Terra Vigilis Environmental Services Group

Lake Beulah Wave Impact Study

Phase 3 Final Report

Prepared for the Lake Beulah Management District

September 29, 2025

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Executive Summary

Introduction

In 2024, the Lake Beulah Management District LBMD) retained Terra Vigilis Environmental Services Group (TVES) to conduct studies focused upon wave enhancing (surf mode) wake boats and their lake bottom and shoreline impacts to Lake Beulah. This project began in the winter of 2024 and continued through summer 2025. The work has included three phases. Phase 1 involved a submersible drone survey of identified lake bottom damage sites. Phase 2 and 3 were conducted during the spring and summer of 2025 and focused upon demonstration of subsurface waves and propeller downwash impacts to the lake bottom and aquatic habitat, and surface wave impacts to the near shore of Lake Beulah. During Phase 2 and 3, a study design was organized to demonstrate a causal relationship between wake boats in surf mode in both start-up and passes operations and their lake bottom impacts at selected sites and depths in Lake Beulah. Submersible commercial drone and camera technologies were deployed during these phases of the project.

The following executive summary highlights the final report and findings contained therein.

Major Findings from Lake Beulah (Winter 2024-25) Lake Bottom Impact Survey

The principal findings of the Phase 1 project confirmed riparian owner concerns for lake bottom impacts. Visual evidence of loss of aquatic plant life including Coontail, Cabbage (Broad-leaf Pondweed), and Chara is noted. These aquatic plants are regarded as ideal habitat for gamefish. Of significance, these plant species are known to possess root structures that make them particularly susceptible to damage (dislodgement) from subsurface waves and propeller downwash. These plant loss impacts are observed at all survey sites.

Of particular concern is note that many of the high impact damage areas are within or border the Lake Beulah "Critical Habitat Areas" designated by the Wisconsin Department of Natural Resources (WDNR) in 1994. (See Figure 1).

CRITICAL HABITAT AREAS

Lake Beulah has eight sensitive areas designated by the DNR in 1994. These were further designated as critical habitats by the DNR.

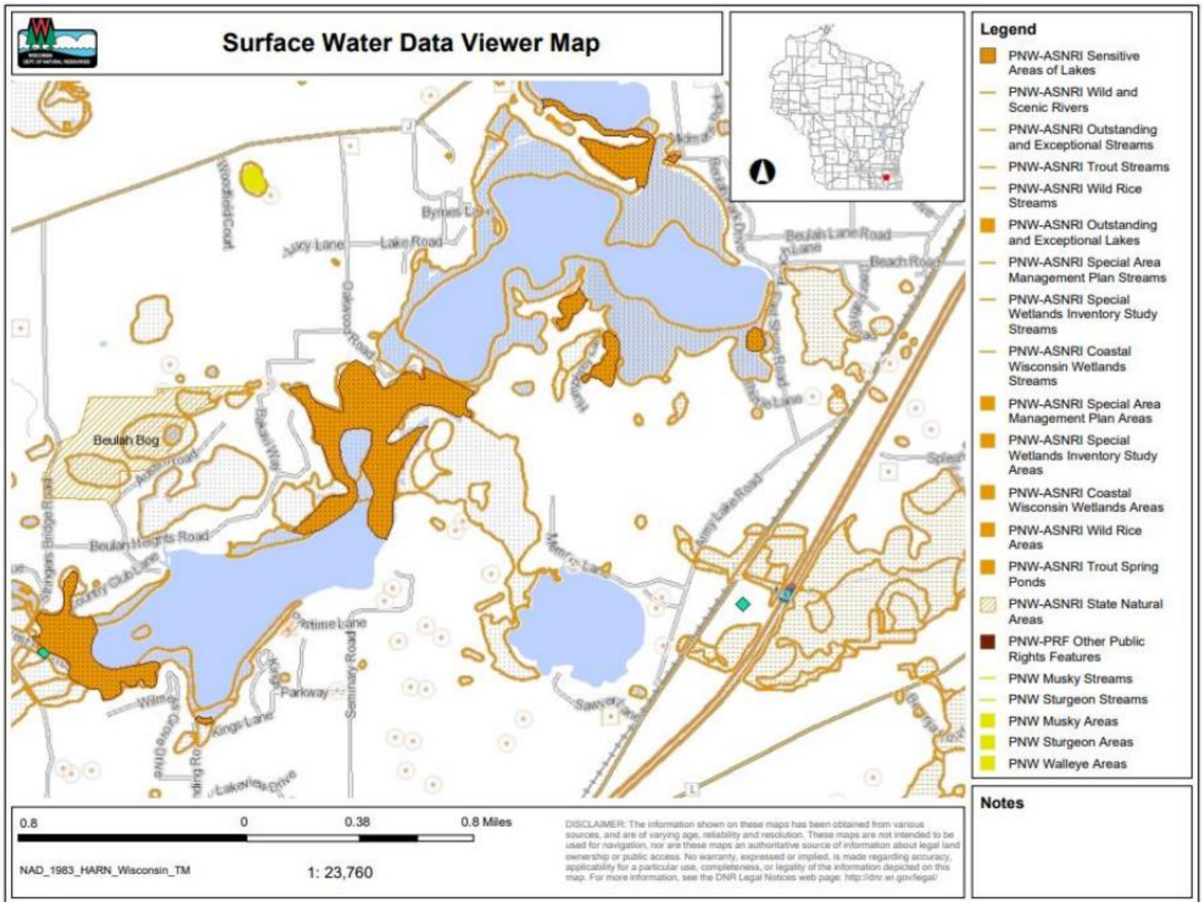


Figure 1 Lake Beulah "Critical Habitat Areas"

Lake Beulah Management District (LBMD) officials expressed interest in demonstrating that propeller downwash (slipstream) causation was a mechanism for these threats. The use of Wake Boats in "surf mode", utilizing large wave displacement equipment, was noted as a suspect vessel. The Phase 1 study identified the need for additional science-based study of in-lake surface and subsurface wave impacts to better understand and manage these phenomena.

Major Findings of the In-Lake Study: Surface Wave Impacts at Lake Beulah

Phase 2 & 3 of the in-lake project involved a comparative study of vessel-based surface wave characteristics and impacts to the near shore. Video imagery and surface measures of wave heights and wave energy calculations were completed. Comparisons between the wave characteristics of planing water ski boats (and other vessel types) and wake boats in "surf mode" was accomplished. Wave propagation from boats operating at distances of both 200 feet (current statutory requirement) and 500 feet from shoreline areas with steep slope were measured to establish impacts and inform the establishment of appropriate buffering distances to be established on Lake Beulah.

Wave Heights on average were at least 2X as high for Wake Boats in Surf Mode compared to planing Boats at the same 200-foot distance from shore.

This results in Wave Energy from a Wake Boat in Surf Mode that is 4X the amount of Wave Energy from a planing water ski boat at the same distance. To dissipate the Wake Boat in Surf Mode wave to the same height and energy as a planing water ski Boat at 200 ft requires increasing the distance from shore to over 500 feet. This corresponds with results from other studies including: SAFL (U of Minnesota), WEC, TVES-NLMD and TVES Lake Waramaug, CT 2024, and McFarlane, 2019.

(See Literature review section of the Lake Beulah final report)

Major Findings of the In-Lake Study: Sub-surface Wave Impacts at Lake Beulah
Phase 2 & 3 of the in-lake project involved a comparative study of vessel-based subsurface wave characteristics and imagery capturing evidence of deep-water subsurface waves and propeller downwash impacts to the lake bottom, sediment re-distribution and critical aquatic plant life damage events. Site selections were identified based upon typical start up and turn around areas used by wake surf operations on Lake Beulah. (See Figure 6).

The study revealed impacts of aquatic plant damage and lake bottom disturbances from wake surf operations in depths of 15 and 21 feet, and sediment movement at 25-foot depths. Comparative data did not reveal deep subsurface wave or propeller downwash effects from planing or "start-up" with water ski boats or other vessel types. Deep water videography established fluid kinetic energy effects to the lake bottom sediments to include sediment re-distribution and aquatic plant life disturbance for Wake Boats in Surf Mode during start-up and course pass operations. Similar comparative downwash "slipstream" depth data is available from additional studies conducted at Payette Lake, Idaho (Ray, 2021). These impacts were not seen with traditional planing water ski boats under the same testing conditions, i.e., start-up and course passes.

The final report also contained a detailed literature review of studies which have addressed similar large wave impacts in freshwater lakes in the Midwest, far West and Southeastern portions of the United States. Implications for lake ecosystems are described based upon these findings.

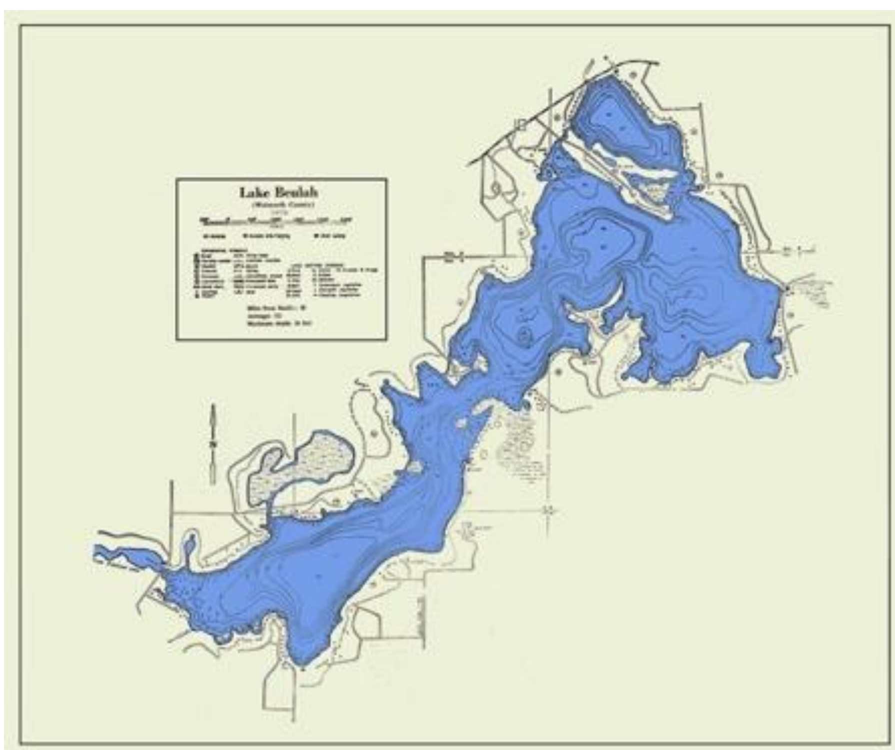
Appropriate references to studies informing portions of the current Lake Beulah research are cited.

1. Introduction (Final Report)

Terra Vigilis Environmental Services Group (TVES) was retained to provide a water quality and wave impact study for the Lake Beulah Management District (LBMD). The scope of work included a three-phase study. The first phase focused upon gathering subsurface videographic evidence supporting recent lake bottom disturbances described by riparian owners and officials from the LBMD. The second and third phases involved an in-lake study of large displacement wave impacts to the subsurface, near shore, lake bottom sediments and aquatic plant life of Lake Beulah. Measures and calculations of wave energy, wave characteristics, and wave attenuation distances were also gathered. The Phase 2 & 3 project involved a specific study of subsurface waves and propeller downwash depths to include videos of lake bottom sediment redistribution and aquatic plant disruption.

Site Description: Lake Beulah, East Troy, Wisconsin

Lake Beulah is a freshwater, Mesotrophic, lake located in southeast Wisconsin. The Lake size is approximately 812 acres with an average depth of 17 feet and maximum depth of 58 feet. (Latitude 42.821, Longitude -88.388)



The lake is approximately 4.0 miles long and has a variable yet maximum width of 1.5 miles. The surface elevation of the lake is 820 feet. Flat portions of the lake bottom consist of muck (60%) and sand (40%). An important element of the Lake Beulah lake bottom is marl, a lime rich-mudstone. The surrounding topography is hilly, and the lake side slopes are steep with sloping lake bottom features. Bathymetric data and video imagery confirms a lake which is rich with underwater reefs from shallow to deep lake bottoms.

