Terra Vigilis Environmental Services Group

Water Quality and Wave Impact Study
Phase 2 Report

Prepared for the North Lake Management District

July 20, 2022

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Introduction

Terra Vigilis Inc was retained to provide a water quality and wave impact study for the North Lake Management District (NLMD). The scope of work included a two season (Phases 1 & 2) study effort to determine the wave propagation impacts on surface and subsurface portions of North Lake. North Lake is a freshwater lake located in Southeast Wisconsin in Waukesha County. The Lake is approximately 440 acres* with both drainage and spring fed aspects. The lake is fed by the small and large Oconomowoc rivers, the Mason Creek and Mud Lake (Cornell). Natural springs are located throughout both lake basins. The larger of the lake basins is approximately 338 acres with a maximum depth of approximately 78 feet. The small lake basin is approximately 102 acres with a maximum depth of 78 feet. The small lake basin has a prominent shallow water shelf around its perimeter which extends outward from the shoreline to about 100 feet. The large lake basin also has a shallow water shelf which extends outward from the shoreline at varying distances. The bottom of the lakes then slopes downward to their deepest portions in the middle of each lake. Both lake basins are comprised of various combinations of marl, clay, silt, sand, and gravel substrates.
*WDNR derived

Significant increases in Wakeboard boating activity on North Lake has been a stated concern of lake residents, quantified by two separate surveys conducted in 2018 and 2019. Cited issues in the survey data included concern for the size and impact of both surface and subsurface wave activity from Wakeboard boats, particularly in "surf mode". Specifically, the survey identified for further study, the impacts of these waves on near shore bottom sediments, other recreational boating vessels, lake bottom redistribution of sediments, and plant and fish habitats.

The Phase 1** portion of the study conducted in 2020 included measurements of wave features from Wakeboard boats (heights, troughs, frequency) in addition to other vessels on North Lake which included Pontoon boats, ski boats, fishing boats and personal watercraft (PWC). Commercial drone technologies were used to provide metrics and videography which measured both surface and subsurface wave characteristics on a comparative basis. This included imaging of plume development and redistributed sediments with particular attention at the Wildwood point reef. An Aquatic Plant Life survey was also conducted.
**https://storymaps.arcgis.com/stories/a4431437506b4cd990f31c999128301b
and: PioScholar Bales Navin NorthLake

The Phase 2 study provided a limited evaluation of water chemistry and water clarity across multiple sample sites. It also evaluated the wave features propagated from Wakeboard boats in "surf mode" and other vessels. A Wake Boat in "Surf Mode" is defined as a Wakeboard boat operating at a slow speed, with high bow angle (12-15 degrees), stern ballasting of 3,000 to 5,000 pounds of water and very powerful engine propulsion.

The Phase 2 study also addressed the nature of the Wakeboard boat surf mode propeller downwash in addition to near shore impacts. In addition, limited water chemistry studies were conducted with a Wakeboard boat in surf mode to assess nutrient changes in the water column. Water sampling included total phosphorus levels, dissolved oxygen at variable depths, water temperatures, water clarity and total suspended solids (see Appendix B). It is important to note that the water quality data collected in 2022 will be synchronized with recreational boat counts, weather data, and water level monitoring, all of which will be summarized in the Phase 3 report for this study by SEWRPC staff after the 2022 boating season monitoring has been completed. A detailed description of methodologies and equipment used in the Phase 2 study is available in Appendix D.

This Phase 2 study reflects the combined scientific expertise of a collaborative research effort between Carroll University (Departments Aviation Science, Environmental Science and Chemistry) and Terra Vigilis with input from the North Lake Management District and Southeastern Regional Planning Commission (SEWRPC). This Phase 2 report summarizes the findings from the summer of 2021. A preliminary summary of these data was provided to the NLMD at the September 17, 2021 public meeting (see Appendix A). However, it is important to point out some additional wave characteristics comparisons of speed boats and wake board boats will be carried out in the 2022 season to finalize the Phase 2 study.

Research Study Domains

There were six primary "domains" of study contained within the Phase 2 study. These domains included:

1. Summary of Water Quality sites, parameters, and dates collected
2. Lake sediment re-distribution phenomena
3. Submersible nearshore aquatic plant and aerial shoreline mapping survey
4. Propeller Downwash Effects
5. Wave Oscillation Data at Staggered Distances from Shoreline
6. Nutrient Load Differences (pre-post) from Wakeboard Boats in Surf Mode

The reader is invited to review data summaries, commentary, and recommendations across these six domains. Note that the analysis and interpretation of the water quality data is being completed by SEWRPC staff in their summary report for this project.

Domain 1 Water Quality sites, parameters, and dates collected

The Phase 2 study included Phosphorous and Dissolved Oxygen in addition to total suspended solids (TSS) since the water inflows from rivers directly impacts North Lake.

Some water chemistry sampling was conducted during 10 weeks at seven sites on North Lake. See Figure 1. The sites included river inlets at both the North and South ends of the "Big Lake" (large and small Oconomowoc rivers, Mason Creek, and the inlet from Cornell Lake). Additional testing sites in the small lake basin have also been sampled. Water depths at the seven sites are as follows:

Site #	Water depth
1	25'
2	23'
3	26'
4	21'
5	17'
6	20'
7	22'

Figure 1: Sample Sites

Each water sample was collected utilizing a “grab” procedure by submersing the sample bottle 6” below the water surface to draw in and collect a water sample. Bottles were stored in a cooler with freeze packs while on the water, and then stored in a refrigerator on shore until the water samples were delivered to the shipper within a cooler packed with ice for overnight delivery to a Wisconsin State certified laboratory where analyses were conducted on all samples with proper cooling and preservation of samples per protocols.

All the water quality data collected in 2021 is included in Appendix B of this report and will be uploaded into the WDNR SWMS database. Water quality samples will continue to be collected in 2022, and analysis and interpretation of all the water quality data over the entire study period is being completed by SEWRPC staff in their summary report for this project.

Domain 2 Lake Sediment Redistribution (Bottom Sediments)

The research staff from Terra Vigilis and Carroll University first observed plume events captured by aerial drone flights over the Wildwood point reef in 2020. This unexpected phenomenon led to an effort to understand the corresponding subsurface impacts on the Wildwood Point reef.

Aerial imagery from a drone survey shows how general boating conditions on the Small Basin of North Lake can create significant resuspension of nearshore substrates at Wildwood Point, which can at times travel across the point and into the Large Basin of North Lake. It is not possible to separate the impacts from any one type of boat in this footage, but it does indicate that recreational boating can impact the nearshore resuspension of sediments in the Little Basin of North Lake. This is consistent with results of the wave measurement comparison analysis in Domain 5 below. (See Figure 2-Video).

Figure 2-Video: Sediment Redistribution

Nonetheless, based upon the wake differences among boats and careful review of extensive video imagery, it is clear that the most intense waves are generated from the Wake boats in surf mode compared to the other boats on the water (see aerial visualization of boat wave comparisons here:
("https://storymaps.arcgis.com/stories/a4431437506b4cd990f31c999128301b"
North Lake Wave Propagation & Water Quality (arcgis.com)

Accordingly, particular attention was paid to sediment redistribution in the area along the Wildwood reef which separates the large and small lake basins (See Domain 3).

Domain 3 Submersible nearshore aquatic plant and aerial shoreline mapping survey

Results from the underwater aquatic plant and lake bottom videography survey revealed the healthy presence of several native species (e.g., Flat-stem pondweed, Fries Pondweed, and Vallisneria) and one exotic invasive species (i.e., Eurasian Watermilfoil) of aquatic submergent plants. The submersible verified that there was moderately abundant plant growth observed in water depths less than or equal to 10 feet and that there are essentially no or very limited plants in waters greater than 10 feet and not plants deeper than 15 feet in depth (see Figure 3 Video). This is likely due to light limitations, and previous aquatic plant surveys in the large basin support this finding. In years 2012 and 2018 aquatic plant surveys indicate that 93 percent and 95 percent of the plant community were observed in depths less than or equal to 10 feet, respectively. Hence, only about 5 to less than 10 percent of the remaining aquatic plant community was observed in depths from 10 to 15 feet, and no plants in water depths greater than 15 feet. This is consistent with what was observed in Figure 4 video showing abundant plants at 2.28 feet and Figure 5 video showing no plants at 13.56 feet.

The Figure 3 video seems to show or suggest that there may be some deposition of sediments on top of what appear to be plants in these deeper waters (i.e., 10 to 15 feet), however this was not verified. If such sediments were depositing within these areas, it could potentially be inhibiting growth of plants in North Lake in depths greater than 10 to 15 feet. However, given that almost no plants are found in either basin in depths greater than 10 to 15 feet since at least year 2012, inhibition of plant growth due to sedimentation redistribution has not been verified. Nonetheless, if it could be verified that boat generated waves were contributing to increased sediment deposition in these nearshore areas, this would be an important finding to the overall health of the Lake.

Underwater ROV Footage

Figure 3 Video - Fall 2020 Wildwood Point Reef

Figure 4-Video Wildwood Point reef - Spring 2021

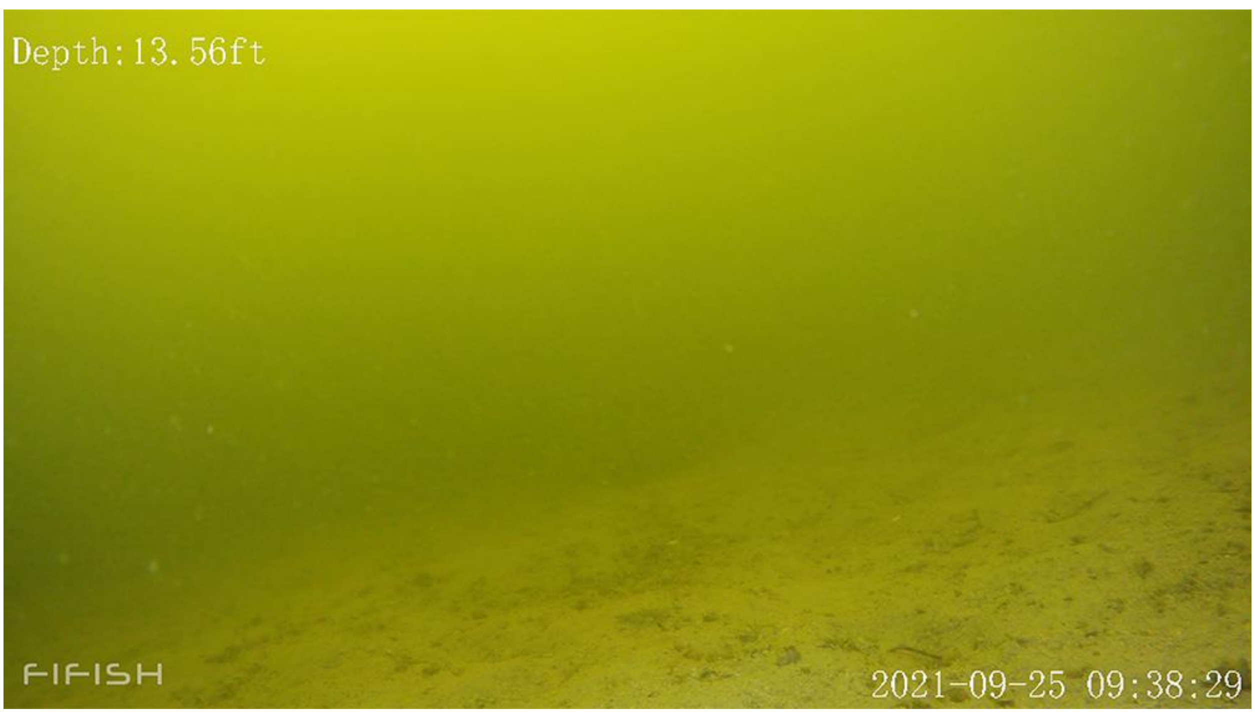


Figure 5-Video Wildwood Point reef - Fall 2021

Commercial drone surveys (3D imagery) were conducted across the shoreline perimeter for North Lake, allowing archival of the data on a password protected google drive for future research involving shoreline erosion comparisons (and correlated with measured lake water levels). Copies of all this imagery will be provided to the North Lake Management District, SEWRPC, and/or the WDNR, so that it remains available for use to the public in the future. See Figure 6.

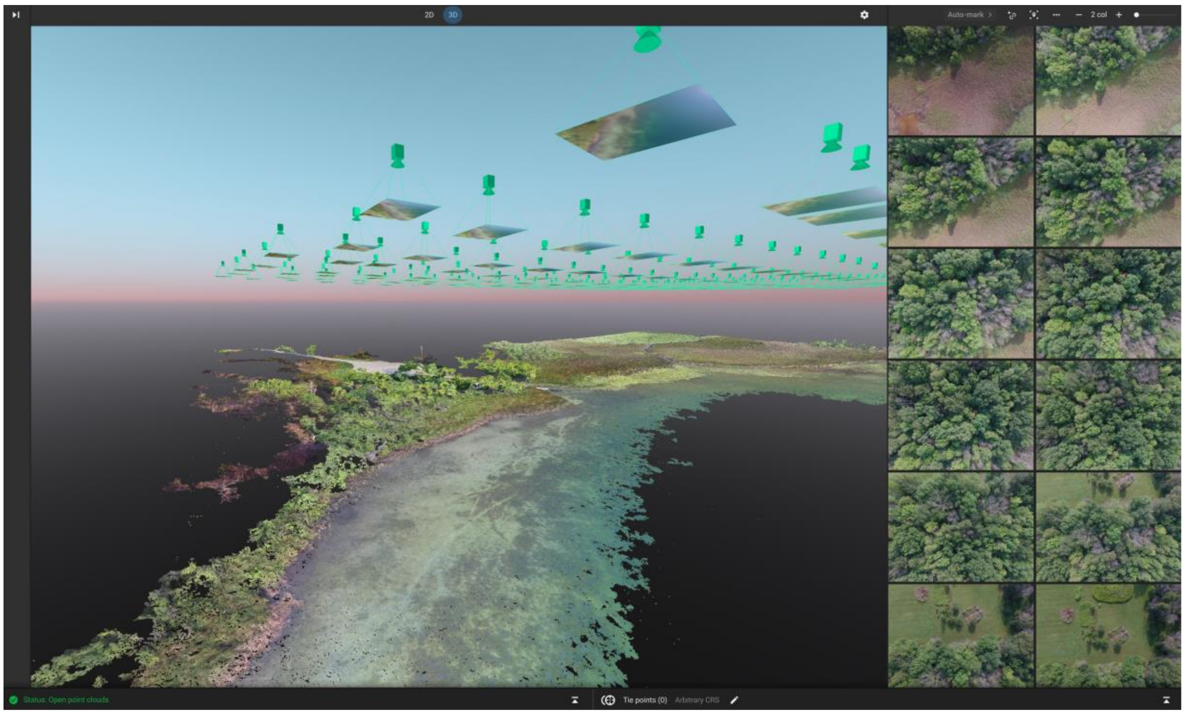


Figure 6: Drone Mapping “plates “above a shoreline

Domain 4 Propeller Downwash Effects

The Phase 2 study included measurement of propeller downwash dynamics for selected vessels in use on North Lake. Measurements included a combination of underwater photography and videography imagery of fibre optics responding to propeller downwash energy and water movement as deep as 20 plus feet. See Figure 7-Video.

All boats produce a subsurface propwash, but wakeboard boats in surf mode produce propwash depths nearly 3-4 times greater than the other vessels, which is due to differences in propeller angles, ballasting and larger engine output. Data gathered on July 2, 2021 demonstrated that prop downwash depths of no more than 3-5’ were observed for Pontoon boat, ski boat, and PWC while planing.

Figure 7-Video: Camera views at staggered depths showing fibre optic responses to Wakeboard boats in surf mode.

Figure 8 illustrates how a wakeboard boat operating in surf mode could potentially resuspend or disrupt lake bottom sediments as the subsurface wave energy from downward propwash moves towards the nearshore lake bottom. Demonstration of the actual impact to the bottom was not within the design of the Phase 2 study. Regardless, given this finding, increases in suspended sediments in the shoreline areas of North Lake when Wake boat vessels are operating is a possibility and it is consistent with elevated total phosphorus concentrations which are summarized in Domain 6.

