IMPACTS ON NUTRIENT AND SEDIMENT RESUSPENSION BY VARIOUS WATERCRAFT ACROSS MULTIPLE SUBSTRATES, DEPTHS, AND OPERATING SPEEDS IN INDIANA'S LARGEST NATURAL LAKE[2]

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ABSTRACT. While a key component of lake recreation, watercraft are capable of impairing water quality, including via resuspension of nutrients and sediments from the lake bottom. As water quality influences the ecological, economic, and recreational capacities of a lake, this study set out to investigate nutrient/sediment resuspension by watercraft on Indiana's largest natural lake, Lake Wawasee. Four experiments were performed to test the following variables in substrate resuspension by watercraft: (1) lake bottom substrate type, (2) water depth, (3) watercraft type, and (4) operating speed. Nutrient/suspended sediment samples were collected before and after the watercraft passed through the sampling area and their averages were compared using t-tests. Nutrient resuspension was observed after the wake boat in 5 ft of water, and no resuspension by any watercraft in 10–15 ft of water. Resuspension was observed after plowing (near plane) in 5 ft of water or idling in 3 ft by multiple watercraft. The results suggest that recreationalists use high impact watercraft and operational styles in water $\geq$10 ft in Lake Wawasee. Differences in macrophyte assemblage (including non-native invasive starry stonewort, *Nitellopsis obtusa*) likely had a large impact on the resuspension potential of one testing area. Boating restrictions based on speed and water depth can support the recreation that draws people to lakes while protecting the lake from some damage by that recreation. Lake managers should also consider variation in bottom substrate across their lake to identify areas particularly sensitive to boating and nutrient resuspension.

Keywords: boat recreation, sediment and nutrient resuspension, lake bottom substrate, water quality

INTRODUCTION

Watercraft are a significant component of lake recreation. In lake-abundant communities, such as Kosciusko County, Indiana, watercraft recreation boosts the local economy. Fishing and boating industries contribute over 150 million dollars annually to Kosciusko County (Bingham & Bosch 2016). In 2012, properties within 500 ft of 41 major Kosciusko County lakes made up over half of the county's residential property tax revenue (Bosch et al. 2013). Residential properties around Lake Wawasee, the largest lake in Indiana, accounted for 5.4 million dollars of tax revenue in the same study. Some of these economic benefits are directly related to the water's actual or perceived water quality (Ara et al. 2006; Nicholls & Crompton 2018), and boating can have a negative impact on water quality (Wagner 1990; Asplund 2000).

In many lakes, residents can easily observe watercrafts' impacts to water clarity due to resuspended bottom substrate. Researchers have observed a decrease in nearshore water clarity after high intensity boating in Clear Lake, IA, Lake Tahoe, CA, and elsewhere (Anthony & Downing 2003; Alexander & Wigart 2013). Boaters on Lake Wawasee, Indiana identified "muddy water after boats stir up the bottom" as a condition that interfered with their recreational experiences, ranking third out of sixteen listed concerns in a survey of 515 Wawasee residents and businesses (Peel 2007). While visual appeal is valuable to those who enjoy lakes, lake managers are also concerned about the ecological impact of resuspended sediments. Resuspension of compounds like nitrite (NO_2^-), nitrate (NO_3^-), and soluble reactive phosphorus (SRP) makes them easily accessible for algae and cyanobacteria growth, further reducing water clarity (Yousef et al. 1980; Nedohin & Elefsiniotis 1997). Suspended

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[2] All supplemental material can be accessed by clicking on the "Supplemental Materials" Link on the IAS Proceedings page (https://www.indianaacademyofscience.org/publications/proceedings).

sediment (SS) may directly harm macroinvertebrates and fish (Newcombe & MacDonald 1991). Watercraft are not the only cause of internal nutrient loading. Wind action can also mix sediments, and watercraft and wind can work in conjunction to slow resettlement of resuspended particles and extend high turbidity events (Anthony & Downing 2003; Zhu et al. 2015). Variations in bottom substrate influence the resuspension potential of bottom sediment (Wagner 1990; Beachler & Hill 2003).

Types of watercraft and operational styles also influence resuspension. Wake boats are designed and operated to maximize wake, pontoons are well suited for slower leisure, and personal watercraft quickly skim the surface. Watercraft and boating practices have changed over time. Boats have become more powerful, and watercraft recreation has gained popularity over the years (Beachler & Hill 2003), a point further supported by the rise in popularity and relevance of wakesurfing and wake boats (Ruprecht et al. 2015).

Wawasee's high boat density, prevalence of power boating, and known economic impact of watercraft inspired this study (Peel 2007; Bosch et al. 2013), and the goal of this study was to gain understanding of watercraft impacts at the level of the recreationalist and create ecologically relevant boating recommendations. A series of *in situ* nutrient/suspended sediment measurements was performed before and after watercraft passes to (1) to characterize the resuspension potential and composition of each substrate type present in our study lake, (2) determine the smallest depth of water necessary to minimize resuspension across watercraft types, (3) test the belief that no resuspension occurs if navigating shallow waters or channels at idle speeds (approximately 800–1,000 RPM), and (4) test for the impact of nearshore plowing (approximately 2,000 RPM), a common boating style on our study lake. These experiments can help establish boating guidelines that protect water quality while preserving recreationists' engagement on the lake.