Lake Beulah is a spring fed lake formed originally by a dam established in the 1830s. The watershed of the Lake is situated in the larger Mukwonago watershed (HUC Hydrologic Unit Code 07120006) The watershed is a combination of both forested and agricultural land. Lake Beulah is highly regarded as a fishing lake with a vibrant population of freshwater game fish including Muskie, Northern Pike, Walleye, Smallmouth bass, Largemouth bass, Crappie and Panfish.

Shoreline development includes residential homes, seasonal cottages and several camps (public/private clubs). Public access is available at a single site administered by the Town of East Troy.

The most recent bathymetric map (1967) was obtained by TVES and is shown in Figure 2. This mapping resource along with bottom mapping electronics, (Hummingbird Helix 7) and GPS were utilized to facilitate the location and selection of test sites at various depths. A weighted and marked line (12-inch markers) was used to accurately measure actual water depths at the test locations.

Lake Beulah is surrounded by two jurisdictions: the Town of East Troy and Village of East Troy. The lake is managed by the Lake Beulah Management District which was formally established as a lake district in 1995. Previously, the lake was managed by the Lake Beulah Protective and Improvement Association (circa 1894). There are approximately 400 Riparian owners of record on the lake.

The introduction of Wake Boats to Lake Beulah began in approximately 2015, and prompted concern for large wave impacts, and possible water quality and bottom scrubbing effects. The LBMD elected to conduct scientific studies on these impacts in 2024 in order to inform policymaking regarding management of these impacts.

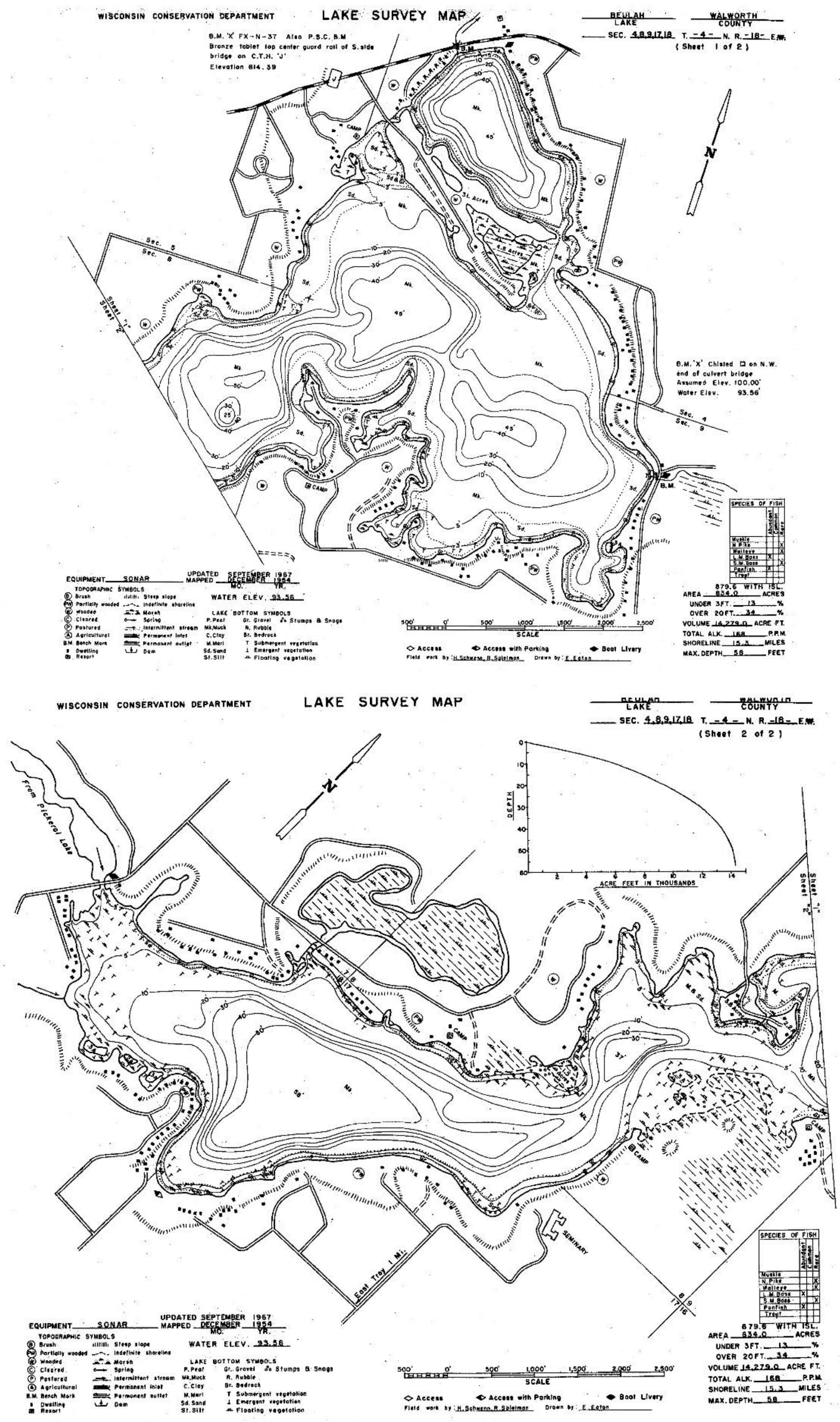


Figure 2 Lake Beulah Bathymetric Map (1967)

2. Literature Review (Large Wave Impacts)

The introduction of Wake Boats/Surf Mode capable, to the freshwater lakes throughout the United States began around 2010. The marine industry currently (2025) produces vessels with wave enhancing design characteristics allowing for the creation of large displacement waves of approximately 3–4 foot surface heights behind the transom. The typical Wake Boat utilized for "surf mode" operations has three primary engineered characteristics allowing for large displacement wave production including:

1) A powerful engine (350-600 hp)
2) Ballasting systems
3) Wave shaping technology (hull shape, gates, wedges, wave enhancing devices)

These vessels typically operate at 9-12 mph to maximize large displacement wave production for wake surfing. This "plowing" mode of operation (versus planing) typically results in a high bow angle, and low stern configuration.
The spread of these recreational boats across the country has been controversial, with increasing public concerns for wave impacts to other surface vessels, near shoreline, fish and waterfowl habitat, and shoreline structures. These concerns have prompted scientific study which has produced a growing body of data supporting surface and subsurface waves and propeller downwash impacts. In particular, the studies reveal:

- Wave attenuation distances which require longer buffering zone distances to mitigate damage
- Lake bottom disruption and re-distribution impacts from subsurface waves and propeller downwash of wake boats in surf mode.
- Nutrient release, lake bottom "scrubbing" damage, and related unseen impacts from powerful wave energy.
- The bathymetric characteristic of a particular lake is a variable, with shallower and smaller lakes (less than 20 feet depth and less than 100 acres) showing more evidence of large wave impacts.

The present study was designed to establish evidence of both surface and subsurface large wave impacts to Lake Beulah. Commercial drone technologies have been employed in this project to capture imagery allowing ease in understanding these impacts.

The current project benefits from reference to additional studies being conducted in the Midwest, far West and Southern portions of the United States. These comparative studies have occurred on freshwater lakes with a similar focus upon large wave impacts to the near shore, lake bottom and wave energy comparisons between wake boats in surf mode and traditional planing water ski boats.

Studies of Interest

Water Environment Consultants, SC (WEC) completed a recent (2021) wave impact analyses on Lakes Burton and Rayun in the northeast corner of Georgia. In addition, the WEC group studied three of six lakes in a series of reservoirs created by the Tallulah River system (owned and operated by the Georgia Power Company). This work was completed in 2020-21.

The principal findings of the WEC project established that wake board boats in surf mode (Maximum ballasting, slow speed, high bow angle) produce a more powerful wave, with higher speed, height and energy resulting in a need for longer attenuation distances than waves produced from wake board boats in non-surf mode and/or traditional planing water ski boats. Longer buffering distances (500 feet) from shore and other vessels were called for to manage these impacts.

Note to the reader: *Wave Energy (E) per unit area is proportional to the square of the wave height (h): $E \propto h^2$. In other words, if wave A is two times the height of wave B, then wave A has four times the energy per unit area of water surface compared to wave B. As another example, a 14-inch wave is twice as powerful as a 10-inch wave ($2 = 1.4^2$). This formula was used in TVES calculations relative to wave energy. A similar method is used in the SAFL data allowing comparisons.*

An interesting comparison from the WEC work involving wind waves versus wake surfing vessel wakes is also noted:

" *Wakesurfing vessel wakes exceed wind waves at every site at distances within 500 feet of the vessel sailing line. In contrast, typical cruising vessel wakes do not exceed wind waves at every site, except within a very close proximity to the vessel, i.e., 75 feet*"

Consideration for shoreline erosion was included in the WEC (2021) project. Although shoreline erosion is a complex predictive problem, influenced by localized conditions such as sediment properties, topographic slope, presence of hard structures and vegetation, the WEC study did conclude that wake surfing and wakeboard boating vessels are much more likely to contribute to shoreline erosion than typical boat waves or wind waves.

Finally, the WEC study addressed shallow near shore areas for lake bottom scrubbing impacts by wake surf mode vessels. Risks for "slip failure" of the soils behind sea walls leading to bulkhead failures was reported. "Overtopping" effects based on excessive wave heights from the surf mode wakeboard vessels can also produce structural damage per the WEC (2021) data.

Previous studies by Terra Vigilis Environmental Services (TVES) conducted on both midwestern lakes (North Lake Management District, WDNR Grant Funded, 2019-2021), and Eastern states (Lake Waramaug, Connecticut, 2023-24) have established similar impacts based on large wave energy by wake boats in surf mode.

TVES completed comparative studies of wave attenuation distances, lake bottom scrubbing, sediment redistribution and nutrient release events following wake surf mode activity. High energy wave features with lake bottom scrubbing impact and plume development are documented in the TVES 2020-21 data. Nutrient release (Phosphorous) into the water column has also been reported in the TVES work. TVES has also completed research on depth of subsurface waves and propeller downwash ("slipstream") demonstrating lake bottom impacts to 26 feet (Lake Waramaug, 2024).

The University of Minnesota, St. Anthony Falls Lab (SAFL) project (2020, 2025) headed by Jeff Marr and his research team, has also studied the impact of wake boats in surf mode relative to wave attenuation distances, wave energy measures and surface waves and propeller downwash depths. Marr et al., have called for extended buffering distances of 500-700 feet from active surf mode vessels, and the research team published additional work in August 2025 measuring subsurface waves and propeller downwash depths using sonar acoustic returns.

Alex Ray from the Western Colorado University has completed a series of studies (2020-21) at Payette Lake, Idaho. This work has focused on the impact of propeller slipstreams (downwash) on lakebed sediments in Payette Lake. Based upon concern for nutrient load impacts to the waters of this large lake system, and specifically the risk of toxic blue green algae and other cyanobacterial blooms, the author studied non-buoyant jet streams produced by a current model, (2019 Axis T-23) wake boat in surf mode. Significant impacts from surf mode operations and their consequent slipstream lake bottom impacts on sediment redistribution were delineated in this work. See Figures 1 and 2.