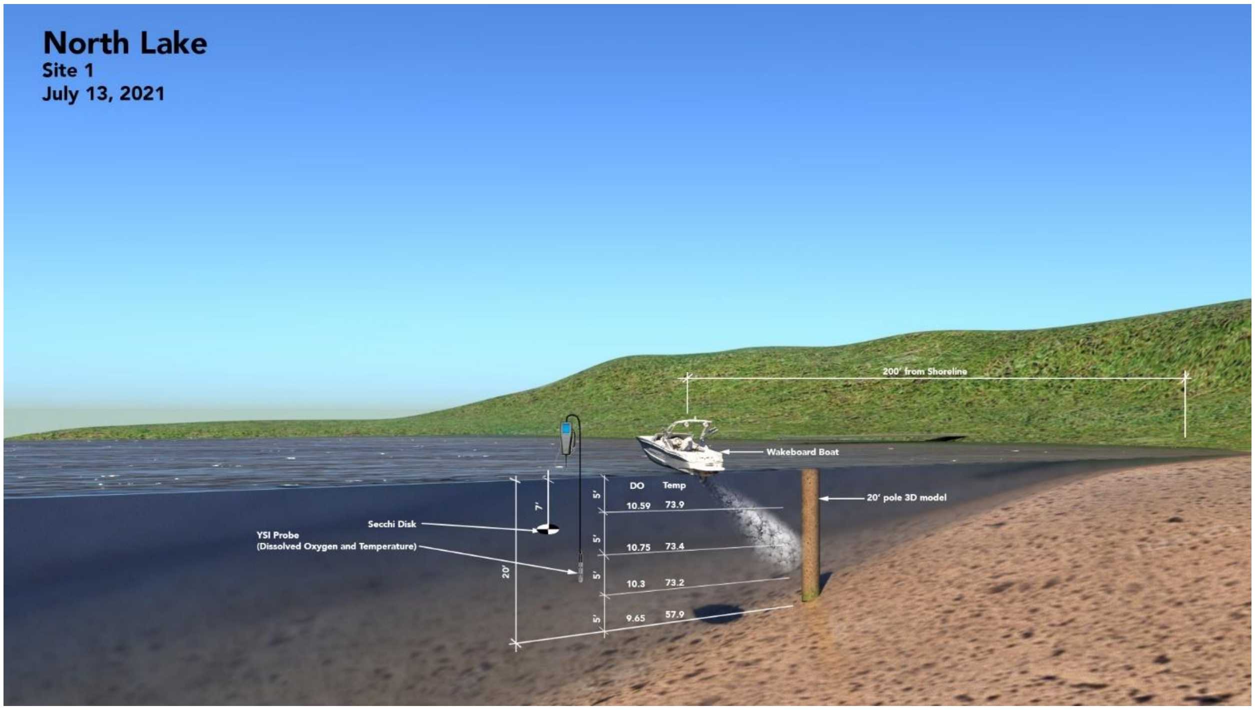


Figure 8: Computer Generated 3D Model of Propeller Downwash
(using bathymetric data of North Lake little lake basin)

Domain 5 Wave Oscillation Data at Staggered Distances from Shoreline

The Phase 2 study required measurements of wave impacts on near shore and lake bottom from vessels in common use on North Lake. Identification of these vessel categories was from Lake resident survey data previously reported. The categories included:

- Personal watercraft PWC
- Pontoon Boat
- Speed Boat
- Wakeboard Boat

Multiple vessels were tested during the 2020 and 2021 boating seasons. These vessels were producing wave effects measured from various distances ranging from 200 to 400 feet from shoreline in the little basin lake on calm water days. The operational characteristics of the vessels was standardized for study purposes e.g., pontoons at slow cruising speeds, PWC at legal speed limits (35mph), speed boat at operational speeds for skiing, and wake surf mode operations at 15-degree bow angle, full ballasts and slow speed (maximum wave effect).

Background

Before discussion of the results for this section, it is important to provide some background on general characteristics of waves, how they move through the water, and what affects them. Figure 9 shows the relationship between water depth and wave behavior. In deep water conditions (i.e., water depths greater than ½ wavelength of a wave) the speed and wavelength of a wave are constant and are not influenced by the lake bottom and water particles move in a circular motion. For example, a single wave with a wavelength of 20 feet is considered a deep wave in depths of 10 feet or greater. Wavelength is defined as the distance between the top or crest of the wave to next or adjacent crest or from trough (bottom of wave) to trough. Although not illustrated on the diagram, wave amplitude is the difference in height between a wave crest and adjacent wave trough. Wave frequency is defined as the number of waves that pass over a certain time frame.

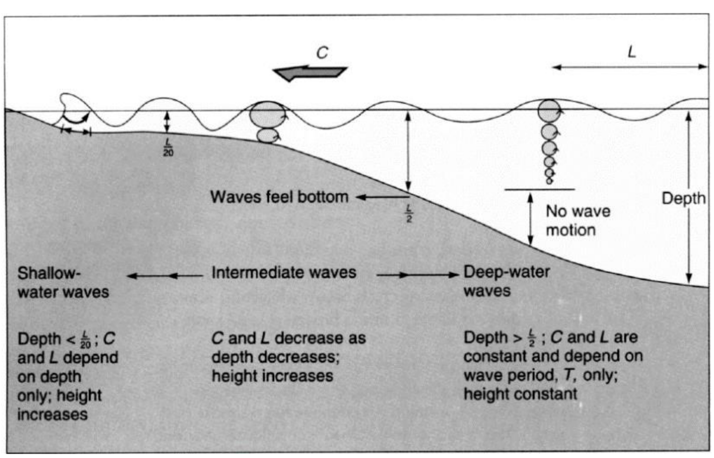


Figure 9. Relationship Between Water Depth and Wave Behavior

Source: John A. Knauss, Introduction to Physical Oceanography, and SEWRPC

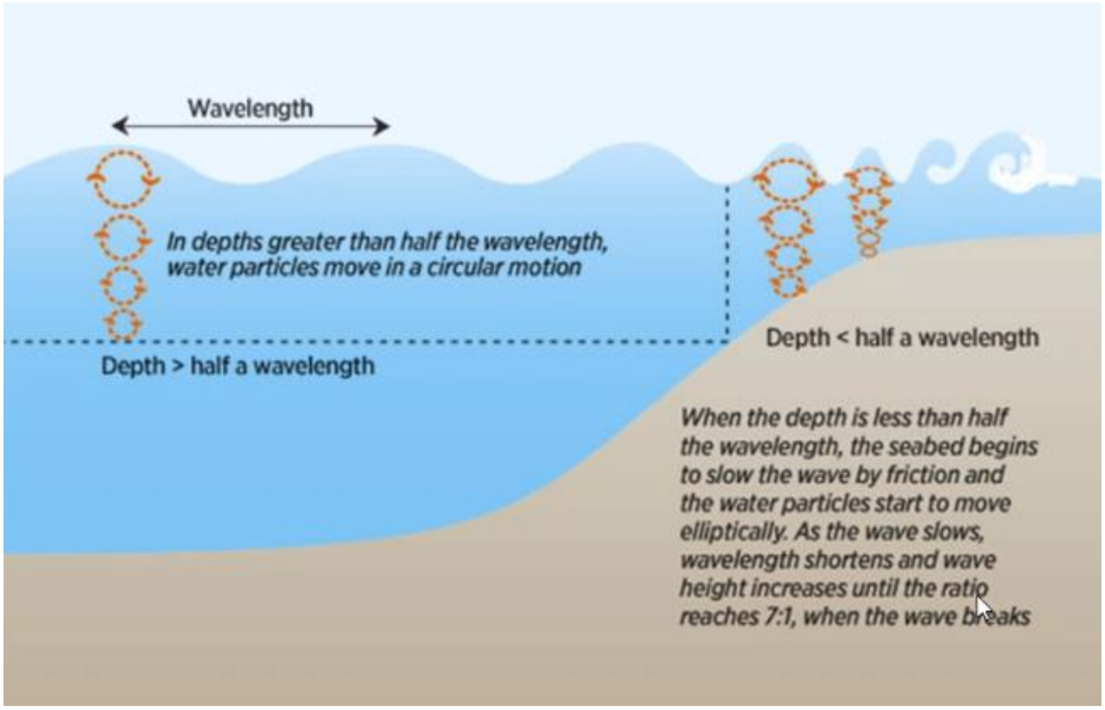


Figure 10: Wave Propagation Physics as waves approach and pass over near shore, shallow water areas

When water depth is less than half the wavelength of a wave, the lakebed begins to slow the wave by friction and the water particles start to move elliptically as shown in Figure 10. As the wave slows, wavelength shortens, and wave height increases until the ratio reaches or exceeds 7:1 (wavelength/wave height), when the wave breaks. As shown in Figure 9 the wave is considered an intermediate wave, meaning some interactions with the lake bottom, if water depths are between ½ and 1⁄20 of the wavelength. Below 1⁄20 wavelength, the wave is considered a shallow water wave. For the example given, a wave with a wavelength of 20 ft would be an intermediate wave between 10 ft and 1 ft of depth and a shallow wave below 1 ft of depth. These definitions become important for understanding the results of this study and its relationship to other wave studies or research.

Wave energy can be quantified using the following SI unit equation derived from linear wave theory or Airy wave theory below as summarized in the University of Minnesota – St. Anthony Laboratory Report: “A Field Study of Maximum Wave Height, Total Wave Energy, and Maximum Wave Power Produced by Four Recreational Boats on a Freshwater Lake” published February 2022:

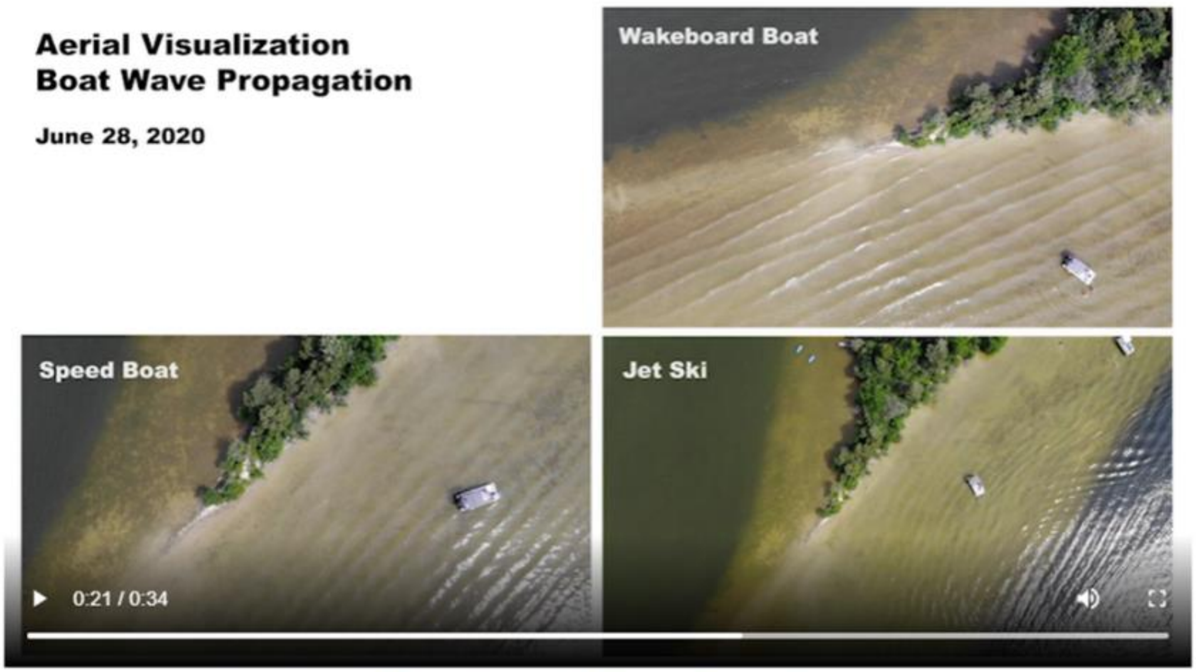
$$E_i = \frac{\rho g {H_i}^2 \lambda_i}{8}$$

In this equation, ρ is the density of water (kilograms/meter3), g is the gravitational acceleration constant (meters/second2), Hi is the wave height (meters) and λi is wavelength (meters). This equation indicates that the total energy per unit crest length within a single wave is related to the density of the water (ρ), the square of wave height, and the wavelength of the wave --- this is important to keep this in mind for evaluating study results. Since water density and gravitational acceleration are constants (i.e., do not change), the amount of energy in a wave depends on its height and wavelength as well as the distance over which it breaks. Given equal wavelengths, a wave with greater height or amplitude will release more energy when it falls back to lake levels than a wave of lesser height. Hence, Energy (E) per square meter or square foot is proportional to the square of the height. In other words, if wave A is two times the height of wave B, then wave A has four times the energy per square meter or square foot of water surface as wave B.

Note that a single pass by a motorized boat can produce multiple waves, which can collectively be referred to as a “wave packet” (see the University of Minnesota – St. Anthony Laboratory Report: “A Field Study of Maximum Wave Height, Total Wave Energy, and Maximum Wave Power Produced by Four Recreational Boats on a Freshwater Lake” published February 2022). In general, these researchers found that the main contribution of the wake wave packet (i.e., biggest waves) occurred over 35-40 seconds from the start of the packet or first wave from all vessels studied. Also see this following publication for description of boat generated wake dynamics (Bilkovic, D., M. Mitchell, J. Davis, E. Andrews, A. King, P. Mason, J. Herman, N. Tahvildari, J. Davis. 2017. Review of boat wake wave impacts on shoreline erosion and potential solutions for the Chesapeake Bay. STAC Publication Number 17-002, Edgewater, MD. 68 pp.).

Season 2020 Results

In 2020 Terra Vigilis and Carroll University conducted an aerial and subsurface wave oscillation comparison among several different boating vessels on North Lake. (see link here at https://storymaps.arcgis.com/stories/a4431437506b4cd990f31c999128301b). As shown in the visual aerial comparison (see Figure 11 below) and video footage, the distances between waves from jet skis are shorter (i.e., shorter wavelength) and more numerous (i.e., greater frequency) than either speed boat or wakeboard boat waves and they do not appear to disrupt nearshore substrates.



Aerial Visualization of Different Types of Waves

Figure 11: Aerial Visualization of different Wave Propagations from various vessels

In contrast, both the speed boat and wakeboard boat footage show that nearshore sediments are being disrupted from the higher energy waves generated from each of these vessels. However, the wakeboard boat waves seem to create a greater disruption of sediments compared to the speedboat wave footage. The waves from the wakeboard boat are large enough that they create white cap waves that break in the nearshore, which creates a greater disturbance of sediments in this area that can be seen in the footage.

It is important to note that shoreline slope can also affect wave characteristics. In the video footage, there is a light-colored bench (shelf) that contains shallow water compared to the darker colored deeper waters. This lighter colored bench is roughly where the 5-foot water depth transitions to deeper darker water. As shown in Figure 12 this bench from the shoreline to 5-foot depth is flatter or comprised of a gentler (8 percent) slope than the deeper parts of the lake, except when waters exceed 60 feet in depth. This bench is characteristic of the entire shoreline of North Lake in both basins and is largely comprised of sand substrates. Carroll University students determined that substrates within this bench contained between 3 to 23 percent organic matter. This is consistent with previous observations by Dr. Jerry Kaster (former, UW-Milwaukee professor) that North Lake bottom sediments contained between 3 and 59 percent organic matter, which generally increases with depth (see North Lake Project: Paleolimnology, Geochronology, Sediment Size Fractionation, and Suspended Sediment Load, conducted by Jerry Kaster, 1992). In addition, sediment size fractionation generally indicates that the shallow areas were mostly comprised of sand but become siltier with increased depths. Shallow areas generally contained about 5 to 40% silt and the deepest stations are composed almost exclusively of silt with little sand present. Nonetheless, lake bottom sediments were also found to contain minor amounts of clays (i.e., 1 and 5 percent) and 35 percent marl or calcium carbonate. These are important findings because these silts, clays, and marl substrates are easily disturbed and resuspended into the water column, which is most likely what is being disturbed and redistributed from the waves shown in the video footage.

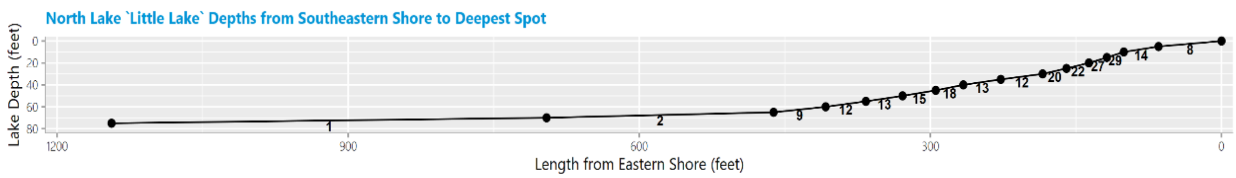


Figure 12: Typical bathymetry at the study site in the small basin of North Lake showing a gradual increase in water depth with distance from shore.