METHODS

Study site.—Lake Wawasee ("Wawasee" onward), a 3,006-acre glacial lake in the northeast corner of Kosciusko County, Indiana (41° 23′ 54.5748″ -85° 41′ 53.8224″), is the largest natural lake in the state. Wawasee receives an influx of recreationalists in the summer for fishing, skiing, wakesurfing, and other activities. Wawasee's morphology is shallow on average; 45% of the lake is < 10 ft deep (Peel 2007).

Field sampling occurred at multiple water depths in four areas across Wawasee based on previously observed substrate types: Conklin Bay (muck), Johnson's Bay (muck), Black Point (sand), Bayshore Point (marl) (Fig. 1). During the sampling process, we observed that Johnson's Bay muck substrate was covered in aquatic macrophytes, while Conklin was not. Impacts of this unexpected variable are covered in the results and discussion sections.

Design.—Sampling was performed on 9–10 May 2018. Five popular types of watercraft were employed: center mount inboard (inboard), inboard/outboard runabout (runabout), personal watercraft (PWC), standard pontoon, and V-drive wake boat (wake boat). A local marina selected make/models and lengths of these watercraft types to represent the most common local watercraft (Table 1), and they provided and operated the watercraft during tests. Four tests were designed, each with several boat runs in various operating conditions.

Tests.—*Bottom substrate test:* The runabout was driven in "near plane" (low in water before watercraft begins to level off to flat, "on plane" operation; approximately 2,000 RPM) in shallow water (0.9 m; 3 ft) at each of the four lake areas, intentionally resuspending sediment. Water samples were gathered – one at the surface (0 m) and two at 0.5 m – before and after each boat run to observe potential change in concentration of nutrients and suspended sediments in the water. Pre-run levels also established a baseline for nutrient levels in undisturbed water. We hypothesized that the muck substrates of Conklin and Johnson's bays would be most sensitive to boat action.

Watercraft vs. water depth: This test was designed to determine the smallest depth of water required to minimize or inhibit sediment resuspension for each watercraft type. Boats ran through 1.5 m (5 ft), 3.0 m (10 ft) and 4.6 m (15 ft) depths at their common operating speeds/RPMs (on plane for all watercraft except the wake boat; Table 1). Water samples were taken from the surface, middle, and near bottom of the water column for each run depth, with the exception of some shallow (1.5 m) sampling in which the near bottom was sampled twice because the water was not sufficiently deep for three distinct sampling

