Impacts on sediment resuspension by various watercraft across multiple substrates, depths and operating speeds in Indiana's largest natural lake

Adrienne Daeger*[1], Nathan S. Bosch[1], Ryan Johnson[1]

[1] Lilly Center for Lakes & Streams, Grace College, Winona Lake, IN 46590, USA

**Corresponding author: daegera@grace.edu*

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, we set out to investigate nutrient/sediment resuspension by watercraft on Indiana's largest natural lake, Lake Wawasee. We performed four experiments 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. We collected nutrient/sediment samples before and after the watercraft passed through the sampling area. We computed a t-test for the difference between the averages of pre-boat run and post-boat run nutrient levels for each experiment. We observed nutrient resuspension 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 in 5 ft of water or idling in 3 ft by multiple watercraft. We recommend recreationalists use high impact watercraft and operational styles in water ≥10 ft in Lake Wawasee. Differences in macrophyte assemblage (including non-native invasive starry stonewort, *Nitellopsis obtuse*) 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.

Key words: boat recreation, sediment and nutrient resuspension, lake bottom substrate, water quality.

Watercraft are a significant component of lake recreation. In lake-abundant communities, such as Kosciusko County, Indiana, watercraft recreation can impact the local economy. Fishing and boating industries contribute over 150 million dollars annually to Kosciusko County (Bingham and 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 and 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, Iowa, Lake Tahoe, and elsewhere (Anthony and

Downing 2003, Alexander and 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 that enjoy the lakes, lake managers are also concerned for 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 and Elefsiniotis 1997). Suspended sediment (SS) can directly harm macroinvertebrates and fish (Newcombe and MacDonald 1991). Watercraft are not the only cause of internal nutrient loading. Wind action can also kick up sediments, and watercraft and wind can work in conjunction to slow resettlement of suspended particles and extend high turbidity events. (Anthony and Downing 2003, Zhu et al. 2015). Variations in bottom substrate influence the resuspension potential of bottom sediment (Wagner 1990, Beachler and 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 are more powerful, and watercraft recreation has gained popularity over the years (Beachler and Hill 2003), a point further supported by the rise in popularity and relevance of wakesurfing and wake boats (Ruprecht et al. 2015).

These economic and ecological relationships over boating inspired this study on Lake Wawasee to understand watercraft impacts at the level of the recreationalist and create ecologically relevant boating recommendations. We performed a series of in situ nutrient/sediment measurements 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 convention that no resuspension occurs if navigating shallow waters or channels at idle speeds, and (4) test for the impact of nearshore plowing, 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.

Study site

We performed the study on 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"), the largest natural lake in the state. Wawasee receives an influx of recreationalists in the summer for fishing, skiing, wakesurfing, and other activities. In a 2007 assessment, Peel noted Wawasee's shallow morphometry; 45% of the lake is <10 ft deep. Peel's study also describes the lake's watercraft counts and use patterns; its high boat density, popularity of power boating, and economic impact potential inspired this study (Peel 2007; Bosch et al. 2013).

Field sampling occurred at multiple water depths in four areas across Wawasee based on historical 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.

Materials and methods

Sampling was performed 9–10 May 2018. We utilized five popular types of watercraft: 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. We designed four tests, each with several boat runs in various operating conditions.

Tests

Bottom substrate test: we drove the runabout near plane (approximately 2,000 RPM) in shallow water (0.9 m; 3 ft) at each of the four lake areas, intentionally suspending sediment. We took water samples – 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 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: We designed this test 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**). We sampled 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 depths. We alternated boat runs between the two muck locations, Johnson's and Conklin bays, for this test to allow water to settle between runs.

Idle speed: To test the convention 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.

Nearshore plowing: Many Wawasee recreationists enjoy leisurely rides around the lake, often in shallow water at a slow pace (approximately 2,000 RPM). We tested the impact of nearshore plowing on bottom sediment resuspension using the inboard, pontoon, PWC, and runabout watercraft. We performed the runs in Johnson's and Conklin bays, and the runs were performed in 1.5 m (5 ft) water to simulate low speed shoreline cruising. We took nutrient and sediment samples at 0 m, 0.5 m, and 1.5 m before and after each run.

