

Waves, Wind, Watercraft, and Water Clarity A Study of Sediment Resuspension in Clark Lake



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Table of Contents

Table of Contents	iii
List of Figures.....	iv
Summary	1
Introduction	2
Water Clarity	3
Marl Formation / Sediment Composition	3
Marl Formation.....	3
Sediment Particle Size and Turbidity.....	4
Wind, Turbidity, and Secchi Disc Monitoring.....	12
Recreational Watercraft Experiments.....	21
Wave theory	29
Mixing and Redistribution.....	29
Conceptual Model of Marl in the Lake	30
Conclusions and Recommendations.....	36
References.....	38

Cover Photo: Taken by Justin Barrick on September 16, 2006. The lake was in a very turbulent and turbid state with a strong southwest wind.

List of Figures

Figure 1 Marl on the bottom of Clark Lake.....	4
Figure 2 Sediment particle size separation in the lab.	5
Figure 3 Percent of sediment particles in different particle size classes around the lake based on all five particle size classes.	6
Figure 4 Percent of sediment particles in the four smaller particle size classes..	7
Figure 5 Distribution of sediment particles in the three smallest particle classes.	8
Figure 6 Percent of sediment finer than 250 μm at different lake depths.	9
Figure 7 Total suspended solids (TSS) measured 10 cm below the water surface. The corresponding particle size of spherical particles that would settle 10 cm based on Stoke's Law.	10
Figure 8 Change in turbidity over time measured in the upper 10 cm after mixing approximately 100 g/L of sediment from different locations in the lake. Turbidity expressed as NTU per initial gram of sediment. Sample depths of the different sediment and best fit log-linear lines shown.	11
Figure 9 Relationship between 100 minute turbidity measurements (expressed as NTU per original gram of sediment) and the fraction of the sediment that is in the silt/clay particle size fraction (passing the 270 sieve).	11
Figure 10 Recorded direction of wind from the weather station at Whitefish Dunes State Park.	12
Figure 11 Percentage of recorded wind directions.....	12
Figure 12 Average monthly depth of Secchi measurements in Clark Lake, 2005 and 2006.	14
Figure 13 Average, minimum, and maximum Secchi disc measurements in Clark Lake, 1986 – 2006.....	14
Figure 14 Turbidity vs. wind direction and speed, June 1 – July 1, 2006.....	15
Figure 15 Turbidity vs. wind direction and speed, July 1 – Aug 1, 2006.....	16
Figure 16 Turbidity vs. wind direction and speed, Aug 1 – Sept 1, 2006.....	16
Figure 17 Turbidity vs. wind direction and speed, Sept 1 – Oct 1, 2006.....	17
Figure 18 Turbidity vs. wind direction and speed, Oct 1 – Nov 1, 2006.	17
Figure 19 Comparison of Secchi depth monitoring at all locations with the continuous turbidity recorded near the west boat landing. Turbidity monitoring began June 1.....	19
Figure 20 Turbidity, wind speed, boat count and Secchi depth measured at the deep hole.....	19
Figure 21 Turbidity, wind speed, boat count, and Secchi depth measured at the East Bay site.	20
Figure 22 Turbidity, wind speed, boat count, and Secchi depth measured at the Mueller's Point site.....	20
Figure 23 Turbidity, wind speed, boat count, and Secchi depth measured at the Hinnenthal site.	21
Figure 24 Schematic of experimental boating lane layout.	22
Figure 25 Jet-ski taking off in boating experiment.....	23
Figure 26 Turbidity and TSS taken at 4 feet/startup speed.....	24

Figure 27 Turbidity and TSS taken at 4 feet/medium speed	24
Figure 28 Turbidity and TSS taken at 4 feet/high speed.....	25
Figure 29 Turbidity and TSS taken at 6 feet/startup speed	25
Figure 30 Turbidity and TSS taken at 6 feet/medium speed	26
Figure 31 Turbidity and TSS taken at 4 feet/high speed.....	26
Figure 32 TSS measured at 0 and 10 minute interval following first pass of watercraft.	28
Figure 33 Percent of fine sediment (<250 um) vs. measured depth of sediment sampling locations. Included are all 3 boat speeds for the 160 hp inboard- outboard showing a decreasing ability to resuspend sediment from the 4 to 6 ft depths.	28
Figure 34 Modeled resuspension/depositional areas - NE wind at 10 mph.	31
Figure 35 Modeled resuspension/depositional areas - NE wind at 15 mph.	32
Figure 36 Modeled resuspension/depositional areas - NW wind at 10 mph.....	32
Figure 37 Modeled resuspension/depositional areas - NW wind at 15 mph.....	33
Figure 38 Modeled resuspension/depositional areas - SE wind at 10 mph.	33
Figure 39 Modeled resuspension/depositional areas - SE wind at 15 mph.	34
Figure 40 Modeled resuspension/depositional areas - SW wind at 10 mph.....	34
Figure 41 Modeled resuspension/depositional areas - SW wind at 15 mph.....	35

Summary

While it is clear that the resuspension of sediments in a lake increases turbidity and reduces water clarity, it is not always clear what controls this resuspension. This study combined boating experiments and continuous turbidity measurements with applied wave theory and sediment analysis to evaluate the mechanisms contributing to the resuspension of sediment in Clark Lake in Door County.

Wind and watercraft produce waves that contribute to sediment resuspension in the lake. The finer sediments of Clark Lake can remain suspended in the water for many hours. They appear to be the major contribution to reduced water clarity. Sediment particle size distribution around the lake was consistent with redistribution and settling influenced by wind and wave motion. Finer sediment was concentrated in deeper areas or areas with a short fetch in predominate wind directions. Experiments also showed that boating increased sediment resuspension depends on both engine size and water depth. Water turbidity increased gradually over the summer consistent with an increased mobilization of finer sediment. Increases in early summer coincided with periods of boating and in later summer with periods of higher wind.

Once sediment is resuspended in the lake, it can settle in a different location. Even if the sediments are randomly distributed across the lake, over time, it is anticipated that finer, more easily suspended sediment will eventually become concentrated in areas where it is less likely to be resuspended. Once sediment settles in these "deposition" areas, it is less likely to be resuspended, whereas sediment that settles elsewhere has a high likelihood of being resuspended. Deeper parts of the lake, for example, will likely become areas of finer sediment accumulation. Wind and boats are unlikely to resuspend sediment that has deposited in deeper portions of the lake. Boating can resuspend sediment that settles in areas less susceptible to wind resuspension. This resuspended sediment may then re-settle in areas likely to be impacted by wind resuspension and can then be resuspended many times before it finally settles into deeper stable areas. As a result, the sediment suspended in the lake at any time reflects not only the characteristics of that resuspension event, but also the pattern of sediment redistribution resulting from previous boating or wind. As a result, increased resuspension by boating is likely to increase summer turbidity in two ways: 1) in the short term by a localized immediate increase in turbidity in shallower parts of the lake where the boat provides sufficient energy to lift sediment particles; and 2) over the long term by transferring material from areas of deposition to areas of potential future resuspension. In short, the impact of boating on water clarity may be more subtle when it increases the amount of sediment available for wind.

Introduction

Clark Lake is an 868 acre lake located in the Towns of Jacksonport and Sevastopol. It is a hardwater, impounded drainage lake that receives water from direct precipitation, groundwater, and stream flow and drains to Lake Michigan. Clark Lake is in Door County and on some days it is a heavily used body of water. It is surrounded by approximately 300 permanent and seasonal homes and the south shore of the lake includes Whitefish Dunes State Park.

Clark Lake has a maximum depth of 25 feet, with a mean depth of 7 feet. There are approximately seven miles of shoreline. Two public boat ramps are present on the lake. Common fish species include northern pike, walleye, smallmouth bass, and panfish, with largemouth bass and trout also present (Hogler, 2005).

Clark Lake has an 11,200 acre watershed. Lost Lake is a 91 acre lake at the headwater of Logan Creek. Much of the watershed drains to Logan Creek which feeds Clark Lake. Groundwater also contributes to Logan Creek and Clark Lake. Stream flow in Logan Creek varies substantially throughout the year. Land use in the Clark Lake watershed is dominated by dairy agriculture, but some of the watershed is being converted to residential developments, a trend which has been continuing over the past decade.

Clark Lake can be a relatively “cloudy” or turbid lake at certain times of the year. This turbidity appears to reflect the suspension of bottom sediments in the lake. An investigation of the lake turbidity was part of the UWSP Clark Lake study in 2005 and 2006. The purpose of this study was to increase our understanding of the water clarity of Clark Lake. Different sources of sediment resuspension were evaluated to determine their importance to lake water clarity and turbidity. In the sections below, we provide background information on sediment resuspension and Clark Lake sediments and describe a series of experiments exploring how sediment is resuspended in the lake.

Water Clarity

Suspended matter in water causes light to be reflected and leads to a “cloudy” appearance to the water. This reduces light transmission in the water and is characterized here as reduced water clarity. Water clarity is important because it impacts light passage to the bottom and influences the growth of aquatic plants. Direct effects of increased suspended sediment include interference with invertebrate growth and modification of the lake bottom which may alter habitat for invertebrates and fish.

Water clarity is related to light absorption and the quantity of suspended material in the water. The relationship between the three can be complex (Davies-Colley and Smith, 2001). In this report, most of the water clarity measurements used light scattering or turbidity. This is a measure of the quantity of light scattered by reflection. The quantity of light scattered by a particle depends on the size and shape of the particle. Laboratory measurements of turbidity measure the quantity of light that is scattered at a 90 degree angle from the light direction. The quantity of light scattered is compared to that in standards made of formazine. Results are reported in nephelometric turbidity units or NTU. Other measurements used the Secchi disc, a black and white disk that is lowered into the water until it is no longer visible and then retrieved until it can be seen again. The Secchi disc is a measure of visual water clarity. The third measurement used was the quantity of particulate solids in the water sample. This is determined by filtering the sample and then determining the mass of solids per volume of water.

Marl Formation / Sediment Composition

The principal sources of reduced water clarity and turbidity in a lake are suspended sediment, algae, and water color. Measurements of chlorophyll *a* and phosphorus in Clark Lake suggest algal abundance is usually low and appears that the primary source of reduced water clarity is suspended lake sediment. This sediment includes all the solids that settle to the bottom of the lake, but in Clark Lake the finer portion of the sediment includes silt, clay and organic matter from the watershed and settling plant and animal fragments. In Clark Lake it appears to be dominated by calcium carbonate (CaCO₃) or marl that forms in the lake and settles to the lake bottom.

Marl Formation

Marl is formed when the calcium concentration and pH of the water is high enough to form solid CaCO₃. The groundwater entering Clark Lake has high calcium concentrations because it passes through the calcium-rich (dolomitic) bedrock. When groundwater enters the lake, CaCO₃ can form when the pH of the water increases. The pH increases in the lake as the carbon dioxide

content equilibrates with lower atmospheric levels or plants and algae withdraw carbon dioxide and bicarbonate from the water. The result is the formation of marl and a decrease in calcium concentration of the water (Figure 1).



Figure 1 Marl on the bottom of Clark Lake

We can estimate the annual quantity of marl formed based on our measurements of calcium entering and leaving the lake, and estimates of water flow. Assuming an average calcium hardness difference of approximately 40 mg/L as CaCO_3 between the inflowing groundwater and the outflow from the lake, and an annual stream flow of almost 400 million cubic feet/year, we estimate an annual marl formation of approximately 450 kg. If that annual quantity of marl would be uniformly distributed across the lake, it is approximately 130 g of marl/m² of the lake surface/year. The water content of sediments collected from several regions in the lake was 30-70% water. Assuming the average sediment water content is 50% and the marl density is 2.6 g/cm³, we estimate an annual marl formation depth is equivalent to approximately 0.1 mm across the lake per year. While that is a relatively small amount of marl on an annual basis, after 10,000 years of marl formation, that would be equivalent to 1 m of marl across the entire lake. Of course, not all of the marl that formed in the lake is still in the lake. Resuspension of marl, particularly near the outlet, leads to marl movement through the outflow and loss from the lake.

Sediment Particle Size and Turbidity

Experiments were performed to examine the variations in sediment particle size and light scattering and how that varies around the lake. Surface sediment was sampled and separated into different particle size fractions using

sieves. Settling experiments were also performed to determine how turbidity varies after mixing in different portions of the lake.

Sediment particle size was determined by retention on different sieves. Sieve sizes of 35 (500 μm), 60 (250 μm), 140 (106 μm), and 270 (53 μm) were used for the separation. After sieving, the sediment captured on the sieves was determined by drying overnight at 105°C and weighing the following day. The distribution of particles sizes at different locations in the lake was expressed as the fraction of the sediment within the different particles sizes. The results give us a spatial pattern of sediment sizes and are useful in understanding how sediment is distributed within Clark Lake.



Figure 2 Sediment particle size separation in the lab.

To explore how sediment particle sizes are distributed in the lake, particle size measurements were made on the sediment samples collected throughout the lake. The results were presented as the percent of each particle size at each location. The percentage distribution was also recalculated for progressively smaller groups of particles by basing the calculations on only the finer particles. The results of these separations are shown in Figures 3, 4 and 5. Figure 3 shows the distribution among all five size fractions. Many of the shallow sites had particle size distributions dominated by particles in the medium sand category ($> 500 \mu\text{m}$) as shown in purple. This trend is more pronounced for the four and three particle size separations in Figure 4 and Figure 5. In particular, the south and north/north east sides of the lake have particle size distributions dominated by the coarser particles. The opposite was found in the deeper sites where the sediment is dominated by particle sizes of fine sand (53-105 μm) and clay/silt ($< 53 \mu\text{m}$) particle sizes shown in yellow and red, respectively.

The results suggest a variation in dominant particle size with depth and location in the lake. Because particle size controls both resuspension and settling this is not surprising. Deeper portions of the lake are less likely to experience frequent resuspension because wave height may be too small to reach the bottom in those areas. This was confirmed by field results. Figure 6 shows the change in percentage of fine sediments with depth. It appears that, in general, deeper areas of the lake accumulate finer sediments and shallower areas are more likely to experience an erosion or loss of finer sediments.

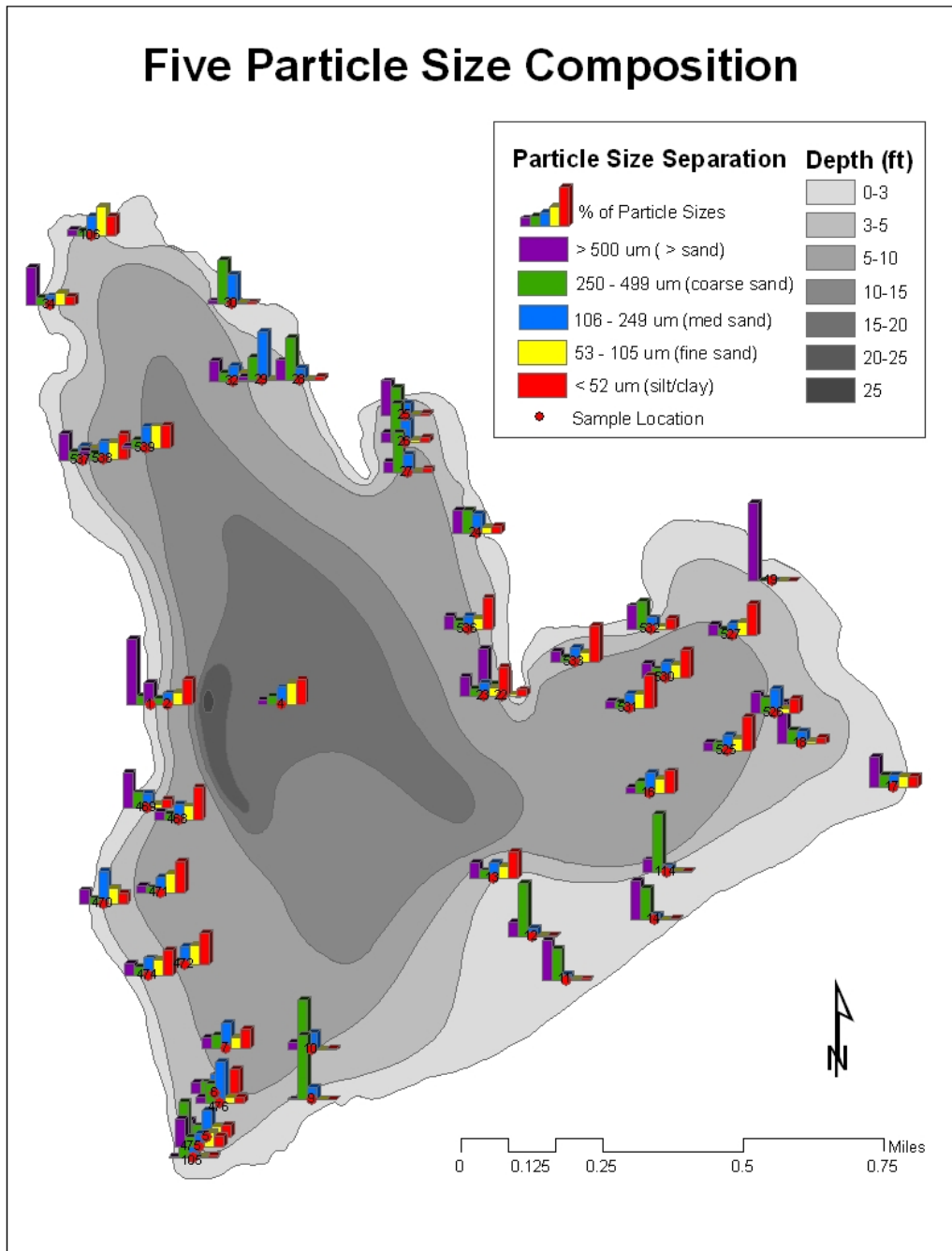


Figure 3 Percent of sediment particles in different particle size classes around the lake based on all five five particle size classes.