"According to modeling results, wake boat slipstreams have the potential to affect bed sediments at 33' of depth" Ray, 2021

Ray goes further by noting,

"*Adding passengers and ballast also creates higher slipstream velocities, as it increases drag on the boat. Additionally, while most boats pass through the RPM band correlating to the highest slipstream velocities (during acceleration to planing mode), surf-boats are often continuously operated at the speed where displacement, slipstream velocities, and trim angle are highest."*

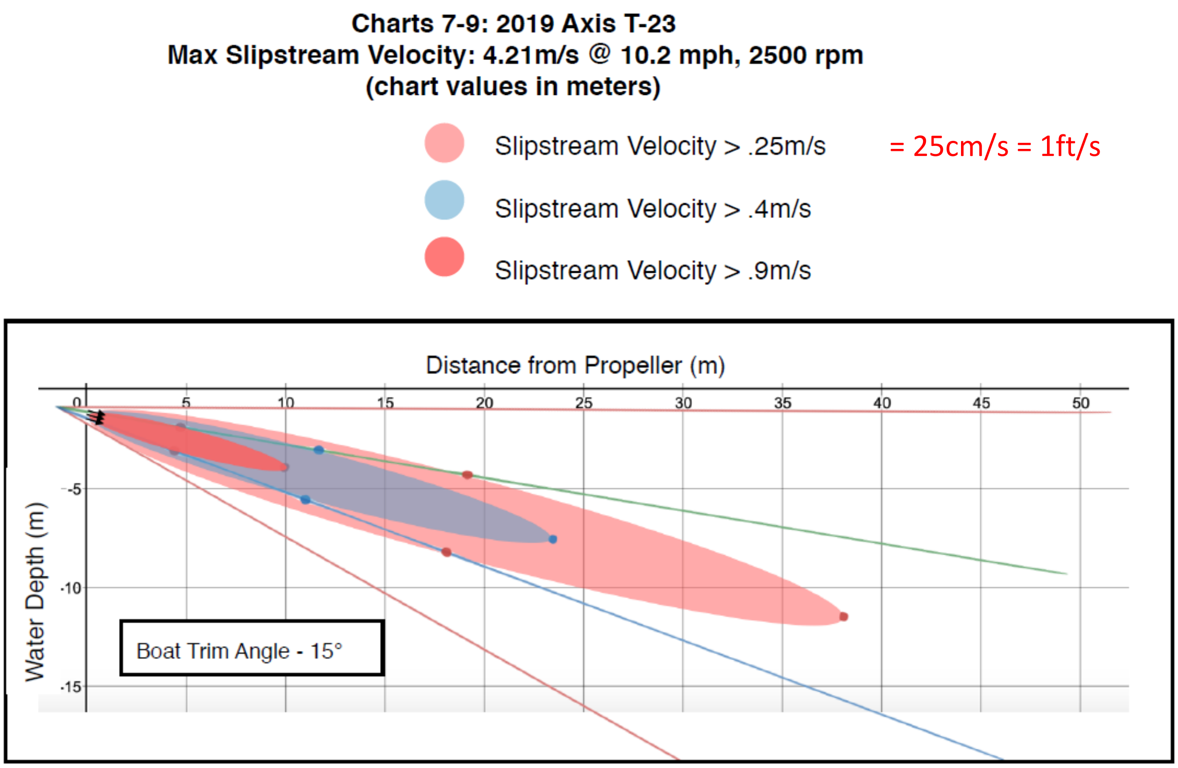
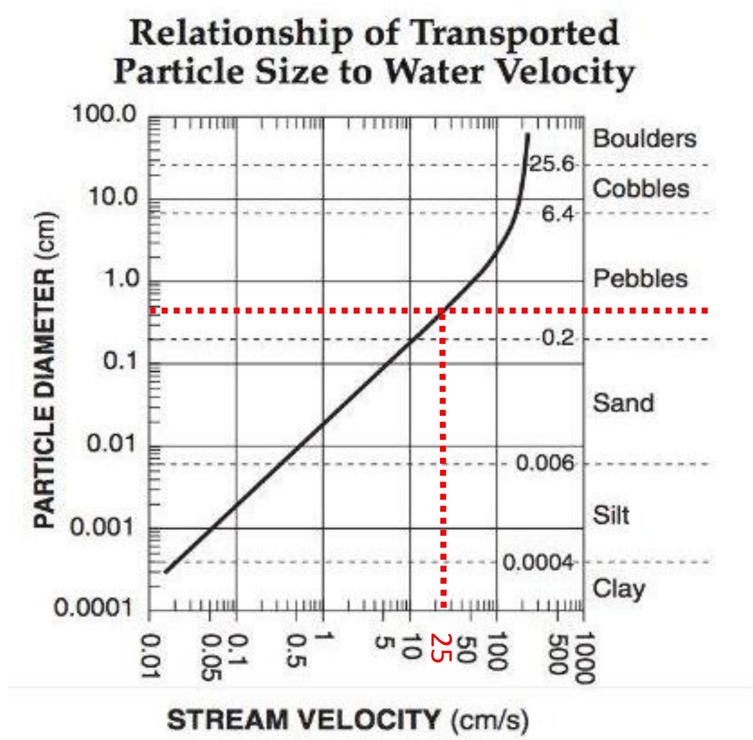


Figure 3 Propeller Slipstream Dynamics Payette Lake. Ray (2021) Final Report, Payette Lake



Figures 4: Sediment Redistribution: Water velocity needed to move particles based on size, Payette Lake 2021.

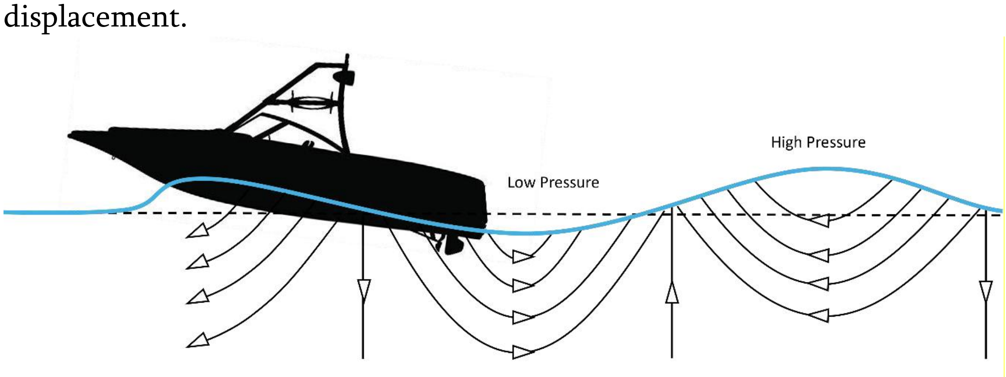
A timely meta-analysis of existing science on wake boat large wave impacts was recently organized by Professor Gregor McFarlane of the University of Tasmania (Australian Maritime College). A summary of his findings includes the following:

1. Wake energy/power is directly related to wake height and goes up exponentially. Wake/surf boats can generate wakes that are 10-25 times more powerful than wakes from boats operated on plane.
2. The results of scientific studies and recommendations from numerous sources and jurisdictions generally point to a distance of 500 feet or more from shore to reduce safety and erosion risks from wake/surf boats. Distances of 200-250 feet are clearly not effective.
3. The best correlation to wake energy and erosion potential is not boat length but rather "boat size", which is analogous to displacement. Displacement is the key factor in 2018 performance tests of surf boats.
4. Boats operating at transition speed* generate the most damaging wakes.
5. Boats operating below planing speeds include surf boats (8-13 mph), wakeboarding (typically 15-20 mph), and those towing inflatables (15-20 mph). Waterski boats typically operate at higher speeds (20-30 mph), on a plane.

**Transition speed is any speed between slow-no wake speed and the speed required for a boat to operate on a plane.*

Subsurface Waves and Propeller Downwash Studies:

Note to reader: In addition to propeller downwash there are three other types of subsurface waves generated by non-planing, large displacement vessels that can impact lake bottoms, aquatic plants, and habitat. The diagram below from the SAFL Phase 2 Report shows the subsurface wave types that are created by a displacement hull. These subsurface waves are more pronounced (and have higher energy and penetrate to deeper water depths) for wake boats in surf mode that have a large boat weight and ballasting resulting in more water displacement.



The Bow Wave is a pressure wave (down and forward) that forms at the bow of a boat hull as it displaces water during forward motion. The Stern Wave is a pressure wave that forms at the stern of a boat generated by the restorative upward motion of the water as it fills the volume (hole) previously displaced by the hull. Transverse Waves are a series of wake waves that extend astern and move in the same direction and speed as the powerboat itself, with crests oriented perpendicular to the direction of boat travel. Transverse Waves cause repetitive pressure waves that can penetrate to deep water depths for a sustained period (minutes).

Multiple studies have established that "unseen" energy related to these large waves, have significant impacts to subsurface structures, lake bottom integrity, sediment release and water chemistry. In addition, the subsurface energy impacts to shoreline structures, the bottom composition securing sea walls and related structures has also been noted as a concern. In shallower areas, impacts to fish habitat, waterfowl nesting and aquatic plant life have been noted. Deep water disturbances by Wake boats in surf mode have been measured to 25'. These effects are **not reflected when compared with other recreational vessels.**

To summarize, there is impressive consistency to the studies being conducted which demonstrates larger, faster, high energy, large displacement wave risks (both surface and subsurface) directly related to Wake Boats in "surf mode". These impacts are not demonstrated with traditional, less powerful water ski boats which operate on a "planing" configuration. These findings reveal impacts across multiple areas including:

1) Surface threats to other vessels
2) Near shoreline disruptions
3) Lake bottom scrubbing effects
4) Shoreline structure impacts
5) Nutrient release events to the water column
6) Deep penetration of subsurface waves and propeller downwash effects (e.g., fish habitats)
7) Wave attenuation distances prompting changes to traditional buffering distances

This final report of the Lake Beulah project by TVES, has also referenced examples from comparative studies of large wave energy surface and subsurface impacts to underscore the consistency of these data.

3. Wave Impact Study Lake Beulah, Wisconsin: Methodology

The Lake Beulah study was conducted in three phases including:

- In-Lake Phase 1, winter season (frozen lake) survey of selected lake bottom impact sites reflecting aquatic plant and lake bottom impacts via submersible drone imagery technologies.

- In-Lake Phase 2, videography of subsurface waves and propeller downwash impacts by Wake Boat in "Surf Mode" and typical planing boat. Both start-up and course pass testing conditions were performed as part of the study design at selected test sites.

- In-Lake Phase 2, measures of surface wave impacts (near shore) taken at steep shorelines with waves generated at 200-foot distances from shore by two vessel categories (planing Boat and Wake Boat in Surf Mode).

- In-Lake Phase 3, replication of Phase 2 surface and subsurface impacts with the addition of a more representative Wake boat and other vessel types

Commercial submersible drone technologies and fixed high resolution underwater cameras were used to measure wave dynamics as well as to capture fluid kinetic energy impacts to the lake bottom.

Detailed description of the UAS devices (drones) used in the present study follow. In addition, the subsurface measurement equipment, camera specifications and imagery preparation techniques are explained.

Together, these measures provide a clearer picture of large displacement wave impacts to Lake Beulah and a basis for comparable recreational lakes where wake boats in surf mode operations are occurring.

Methodology and Equipment

The Phase 1 survey of lake bottom impacts was completed by using a commercial underwater drone with 300 feet of tethered power and a communication/control source. (See Figure 7). The submersible measurement system utilized was a remote underwater rover with surface maneuvered commands from remote pilot using a virtual goggle system. The ROV was capable of a 300-foot range. The ROV was equipped with a propulsion system, powerful lighting (4,000 lumens), cameras and a mechanical arm to grasp and hold objects. See Figure 5.