Field sampling methods

To start both sampling days, we collected data 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 both sampling days.

For each test, we marked off the 27 m-long sampling area of the correct water depth with 3 buoys. A sampling boat slowly approached the middle buoy to take 3 pre-run water samples with Van Dorn water samplers (sampling depths described for each test below) 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 Dorns collected post-run samples at the same depths as pre-run samples. We reestablished the sampling area in a new position every run to allow water and sediment to settle and switched areas of the lake altogether between tests.

Upon retrieval, water samples were stored in a dark cooler with icepacks then refrigerated at ~5 C until being 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 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). We calculated total nitrogen (TN) as the sum of NO_2, NO_3, and TKN concentrations.

Data analyses

After rejecting results from two dirty samples (which contained bottom substrate rather than just a water column sample), we computed a t-test for the difference between the averages of pre-runs and post-runs for each experiment. The t-tests gave us a 95% confidence interval for the difference from pre-tests to post-tests. We chose to use confidence intervals instead of p-values because the number of experiments performed could lead to false positives.

We also plotted the pre-test and post-test averages for each experiment with confidence intervals for both pre-tests and post-tests. Note that 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.

Results

Confidence intervals for each test are available as tables on the online supplement.

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 13-22 km/hr). High wind speeds may have elevated pre-run nutrient/sediment levels (Anthony and Downing 2003). Stratification was evident in both Conklin and Johnson's Bay. Nutrient and sediment levels did not vary notably by sampling depth in any pre-run samples.

Bottom substrate: Statistically significant increases occurred at Bayshore (marl) in SS, TN, and TP, and at Black Point (sand) in SS (**Fig. 3**). Other increases were present, but not significant, such as those by NH_3 and SiO_2. Pre- and post-run results were highly variable in these two locations. Johnson (muck) saw increased variation in SiO_2, and Conklin (muck) in SS, TN, and TP. Generally, water closer to the substrate (triangle symbols; **Fig. 3**) experienced more resuspended material than the surface samples (circles), even in shallow water. This is especially visible in Conklin's post-run results. Bayshore's pre-run surface water sample had unusually low results for Cl, SO4, 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. Muck in 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 (**Fig. 4**). Other watercraft are likely to influence TN, but we observed no significant differences in these tests. SS and TP also increased post-wake boat on average, but not significantly. No other parameters increased notably by the rest of the watercraft in any depths. The results pre- and 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 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 varies between and within lakes. In our bottom substrate test, Wawasee's marl significantly resuspended SS, TN, and TP, and influence by Conklin muck was also likely. The intense boating conditions of this test did not disturb Johnson's muck substrate, however. Underwater photography confirmed the presence of a thick bed of macrophytes present in Johnson Bay during the study. These plants covered the muck substrate, unlike in Conklin. Surveys from 2009 show Conklin and Johnson bays differ in macrophyte assemblage, most notably in Johnson's population of invasive starry stonewort (*Nitellopsis obtuse*; V3 2009). Further research is required to determine the potential of all macrophytes to limit substrate resuspension. We advise consideration of maintaining healthy macrophyte populations in heavily boated areas accordingly. 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).

We observed nutrient resuspension 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. We recommend limiting on or near plane recreation to depths ≥ 10 ft in Lake Wawasee. We did not test the wake boat with an empty ballast in this study, but a conservative management strategy may limit on or near plane, empty ballast operation to these depths as well.

Although we often recorded increases under multiple situations, most increases were not statistically significant. Variability of the samples post-run did increase more consistently. 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 and 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 sediment analyses.

According to these data and other studies, 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.

Acknowledgments

Thank you to Wawasee Boat Company for providing watercraft and operators for the study; lake residents for financial support; Seth Bingham for assistance in study design and execution; Lilly Center student research team members Hayden McCloskey, Grant Hoffert, and Benjamin Logan for data collection and entry; Alex Hall for drone operation and report review; Abby Phinney for report review; and Ken Wagner and other associate editors.