Four Particle Size Composition

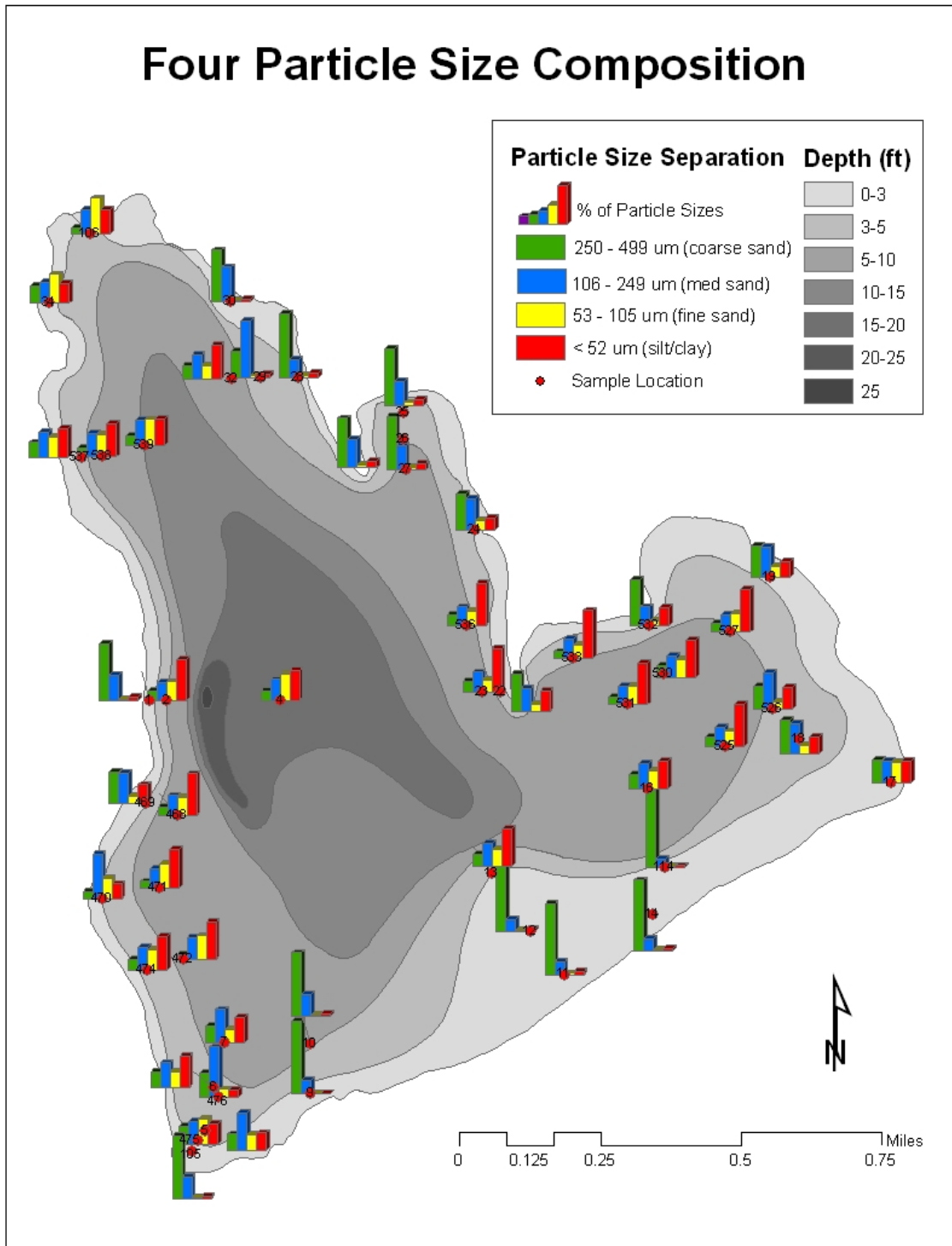


Figure 4 Percent of sediment particles in the four smaller particle size classes.

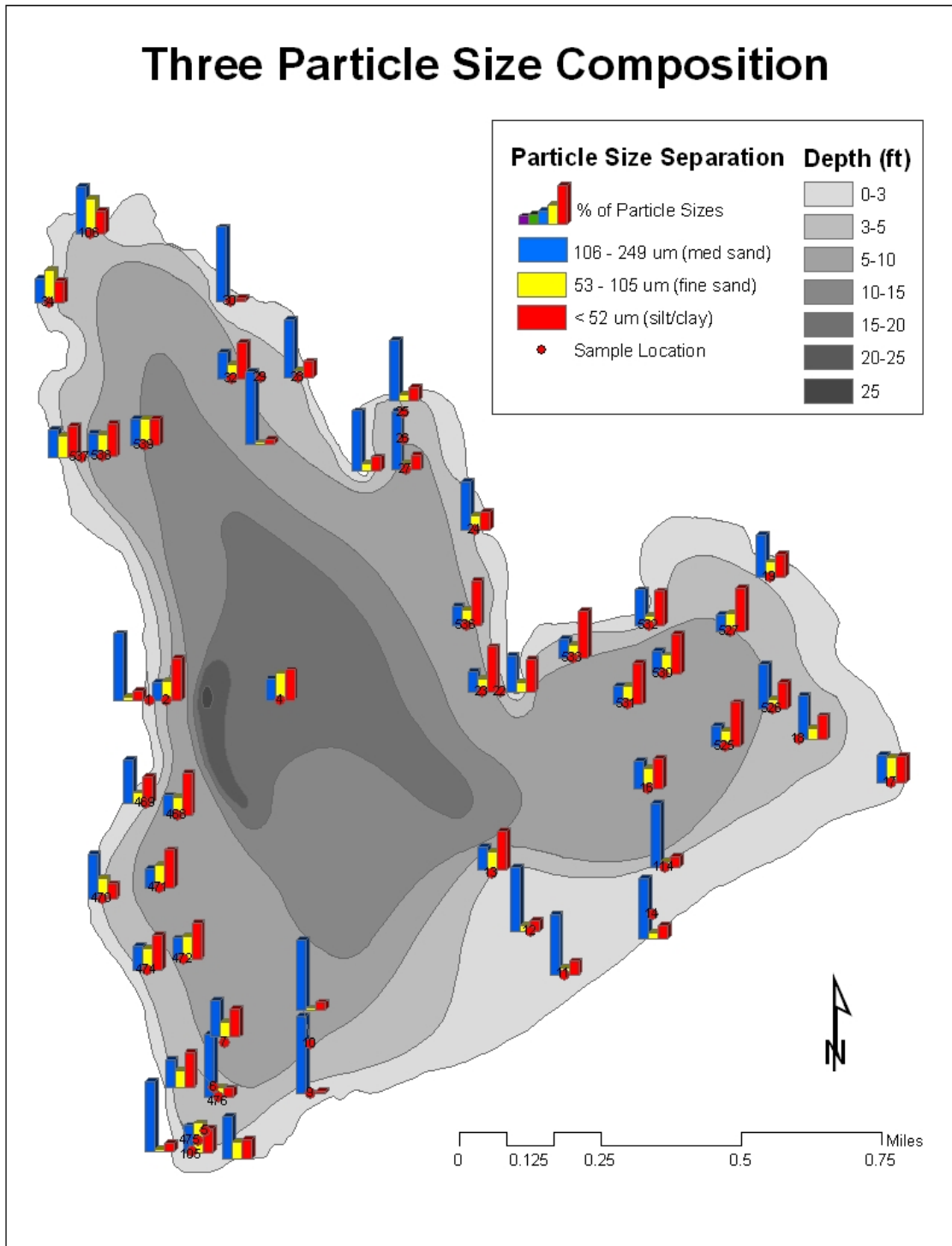


Figure 5 Distribution of sediment particles in the three smallest particle classes.

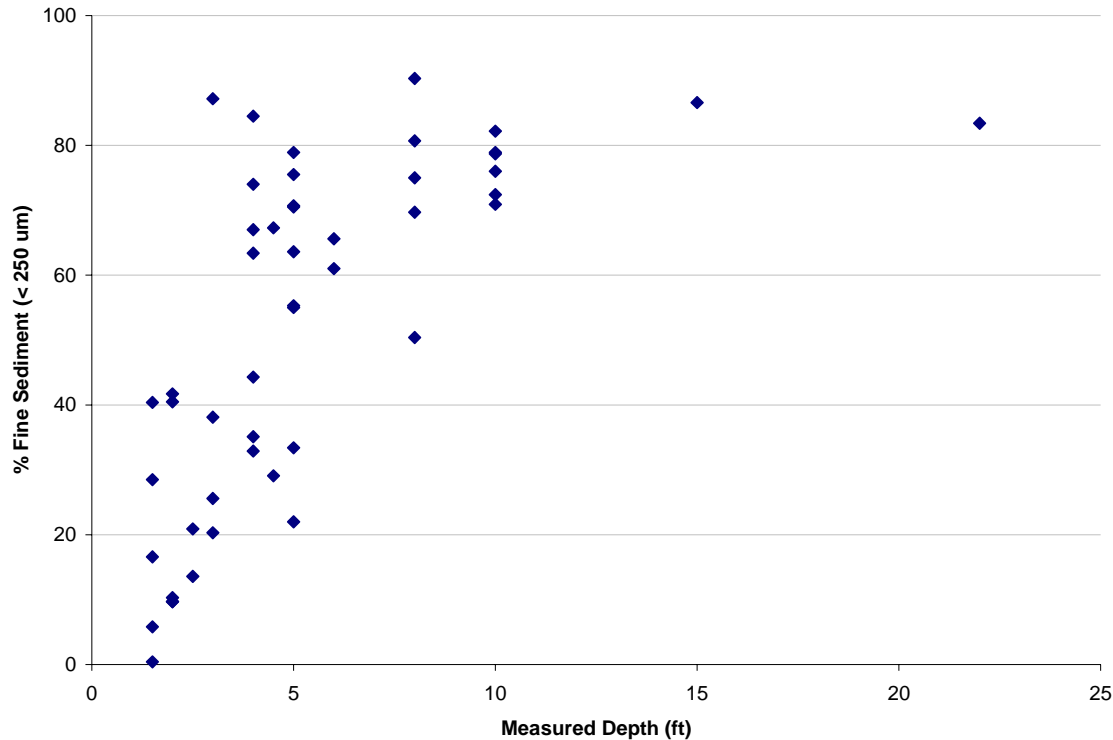


Figure 6 Percent of sediment finer than 250 μm at different lake depths.

Water clarity in the lake is influenced by the quantity and size of particles that remain suspended in the water for relatively long periods of time. We can estimate the relationship between settling rate and particle size using Stoke’s Law and assuming for simplicity that the sediment particles are spherical with a density similar to calcium carbonate. The settling rate of the particles decreases rapidly as the particle size decreases. For example, a 50 micron (0.05 mm) particle will settle 2 m in approximately 13 minutes, but a 10 micron particle (one-fifth the size) will take approximately five hours to settle the same distance (approximately twenty-five times as long). These calculations suggest that turbidity that persists in the lake over several hours is likely to be dominated by the very small particle size fractions because it takes them so long to settle.

To better understand how turbidity can be generated in different portions of the lake and how the finer sediment is distributed, sediment samples from different portions of the lake were mixed and allowed to settle. In Figure 7, the suspended solids concentration over time is shown for three samples. In this experiment, only a small quantity of the sediment remained in suspension after ten or fifteen minutes (measured 10 cm from the water surface), suggesting most of the sediment particles were larger than 10 microns (0.01 mm). The results in Figure 7 also show a difference in the distribution of finer sediments in different portions of the lake. Consistent with results presented earlier, the deeper portions of the lake have a larger fraction of the sediment in

finer size classes. Sediment still in suspension after 15 minutes would correspond to particle diameters less than 10 micron (0.01 mm). That contrasts with the sample that was collected from the south shore that had a much smaller percentage of the particles in that very fine sediment fraction.

To link the observations on particle size and turbidity, experiments were performed to examine turbidity remaining in the water after mixing. Samples from different portions of the lake were mixed and then allowed to settle. Turbidity was measured over time approximately 10 cm from the top of the water. Figure 8 shows the variation in turbidity expressed as NTU per gram of initial sediment over time. Similar to variations in sediment particle size, there is a relationship between location in the lake and turbidity remaining at different times. In particular, shallow locations in the lake that have fewer finer particle sizes have less turbidity after mixing than deeper portions of the lake. Figure 9 shows turbidity in the water is related to the fraction of the particles that are in the finer sediment sizes, as would be expected.

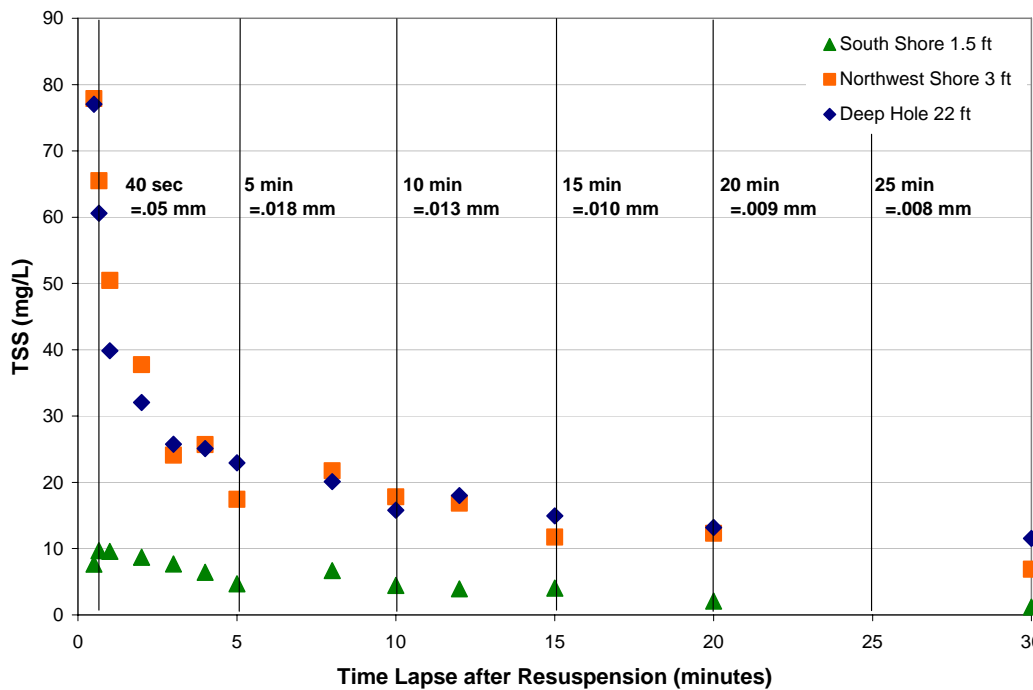


Figure 7 Total suspended solids (TSS) measured 10 cm below the water surface. The corresponding particle size of spherical particles that would settle 10 cm based on Stoke’s Law.

