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Introduction

The Lake Wedowee Property Owners Association (LWPOA) represents approximately 500 lake property owners. Many owners have experienced damage to their boats, docks and seawalls due to high wakes. Residents have reported small craft being swamped. Small children swimming in shallow water can be at risk of drowning as large wakes approach shore.

In May 2022 the LWPOA surveyed members about their experience with wakes created by wakesurfing. Our membership was encouraged to invite non-members to respond to the survey. Our goal was to solicit as much feedback as possible. We received 363 responses to the survey. The survey results are summarized in the Supporting Documentation section of the document. Also provided are anecdotal comments where property owners were asked to describe damage to their property.

We have reviewed two wakesurf related studies performed in Georgia and Minnesota.

*Boat Wake Impact Analysis (January 2021)
Lake Rabun and Lake Burton, Georgia
(Referred to as Study #1)

*Field Study of Maximum Wave Height, Total Wave Energy and Maximum wave Power Produced by Four Recreational Boats on a Freshwater Lake (February 2022)
University of Minnesota
(Referred to as Study #2)

These studies are included in the Supporting Documentation section. We will refer to various aspects of these studies in the Analysis section of this document. Although many stakeholders have expressed frustration when faced with property damage or safety concerns due to wakesufing the LWPOA will rely on data to formulate our proposed regulation. *Following the Science* is an often-used but seldom followed adage.

Data Analysis

Analysis of LWPOA Survey Results:

Total responses: 363

Of the 363 responses, 218 or 60% of the total were from LWPOA members. Another 143 responses were from non-members. LWPOA membership participation was about 44%. A summary of the survey data is below. Detailed data can be found in the Supporting Documentation section of this document.

- 63% claim to have experienced damage to their property due to high wakes.
- 85% feel wakesurfing creates a safety hazard.
- 15% of all water sport activity is wakesurf related
- 8% of all boats owned by respondents are wakesurf boats
- 89% would support regulating wakesurf activity

Analysis of 3rd Party Studies:

As previously mentioned, all motorized water craft create wakes. Wakesurf craft by design create much larger wakes and greater wave energy when compared to other vessels. Table ES-2 in Study #1 indicates wakesurf boat energy is 581% greater than a generic cruising vessel. At a distance of 500 feet that energy is still 499% greater. Study #1 Table ES-2 also compares wakesurf boat wakes to wakeboarding vessels. Wakeboarding is far less a threat a threat to safety and shoreline structure. The LWPOA therefore considers wakeboarding activity in the same category as other on-plane boating sports such as water skiing, tubing, or cruising.

From a boating safety standpoint wakesurfing creates far more collateral risk. Small craft such as kayaks, canoes and paddleboards are at a higher risk of swamping or capsizing due to large waves from wakesurf boats. The US Coastguard cited "flooding/swamping" as the 4th most common type of accident in 2019 resulting in 45 deaths. (US Coastguard, 2020) Additionally, forces of wake/wave were contributing factors in 12 deaths and 117 injuries. 'Falls Overboard" resulted in 119 deaths in 2020.

Study #1 (page V and VI) indicates large wakes can:

- Increase the risk of falls overboard
- Increase the risk of swamping small craft with low free-board
- Increase incidents of vessels being slammed into docks resulting in injury

Contained in Supporting Documentation is a section with anecdotal comments from survey respondents describing damage due to large wakes. There is no question the damage to property is attributable to wakesurf watercraft.

Large wakes also accelerate erosion of shorelines. Softer, non-protected banks quickly erode and contribute to suspended particulate, or sedimentation pollution. Some areas of the lake are naturally rocky bluffs and are not affected, however mud banks and gravel bars are at risk. Below are two illustrations from Lake Wedowee showing how shore erosion impacts the shoreline. Again, we understand all motorized boats create wakes. However, the mature trees that are nearly falling into the lake suggest recent shore erosion. Home owners are reporting loss of property necessitating hardening of natural shorelines. Often seawalls or riprap must be installed.

Study #2 (Page 6) cites field studies that indicate a four-fold increase wave energy under wakesurf conditions. Propeller wash can penetrate 16' of water contributing to turbidity in shallower areas of the lake.

Study #1 (Figure 2-2) is a photo of a popular wakesurf boat. (Malibu 22LSV) with a graphic scale to measure wave height. This wave is over 4 feet high, optimal for wakesurfing but dangerous to nearby craft, swimmers or structures.

Waves attenuate (diminish) over distance travelled. Study 1 (Figure 2-14) graphically illustrates the relationship between wave height and distance from boat center. Cruising or skiing as well as wakeboarding deliver reasonable attenuation at 150 feet. Wakesurf waves do not attenuate to 1 foot in height until 500-foot distance is reached. This assumes a 2.25-foot wave is created. If the boat creates a four-foot wave as previously illustrated, the wave will have destructive potential well beyond 500 feet.

The State of Tennessee enacted a new law in May 2022 that prohibits wakesurfing and wakeboarding in areas less than 200 feet from shore, other boats or shore structure. We applaud the state of Tennessee for acting in the best interest of property owners. We respectfully disagree however with the restriction placed on wakeboarding. Wakeboarding has proven to inconsequential to property damage or safety. Referring again to Study 1 Table ES-2. Additionally, waves created by wakesurf boats do not appreciably attenuate in just 200 feet.

Recommendation for Wakesurf Regulation

Based on our survey results- only 8% of boats owned by survey respondents are wakesurf boats. Additionally, only 15% of respondents participate in wakesurfing activity.

The data contained in both studies strongly indicate the large wakes created by wakesurf activity damages shoreline structures and compromises safety.

Since a minority of boaters are creating the vast majority of issues it seems prudent to regulate wakesurfing activity to portions of the lake where shore structures will not be put at risk. It is also clear other boating activity such as cruising, skiing, wakeboarding should not be regulated.

Some well-meaning groups have advocated a no-wake zone at arbitrary distances from shore, structure or other boats. Since the data proves a wakesurf waves require 500 feet to attenuate to a one-foot level, 100 foot or even 200-foot buffer zones are inadequate. There are unintended consequences to no-wake buffers. Using Lake Wedowee as an example:

Shoreline miles: 270 miles
Shoreline Buffer Zone: 200 feet
Total Lake Area: 10,500 acres
1 Acre = 43,560 square feet

Such a scenario would mean 6,545 acres or 62% of lake area would be designated a no-wake zone. All recreational boating over idle speed would be forced into 38% of the current lake area. This would create more of a safety hazard than we already have.

Kindly support us in bringing a bill forward that would make wakesurfing unlawful within 500 feet of any other boat, shoreline or shoreline structure. This will impact the least number of boating enthusiast while enhancing safety and protect property.

We are sensitive to the fact the proposed regulation would be not be supported by some of your colleagues. However, in 2009 Alabama Legislature passed a bill specific to certain lakes. 2009 Alabama Code Title 33- Navigation and Watercourses, Chapter 6A-Recreational Vessel and Residence Boat Sewage Discharges Regulated. Section 33-6A-3.1 regulates or prohibits certain vessels from Lake Marten, Weiss Lake and Lake Wedowee. We are hopeful this legislation sets precedent that regulations that work for certain interests can be enacted.

Sincerely Yours:

LWPOA Board

Supporting Documentation

Study #1

Boat Wake Impact Analysis
(January 2021)
Lake Rabun and Lake Burton, Georgia

Boat Wake Impact Analysis

Lake Rabun and Lake Burton, Georgia

Prepared for:

Lake Rabun Association, Inc.
&
Lake Burton Civic Association

1/20/2021

Prepared by:

Water Environment Consultants
Mount Pleasant, SC

WEC

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Executive Summary

Water Environment Consultants (WEC) was contracted by the Lake Rabun Association, Inc. (LRA) and the Lake Burton Civic Association (referred to hereafter as the Associations) to evaluate and quantify the incremental recreational and environmental impacts of wakeboarding and wakesurfing boats (wake boats) on the respective lakes, located in Northeast Georgia. The Associations are concerned about larger wakes causing unsafe conditions on the lakes, as well as other adverse effects such as increases in shoreline erosion, and collateral damage to docks or vessels or other structures. The goal of this study is to provide the lake associations with a technical reference to facilitate discussions with Georgia Power Co., Georgia Department of Natural Resources (GADNR) and other appropriate regulatory and legislative agencies to pursue the development and implementation of management measures to improve safety and minimize the adverse effects of wake boats.

As mentioned above, the primary concern of the Associations is the *safety* of boaters and swimmers. Safety is also of primary importance for Georgia Power, as illustrated by their published Core Safety Beliefs:

(1) Safety takes precedence over all other requirements;

(2) Safety is a personal value;

(3) All hazards can be controlled; and

(4) The “Spirit of Safety” is a constant.

The Associations are concerned about increased risk of injury or death of boaters and swimmers that is caused by increasingly large wake waves on the lakes. Large wakes can create unsafe conditions by swamping recreational craft, impacting other boats, or causing falls overboard. Small craft, including canoes, kayaks, and sailboats are particularly at risk of being swamped, broached, or capsized by steep waves from wake boats. In their statistical report of recreational boating accidents, the U.S. Coast Guard cited that “flooding/swamping” was the 4th most common type of accident reported in 2019, resulting in 45 deaths and 124 injuries (U.S Coast Guard 2020). Between 2015 and 2018, it was the 3rd most common boating accident. Additionally, “forces of wave/wake” was one of the top ten contributing factors in accidents in 2019, resulting in 12 deaths and 117 injuries. “Falls overboard” was the fifth most common accident in 2019, resulting in 189 deaths and 122 injuries (U.S Coast Guard 2020).

As detailed by this report, wake boats produce much higher waves than typical cruising or waterskiing craft, and they also produce longer, more energetic waves. The increases in wave heights and wave lengths caused by wake boats increase the risk of injury or fatal accidents on these lakes through several possible mechanisms. These larger waves can:

- Increase risk of swamping of small crafts that have a low freeboard, which in turn increases risk of drowning or injury;
- Increase risk of falls overboard, which also increases risk of drowning or injury;

- Increase incidence of cruising boats slamming into waves, resulting in passenger injury; and
- Increase incidence of vessels being pushed or slammed into docks or shoreline bulkheads, which increases risk of injury or death for people near the vessel.

These increased risks are substantiated by anecdotal reports on Lake Rabun and a survey of its members conducted in 2020. The survey received 486 responses, which is a very high response rate (57%) for member surveys (see Appendix A of this report). Seventy-five percent of survey responses indicated that wake boats create a boating safety issue. Member comments included multiple safety incidences or safety concerns:

> *"We were visiting friends on the lake who were in lockdown due to covid. We were in our boat, approximately 10 feet away from their dock and seawall, chatting with them on their dock. A wakeboat came by and the wake was so large that it crashed our boat into the seawall, even as we were making every effort to move away from it. Ultimately this led to our boat sinking and being declared a total loss. I just don't believe Lake Rabun is large enough to accommodate this size boat."*
>
> *"Difficult to enjoy the lake safely with small children. Can no longer do normal water skiing. Difficult to swim near our dock. Difficult and unpleasant to drive a pontoon boat."*
>
> *"Two times ballast boat waves have come over the bow of my 22' open bow boat. I felt there was a danger of sinking. Generally it is not pleasant to navigate rough water and big waves. This is ruining our boating experience."*
>
> *"We have small children who are often knocked over by such huge waves."*
>
> *"With the wake boats so numerous and dominant out on the water now, I can't remember the last time being on the lake where I didn't fear for my family's safety at least once. This is true of time we spend on our boat, as well as time we spend swimming near our dock."*
>
> *"Dropping the boat in the water and taking the boat out of the water, getting in and out of the boat during that time is really dangerous when giant waves come in."*
>
> *"The larger waves directly affect the ability to steer a boat. On many occasions I have been unable to steer one of my boats and worried that I would be pushed into another boat."*
>
> *"While untying boat (with 3 people in it) at dock, the wave was so strong that one of the people on boat was thrown in water!"*

Swamping typically means that a boat fills with water but remains floating. According to the LRA, there have been numerous anecdotal reports of wakes causing swamping or water coming over the bow and gunwales of a boat such that it raises the risk of total swamping. The LRA member survey results show that 66 percent of respondents (227 members) reported occasional or frequent swamping caused by wake boat waves.

Cruising boats hitting large wakes can cause injury or death. One incident on Lake Rabun involved a boat passenger thrown in the air after their boat hit a large wave from a wake boat. Injury to the passenger required treatment at the emergency room. Another example includes a tragic accident on Lake Burton on July 18, 2014 that claimed the life of a boy who was ejected from a boat when it hit a large wake. This incident did not necessarily involve a wake boat generated wave, but it illustrates the fact that large wakes increase the risk of fatal accidents. The LRA member survey results indicate that 95 percent of respondents (329 members) reported occasional or frequent jostling of boat passengers caused by wake boat waves, and 14 percent of respondents (47 members) reported occasional or frequent injury of boat passengers caused by wake boat waves.

In addition to impacts to other vessels, the wake impacts to docks and bulkheads can cause unsafe conditions. Anecdotal reports also include vessel wakes overtopping docks and sweeping deck chairs into the water, even though the wake boats were outside the 100-ft buffer. As witnessed in the wake measurement study on Lake Rabun, a wakesurfing wake can easily overtop a bulkhead even 300 ft from the sailing line (see Figure 3-3). The LRA survey responses summarized above include an incident where a wake boat wave caused a boat to crash into a bulkhead, resulting in sinking of the boat. The LRA member survey results indicate that 83 percent of respondents (291 members) reported occasional or frequent endangerment or inconvenience of swimmers or people on docks caused by wake boat waves.

Many parts of these lakes are quite narrow, including most of Lake Rabun and much of Lake Burton. It is in these narrow channels where safety is of particular concern. These channels are generally 500 ft wide or less, with a typical width around 300 feet. Within these channels, large wakes may cause passing vessels to yaw and alter course, increasing the risk of collision. The curving nature of the channels causes wake heights to amplify on the insides of the channel bends, increasing wake hazards in these areas. Additionally, two passing wake boats in the channel can create much larger waves where their wakes intersect. Therefore, large waves from wake boats increase the risk of accidents in the narrow areas of the lakes.

To quantify the incremental increase of wake boat impacts requires an understanding of wake conditions generated from both a wake boat as well as a typical vessel operating on the lakes. One previous study focused on wake boats was commissioned by the Water Sports Industry Association (WSIA) in 2015 to scientifically measure the wake heights and wake energy produced by a wake boat. WEC used data from the WSIA study to produce wake height plots for a wakesurfing, wakeboarding, and typical cruising (e.g., waterskiing) operating conditions in deep water, as shown by the dashed curves in Figure ES-1. The figure shows the wake height on the vertical axis and the distance away from the vessel sailing line on the horizontal axis. The figure illustrates how the wake height attenuates with increasing distance away from the vessel.

Figure ES-1 also includes curves based on wake measurements made by WEC. On September 30, 2020 WEC conducted a field study on Lake Rabun to: 1) validate and verify data from the WSIA wake analyses; and 2) quantify wake heights and wake attenuation at a site-specific location in one of these north Georgia lakes. The methodology incorporates a wake sport vessel making consistent passes near two stationary wave gage instruments. The vessel operated in cruising/skiing, wakeboarding, and wakesurfing conditions to simulate wakes generated from operational conditions. WEC analyzed the wave gage data, created wave attenuation curves based on the data, and compared the results from the WSIA study, as shown in Figure ES-1 (the WEC data are indicated by the solid line curves). A comparison of the wave height curve for cruising/skiing operation in Figure ES-1 to the wave height curves for wakeboarding and wakesurfing operation shows that wakeboarding and wakesurfing operation produces much higher wave heights than those generated by cruising or typical water skiing.

The Georgia "Rules of the road for boat traffic" (O.C.G.A § 52-7-18) require boats to maintain idle speeds within 100 ft of "of any vessel which is moored, anchored, or adrift outside normal traffic channels, or any wharf, dock, pier, piling, bridge structure or abutment, person in the water, or shoreline adjacent to a full-time or part-time residence, public park, public beach, public swimming area, marina, restaurant, or other public use area." Given the existing Georgia rules, the increases in wake heights 100 ft from the vessel represent the increases in impacts to docks or shorelines caused by wake boats under the current wake management regime. As shown by Table ES-1, at this distance, a wakeboarding wake at the shore is 22% larger than a typical cruising vessel wake, and a wakesurfing wake is 111% larger than a typical cruising vessel wake. Based on these data, the proliferation of wakesurfing and wakeboarding boats on the lakes resulted in large increases in wake heights reaching docks and shorelines, as allowed under the current rule requiring non-idling boats to maintain a 100 ft buffer.