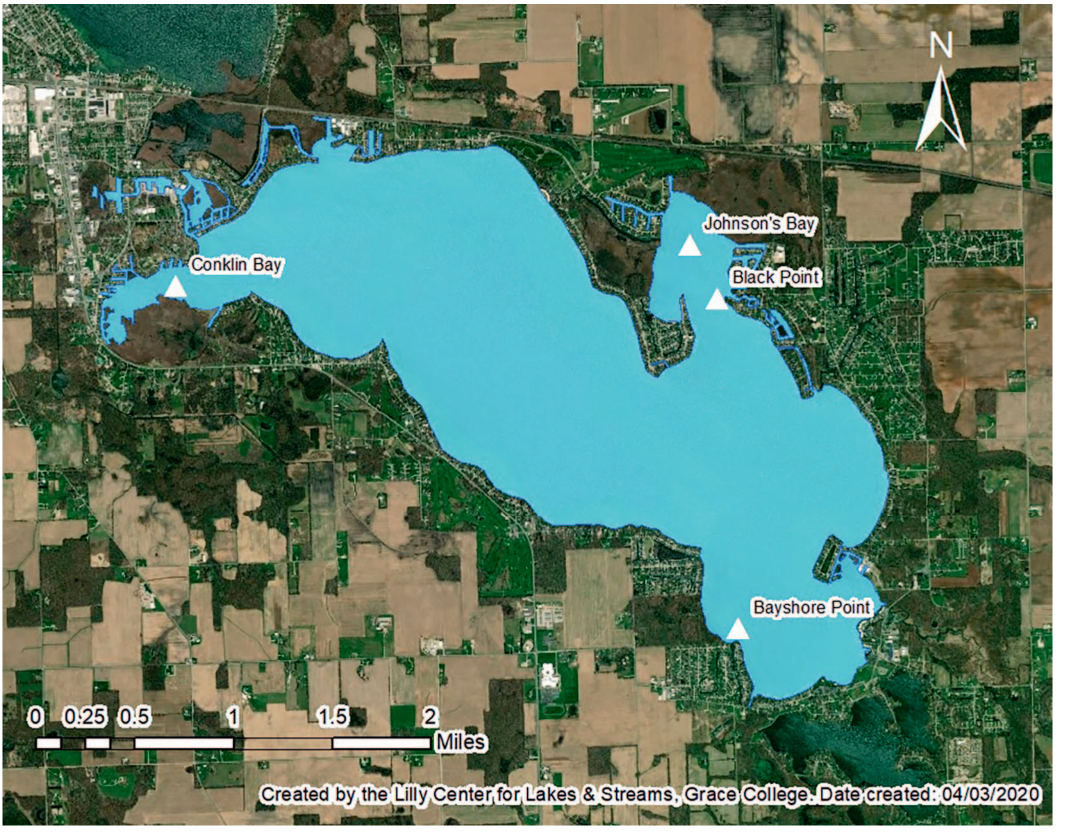

Figure 1.—Four sampling areas on Lake Wawasee, Kosciusko County, Indiana.

depths. Boat runs were alternated between the two muck locations, Johnson's and Conklin bays, to allow water to settle between runs.

Idle speed: To test the belief that idling (approximately 800–1,000 RPM) through channels or shallow water limits resuspension, each watercraft type was run at idle speeds in shallow (0.9 m, or 3 ft), muck substrate water. Water was sampled once at the surface and twice at 0.5 m before and immediately following each run.

High wake nearshore plowing: Many Wawasee recreationists enjoy leisurely rides around the lake, often in shallow water at a slow pace (approximately 2,000 RPM) that displaces more water than no wake or on-plane operation. The impact of this nearshore plowing on bottom sediment resuspension was tested using

Table 1.—Watercraft and operating speeds utilized in this study. Asterisk indicates the RPMs considered as "standard operation" for that watercraft in this study. The wake boat was operated with a full ballast for all tests.

Watercraft	Make/Model	Length (ft)	Approx. Near Plane RPM	Approx. On-Plane RPM
Center mount inboard	Ski Nautique 200	20	2000	3000*
Inboard/outboard runabout	Regal 2100	21	2200	3200*
Personal watercraft	Sea-Doo GTI	–	3000	4500*
Standard pontoon	JC Neptoon Evinrude (115 hp)	23	2000 – 3000	3500*
V-drive wake boat	Nautique 210	21	2000*	3000

Table 2.—Lake area water quality measurements, taken from 1 m below surface and 1 m above lake bottom.

Parameter		Conklin May 9	Johnson's May 9	Conklin May 10	Johnson's May 10
pH	Surface	8.37	8.39	8.31	8.27
	Bottom	8.21	8.08	7.27	8.10
Conductivity (mS/cm)	Surface	0.374	0.377	0.369	0.379
	Bottom	0.386	0.378	0.565	0.376

the inboard, pontoon, PWC, and runabout watercraft. Runs were performed in Johnson's and Conklin bays in 1.5 m (5 ft) water to simulate residents cruising the shoreline at low speeds. Nutrient and suspended sediment samples were collected at 0 m, 0.5 m, and 1.5 m depths before and after each run.

Field sampling.—Data was gathered on general water quality parameters (water temperature, °C; dissolved oxygen, mg/L and % saturation; pH; and conductivity, mS/cm) using a Hydrolab Quanta multi-probe sonde at each meter of water, surface to 1 m above bottom. A Kestrel 3500 weather meter measured air temperature (°C) and maximum and average wind speed (kn), at the beginning of sampling at both Conklin and Johnson's Bays during both sampling days.

For each test, a 27 m-long sampling area of the correct water depth was marked off with three buoys. A sampling boat slowly approached the middle buoy, and three Van Dorn water samples were used to collect pre-run samples (sampling depths described for each test above) without disturbing the substrate. The testing boat drove through the sampling area at the speed determined by the test, and the sampling boat gently approached the middle buoy again. Three Van Dorn water samples were collected post-run at the same depths as pre-run samples. The sampling area was reestablished in a new position every run to allow water and resuspended sediment to settle and switched areas of the lake altogether between tests.

Upon retrieval, water samples were stored in a dark cooler with icepacks and refrigerated at $\sim 5°$ C until they were shipped for lab analysis according to the Lilly Center for Lakes & Streams (Lilly Center) quality assurance plan approved by the Indiana Department of Environmental Management (Lilly Center 2021).

Analytical methods.—The National Center for Water Quality Research (NCWQR) at Heidelberg University performed nutrient and suspended sediment analysis of all samples, reporting concentrations of ammonia (NH_3), chloride (Cl^-), sulfate (SO_4^-), nitrite (NO_2^-), nitrate (NO_3^-), silica (SiO_2), soluble reactive phosphorus (SRP), total phosphorus (TP), total Kjeldahl nitrogen (TKN), and suspended solids (SS; NCWQR 2013). Total nitrogen (TN) was calculated as the sum of NO_2^-, NO_3^-, and TKN concentrations.

Data analyses.—After rejecting results from two dirty samples that contained bottom substrate rather than just a water column sample, unpaired t-test (as three measurements were taken before and three after each boat drove through) were computed for the difference between the averages of pre-runs and post-runs for each experiment. The t-tests gave a 95% confidence interval for the difference between pre-tests and post-tests. The confidence intervals were used instead of p-values because the number of experiments performed could lead to false positives.