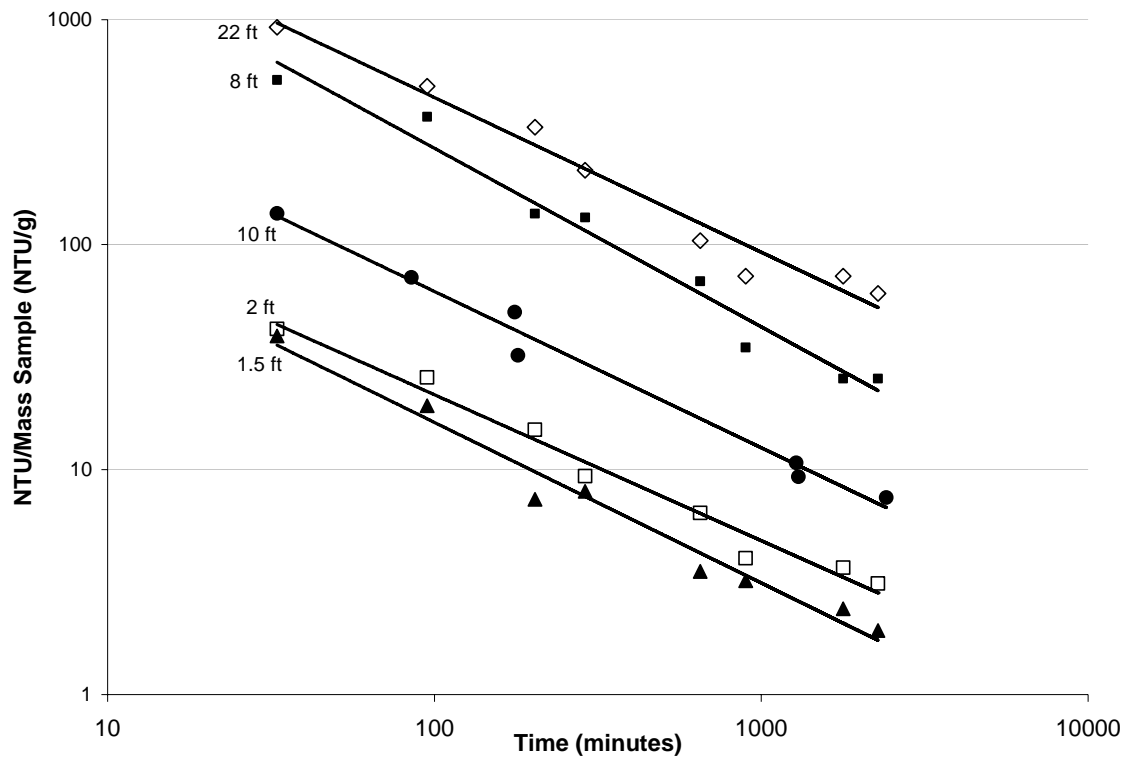


Figure 8 Change in turbidity over time measured in the upper 10 cm after mixing approximately 100 g/L of sediment from different locations in the lake. Turbidity expressed as NTU per initial gram of sediment. Sample depths of the different sediment and best fit log-linear lines shown.

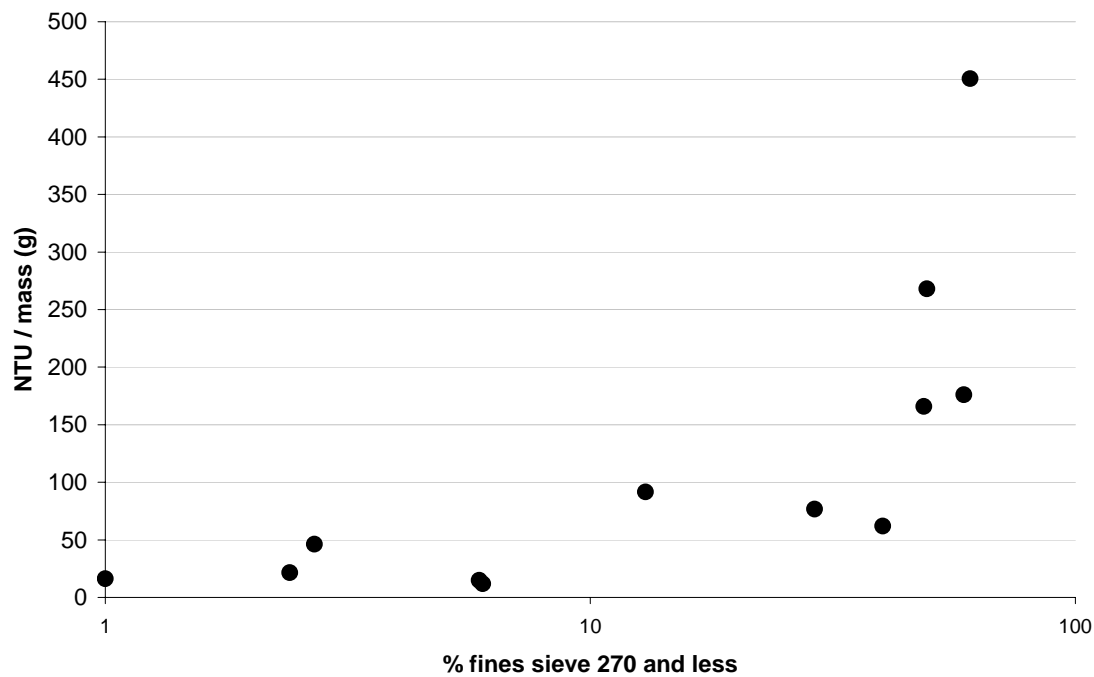


Figure 9 Relationship between 100 minute turbidity measurements (expressed as NTU per original gram of sediment) and the fraction of the sediment that is in the silt/clay particle size fraction (passing the 270 sieve).

Wind, Turbidity, and Secchi Disc Monitoring

Clark Lake is a relatively large lake and wind can result in wave generation that can resuspend sediments. To understand how wind might impact wave formation, wind data was collected from a weather station located at the Whitefish Dunes State Park adjacent to Clark Lake. Figures 10 and 11 are the recorded wind directions from April 14, 2006 through January 7, 2007. Wind direction and speed was collected every fifteen minutes and summarized. It can be seen that the southwest wind direction (50%) is the prevalent wind direction, followed by the northeast (28%), the north (10%), and the remaining 5 directions (12%).

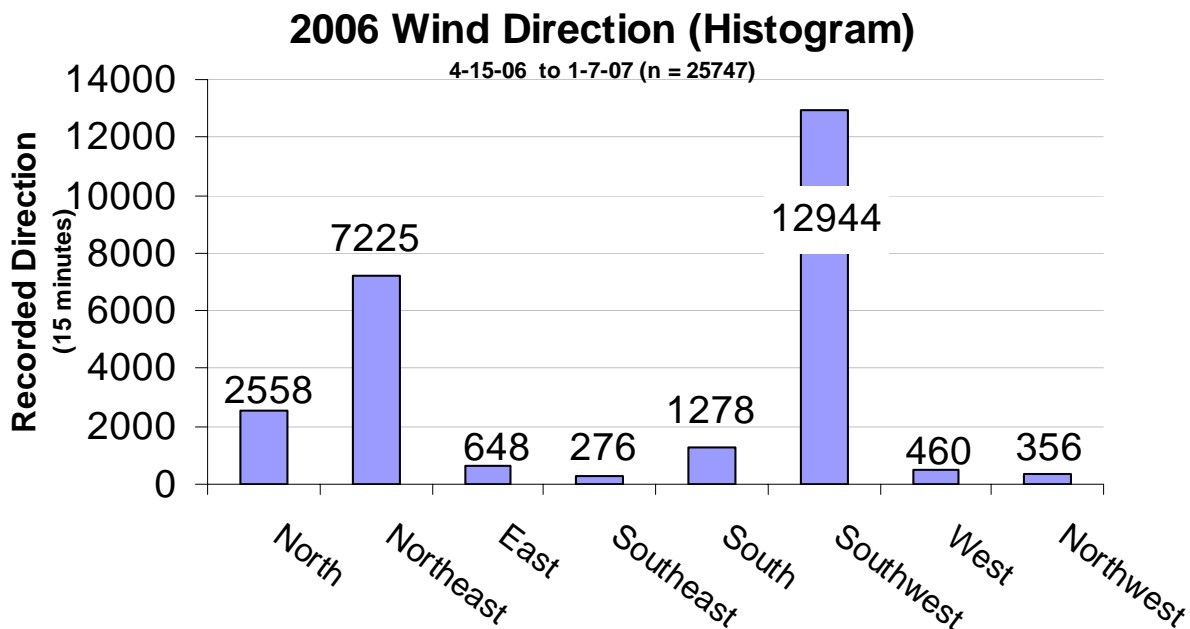


Figure 10 Recorded direction of wind from the weather station at Whitefish Dunes State Park.

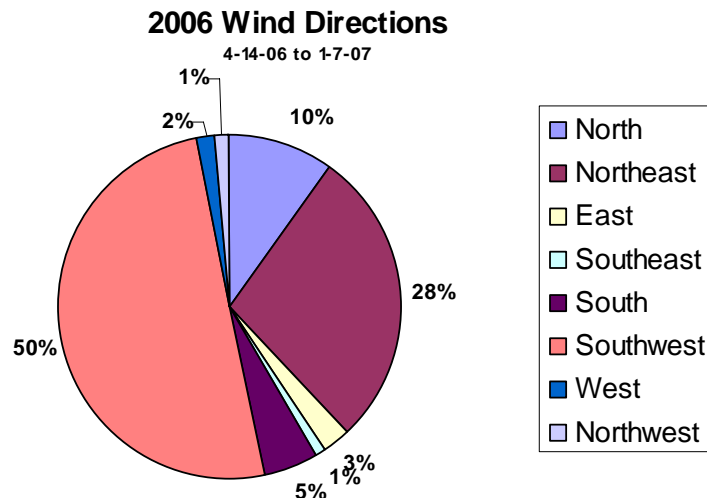


Figure 11 Percentage of recorded wind directions.

Continuous turbidity monitoring was performed using a Hydrolab MS5 sonde with a self cleaning wiper and temperature probe placed approximately 3 ft below the water surface. The sonde was attached to a navigational buoy off the west access on Clark Lake in 2005 and 2006. Complications arose with the 2005 deployment because the sonde was deployed too close to the lake bottom. We suspect the sonde bounced off the bottom with wave action, and while this information showed higher turbidity during windy days, it was also likely recording very high values from mixing with the sediment and therefore was not indicative of the water in the lake so the 2005 data was left out of analysis. This situation was corrected for the 2006 deployment.

Secchi disc depths, boat counts, and daily observations were made by Clark Lake Advancement Association (CLAA) volunteers at four sites on the lake to determine how turbidity and water clarity might be linked to wind and boat traffic. The number of watercraft was estimated over a 5 minute period at each location.

Secchi disc depth is a measure of water clarity that is related to the amount of algae, suspended solids, and color of the water. Clark Lake exhibits varying water clarity throughout the growing season and year to year. Secchi disc depths through 2005 and 2006 showed water clarity generally in the good to fair range for most of the summer, but they were greater in the spring and early summer (Figure 12).

The sediment studies showed that (1) fine sediment particles can be suspended in the water column and remain suspended as they slowly settle and (2) disturbing the sediment can resuspend fine particles. There are a variety of ways that sediment can be resuspended, including wind, boat traffic, and fish activity. Marl formation can also lead to variations in water clarity as fine particles are generated through calcium carbonate precipitation.

It is difficult to discern a long term trend in water clarity with this information, but there is some evidence that Clark Lake may be experiencing a general decrease in Secchi disc depth measurements. Figure 13 compares the average 1986–1999 monthly depths with more recent measurements from 2000–2006 showing the average is lower in more recent years. Year to year variation makes this comparison difficult, however, the summer of 2006 exhibited better than average (deeper) Secchi disc depths and some of the deepest recorded Secchi disc depths. The observed increases in water clarity may be attributed to water chemistry, weather patterns, human usage, or the recently introduced zebra mussel (*Dreissena polymorpha*).

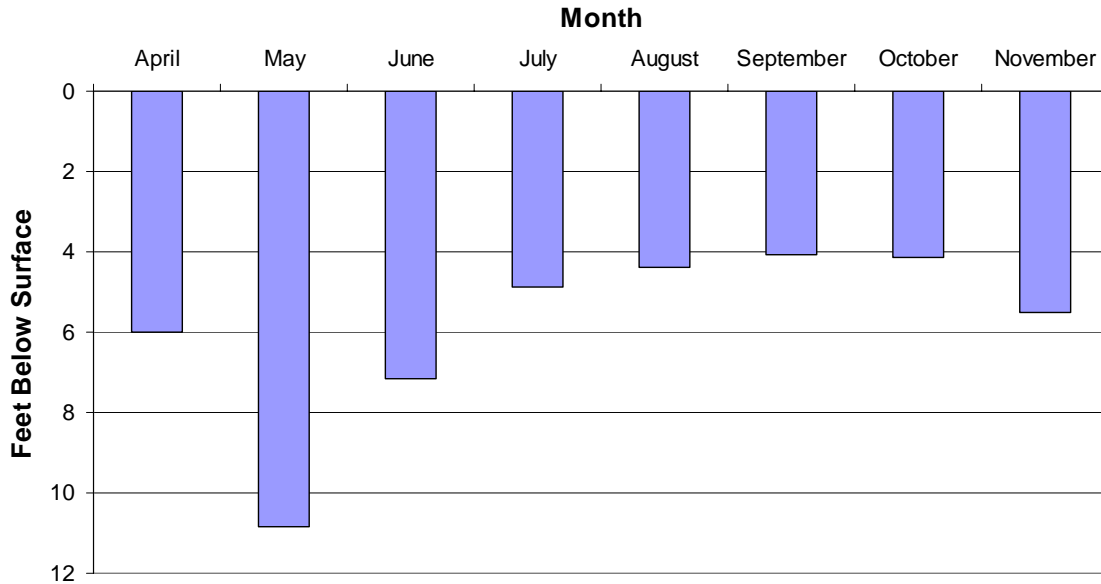


Figure 12 Average monthly depth of Secchi measurements in Clark Lake, 2005 and 2006.

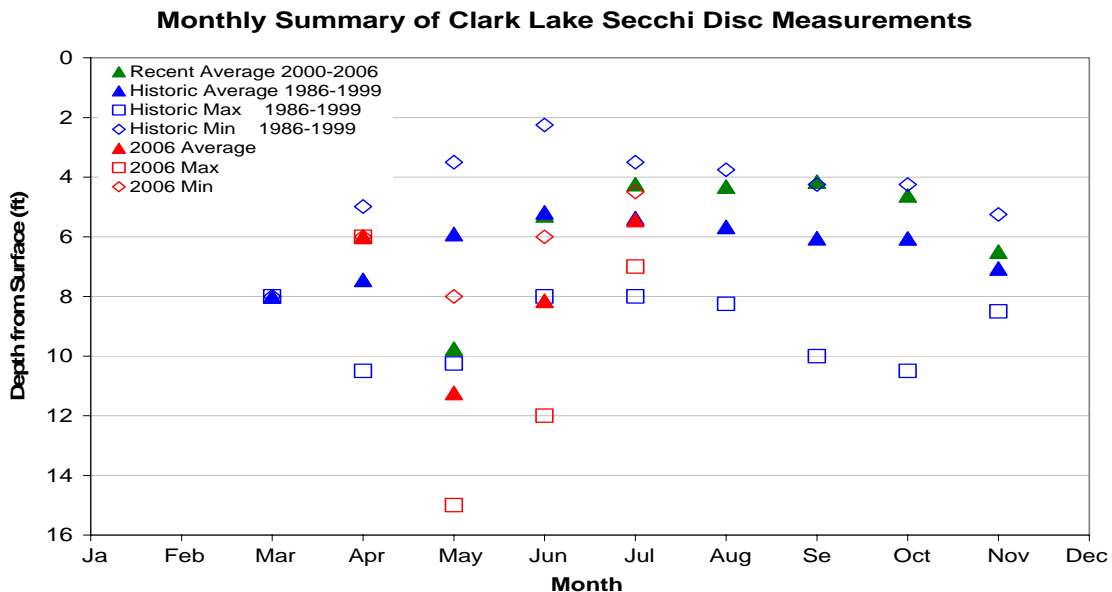


Figure 13 Average, minimum, and maximum Secchi disc measurements in Clark Lake, 1986 – 2006.

A qualitative comparison of wind direction, wind speed, and lake turbidity can be made by examining Figures 14–18 showing the continuous measurement made during 2006. In June, the lake turbidity is relatively low and even following relatively high wind speeds of 15-20 mph in mid-June, there lacks a corresponding increase in turbidity. In July, the turbidity is higher, but similar to June, the relationship between wind speed and turbidity is not easy to identify. Later in July, there appears to be an increase in turbidity following a relatively longer period of high winds (15 to more than 20 mph). Several

subsequent wind events appear to coincide with increases in turbidity. In August and September, a stronger relationship between wind from the northeast and turbidity develops. Overall, the turbidity is higher than earlier in the summer, and on those days that relatively high winds from the northeast were recorded, it appears there is an increase in turbidity. This is consistent with the location of the turbidity monitor near the west boat landing. Winds from the northeast would have a relatively long fetch in the direction of the boat launch and would likely develop larger waves near the monitoring location. That would increase the likelihood of resuspending sediment near the monitor. The southwest wind direction was the only other wind direction in which an increase in turbidity was observed. This may be attributed to a southwest wind direction that was in many occurrences stronger than the other wind directions and would last for a long enough period of time thereby significantly increasing lake wide turbidity. Overall, it also appears that some of the increases in lake turbidity lags behind an increase in wind speed. When the wind speed slows, it takes some time before the turbidity decreases. This is consistent with the laboratory tests showing the relatively long time to settle the very fine marl particles.