The effects of boat wakes on these lakes are much greater than those caused by typical wind waves. WEC calculated typical monthly maximum wind wave conditions at two locations within Lake Rabun and three locations within Lake Burton. Using the wake height curves developed from the field study, WEC compared wake heights with estimated maximum monthly wind wave heights at the five sites.

In narrow areas of the lakes, wind waves are very small. Therefore, vessel wake heights are much higher than typical monthly maximum wind wave heights. Even at sites with the largest fetches that generate the largest wind waves, wake boats moving 100-feet off the shoreline create waves exceeding the monthly maximum wind waves. Therefore, vessel wake effects should not be dismissed as insignificant as compared wind wave effects, which may be the case in much wider lakes.

Table ES-2 presents the percent increase in wake impacts on shoreline erosion potential as compared to a typical cruising vessel. WEC evaluated change in wave energy, which is generally considered related to shoreline erosion. Given the present management rules requiring only a 100-ft buffer distance between non-idle speed boats and the shoreline, these results indicate that wave energy from wakesurfing and wakeboarding vessels are much more likely to contribute to shoreline erosion than typical boat wakes or wind waves. Shoreline erosion from waves depends on localized conditions. Erosion may not be an issue where the shoreline is hardened (e.g., many homes on each lake have vertical bulkheads or rock shoreline stabilization), but sensitive shoreline areas may require wake management measures to minimize the potential for wake-induced erosion.

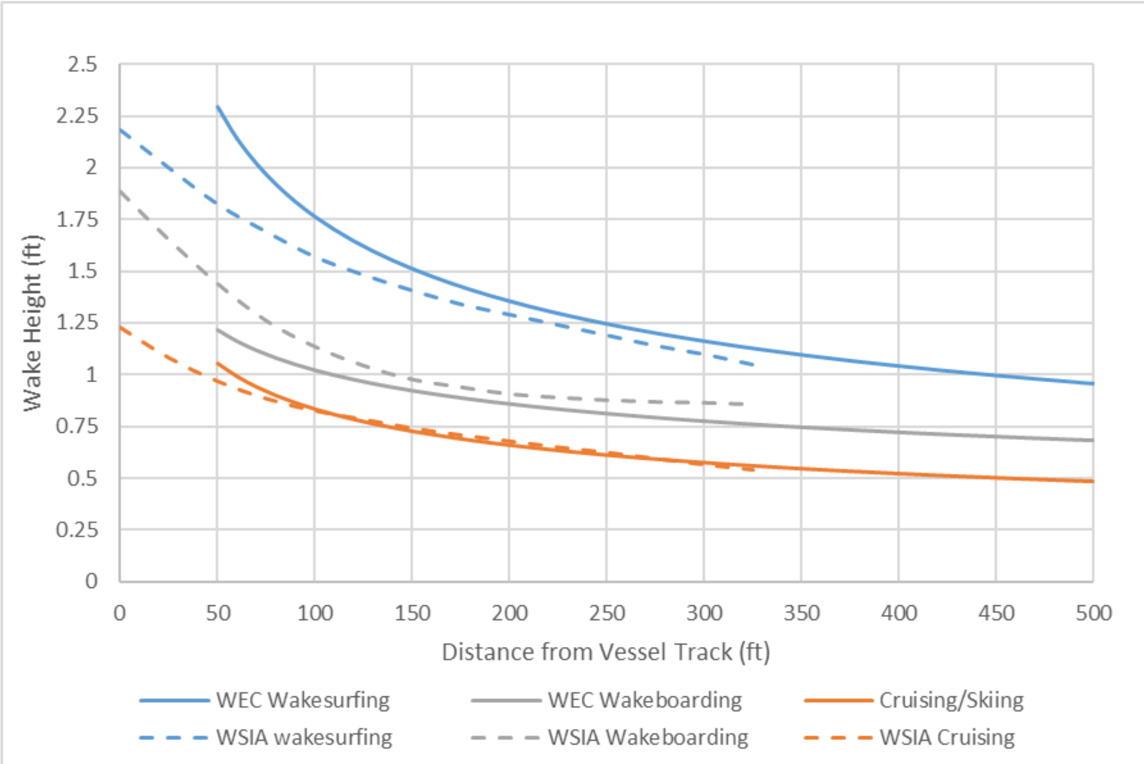

Figure ES-1. WEC measured wake heights and wake attenuation compared to WSIA study (digitized deep water curves from Goudey and Girod 2015)

Table ES-1. Increase in measured wake heights as compared to cruising vessel

Distance from sailing line (ft)	Increase in height (ft)		Percent increase	
	Wakeboarding	Wakesurfing	Wakeboarding	Wakesurfing
100	0.2	0.9	22%	111%
150	0.2	0.8	27%	108%
200	0.2	0.7	30%	105%
250	0.2	0.6	33%	104%
300	0.2	0.6	35%	102%
400	0.2	0.5	39%	100%
500	0.2	0.5	41%	98%

Table ES-3 presents the percent increase in wake forces on vertical wall structures. At the 100-ft distance, the minimum buffer required under the present management rules, the lateral wave forces from wakeboarding wakes are 25 percent greater (an increase of 359 pounds per linear foot) than those from cruising vessels, and lateral wave forces from wakesurfing wakes are 131 percent (1,900 pounds per linear foot) greater. These results indicate that these larger waves are more likely to cause damage to dock and shoreline structures that are not built to withstand repeated exposure to these larger waves.

Table ES-2. Wave energy at the shoreline and percent increase compared to cruising vessels

Vessel Distance from Shore (ft)	Energy (ft·lb) Cruising	Energy (ft·lb) Wakeboard	Energy (ft·lb) Wakesurf	Percent Increase Wakeboard	Percent Increase Wakesurf
100	2587	4346	17621	68%	581%
150	1964	3549	12948	81%	559%
200	1615	3073	10405	90%	544%
250	1387	2749	8782	98%	533%
300	1226	2509	7646	105%	524%
400	1008	2173	6144	116%	510%
500	866	1944	5186	124%	499%

Table ES-3. Horizontal wave forces on vertical walls and percent increase compared to cruising vessel

Vessel Distance from Shore (ft)	Force per linear foot (lbf/ft) Cruising	Force per linear foot (lbf/ft) Wakeboard	Force per linear foot (lbf/ft) Wakesurf	Percent Increase over Cruising Wakes Wakeboard	Percent Increase over Cruising Wakes Wakesurf
100	1454	1813	3354	25%	131%
150	1253	1623	2810	29%	124%
200	1129	1501	2482	33%	120%
250	1041	1413	2257	36%	117%
300	975	1345	2089	38%	114%
400	880	1245	1851	42%	110%
500	812	1173	1687	44%	108%

WEC evaluated the incremental impact of wake boats on berthing conditions at docks on the lake. Wakes can adversely impact vessels moored to docks either by causing damage to boats or docks, or by creating unsafe conditions for boarding or disembarking. The industry standard for "moderate" tranquility in a marina (which permits 25% greater wave action than "good" tranquility conditions), allows for 0.6-ft high waves when boats are oriented in the same direction as the wave (head seas). The calculated have height for a cruising vessel traveling passing 250 ft from the shoreline (0.6 ft) satisfies the moderate criterion. However, wakesurfing and wakeboarding wave heights do not meet the moderate criterion even if the vessels pass 500 feet from shore. At the 100-ft distance, the minimum buffer required under the present management rules, the wake heights from wakesurfing and wakeboarding are 0.4 and 1.2 feet above the moderate berthing criterion, respectively. This supports the conclusion that the current management measures are insufficient to avoid vessel wakes from creating poor vessel berthing conditions at docks, and there is a potential for wakes to cause physical damage to boats or docks, or create unsafe conditions for boarding or disembarking from moored boats.

The above summarizes the significant increase in wake heights caused by wake boat vessels, the increased force and energy of these wakes, and the potential for destructive damage to shoreline and property; however, as discussed above, the Associations are most concerned with the safety of boaters and swimmers. Under the current management measures, the larger wave heights and wave lengths generated by wake boats increase the risk of injury or death on these lakes, as compared to conditions prior to the proliferation of wake boats. Anecdotal reports of unsafe conditions from boat wakes supports the conclusion that the present management rules are insufficient and/or insufficiently complied with to provide reasonably safe recreation on the lake for small crafts. In the absence of new management measures, the increasing trend in the number of wake boats on the lakes will continue to increase the risk for injury or fatality from boating accidents related to swamping or interaction with boat wakes.

Altogether, our review and analysis of the available data on wake boats and their effects on Lake Rabun and Lake Burton supports the conclusion that the present rules should be complemented by additional management measures suitable for narrow, deep lakes such as these. It is likely that the best management regime adopted for any given site will need to involve a combination of operational and non-operational measures. Below are management measures for consideration.

Operational measures may include:

1. Restrict the factory installed ballasts from being filled to maximum capacity and prohibit the use of additional ballast items (i.e. “fat sacs”). Doing so would reduce vessel displacements and lower wake heights.

2. Limit wakesurfing and wakeboarding to the middle sections of the widest parts of the lake.

3. Restrict wake boats to operate in normal unballasted cruising conditions or no-wake conditions within the narrow sections of the lake.

4. Require wakeboarding operations try to stay at least 100 yards away from any shoreline, dock, fixed objects or small craft. A 100-yard distance (a football field length) is likely more easily visualized by a boat operator than one described as a 300-ft distance. At a 100-yard buffer distance, wakeboarding wake heights will be slightly less than waterskiing or cruising wake heights at a 100-ft buffer distance. For wakesurfing operations, require the vessel maintain a 150-yard buffer distance. At 150 yards from the sailing line, the wake height is approximately 1 ft, still slightly larger than a cruising/skiing vessel at the 100-ft buffer distance, but it will be more manageable than the under the existing rules. These additions would result in only a few permissible wake boat zones in the middle of the widest parts of the Lake Rabun and Lake Burton.

5. Prohibit wakesurfing and wakeboarding operation under low light conditions (dusk, dawn or night) when wakes are less visible to others.

6. Prohibit on-board ballast when cruising or waterskiing. Often, wakeboat operators simply fail to empty ballast while cruising or waterskiing.

Non-operational measures that may include:

1. Post signage where wake boats should minimize their wake,
2. Engage in outreach activities to educate the public regarding vessel wake impacts and provide wake management guidelines similar to those provided by the WSIA (except with a revised minimum buffer distance of 100-yards/150-yards from the shoreline and inclusion of a buffer distance around small craft),
3. Coordinate with neighboring lake associations to pool resources and identify other successful means of wake management.

To provide data to assess the effectiveness of wake management measures or the need for adjustment of wake management measures, WEC recommends that the Associations track occurrences of boat wake incidences. This may include requesting members to report any safety incidences or personal property damages as a result of wake boat operation. This should be documented with available specific information regarding the time and date of the incident(s), a detailed description of the damage, along with videos or photographs, and the registration number of the watercraft rendering the damage, if possible.

1 Introduction

The Lake Rabun Association, Inc. (LRA) and the Lake Burton Civic Association (referred to hereafter as the Associations) retained Water Environment Consultants (WEC) to complete this evaluation of boat wakes and related effects caused by wakesurfing activities on the lakes. The lakes are located in the northeast corner of Georgia and are three of six lakes in a series of reservoirs that follow the original path of the Tallulah River (Figure 1-1). The lakes are owned and operated by the Georgia Power Company and used to generated hydroelectric energy. With the growing popularity in the sport of wakeboarding and wakesurfing, an increasing number of wake-enhancing vessels (wake boats) operate on each reservoir.

The Associations are concerned about larger wakes causing adverse effects in several ways, including safety, increases in shoreline erosion, and collateral damage to docks or vessels or other structures. The goal of this study is to provide the Associations with a technical reference to facilitate discussions with Georgia Power Co., Georgia Department of Natural Resources (GADNR) and other appropriate regulatory and legislative agencies to pursue the development and implementation of management measures to minimize adverse impacts of wake boats.

As directed by the Associations, this study aims to evaluate and quantify the incremental increase in wake boat impacts as compared to typical vessels and naturally occurring wind-waves on the lake. This gives an indication of the changes in boat wake effects following the advent of wakesurfing and wakeboarding activities on the lake. The report is subdivided into the following sections:

- Section 2, Background on vessel wakes: presents background information on vessel wakes and their impacts;
- Section 3, Wake Impacts: presents estimates of the incremental increase of wake boat impacts on shoreline erosion, dock structures, moored vessels, and safety; and
- Section 4, Management Measures: Suggests possible management strategies to minimize adverse impacts from wake boats.

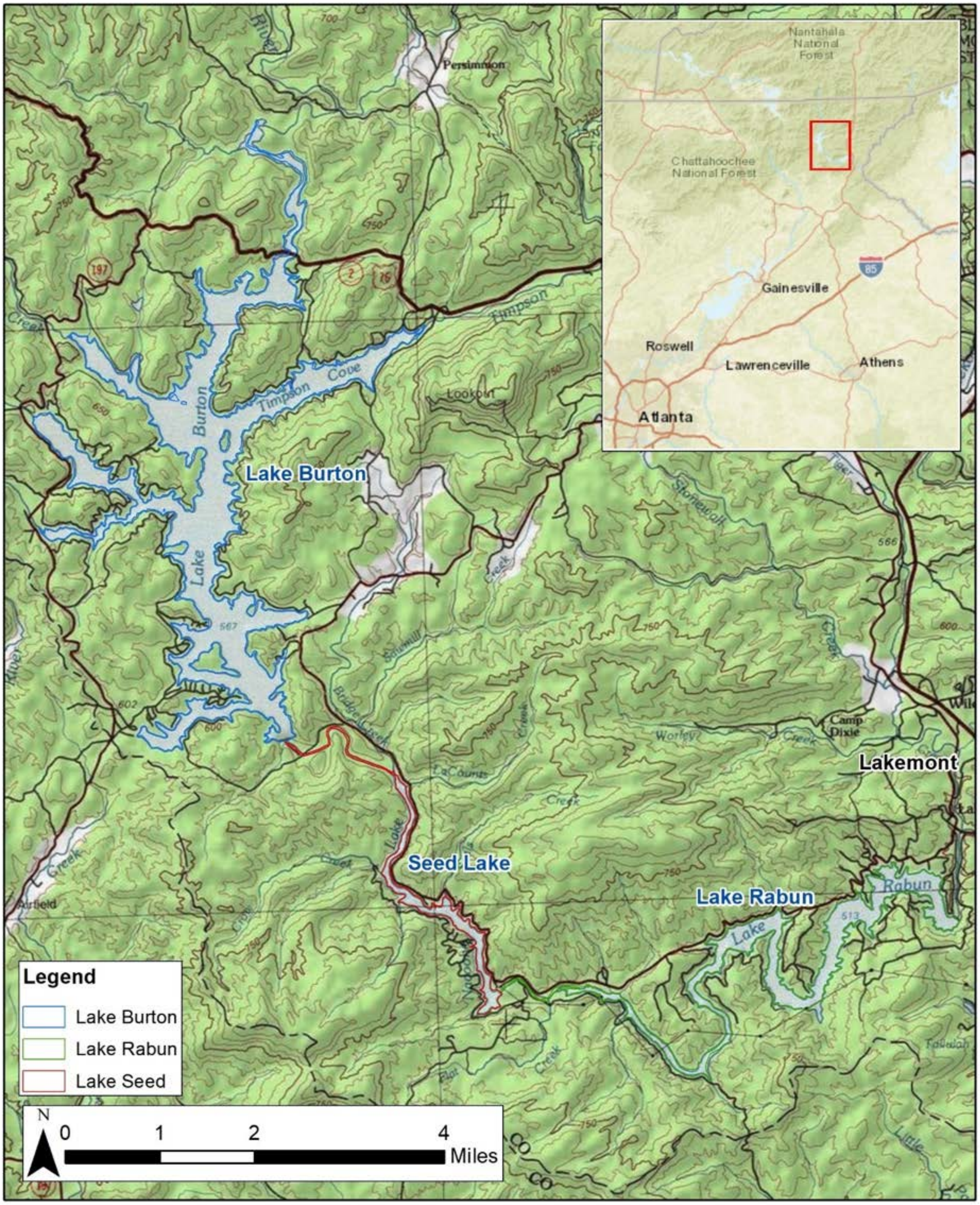

Figure 1-1. Project location map

2 Background on Vessel Wakes

2.1 Vessel Wave Patterns

The general wave pattern generated by recreational vessels is affected by water depth and vessel speed. At sub-critical speeds, all vessels produce a wave pattern termed the Kelvin wave pattern (Figure 2-1), which includes two wave types: transverse and divergent waves. Transverse waves propagate parallel to the vessel's sailing line. The height of these waves is largely a function of vessel displacement-length ratio, with a heavy, short vessel producing higher waves (Macfarlane 2009). Divergent waves propagate obliquely to the vessel's sailing line, as shown in Figure 2-1, and they are generally steep and close together near the vessel.