The pre-test and post-test averages with confidence intervals were plotted for each experiment. These confidence intervals are different from the confidence intervals of the t-test, but are related because the standard error of a difference of two equally sized samples is the square root of the squares of the standard errors of each sample (Newham et al. 2021).

RESULTS

Lake water quality measurements were within normal ranges at our sample areas (Table 2; Fig. 2), though wind speeds were moderately high both sampling days (gusts of 7–12 kn). High wind speeds may have elevated pre-run nutrient/ suspended sediment levels (Anthony & Downing 2003). Stratification was evident in both Conklin and Johnson's Bay. Nutrient and suspended sediment levels did not vary notably by sampling depth in any pre-run samples.

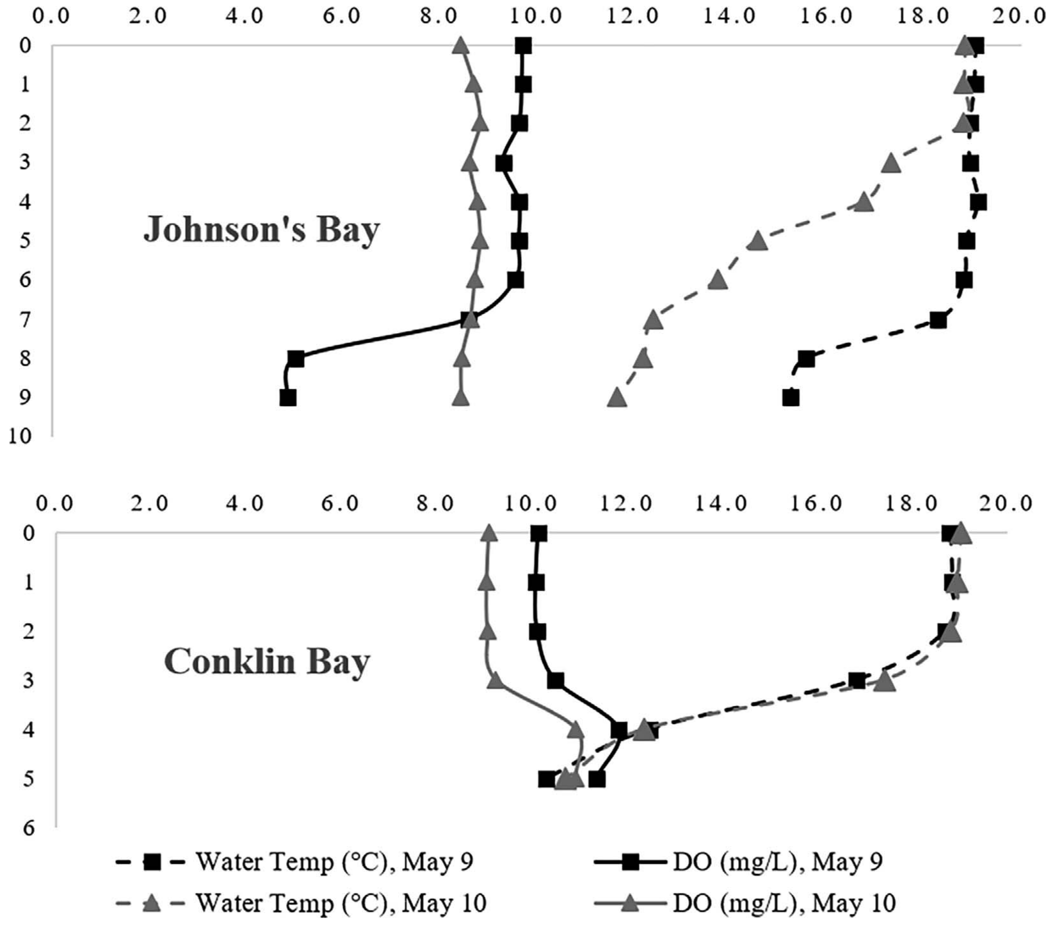

Figure 2.—Water temperature (°C) and dissolved oxygen (DO; mg/L) profiles by water depth (m) for both sampling days at Conklin and Johnson's Bays.

Bottom substrate.—Statistically significant increases occurred at Bayshore (marl) in SS, TN, and TP, and at Black Point (sand) in SS (average change 131.1 mg/L, confidence intervals available in supplemental material; Fig. 3). NH_3 and SiO_2 increased, but not significantly. Johnson (muck) had increases in SiO_2, and Conklin (muck) in SS, TN, and TP, though due to variation of the post-run results, these increases were not statistically significant. Bayshore's pre-run surface water sample had unusually low results for Cl^-, SO_4^-, and TN, resulting in high pre-run variability.