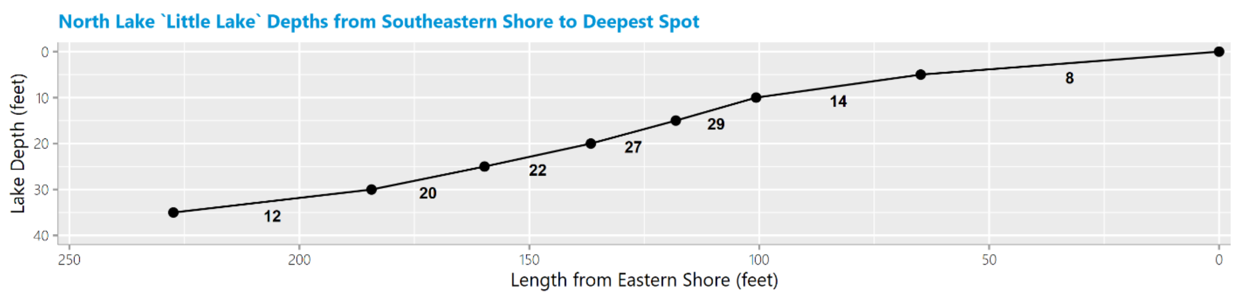


Figure 12A: Enlarged nearshore area of Figure 12

A depth of 35 ft is about 250 ft from shore. The maximum depth of 75 ft is about 1150 ft from shore. Calculated slopes are shown underneath the line between each 5-foot depth increment change. Source: SEWRPC.

In 2020 the team also conducted nearshore footage both below water and above water to better visualize and measure impacts of boat generated waves near the shoreline.

Time stamped video imagery with a surveyor's pole and measuring stick were used to generate the data for wave height and wavelength measurements from various vessel types (see Figure 13). This data was then used to generate a 3D model of the "wave packets" for each vessel type and time align them based on the first wave crest (see Figure 14). Researchers found that the main contribution of the wave packet occurred over 35-40 seconds from the first wave of the wave packet. In this study the beginning of a wave packet from each vessel type is captured (14 seconds duration), and then the first crest of each wave packet is aligned to compare the significant differences in the initial wavelengths and wave heights. The remaining 20-25 seconds of the wave packet become more repetitive waves, that slowly diminish in height and energy.

Wave Measurements at 15 meters from shoreline

Wakeboard Boat Wave		
Wavelength (Feet-Inches)	**Height (inches)**	**Time from first crest (seconds)**
---------------	2.0	0.00
15' 4"	-2.0	1.10
---------------	8.0	1.99
17' 11"	-2.0	3.10
---------------	4.0	4.02
20' 5"	-2.0	5.94
---------------	3.5	6.17
15' 4"	-2.0	8.07
---------------	4.0	8.99
12' 10"	-3.0	10.04
---------------	2.0	10.95
	-3.0	12.09
---------------	4.0	12.99

Pontoon Boat Wave		
Wavelength (Feet-Inches)	**Height (inches)**	**Time from first crest (seconds)**
---------------	3.0	0.00
20' 5"	-3.0	1.98
---------------	5.0	3.00
17' 11"	-2.0	4.11
---------------	3.0	5.11
17' 11"	-1.0	6.89
---------------	1.5	7.10
10' 3"	-2.0	8.17
---------------	1.0	9.13
10' 3"	-1.0	10.07
---------------	1.0	10.98
	-2.0	11.99
---------------	1.0	12.91

Jetski Wave		
Wavelength (Feet-Inches)	**Height (inches)**	**Time from first crest (seconds)**
---------------	2.0	0.00
12' 5"	-2.0	2.04
---------------	3.0	3.00
15' 4"	-2.0	4.09
---------------	3.0	5.09
17' 2"	-1.0	6.89
---------------	1.5	7.06
11' 6"	-1.0	8.15
---------------	1.0	9.10
11' 3"	-1.0	10.00
---------------	1.0	10.90
	-1.0	11.99
---------------	1.0	12.88

Figure 13: Comparative Wave Oscillation Data Generated 250' from Shoreline

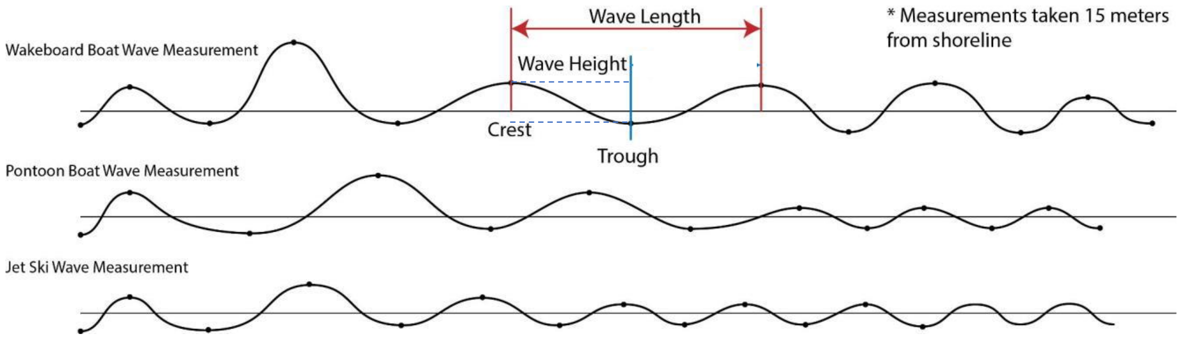


Figure 14: 3D model of Wakeboard, Pontoon, and Jet Ski Wave oscillations created from displacement data

Above surface impacts

Observation: Like the aerial videos summarized above, these figures show that the jet ski and pontoon boat waves are much smaller and do not disrupt nearshore substrates compared to the wakeboard boat waves. However, the wakeboard boat generated waves are much larger and produce a spilling breaker wave on the shoreline. Comparison of the wavelength and wave height measurements for each vessel indicates that the wakeboard boat waves contained greater average wavelengths and wave heights (both average and maximum) compared to either the pontoon or jet ski waves. Based upon the first five measured waves for each vessel type, the mean wavelengths were 16.4 feet for the wakeboard boat, 15.4 for the pontoon boat, and 13.5 for the Jet ski. Similar to the wavelength results the observed maximum wave heights were 10 inches for the wakeboard boat, 8 inches for the pontoon boat, and 5 inches for the Jet ski. The average wave heights were 6.2 inches for the wakeboard boat, 3.9 inches for the pontoon boat, and 3.1 inches for the Jet ski. Hence, wakeboard boat waves are larger and contain greater energy than the other vessels measured and are much more disruptive to nearshore substrates causing significant disruption of sediments along the entire length of the nearshore area with only one pass of the boat.

Subsurface impacts

Subsurface footage in 5-10 feet of water depth shows that the plants are being affected by the waves passing through by all boating vessels but note that no sediments were being disrupted at these depths. Nonetheless, it can be seen from the underwater footage of wakeboard boats that the resulting wave is moving/disrupting both the submersible and the rooted aquatic vegetation much more rigorously than either the jet ski or pontoon boat generated waves. As previously mentioned, the average wavelengths were 16.4 feet for the wakeboard boat, 15.4 feet for the pontoon boat, and 13.5 feet for the Jet ski. Based upon these measurements and noting the equations above, one-half the wavelength would equate to shallow water wave depth conditions of about 8.2 feet for the Wakeboard boat, 7.7 feet for the pontoon boat, and 6.8 feet for the jet ski. The greater wavelengths equate to greater energy waves and the wakeboard boat waves influence or penetrate to deeper depths than either the pontoon or jet ski. These results are consistent with the video footage of subsurface disturbance for all three vessel types.

Problems/issues
Since the wave measurements were taken 15 meters or 50 feet from the shoreline of the little basin of North Lake, that would equate to a water depth of about 2' to 4'. This indicates that the waves generated from each vessel being measured were being influenced by the bottom of the lakebed (i.e., shallow water wave depth conditions). This likely means that wavelengths were likely underestimated and that wave heights were likely overestimated in this study. Nonetheless, maximum wave height characteristics for wakeboard boats in this study were comparable to the aforementioned University of Minnesota study measured closer to shore. In other words, the wakeboard boat maximum wave height of 10 inches operating 250 feet from shoreline was in agreement or within range reported for maximum wave height generated by a wakeboard boat in full ballast condition between 200 to 300 feet from the operating vessel as shown in Figure 15 from the aforereferenced report below. In that study 200 feet and 300 feet distances from an operating wakeboard boat generated maximum wave heights (depending on the Wakeboard boat model) ranging from about 9 to 19 inches and 9 to 17 inches, respectively.

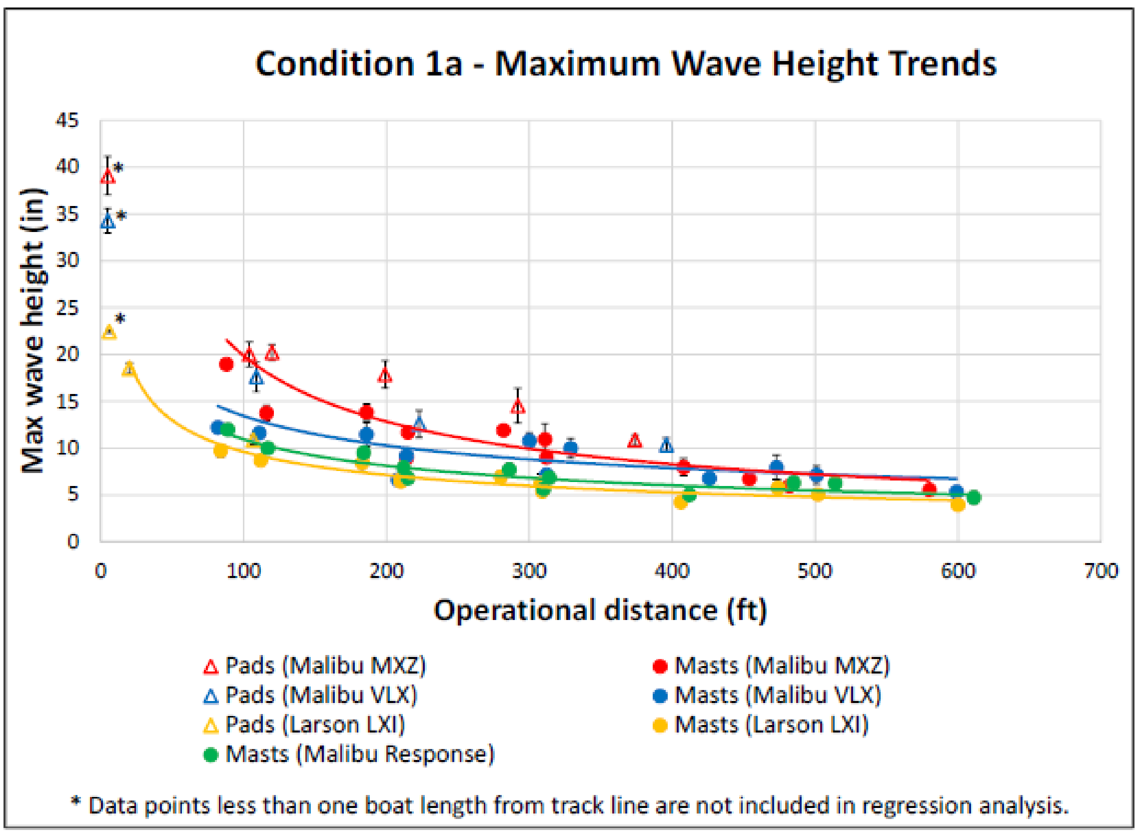


Figure 15: Condition 1a – Maximum wave heights over operating distance
Source: University of Minnesota – St. Anthony Laboratory Report: "A Field Study of Maximum Wave Height, Total Wave Energy, and Maximum Wave Power Produced by Four Recreational Boats on a Freshwater Lake" published February 2022.

Season 2021 Results

The Phase 2 study in 2021 captured wave propagation video footage and measurement of wave characteristics produced by various vessels passing at distances of 200, 300 and 400 feet from shoreline. Testing was performed in the little lake basin on calm water days. The operational characteristics of the vessels was standardized for study purposes e.g., pontoons at slow cruising speeds, PWC at legal speed limits (35mph) and wake surf mode operations at 15-degree bow angle, full ballasts and slow speed (maximum wave effect). The data as reflected in Figures 16 and 17 show the wave oscillations from wakeboard boats in surf mode. Comparative data from recent research work conducted in various parts of the country are consistent with these observations. (See the University of Minnesota – St. Anthony Laboratory Report: "**A Field Study of Maximum Wave Height, Total Wave Energy, and Maximum Wave Power Produced by Four Recreational Boats on a Freshwater Lake**" published February 2022 which specifically details wave energy impacts. "**Analyzing Threats to Water Quality from Motorized Recreation on Payette Lake, Idaho**", Western Colorado University, August 2020). Particularly notable in all of these studies is that wave oscillations produced by wakeboard boats in surf mode are capable of near shore bottom scrubbing effects from distances of 300 feet or greater from shore.

In this Phase 2 study, subsurface video measurements were taken at 1-4' below the surface. As noted in the Background section above on general characteristics of waves, the wave breaks due to decreasing water depths within the nearshore area. Of interest, the measurements of other categories of vessels diminish rapidly at these distances and depths from the near shore.

