monitoring program, even in 2017 and 2018 when sampling frequency was biweekly. In addition to this temporal mismatch between the passage of sediment-laden water and TP sampling, it is also possible that sediment-laden water passing inshore, offshore, above, or below the sample intake point could also be undetected. Using hypothetical scenarios, Scavia et al.[8] showed that accounting for the additional TP from these events requires only 3−5 events per year, each lasting 1−5 days.

Total Phosphorus. The relationship between turbidity (T) and total phosphorus in samples taken at the same time at Point Edward was not statistically significant, likely due to the relatively narrow range of conditions. However, there was a positive relationship ($TP = 8957T_2 - 80.3T + 2.0$, $R^2 = 0.32$), and the observations are consistent with data spanning several orders of magnitude from nearshore stations at the north end of our study area off Point Clark, Ontario[28] (Figure S3). While more observations spanning a wider range of conditions are needed at Point Edward, we assume this sediment is carrying a phosphorus burden similar to that observed along the Ontario nearshore.[28]

Ice Coverage. Ice coverage was similar in Michigan and Ontario in 2016 and 2017 (Figure S4). In 2016, there were 16 and 21 days with at least 40% ice cover in Ontario and Michigan, respectively. In 2017, there were 17 and 12 days. There was substantially more coverage in 2018, with 66 days of more than 40% coverage in Ontario and 36 days in Michigan.

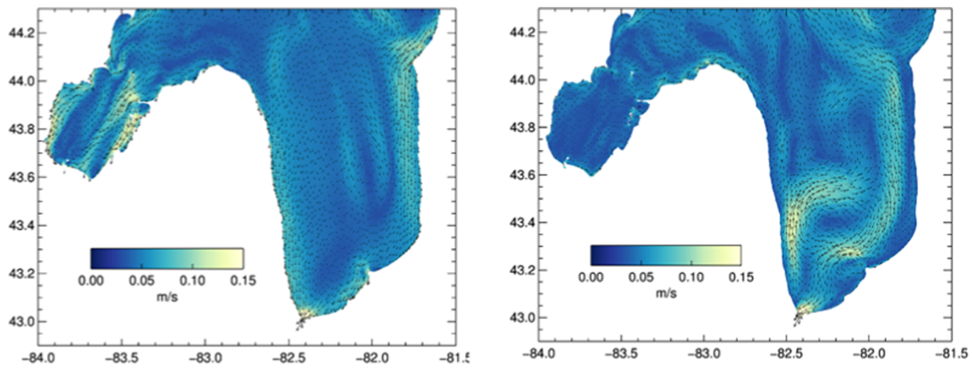

Figure 7. Modeled monthly mean surface flow for April (left) and October (right) 2016.