Figure 5 ROV “Fifish” Model V-EVO 4K60

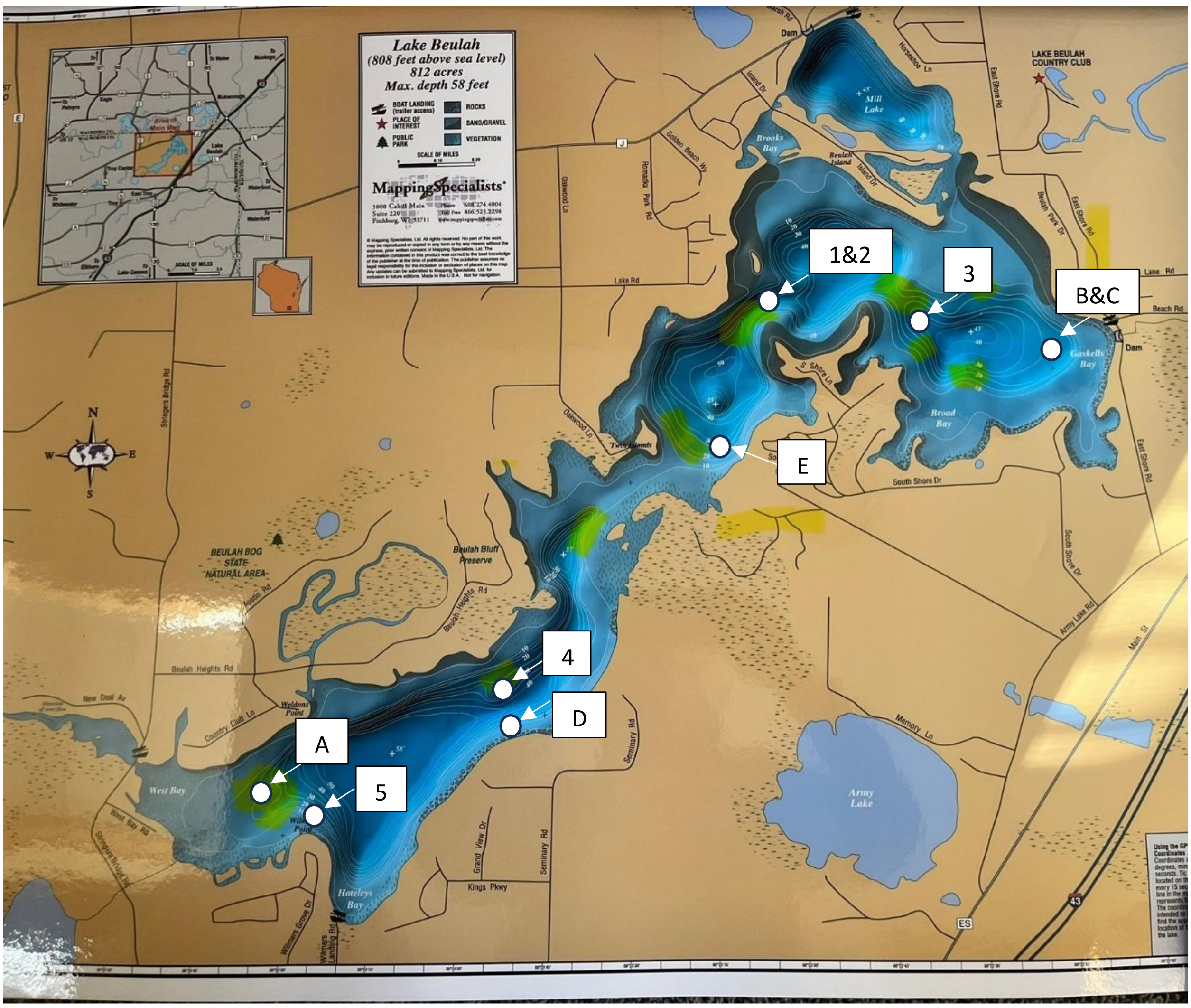


Figure 6 Lake Beulah Bathymetric Map with Phase 1 study survey site locations (1-5), Phase 2 test site locations (A-D), Phase 3 test site locations (1,2,D,E)

Assurance as to adequate ice depth for deployment of personnel and equipment to the survey sites was accomplished. Sites 1-5 were chosen as locations for lake bottom survey based upon evidence of lake bottom scarring and aquatic plant impacts. (See Figure 6). Wake Boats in surf mode were noted by LBMD authorities as typically operating with repeated startups, operating passes and turn arounds in these areas. Representative video and still imagery were captured in these survey sites and are presented in the results section of this report.

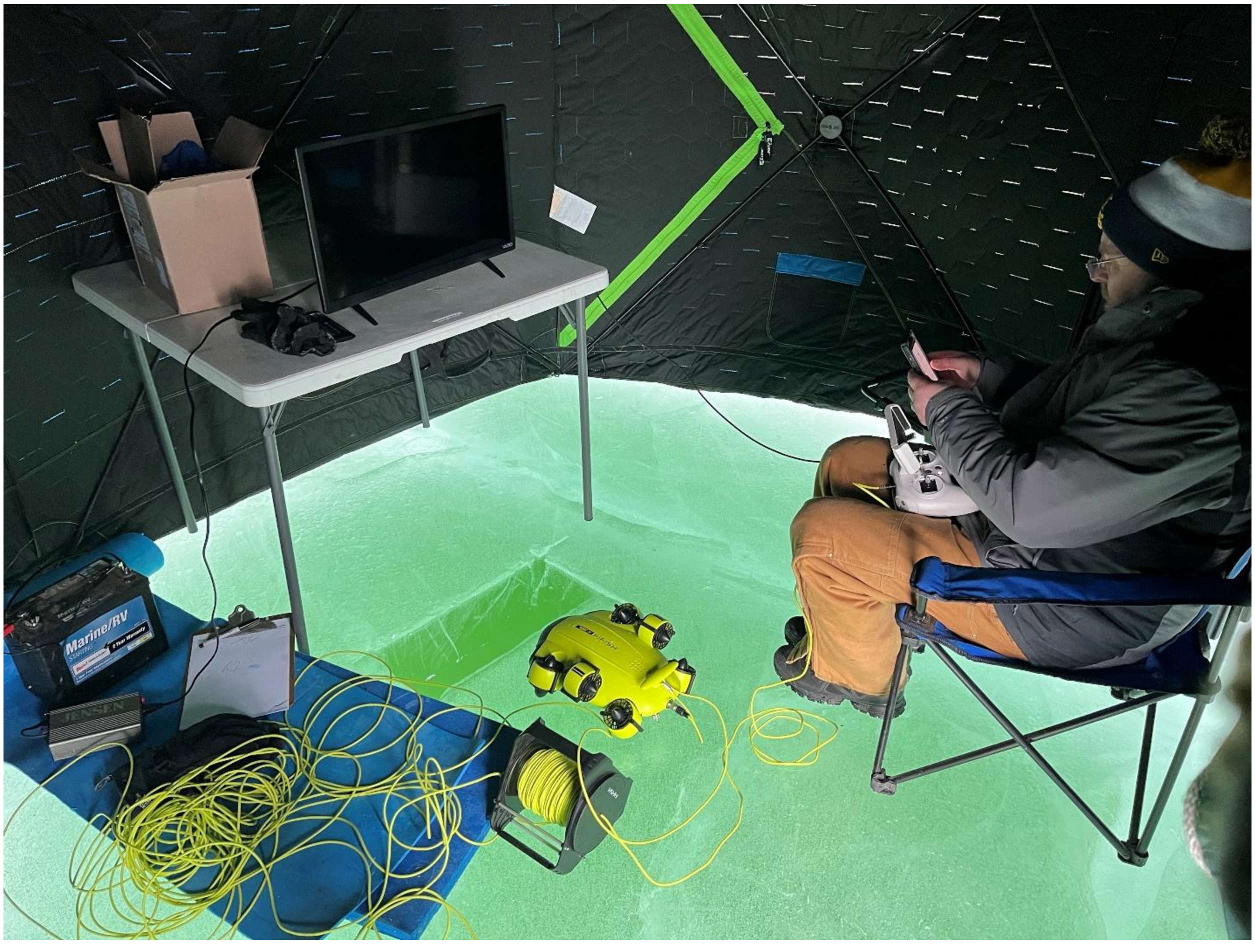


Figure 7 Submersible drone operations at Phase 1 survey site

The Phase 2 subsurface waves and propeller downwash testing involved a combination of controlled test runs executing 3 startups and 3 surf mode passes on a predetermined course at selected depths. Surface and subsurface fixed camera placements allowed for video capture of lake bottom impacts. Three separate test sites were used. Test site A was chosen for a uniformly flat lake bottom of 15 feet. Test site B was chosen for a similar flat lake bottom of 21 feet depth. Test site C was at 25 feet.

A current model (2025) wake boat in surf mode (Moomba,"Craz" 4,700 lbs dry weight, LOA 22', 4,500 lbs ballast, Raptor 350 hp engine, Wave Shaper (Gate/plate), and AutoWake Controls).

The comparative planing water ski boat was a 185 Sea Ray, Bow Rider, with a 4.3L V6 MerCruiser I/O engine (150 hp), 2,800 dry weight, no ballasting. The operational speeds of each vessel were chosen as representative for typical operations (Wake/Surf mode 10 mph, Water Ski Boat mode 22 mph). Experienced pilots were utilized for each vessel during testing conditions.

During Phase 3 testing the addition of a more representative wake boat was accomplished. This was a 2021 Axis A 24, with a 430 hp engine, wedge and surf gates, empty weight of 6,000 lbs and ballasting capacity of 5,300 lbs.

Phase 3 surface and subsurface testing also included comparative data from the following other vessel types representative of boats used on Lake Beulah:

Pontoon Boat: 2019 Lund LX 220, Tritoon pontoon boat with a 200 hp outboard.
Jet Boat: 2018 Scarab 165, 15'9 length, 1,600 lbs empty weight, 250 hp Rotax engine.
Water Ski Boat: 1987 Crestliner Nordic 205, 305 hp I/O engine, 2,950 lb empty weight.

Buoy markers were secured at each test site, and startup and passes were obtained for a Wake Boat in surf mode and compared to planing boat and other vessel types operating on the same course. Surface and subsurface fixed camera placements allowed for video capture of lake bottom impacts. During testing, multiple, separate startup and pass events for each vessel type were performed. See the results section for a data summary and imagery reflecting fluid kinetic energy impacts. Video imagery reflecting subsurface waves and propeller downwash and any resulting bottom sediment impacts were obtained for each vessel type.

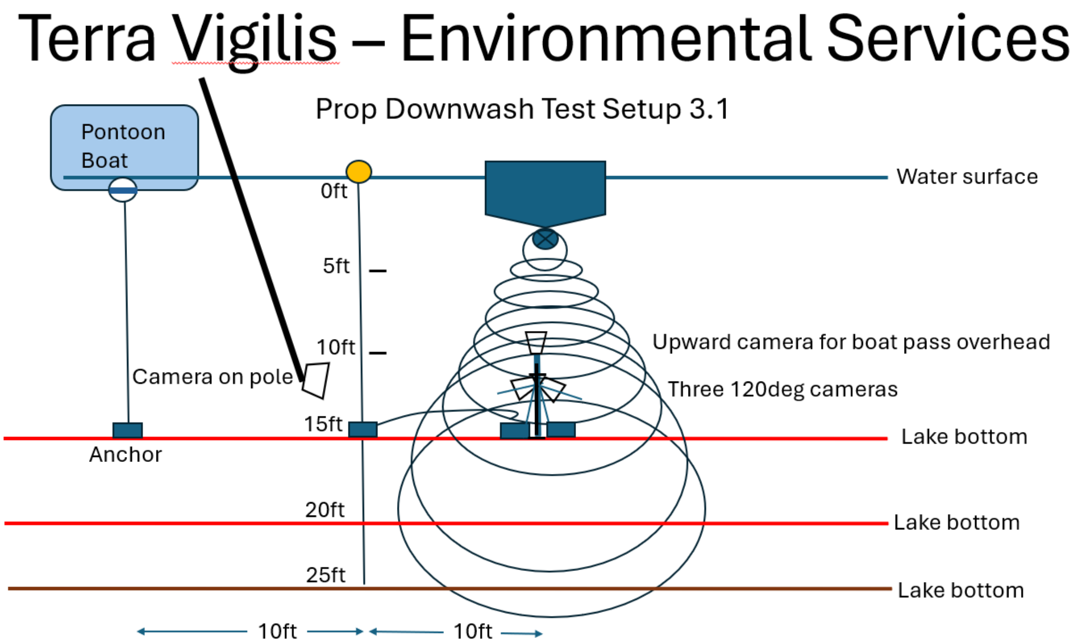


Figure 8 Engineered Subsurface camera system and test setup

A multi-camera tripod system (Figure 9) was lowered and anchored to the lake bottom at designated test sites (and depths) to record subsurface waves and propeller downwash impacts to lake bottom aquatic plants and sediment disruptions and re-distribution into the water column. A marker buoy was used as a reference on the surface for the test vessels to pass directly over the subsurface camera system.