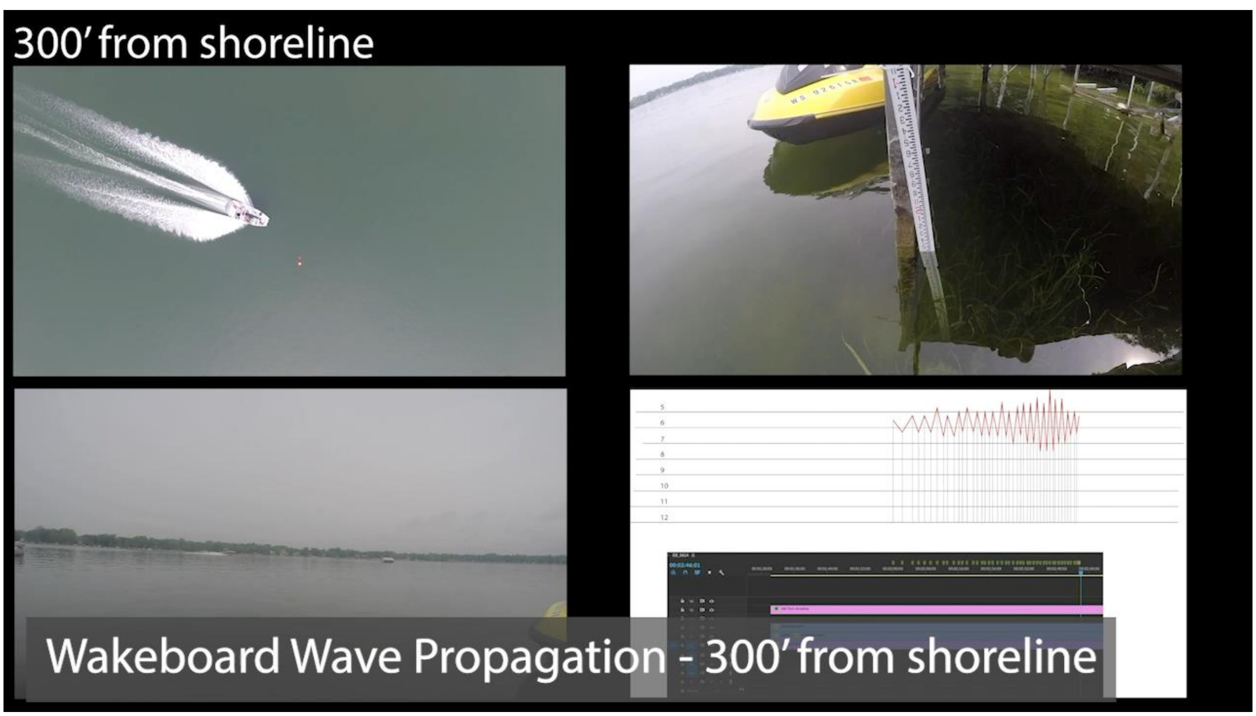


Figure 16-Video: Comparative Wave Oscillation Data 300' from Shoreline

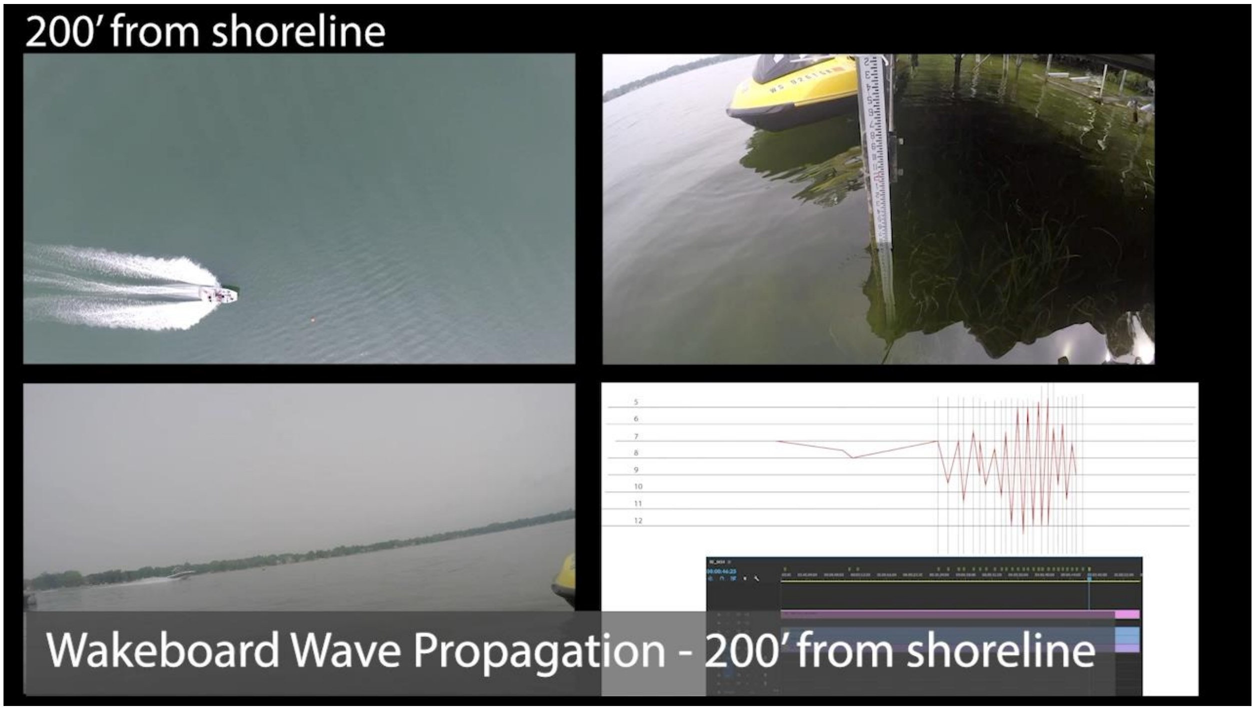


Figure 17-Video: Comparative Wave Oscillation Data 200’ from Shoreline

The wakeboard boat wave propagation comparison shows that all the waves heights are much higher and have great wavelengths and heights from the pass at 200 feet compared to 300 feet from the shoreline.

Although these results indicate a reduction in the wave energy when boats were run 100 feet further from shoreline (i.e., 300 feet versus 200 feet) it is important to note that these wakeboard boat waves are smaller in maximum wave height compared to previous wakeboard boat runs in 2021 and current research as noted above in part due to the wave characteristic measurements being taken in deeper water depths (4-5’). These wakeboard boat passes generated maximum wave heights of 8 inches and 4.5 inches for the 200 feet versus 300 feet passes, respectively. In 2020 the wakeboard boat run 250 feet from shore generated a 10 inch maximum wave height in 18-24” of water depth (see above). In addition, the Minnesota study reported wave heights ranging from about 9 to 19 inches and 9 to 17 inches 200 feet and 300 feet distances from an operating wakeboard boat depending on the wakeboard boat model, respectively. The 2021 video at 200’ show the initial waves of the wave packet breaking before reaching the shoreline, however it cannot be seen from the video footage if sediments were disrupted in the nearshore area (as compared to the 2020 aerial videos). At 300’ the waves do not appear to break until reaching the shoreline and therefore remained smaller rolling waves. Hence, these recorded waves do not show direct impact on the nearshore area or shoreline of North Lake (as compared to the 2020 4-Quadrant videos from the Phase 1 Study).

Problems/issues

As previously noted above, since the wave measurements were taken 15 meters or 50 feet from the shoreline of the little basin of North Lake, this likely means that wavelengths were likely underestimated and that wave heights were likely overestimated. With that being said, it is unclear why these waves are so much smaller than previous runs and other research.

Season 2022 Results

In Season 2022 TV and Carroll University plan to measure wakeboard boat wave propagation video footage and wave characteristics from 400 feet from shoreline for comparison to the 200 and 300 feet distances from shoreline in 2021. In addition, speed boat wave propagation video footage and wave characteristics will also be measured from boating pass distances of 200, 300, 400 feet from shoreline for comparison to the wakeboard boat wave characteristics. Results from this section will be included with the final Wave Study report from TV and Carroll University.

Domain 6 Nutrient Load Differences (pre-post) from Wakeboard Boats in Surf Mode

On September 25, 2021 a test was performed to measure phosphorous release by roil effect (i.e. creating water turbidity by disturbing the sediment) from wave propagation produced by surf mode operations on a standard course length of approximately 800 yards along a buoy course 200' from the shoreline (See Figure 18).

Measurements of Phosphorous before and after the disturbance of sediments due to wakeboard boat downwash effects was accomplished by collecting water samples 6" below the water surface 100' from the shoreline where the water depth was 3-5' deep. A total of 2 course runs (North and South) were made at standard surf mode features (full ballasting, raised bow angle and approximately 10 mph of operating speed). Calm water conditions were present. The water depths along this course were determined by doppler study and ranged from 25 feet of depth at the southern end of the course and 15 feet at the northern end of the course. The data gathered (following laboratory analyses) showed a range of phosphorous increases in the water column along this course (3 sites sampled) from 17% to 33 % increase within 30 minutes of initial disturbance. See Table 1.

Table 1 Comparative values at 3 test sites pre-post

Pre-test	Secondary Baseline	Post-test	Difference	Percent change
Site A 0.012	0.014	0.014	0.002	17%
Site B 0.012	0.010	0.015	0.003	25%
Site C 0.023*	0.011	0.016	0.004	33%

*this test result was an outlier compared to all the other Pre-test samples (avg = 0.012)

Figure 18: Course and Sampling Sites for Nutrient Load Differences (pre-post) from Wakeboard Boat in Surf Mode

Summary

The Phase 2 study of water quality and wave propagation effects has been completed. Identification of six study domains have been detailed with graphs, figures and descriptive narratives provided throughout this report.

1. There are significant differences noted between the wave characteristics and impacts of wave action (both surface and subsurface) from powered vessels studied on North Lake in the Phase 2 research completed. Less impactful wave effects are noted from Pontoon boats, fishing vessels, and PWC compared to Wakeboard Boats in “Surf Mode”. All boats tested had both surface and subsurface impacts, however, the wakeboard boats in surf mode had significantly greater wave impacts compared to those other vessels. Wave characteristics of ski boats will also be studied in 2022.
2. Propeller downwash characteristics for wakeboard boats in surf mode have been measured at depths greater than 20 feet. This depth effect is nearly 3-4 times greater than the other three categories of vessels in use on North Lake owing to reduced engine power, propeller angles, hull design, lack of ballasting, and the mode of operation (hull “planing”).
3. Near shore impacts from wave propagation show significant differences between vessel type and distance from shoreline. At measured distances from shoreline (300’) Wakeboard boats in surf mode produce wave oscillations larger than all other categories with bottom impacts including re-deposition of sediments. This effect is particularly notable on the little lake due to its smaller area (105 acres) compared to the Larger basin as well as the shallow water “shelf” that encompasses both basins.
4. Wakeboard boats in surf mode operating 200 feet from shore within depths of 15 to 25 feet of water were associated with a 25% increase in total phosphorus concentrations in the water column after periods of less than 30 minutes. Water samples were taken in depths of 5 to 8 feet of water depth. Although no turbidity or total suspended solid measurements were taken during the course of this test run, the water was observed to be cloudy from the wave generated turbulence. It is important to note that no other vessels were tested in this same manner.
5. Preliminary assessment of the water quality and recreational use in the 2021 season suggests that periods of high boating activity on weekends were associated with increased Total Suspended Solids (TSS) compared to midweek. However, it is important to note that water quality and recreational boating surveys continue to be collected and will be summarized by SEWRPC staff as part of the final summary report for this overall study.
6. Re-deposition effects are notable from persistent Wakeboard boat activity in surf mode on the little lake basin with evidence of plume deposits along the majority of the Wildwood Point reef. Depositional materials appear to have an impact on aquatic plant life. However, this sediment deposition could not be solely attributed to only wakeboard boats (i.e., all types of vessels are operating simultaneously on the Lake) as this was neither verified or measured as part of this study.

7. Wave energy from all boats does not stay where the boating occurs, and it moves toward the shoreline where the water is shallower. However, only wakeboard boats in surf mode generate waves that disturb or disrupt sediments within the shallow benches (i.e., less than 10 feet) of North Lake compared to all the other vessels.

Recommendations

The following recommendations for actions are offered to the NLMD for consideration.

- Consideration by the NLMD for continued requirements to assure deep water operations for Wakeboard boats in surf mode on the waters of North Lake are recommended. The small size of the little basin (105 acres) argues for use of surf mode in the large basin only to avoid sediment and nutrient dispersal by wake boat and surf mode operation. Use of wake boat in surf mode on the large basin (335 acres) should be done only in the middle of lake and avoid the north and south bays.
- Consideration by the NLMD for continued and compelling educational efforts (Stewardship committee) to all lake residents on water quality and wave propagation effects.
- A study in 2022 should focus upon Phosphorous loading at all 7 sites on North Lake and a specific measure of Phosphorous at the outflow of the small lake basin outlet (Oconomowoc River).
- A replication of the 400’ wave oscillation data should be completed and also include a ski boat at 200’, 300,’ and 400’.
- Development and integration of opinions regarding mitigation of human-induced wave action which effects near shore bottom sediments, water quality, fish habitats, and vegetative communities by Subject Matter Experts (SMEs) from SEWRPC collaborating on this study.
- NLMD should assume responsibility for coordinating the scheduling of other volunteer and OSD measurement efforts (boat count, water quality, etc.) with the Terra Vigilis Water Quality Sampling Schedule for 2022 (Appendix C). This coordination should include data sharing in addition to time schedules.
- Terra Vigilis and NLMD and SEWRPC should schedule monthly update of progress, plans, and data review commencing June through September 2022.

Appendix A: 2021 NLMD Phase 2 Study – preliminary summary 09/17/21

Appendix B: 2021 Water Quality & Weather Data at North Lake

Appendix C: Water Quality Sampling Schedule for 2022 (2Q and 3Q)

Appendix D: Methods and Equipment List

North Lake Management District (NLMD)

Water Quality and Wave Propagation Study

Phase 2

17 September 2021

Terra Vigilis Environmental Services Group

Introduction

The purpose of this summary is to review tasks completed as of 24 August 2021 relative to the NLMD scope of work contract. This project addresses wave propagation differences among powered vessels. The study encompasses both surface and subsurface wave measurements, and their effects upon sediment movement. The work is supported in part by WDNR grants.

Study Aspect A: Wave Physics

The Terra Vigilis team has completed the engineering and field testing for a prop downwash measurement system. This device provides subsurface video imagery of wave impacts from the primary types of powered vessels that are in use on North Lake. These vessels include:

- Personal Watercraft PWC
- Pontoon Boats
- Water Ski Boats
- Wake Board Boats in Wake Surf mode

The measurement system will also provide a unique computer enhanced model for integration with bathymetric data for the small lake basin.

Equipment

- Secchi disk
- YSI Probe for DO, Temps
- Standard Core Sample Probe
- Boston Whaler 13' with Lowrance Depth/Temp system
- DJI Phantom 3 Professional Quadcopter Drone
- Qysea Fifish V6S Commercial Submersible
- State Certified Labs for Phosphorous/TSS samples.