The obvious resuspension caused by the shallow, high-churn boat pass of this test did not result in increases of Cl^- or SRP for any samples in any substrate, though Conklin's SRP was slightly lower in the post-run sample. Johnson Bay was the most resistant to resuspension across all parameters. Key resuspended parameters identified in this test (NH_3, SiO_2, SS, TN, and TP) are the focus of the following tests.

Watercraft type vs. water depth.—Total nitrogen significantly increased after the wake boat ran through 5 ft water, but not 10–15 ft (increase of 0.34 mg/L; Fig. 4). SS also increased post-wake boat by 48 mg/L on average, but not significantly. No other parameters increased notably by the rest of the watercraft in any depths. The results post-PWC were the least variable across all parameters.

Idle speed.—TN was significantly higher post-PWC pass at idle speed, though that increase was small (Fig. 5). The inboard induced a significant increase in TN and slight

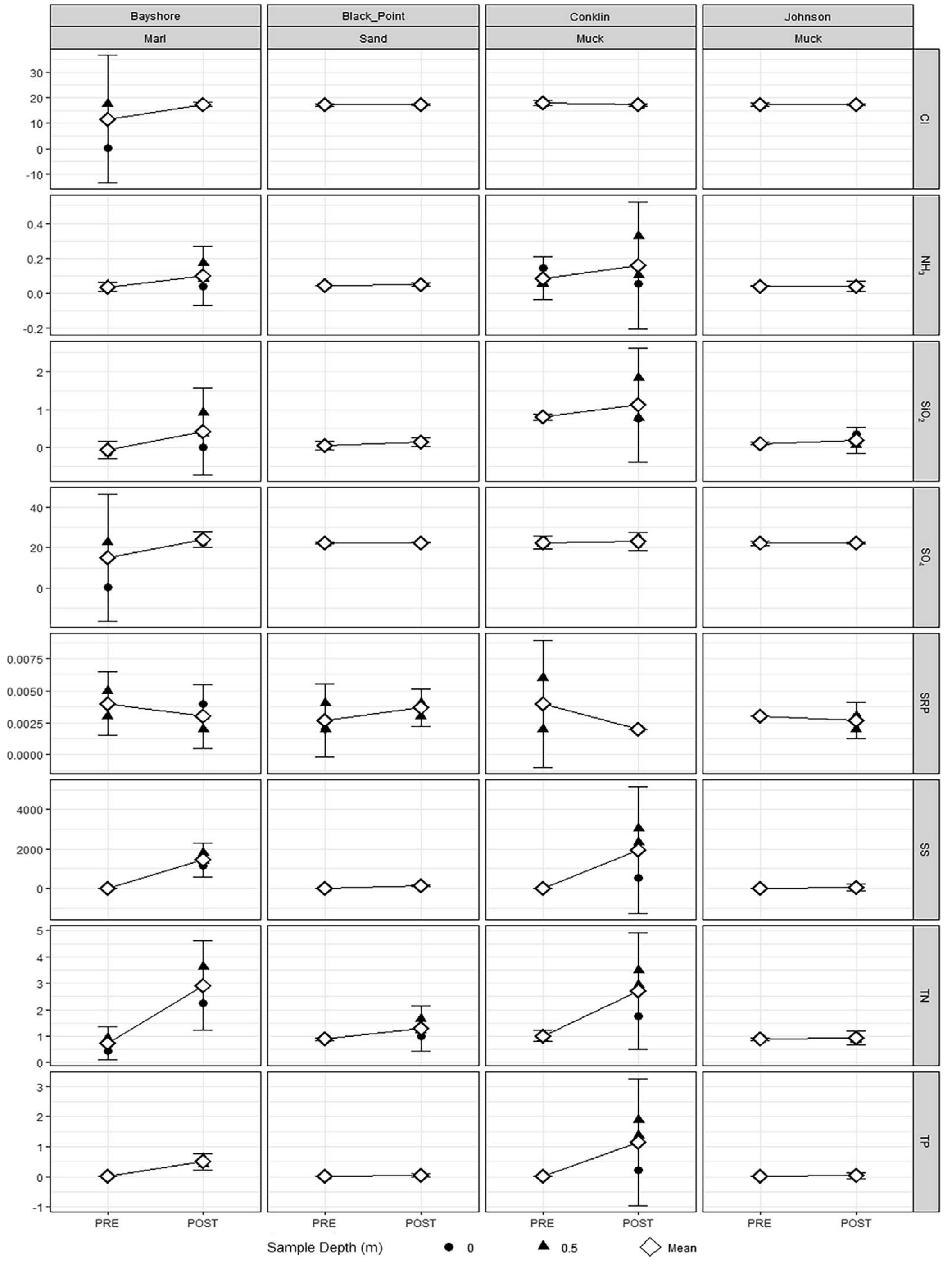

Figure 3.—Pre- and post-run averages of the bottom substrate test by watercraft and parameter. Error bars represent 95% confidence intervals of the averages. All parameters are in mg/L (for example, TP is mg P/L).