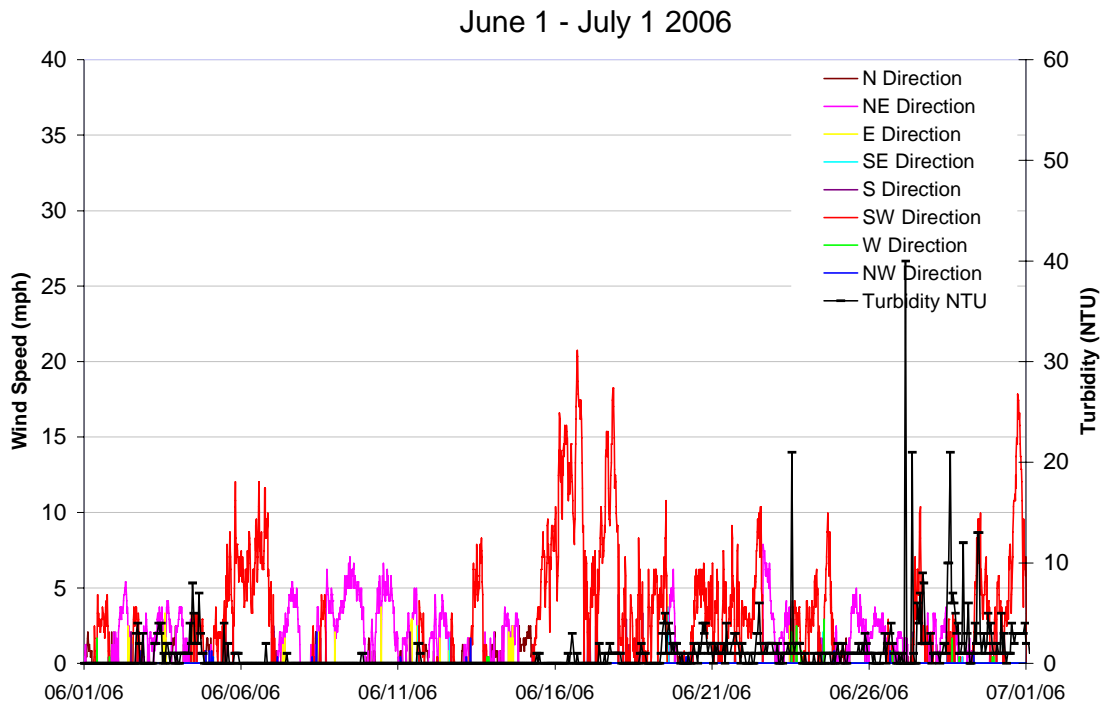


Figure 14 Turbidity vs. wind direction and speed, June 1 – July 1, 2006.

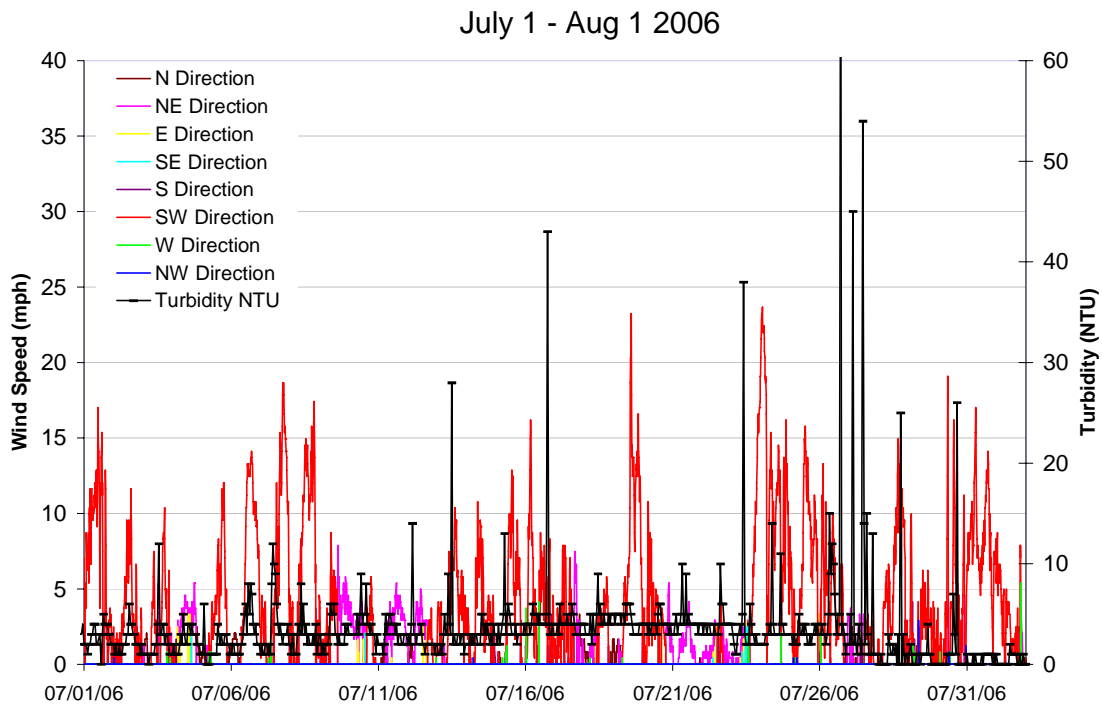


Figure 15 Turbidity vs. wind direction and speed, July 1 – Aug 1, 2006.

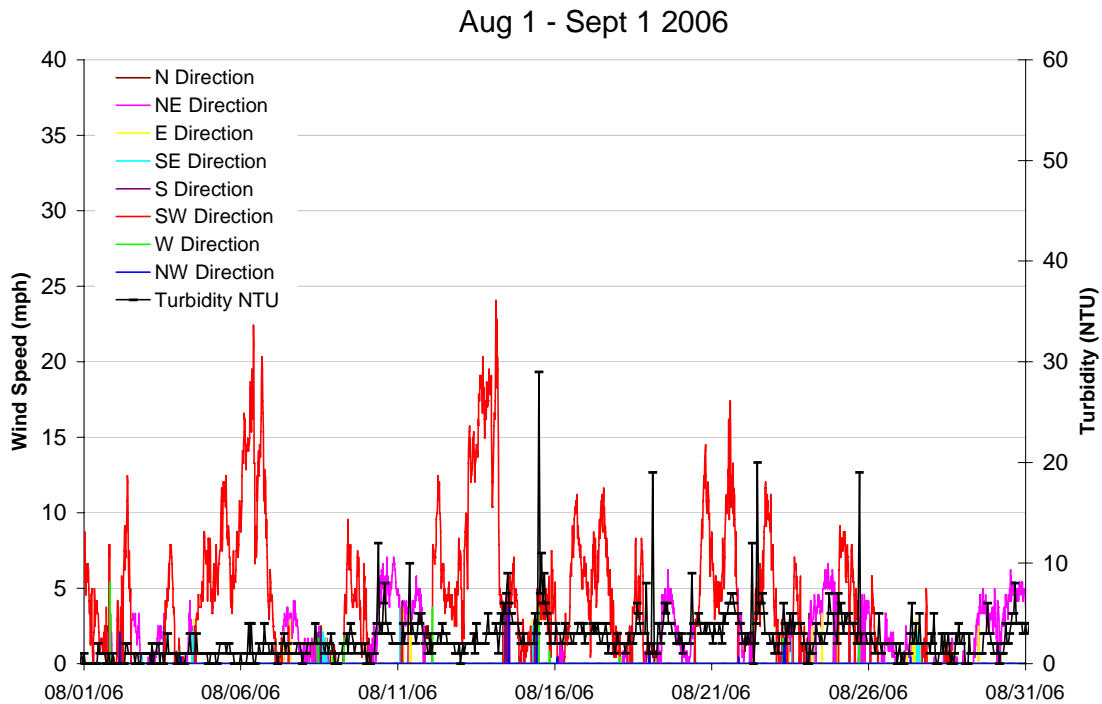


Figure 16 Turbidity vs. wind direction and speed, Aug 1 – Sept 1, 2006.

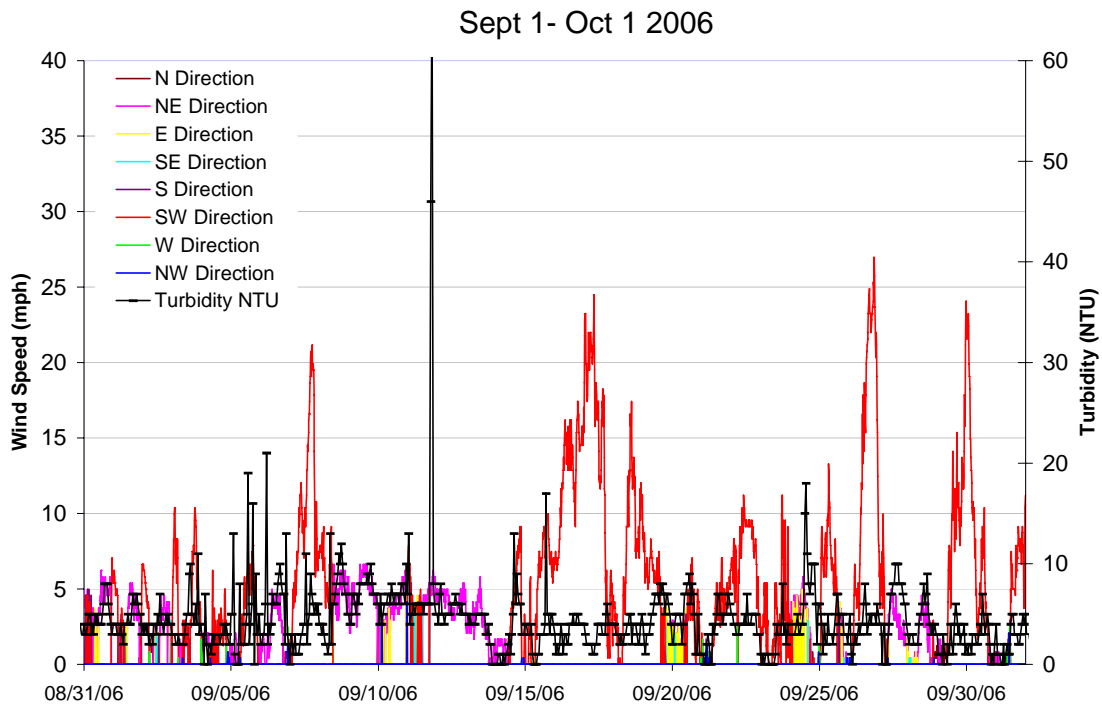


Figure 17 Turbidity vs. wind direction and speed, Sept 1 – Oct 1, 2006.

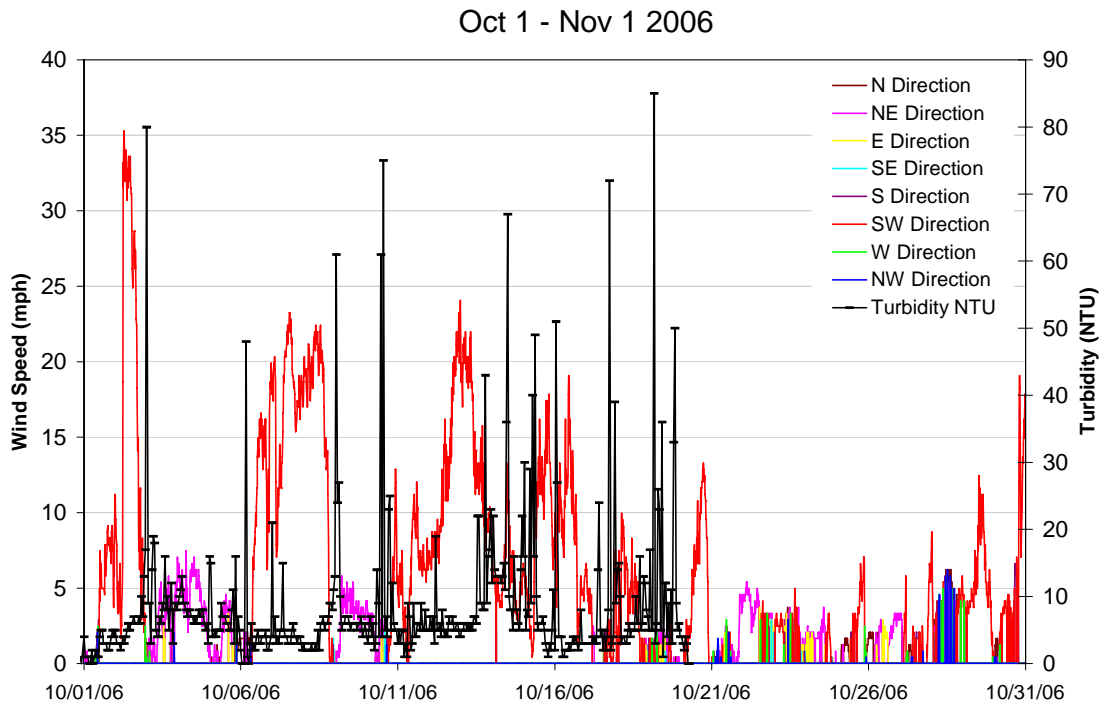


Figure 18 Turbidity vs. wind direction and speed, Oct 1 – Nov 1, 2006.

Figures 19-23 compare Secchi disc depth measurements, boating activity and turbidity in the lake. Figure 19 shows the general increase in turbidity during the summer is accompanied by a decrease in Secchi depths at all locations. The summer started with relatively low turbidity and deep Secchi depths, but over time, the Secchi depth decreased and the turbidity increased. Figures 20-23 compare boating activity with turbidity, wind speed and Secchi measurements at individual locations. At all sites, there is a decrease in Secchi disc depth that follows the increased boating activity and increased wind speed on Memorial Day weekend. There is also an increase in turbidity that lags that increase in boating activity and wind. A consistent increase in turbidity and decrease in Secchi disc depth was observed from mid-June to early July. At all monitoring locations, the Secchi disc depth decreased during that two week period and the turbidity rose at the monitoring point. This decreased water clarity seems to precede the increased boating activity near the Fourth of July weekend and when high wind activity prior to the time period may have contributed to the decrease. The elevated turbidity and reduced Secchi depths then appear to persist through the remainder of the summer, although Secchi disk monitoring frequency was reduced during that period.

The results suggest a possible relationship between boating activity and lake clarity, but that it is also complex. The early spike in boating activity is accompanied by a decrease in Secchi disc depths, but may be associated with wind conditions during the same period. Later in the summer, the reduced water clarity was not directly associated with a large increase in boating activity. Further, as the summer progressed, there appeared to be a stronger relationship between wind from the northeast and turbidity at the monitoring location.

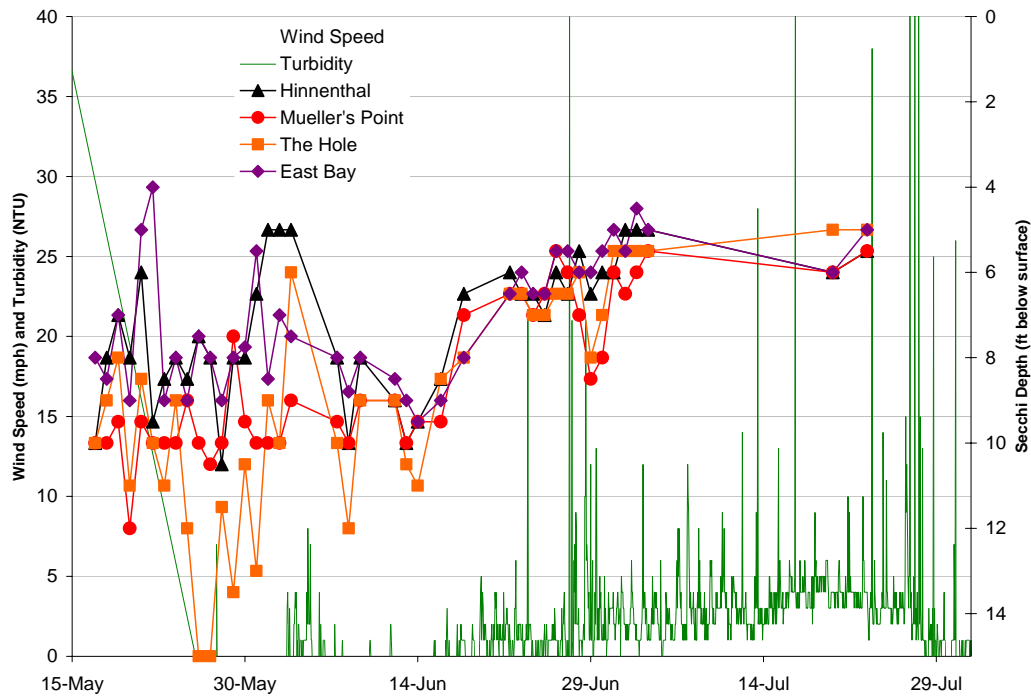


Figure 19 Comparison of Secchi depth monitoring at all locations with the continuous turbidity recorded near the west boat landing. Turbidity monitoring began June 1.