As vessel speed increases or water depth decreases, the vessel will approach the critical speed, which is the point at which the vessel waves reach their maximum speed. The vessel will experience a peak in resistance at the critical speed. At critical speed, the wave pattern may consist of only one long-period wave, termed a wave of translation, propagating parallel to the sailing line.

At super-critical speeds (i.e., higher than the critical speed), a vessel's wake pattern changes again. At these speeds, transverse waves disappear, and divergent waves propagate at a greater angle away from the sailing line.

Whereas significant transverse waves can be generated by large commercial vessels, they are generally not a significant problem caused by recreational vessels. Therefore, divergent waves are the focus of our analysis.

2.2 Vessel Speeds

In addition to the three vessel wave patterns described above, there are also three vessel speed regimes. Displacement speed is the slowest regime. The upper limit of the displacement speed regime is the hull speed, which is the point at which the longest wave generated equals the waterline length of the vessel. To travel faster than hull speed, the vessel must begin to "climb its own bow wave." In general, operating at speeds up to 75% of the maximum displacement speed will produce modest wash height and period (Macfarlane 2009).

Above the hull speed, the vessel moves into the semi-displacement speed regime. The transverse waves move aft of the transom, and the running trim increases. In this regime, wave making resistance is at its highest, and wake height increases to its maximum. Semi-displacement speeds occur when the vessel appears to be "climbing the hump" before planing, which is often referred to as hump speeds. This is a speed regime to avoid when there is a need to minimize vessel wake heights.

The third speed regime is high speed. For vessels with a power-to-weight ratio sufficient to travel faster than hull speed, they can power through the hump just above hull speed before entering the high-speed regime. For vessels with a planing hull, this will be point at which the boat begins to plane.

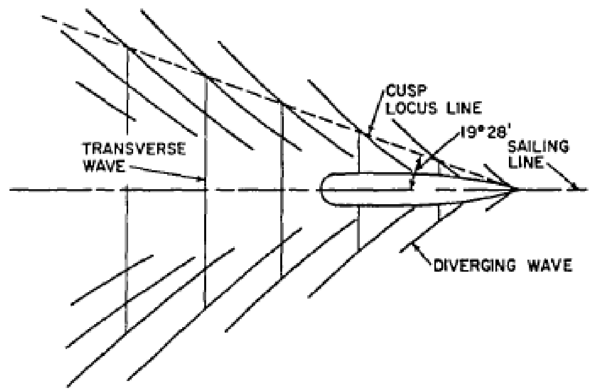

Figure 2-1. Sub-critical vessel wake pattern (Sorenson 1973)

2.3 Vessel Wave Propagation

Vessel wakes spread out and are reduced in amplitude as they move away from the vessel sailing line. As a packet of waves propagates, the waves are affected by both dispersion and attenuation. Wave dispersion is caused by varying wave lengths within a wave packet moving at different speeds. This results in the wave packet widening as it moves away from the sailing line. What appears as a few wake waves near the vessel will appear to become a larger number of waves at increasing distances from the sailing line.

In deep water, before the wave interacts with the bottom, wave attenuation is primarily caused by diffraction, which spreads wave energy along the wave crest. As water becomes shallower, the wave interacts with the bottom, and wave transformation is affected by refraction, shoaling, and bottom friction. Waves may also be reflected by the shoreline, structures or the bottom.

Wave transformation processes generally cause an attenuation in wave height as the wave propagates away from the sailing line, until it reaches very shallow water, at which point wave shoaling causes an increase in wave height before wave breaking. The wave period, however, does not change during wave propagation.

Estimates of wave transformation can be provided by numerical models, but more commonly wave attenuation is estimated by empirical evidence from either laboratory scale models or field measurements of the vessel wakes of interest. This analysis relies upon field measurements of wake boat waves from three sources. Two of these sources are prior studies, Goudey and Girod (2015) and Ruprect et al. (2015), and the third is field measurements completed by WEC on Lake Rabun. The following subsections summarizes this data.

2.4 Wake Boats Waves

There has been an increasing number of recreational boats on Lake Rabun and Lake Burton that are designed and manufactured for the sport of wakeboarding and more recently, wakesurfing. These wake boats are designed, through the use and control of ballast and customized trim, to maintain a breaking wave at the optimal operational speed (typically 10 knots for wakesurfing and 19 knots for wakeboarding) (Ruprect et al. 2015). Wake heights generated by some boats can exceed four feet immediately behind the vessel, according to manufacturer marketing (e.g., Figure 2-2 shows a screen shot from a promotional video for the Malibu 22 LSV wave with factory ballast setup).

Wakesurfing vessels use wake enhancement devices (WED) to increase the speed at which the vessel can maintain its critical speed condition, ensuring that they can generate large displacement waves at speeds between 12 and 19 knots (Ruprect et al. 2015). WED may include: increasing the ballast in the vessel (either through inflatable water bags or internal ballasting); modifying the hull design; installing wedge platforms on the stern of the vessel which impacts vessel trim; and installing elevated towing platforms (Ruprect et al. 2015). Ballast can also be distributed unevenly to enhance wake height: placing the majority of the ballast near the aft corner on the side to be surfed (biased ballasting) will produce a larger wave on one side of the boat than the other.

Vessel wakes have been studied extensively for commercial vessels and recreational vessels, but there are few studies focused specifically on wake boats with WED. WEC reviewed the data from two relevant studies in addition to conducting field measurements of vessel wakes on Lake Rabun. The first is a study by Goudey and Girod (2015) commissioned by the Water Sports Industry Association (WSIA) in 2015 to measure the wake heights and wake energy produced by a wake boat in Orlando, FL. The second is a study completed by Ruprect et al. (2015) to measure wake heights and wake energy from three different late-model wake boats. Lastly, WEC conducted field measurements in September 2020 on Lake Rabun with the goal of measuring site-specific wave heights created by a wake boat and attenuation of the wave heights as they travel away from the vessel.

2.4.1 WSIA Wake Analysis (Goudey and Girod 2015)

In the Spring of 2015, the WSIA commissioned C.A. Goudey & Associates to measure the wakes produced by professional quality wake-sport boats at two lakes in Orlando, FL. The study venues included a reach of shallow-water and deep-water conditions. This is an important distinction, as wave mechanics behave distinctly different whether in deep or shallow water, and shallow water attenuates wake heights more quickly. Lake Rabun is a flooded river valley with relatively deep water in close proximity to the shoreline. Therefore, WEC analyzed only the deep-water results presented by Goudey and Girod (2015), since this is the relevant data for evaluating vessel wake impacts on Lake Rabun.

The vessel used in the study was a Nautique G-23 wake-sport boat, typical of the growing fleet of wake-sport boats available from various manufacturers at the time. The vessel was tested for three different conditions: cruising, wakeboarding, and wakesurfing. "For the cruising condition the boat was operated 'light,' meaning only one person aboard but with a full fuel tank (65 gal.). For the wakeboarding condition the standard factory-installed ballast tanks were filled to capacity, adding 2,850 pounds. For the wakesurfing runs, the weight was supplemented with four 'fat sacks' positioned aft and in the bow, adding another 1,400 pounds for a total displacement of 10,150 pounds" (Goudey and Girod 2015). Figure 2-3 illustrates the vessel operating under wakesurf conditions. The scenarios tested by Goudey

Figure 2-2. Malibu 22 LSV wave with factory ballast setup (Source: Guinn Partners 2019).

Figure 2-3. Nautique G-23 used during WSIA study operating under wakesurfing condition (Goudey and Girod 2015)

and Girod did not include biased ballasting to increase wake heights on one side of the boat, and therefore, these test results do not represent the largest wakes that can be generated by these types of vessels. Wave height sensors, which measured the wake height produced from a vessel passing the testing venue, were spaced at incremental distances from the shoreline. For each of the three conditions (cruising, wakeboarding, and wakesurfing) the vessel passed the wave sensors at varying speeds to simulate the respective operating procedure. Cruising speeds included 20, 25, and 30 mph. Wakeboarding speeds included 21.2, 22.2, and 23.2 mph. Wakesurfing speeds included 10, 11, 11.5, and 12 mph. For this analysis, it is reasonable to assume that the wakes generated by unballasted cruising conditions are representative of the maximum wakes typically generated by other recreational vessels cruising on the northern Georgia lakes, such as waterski vessels.

Goudey and Girod (2015) plotted measured wave heights versus distance from sailing line for each vessel operating condition, and they fit a trendline to the measured data. The WSIA study did not provide tables of the measured data, and therefore, WEC digitized the plotted trendline results for the deep water measurements in the WSIA study, as shown in Figure 2-4. The data points used to generate these curves are provided in Table 2-1.

Figure 2-4 shows the observed attenuation of wave height as the wake travels away from the vessel sailing line. In general, wave heights decrease quickly within the first 50 to 100 feet from the sailing line. After that point, the curves flatten out, as the wave attenuates more slowly at greater distances from the sailing line. This figure highlights the difference in wake height between the three operating conditions. Of the three operating conditions, wakesurfing generated the largest wake heights, wakeboarding generated smaller wake heights, and cruising produced the smallest wake heights.

Of interest to our analysis are the incremental increases in wake heights created by wakeboarding and wakesurfing beyond that of typical cruising boat wakes. As mentioned previously, it is reasonable to assume that the wakes measured for cruising conditions are representative of the wakes typically generated by other recreational vessels cruising on Lake Rabun and Lake Burton. Therefore, the incremental increase is calculated as the wakeboarding and wakesurfing wave heights minus the cruising wave heights. Table 2-2 presents the incremental increase in wave heights at the shoreline due a wakesurfing and wakeboarding vessel as compared to a cruising vessel.

In Georgia, the "Rules of the road for boat traffic" (O.C.G.A § 52-7-18) state that "No person shall operate any vessel or tow a person or persons on water skis, an aquaplane, a surfboard, or any similar device on the waters of this state at a speed greater than idle speed within 100 feet of any vessel which is moored, anchored, or adrift outside normal traffic channels, or any wharf, dock, pier, piling, bridge structure or abutment, person in the water, or shoreline adjacent to a full-time or part-time residence, public park, public beach, public swimming area, marina, restaurant, or other public use area." Given the Georgia rules, the differences in wake heights 100 ft from the vessel represent the increases in impacts under the current wake management regime. Based on the data in Table 2-1, a cruising vessel produces wakes of about 0.8 feet in height at a distance 100 feet from the vessel. In comparison, a wakesurfing or wakeboarding boat produces wakes about 1.6 or 1.1 feet in height, respectively, at the same distance (100 feet) from the vessel. As shown by Table 2-2, at this distance, a wakeboarding wake is 37% larger than a typical cruising vessel wake, and a wakesurfing wake is 90% larger than a typical cruising vessel wake. Based on these data, the proliferation of wakesurfing and wakeboarding boats on

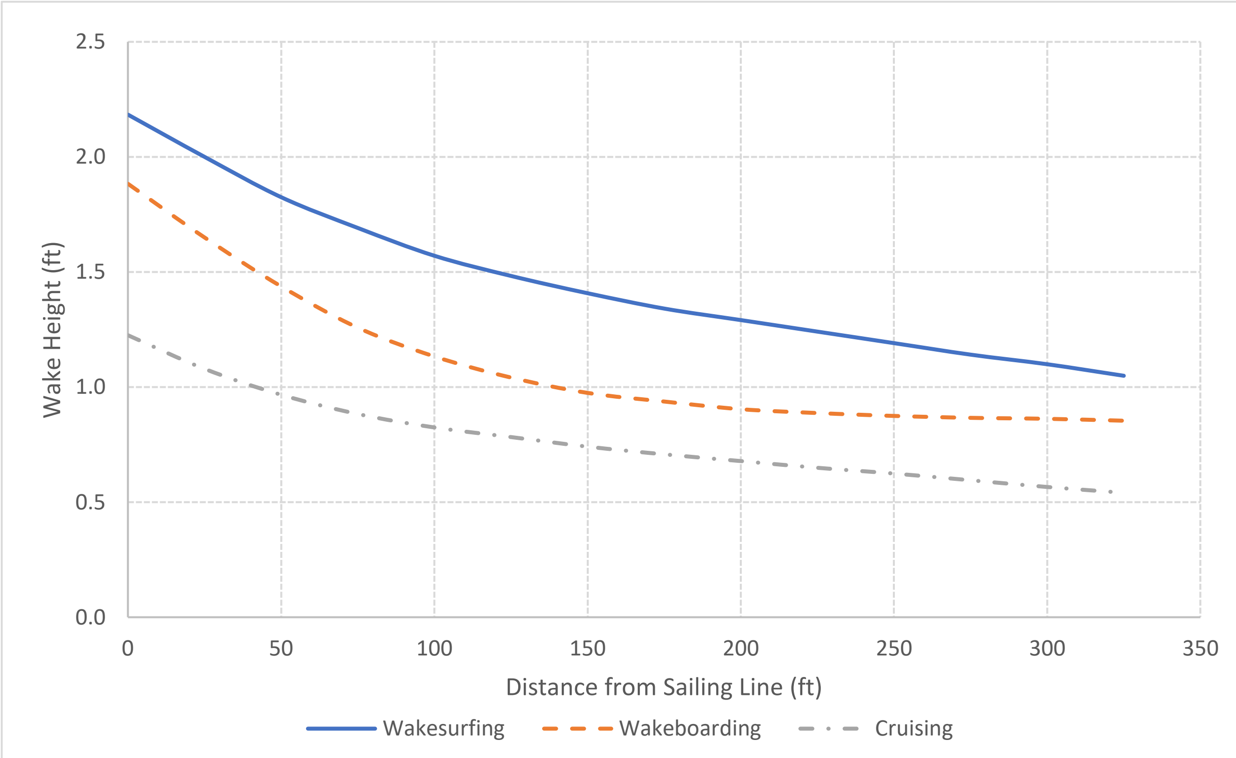

Figure 2-4. Wake height vs. distance from sailing line at deep water site (digitized curves from Goudey and Girod 2015)

Table 2-1. Wake heights vs. distance from sailing line

Distance from Sailing Line (ft)	Wave Height (ft)		
	Wakesurfing	**Wakeboarding**	**Cruising**
0	2.2	1.9	1.2
25	2.0	1.7	1.1
50	1.8	1.4	1.0
75	1.7	1.3	0.9
100	1.6	1.1	0.8
125	1.5	1.0	0.8
150	1.4	1.0	0.7
175	1.3	0.9	0.7
200	1.3	0.9	0.7
225	1.2	0.9	0.7
250	1.2	0.9	0.6
275	1.1	0.9	0.6
300	1.1	0.9	0.6
325	1.1	0.9	0.5

Table 2-2. Increase in wake height as compared to cruising vessel

	Increase in height (ft)		Percent increase	
Distance from sailing line (ft)	**Wakesurfing**	**Wakeboarding**	**Wakesurfing**	**Wakeboarding**
100	0.7	0.3	90%	37%
150	0.7	0.2	90%	31%
200	0.6	0.2	90%	33%
250	0.6	0.3	91%	40%
300	0.5	0.3	94%	52%

Lake Rabun and Lake Burton has resulted in large increases in wake heights, as allowed under the current rule requiring non-idling boats to maintain a 100 ft buffer.

WEC estimated average wave periods generated by each operating condition by measuring the water surface elevation time series plots given by Goudey and Girod (2015). The resulting estimates of average wave period of the largest waves (approximately five) in each wake are listed in Table 2-3. The results show increasing wave period from cruising to wakeboarding to wakesurfing conditions. This is important, because an increase in wave period results in increases in wave energy and wave power, which in turn may affect other vessels, docks, or shoreline erosion. Typically, when a vessel increases its speed, the wave period of the generated wake also increases. However, this is not the case when comparing the three vessel operating conditions in Table 2-3, because the increased ballasts for wakeboarding and wakesurfing conditions increase the vessel displacements, which increases the wave periods of the vessel wakes.