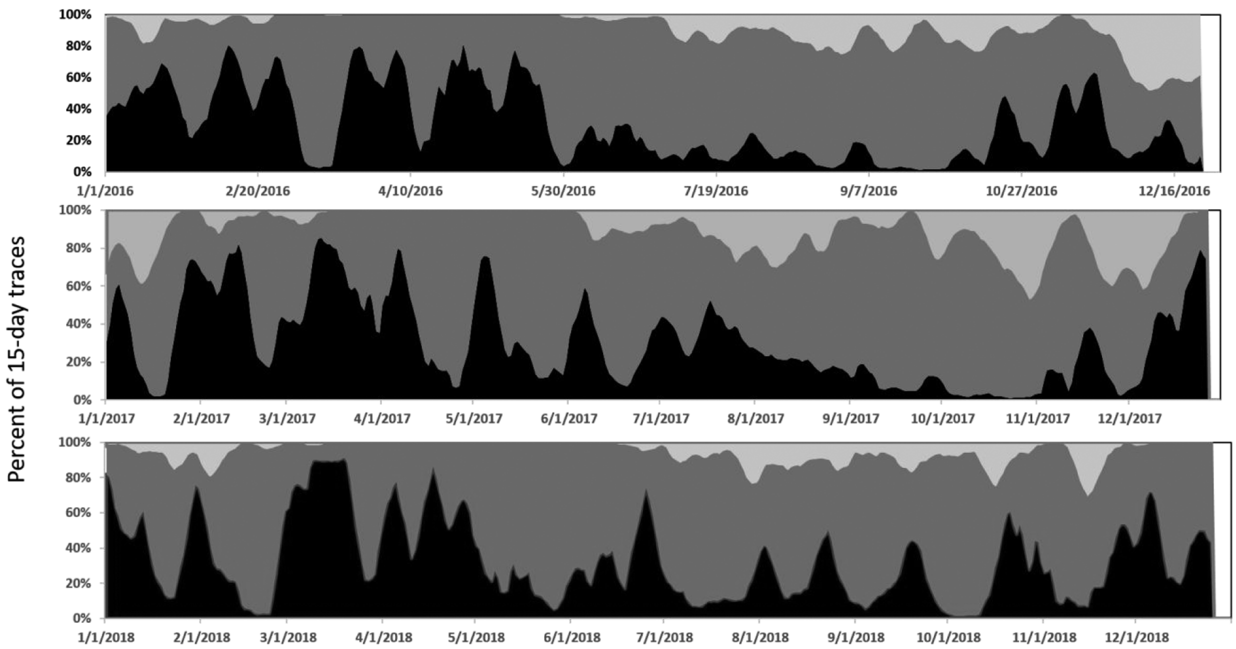

Figure 8. Percent of 15-day traces of water passing the Point Edward station that originated in the center (light gray), Ontario (dark gray), and Michigan (black) regions.

Sediment Resuspension. Of the usable Ontario images, 72, 57, and 60% showed occurrences of moderate or large sediment resuspension in 2016, 2017, and 2018, respectively. These frequencies are similar to those reported for 2010 (64%) and 2012 (54%) for the same region.[14] The percentages for large occurrences were 22, 38, and 41% for 2016, 2017, and 2018, respectively. While clouds substantially reduced the number of usable images in winter and spring, it is clear that most of the moderate to large resuspension occurs then (Figure 4), with far less occurring during summer in all 3 years. Along the Michigan shore, there were 130, 99, and 82 usable images in 2016, 2017, and 2018, respectively, and of those, 46, 49, and 65% showed moderate resuspension. There were only three cases of large resuspension across the 3 years, and there were far more images with no resuspension than in Ontario (Figure S5).

Wave Impacts. Waves at the two WIS stations were generally higher in fall through early spring in 2016, and the depths at which the bottom influences the waves for waves over 1 m were deeper (Figure 5). Because the waves were generally smaller with shorter periods during summer, the depths of bottom influence were shallower. In fall through early spring, bottom impacts and potential resuspension could occur at a depth shallower than 30−50 m, whereas, in summer, potential resuspension depths were in the 15−20 m range. Similar dynamics were observed in 2017 (Figure S6).

Because the depths of potential impact during the fall through early spring occur at depths in the Ontario nearshore region where satellite images show large resuspension (Figure 6), we attribute these events to wind-driven resuspension. Resuspension was moderate or did not occur during summer when the waves were smaller and the depth of impact shallower. Most of the large resuspension events resulted in increased turbidity at Point Edward; however, 19% of the large resuspension cases did not correspond to increased turbidity. This is likely due to flow patterns as discussed below.

Transport to the St. Clair River. To influence turbidity and phosphorus concentration at the Point Edward station, the resuspended sediment has to be transported there. While Lake Huron's large-scale general circulation is counterclockwise with flow southerly in Michigan and northerly in Ontario,[29,30] our higher-resolution model shows more complex flows (Figure S7). For example, monthly mean surface currents in April 2016 are southerly in both Michigan and Ontario, whereas in