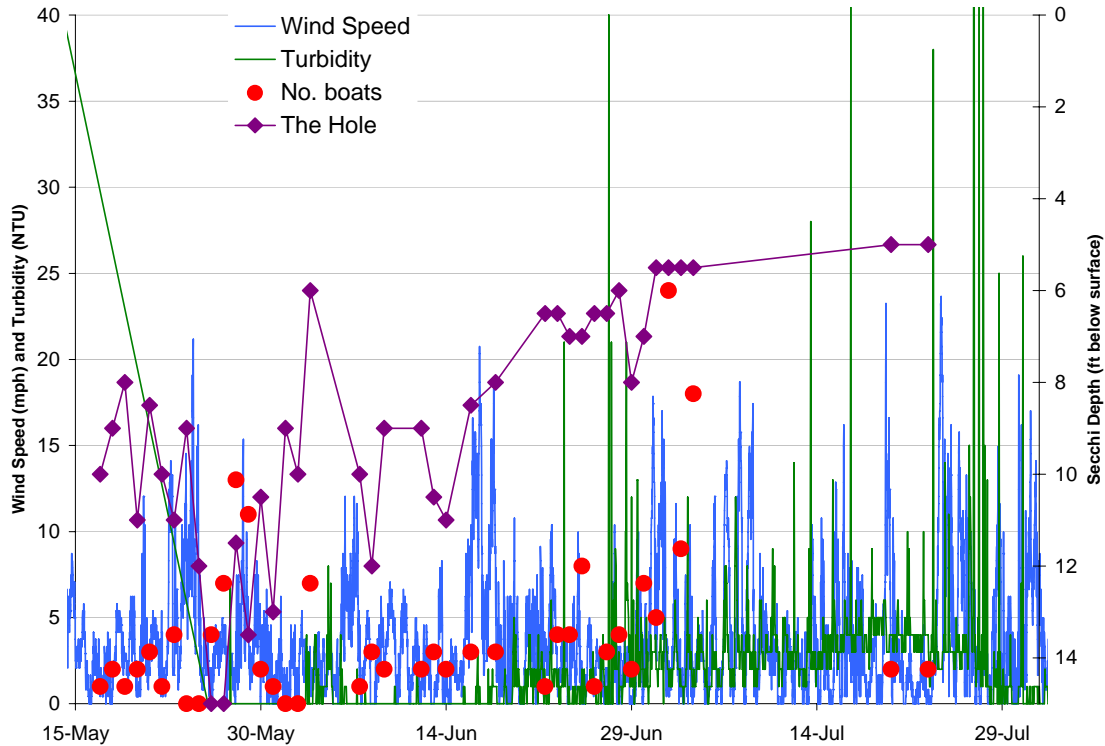


Figure 20 Turbidity, wind speed, boat count and Secchi depth measured at the deep hole.

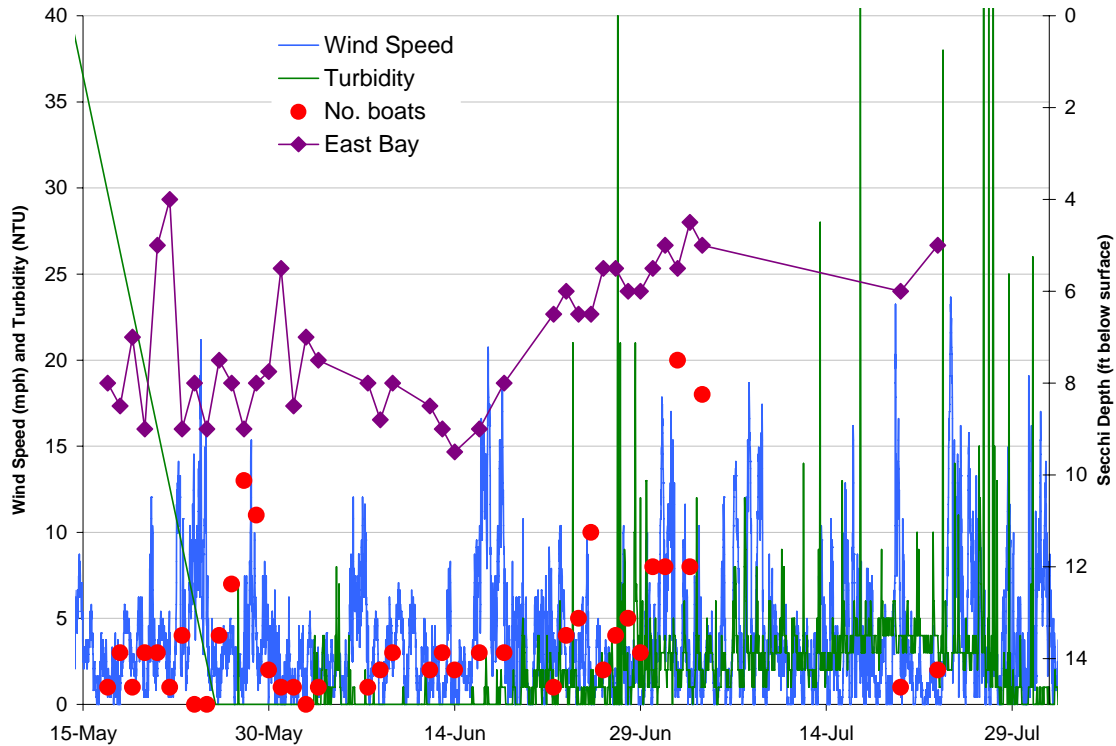


Figure 21 Turbidity, wind speed, boat count, and Secchi depth measured at the East Bay site.

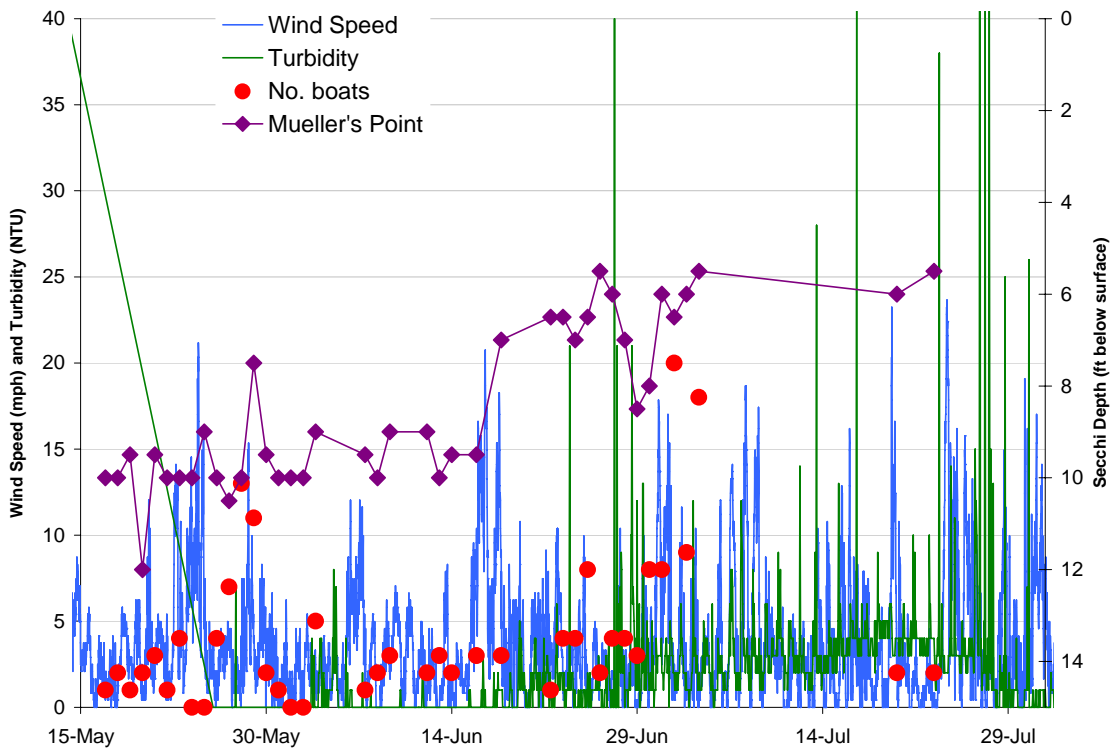


Figure 22 Turbidity, wind speed, boat count, and Secchi depth measured at the Mueller's Point site.

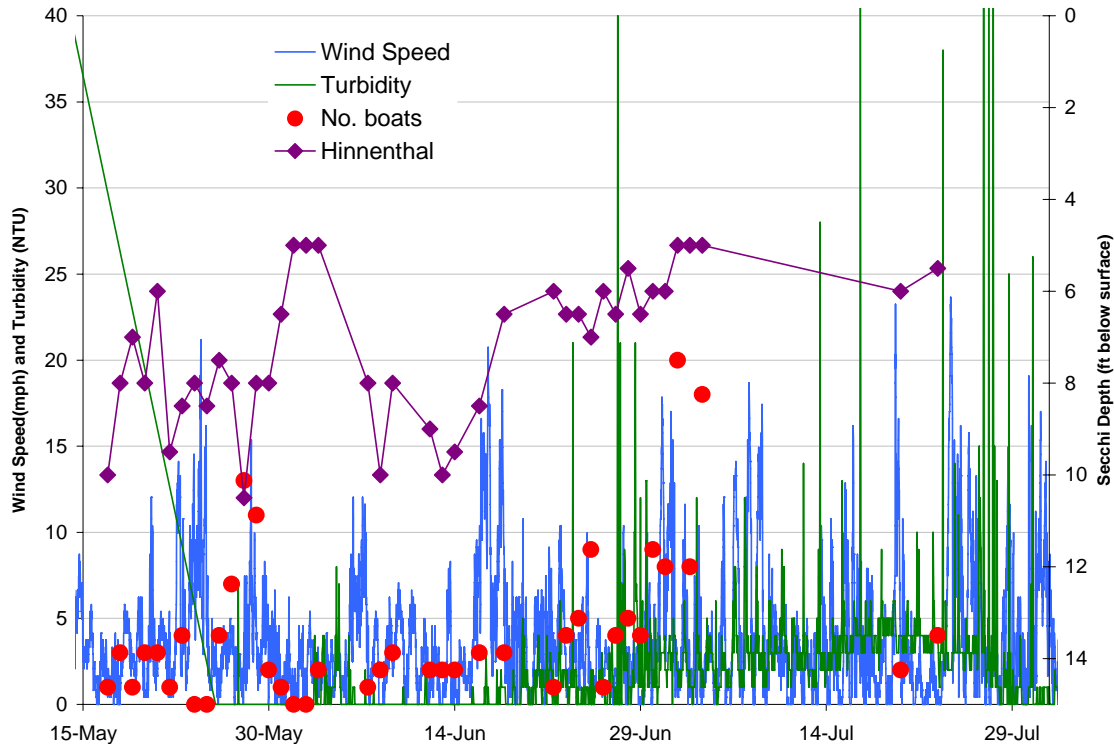


Figure 23 Turbidity, wind speed, boat count, and Secchi depth measured at the Hinnenthal site.

Recreational Watercraft Experiments

To better understand the effects of recreational boating traffic upon water clarity and turbidity in Clark Lake, a study of the resuspension capabilities of watercraft was performed. We selected a section of shoreline along the southwest portion of Clark Lake that was typical of the sediment composition of the near shore region and had sediment that was relatively homogenous. We used recreational watercraft driven at different speeds and measured turbidity with monitoring sondes, measured Secchi disc depths and analyzed water samples for suspended solids.

Four types of watercraft were examined in the tests: a 160 horsepower (hp) inboard-outboard, a 100 hp outboard, a 30 hp pontoon, and a jet ski. All were driven at two depths (4 and 6 ft), at speeds of no wake (3-4 mph or less), medium (8-9 mph), high (20 mph), and a start up speed with a tilt of approximately 225 degrees.

Turbidity sondes (YSI 6600, Hydrolab MS5, and Hydrolab DS5X) were used to take continuous turbidity (NTU) and temperature ($^{\circ}\text{C}$) measurements from start to finish of the trials. The sondes were mounted approximately 2 ft below the surface and measurements were taken at 15 or 30 second increments, depending upon sonde model. Water samples, Secchi disc measurements, and visual observations were taken prior to, immediately after, and 10 minutes

following the watercraft passing a sonde station. Water samples were taken a full arms length (approximately 2 ft) below the water surface for later determination of total suspended solids and turbidity.

Boating lanes were set at depths of 4 and 6 ft. Boating lanes and turbidity sondes were set up prior to the experiments and drivers operated parallel to the lake shore at two different water depths. A buoy and stake with an attached monitoring sonde was established to mark the watercraft route for a given depth contour. The watercraft began at a complete stop directly behind the first sonde station in the 4 ft run and incrementally increased speed from startup accelerating through to high speed (Figure 24 and Figure 25). A second run was then performed at a depth of 6 ft. The lanes were left idle for approximately 25 to 30 minutes to allow suspended solids settle back to the bottom. The lanes were then reused for duplicate runs in which each scenario was repeated three times.

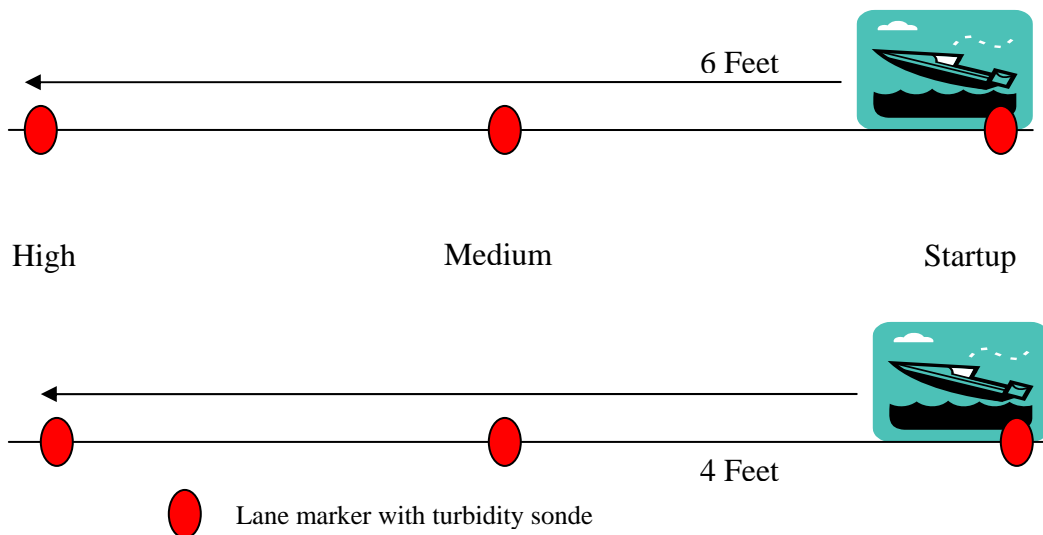


Figure 24 Schematic of experimental boating lane layout.



Figure 25 Jet-ski taking off in boating experiment.

Figures 26 through 31 show a comparison of continuous turbidity monitoring and TSS collected during the watercraft experiments. The results show watercraft can influence the turbidity of the water by resuspending sediment. As anticipated, the impact was greater at the 4 foot depth than at the 6 foot depth. Boat motors move water as they propel the boat forward. This movement is stronger nearer the motor and the sediment in shallower water is more likely to experience greater force from motor operation. Bottom sediments are expected to become finer as the lake depth increases and as a result, they would be more easily resuspended. Figure 6 presented earlier suggest there would be a relatively high concentration of fine sediment at depth of 4 and 6 foot. In shallower water, it is likely that the force for resuspension would be greater, but that there is less fine sediment present.

Watercraft startup had the greatest impact on resuspension in these experiments. We found that during the startup speed the boat and motor were angled in a way that would direct more force to the lake bottom. In this position, the boat is much more capable of resuspending sediment than the medium or high speed. This is likely due to the increased shear force the boat needs to propel itself forward. The direction at which the force is angled towards the bottom sediment is an angle that is more likely to reach the lake bottom. The size and draft of the boat likely played a role in resuspension at startup as the boats that were bigger and usually sit deeper in the water and will likely take a longer time and bigger motors to move then forward. In doing so the boat would be displacing more water and increasing its capability to resuspend sediment.

The type of boat also influenced the quantity of sediment resuspended. The 160 hp inboard-outboard and the 90 hp outboard had the greatest affect on turbidity. The smaller pontoon and jet-ski also resuspended sediment, but in these experiments had a lesser impact on turbidity than the larger boats.