Goudey and Girod (2015) evaluated the relative importance of the vessel wakes on shoreline erosion by comparing to wind waves. Wave height alone is a poor indicator of potential shoreline erosion, and derived parameters such as wave energy, power and energy per unit wave height are much better indicators of potential erosion (Macfarlane et al. 2008). Goudey and Girod (2015) cite Macfarlane et al. (2008) in asserting that “cumulative energy of all the waves associated with a wake is the best measure,” but our review did not find this claim anywhere in Macfarlane et al. (2008). Goudey and Girod (2015) then sum the cumulative wave power from vessel wakes and compare to cumulative power from various wind wave scenarios. The approach is flawed, however, because it neglects consideration of the fact that there is a threshold below which waves will not cause erosion. Erosion only occurs when the wave-generated shear stress at the bottom is sufficient to mobilize bed sediments. The error in the approach used by Goudey and Girod (2015) is illustrated by the fact that simply summing the energy from many small wind waves that are insufficient to individually mobilize bottom sediments may exceed the energy of a single boat wake that is sufficiently powerful to mobilize bottom sediments. In this scenario, the method used by Goudey and Girod (2015) would incorrectly conclude that the cumulative energy from the small wind waves is more impactful to shorelines than that from the single boat wake.

Table 2-3. Estimated average wave periods based on time series plots from Goudey and Girod (2015)

Operating Condition	Average wave period (s)
Cruising	1.8
Wakeboarding	2.0
Wakesurfing	2.2

Goudey and Girod (2015) conclude that shorelines that routinely experience wind-driven waves are more tolerant of wakes from all types of boating activity, and given the persistence of wind waves, in many settings they represent a more significant source of shoreline impact than boat wakes. WEC agrees with this conclusion for shorelines exposed to large fetches and subjected to energetic wind wave action. However, for shorelines along narrow water bodies with short fetches, such as the reservoir lakes in northern Georgia, wind waves are not the most dominant factor impacting shoreline, as discussed further in Section 3.2 of this report.

2.4.2 Ruprecht et al. (2015) Wake Analysis

Ruprect et al. (2015) tested the hypothesis that wakesurfing waves are equivalent to wakeboarding waves by conducting a series of field measurements on three different wakeboarding vessels. The boats tested included: a Malibu Wakesetter VLX (2014); a Tigé RZ2 Platinum Edition (2011) and a Super Air Nautique G23 (2014). The methodology included measurement of vessel wakes using multiple wave gauges in a deep water environment unaffected by strong currents or wind. The experimenters set up an 820 ft long sailing line using four floating buoys, and wave gauges were deployed at distances of 72, 115 and 246 ft from the sailing line.

The testing program included a range of vessel speeds and ballast conditions. Each vessel was tested at speeds of 9, 12, 16, 22, 28, and 35 mph. Ruprect et al. (2015) tested the vessels with full ballasts (except 12 and 35 mph), without towing a rider and with 1 to 4 people onboard. Biased ballasting was used at 12 mph to undertake an examination of waves generated in association with wakesurfing. Empty ballasting was used at 35 mph for comparison with waves generated by waterski vessels at their operational speed. Replicate runs were completed for each vessel, resulting in a total of 36 runs per vessel.

Ruprect et al. (2015) found that, regardless of design differences, all three vessels generated a similar wake for a given speed. At 72 ft from the sailing line the wave typically had a large maximum wave height, with waves bunched in a tight wave train. Table 2-4 summarizes the average maximum wave height (H_{max}) measured at 72 ft from the sailing line for all three boats tested. The highest average H_{max} values were recorded at 9 mph for wakeboarding activities and 12 mph for wakesurfing activities.

Table 2-5 summarizes the average peak wave period (T_{peak}) at 72 ft from the sailing line for all three boats tested. Peak wave period was defined as the wave period of the highest wave in the wave train. Similar to the measurements by Goudey and Girod (2015), the lower speeds at which the largest wave periods were recorded are also the speeds at which the highest waves were generated.

Table 2-4. Average maximum wave heights measured by Ruprecht et al. (2015) at 72 ft from the vessel sailing line

Speed (mph)	Average Maximum Wave Height, H_{max} (ft)
9	0.89
12	1.25
16	0.79
22	0.72
28	0.62
35	0.43

Table 2-5. Average peak wave period measured by Ruprecht et al. (2015)

Speed (mph)	Average Peak Wave Period, T_{peak} (s)
9	2.02
12	2.02
16	1.85
22	1.75
28	1.61
35	1.57

Table 2-6 summarizes the average energy of the maximum wave height (Energy H_{max}) at 72 ft from the sailing line for all three boats tested. The highest average Energy H_{max} values were recorded at 9 mph for wakeboarding activities and 12 mph for wakesurfing activities.

Ruprecht et al. (2015) found that the wave energy associated with the single maximum wave height for wakesurf operating conditions is approximately four times that of wakeboard operating conditions. Because wakesurfing, wakeboarding and waterskiing each produce significantly different waves, Ruprecht et al. (2015) recommended that these three activities be assessed and managed separately. Ruprecht et al. (2015) give only two examples of management options, including:

- Restrict those activities to wide parts of the river to allow for natural wave height attenuation.
- In certain situations, where maximum wave height is a concern, and insufficient distance is available to allow for natural attenuation, management of the sport may result in restricting activities or the implementation of artificial shoreline enhancements (i.e. bank armoring, rip-rap, rock fillets etc.).

Table 2-6. Energy of maximum wave measured by Ruprecht et al. (2015)

Speed (kt)	Speed (mph)	Average Energy of Maximum Wave, Energy H_{max} (kg.m/s2)
8	9	595
10	12	1219
14	16	379
19	22	286
24	28	175
30	35	90

2.4.3 WEC Field Measurements and Wake Analysis

On September 30, 2020 WEC conducted a field study on Lake Rabun to: validate and verify data from the aforementioned wake analyses; and quantify wake heights and wake attenuation at a site-specific location. WEC placed two wake monitoring instruments at two distances from the sailing line (162 and 267 ft) to measure the attenuation of the wake height propagating away from the sailing line. A SonicXB gauge, manufactured by Ocean Sensor Systems, Inc., was mounted an aluminum tripod at each monitoring location. Figure 2-5 shows the sensor mounted above the water surface. The sailing course and instruments were set up in an area of Lake Rabun where the bottom is less than 35 feet deep. Figure 2-6 shows the test venue, sailing line, and instrument locations.

The field study included a total of 49 test cases using a 2017 Super Air Nautique G22 (Figure 2-7) wake boat driven by an experienced captain. The test cases included three operational modes: cruising/waterskiing, wakeboarding, and wakesurfing. Three vessel speeds were tested for each operational mode, and five replicate tests were completed for each vessel speed.

The cruising/waterskiing tests included two passengers with no additional ballast (i.e., ballast tanks were empty). The combined gross weight of the boat, passengers and gas was roughly 6,000 lb. Test speeds included 20, 25 and 30 mph. Figure 2-7 shows the boat running on a plane during the cruising/waterskiing tests.

For the wakeboarding tests, the factory-installed internal ballast tanks were filled, resulting in a combined gross weight of roughly 8,000 lb. Test speeds included 21, 22 and 23 mph. Figure 2-8 shows the boat with a full ballast tank during the wakeboarding tests.

For the wakesurfing tests, an additional ballast bladder was added on board for an extra 2,000 lb., roughly, bringing the gross combined weight to approximately 10,000 lb. Test speeds included 10, 11 and 12 mph, with a couple additional runs at 9 mph. Figure 2-9 shows the boat operating under wakesurfing conditions.

Figure 2-5. SonicXB gauge mounted to tripod in Lake Rabun

For each test case, WEC measured the maximum wake height at each gauge. The maximum wave heights for each vessel speed and operational condition were then averaged. WEC developed a wave attenuation equation for each operational condition. Macfarlane and Renilson (1999) give the following equation to describe the attenuation of divergent wakes according to deep-water vessel wave theory:

$$H = \gamma y^n$$

where H is the wake height, y is the distance from the sailing line, and γ is a vessel-dependent function of speed. The exponent n has a theoretical value of -⅓ for divergent wakes. Macfarlane (2002) analyzed a wave wake database and found that the deep water, divergent wave decay exponent generally varies between a range from -0.22 to -0.4, and -0.33 is considered a reasonable engineering approximation. WEC used the Lake Rabun test data to solve for the variables γ and n for each operational condition, using the average wave height from the vessel speed producing the maximum

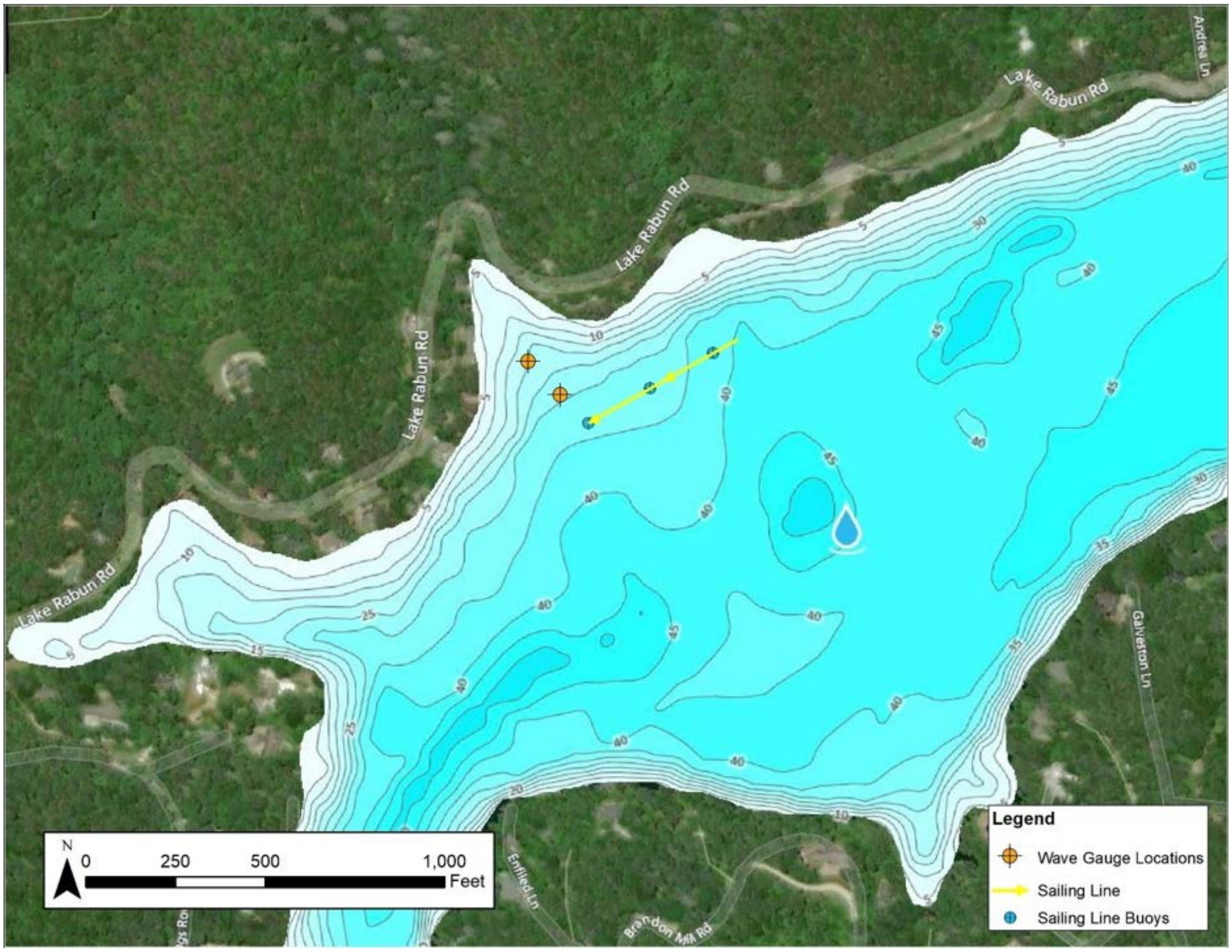

Figure 2-6. Wake measurement instrument locations and sailing course

Figure 2-7. Super Air Nautique G22 during cruising/waterskiing test run

Figure 2-8. Super Air Nautique G22 with full ballast during wakeboarding test run

Figure 2-9. Super Air Nautique G22 with additional ballast during wakesurfing test run

wake heights. The result is an equation to describe the wake heights and attenuation at various distances other than those where they were directly measured.

Figures 2-10 through 2-12 illustrate the wave curve results for each operating conditions. Figure 2-13 compares the Lake Rabun wake attenuation results to the WSIA wake boat study results from Goudey and Girod (2015). As noted earlier, only the deep water results from the WSIA study are shown in Figure 2-13, because the Lake Rabun test site was in deep water. Overall, the Lake Rabun observations are generally consistent with those from the WSIA study. Wake attenuation measurements from the cruising/waterskiing scenario on Lake Rabun are very similar to those measured by Goudey and Girod (2015). The Lake Rabun measurements for wakeboarding conditions are slightly lower than those observed by Goudey and Girod (2015). The Lake Rabun measurements for wakesurfing conditions are slightly higher than those observed by Goudey and Girod (2015).

The results can be used to determine the appropriate minimum buffer distance for wake boats (i.e., the minimum distance that wake boats should maintain from shoreline and other vessels). As discussed earlier, the Georgia "Rules of the road for boat traffic" (O.C.G.A § 52-7-18) states that non-idle vessels should maintain a 100-ft buffer distance from other vessels, people, structures and shorelines.

An appropriate buffer distance for wakeboard/wakesurfing boats might be one that produces wake heights that are similar to those from cruising/waterskiing boats at the buffer distance. As recommended by Ruprecht et al. (2015), these three activities can be assessed and managed separately.

As shown by the Lake Rabun results (Figure 2-14), the typical maximum wake height for cruising/waterskiing boats is about 0.8 ft at the currently effective 100-ft buffer distance. During wakeboarding conditions, the wake height is reduced to 0.8 ft at a distance of about 225 feet from the sailing line. A possible management measure based on this data would be to require a minimum buffer distance of 225 feet during wakeboarding operation. For wakesurfing, the wave height equation indicates the height does not attenuate to 0.8 ft until approximately 950 feet from the sailing line. At 500 feet of the sailing line, the wake height is approximately 1 ft. Appropriate buffer distances for wakesurfing operation may include 500 feet (allowing for higher and more powerful waves), or 950 feet (requiring wave heights no greater than typical cruising/waterskiing conditions).

Table 2-8 summarizes the average wave period from the Lake Rabun field data. Since waves generated by wakeboarding and wakesurfing have longer periods than those from cruising/waterskiing, they have more energy and power. Therefore, even a 225-ft buffer for wakeboarding and a 950-foot buffer for wakesurfing conditions will still allow waves to impact other vessels, structures, or the shoreline with more power than those from cruising/waterskiing at a 100-ft buffer distance.