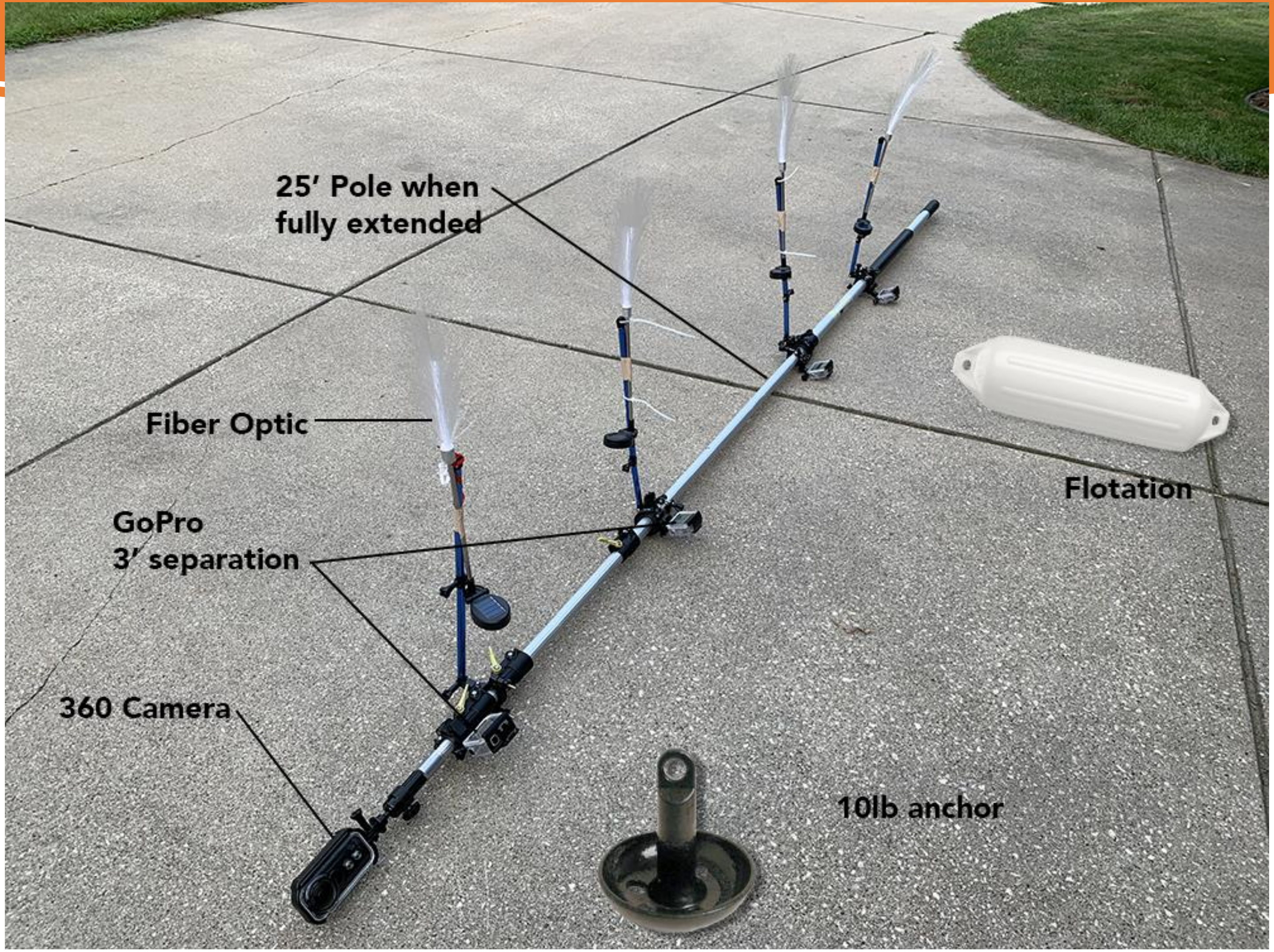
Qysea FiFish V6S

YSI Dissolved Oxygen Probe

DJI Phantom 3 Professional

Secchi Disk

Prop Downwash Measurement



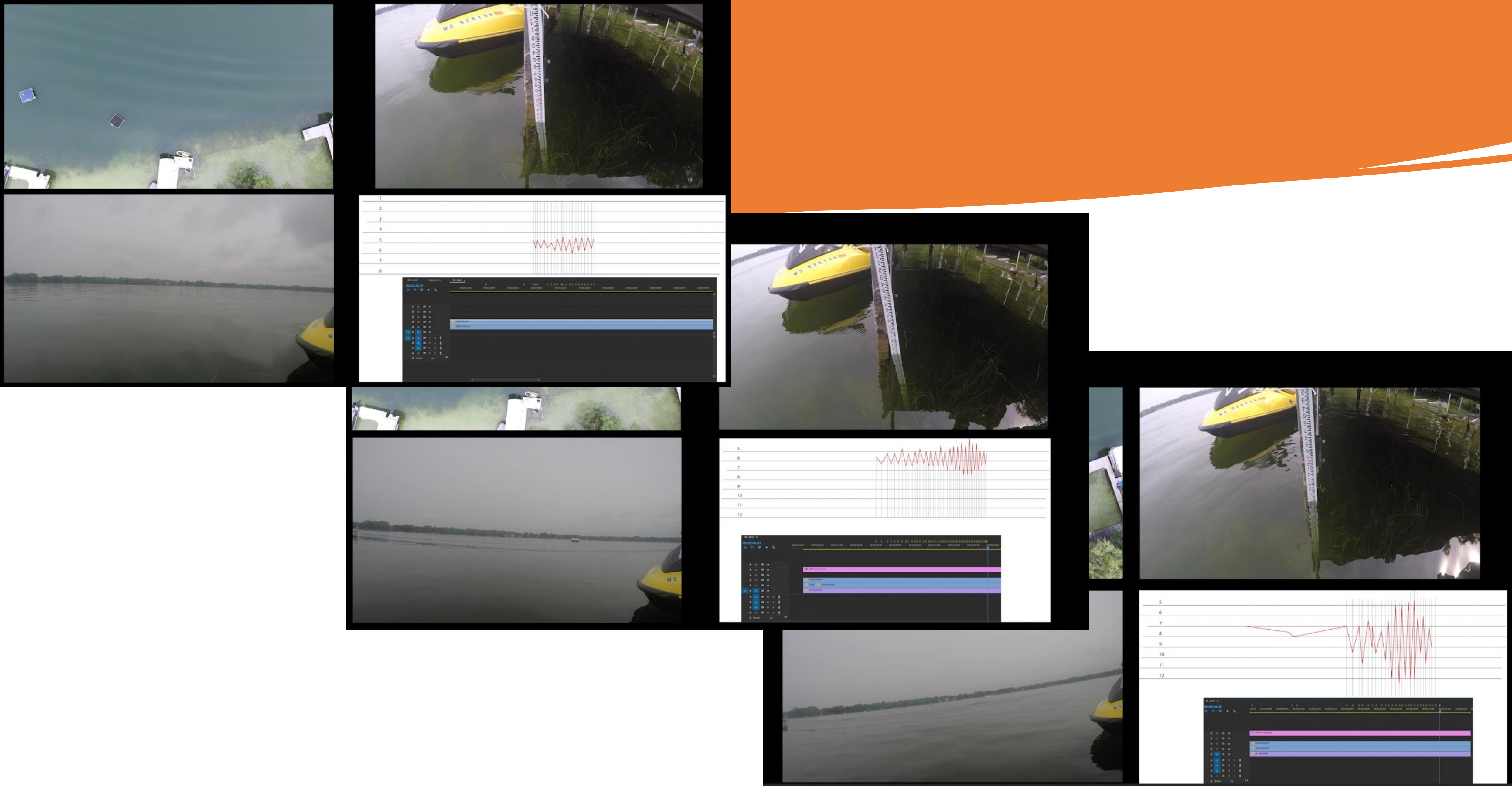

14’ Below Surface
17’ Below Surface
20’ Below Surface


Depth:6.63ft
FIFISH
2021-07-13 11:46:18

Study Aspect B: Shoreline Impacts

The study design requires measures of surface wave impacts at variable distances. These distances include 200’, 300’ and 400’ from shoreline perimeters in the small lake basin. Aerial drone images will be collected during August.

400’ from shoreline

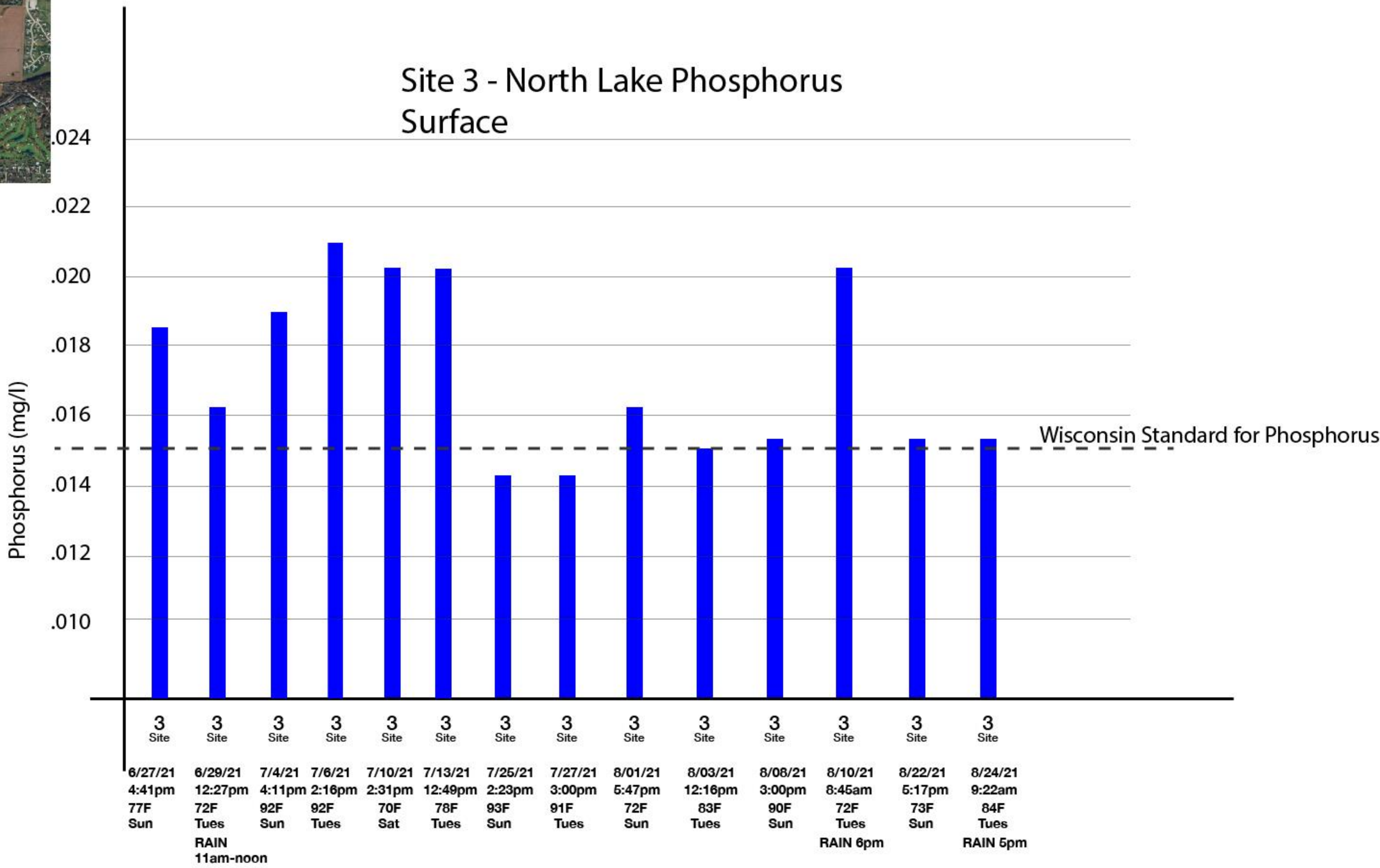


Study Aspect C: Water Chemistry

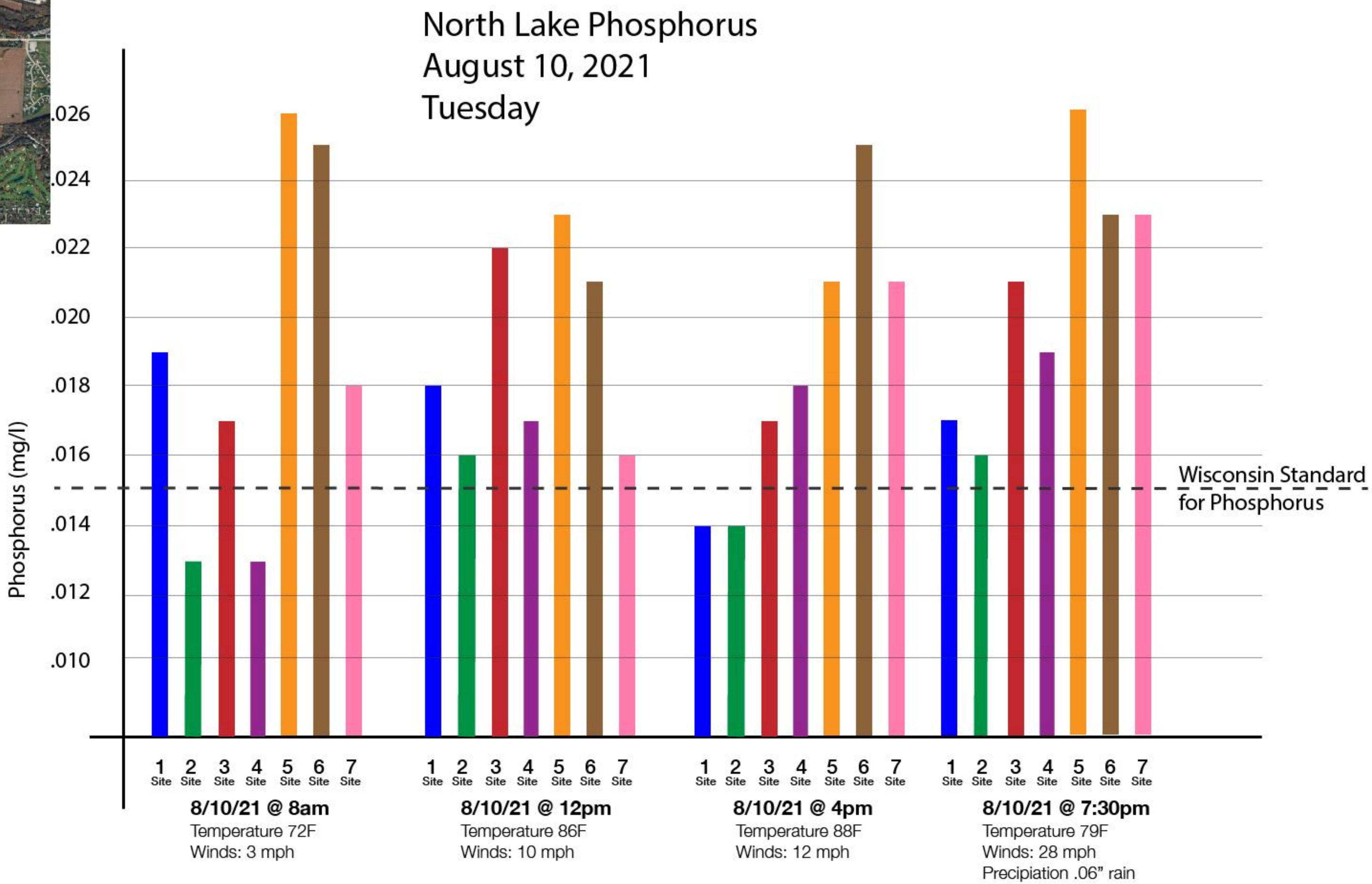
Weekly water sampling consisting of dissolved oxygen (DO), total suspended solids (TSS) and Phosphorous have been gathered at multiple sites. Measurements of water clarity by Secchi disc have also been completed at each of these sites. Temperature and DO were sampled at multiple depths (5’,10’,15’,20’), and to identify thermocline depth (17 feet in June and July).

The required WDNR laboratory analyses are provided monthly.