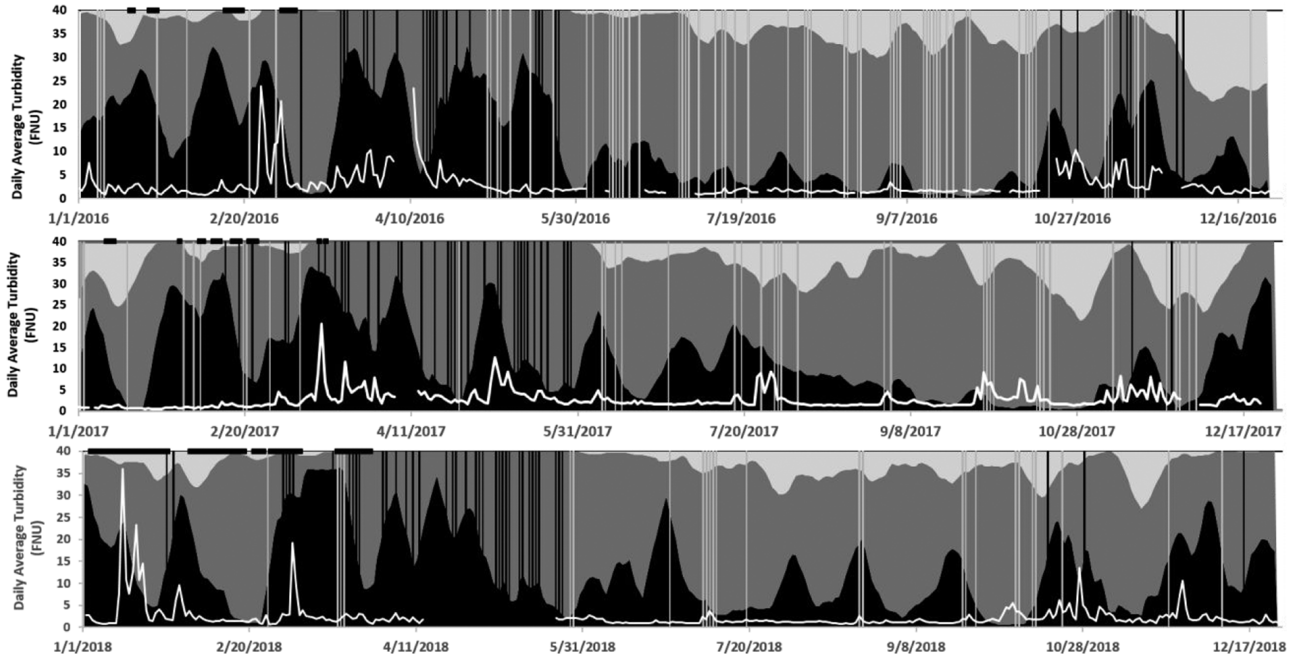

Figure 9. Alignment of large resuspension events (vertical black bars), >40% ice cover (horizontal black bars), turbidity at Point Edward (white line), and 15-day traces as in Figure 8 for 2016 (top), 2017 (middle), and 2018 (bottom). Note that there are periods of missing turbidity data and periods of unusable images.

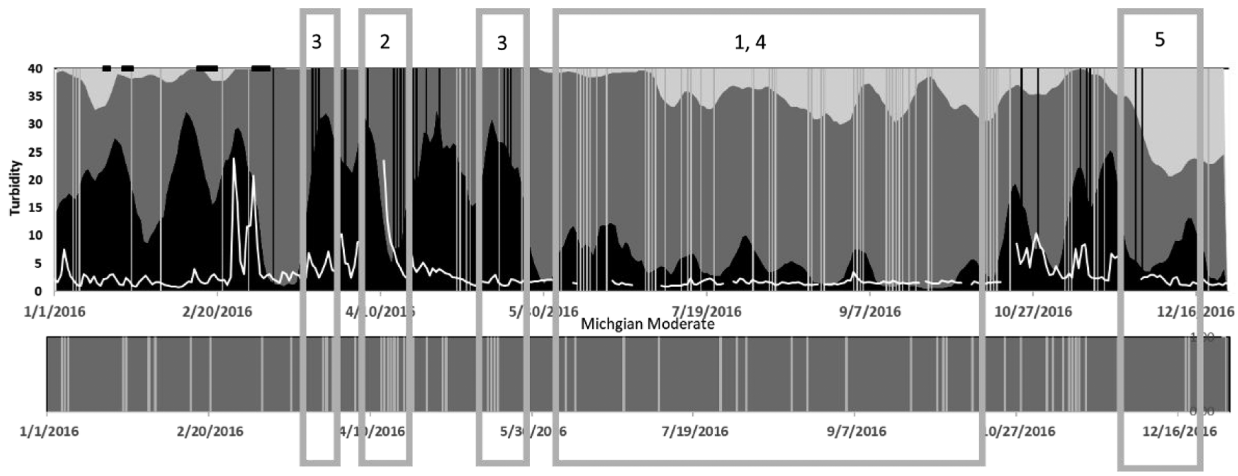

Figure 10. As in Figure 9, with large and moderate resuspension in the Ontario region (upper) and moderate resuspension in the Michigan region (lower). There were no large events in the Michigan region. Gray rectangles correspond to scenarios described in the text.

October there is a persistent clockwise gyre with flow northerly in Michigan and southerly in Ontario (Figure 7).