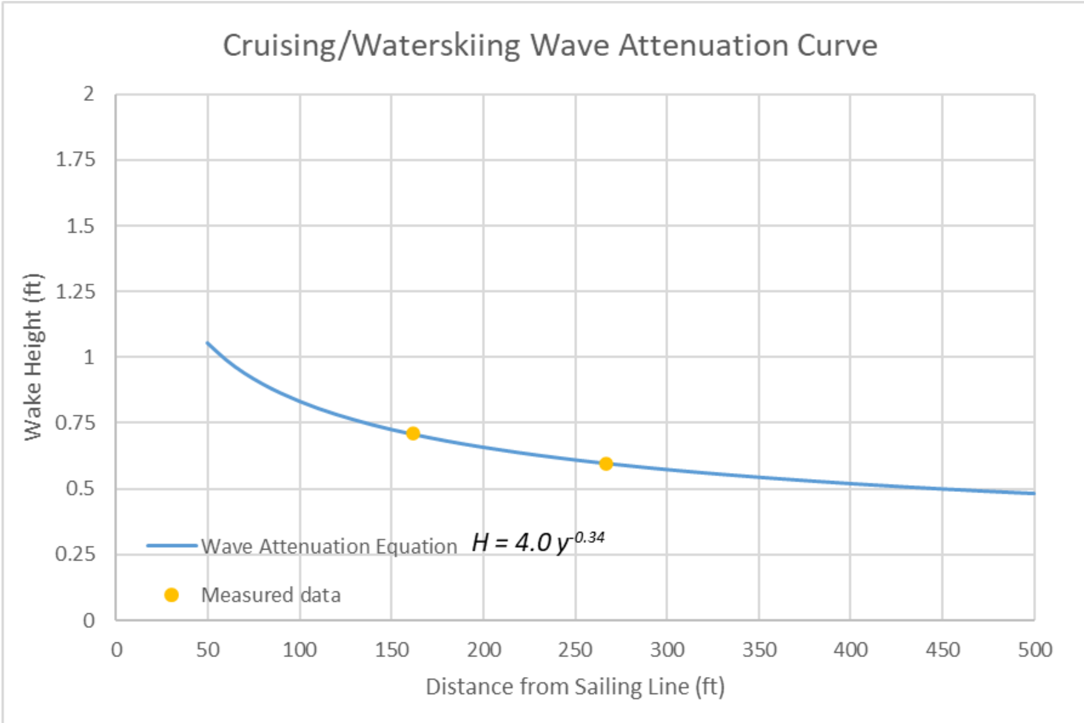

Figure 2-10. Maximum wake height versus distance from sailing line for cruising/waterskiing conditions at Lake Rabun

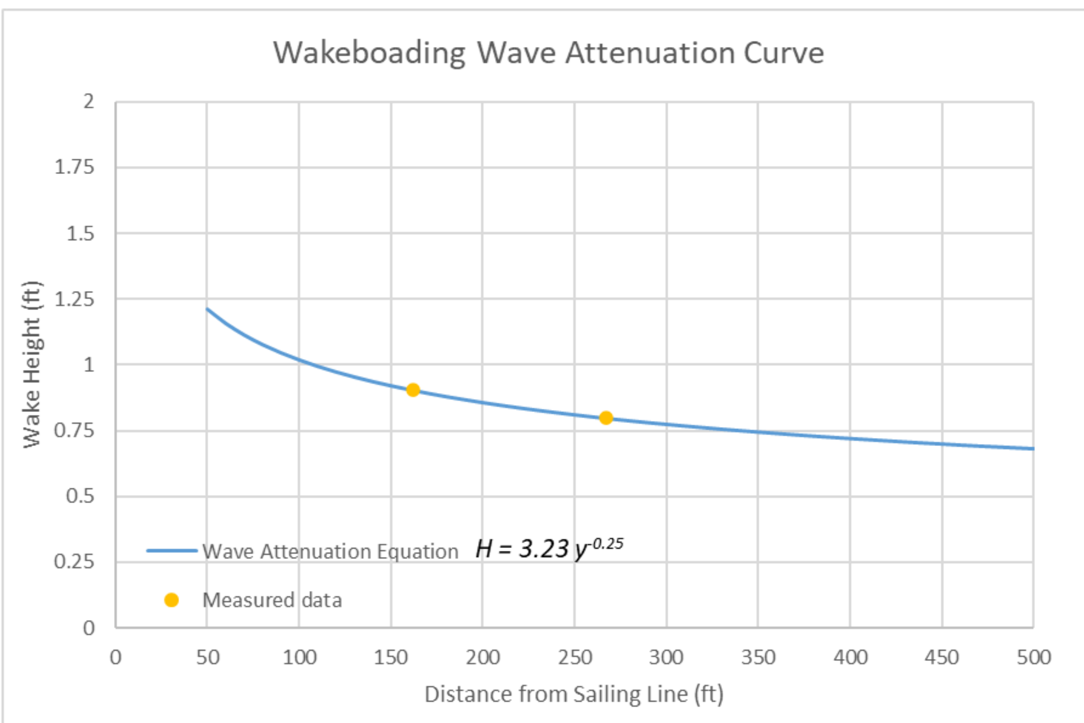

Figure 2-11. Maximum wake height versus distance from sailing line for wakeboarding conditions at Lake Rabun

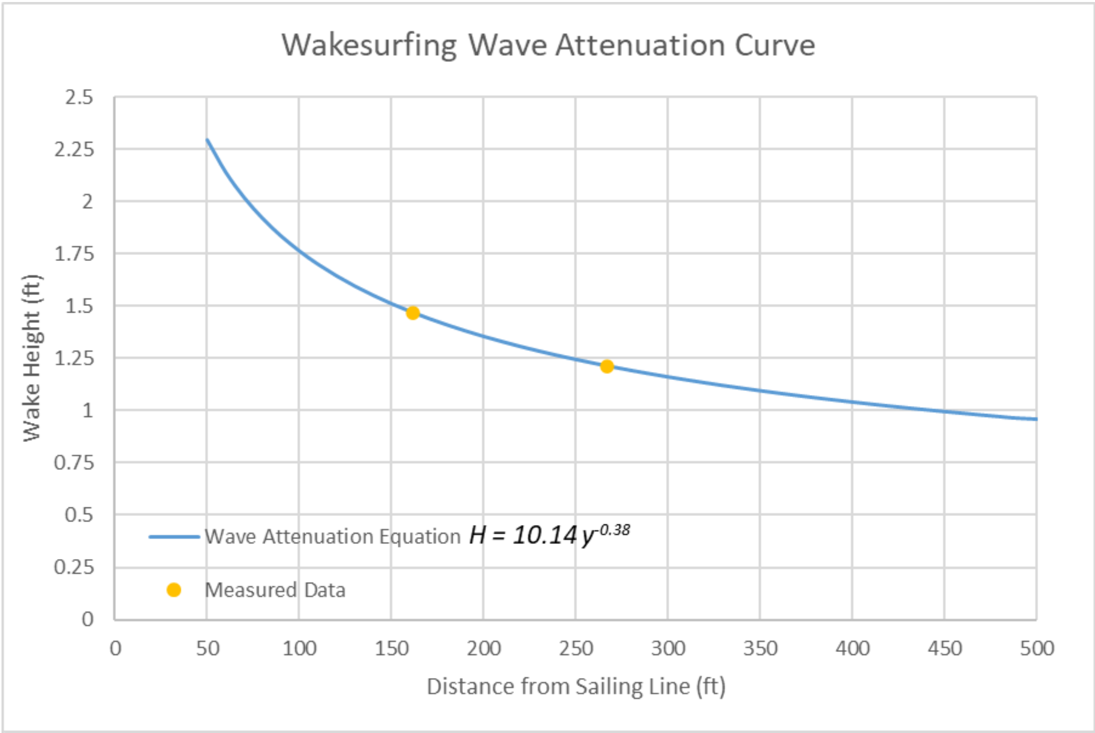

Figure 2-12. Maximum wake height versus distance from sailing line for wakesurfing conditions at Lake Rabun

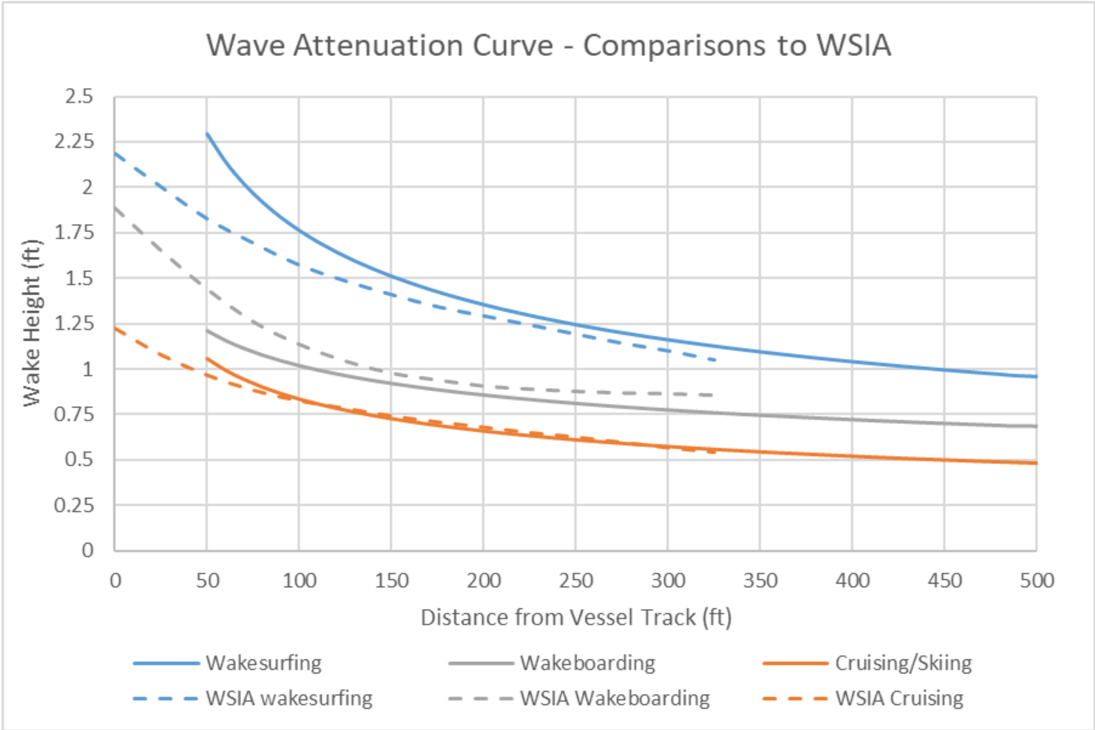

Figure 2-13. Comparison of Lake Rabun field study results to 2015 WSIA study results for deep water measurements

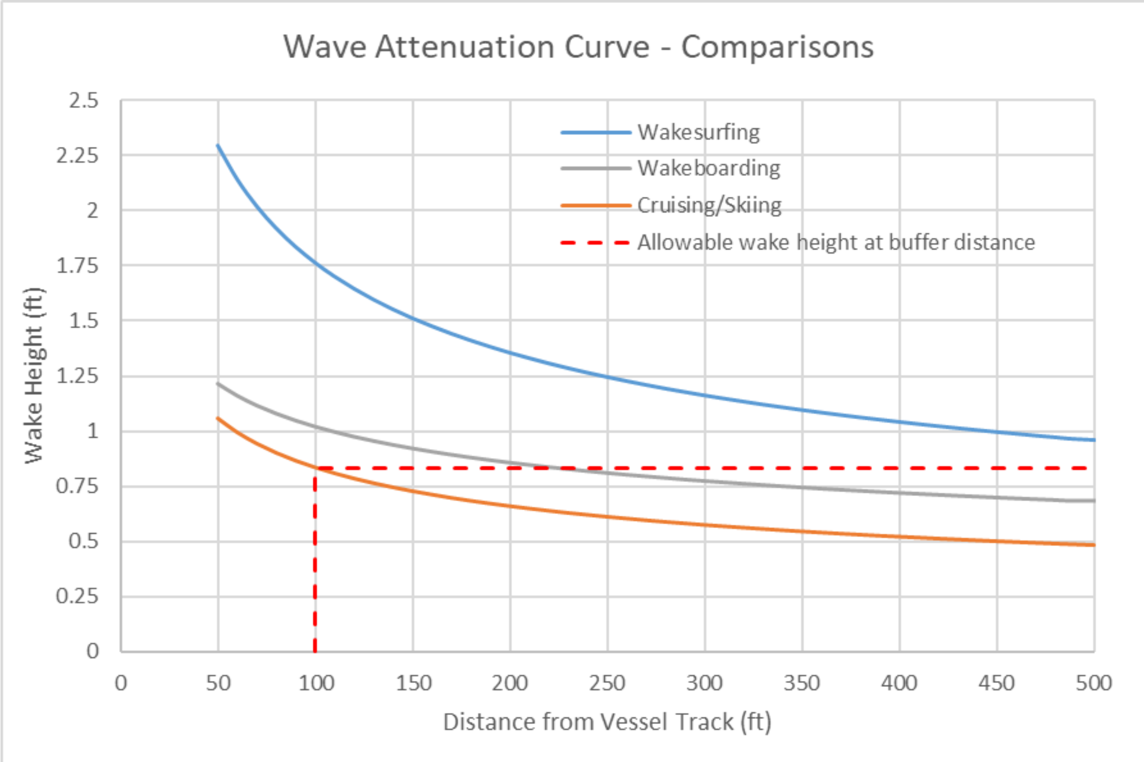

Figure 2-14. Wake attenuation curves from Lake Rabun field study and example of allowable wave height at buffer distance

Table 2-7. Incremental increase in wake height, by feet and percentage, for wakeboarding and wakesurfing as compared to cruising conditions

Distance from sailing line (ft)	Wakeboarding [ft and (%)]	Wakesurfing [ft and (%)]
100	0.2 (22%)	0.9 (111%)
150	0.2 (27%)	0.8 (108%)
200	0.2 (30%)	0.7 (105%)
250	0.2 (33%)	0.6 (104%)
300	0.2 (35%)	0.6 (102%)
400	0.2 (39%)	0.5 (100%)
500	0.2 (41%)	0.5 (98%)

Table 2-8. Average wave period of vessel wakes by operating condition from Lake Rabun field data

Operating Condition	Average wave period (s)
Cruising	1.7
Wakeboarding	1.8
Wakesurfing	2.1

3 Wake Impact Assessment

This report section evaluates wake boat impacts on Lake Rabun and Lake Burton, with a focus on the incremental increase in impacts from wakesurfing and wakeboarding vessels above and beyond those from typical cruising vessels. The evaluation includes an analysis of wind waves, followed by an assessment of impacts to shoreline erosion, dock and shoreline structures, moored vessels and safety.

3.1 Wind Wave Analysis

WEC calculated wind wave conditions at five locations within Lake Rabun and Lake Burton using the straight-line fetch methodology and equations described in the U.S. Army Corps of Engineers' (USACE) Coastal Engineering Manual (CEM) (USACE 2011). The method estimates wind wave growth along a fetch for a given wind speed. WEC did not assess all shoreline locations, but instead chose locations representative of typical fetch distances, as depicted in Figure 3-1. These locations include sites in narrow areas of each lake that are relatively sheltered from wind wave action, as well as sites exposed to longer fetches and larger wind waves. Wind waves were not analyzed here as conditions are expected to be similar to the other narrow sites, particularly the one on Lake Rabun. For each location, wind waves were estimated for the shore-perpendicular fetch line, as well as fetches rotated 45° in either direction.

Wind wave growth is a function of fetch length and wind speed. Areas with longer fetches (i.e., wider parts of the lake) allow for larger wind waves. To determine and representative wind speed, WEC analyzed hourly wind records from the Toccoa Airport located roughly 14 miles southeast of Lake Rabun. Winds records dated from 2012 through 2020. WEC chose a monthly return period to evaluate monthly maximum wind waves. In other words, this wind speed should be expected to occur once every month. This will result in a wind wave estimate that is conservatively high for comparison to vessel wakes that occur on a more frequent weekly basis.

Table 3-1 summarizes the results of the wind wave analysis. Per the CEM methodology, WEC adjusted the wind time-averaging duration iteratively to identify the maximum fetch-limited wind wave growth conditions for each fetch. The reported wind-wave condition in Table 3-1 is the average of the shore-normal and the ±45° fetch results at each location. The CEM method estimates the significant wave height, H_s, which is the average of the highest one-third of waves in the irregular wave field. The maximum wave height is estimated as $1.6H_s$, which is a value approaching the average height of the highest one percent of waves during storms (Federal Emergency Management Agency [FEMA] 2007).