North Lake - Phosphorus



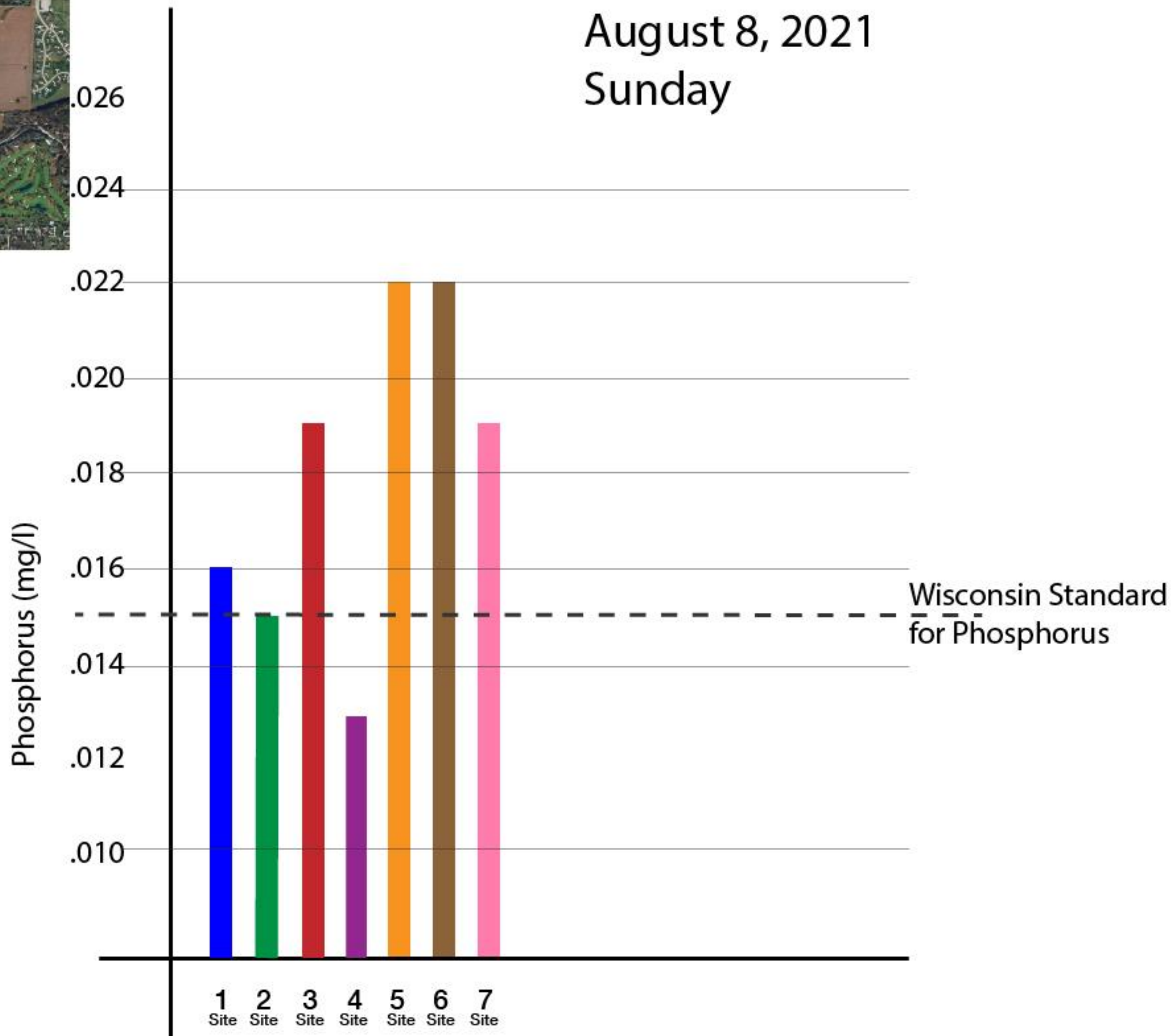
North Lake - Phosphorus



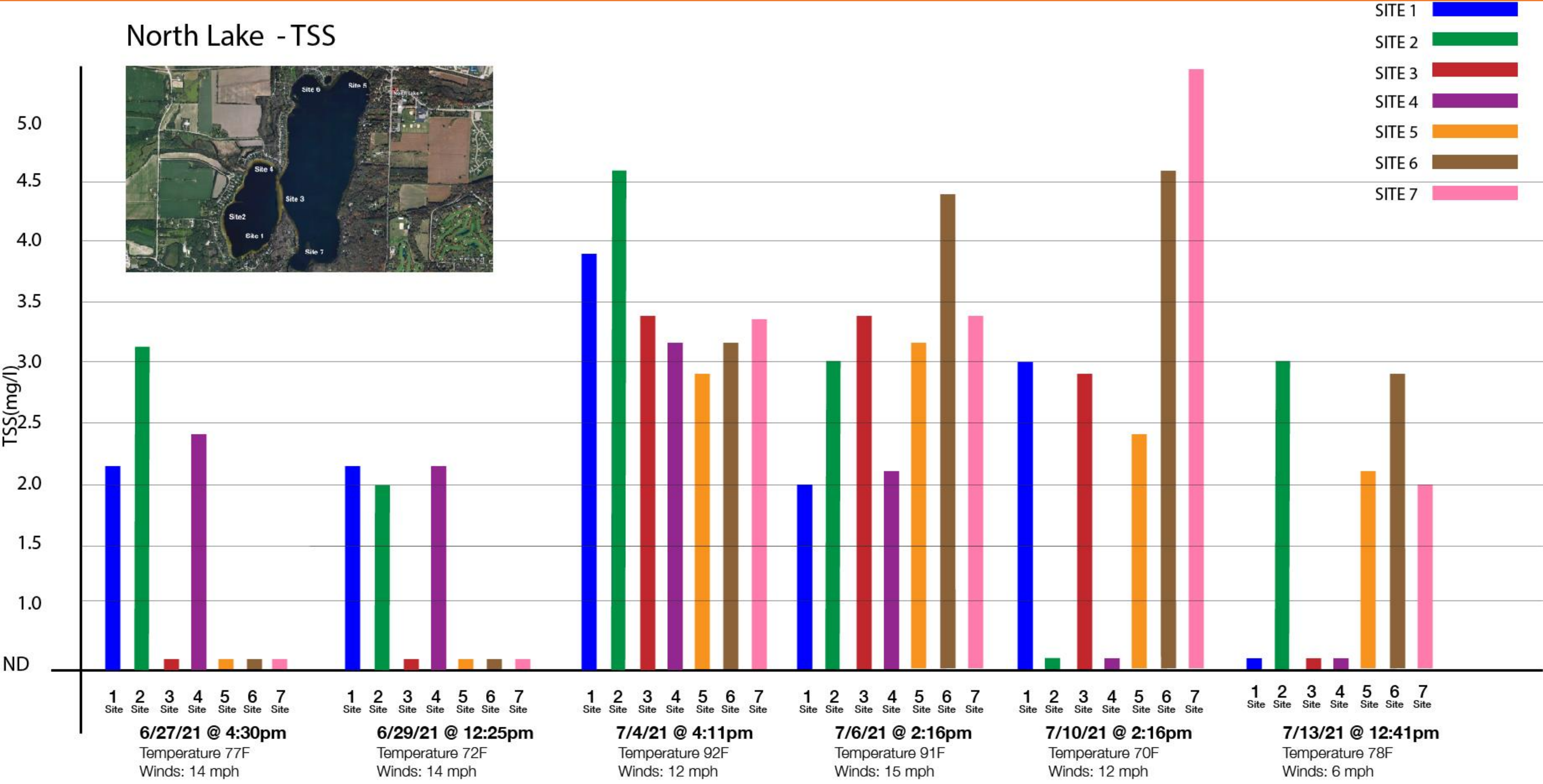
North Lake - Phosphorus

SITE 1
SITE 2
SITE 3
SITE 4
SITE 5
SITE 6
SITE 7

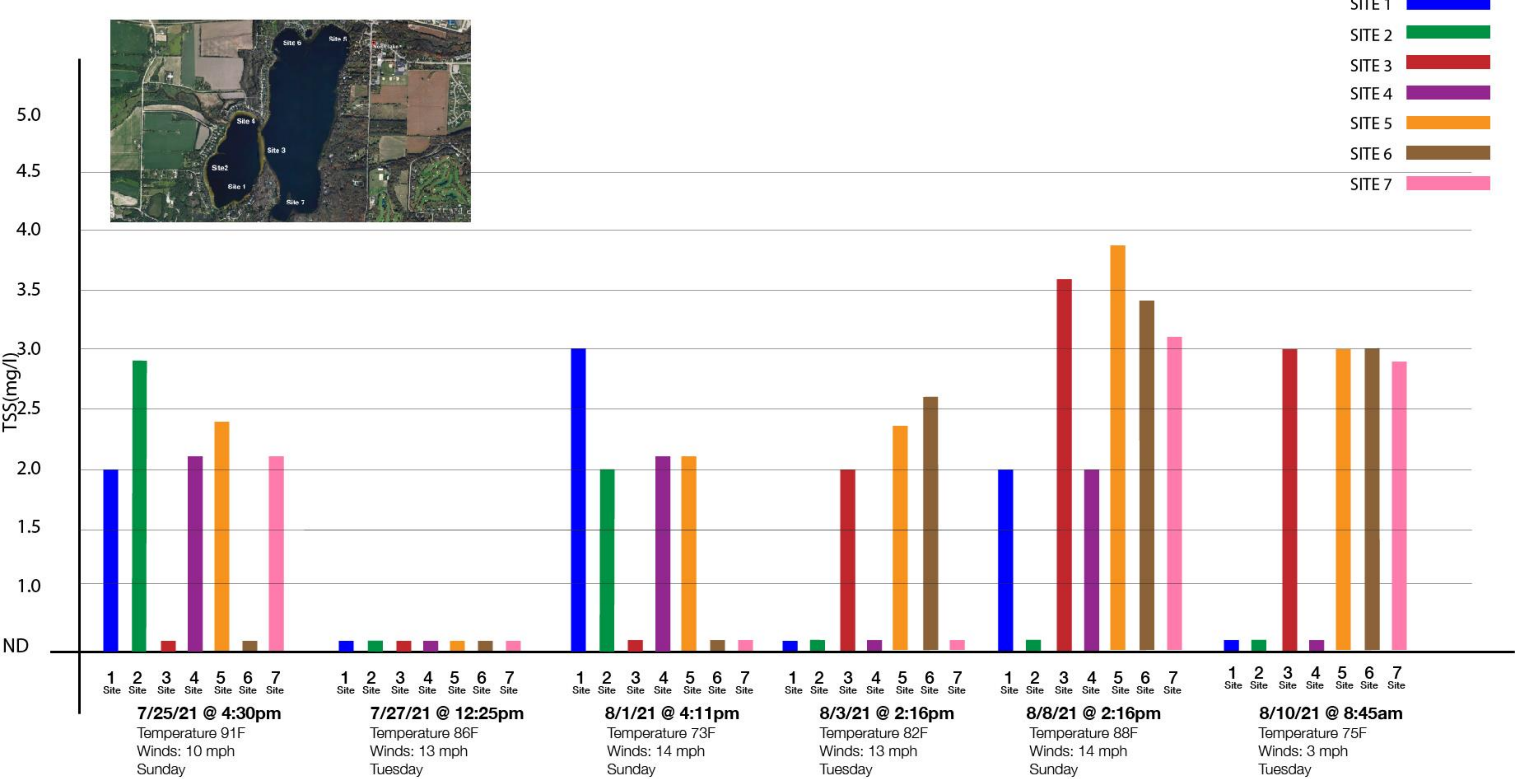
North Lake Phosphorus
August 8, 2021
Sunday



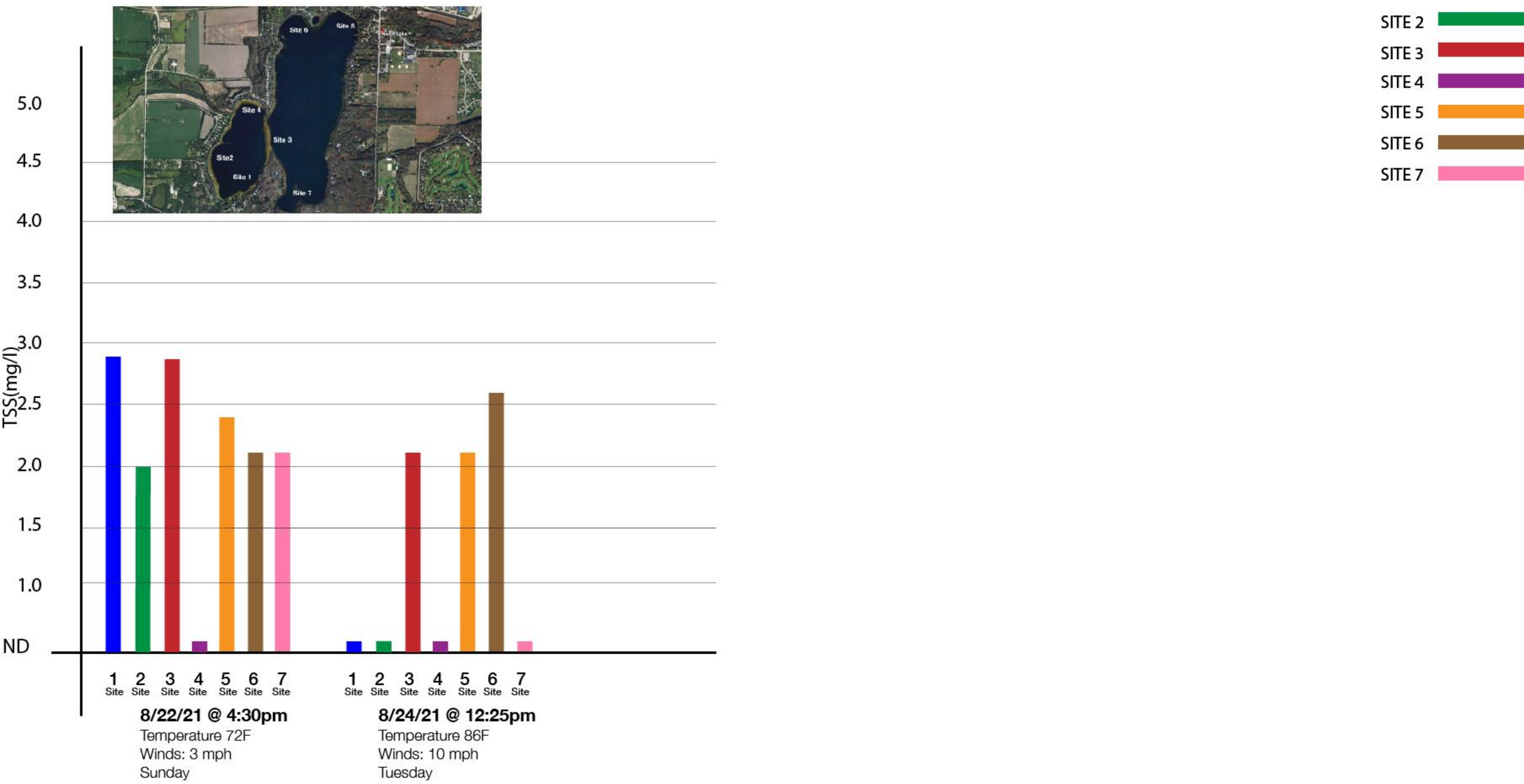
8/8/21
Temperature 72F
Winds: 3 mph

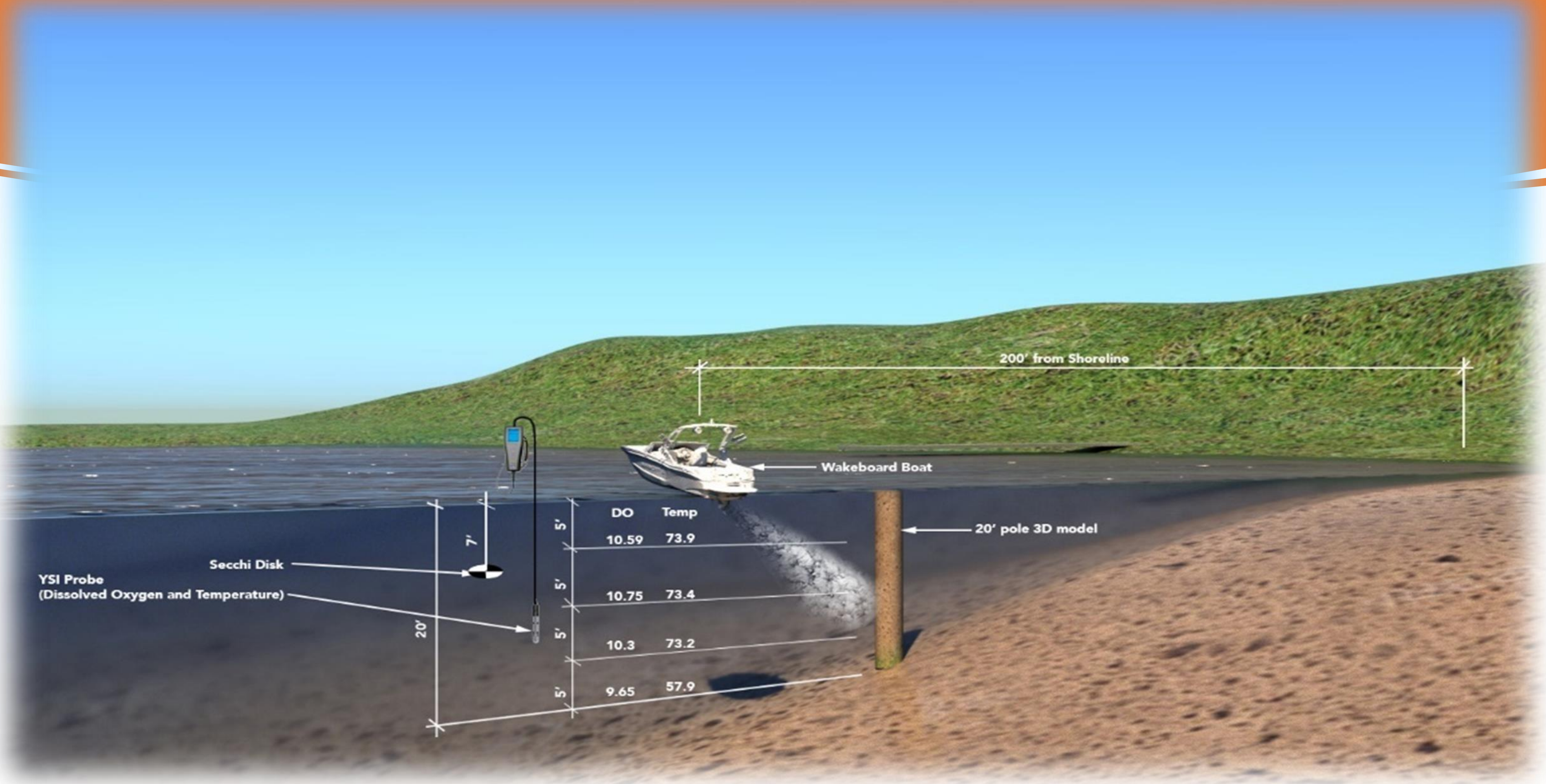

North Lake - TSS
SITE 1
SITE 2
SITE 3
SITE 4
SITE 5
SITE 6
SITE 7
TSS(mg/l)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
ND
Site 6
Site 5
Site 4
Site 3
Site2
Site 1
Site 7
1 Site 2 Site 3 Site 4 Site 5 Site 6 Site 7 Site
6/27/21 @ 4:30pm
Temperature 77F
Winds: 14 mph
6/29/21 @ 12:25pm
Temperature 72F
Winds: 14 mph
7/4/21 @ 4:11pm
Temperature 92F
Winds: 12 mph
7/6/21 @ 2:16pm
Temperature 91F
Winds: 15 mph
7/10/21 @ 2:16pm
Temperature 70F
Winds: 12 mph
7/13/21 @ 12:41pm
Temperature 78F
Winds: 6 mph

North Lake - TSS



North Lake - TSS




200' from Shoreline
Wakeboard Boat
20' pole 3D model
DO
Temp
10.59
73.9
10.75
73.4
10.3
73.2
9.65
57.9
5'
5'
5'
5'
7'
20'
Secchi Disk
YSI Probe
(Dissolved Oxygen and Temperature)

Analyses and Commentary Across all Domains

Questions

Appendix B: 2021 Water Quality & Weather Data at North Lake

For each of the figures with timelines (Figs. 1,2,3,4,5) the major gridlines on the X axis represent Sundays with one-week intervals. High traffic weekends are shown on or immediately preceding the major X axis gridline. Low traffic weekdays (typically Tuesdays) are shown 2/7th across an interval.