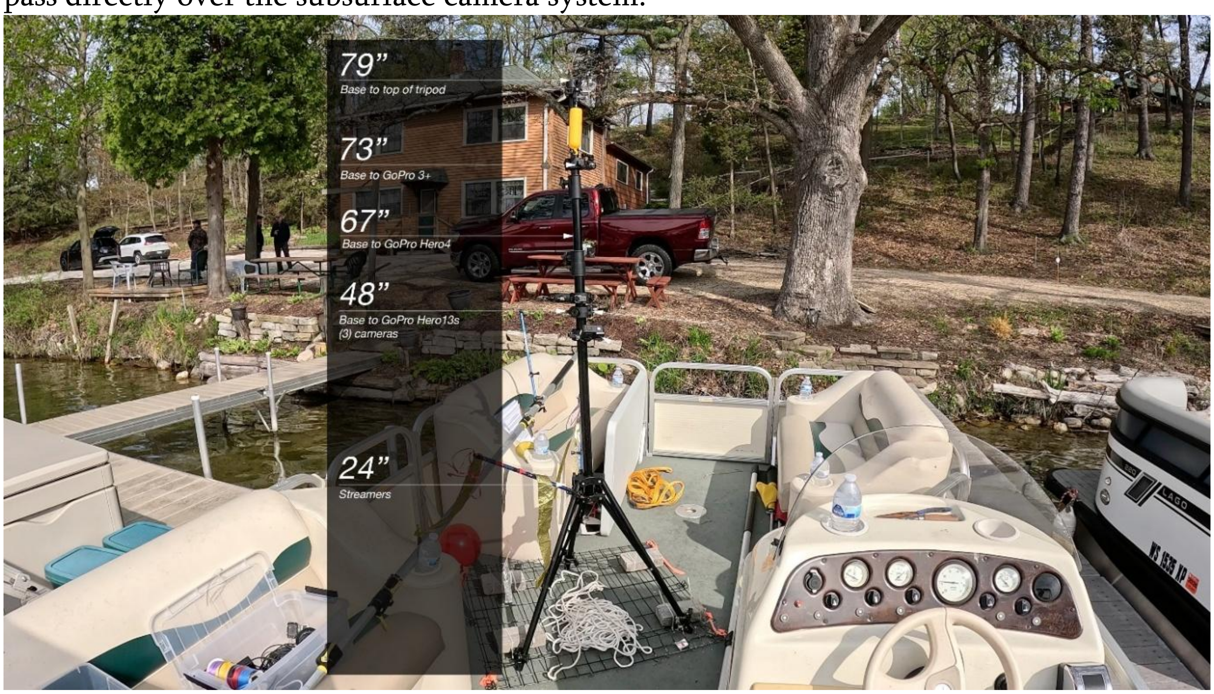


Figure 9 Submersible Multi-camera tripod system

A twenty-five-foot telescoping aluminum pole with a wired camera system was also deployed at each test site to verify subsurface equipment positioning and lake bottom conditions. The telescoping pole had a CanFish CF1 Live Underwater Camera attached at the bottom of the pole to visually see and record. The CF1 camera features a high-definition wide-angle lens, supporting 1080P video and 2MP photos for clear and detailed underwater visuals. An 18-inch extended fixture was attached at a 90-degree angle to the vertical pole at the top to provide a reference for the camera orientation underwater. All video captured was date and time stamped.

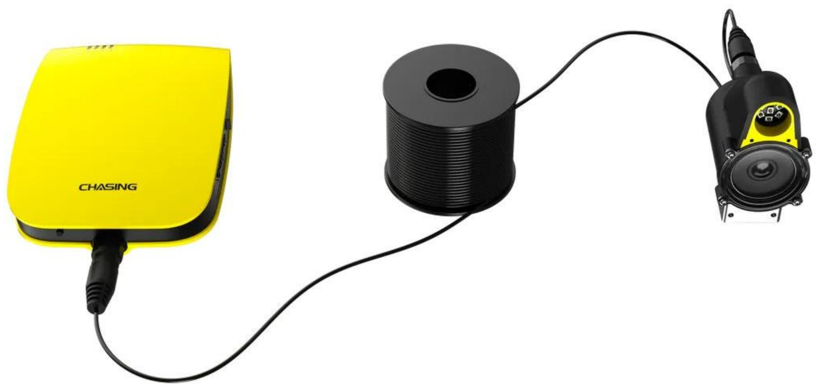


Figure 10 CanFish CF1 Live Underwater Camera System

The Phase 2 & 3 testing also included videography of near shore (200 and 500 foot from shoreline) wave propagation impacts to the shoreline located on the southeast portion of Lake Beulah. This location (Site D) was chosen for the lake bottom topography which includes a steep sloping lake bottom and riprap shoreline with representative riparian owner dockage and piers. Standardized survey poles were placed to measure comparative wave heights at the near shore following passes by the test vessels (wake boat in surf mode, jet boat, pontoon boat and planing water ski boat).

Buoy markers were placed at 200 and 500 foot distances from the shoreline at Site D allowing for a professional driver, operating a Wake Boat in Surf Mode, and representative planing boats to make multiple individual course passes parallel to the shoreline. Multiple surface, cameras recorded each pass with pause intervals allowing wave activity to dissipate fully between passes. Wave heights were measured in a repeated measures design. Wave energy was also derived from these measurements. See the results section for a data summary and graphic display of these comparative data sets.

All TVES submersible equipment and hardware were pre-tested for stability, signal reliability, and battery supply prior to testing conditions.

4. Wave Impact Study Lake Beulah, Wisconsin: Results

The Phase 1 Lake Beulah lake bottom survey results were gathered on 8 February 2025. A winter ice tent structure was erected at the pre-selected sites chosen by the LBMD authority. (See Figure 6) Multiple sites were used to gather lake bottom data imagery with a commercial submersible ROVER vehicle operated by a TVES professional commercial drone pilot using virtual FPV (First Person View) goggles and computer consoles as shown in the methodologies section. Clear evidence of substantial lake bottom disruption is revealed in these images. Of significance, the aquatic plant damage is extensive and notable for plant loss in large areas of the survey. Plant survey data provided to TVES by the LBMD establishes that these areas are heavily populated by several aquatic plant species including Cabbage (Broad-leaf Pondweed), Coontail and Chara. (See Figure 11)

Figure 11 Phase 1 Video Survey of Lake Bottom at Sites 1-5
Site 1: West Horns 15-25 Foot Depth

Site 2: West Horns 15-25 Foot Depth
Site 3: East Horn 10-30 Foot Depth
Site 4: Mid-lake hump in Long Lake 15-30 Foot Depth

Site 5: Sandbar off Wilmers Point 15-30 Foot Depth

Subsurface Waves and Propeller Downwash Impacts

Phase 2 subsurface waves and propeller downwash test results reflect comparative data on subsurface impacts effected by a wake boat in surf mode and a planing water ski boat. Figures 12-15 reveal impacts to the lake bottom (sediment and plant disturbance) in both 15', 21' depths by wake boat in surf mode operations both for start-up and buoy pass (at operational speed) testing conditions. Minimal apparent impact is shown at 25' depth (a site with marl lake bottom and devoid of plant habitat). See Figures 16-17. Figures 18-19 do not reveal planing water ski boat impacts to the lake bottom at depths of 15 feet or greater. In the Phase 2 study, sediment disruption was not apparent at 25-foot depth due to several factors including: hard marl lake bottom at Site C, and propeller downwash angle and energy from the wake boat obtained and used for the Phase 2 study.

In the Phase 3 study with a more representative Wake boat in surf mode with a larger water displacement (weight) and larger engine (430hp), sediment movement was observed at 25-foot depth. Similar findings of sediment disturbance and redistribution at 26-foot water depth at Lake Waramaug (TV-ES study) can be attributed to the presence of deep penetrating subsurface waves from the wake boat in surf mode and the presence of fine silt sediment on the lake bottom.

The TV-ES In-lake studies at Lake Waramaug and Lake Beulah provide videos at 26' and 25' respectively showing fine sediment (dark silt) moving onto and off the gray brick used to anchor the camera tripod. Fine silt needs a water velocity less than 0.3ft/sec to move it. The SAFL Phase 2 report describes and confirms that water movement caused by bow/stern waves and transverse waves go even deeper than from propwash, and the sequence of when they occur relative to the boat passing overhead are confirmed by the videos. In previous reports all of those hydrodynamic effects were typically classified just as propeller downwash, however with the videos and the vessel displacement hydrodynamics explanation, there is now a better understanding and appreciation of the various and specific hydrodynamic effects that each cause sediment movement at those depths (i.e. bow/stern waves and transverse waves in addition to and separate from propeller downwash).

Vertical water velocity is also redirected/deflected to a Horizontal velocity when the bow wave reaches and impacts the lake bottom, and the reverse for water movement from the Stern Wave. The Horizontal velocity is significant in that water is rapidly moving to fill the "hole" in the water behind the wake boat in surf mode. This results in sediment being “sucked” off the lake bottom and creating plumes seen from above. This phenomenon is additional to and separate from, propeller downwash and can occur at even deeper depths for extended periods of time as seen in the videos.

SAFL in their Phase 2 report explains how they selected a threshold of 0.3ft/sec which can move/disturb coarse sand/silt. Smaller particles need less water velocity to be disturbed (as the TV-ES videos demonstrated) compared to larger particles which need a higher water velocity to be disturbed. Note also that smaller particles are more likely to contain organic (nutrient) material that will be suspended for longer periods of time in the water column as compared to larger particles like sand and pebbles which are more inorganic, mineral based.

Subsurface Lake Bottom Impact Summary:

A buoyed course was established for testing in selected depths. Comparative data on lake bottom impacts was recorded for test vessels including wake boat (surf mode), ski boat (I/O), jet boat, and pontoon boat.

Operating Mode	Outcome at 15' and 20' depths*
Wake boat start up	***Impact***
Wake boat pass at 10.5 mph	***Impact***
Ski boat start up	No Impact
Ski boat pass at 25 mph	No Impact
Jet boat start up	No Impact
Jet boat pass at 32 mph	No Impact
Pontoon start up	No Impact
Pontoon pass at 32 mph	No impact

*Sediment disturbance noted at 25 ft

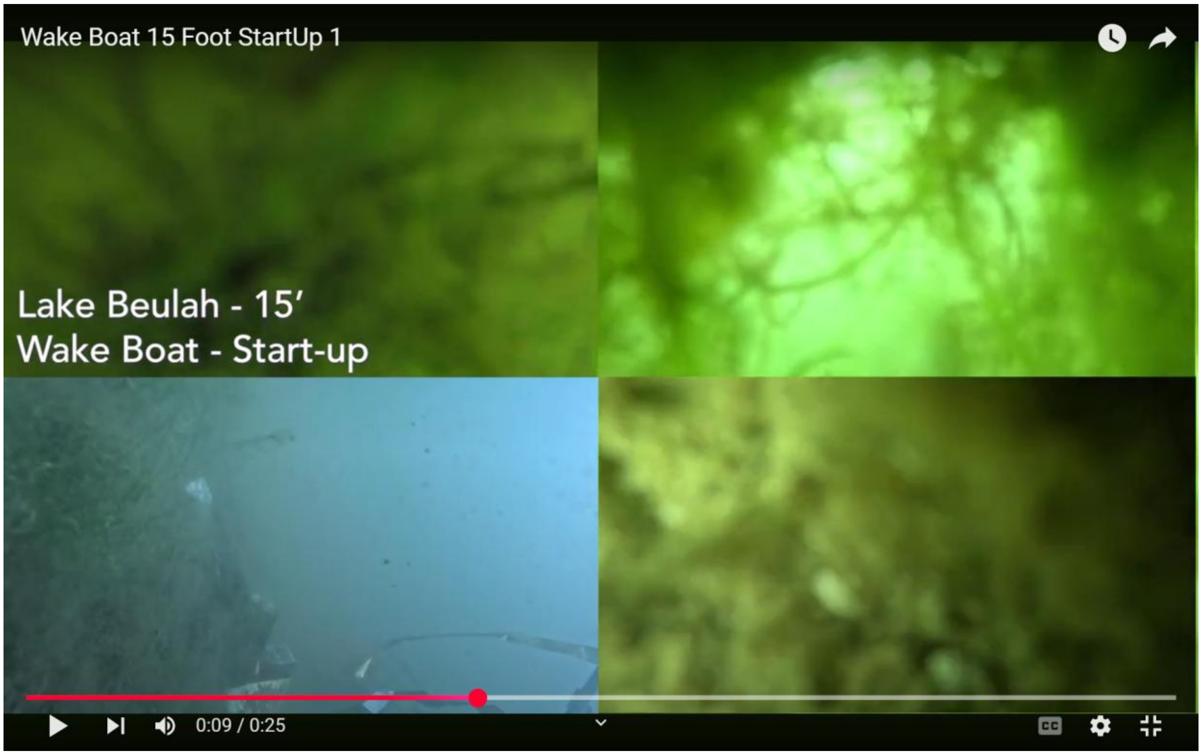


Fig. 12 Phase 2 Subsurface Waves and Propeller Downwash Impacts of Wake Boat Startup at 15 Feet

Fig. 12A Phase 3 Subsurface Waves and Propeller Downwash Impacts of Wake Boat Startup at 15 Feet

Figure 13 Phase 2 Subsurface Waves and Propeller Downwash Impacts of Wake Boat Pass at 15 Feet