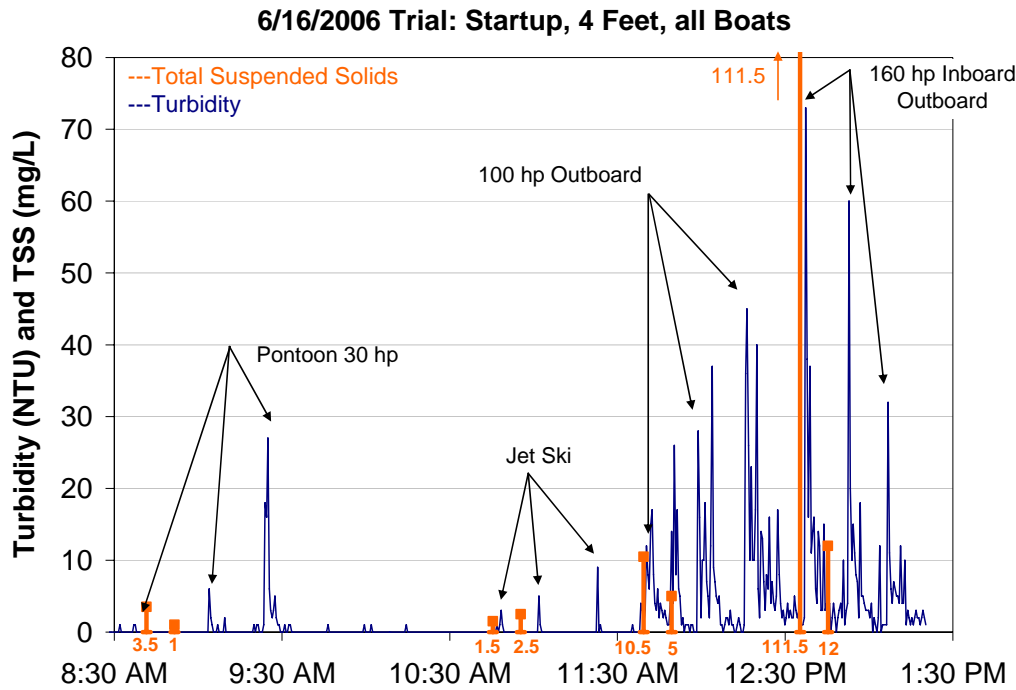


Figure 26 Turbidity and TSS taken at 4 feet/startup speed

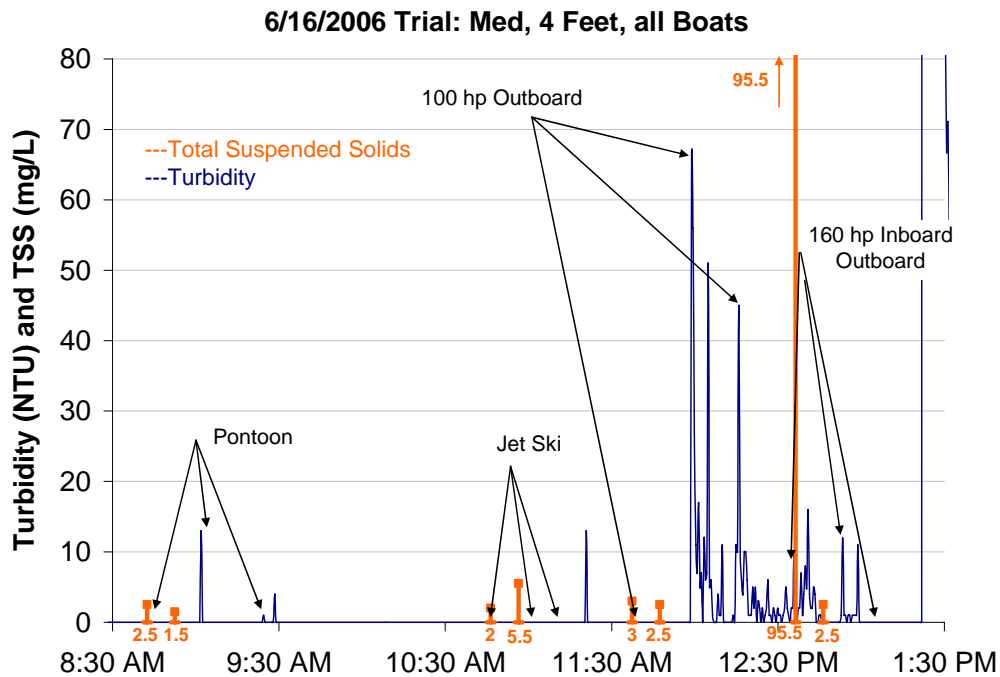


Figure 27 Turbidity and TSS taken at 4 feet/medium speed

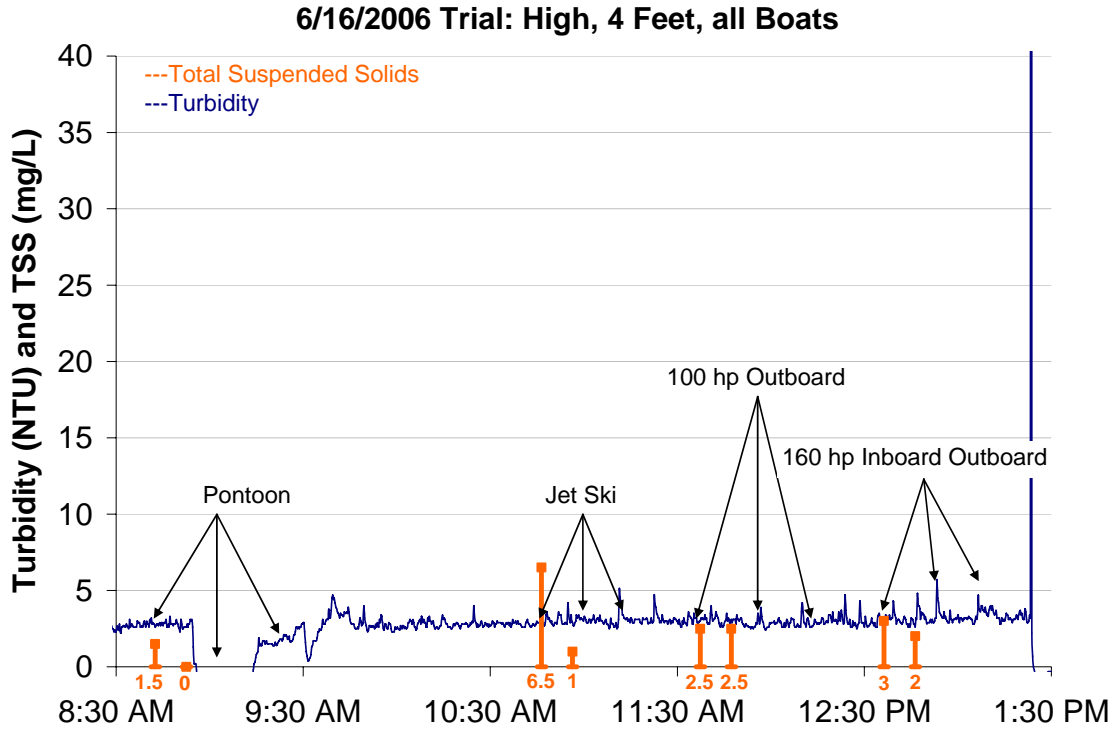


Figure 28 Turbidity and TSS taken at 4 feet/high speed

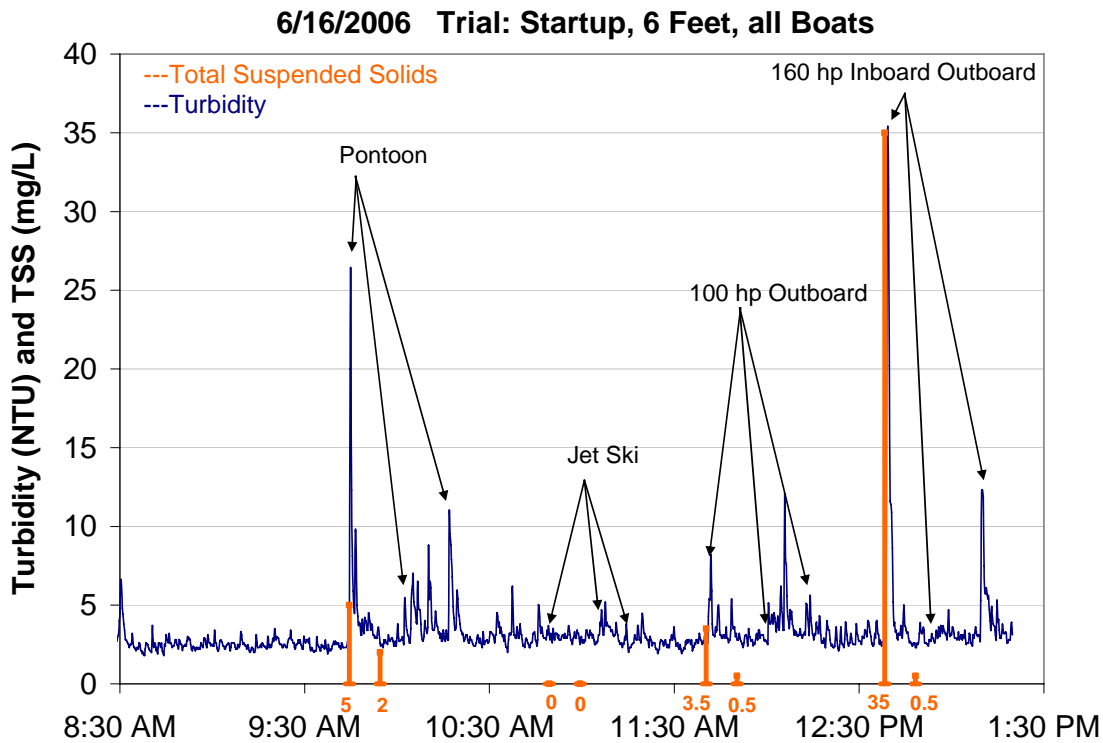


Figure 29 Turbidity and TSS taken at 6 feet/startup speed

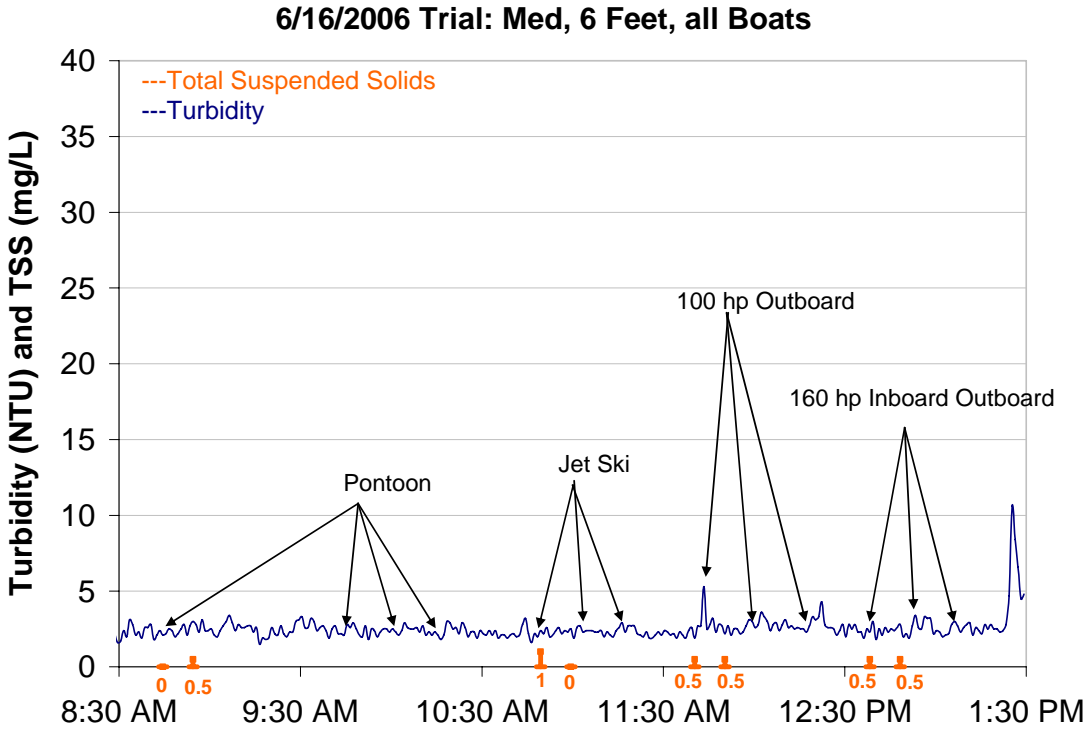


Figure 30 Turbidity and TSS taken at 6 feet/medium speed

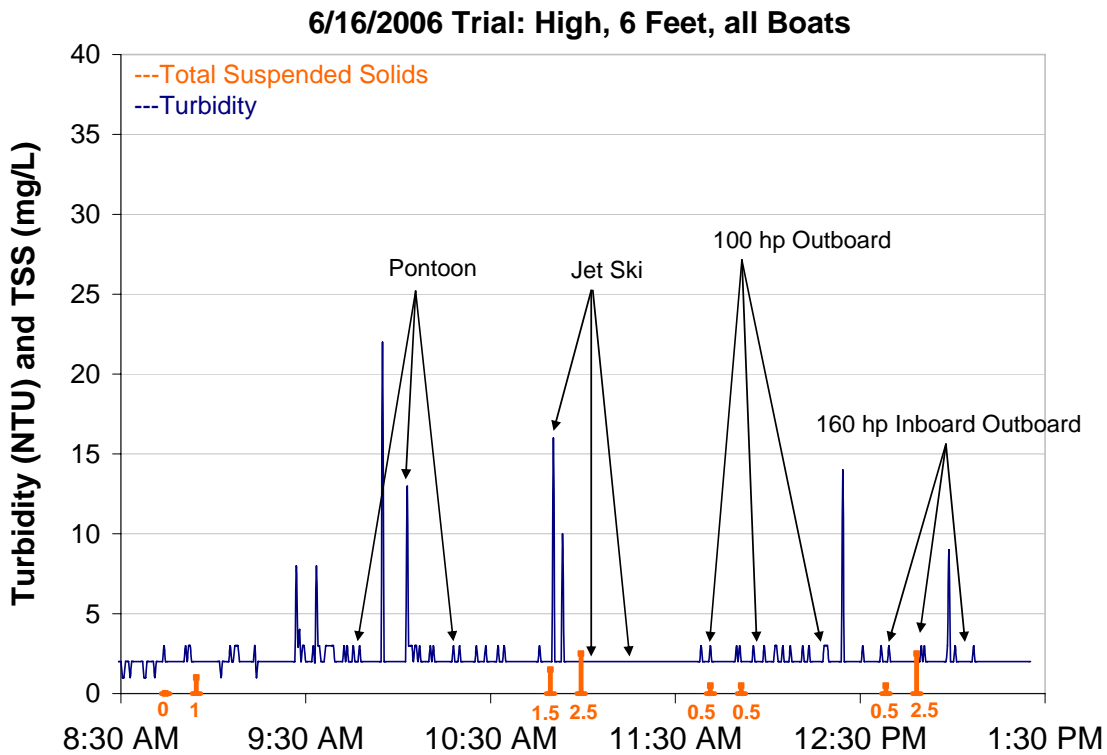


Figure 31 Turbidity and TSS taken at 4 feet/high speed

Figure 32 summarizes the TSS measurements made directly after the passage of the boat. Similar to the turbidity measurements, the 4 foot depth was more susceptible to resuspension than the 6 foot depth. In general, there is a pattern of decreasing resuspension from startup to high speed at both depths. During the 6 foot trial relatively low suspended solids concentrations were measured at the medium and high speeds. The highest values for both depths occur at the startup speed except for the jet-ski that registered a high at the med speed, 10 minute and the high speed, 0 minute sampling. The jet-ski was the only watercraft to respond in this way, and it is not clear what caused that difference. When TSS is compared to boat type the 160 HP inboard-outboard had the greatest ability to resuspend sediment. The 100 HP outboard also had a relatively high resuspension of sediment. During and after the experiments, we observed that resuspended sediment tended to drift from the experimental lanes to shallower water. The prevailing movement of water was towards shore in a clockwise rotation around the lake. This demonstrated how sediment resuspended from deeper portions of the lake can become redeposited in shallower areas where it is more likely to be resuspended later by wind or watercraft activity.

Figure 33 compares the TSS concentrations at the different depths with the variation in fine sediment composition described earlier. The figure shows that these boating experiments were performed at water depths where a relatively large quantity of fine sediment is likely present. This accumulation of fine sediment likely reflects the lower probability of wave resuspension at these depths, but the watercraft experiments show that boating activity can disturb fine sediment at these depths.

In summary, the role and ability of recreational boat traffic on resuspending sediment in Clark Lake demonstrated that:

- No-wake speeds had an undetectable impact on the sediment.
- In general, the bigger the boat, motor, and draft of the boat the more likely it will resuspend sediment.
- Boats operated in a shallower depth of water were more likely to resuspend sediment.
- Startup of a boat can lead to greater resuspension when the angle of boat directs the force to the bottom of the lake.