A comparison of wake heights from WEC's field study with estimated maximum monthly wind wave heights at the five sites is shown in Figure 3-2. Because the lakes are generally narrow, wind waves are relatively small at each site. Portions of Lake Burton, however, can be wider than the other lakes and susceptible to larger wind driven waves. 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 very close proximity to the vessel (i.e., less that 75 feet

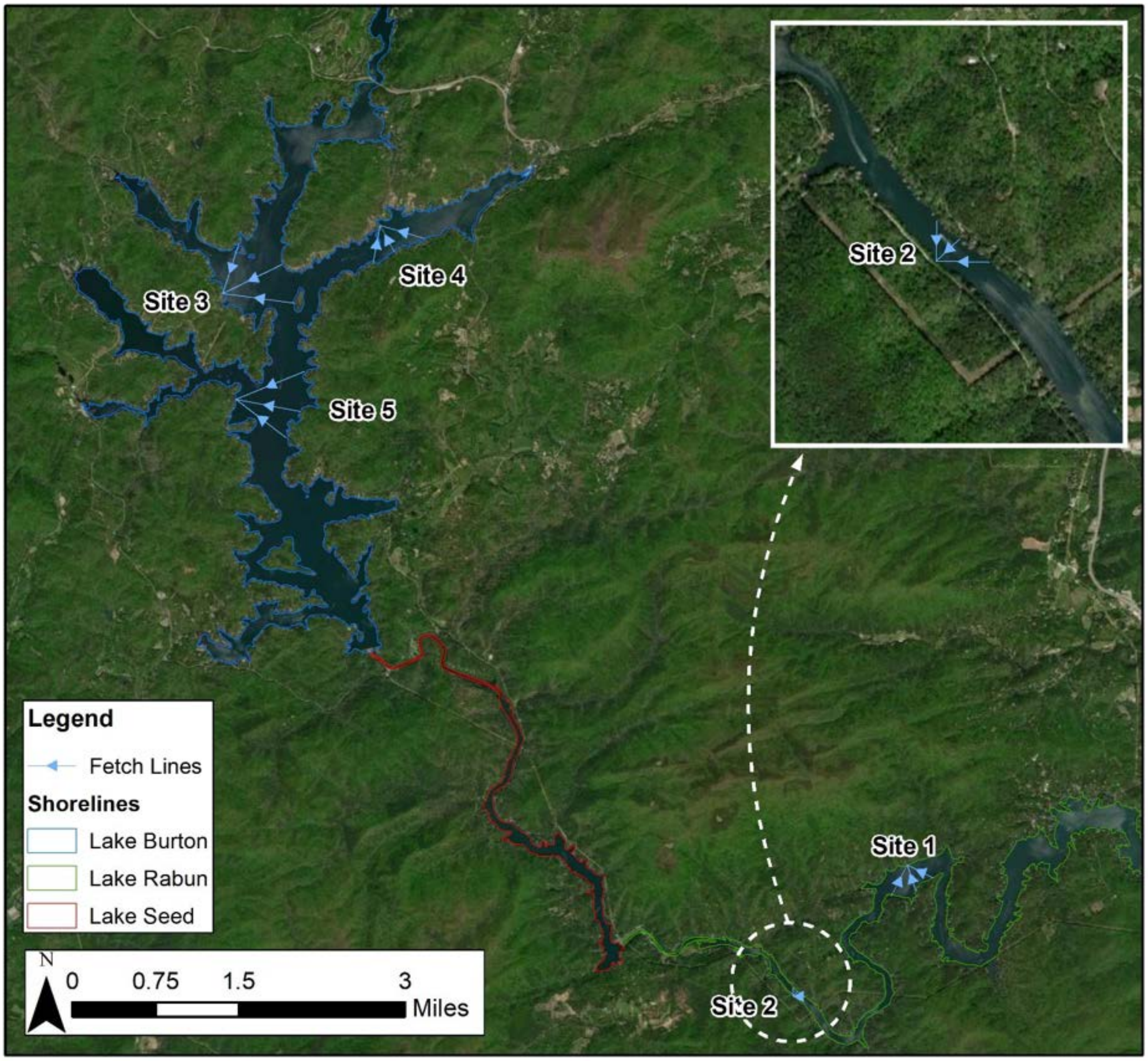

Figure 3-1. Straight-line fetch analysis locations within Lake Burton and Lake Rabun

Table 3-1. Summary of average wind wave estimates for monthly event at each location

Variable	Site 1	Site 2	Site 3	Site 4	Site 5
Fetch length (mi)	0.28	0.08	0.58	0.34	0.61
Observed wind speed (mph)	28.8	28.8	28.8	28.8	28.8
Observed wind duration (min)	2	2	2	2	2
Duration for fetch-limited conditions (min)	15	7	25	18	26
Adjusted wind speed, U_t (mph)	25	26	25	25	25
Calculated sig. wave height, H_s (ft)	0.40	0.23	0.57	0.44	0.59
Calculated maximum height, H_{max} (ft)	0.64	0.36	0.91	0.71	0.94

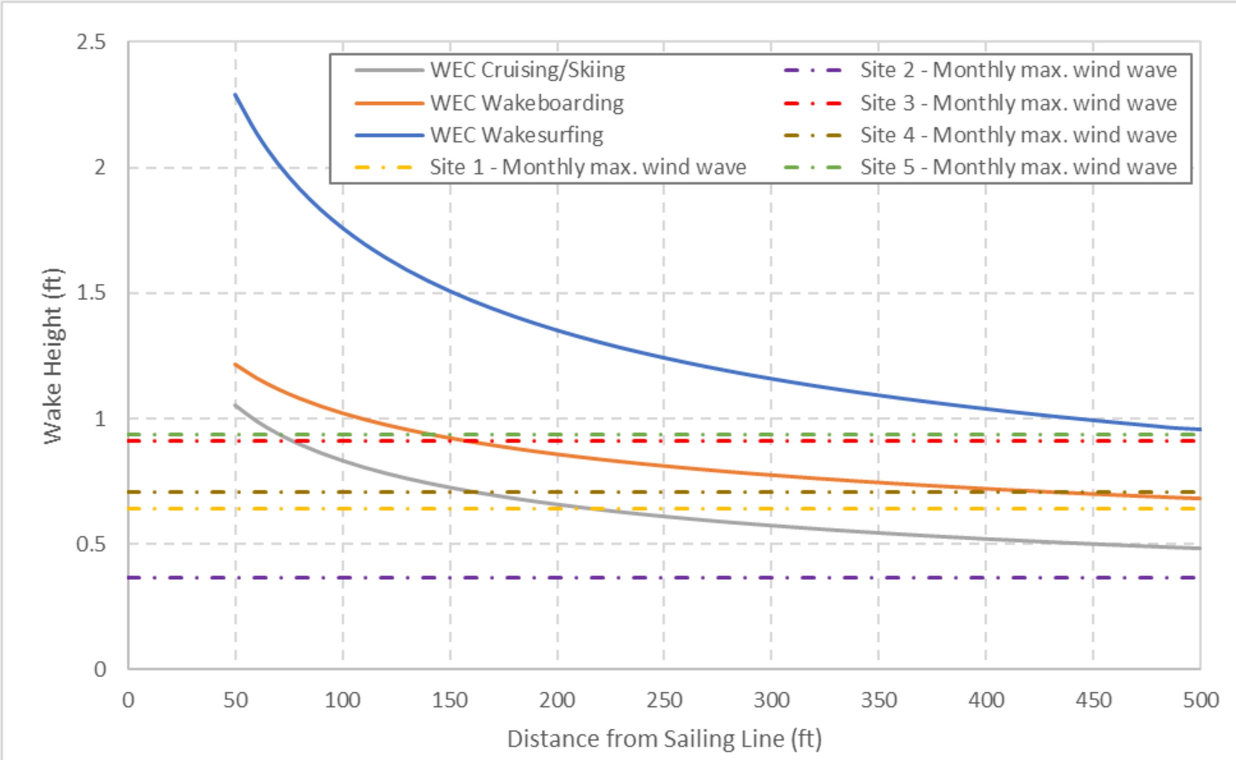

Figure 3-2. Comparison of WEC measured wake heights to maximum monthly wind wave heights

from the vessel). Therefore, vessel wake effects should not be dismissed as insignificant as compared wind wave effects, which may be the case in much wider lakes.

3.2 Shoreline Erosion

Vessel wakes have been shown to have the potential for adverse impacts to shorelines, including shoreline erosion (Castillo et al. 2000, Bauer et al. 2002), scour of the bottom of the shoreface, and temporary reduction in water clarity (USACE 1994, Asplund 1996). Shoreline erosion in a reservoir such as Lake Rabun and Lake Burton are a complex process dependent on site-specific, localized conditions, such as the sediment properties, topographic slope, presence of hard structures or vegetation, surface runoff, groundwater seepage, slumping, lake water levels and incident wave climate. Quantifying estimates of actual site-specific erosion rates is beyond the scope of this study. Instead, WEC evaluated the incremental changes in wave energy, which is generally considered related to shoreline erosion. Wave energy is a better measure for evaluating shoreline erosion than wave power (Macfarlane et al. 2008, USACE 2017). Ideally, cumulative wave energy above a critical minimum threshold to start causing erosion is likely the best way to compare vessel wakes and wind wave impact on shoreline erosion, but that level of analysis is beyond the scope of this study.

Wave energy can be expressed by the following formula:

$$E = \frac{\rho g^2 H^2 T^2}{16\pi}$$

Where E = Energy,
ρ = water density,
g = gravity
H = wave height, and
T = wave period.

Using the above equation, WEC computed the wave energy at the shoreline using the wave attenuation curves from the Lake Rabun measurements (Section 2.4.3 of this report) and the wind-generated wave estimates from the previous section. Based on the resulting wave energy, WEC calculated the incremental increase of energy from wakesurfing and wakeboarding vessels compared to a cruising vessel (Tables 3-2 and 3-3). The results are based on vessels passing at varying distances from the shoreline. The incremental increase as compared to cruising vessels is provided as a calculated value and percentage. From these tables, a wakesurfing wake 100 ft from the vessel's sailing line has 581% (15,034 foot·pounds) more energy than a cruising vessel's wake that traveled the same distance.

The percent increase is even larger when compared to the wind-waves at the two study locations within Lake Rabun (Table 3-3). Table 3-3 compares vessel wake wave energy to the wind wave energy at the longest fetch evaluated in the previous section (Site 5). The monthly maximum wind wave energy at this site is far lower than the vessel wake energy largely because the wind waves are a shorter wave period of 1.2 seconds as compared to the wakeboarding and wakesurfing periods of 1.8 and 2.1 seconds, respectively. The wave energy is proportional to the *square* of the wave period, and therefore the longer waves from the vessels produce much greater wave energy than individual wind waves.

Given the present management rules requiring only a 100-ft buffer distance between non-idle speed boats and the shoreline, these results indicate that wave energy from wakesurfing and wakeboarding vessels are much more likely to contribute to shoreline erosion than typical boat wakes or wind waves. As mentioned above, shoreline erosion from waves depends on localized conditions. Erosion may not be an issue where the shoreline is hardened (e.g., many homes on Lake Rabun have vertical bulkheads or rock shoreline stabilization), but sensitive shoreline areas may require wake management measures to minimize the risk of wake-induced erosion.

3.3 Structures

Estimating wave forces on structures is a complex task that is dependent on the specific structure type and geometry (e.g., pile diameters, deck height, horizontal members, vertical wall height, etc.). Dock and boathouse structures along each lake are also subjected to wave uplift forces on the underside of decks, wave drag forces on piles, horizontal loads on vertical faces of structures, and mooring line loads from moored vessels. Evaluating each of these types of loads is unnecessary to give a general illustration of the relative impact of various waves on structures. As a simplified measure to

Table 3-2. Wave energy at the shoreline and percent increase compared to cruising vessels

Vessel Distance from Shore (ft)	Energy (ft·lb)			Percent Increase	
	Cruising	Wakeboard	Wakesurf	Wakeboard	Wakesurf
100	2587	4346	17621	68%	581%
150	1964	3549	12948	81%	559%
200	1615	3073	10405	90%	544%
250	1387	2749	8782	98%	533%
300	1226	2509	7646	105%	524%
400	1008	2173	6144	116%	510%
500	866	1944	5186	124%	499%

Table 3-3. Wave energy at varying distances from sailing line and percent increase as compared to wind-waves

Vessel Distance from shore (ft)	Energy (ft·lb)			Percent Increase over Wind Waves	
	Long Fetch Wind Waves	Wakeboard	Wakesurf	Wakeboard	Wakesurf
100	666	4346	17621	553%	2546%
150	666	3549	12948	433%	1845%
200	666	3073	10405	362%	1463%
250	666	2749	8782	313%	1219%
300	666	2509	7646	277%	1048%
400	666	2173	6144	226%	823%
500	666	1944	5186	192%	679%

demonstrate the incremental effect of varying wake heights on structures, WEC estimated horizontal wave forces on a vertical wall structure.

The wave load method prescribed by FEMA is given by Walton et al. (1989), who recommend the methodology of Ham-ma and Horikawa (1964 & 1965 *in* Walton et al. 1989). This same methodology is recommended in the American Society of Civil Engineers (ASCE) standard ASCE 07-10, *Minimum Design Loads for Buildings and Other Structures* (ASCE 2010), and FEMA's *Coastal Construction Manual* (CCM) (FEMA 2011).

Table 3-4 summarizes the lateral wave force on a vertical wall, in units of pounds-force (lbf) per linear foot of shoreline, and percent increase as compared to a cruising vessel. At the 100-ft distance, the minimum buffer required under the present management rules, the lateral wave forces from wakeboarding wakes are 25 percent greater than those from cruising vessels, and the lateral wave forces from wakesurfing wakes are 131 percent greater than those from cruising vessels (i.e., the forces on the wall are more than double those from cruising vessels). Even with a 500-ft buffer distance, the

Table 3-4. Horizontal wave forces on vertical walls and percent increase compared to cruising vessel

Vessel Distance from Shore (ft)	Force per linear foot (lbf/ft)			Percent Increase over Cruising Wakes	
	Cruising	Wakeboard	Wakesurf	Wakeboard	Wakesurf
100	1454	1813	3354	25%	131%
150	1253	1623	2810	29%	124%
200	1129	1501	2482	33%	120%
250	1041	1413	2257	36%	117%
300	975	1345	2089	38%	114%
400	880	1245	1851	42%	110%
500	812	1173	1687	44%	108%

lateral force from a wakesurfing wake is more than twice that of a cruising vessel at the same distance. These results indicate that these larger waves are more likely to cause damage to dock and shoreline structures that are not built to withstand repeated exposure to these larger waves.

The results in Table 3-4 should not be directly compared to those for wave energy discussed in the previous section on shoreline erosion, because the wave force on a vertical wall is different than wave energy. Wave energy increases with the square of the wave height and the square of the wave period (or wave length). In contrast, wave force acting on a vertical wall increases with wave height, and it is not affected by changes in wave length. Therefore, increases in wave height and wave length caused by wake boats are expected to cause much greater increases in wave energy than wave force on a vertical wall. The results of our analysis are consistent with this expectation.

Wave reflection can further amplify the impacts on dock and boathouse structures. Many properties along the shoreline of Lake Rabun and Lake Burton are protected by vertical bulkheads. In general, vertical walls reflect 70 to 100 percent of incoming wave energy (Thompson and Hadley 1995). The reflected waves can interact with other incoming waves to cause even greater increase in forces on dock and boathouse structures than the increases described above.

In shallow areas, waves can also cause scour of the lake bottom along the toe of bulkheads or around pilings. Scour depth below the surrounding grade is typically estimated as equal to the incident wave height. Therefore, at the effective 100-ft minimum buffer distance, the incremental increase in potential lake bottom scour near shallow water structures caused by wakeboarding is minor (up to 0.2 ft). On the other hand, wakesurfing wakes can potentially cause up to 0.9 ft more bottom scour at the toe of shallow water structures. Toe scour can lead to slip failure of the soils behind the wall, resulting rotation of the wall or “kick out” at the toe. Increased scour from boat wakes increases the risk of bulkhead failure, because failure of the toe will generally lead to failure throughout the entire structure.

Increased wave overtopping from boat wakes also increases the risk of bulkhead failure. Figure 3-3 shows a wake impacting a bulkhead during the Lake Rabun field measurements. The wake was

Figure 3-3. Example wave run-up from wakesurfing wave impact during field testing

generated from the test vessel operating in wakesurfing conditions, and the wall is approximately 300 ft from the sailing line. Maximum height of wave spray at the wall was in the range of 5 to 6 feet above the lake water surface, and a fraction of this water falls behind the wall (wave overtopping). Repetitive overtopping of structures can slowly erode material on the backside of walls and, if not reinforced, the structure could eventually fail as a result of this erosion. Figure 3-4 shows an example of erosion from wave overtopping behind a bulkhead on Lake Burton. Also, overtopping can cause excess water pressure behind the bulkhead, which can cause anchor failure or toe “kick-out” failure.

3.4 Damages

As discussed above, increased boat wake heights can result in damage or failure of shoreline bulkheads by way of increased wave scour at the toe of the structure or increased wave overtopping of the structure. The costs of these damages are unknown for Lake Burton; however, a recent survey provides an indication of the cost of damages on Lake Rabun. The LRA conducted a member survey during November 30 – December 6, 2020 and received 486 responses, which is a very high response rate (57%) for member surveys. A summary of the member survey is provided in Appendix A

Figure 3-4. Erosion of soils from behind bulkhead on Lake Burton

of this report. Table 3-5 summarizes the results for the responses to the question "Have you experienced shoreline erosion or structural damage as a result of large waves?" The table also includes the responses to the same question from a 2018 survey. The table shows an increasing rate of shoreline and structural damage caused by large waves.