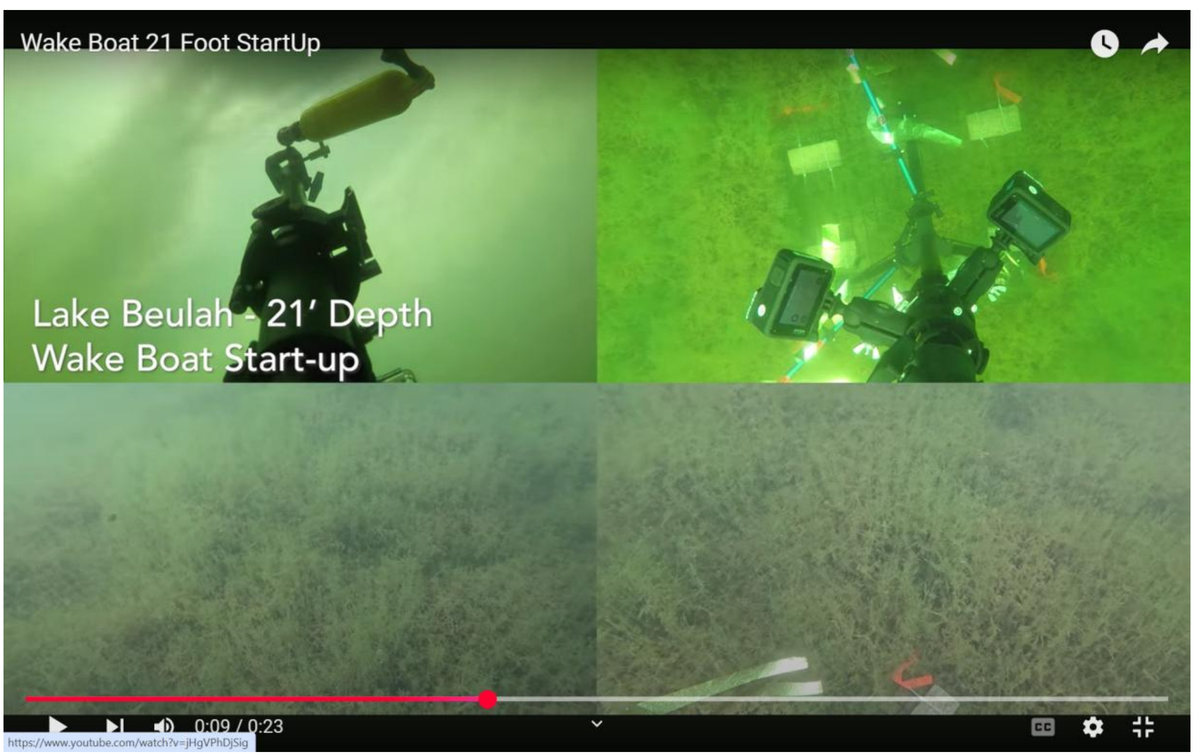


Figure 14 Phase 2 Wake Boat Startup at 21 Feet

Figure 15 Phase 2 Wake Boat Pass at 21 Feet

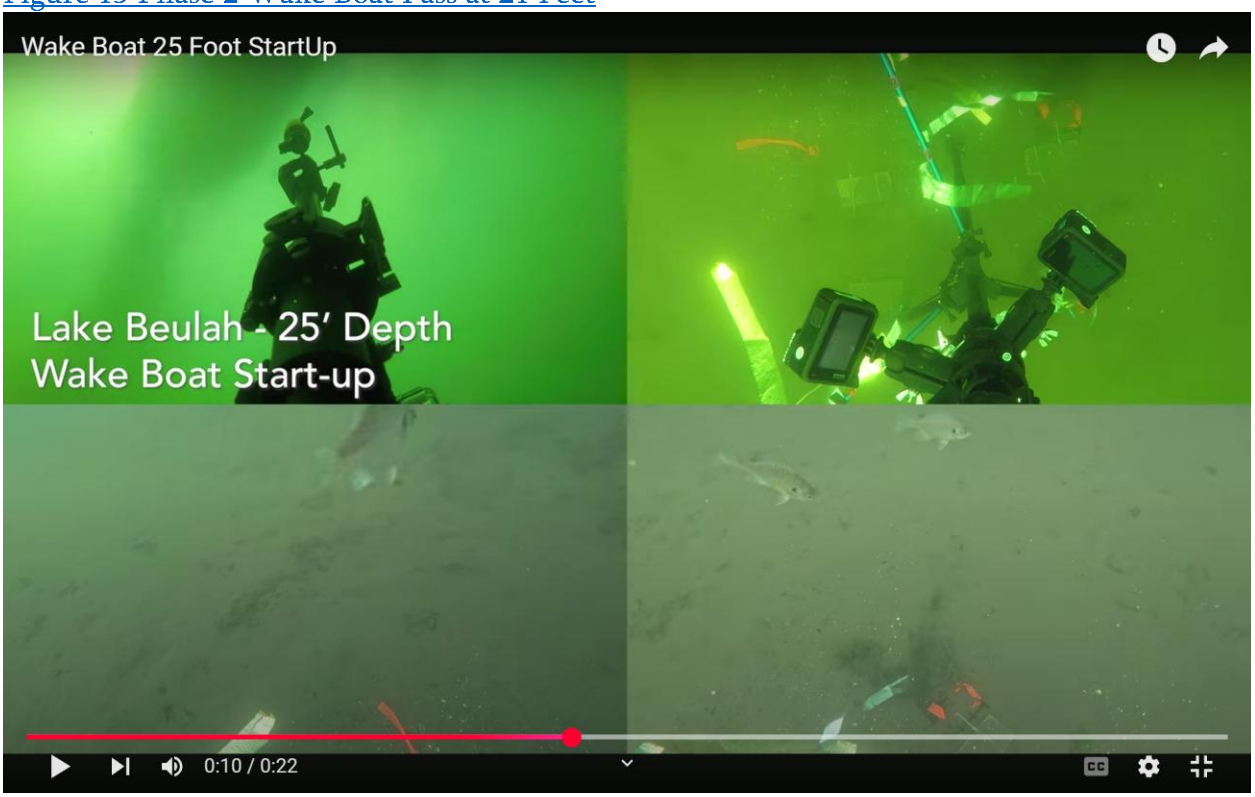


Figure 16 Phase 2 Wake Boat Startup at 25 Feet

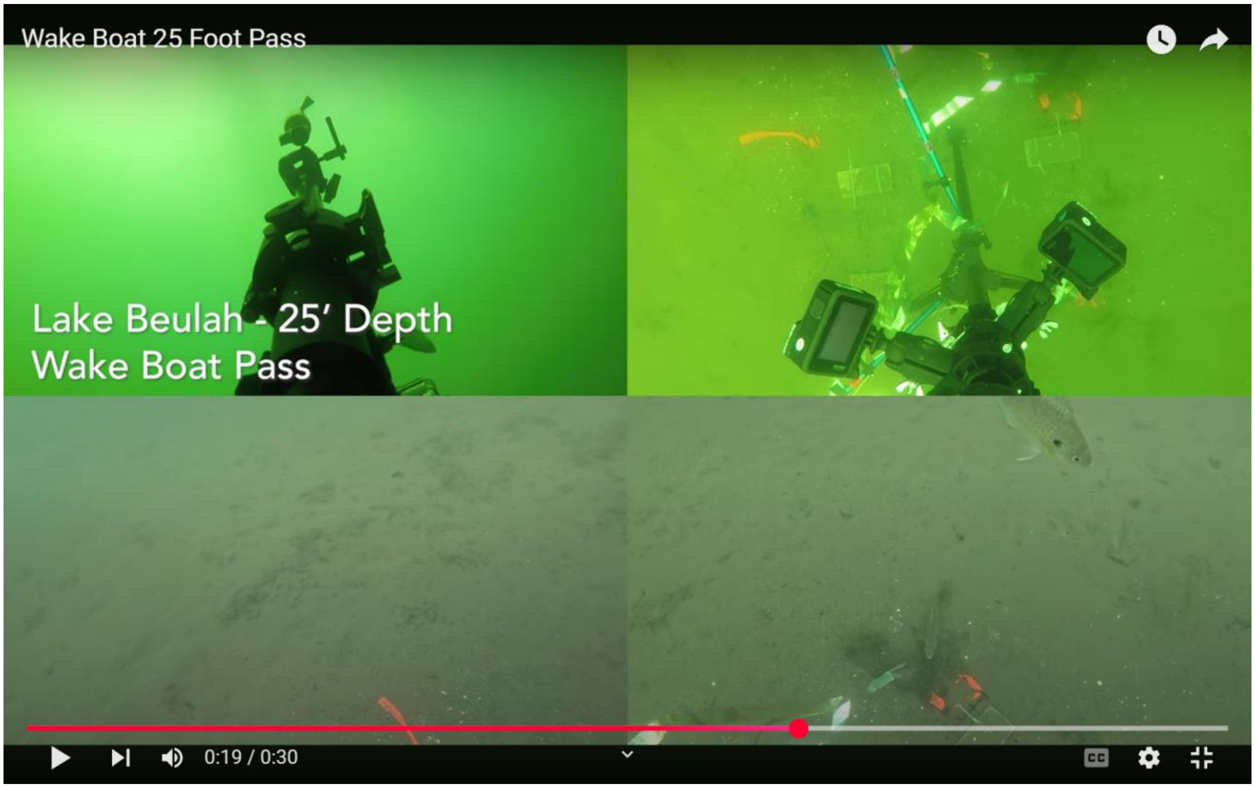


Figure 17 Phase 2 Wake Boat Pass at 25 Feet

Figure 17A Phase 3 Wake Boat Pass at 25 Feet

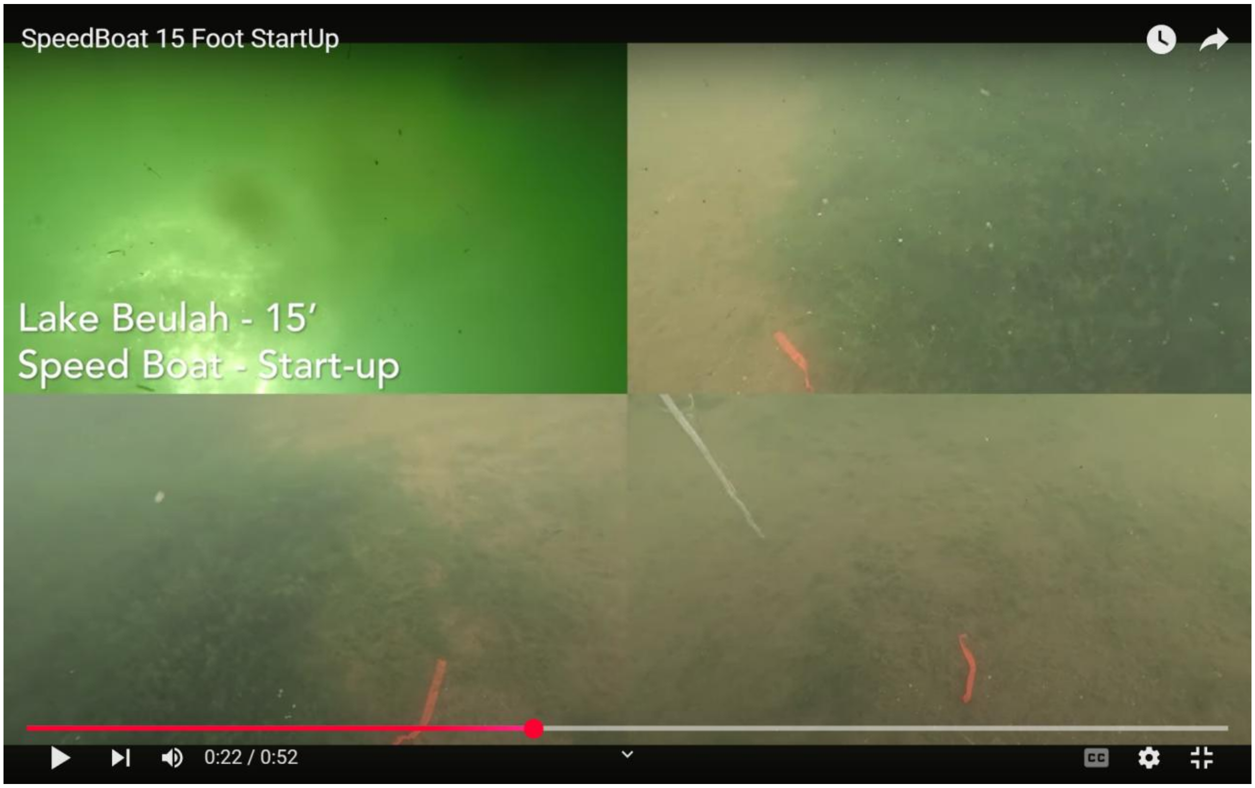


Figure 18 Phase 2 Speed Boat Startup at 15 Feet

Figure 19 Phase 2 Speed Boat Pass at 15 Feet

Surface Wave Impacts at Shoreline (Phase 2 May, Phase 3 July)