While this variability played out daily and seasonally, patterns emerged from analysis of the 15-day traces of source water passing the Point Edward site (Figure 8). With the exception of early winter 2016 and 2017, most of the water passing the Point Edward site originates within the 30 m depth contours. In 2016 and 2018, southerly flows from Michigan tended to alternate with flows from Ontario in fall and winter, consistent with the reported winter circulation patterns[31] due to the tendency for higher wind speeds during these periods. During the summer and into early fall, southerly flows in Ontario dominate across years, with variability driven by episodic wind conditions, noted by the spikes in Michigan-fed waters.

Timing of Resuspension, Currents, and Turbidity. Moderate resuspension did not increase turbidity in 2016 and only occasionally in 2017 (Figure 6); however, there was a strong relationship between elevated turbidity and large resuspension. Large Ontario resuspension and elevated turbidity occurred primarily in fall, late winter, and early spring, although there likely was additional winter resuspension when cloud cover prevented observation in satellite imagery (e.g., January 2018). The lack of large resuspension between January and March in 2016 and 2117 may also correspond to periods of greater than 40% ice cover (Figures 9 and S4). The periods of increased turbidity and large resuspension in 2018 that correspond to periods of greater than 40% ice cover (e.g., mid-January, early March) are a result of ice cover and resuspension being present in different sections of the region (e.g., Figure S8).

Increased turbidity coincided with Ontario flow (e.g., April 2016, early October 2017, January 2018, October 2018), but also occurred when some of the flow was from Michigan (e.g., late February 2016, March 2017) (Figure 9), even though there were very few instances of large resuspension on the Michigan shore, and those moderate events were generally less frequent and much smaller than on the Ontario shore. Because Nicholls[18] suggested that increased TP concentrations might be driven by flow along the Michigan shore of resuspended Saginaw Bay sediment, we explored these relationships further.

Comparing the timing of increased turbidity with resuspension events and flows from both Ontario and Michigan in 2016 (Figure 10), we observed five scenarios:

(1) Increased turbidity at Point Edward was only observed with large Ontario events. Most of the moderate Michigan events co-occurred with large Ontario events.

(2) In mid-April, there were large Ontario events, the flow mostly from Ontario, and increased turbidity observed at Point Edward.

(3) In mid-March and late-May, there were large Ontario events and moderate Michigan events, with flow mostly from Michigan, and relatively low turbidity, suggesting that the Ontario events did not impact Point Edward at those times.

(4) During summer, there are only moderate events in both regions, the flow is mostly from Ontario, and turbidity remains low at Point Edward.

(5) In December, there are large Ontario events, but the flow is from the central region of Lake Huron and turbidity remains low at Point Edward.

There were similar patterns in 2018 and 2017 (Figure S9), although in 2017 there were periods of increased turbidity associated with moderate resuspension. Taken together, these scenarios and the Supporting Information for the other 2 years show that elevated turbidity occurred most often with large resuspension along the Ontario shore at times when the flow is from that region. That sediment load is driven by wave-induced resuspension within 30 km from shore at depths of 30−50 m (Figure 6). Earlier studies in the Ontario nearshore[28] showed that the influence of land runoff is small and restricted to the shoreline fringe relative to the broader nearshore. While that load may, over time, contribute to the sediment that gets resuspended, it is unlikely to be the proximate cause of what is detected in the satellite imagery.

When the flow is from Michigan or down the center of the lake, little of that resuspended material flows to the outlet as monitored at Point Edward. When turbidity was high during modest Michigan resuspension, it most often occurred during large Ontario events. This is consistent with the fact that the frequency and spatial extent of resuspension in Michigan were considerably less than in Ontario. Even if there was a contribution from Michigan, it would not likely be detected at Point Edward because the river generally operates as parallel streams of poorly mixed Michigan and Ontario waters,[32,33] and elevated TP concentrations were not observed in the 93 measurements between 1998 and 2016 at a station along the Michigan side of the river at Port Huron (Figure 1). It is also worth noting that at typical depth-integrated flows along the Michigan shore (0.01−0.03 m/s; Figure S2), it would take 55−160 days for resuspended Saginaw Bay sediment to reach the St. Clair River, as hypothesized by Nicholls.[18]

These elevated turbidity events are often missed by sampling at Point Edward; they are, however, captured by ECCC downstream, in the St. Clair River at Port Lambton, after the river has become well mixed. Inclusion and increased characterization of the Lake Huron sediment load would improve the total phosphorus loading estimates entering the river. There is, in particular, a need to characterize the phosphorus content of the sediments and its potential bioavailability.