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

Table 1. Watercraft and operating speeds utilized in study. Askerisk indicates the speed we considered "standard operation" for that watercraft in this study.

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

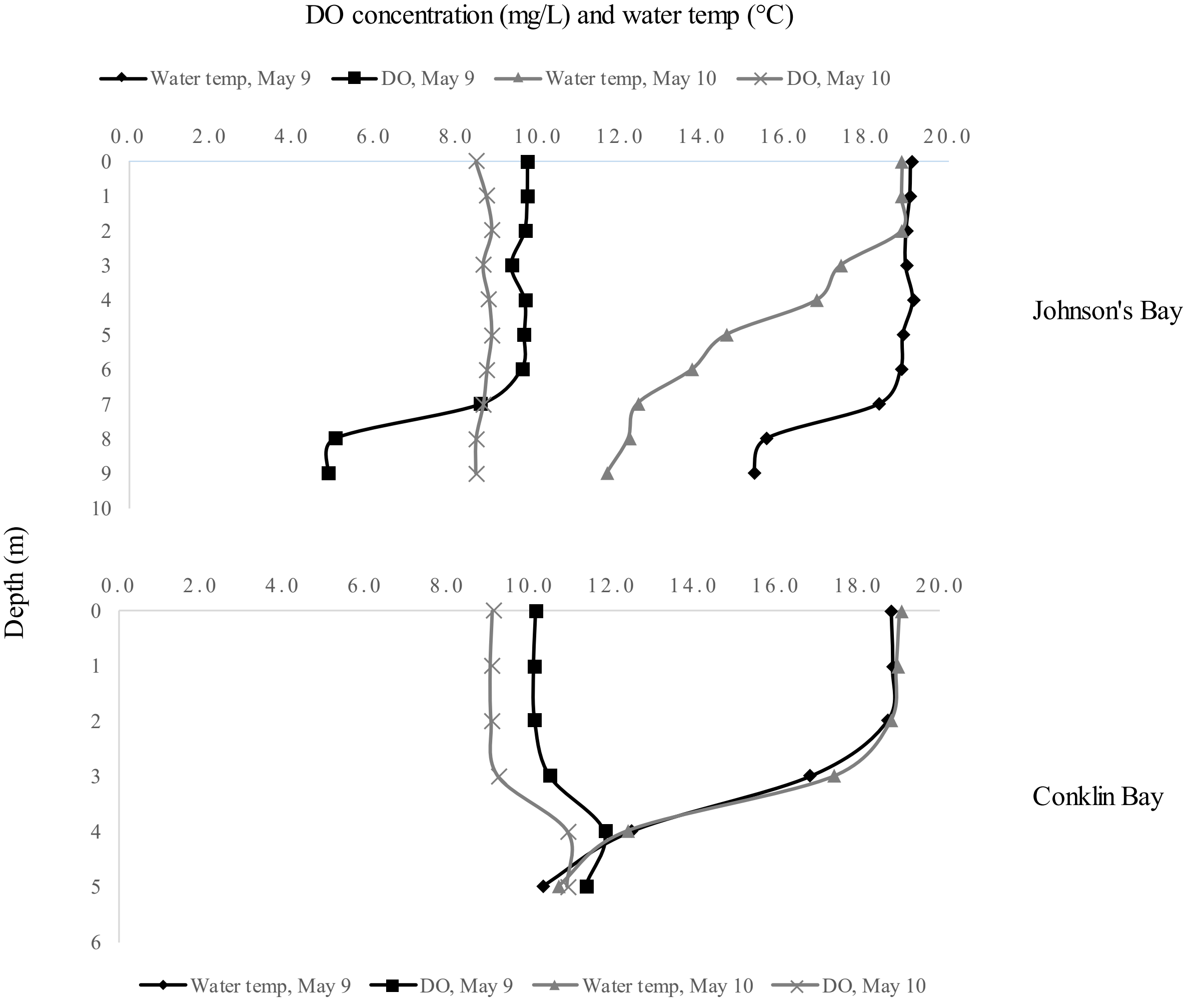

Figure 2. Water temperature (in C) and dissolved oxygen (DO; mg/L) profiles by water depth (m) for both sampling days at Conklin and Johnson's bays.