Phosphorus

Samples were gathered at site 3 on the large lake basin which was identified from the Phase 1 study as a critical transfer location from the small to large lake basin and an area where plume deposits were identified to be settling after persistent disturbance from boating activity.

	Phosphorus
Date	**Site 3**
27-Jun	0.0184
29-Jun	0.0168
4-Jul	0.0191
6-Jul	0.0211
10-Jul	0.0209
13-Jul	0.0201
18-Jul	0.0161
20-Jul	0.0174
25-Jul	0.0143
27-Jul	0.0147
1-Aug	0.0162
3-Aug	0.0156
8-Aug	0.0157
10-Aug	0.0206
22-Aug	0.0159
24-Aug	0.0159

Table 1: Phosphorus

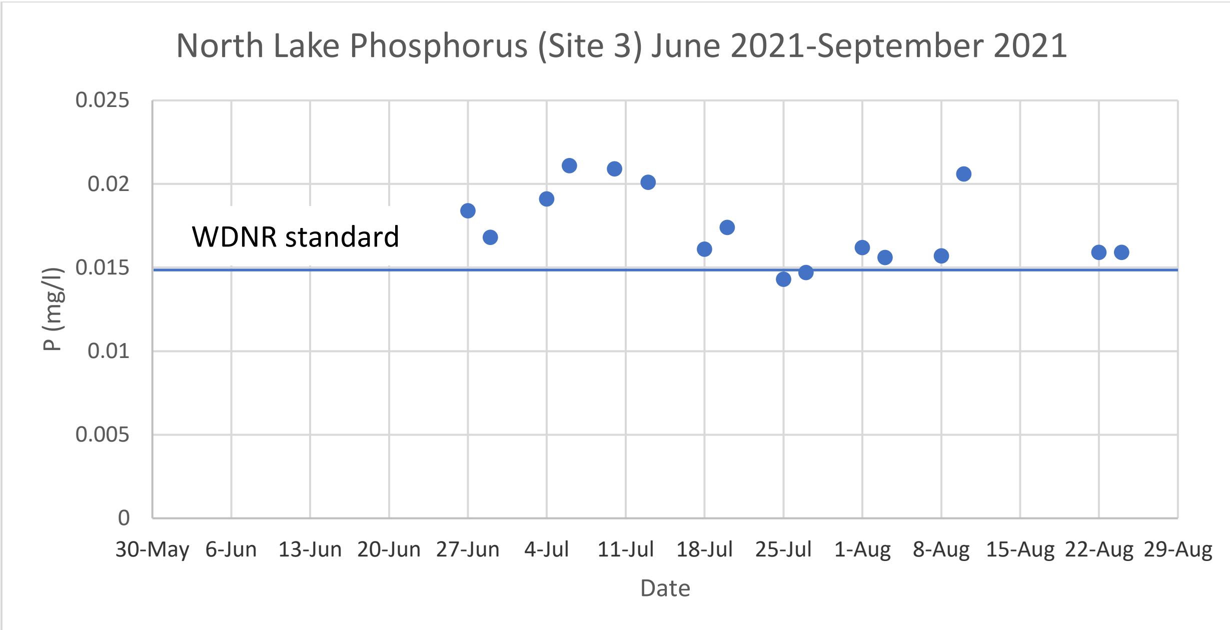


Figure 1: Total Phosphorous

Dissolved Oxygen (DO) and Water Temperature

Readings were taken at staggered depths of 5',10',15', and 20' (when possible based on lake bottom depth).

To determine the thermocline layer, a DO/temperature probe was lowered and the marked change in water temperature was used to determine where the thermocline began at each site (with sufficient depth). The thermocline in 2021 was approximately 17 feet with a generally uniform value across the lake throughout the summer.

Dissolved Oxygen (mg/L):

Date	Depth (ft.)	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7
2-Jul	5	10.59	10.89	9.89	11	9.43	11.12	9.7
2-Jul	10	10.75	11.05	8.96	10.87	9.35	10.59	9.62
2-Jul	15	10.3	11.19	9.11	9.26	8.18	6.87	9.71
2-Jul	20	9.65	9.33	9.13	7.98			8.8
6-Jul	5	10.86	11.21	11.85	11.8	11.68	12.86	11.7
6-Jul	10	11.9	10.88	11.49	11.22	11.23	11.47	10.8
6-Jul	15	10.83	11.8	11.36	11.32	8.26	9.7	9.87
6-Jul	20	10.19	9.77					
13-Jul	5	9.22	9.37	10.09	9.17	10.11	9.98	10.71
13-Jul	10	9.55	9.26	9.96	8.8	9.86	9.42	10.12
13-Jul	15	9.08	8.8	9.25	8.15		9.63	8.56
13-Jul	20	6.75	7.13	5.33	4.43		3.69	4.2
10-Aug	5	8.05	7.99	8.33	8.2	8.67	8.22	7.8
10-Aug	10	7.9	8.03	5.46	7.95	8.71	8.22	8.13
10-Aug	15	7.26	7.56	0.27	6.88		6.49	5.93
10-Aug	20	4.19	4.1	0.22	4.43		0.89	0.23

Table 2: Dissolved Oxygen

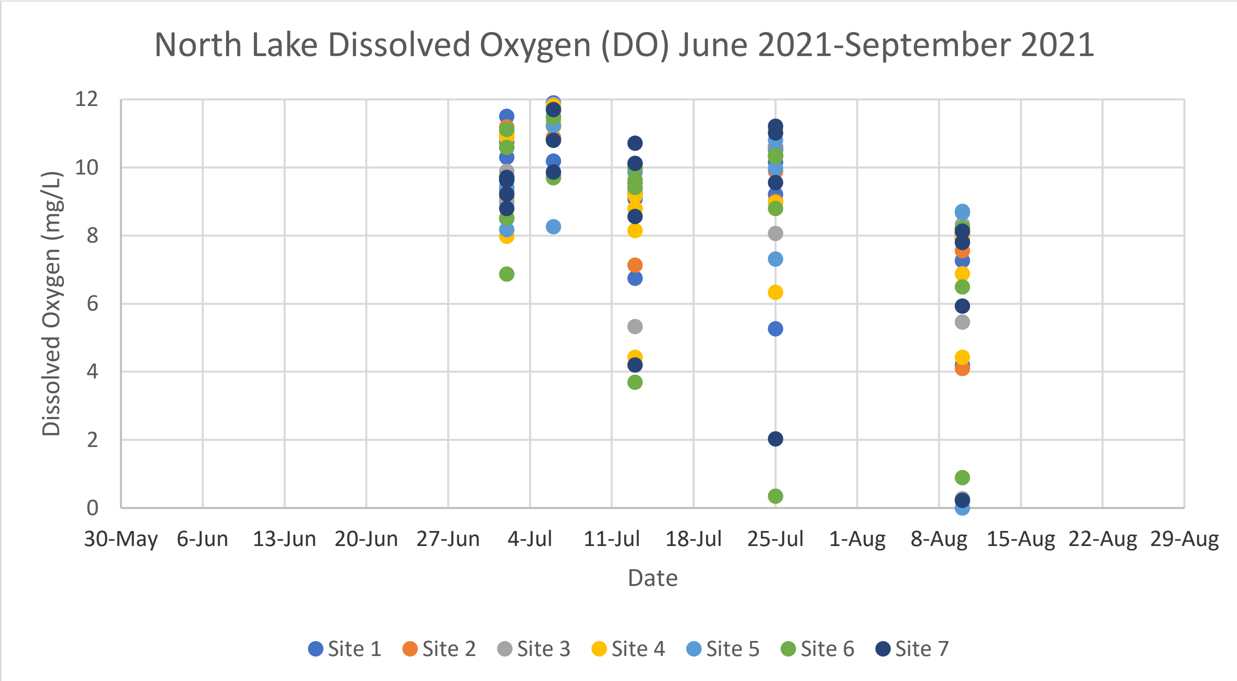


Figure 2: Dissolved Oxygen

Temperature (F)

Date	Depth (ft)	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7
2-Jul	5	74.7	75.2	74.8	74.7	74.1	74.5	75.4
2-Jul	10	74.3	74.8	61.7	74.5	73.8	73.9	74.8
2-Jul	15	69.6	67.6	72	71.2	70.9	70	72
2-Jul	20	57.9	57.6	72	56.5			59.2
6-Jul	5	81.1	79	78.6	83	81.9	79.7	78.2
6-Jul	10	78.9	78.3	78	79.3	80.6	78.2	77.8
6-Jul	15	72.4	72	77.1	78.9	76.2	74.5	74.1
6-Jul	20	60.7	59.7	70.5				
13-Jul	5	73.9	73.3	73.8	73.2	73.8	73.4	74.7
13-Jul	10	73.4	73.25	73.6	73	73.6	73.2	73.9
13-Jul	15	73.2	73	73.4	72.9		72.3	73.4
13-Jul	20	59.5	59.5	61.5	61.9		61.9	64.6
10-Aug	5	76.3	76.3	75.9	76.5	76.1	76	75.7
10-Aug	10	76.3	76.2	74.5	76.3	76	75.9	75.6
10-Aug	15	75.6	76.1	65.8	76.1		65.8	75.3
10-Aug	20	64.6	64.4	66.3	67.2		66.3	67

Table 3: Water Temperature

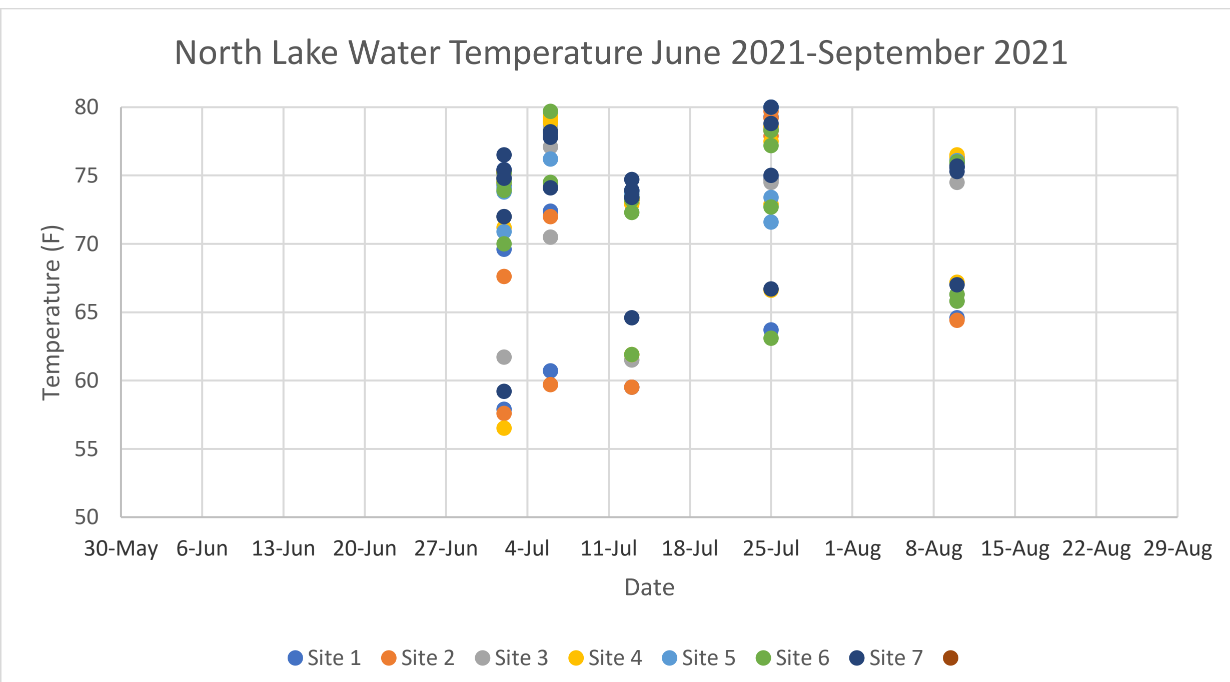


Figure 3: Water Temperature

Total Suspended Solids (TSS)
Attention is drawn to the North Lake basin primary inlets of Mason Creek (Site 6) and the Oconomowoc River (Site 5).

TSS

Date	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7
27-Jun	2.2	3.2	2	2.4	2	2	2
29-Jun	2.2	2	2	2.2	2	2	2
4-Jul	3.8	4.6	3.4	3.2	2.8	3.2	3.4
6-Jul	2	3	3.4	2.2	3.2	4.4	3.4
10-Jul	3	2	2.8	2	2.4	4.6	5.4
13-Jul	2	2	3.6	2	2.2	2.8	2
18-Jul	4	3.4	5.8	2.2	5.6	4.8	4
20-Jul	2.4	2.6	4.8	2.8	5	6.6	3
25-Jul	2	2.8	2	2.2	2.4	2	2.2
27-Jul	2	2	2	2	2	2	2
1-Aug	3	2	2	2.2	2.2	2	2
3-Aug	2	2	2	2	2.4	2.6	2
8-Aug	2	2	3.6	2	3.8	3.4	3.2
10-Aug	2	2	3	2	3	3	2.8
22-Aug	2.8	2	2.8	2	2.4	2.2	2.2
24-Aug	2	2	2.2	2	2.2	2.6	2

Table 4: Total Suspended Solids (TSS)

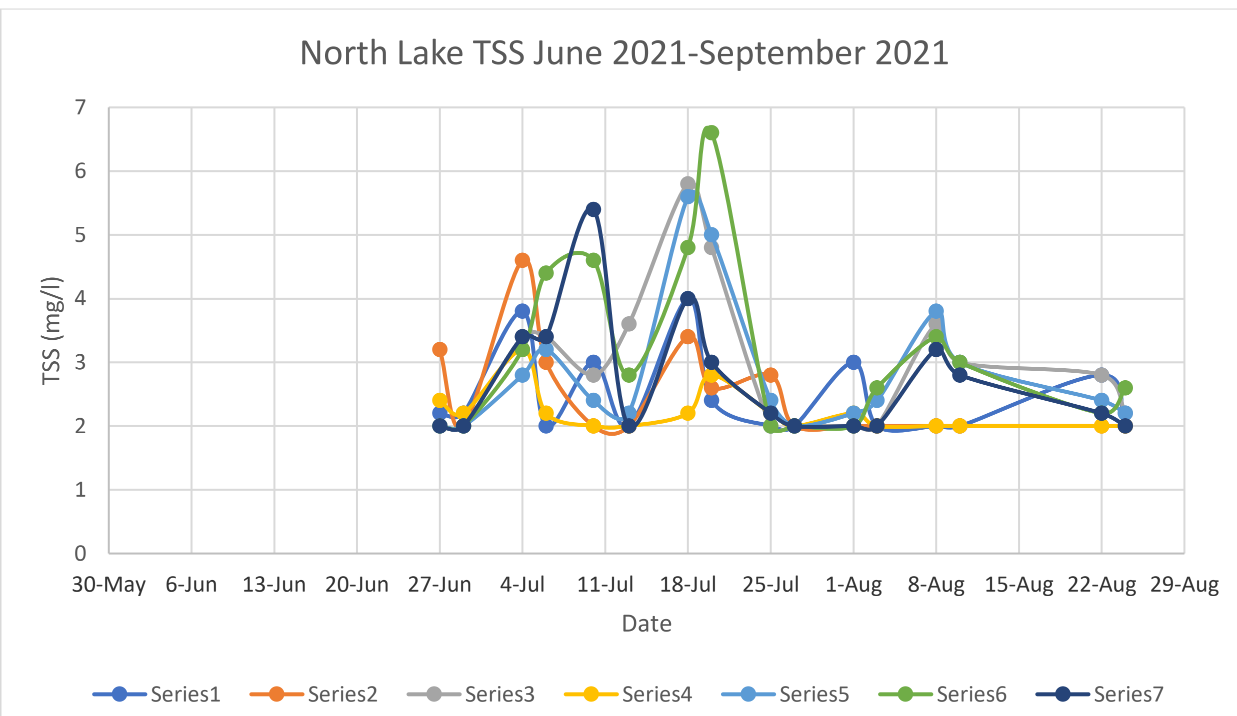


Figure 4: Total Suspended Solids (TSS)

Water Clarity

Standard measurements of water clarity were gathered with Secchi disk methods at all 7 sites twice weekly during 10 weeks in both Lake basins.