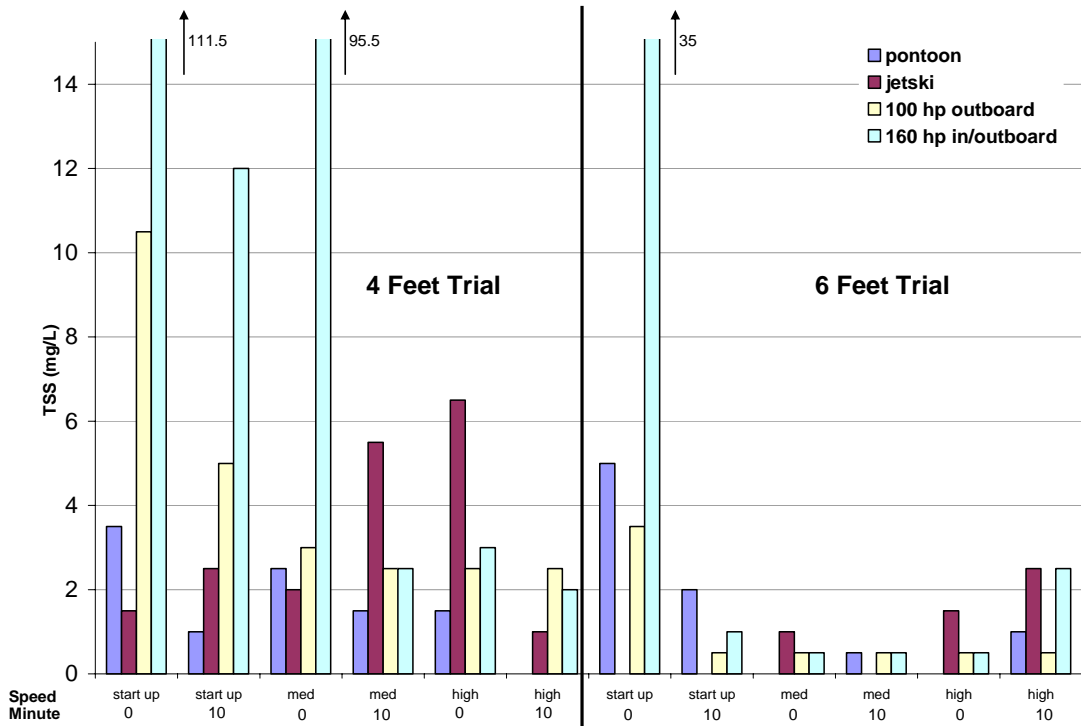


Figure 32 TSS measured at 0 and 10 minute interval following first pass of watercraft.

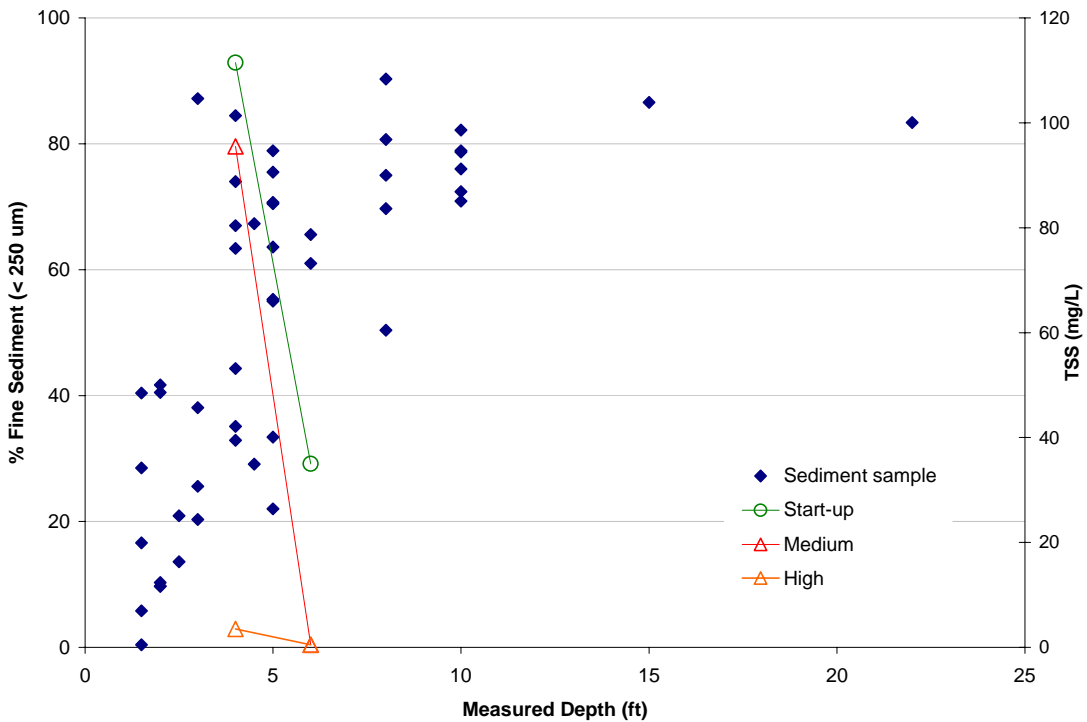


Figure 33 Percent of fine sediment (<250 μm) vs. measured depth of sediment sampling locations. Included are all 3 boat speeds for the 160 hp inboard-outboard showing a decreasing ability to resuspend sediment from the 4 to 6 ft depths.

Wave theory

Mixing and Redistribution

The relatively small annual marl formation estimate suggests that most of the marl in the lake is the result of accumulation of marl formed from previous years. Because we know that the marl is mixing and redistributing in the lake it is likely that marl dynamics in the lake are important to water clarity.

To explore marl mixing, we sought to link the observations on sediment composition with bottom mixing from wind and waves. A model for the wave height in Clark Lake was developed based on wind speed and fetch at different portions of lake using an approach described in the scientific literature (Carper and Bachman, 1984). This theory incorporates wind speed and direction, fetch, and depth to determine if resuspension of sediment will occur at modeled locations. Surface waves are created when wind blows across a lake and each of these waves have a wavelength attributed to it. When a wavelength becomes large enough and one half of the wavelength extends to the bottom of the lake at any particular location, the oscillating horizontal motion of the water immediately over the sediment surface is sufficient for resuspension of sediment to occur. Areas of the lake that are shallow relative to the wave height that can develop are likely to be areas of erosion. Marl that settles in those areas is subject to resuspension back into the water. Conversely, areas of the lake that are deeper than the wave height are likely to be areas of deposition because marl that settles in those areas is unlikely to be resuspended.

The computations were incorporated into a Geographic Information System (GIS) using ArcGIS (ESRI, 2004) software. For different wind speeds and directions, fetch and wave depths were calculated on a 20 x 20 m grid. Each location was calculated as a resuspension or a depositional area dependant upon wind direction, wind speed, and fetch. If the depth at that location was one-half the wavelength or less then that location was characterized as a resuspension area for that wind speed and direction. Modeling was done using four wind directions; northeast, southeast, southwest, and northwest as they were determined the most important wind directions based on the wind data from the weather station at Whitefish Dunes State Park. A WDNR bathymetric map of Clark Lake was used to determine depth. Fetch was calculated using GIS and a measured distance from shore for the designated wind direction. Aquatic macrophyte beds were not considered in the modeling when evaluating fetch as most shallow beds are extremely variable in size and plant abundance. It is understood the shallow aquatic macrophyte communities, both emergent and submergent, dampen wave action upon contact with these communities. This lessens the force and ability of wave action to resuspend particles in these communities potentially leading to decreased resuspension and potential

settling of particles. In the absence of these communities and increase in potential sediment resuspension is assumed.

Figures 34 through 40 show resuspension and depositional areas modeled using four wind directions and wind speeds of 10 and 15 mph. Higher wind speeds do occur and will increase the size of the erosion areas. On days of relatively low wind, much of the lake will be a deposition situation.

Conceptual Model of Marl in the Lake

We have developed a conceptual model for marl mixing, settling, and resuspension in Clark Lake and the influence of boating activity on these properties. The marl that forms each year goes through a settling and resuspension process that ultimately leads to its accumulation in the depositional areas of the lake which are less prone to sediment resuspension. Marl can be easily resuspended from erosional areas, but only large disturbances resuspend marl in the depositional areas (e.g. high wind events and/or large motorized boating activity). The resuspension of marl may increase turbidity in the lake but eventually it will settle back to the lake bottom in both the erosional areas and depositional areas. Any marl that settles in the erosional areas is subject to additional resuspension with relatively low wind speeds and/or large motorized boating activity. The marl is then back in the active resuspension/settling cycle until it settles in a depositional area within the lake.

An important implication of this conceptual model is that lake turbidity at any time is dictated not only by the wind mixing or boating activity at that time, but also by the quantity of marl that resides in areas subject to resuspension. That quantity of "active" marl is likely determined by many previous mixing events because those events lead to marl deposition in erosion areas.

This is a complex view of turbidity in Clark Lake, but it does suggest several generalizations:

- 1) There will always be some turbidity in Clark Lake. Even if all the marl in the lake settles in the deposition areas shown in the Figures 33-40, higher wind speed events would erode some of those areas and move marl into the water. Once in the water, the marl must go through a resuspension/settling process that could take many cycles before it has all resettled into stable areas. Of course, new marl is formed every year and that will also have to go through a settling/resuspension process until it settles into more stable areas.
- 2) Turbidity in the lake reflects both the mixing in the lake and the amount of "active" marl available for resuspension. Active marl can be resuspended at relatively low wind speeds. Although this marl may

settle shortly after the mixing event, it may still remain active because it can settle in erosional areas and be subject to resuspension at relatively low wind speeds. This resuspension/settling process may continue although it would contribute less to lake turbidity over time because the fraction of the distributed marl that remains "active" decreases with time (as more is deposited in deposition areas). Other sources of marl disturbance, such as large motorized boating through deposition areas, can have a similar affect. Long term changes in the turbidity of the lake would reflect not only additional mixing that might occur on a day or weekend, but also how those changes influence the amount of "active" marl.

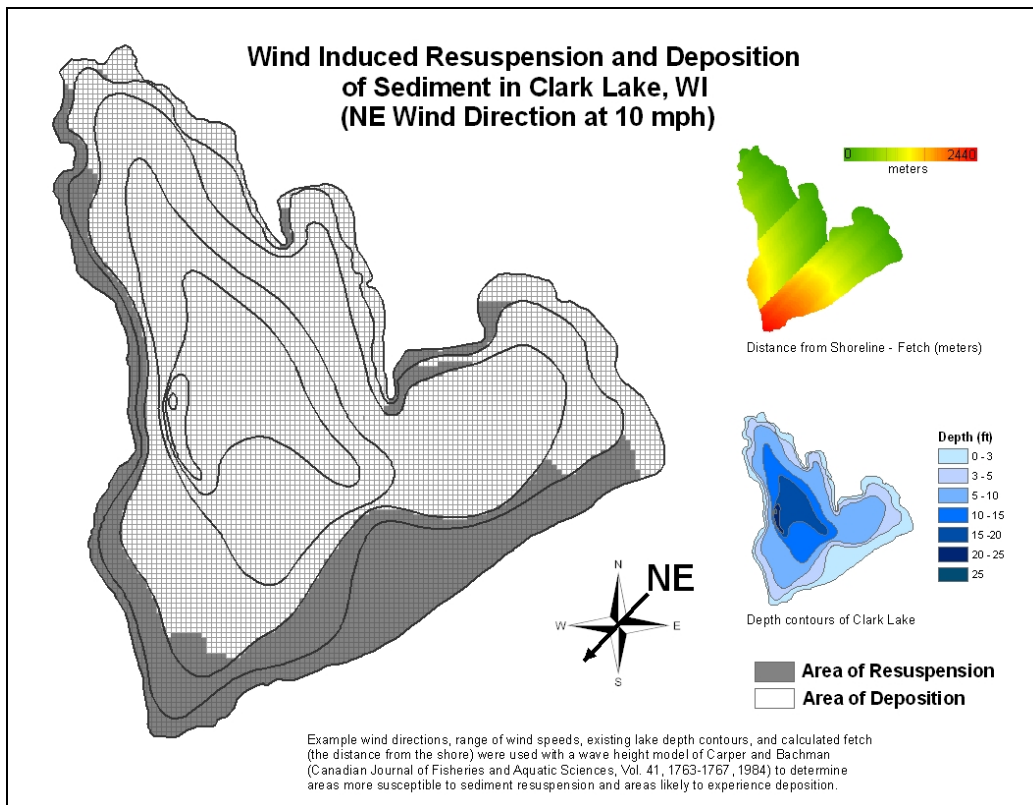


Figure 34 Modeled resuspension/depositional areas - NE wind at 10 mph.

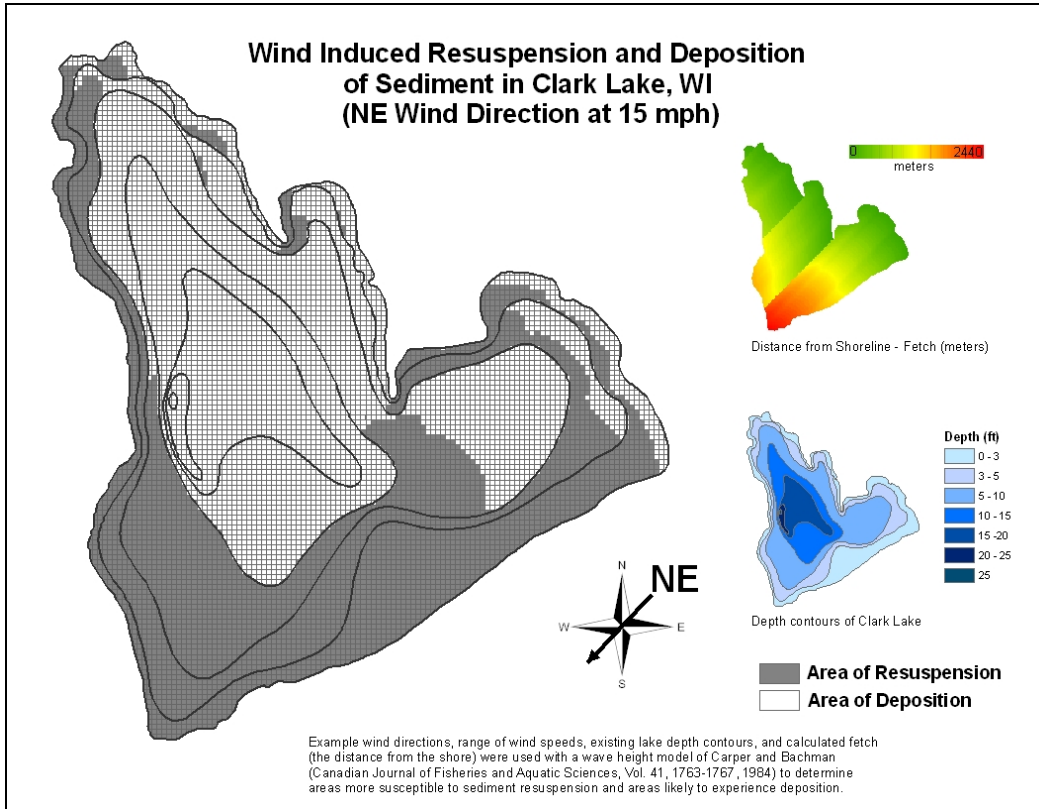


Figure 35 Modeled resuspension/depositional areas - NE wind at 15 mph.

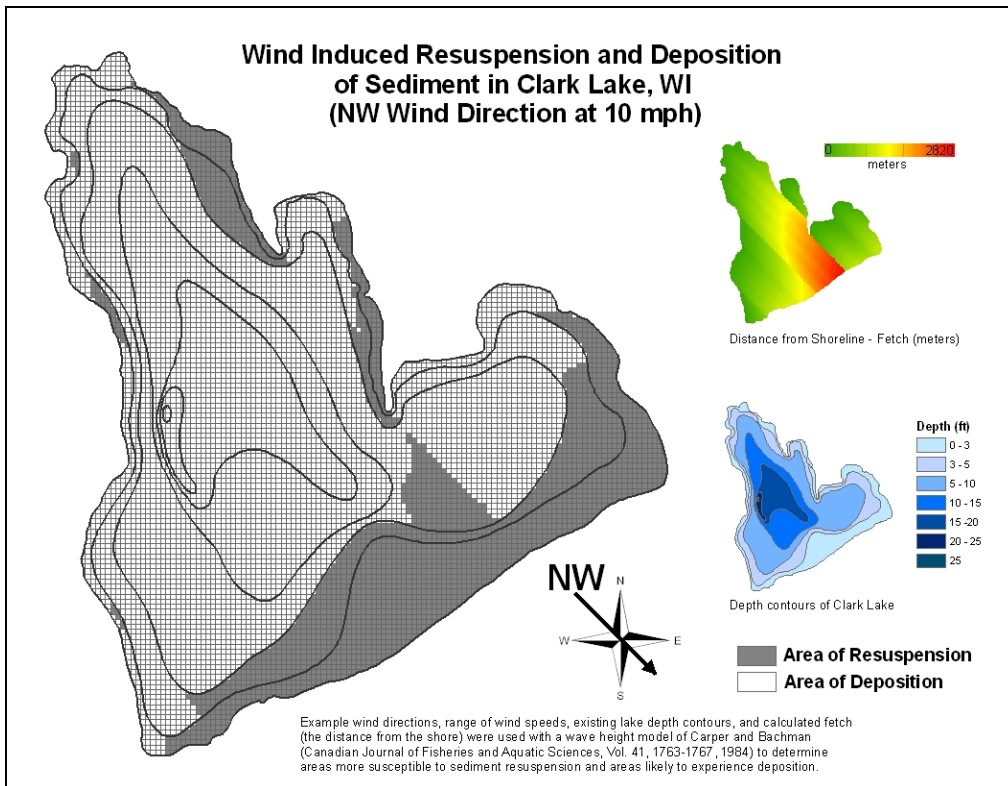


Figure 36 Modeled resuspension/depositional areas - NW wind at 10 mph.