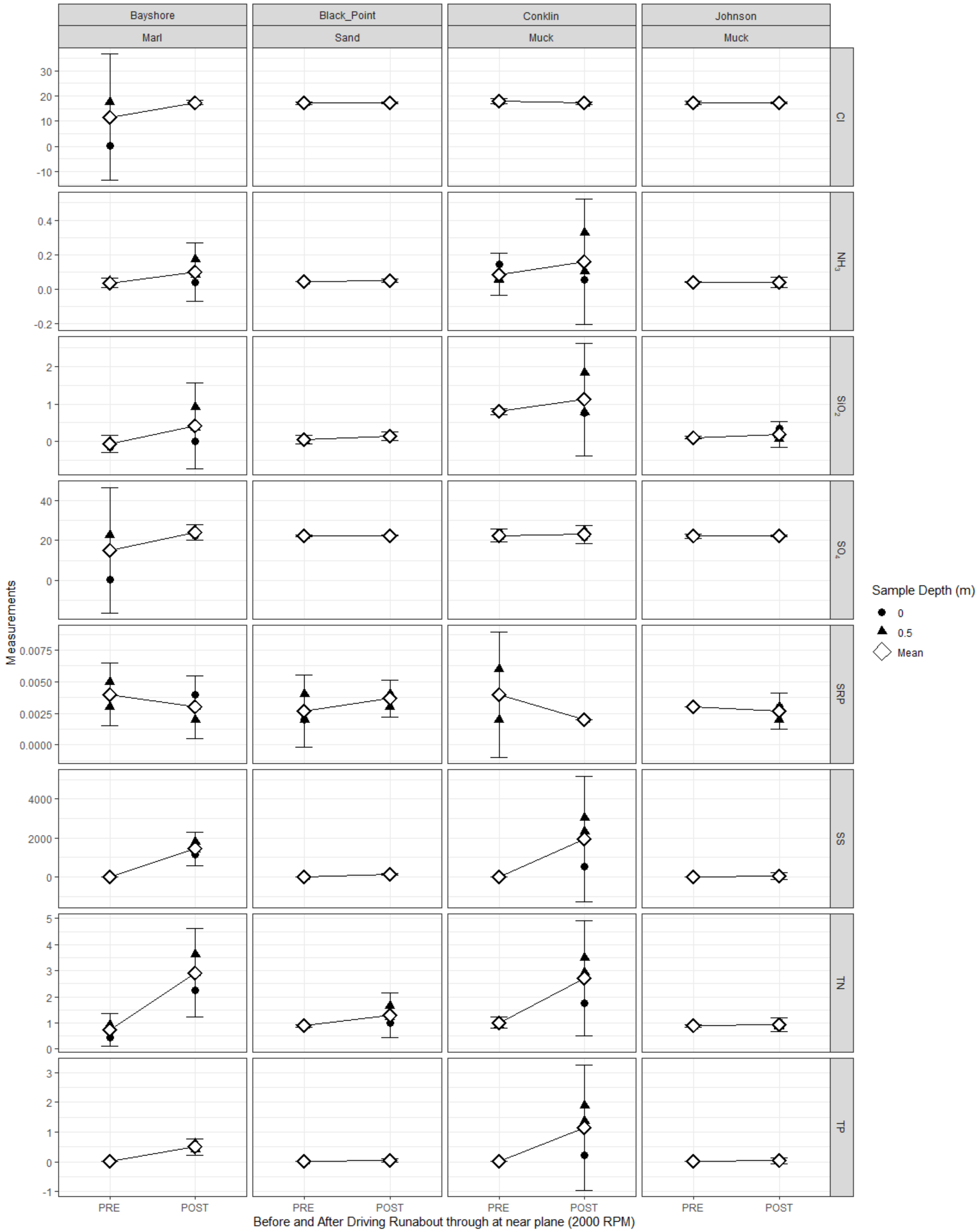

Figure 3. Pre- and post-run averages of the bottom substrate test by watercraft and parameter. Error bars represent 95% confidence intervals of the averages. All parameters are in mg/L (for example, TP is mg P/L).