Comments from survey respondents include:

> *"The constant pounding of wake boat waves against our dock has caused significant damage. I'm repairing it at least twice as much as before the surge in wake boats on the lake. And the small beach area by our dock has eroded so much it's a fraction of what it once was. My children can barely swim/play on that beach area anymore without being jostled and thrown by huge wake boat waves."*

> *"Rock Seawall and patio had no damage for 20 years. Has extensive damage in past 3 years due to gigantic waves reaching shoreline."*

> *"We've had our house for two generations and have never seen such erosion to our shoreline."*

Table 3-5. LRA survey response to the question "Have you experienced shoreline erosion or structural damage as a result of large waves?"

Response	2020 Survey	2018 Survey	Change
No erosion or structural damage	24.5%	33.8%	-9.3%
Minor shoreline damage	38.9%	29.4%	9.5%
Major shoreline damage	28.5%	22.3%	6.2%
Structural damage	32.1%	14.5%	17.6%

The wave-induced damages have resulted in substantial costs to homeowners. Table 3-6 summarizes costs to repair shoreline/structure damage, for those respondents who were able to estimate these costs.

3.5 Moored Vessels

On Lake Rabun and Lake Burton, wakes can adversely impact vessels moored to docks, either by causing damage to boats or docks, or by creating unsafe conditions for boarding or disembarking (for example, see the wave runup in Figure 3-3). The most applicable standards for moored vessels are related to small-craft harbors. PIANC (1994) published criteria for small craft harbor quiescence based on Canadian standards, which limits waves within a marina basin according to the values in Table 3-7. These criteria are for "good" marina basin tranquility conditions. The "moderate" marina basin tranquility conditions are given in Table 3-8. The values presented in Table 3-7 assume some level of vessel occupancy during storm events and are sensitive to vessel/dock orientation to incident wave direction. These criteria are typically used for evaluating conditions in a small craft harbor that would lead to significant physical damage to boats or docks, or that represented a life safety concern. These criteria consider the interaction of the vessel and the dock, and therefore they are far more stringent than those commonly accepted for boats left anchored freely in open water away from structures.

The appropriate criterion to consider for impacts to dock mooring conditions depends on the vessel orientation and the frequency of occurrence. It is reasonable to assume that docked boats on the lakes are typically not oriented parallel to the shoreline. Also, the issue under consideration in the study is the typical operational conditions (i.e., weekly conditions), not extreme storm conditions. Therefore, the appropriate tranquility criterion to consider in Tables 3-7 and 3-8 are the weekly head seas condition.

Figure 3-5 illustrates the wake heights measured on Lake Rabun and the moderate head seas berthing criterion. The calculated wave height for a cruising vessel passing 260 ft from the shoreline (0.6 ft) satisfies the moderate criterion. However, wakesurfing and wakeboarding wave heights do not meet the moderate criterion even if the vessels pass 500 feet from shore. At the 100-ft distance, the minimum buffer required under the present management rules, the wake heights from wakesurfing and wakeboarding are far above the moderate berthing criterion. This supports the conclusion that the current management measures are insufficient to avoid vessel wakes from creating poor vessel berthing

Table 3-6. LRA survey responses estimating cost to repair shoreline/structure damage, if known

	Spent to date	Estimated to complete
Sum	$609,600	$1,057,450
Average	$8,467	$12,441
Median	$2,800	$3,500
# of respondents	72	85

Table 3-7. Marina basin wave tranquility criteria for good conditions

Wave Direction Relative to Vessel	Significant Wave Height (ft) Not exceeded more than once per: Week	Year	50 Years
Head	0.5	1.0	2.0
Beam	0.3	0.5	0.8

Notes: 1. Multiply wave heights by 0.75 for "excellent" and 1.25 for "moderate" conditions.
2. For wave periods > 2 seconds.

Table 3-8. Marina basin wave tranquility criteria for moderate conditions

Wave Direction Relative to Vessel	Significant Wave Height (ft) Not exceeded more than once per: Week	Year	50 Years
Head	0.6	1.2	2.5
Beam	0.3	0.6	0.9

Notes: 1. For wave periods > 2 seconds.

conditions at docks, and there is a potential for incoming wakes to cause physical damage to boats or docks, or create unsafe conditions for boarding or disembarking from moored boats.

In addition, wake wave reflection from vertical bulkheads along the shoreline can further increase wave heights in berthing areas. As mentioned previously, many properties along each lake's shoreline are protected by vertical bulkheads, and waves reflected from these walls can interact with other incoming waves to cause even greater wave heights than those described above.

3.6 Safety

The previous sections highlight the significant increase in wake heights from wake boat vessels, the force and energy of these wakes, and the potential for destructive damage to shoreline and property; however, of utmost importance to the Associations is the *safety* of boaters and swimmers. Safety is also of primary importance for Georgia Power, as illustrated by their published Core Safety Beliefs:

(1) Safety takes precedence over all other requirements;

(2) Safety is a personal value;

(3) All hazards can be controlled; and

(4) The "Spirit of Safety" is a constant.

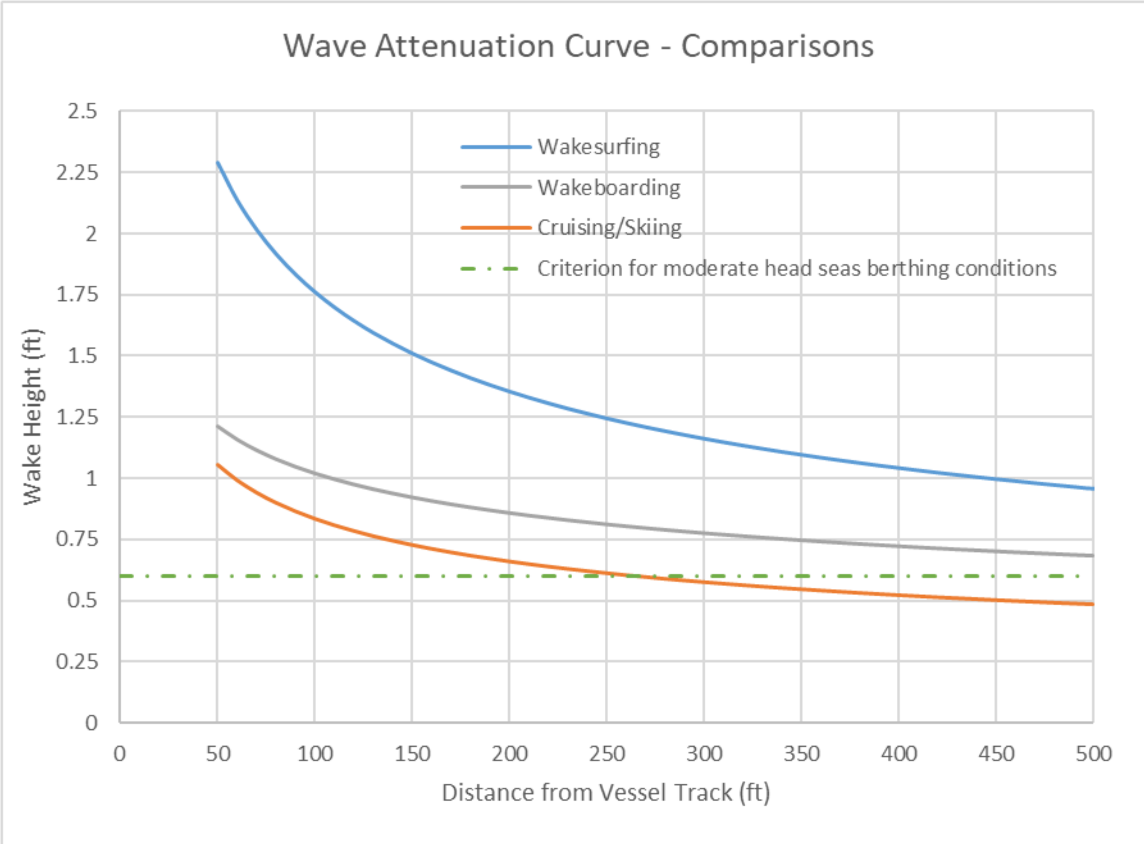

Figure 3-5. Comparison of measured wake heights at Lake Rabun to criterion for moderate head seas berthing conditions

Large wakes can create unsafe conditions by swamping recreational craft, impacting other boats, or causing falls overboard. Small craft, including canoes, kayaks, and sailboats are particularly at risk of being swamped, broached, or capsized by steep waves from wake boats. In their statistical report of recreational boating accidents, the U.S. Coast Guard cited that "flooding/swamping" was the 4th most common type of accident reported in 2019, resulting in 45 deaths and 124 injuries (U.S Coast Guard 2020). Between 2015 and 2018, it was the 3rd most common boating accident. Additionally, "forces of wave/wake" was one of the top ten contributing factors in accidents in 2019, resulting in 12 deaths and 117 injuries. "Falls overboard" was the fifth most common accident in 2019, resulting in 189 deaths and 122 injuries (U.S Coast Guard 2020).

As discussed previously, a wake boat can produce 1.8 ft high waves at a distance 100 feet from its sailing line. Furthermore, when a wake boat turns it can create much larger waves on the inside of the turn, and when there is more than one wake boat operating in the same area of the lake, the intersection of their wakes can cause localized wave heights to double. As mentioned previously, many properties along the lakes' shoreline are protected by vertical bulkheads, and 70 to 100 percent of incoming wave energy may be reflected by these vertical walls. Reflected wake waves can interact with other waves to further increase wave heights in the lake. Not only do wake boats produce higher waves, but they also produce longer waves. Wake boat waves have about a two second period, which corresponds to a 20 ft long wave in deep water.

The increases in wave heights and wave lengths caused by wake boats increase the risk of injury or fatal accidents on these lakes through several possible mechanisms. These larger waves can:

- Increase risk of swamping of small crafts that have a low freeboard, which in turn increases risk of drowning or injury;
- Increase risk of falls overboard, which also increases risk of drowning or injury;
- Increase incidence of cruising boats slamming into waves, resulting in passenger injury; and
- Increase incidence of vessels being pushed or slammed into docks or shoreline bulkheads, which increases risk of injury or death for people near the vessel.

These increased risks are substantiated by anecdotal reports on Lake Rabun. As mentioned previously, the LRA conducted a member survey during November 30 – December 6, 2020 and received 486 responses, which is a very high response rate (57%) for member surveys (see Appendix A of this report). Seventy-five percent of survey responses indicated that wake boats create a boating safety issue. Member comments included multiple safety incidences or safety concerns:

> *"We were visiting friends on the lake who were in lockdown due to covid. We were in our boat, approximately 10 feet away from their dock and seawall, chatting with them on their dock. A wakeboat came by and the wake was so large that it crashed our boat into the seawall, even as we were making every effort to move away from it. Ultimately this led to our boat sinking and being declared a total loss. I just don't believe Lake Rabun is large enough to accommodate this size boat."*

> *"Difficult to enjoy the lake safely with small children. Can no longer do normal water skiing. Difficult to swim near our dock. Difficult and unpleasant to drive a pontoon boat."*

> *"Two times ballast boat waves have come over the bow of my 22' open bow boat. I felt there was a danger of sinking. Generally it is not pleasant to navigate rough water and big waves. This is ruining our boating experience."*

> *"We have small children who are often knocked over by such huge waves."*

> *"With the wake boats so numerous and dominant out on the water now, I can't remember the last time being on the lake where I didn't fear for my family's safety at least once. This is true of time we spend on our boat, as well as time we spend swimming near our dock."*

> *"Dropping the boat in the water and taking the boat out of the water, getting in and out of the boat during that time is really dangerous when giant waves come in."*

> *"The larger waves directly affect the ability to steer a boat. On many occasions I have been unable to steer one of my boats and worried that I would be pushed into another boat."*

> *"While untying boat (with 3 people in it) at dock, the wave was so strong that one of the people on boat was thrown in water!"*

Swamping typically means that a boat fills with water but remains floating. According to the LRA, there have been numerous anecdotal reports of wakes causing swamping or water coming over the bow and gunwales of a boat such that it raises the risk of total swamping. For example, on July 4, 2016, a vessel on Lake Rabun was swamped and sank from the combined effects of multiple wakes flooding over the sides. Although this particular accident was not necessarily the result of wake boats, it illustrates that high wake action can contribute to serious accidents from vessel swamping. The LRA member survey results show that 66 percent of respondents (227 members) reported occasional or frequent swamping caused by wake boat waves. The survey results indicate that wake boat waves significantly increase the risk of boat swamping.

Cruising boats hitting large wakes can cause injury or death. One incident on Lake Rabun involved Mr. Ed Sims, who was cruising in a MasterCraft at dusk. A passenger on his boat was thrown in the air after his boat hit a large wake from a wake boat that suddenly stopped. The airborne passenger landed on the gunwale, bruising multiple ribs requiring treatment at the emergency room. This incident illustrates that low light conditions when wakes are less visible enhance the risk of a serious accident from wake boat waves. Another example includes a tragic accident on Lake Burton on July 18, 2014 that claimed the life of a boy who was ejected from a boat when it hit a large wake. This incident did not necessarily involve a wake boat generated wave, but it illustrates the fact that large wakes increase the risk of fatal accidents. The LRA member survey results indicate that 95 percent of respondents (329 members) reported occasional or frequent jostling of boat passengers caused by wake boat waves, and 14 percent of respondents (47 members) reported occasional or frequent injury of boat passengers caused by wake boat waves.

In addition to impacts to other vessels, the wake impacts to docks and bulkheads can cause unsafe conditions. Anecdotal reports also include vessel wakes overtopping docks and sweeping deck chairs into the water, even though the wake boats were outside the 100-ft buffer. As witnessed in the wake measurement study on Lake Rabun, a wakesurfing wake can easily overtop a bulkhead even 300 ft from the sailing line (see Figure 3-3). The LRA survey responses summarized above include an incident where a wake boat wave caused a boat to crash into a bulkhead, resulting in sinking of the boat. The LRA member survey results indicate that 83 percent of respondents (291 members) reported occasional or frequent endangerment or inconvenience of swimmers or people on docks caused by wake boat waves.

Many parts of these lakes are quite narrow, including most of Lake Rabun and much of Lake Burton. It is in these narrow channels where safety is of particular concern. These channels are generally 500 ft wide or less, with a typical width around 300 feet. Within these channels, large wakes may cause passing vessels to yaw and alter course, increasing the risk of collision. The curving nature of the channels causes wake heights to amplify on the insides of the channel bends, increasing wake hazards in these areas. Additionally, two passing wake boats in the channel can create much larger waves where their wakes intersect. Therefore, large waves from wake boats increase the risk of accidents in the narrow areas of the lakes.

Determining what constitutes safe operating conditions on the lake is necessarily a somewhat subjective assessment. We are not aware of any specific standards to define what wake heights and periods cause unacceptably unsafe conditions on these lakes. Therefore, the evaluation of safety on these lakes should be viewed in the context of managing risk injury or death on the lakes. Recreation on any lake is never without risk, and the goal of management measures should be to reduce risk while still achieving the goal of providing enjoyment of the lake for recreational activities.

Under the current management measures, the larger wave heights and wave lengths generated by wake boats increase the risk of injury or death on these lakes, as compared to conditions prior to the proliferation of wake boats. Anecdotal reports of unsafe conditions from boat wakes supports the conclusion that the present management rules are insufficient and/or insufficiently complied with to provide reasonably safe recreation on the lake for small crafts. In the absence of new management measures, the increasing trend in the number of wake boats on the lakes will continue to increase the risk for injury or fatality from boating accidents related to swamping or interaction with boat wakes.

4 Management Measures

The Associations and Georgia Power should consider revisions to existing management measures to increase safety and reduce risk of injury or death on the lakes while still achieving the goal of providing enjoyment of the lakes for recreational activities. This section of the report reviews existing management measures and wake boat-specific management measures proposed by the WSIA. This is followed by a discussion of potential additional management measure approaches for consideration.