A small decrease in water clarity occurred at Site 4 near the channel during channel dredging operations (July 26-Aug 3) and recovery was noted within 1 week in this area.

Secchi Depths:

Date	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7
3-Jun		6	7	6.5	10.5	12	16.5
27-Jun	9.5	9	10	8.5	8	10	7
2-Jul	9	10	11	9.5	9.5	8	10
6-Jul	7.5	7.5	7	7.5	6	6	7
20-Jul	**9**	9	6	8	6	5	6
27-Jul	**9**	8.5	12	9	10	11	10
1-Aug	8	8	10	7.5	9	9	11
3-Aug	11	10	9	9	8	8	9
10-Aug	12	12	8	12	7	7	9
24-Aug	10	10	7.5	11	8	8	8

Table 5: Secchi Depths

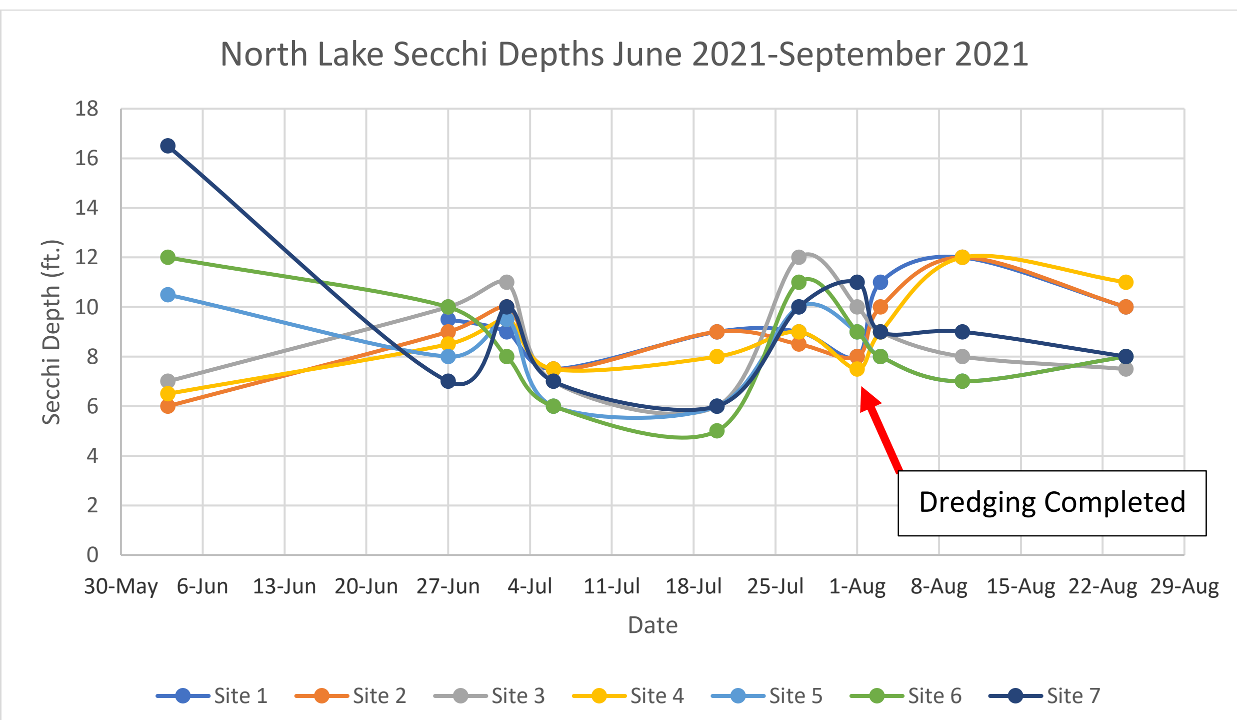
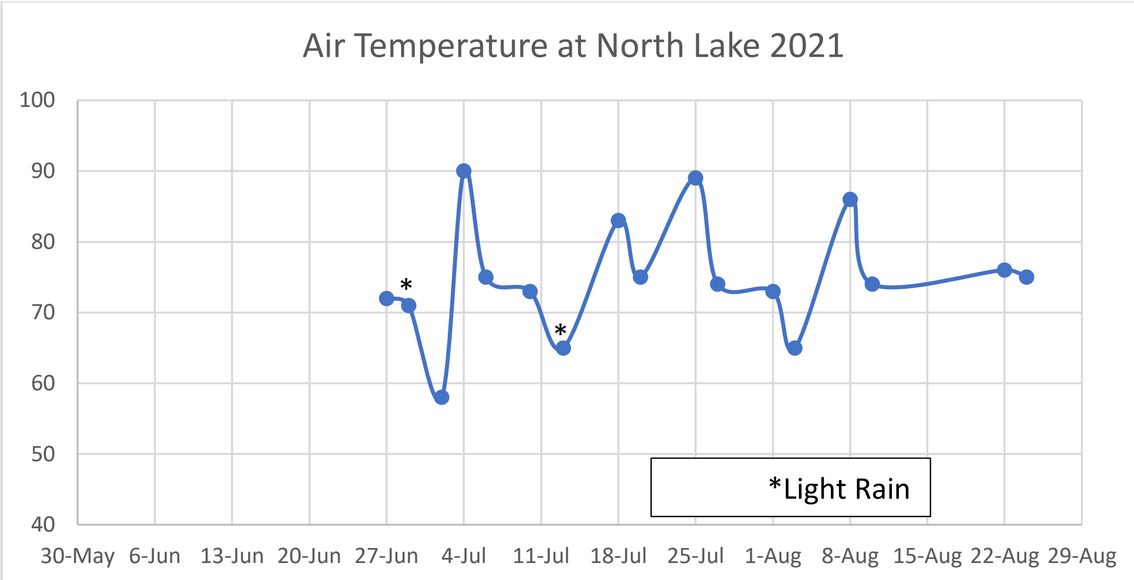
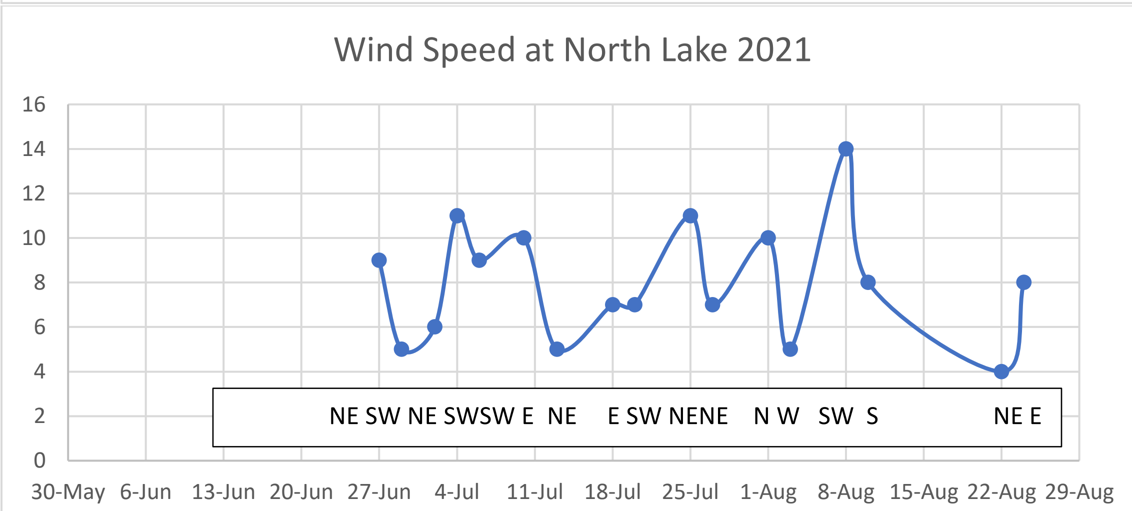
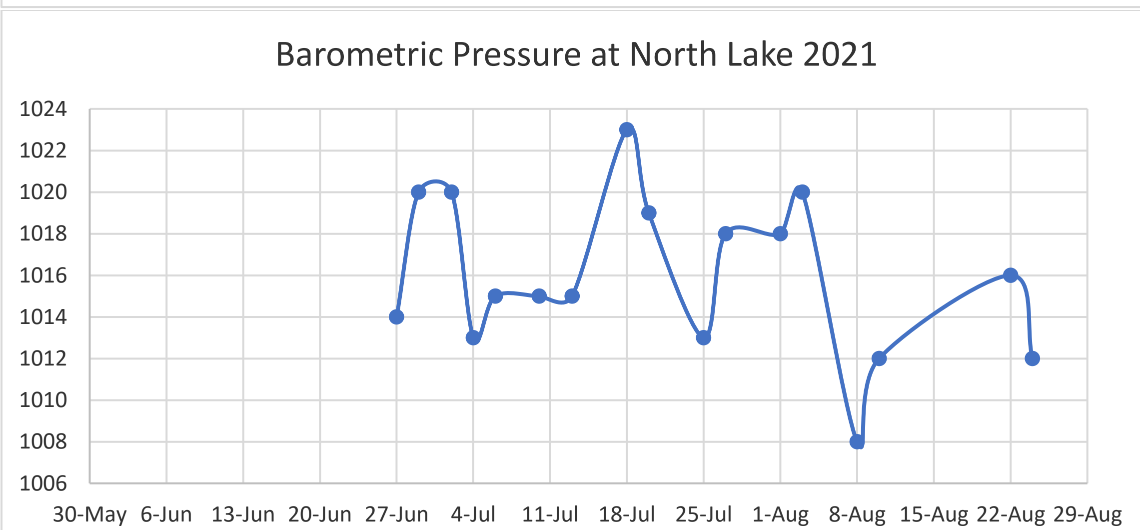


Figure 5: Secchi disk measurements


Air Temperature at North Lake 2021
100
90
80
70
60
50
40
30-May 6-Jun 13-Jun 20-Jun 27-Jun 4-Jul 11-Jul 18-Jul 25-Jul 1-Aug 8-Aug 15-Aug 22-Aug 29-Aug
*
*
*Light Rain


Wind Speed at North Lake 2021
16
14
12
10
8
6
4
2
0
NE SW NE SWSW E NE E SW NENE N W SW S NE E
30-May 6-Jun 13-Jun 20-Jun 27-Jun 4-Jul 11-Jul 18-Jul 25-Jul 1-Aug 8-Aug 15-Aug 22-Aug 29-Aug


Barometric Pressure at North Lake 2021
1024
1022
1020
1018
1016
1014
1012
1010
1008
1006
30-May 6-Jun 13-Jun 20-Jun 27-Jun 4-Jul 11-Jul 18-Jul 25-Jul 1-Aug 8-Aug 15-Aug 22-Aug 29-Aug

2022 NLMD Water Quality Sampling - planned schedule (subject to change due to weather or rain events)

Day	Date	Time	Lead	Assistant
	May			
Sun	5/1/2022	4pm		
W	5/4/2022	9am		
Sat	5/7/2022	4pm	cjl	
W	5/11/2022	9am		
Sun	5/15/2022	4pm	cjl	
T	5/17/2022	4pm	cjl	
Sun	5/22/2022	4pm	cjl	
T	5/24/2022	4pm	cjl	
Sun- Mem Day	5/29/2022	4pm	cjl	
T	5/30/2022	4pm	cjl	
	June			
Sun	6/5/2022	4pm	cjl	
T	6/7/2022	4pm	cjl	
Sun	6/12/2022	4pm	cjl	
T	6/14/2022	4pm	cjl	
Sun	6/19/2022	4pm	cjl	
T	6/21/2022	4pm	cjl	
Sun	6/26/2022	4pm	cjl	
T	6/28/2022	4pm	cjl	

2022 NLMD Water Quality Sampling - planned schedule (subject to change due to weather or rain events)

Day	Date	Time	Lead	Assistant
	July			
Sun - 4th July Wknd	7/3/2022	4pm	cjl	
T	7/5/2022	4pm	cjl	
Sun	7/10/2022	4pm	cjl	
T	7/12/2022	4pm	cjl	
Sun	7/17/2022	4pm	cjl	
T	7/19/2022	4pm	cjl	
Sun	7/24/2022	4pm	cjl	
T	7/26/2022	4pm	cjl	
Sun	7/31/2022	4pm	cjl	
	August			
T	8/2/2022	4pm	cjl	
Sun	8/7/2022	4pm	cjl	
T	8/9/2022	4pm	cjl	
Sun	8/14/2022	4pm	cjl	
T	8/16/2022	4pm	cjl	
Sun	8/21/2022	4pm	cjl	
T	8/23/2022	4pm	cjl	
Sun	8/28/2022	4pm	cjl	
T	8/30/2022	4pm	cjl	
	Sept			
Sun- Labor Day	9/4/2022	4pm	cjl	
T	9/6/2022	4pm	cjl	
Sun	9/11/2022	4pm	cjl	
T	9/13/2022	4pm	cjl	

Appendix D
Methodologies and Equipment Summary
Phase 2 Water Quality and Wave Propagation Study
NLMD

Powered Vessels

1. 2004 16' Boston Whaler with 40 HP Mercury Outboard Engine (standard depth lower unit)
2. 2001 20' Hurricane Deck Boat with 125 HP Mercury Outboard Engine (standard depth lower unit)
3. 2020 Super Aire Nautique Wake Board Boat with 450 HP Inboard Engine, 6,000 lb ballast capacity and adjustable electronic bow /stern angle options
4. 2014 Wake Board Boat (Sport Nautique) with 400 HP Inboard Engine, 4100 lb ballast capacity and adjustable bow/stern angle options
5. 1991 20' Sun Cruiser Pontoon Boat (twin aluminum pontoons) with Yamaha 25 HP (4-stroke) Outboard Engine (standard depth lower unit)
6. 2004 SeaDoo Personal Water Craft (PWC) Model GTX 4TE (supercharged)

Measurement Equipment

1. Terra Vigilis ©Extendable Propwash Measuring System with extender arms and camera system systems at 5 ft, 10 ft, 15 ft, 20 ft and 25 ft staggered depths
2. YSI Pro20 DO and Temp Probe (with digital memory core)
3. Standard Secchi Disks
4. 12' measurement stick model
5. Laser distance gun "Laserlink" RH2 (vessel distances)
6. Lowrance X100C/D Depth Sonar, Temp and Speed Unit
7. Terra Vigilis ©AQUA subsurface measurement system UAV
8. FiFish QY6 ROV with Omnidirectional Camera and Video Goggles

Laboratory Procedures (refrigerated protocols per laboratory specs)

1. TSS samples (surface dips)
2. DO samples (staggered measurements at: surface, 5 ft, 10 ft, 15 ft, 20 ft)
3. TP samples (surface dips)

Drone Equipment

1. DJI Mavic Mini 3 Axis Tilt roll (Quadcopter with camera, ½.3' CMOS, FOV:83, aperture f2.8, range 1m to infinity, Effective Pixels 12M)
2. DJI Phantom III (Quadcopter with camera, as above)
3. FiFish QY SEA 6 ROV with Omni-directional Cameras/LED high power lights
4. DGI Video Goggles

Wave Height Measure Procedures

Procedure 1. The Terra Vigilis Team (TVT) used a sonic sensor attached to a Mavic Pro aerial drone platform. The drone was calibrated from the dock surface prior to flight (constituting a baseline). The drone was flown approximately 3 meters above the surface. As wave actions passed below the sonic sensor a digital measurement was taken.

Procedure 2. The TVT recorded aerial drone video using a high-resolution camera in its nadir position. Images from the videos were extracted and converted to displacement maps. A wire frame computer model was created. The 3D wireframe models were scaled to match known measurements from the images. This photogrammetry procedure was used for the wave heights measurements during sampling. Both wave heights and frequencies were digitally captured.

Procedure 3. The TVT placed an engineered tripod into the water at approximately 30 ft from the shoreline and 6 ft from the dockside. The tripod placement was weighted to alleviate response to wave movement during measurement intervals. A 360-degree camera was attached to the tripod. The camera was placed at 2 ft above the water's surface. The camera video was continuously recorded. All data was time coded and archived. Camera angles included capture of the 12 ft measuring ruler and rod (perpendicular to one another). Post-production analyses included stamped time codes and heights to provide wave frequency.

Procedure 4. The TVT placed an engineered 30' aluminum propwash measuring device with cameras and fibre optic wands at staggered depths of 5', 10', 15', 20' and 25'. Downwash impacts were captured with digital video camera footage at vessel startups and wake surf mode passes within 5' of the anchored device.

Imagery Filtering Processes

Plume Imaging LOC8 software. Adobe Premier software