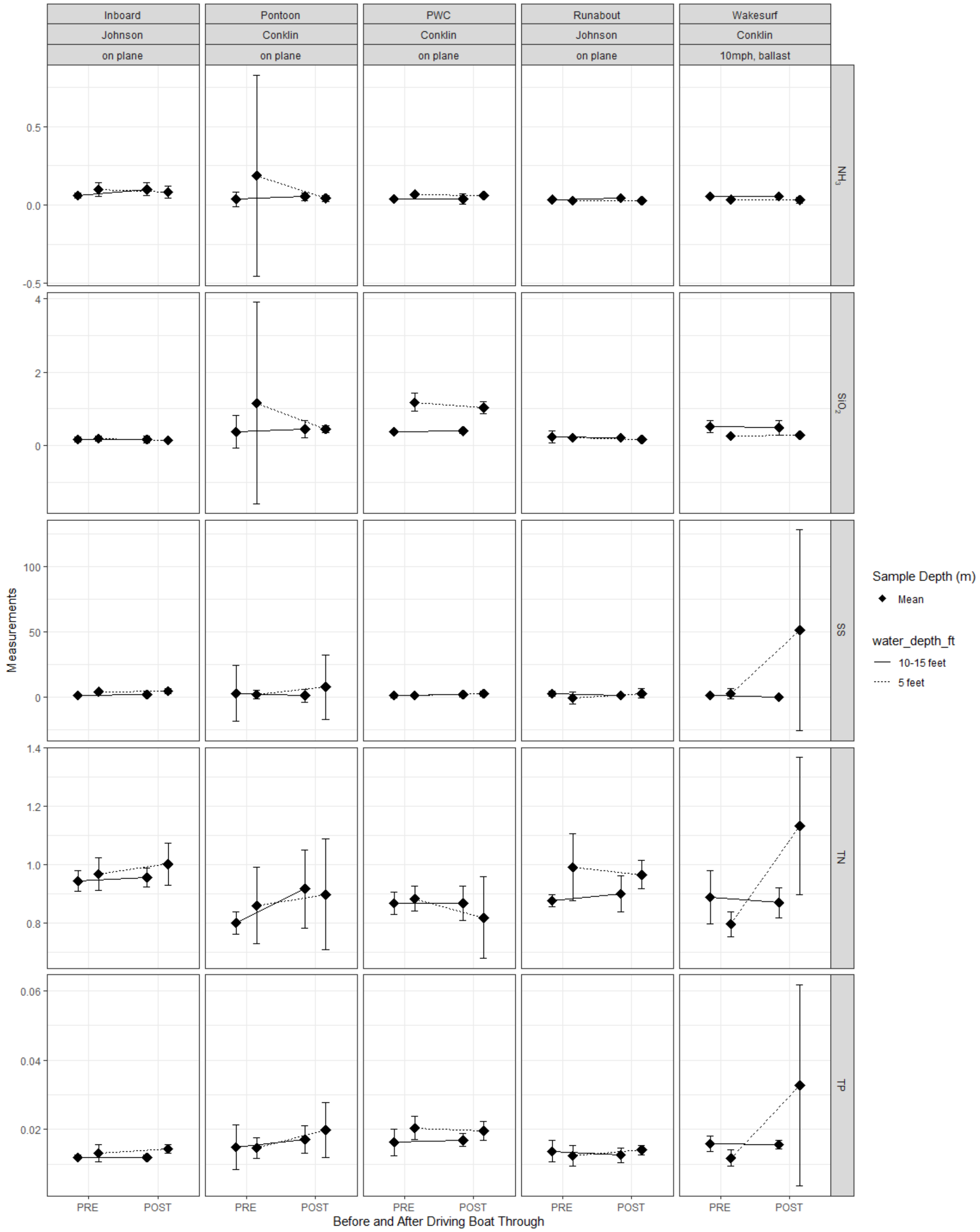

Figure 4. Pre- and post-run averages of the depth test by watercraft and parameter. Error bars represent 95% confidence intervals of the averages. All parameters are in mg/L (for example, TP is mg P/L).