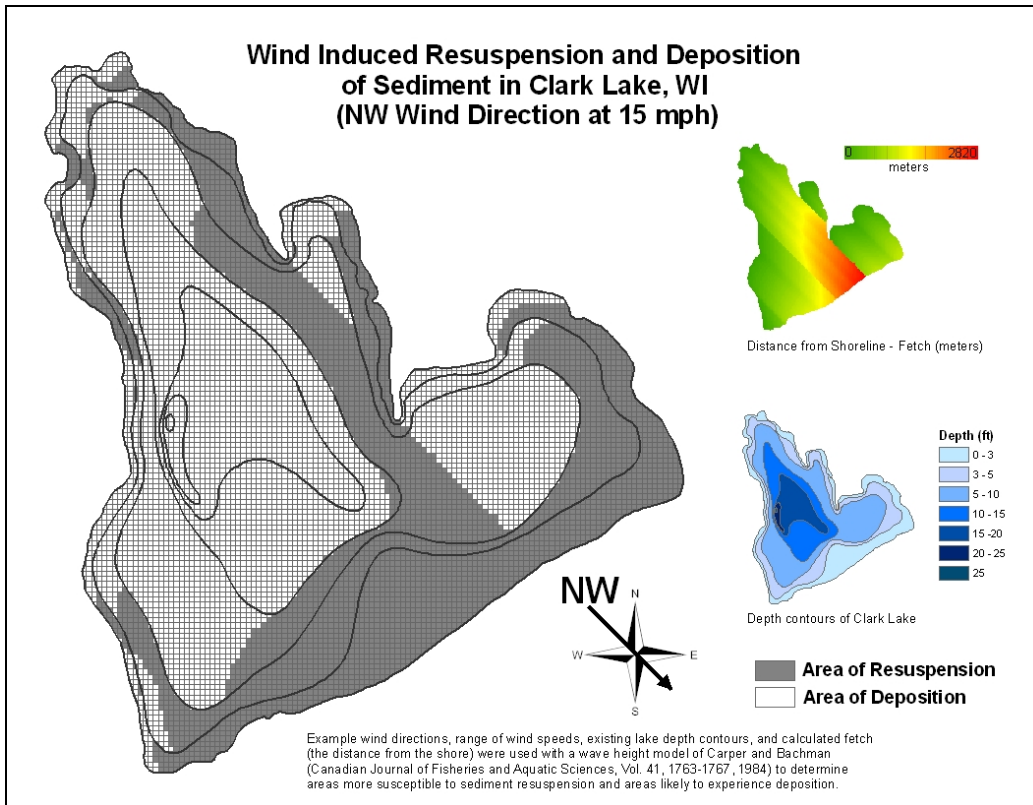


Figure 37 Modeled resuspension/depositional areas - NW wind at 15 mph.

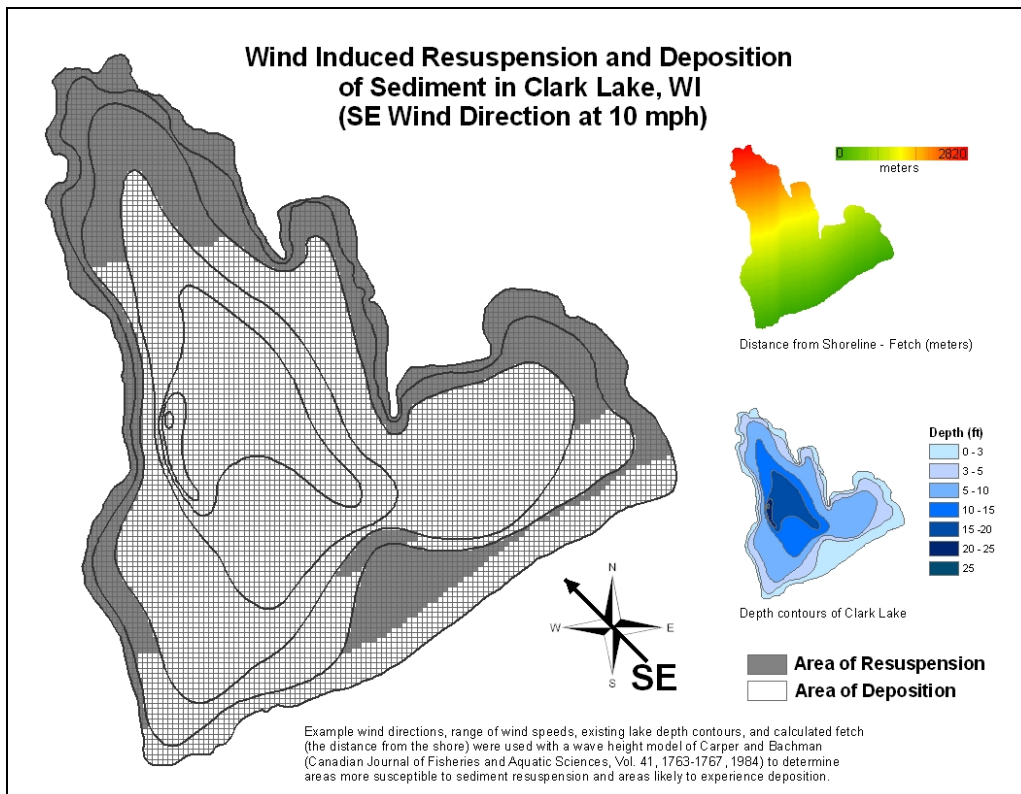


Figure 38 Modeled resuspension/depositional areas - SE wind at 10 mph.

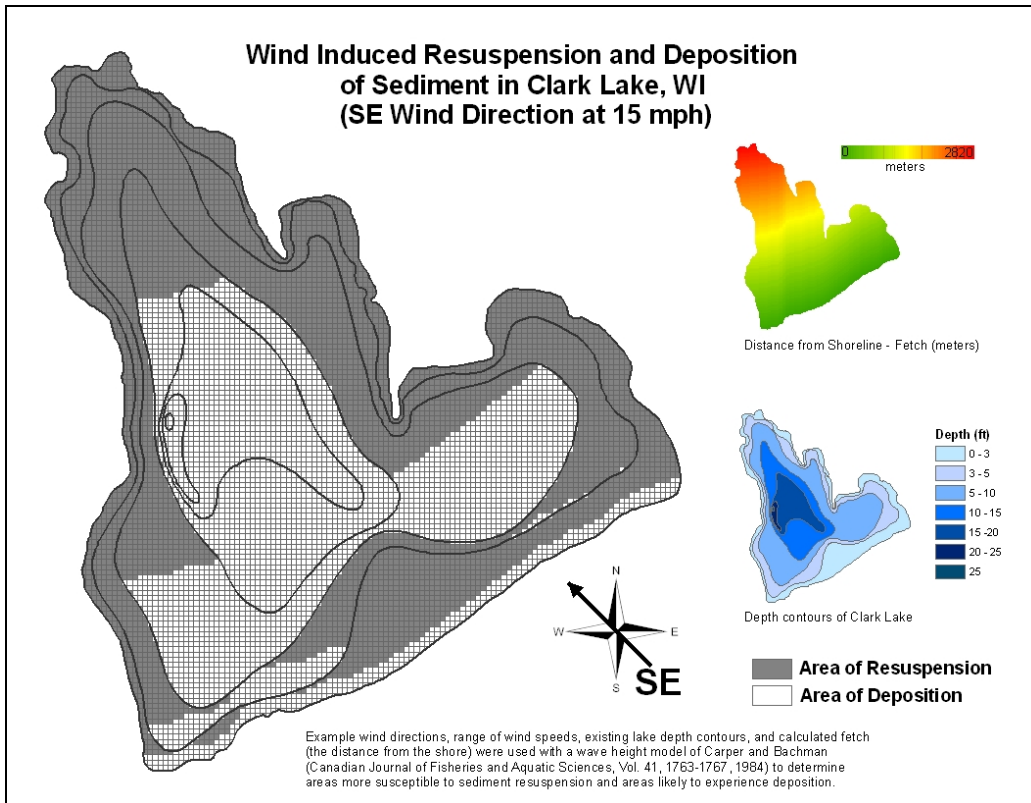


Figure 39 Modeled resuspension/depositional areas - SE wind at 15 mph.

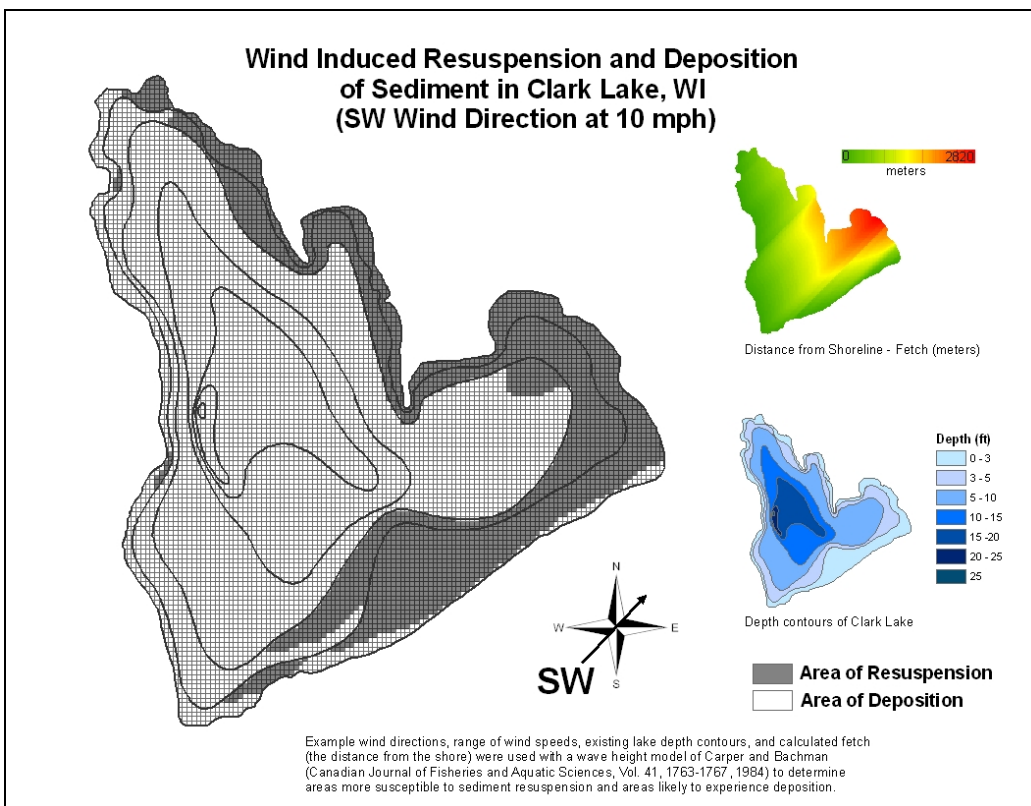


Figure 40 Modeled resuspension/depositional areas - SW wind at 10 mph.

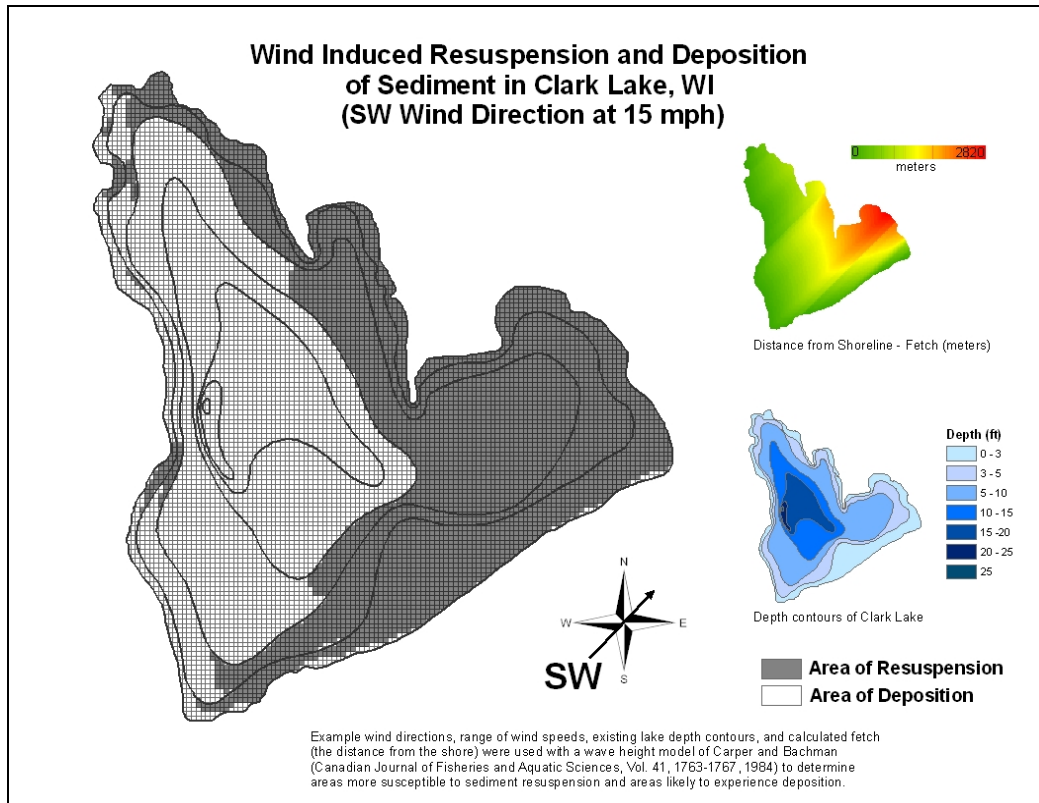


Figure 41 Modeled resuspension/depositional areas - SW wind at 15 mph.

Conclusions and Recommendations

The principal objective of this study was to develop a better understanding of the water clarity in Clark Lake. Based on the experiments performed and a review of the literature, it appears that water clarity in Clark Lake is related to marl formation, sediment redistribution, wind mixing and watercraft activity. We combined this information to develop a conceptual model of marl formation, mixing, and redistribution, and resuspension. The conclusions of this study include:

- That wind and wave mixing can disturb and resuspend sediment from the lake bottom. In doing so wind and wave mixing contributes to decreased water clarity and increased turbidity.
- Recreational watercraft can resuspend solids from the lake bottom, particularly when operated in a startup or non-planing position. Minimal, if any resuspension occurs at the no wake, idle speed in both shallow and deeper depths. We found boats can resuspend sediment in 4 and 6 foot water depths where finer sediments are likely to be deposited. Larger boats and motors, such as the 100 hp outboard and 160 hp inboard-outboard had a great impact on sediment resuspension. This can be if the boat is operated with continued start and stop movements. A strategy should be developed to minimize the use of recreational watercraft of all sizes in depths less than 4 feet of water. Speeds no greater than no wake or idle should be operated in these depths. In depths greater than 4 feet, larger watercraft and motors have a potential to resuspend and reactivate marl when in the startup or non-planeing speeds. Precautions and limits on boat and motor usage and areas of operation may limit the reactivation of marl from the deeper depositional areas within the lake.
- The amount of active marl that is readily resuspendable can be increased by the relocation of marl from depositional areas to resuspension areas. This can occur from watercraft activity and/or wind mixing. Watercraft can resuspend sediments that would be accumulating in areas of the lake less susceptible to wind erosion. Once they are deposited in areas more susceptible to wind mixing, they can contribute to reductions in lake water clarity from wind mixing events.
- Shallow aquatic macrophyte beds, such as hardstem bulrush (*Schoenletus acutus*) are declining (Hoverson and Turyk, 2006) and may contribute to decreased water clarity and increased turbidity because of the lack of sediment protection from wind and wave mixing. The effects of wind and waves can decrease with interception with aquatic plant communities. In the case of Clark Lake with declining shallow aquatic plant beds, the dampening of wave and wind action is not fully understood but we assume

these communities can and do stabilize turbulent water and promote sediment settling. Reestablishment of a thriving shallow aquatic plant community would help to minimize sediment resuspension in shallow areas.

- It has been shown that fluctuations in lake levels, including summer can consolidate sediment and expose part of the lake bed, thereby inducing growth of emergent plant species. Both can aid in decreasing sediment resuspension by consolidating sediment that will be less likely to become agitated and resuspended and by the promoting the growth of shallow aquatic plant communities that will aid in stabilizing turbulent water.
- Although the results of this study represent a relatively short term investigation of water clarity in Clark Lake, they should be able to assist identifying areas of the lake that may be more susceptible to sediment resuspension. The modeling and particle composition maps along with the boating experimentation could be used to aid in developing a plan to identify regions of the lake and depths that need to be managed to improve water clarity and decrease turbidity.

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