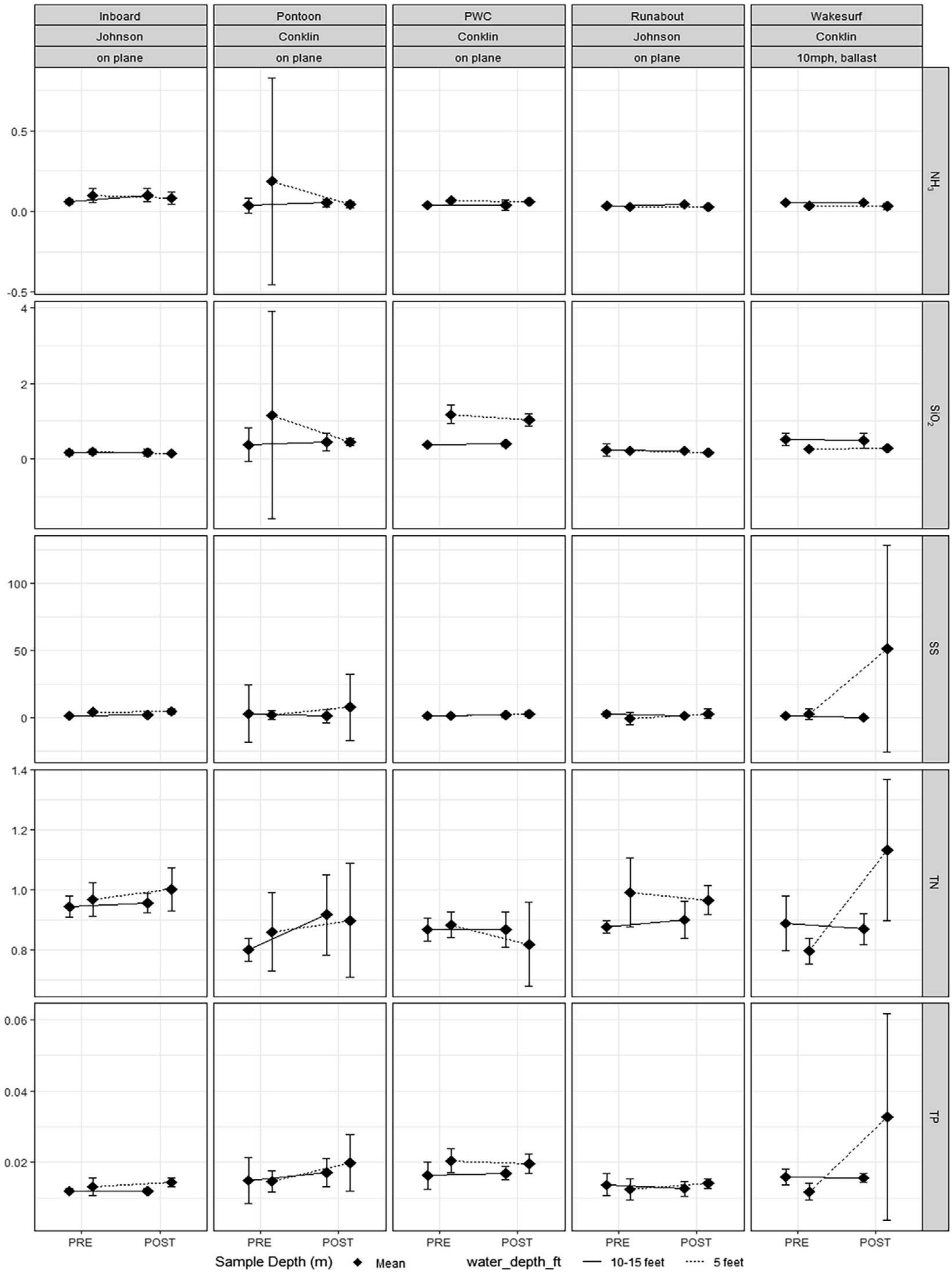

Figure 4.—Pre- and post-run averages of the depth test by watercraft and parameter. Error bars represent 95% confidence intervals of the averages. All parameters are in mg/L (for example, TP is mg P/L).