Limitations and Research Needs. Data from the monitoring program at Point Edward helped improve estimates of the Lake Huron load[12] and identify potentially important additional sources.[8,14] Initial estimates of the Lake Huron load based on that monitoring program[12] were roughly three times higher than earlier estimates,[4] and subsequent analysis[8,14] estimated that load to be 50% again higher due to the missed high-turbidity events. However, ECCC's program was designed originally to understand the sources and dynamics of chemical contaminants in the St. Clair River, not to estimate the P load from Lake Huron. To increase confidence in that load estimate, it is important to assess the spatial and temporal variabilities of phosphorus concentrations in the St. Clair River downstream of the Lake Huron outlet. A more robust effort would integrate Canadian and U.S. sampling to ensure complete spatial coverage. Currently, there is less robust monitoring on the U.S. side of the St. Clair River. If the sampling frequency required to capture the episodic events is prohibitive, it should be possible to deploy continuous measurement of surrogates like turbidity,[34] as has been initiated on the Canadian side. In this way, the relationship between turbidity and TP can be more fully explored and the spatial distribution of the load can be better quantified.

While the relationship we observed between TP concentration and turbidity falls in line with those measured at stations at the north end of the Ontario portion of our region, there is considerable scatter and more study is required to assess this relationship. Further, there have been no estimates of the bioavailability of resuspended sediment from this region. Eadie et al.[35] suggested that sediment resuspension may mobilize biologically available phosphorus, and others have indicated that particulate P from tributaries may include a substantial bioavailable fraction.[36,37] However, much of it could be refractory,[38,39] and particulate P from shoreline erosion is likely mineral-derived with limited bioavailability.[40] It may be possible to assess the P content using archived sediment from ECCC's monitoring at Point Edward and to assess if this content has changed over time. A more detailed assessment of sediment characteristics would also allow the estimation of bottom shear stress thresholds for resuspension.

There were many days for which we could not assess sediment resuspension due to cloud interference with satellite images, and much of that occurred during winter when additional resuspension events were likely. It is also important to note that the image classifications reflect a wide geographic coverage, and the images have a 500 m pixel resolution, whereas the sampling at Point Edward is at a discrete location 100 m from shore and 15 m from the surface. As a result, there could be cases where resuspended sediment was transported inshore or offshore of the sampling point, as well as above or below it. In those cases, resuspended sediment should have produced higher turbidity and added to the load, but the

https://dx.doi.org/10.1021/acs.est.0c00383
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sampling point would have missed it even though the sampling was conducted at the right time.

Implications. This previously unmeasured TP load from Lake Huron does not impact current estimates of the Detroit River's load to Lake Erie because those are based on summing loads below Lake St. Clair[14] or on Detroit River measurements.[12] However, it may impact the attribution of TP sources and thus the potential allocation of load reductions.

Scavia et al.[14] discussed a set of phosphorus load reduction alternatives that could be considered as the United States and Canada embark on adaptive management (AM).[3] Because the sediment portion of the incoming Lake Huron load would be difficult to manage and may even increase with climate change due to increased resuspension frequencies, the AM process will likely need to allocate the needed load reductions to other sources. Through this process, better information and a prioritization of the many important research and monitoring needs will be required. For the upstream Lake Huron load, we have shown that improved research and monitoring are needed to assess the possible sources and their bioavailability. In this way, Lake Huron's contribution to the Lake Erie phosphorus load can be better assessed and tracked over time.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.0c00383.

> Estimating wave depth impact; comparison of water traces; 3-month averaged, depth-integrated currents, and average current speeds; relationship between total phosphorus and turbidity; duration of >40% ice cover; frequency resuspension; significant wave heights and estimated bottom influence depth; monthly averaged surface and depth-integrated circulation patterns; and MODIS image showing regions of both ice cover and resuspended sediment (PDF)

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Notes

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■ ACKNOWLEDGMENTS

This work was supported in part by the Fred A. and Barbara M. Erb Family Foundation grant #903. The authors thank Nathan Hawley for his insights and advice on wave dynamics, Tyler Hesser and Alan Cialone for access to additional wave data, and Lisa Bradley for access to and advice on Environment and Climate Change Canada's real-time turbidity data. This is GLERL Contribution #1945.

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