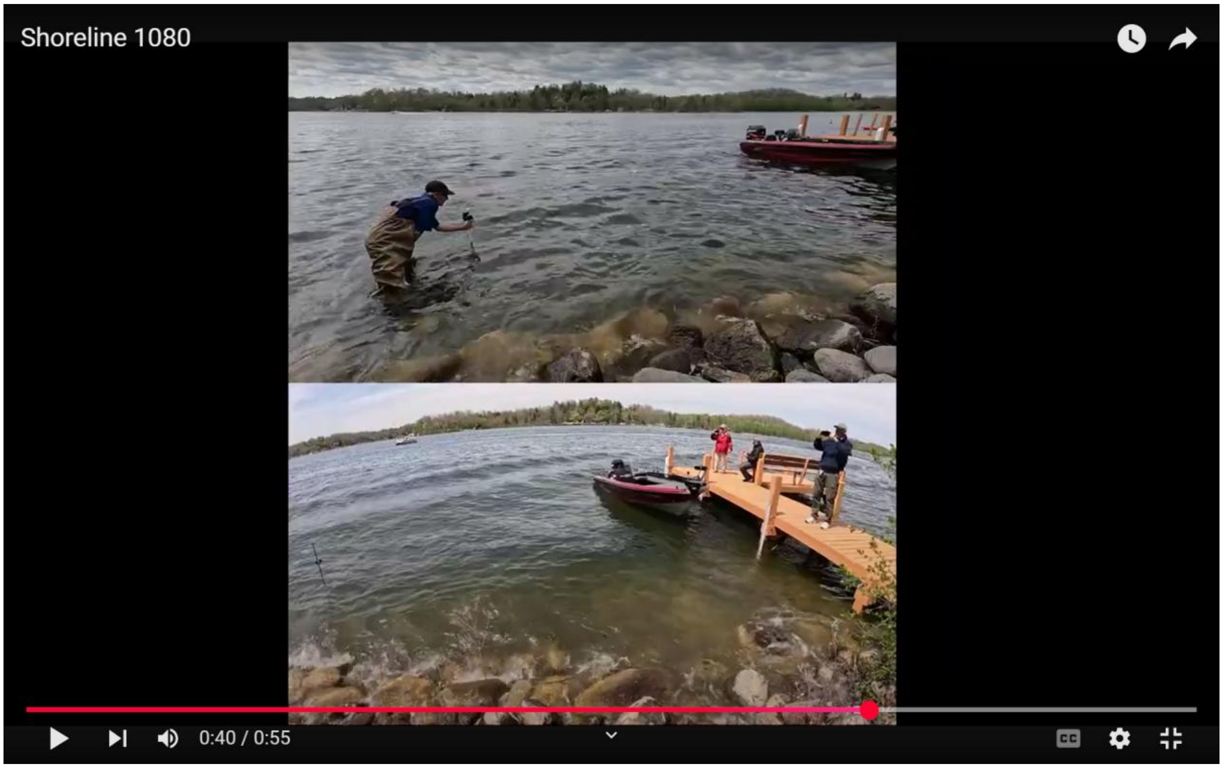
Wave propagation from series of near shore passes at operational speeds at 200 and 500 feet from the shoreline for both wake boat in surf mode and various planing vessels including water ski boats were recorded for demonstration of wave characteristics including wave heights, wave trough depth, and wave amplitude features and near shore surface impacts. (See Figures 20 and 23) Wave height and the resulting wave energy impacts to dockage and a tethered vessel at the dock, are clearly different upon review of the wake boat in surf mode versus planing water ski boat operations. (See Figure 21) Wake boat in surf mode produce wave effects that are more impactful to both dockage, tethered vessels and the shoreline structures compared to a planing boat.

Wake Surf wave height is 2X as high as a planing boat at the same 200-foot distance from shore. This results in Wave Energy from a Wake Boat in Surf Mode that is 4X the amount of Wave Energy from a planing ski boat at the same 200-foot distance from shore. To dissipate the wave from a Wake Boat in Surf Mode to the same height and energy as a planing boat at 100 ft (State statue) requires increasing the distance from shore to at least 500 feet (As seen in Figure 23). This corresponds with results from other studies including: SAFL, WEC, NLMD.

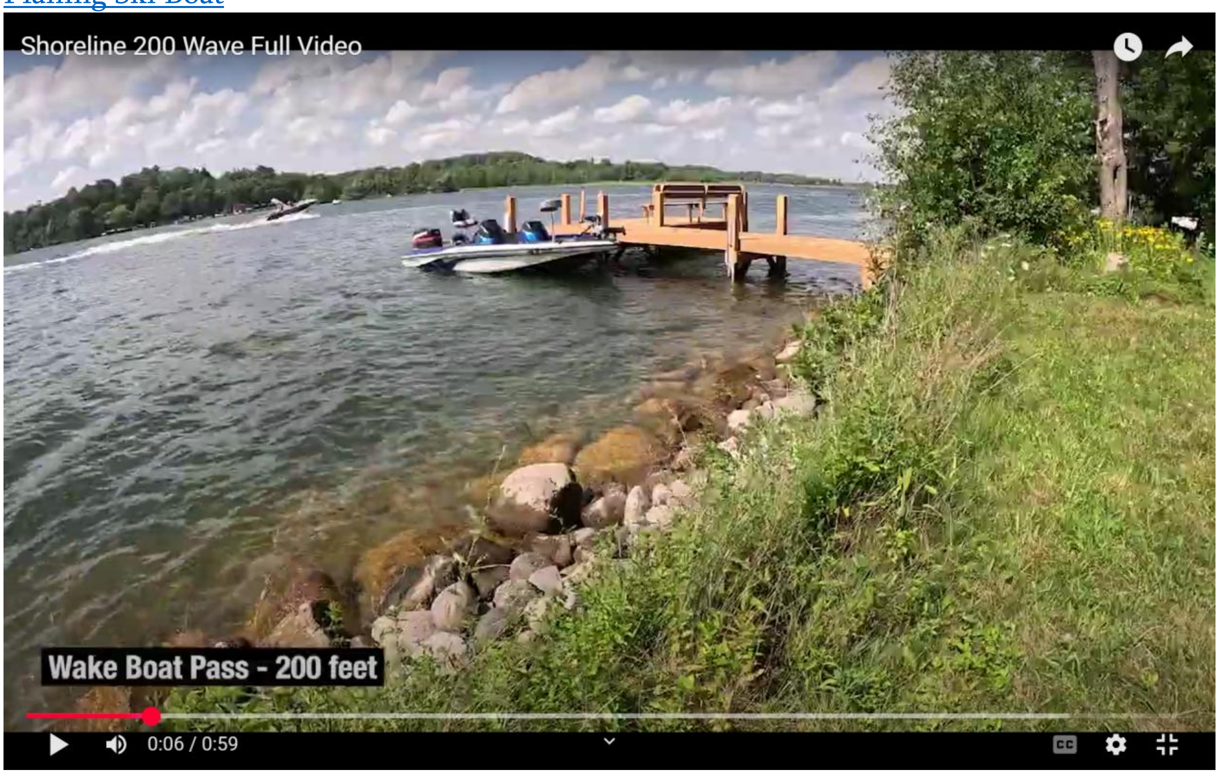
Traditional (non-wake surf mode operation) surface vessel wave buffering distances have been previously established for freshwater lakes though-out the United States. Historically, states have adopted a 100' or 200' standoff distance from shorelines and other vessels to minimize risk and damage. The introduction of Wake Boats, particularly in "surf mode" however, has produced wave features incompatible with existing standoff distance statutes established for the traditional water ski and cruising boats that produce waves that are smaller, with less surface energy and have shorter attenuation distances.
Studies have identified this concern with recommendations for buffering distances ranging from 500' to 1,000' depending upon lake size and shoreline features. The basis for these recommended increased distances are the wave energy impacts based directly upon wave heights.

Also noted is the need for establishing lanes in the center of the lake (at least 500' from shorelines) for wake surf operations as the 200-foot suggestion from the wake sport industry is not sufficient to assure that the wake surf side and selected route on the lake is always facing away from shore due to the switching of the operational stance of different riders (i.e. left foot forward rider prefers a wave on the left (port) side of the boat, while a right foot forward rider prefers a wave on the right (starboard) side of the boat).

The reader is also encouraged to consider the TVES test team observations of the wake surf wave propagation to the far shore (when the wake surf wave is aimed away from the near shore) as being substantial (at a distance of 1,000 feet). See Figure 22. Again, the planing water ski boat wave propagation to the far shore was observed to be minimal.



[Figure 20 Phase 2 Waves Generated 200 Feet from Shoreline of Wake Boat in Surf Mode vs. Planing Ski Boat]



[Fig 20A Phase 3 Waves Generated 200 feet from Shoreline with Wake Boat in Surf Mode]

Figure 20B Phase 3 Comparison of Waves generated 200 feet from Shoreline

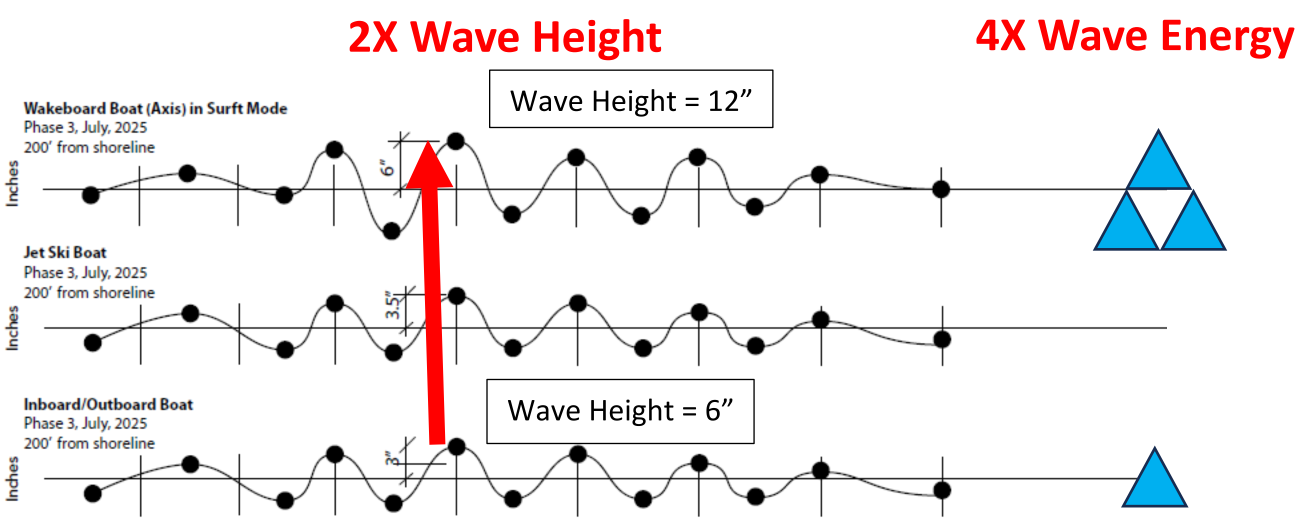


Figure 21 Phase 3: Wave Height and Energy Comparison from Pass 200 Feet from Shoreline