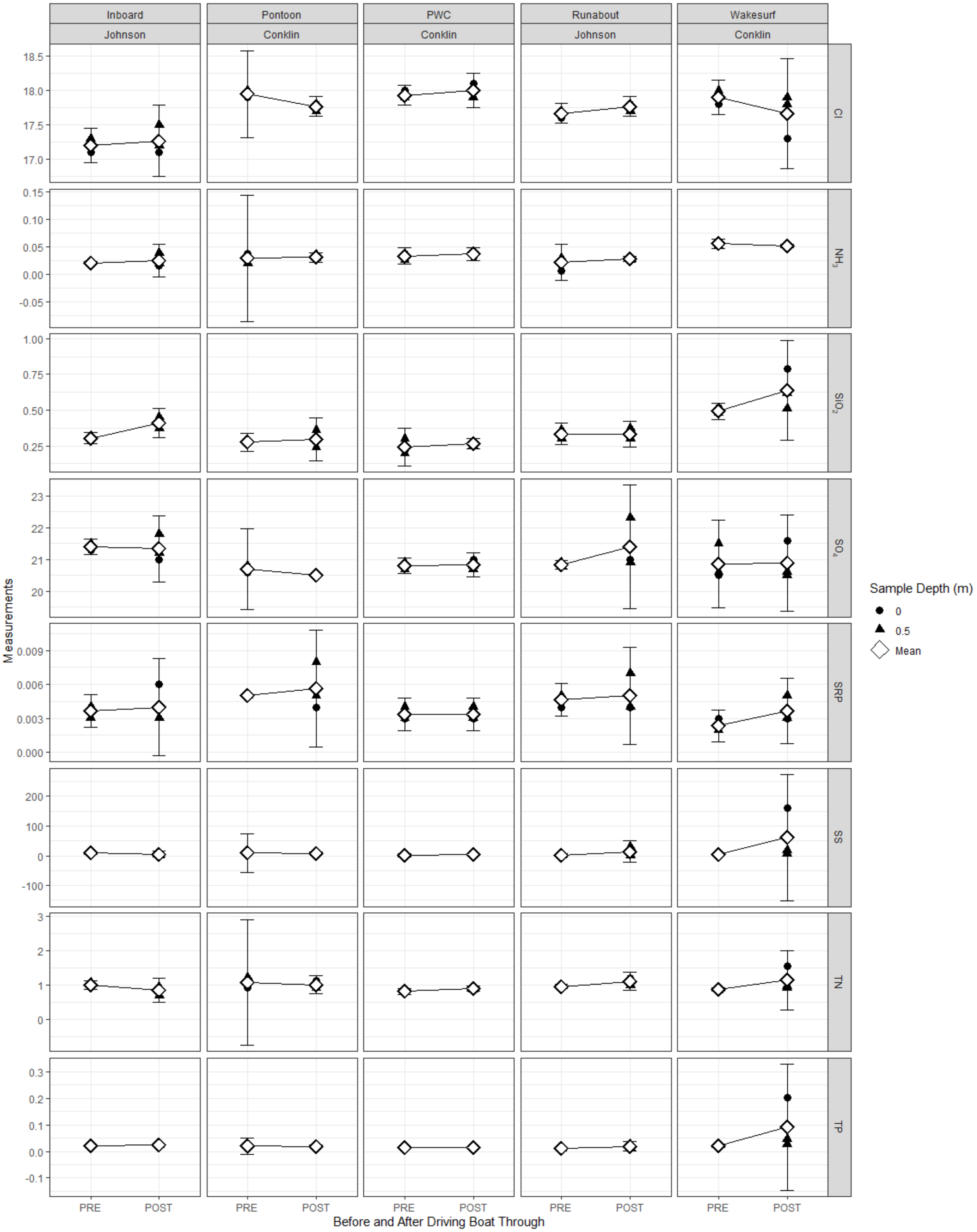

Figure 5. Pre- and post-run averages of the idle speed test by watercraft and parameter. Error bars represent 95% confidence intervals of the averages. All parameters are in mg/L (for example, TP is mg P/L).