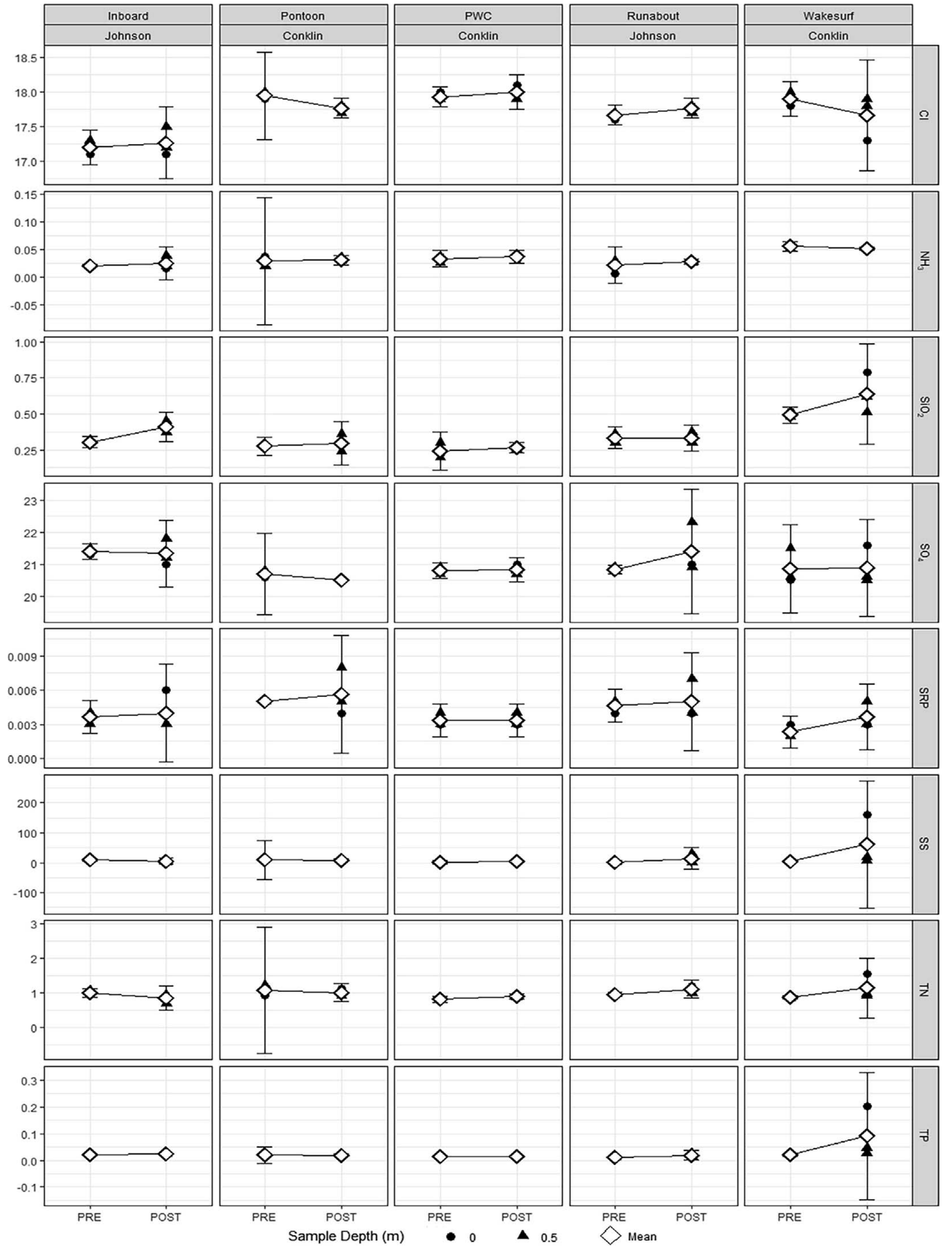

Figure 5.—Pre- and post-run averages of the idle speed test by watercraft and parameter. Error bars represent 95% confidence intervals of the averages. All parameters are in mg/L (for example, TP is mg P/L).