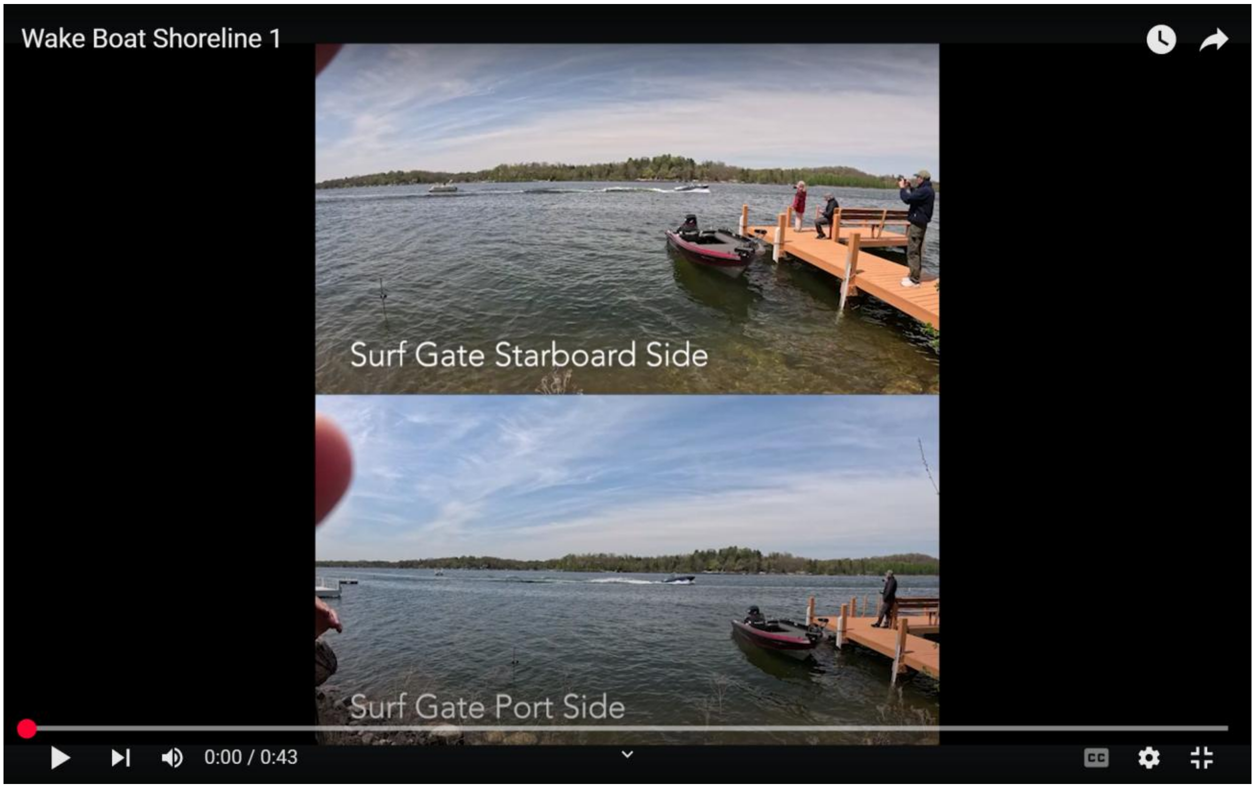


Figure 22 Phase 2 Wave Propagation at 200 feet from Shoreline - Port vs. Starboard Surf Wave

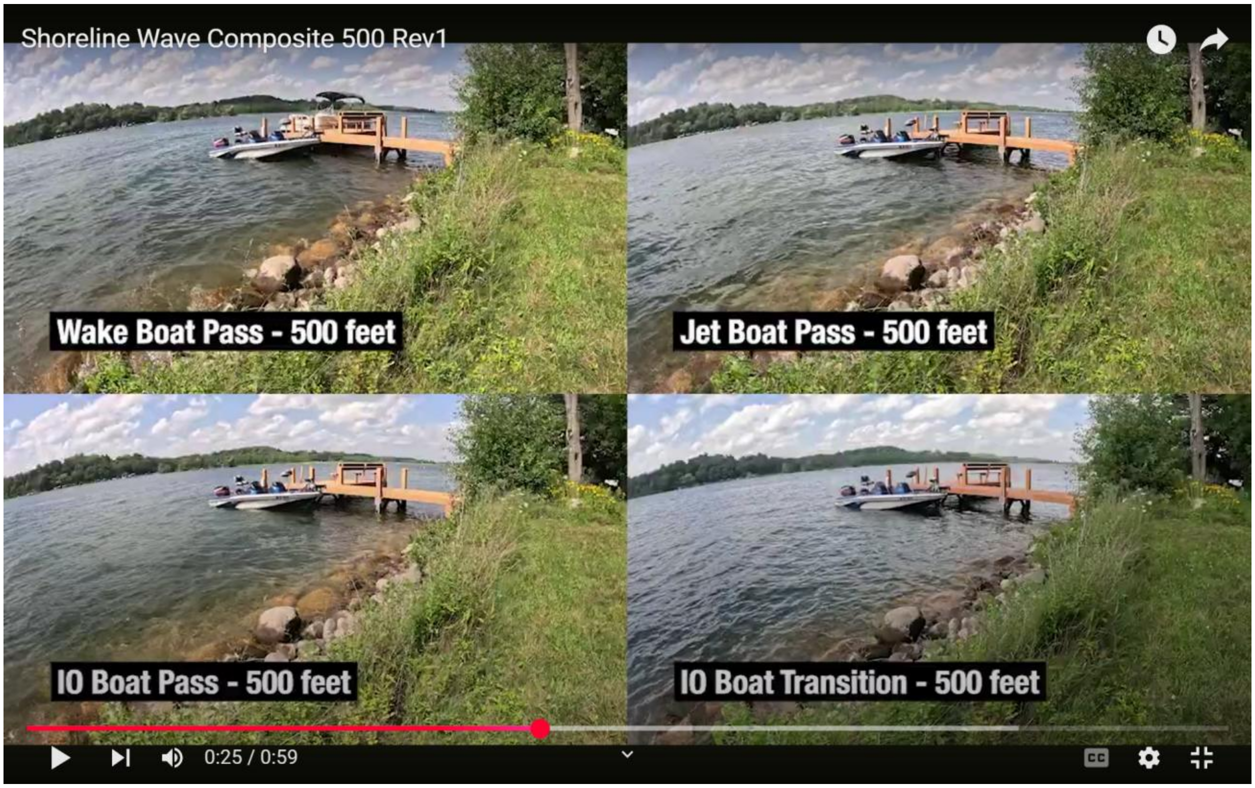


Figure 23: Phase 3 Comparison of Waves Generated 500 feet from Shoreline

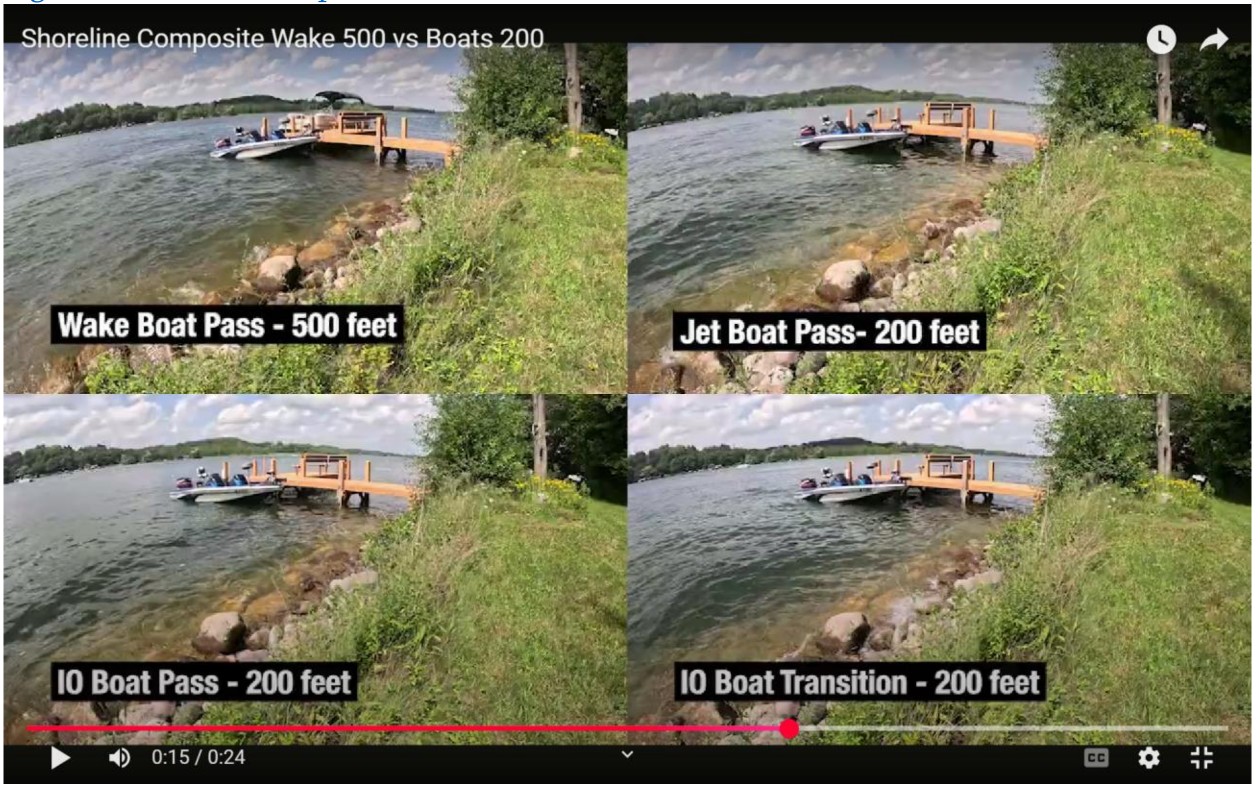


Figure 23A: Phase 3 Comparison of Wake Boat in Surf Mode at 500 feet versus Other boats at 200 feet

5. Summary and Conclusions

Terra Vigilis Environmental Services Group (TVES) was retained to study lake bottom and shoreline impacts recently observed within Lake Beulah, WI by authorities from the Lake Beulah Management District, (LBMD). A three-phase study project has been completed including a lake bottom survey of disturbed sites designated by the LBMD, and comparative in-lake studies on wave propagation and surface waves and propeller downwash differences between a wake boat in surf mode operation and other planing type vessels (pontoon boat, jet boat, water ski boat). Imagery revealed lake bottom impacts to the sediment and aquatic plant life by a wake boat in surf mode during both startup conditions and buoy pass testing. Direct comparison to other vessel types in startup and buoy pass conditions did not reveal bottom impacts.

Several important factors are offered for consideration regarding these findings:

1) Wake boat surf mode operations at 200-foot distance from shoreline revealed near shore dockage and moored vessel impacts. Minimal impact demonstrated from comparative planing vessels including a water ski boat.
2) Wake boat surf operations with at least 500-foot buffer distance from shoreline are necessary to reduce wave height and wave energy to comparable amounts from other planing vessels at 200 feet.
3) Wake boat surf mode operations are producing lake bottom impacts in Lake Beulah which are notable for disturbance to aquatic plant habitat areas. These impacts do not appear to be produced by planing, water ski operations under similar test conditions.
4) Wake boat surf mode operations (subsurface waves and propeller downwash) are producing sediment disruption and re-distribution impacts to the water column. The composition of these sediments was not within the scope of the current study. Direct comparison to a water ski boat in startup and buoy pass conditions did not reveal lake bottom impacts.
5) Recent plant survey data supports sensitive area impacts to aquatic plants considered favorable to game fish and lake water quality in Lake Beulah including Cabbage (Broad-leaf Pondweed), Coontail and Chara.
6) There is a sizable population of "home lake" wake boats capable of surf mode operations on Lake Beulah. This number is aggravated by off-lake Wake boats which also utilize Lake Beulah.
7) A DNR "Critical Habitat Area" study has established that areas being impacted by Wake boat surf mode operations (as described in this report) are occurring in and adjacent to several of the designated critical habitat areas in Lake Beulah.
8) The wake boat obtained for use in the Phase 2 testing was a current model, with a lower powered engine (350 hp), with auto wake controls, compared to a more typical

wake boat obtained for use in the Phase 3 testing with higher engine power (430hp), larger ballasting capacity and higher bow-deck angles.

9) Opinion should be obtained from a subject matter expert (SME) with specific expertise in aquatic plant root structures and fish habitat influence by plants found to be impacted in the current study.

The in-lake study at Lake Beulah has demonstrated that large displacement wave action from wake boats in surf mode are larger and of higher energy than other planing vessels in common use on the lake. These findings are consistent with similar studies, from multiple research groups, in the Midwest, West and Southeast portions of the United States.

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