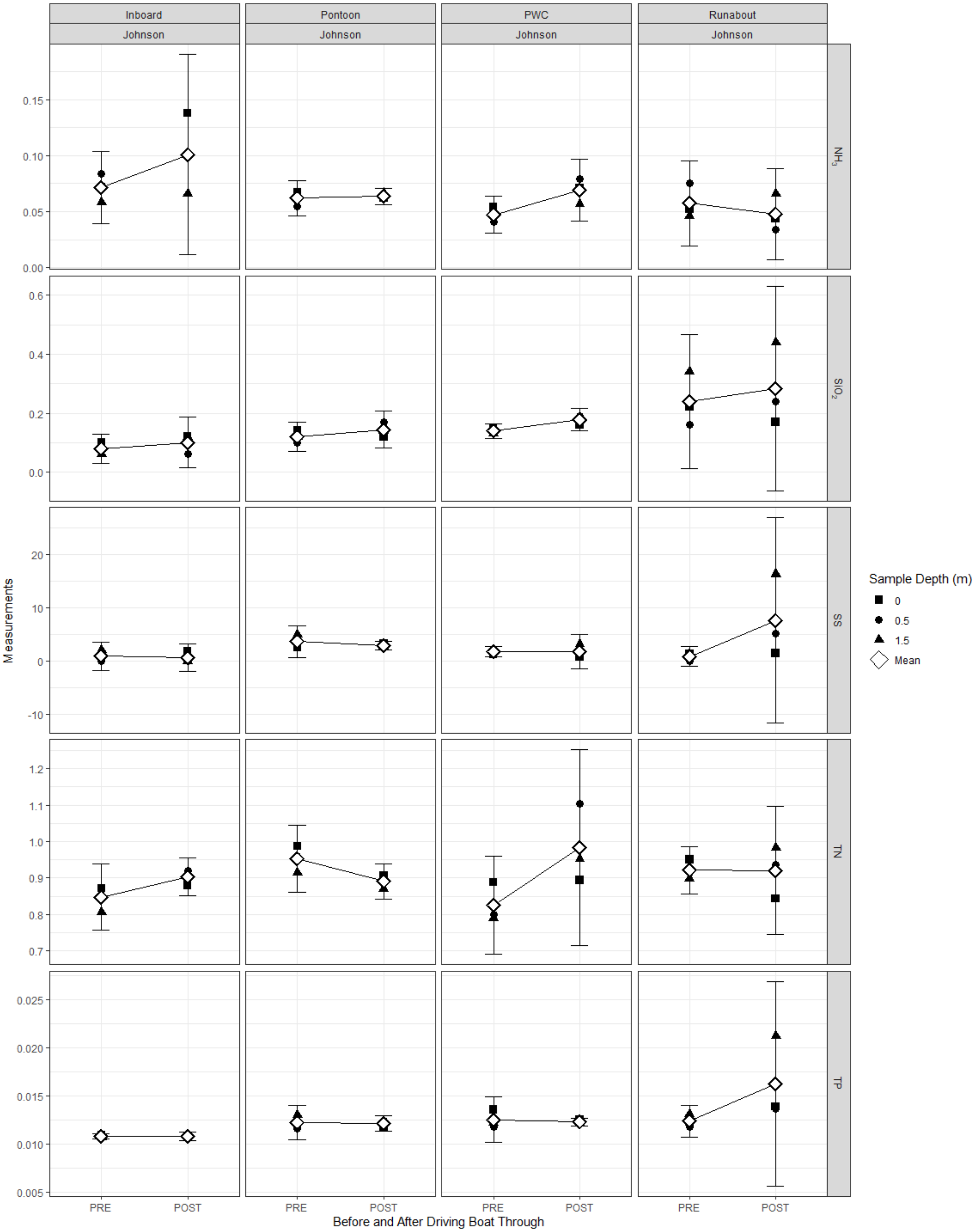

Figure 6. Pre- and post-run averages of the nearshore plowing test by watercraft and parameter. Error bars represent 95% confidence intervals of the averages. All parameters are in mg/L (for example, TP is mg P/L).