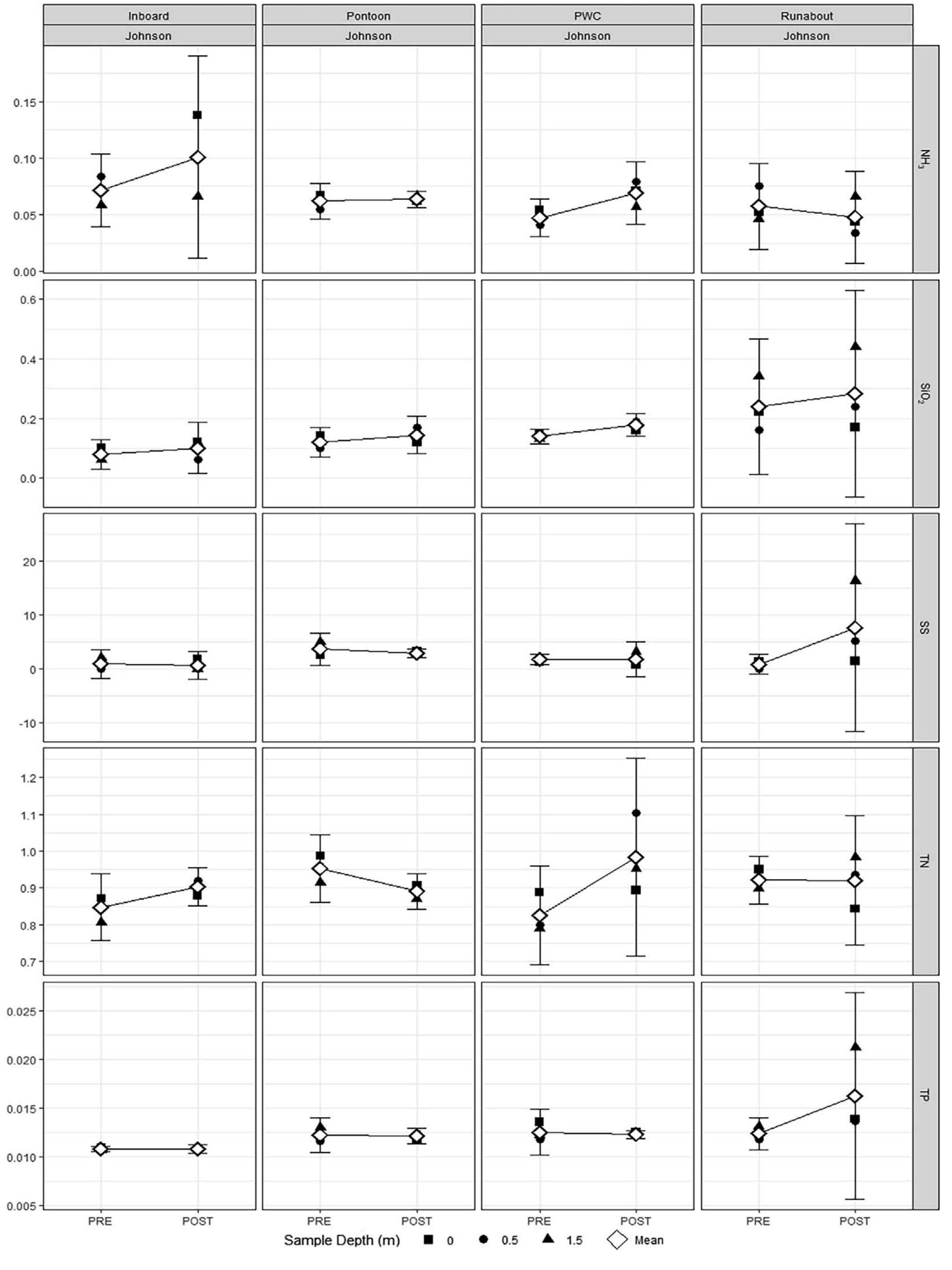

Figure 6.—Pre- and post-run averages of the nearshore plowing test by watercraft and parameter. Error bars represent 95% confidence intervals of the averages. All parameters are in mg/L (for example, TP is mg P/L).

increase in NH_3, while the pontoon had the least apparent resuspension of all tested watercraft. The range of results was smaller for all parameters across both locations and all watercraft compared to other tests.

Nearshore plowing.—The PWC run kicked up a significant amount of SiO_2, but other watercraft only saw slight increases and wide margins of error post-run (Fig. 6).

DISCUSSION

Bottom substrate at sampling locations appeared to significantly influence our results. In the bottom substrate test, SS, TN, and TP were resuspended significantly from Wawasee's marl substrate and watercraft influence on Conklin muck was also likely. The intense boating conditions of this test did not disturb Johnson's muck substrate, however, such as in the nearshore plowing tests. Underwater photography confirmed the presence of a thick bed of macrophytes present in Johnson Bay during the study, the presence of which was not known while planning. These plants covered the muck substrate, unlike in Conklin. Surveys from 2017 show Conklin and Johnson Bays differ in macrophyte assemblage, most notably in Johnson's population of invasive starry stonewort (*Nitellopsis obtusa*; Aquatic Weed Control 2018). Further research is required to determine the potential of particular macrophytes species to limit substrate resuspension. Lake managers should consider maintaining healthy macrophyte populations in heavily boated areas. However, sand substrate may be less of a concern for water quality. These data are particularly influential for these two bays, as they are popular sites on Lake Wawasee for fast watercraft operation (Peel 2007).

Nutrient resuspension was observed after the wake boat in 5 ft of water, and no resuspension by any watercraft in 10–15 ft of water. Runabout and inboard watercraft may also be capable of impacts in 5 ft in water that lacks a stabilizing macrophyte population. The results suggest limiting on or near plane recreation to depths $\geq$ 10 ft in Lake Wawasee. Although a test of the wake boat with an empty ballast was not performed, a conservative management strategy may limit on or near plane, empty ballast operation to these depths as well.

Although increases in measured parameters were often recorded under multiple situations, most increases were not statistically significant. Variability of the samples post-run did increase in many samples, suggesting water column mixing was occurring, but likely in scopes not fully captured by this study. This study focused on the impacts of individual boats *in situ*, but periods of high boat density or recreational intensity can also influence water quality (Alexander & Wigart 2013; Wagner 1990). More research with larger sample sizes would be needed to determine some of these increases with more certainty, and further work could include the impacts of multiple boat passes and suspended sediment analyses.

According to these data, lake managers should consider macrophyte assemblage, bottom substrate, common watercraft types, and local recreation styles when determining boating guidelines on their lakes. Lake managers can write guidelines considering the limiting nutrients or key parameters in their lake based on substrate composition and other factors. Boating restrictions based on speed and water depth can support the recreation that draws people to lakes while protecting the lake from some negative impacts of that recreation.

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