There are existing management measures that apply to boating activities on Lake Rabun and Lake Burton. The Georgia "Rules of the road for boat traffic" (O.C.G.A § 52-7-18) are as follows:

> *(a) All vessels operating on the coastal waters of this state shall conform to the "Steering and Sailing Rules" established by Section II, Rules 11 through 18, of the International Navigation Rules Act of 1977, as amended.*
>
> *(b) All vessels operating on the inland waters of this state shall conform to the "Steering and Sailing Rules" established by Subpart II, Rules 11 through 18, of the Inland Navigation Rules Act of 1980, as amended.*
>
> *(c) It shall be the duty of each operator to keep his vessel to the starboard or right side of the center of any channel, stream, or other narrow body of water; provided, however, this provision shall not give to the operator of a sailing vessel the right to hamper, in a narrow channel, the safe passage of another vessel which can navigate only inside that channel.*
>
> *(d) Powered vessels approaching nonpowered vessels shall reduce their speed so that their wake shall not endanger the life or property of those occupying the nonpowered vessel.*
>
> *(e) Whenever a vessel approaches a bend, point, or other blind area, it shall be the duty of the operator to:*
>
>> *(1) Move as far to the right or starboard as possible;*
>>
>> *(2) Reduce speed to allow for an unexpected stop if necessary; and*
>>
>> *(3) Sound a blast of eight to ten seconds' duration on a sounding device if such a device is carried.*
>
> *(f) No person shall operate any vessel or tow a person or persons on water skis, an aquaplane, a surfboard, or any similar device on the waters of this state at a speed greater than idle speed within 100 feet of any vessel which is moored, anchored, or adrift outside normal traffic channels, or any wharf, dock, pier, piling, bridge structure or abutment, person in the water, or shoreline adjacent to a full-time or part-time residence, public park, public beach, public swimming area, marina, restaurant, or other public use area. This subsection shall not be interpreted to prohibit any person from initiating or terminating water skiing from any wharf,*

dock, or pier owned by such person or used by such person with the permission of the owner of said wharf, dock, or pier nor shall it be interpreted to prohibit the immediate return of a tow vessel to a downed water skier.

(g) No vessel shall run around or within 100 feet of another vessel at a speed greater than idle speed unless such vessel is overtaking or meeting such other vessel in compliance with the rules of the road for vessel traffic.

(h) No vessel shall be operated in such a manner as to ride or jump the wake of another vessel within 100 feet of such other vessel unless the vessel is overtaking or meeting such other vessel in compliance with the rules of the road for vessel traffic and, having passed or overtaken such other vessel, the operator of the passing or overtaking vessel shall not change or reverse course for the purpose of riding or jumping the wake of such other vessel within 100 feet of such other vessel.

(i) Subsections (f), (g), and (h) of this Code section shall not apply to ocean-going ships or to tugboats or other powered vessels which are assisting ocean-going ships during transit or during docking or undocking maneuvers.

Our review and analysis of the available data on wake boats and their effects on the lakes supports the conclusion that the present management rules are insufficient to avoid adverse impacts from the growth in wake boat activity. These adverse impacts include increased risk of shoreline erosion in unprotected areas, increased risk of damage to moored vessels or shoreline structures, and increased risk of unsafe conditions on the lake for small crafts. The present rules should be complemented by additional management measures suitable for narrow, deep lakes such as these.

Based on the results of Goudey and Girod (2015), the WSIA published a Wave Energy Study Summary and Recommendations (2019). The management measures strongly recommended by the WSIA include following:

1. *Always try to wakeboard or wakesurf in the center of any given body of water, and avoid narrow channels or thoroughfares, if possible.*

2. *Always try to stay at least 200 feet away from any shoreline, dock, or fixed objects.*

3. *Maintain a reasonable sound level on your stereo.*

4. *Always respect the shoreline you are using and if the property owner asks that you leave, do so immediately, and always be gracious with the property owner.*

5. *Repetitive passes result in an accumulation of energy reaching the shoreline. Repetition is never a good idea and can lead to risk of waterway conflicts.*

6. The non-surfing side of a wakesurfing boat creates waves that are 10% to 23% smaller with 23% to 33% percent less energy than the surfing side. When possible, present the non-surfing side of the boat to the closest shoreline.

7. Waves tend to increase in height on the inside of a gradual turn. Avoid such maneuvers close to shore.

8. Glass calm water is not a requirement for wake surfing, be respectful and operate as far from shore as you can.

The 200-ft offset recommended by the WSIA, however, is based on the conclusion that "wakeboard and wakesurf wakes/waves, when operated at least 200 feet or more from shore, do not carry enough energy to have a significant impact on most shorelines or on properly maintained docks and other man-made structures." This conclusion is based on an overly simplistic analysis by Goudey and Girod (2015), as discussed previously. Nonetheless, this conclusion is partially true for some shorelines, but it is not true for shorelines exposed to limited fetches and limited wind wave action. At a 200-foot offset, wakesurfing wake heights can still exceed 1.3 feet, which exceeds acceptable mooring conditions.

PIANC (2003) explains that mitigation measures can be divided into three categories: vessel design, operational measures, and non-operational measures. It is likely that the best management regime adopted for any given site will need to involve a combination of operational and non-operational measures. Below are management measures considered in each category:

1. Vessel Design: Hull form is the primary means for managing vessel wakes with hull design. This approach was adopted by some Alaska state agencies by using flat bottom boats to reduce wake impacts on shoreline erosion (Maynord 2008). In addition to hull design, wakesurfing and wakeboarding boats are specifically designed with WED to generate enhanced wakes. Managing wakes by prohibiting certain vessel designs may be a drastic measure, given that there are alternative measures to manage wakes, as discussed below. A prohibition of certain vessel designs would certainly raise many objections from lake users, and therefore the Associations may want to consider advocating for less drastic management measures.

2. Operational measures that may be applicable to Lake Rabun and Lake Burton include:

    a. Restrict the factory installed ballasts from being filled to maximum capacity and prohibit the use of additional ballast items (i.e. "fat sacs"). Doing so would reduce vessel displacements and lower wake heights.

    b. Limit wakesurfing and wakeboarding to the middle sections of the widest parts of the lake,

    c. Restrict wake boats to operate in normal unballasted cruising conditions or no-wake conditions within the narrow sections of the lake.

d. Require wakeboarding operations try to stay at least 100 yards away from any shoreline, dock, fixed objects or small craft. A 100-yard distance (a football field length) is likely more easily visualized by a boat operator than one described as a 300-ft distance. At a 100-yard buffer distance, wakeboarding wake heights will be slightly less than waterskiing or cruising wake heights at a 100-ft buffer distance. For wakesurfing operations, require the vessel maintain a 150-yard buffer distance. At 150 yards from the sailing line, the wake height is approximately 1 ft, still slightly larger than a cruising/skiing vessel at the 100-ft buffer distance, but it will be more manageable than the under the existing rules. These additions would result in only a few permissible wake boat zones in the middle of the widest parts of the Lake Rabun and Lake Burton.

e. Prohibit wakesurfing and wakeboarding operation under low light conditions (dusk, dawn or night) when wakes are less visible to others.

f. Prohibit on-board ballast when cruising or waterskiing. Often, wakeboat operators simply fail to empty ballast while cruising or waterskiing.

3. Non-operational measures that may be applicable to Lake Rabun and Lake Burton include:

   a. Post signage where wake boats should minimize their wake,

   b. Engage in outreach activities to educate the public regarding vessel wake impacts and provide wake management guidelines similar to those provided by the WSIA (except with a revised minimum buffer distance of 100-yards/150-yards from the shoreline and inclusion of a buffer distance around small craft),

   c. Coordinate with neighboring lake associations to pool resources and identify other successful means of wake management.

To provide data to assess the effectiveness of wake management measures or the need for adjustment of wake management measures, WEC recommends that the Associations track occurrences of boat wake incidences. This may include requesting members to report any safety incidences or personal property damages as a result of wake boat operation. This should be documented with available specific information regarding the time and date of the incident(s), a detailed description of the damage, along with videos or photographs, and the registration number of the watercraft rendering the damage, if possible.

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Appendix A. Lake Rabun 2020 Homeowner Survey Summary

Lake Rabun Association Wake Boat Survey
December 2020
Summary of Results

Survey open: November 30 – December 6, 2020

Total responses: 486

Response rate: 57%

Key results:

Q1 Have large waves from wake boats had a negative effect on you while boating on the lake? Select one.

Answered: 485 Skipped: 1

ANSWER CHOICES	RESPONSES	
No	12.99%	63
Occasionally	26.80%	130
Frequently	60.21%	292
TOTAL		485

Q2 How have you been negatively affected by wake boat waves while boating? Select all that apply.

Answered: 401 Skipped: 85

ANSWER CHOICES	RESPONSES	
I limit the amount and times of boating	62.09%	249
Difficulty loading and unloading passengers	51.62%	207
Difficulty navigating boat	70.07%	281
Other (please describe below)	33.92%	136
Total Respondents: 401		

Some comments:

We were visiting friends on the lake who were in lockdown due to covid. We were in our boat, approximately 10 feet away from their dock and seawall, chatting with them on their dock. A wakeboat came by and the wake was so large that it crashed our boat into the seawall, even as we were making every effort to move away from it. Ultimately this led to our boat sinking and being declared a total loss. I just don't believe Lake Rabun is large enough to accommodate this size boat.

Difficult to enjoy the lake safely with small children. Can no longer do normal water skiing. Difficult to swim near our dock. Difficult and unpleasant to drive a pontoon boat.

Two times ballast boat waves have come over the bow of my 22' open bow boat. I felt there was a danger of sinking. Generally it is not pleasant to navigate rough water and big waves. This is ruining our boating experience.

Q3 Do you believe that waves from wake boats create a boating safety issue?

Answered: 476 Skipped: 10

ANSWER CHOICES	RESPONSES	
No	18.49%	88
Yes	75.00%	357
No opinion	6.51%	31
TOTAL		476

Q4 If you believe waves from wake boats create a boating safety issue, please indicate how by answering the following. Select all that apply.

Answered: 357 Skipped: 129

	NEVER	RARELY	OCCASIONALLY	FREQUENTLY	TOTAL RESPONDENTS
Waves swamp my boat	13.16% 45	21.05% 72	46.78% 160	19.59% 67	342
Passengers jostled	1.44% 5	4.02% 14	36.49% 127	58.05% 202	348
Passengers hurt	56.44% 184	29.75% 97	13.19% 43	1.23% 4	326
Skiers or rafters inconvenienced or endangered	2.33% 8	7.00% 24	36.73% 126	53.94% 185	343
Kayakers and paddle boarders inconvenienced or endangered	1.78% 6	5.03% 17	29.59% 100	63.91% 216	338
People on docks or swimming inconvenienced or endangered	4.27% 15	12.82% 45	44.44% 156	38.46% 135	351
Other (please explain below)	2.44% 2	1.22% 1	17.07% 14	79.27% 65	82

Some comments:

We have small children who are often knocked over by such huge waves

With the wake boats so numerous and dominant out on the water now, I can't remember the last time being on the lake where I didn't fear for my family's safety at least once. This is true of time we spend on our boat, as well as time we spend swimming near our dock.

Dropping the boat in the water and taking the boat out of the water, getting in and out of the boat during that time is really dangerous when giant waves come in.

The larger waves directly affect the ability to steer a boat. On many occasions I have been unable to steer one of my boats and worried that I would be pushed into another boat.

While untying boat (with 3 people in it) at dock, the wave was so strong that one of the people on boat was thrown in water!

Q5 Have you experienced shoreline erosion or structural damage as a result of large waves? You may select minor or major shoreline erosion and structural damage as applicable.

Answered: 445 Skipped: 41

ANSWER CHOICES	RESPONSES	
No erosion or structural damage	24.49%	109
Minor shoreline damage	38.88%	173
Major shoreline damage	28.54%	127
Structural damage	32.13%	143
Total Respondents: 445		

Question 5 is a repeat of the same question asked in the 2018 LRA Member Survey. As the table below shows, the percent of respondents reporting shoreline or structural damage has increased over the past two years.

Response	2020	2018	Change
No erosion or structural damage	24.49%	33.78%	-9.29%
Minor shoreline damage	38.88%	29.39%	9.49%
Major shoreline damage	28.54%	22.30%	6.24%
Structural damage	32.13%	14.53%	17.60%

Lake Rabun Association Wake Boat Survey
December 2020
Summary of Results

Some comments:

The constant pounding of wake boat waves against our dock has caused significant damage. I'm repairing it at least twice as much as before the surge in wake boats on the lake. And the small beach area by our dock has eroded so much it's a fraction of what it once was. My children can barely swim/play on that beach area anymore without being jostled and thrown by huge wake boat waves.

Rock Seawall and patio had no damage for 20 years. Has extensive damage in past 3 years due to gigantic waves reaching shoreline.

We've had our house for two generations and have never seen such erosion to our shoreline.

Q6 Cost to repair damage (materials and labor) if known

Answered: 198 Skipped: 288

ANSWER CHOICES	RESPONSES	
Actual amount spent to date on repairs	67.68%	134
Estimated amount to complete repairs	72.73%	144

The following statistics apply to respondents who reported dollar amounts for Question 6.

	Spent To Date	Estimated to Complete
Sum	$609,600	$1,057,450
Average	$8,467	$12,441
Median	$2,800	$3,500
Count	72	85

Q7 Do you believe policies should be put in place to address wake boat activity on Lake Rabun?

Answered: 462 Skipped: 24

ANSWER CHOICES	RESPONSES	
No need for any policies	12.34%	57
Yes, policies are needed	81.82%	378
No opinion	5.84%	27
TOTAL		462

Lake Rabun Association Wake Boat Survey
December 2020
Summary of Results

Q8 How effective do you believe the following policies would be in mitigating any negative effects of wake boat activity?

Answered: 373 Skipped: 113

	NOT EFFECTIVE	SOMEWHAT EFFECTIVE	VERY EFFECTIVE	DON'T KNOW	TOTAL
Restrict times for ballast operations that create larger waves	23.97% 87	36.64% 133	29.75% 108	9.64% 35	363
Limit boat weight	6.94% 25	21.67% 78	54.44% 196	16.94% 61	360
Limit ballast operations to wake boarding and surfing; empty ballast tanks when cruising or waterskiing	14.44% 53	26.43% 97	49.32% 181	9.81% 36	367
Restrict areas of the lake for ballast operations	13.55% 50	24.39% 90	54.20% 200	7.86% 29	369
Require a wider buffer for wake boats (distance to other watercraft or shoreline)	14.52% 53	28.22% 103	52.05% 190	5.21% 19	365
Minimize repetitive wake boat runs in same area	15.30% 56	28.96% 106	46.72% 171	9.02% 33	366
Training and education for wake boat owners and surfers	16.62% 61	31.34% 115	45.23% 166	6.81% 25	367
Other (Please explain below)	6.41% 5	3.85% 3	64.10% 50	25.64% 20	78

Q9 Do you believe policies regarding loud volumes of music from boats on the lake should be adopted?

Answered: 455 Skipped: 31

ANSWER CHOICES	RESPONSES	
Yes	59.34%	270
No	20.66%	94
No opinion	20.00%	91
TOTAL		455

Some comments:

Not all people like the same music. Respect is lost with increased volume.

Loud radios are extremely disruptive and disturbing.

Blasting music load enough for everyone on the shore to hear is noise pollution

Q10 What is your primary concern about wake boats on Lake Rabun? Select one.

Answered: 451 Skipped: 35

ANSWER CHOICES	RESPONSES	
I have no concerns	11.09%	50
Shoreline or structural erosion and damage	39.69%	179
Negative effects on boating (e.g. difficulty navigating or limiting boating activity)	23.50%	106
Boating safety	20.84%	94
Other (please describe below)	4.88%	22
TOTAL		451

Q11 Any other comments you wish to make?

Answered: 221 Skipped: 265

Some comments:

The few who have wake boats significantly interfere with enjoyment of the lake by the many

If families are going to continue to enjoy Rabun together we have to accept wake boats. Kids do not water ski much anymore. I am sure that when ski boats began to replace wood boats on Rabun there were similar responses. We have to be able to allow future generations the ability to enjoy watersports and our beautiful lake together.

Please address this issue. It is affecting our enjoyment of the lake and damaging our property values

I enjoy surfing a lot but unfortunately Lake Rabun is not well suited for modern day surf boats. Or at least not that many and I have no idea how to police them.

As an owner of a wake board boat with ballast I don't believe the problem is with the boat but rather how and where its operated. Owners need to be educated to empty their ballast when not in use and to turn down their speaker volume!!!!!

Study #2

Field Study of Maximum Wave Height, Total Wave Energy and Maximum wave Power Produced by Four Recreational Boats on a Freshwater Lake (February 2022)
University of Minnesota

ST. ANTHONY FALLS LABORATORY

Engineering, Environmental and Geophysical Fluid Dynamics

SAFL Project Report No. 600

A Field Study of Maximum Wave Height, Total Wave Energy, and Maximum Wave Power Produced by Four Recreational Boats on a Freshwater Lake

By:

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Prepared for:

St. Anthony Falls Laboratory, Healthy Waters Initiative

February 2022

Minneapolis, Minnesota

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The authors would like to thank Three Rivers Park District for allowing us the use of facilities at Baker Park Reserve as home base for this study. We thank the McLaughlin family for providing access to their shoreline, dock, lifts, and property on Lake Independence during the study. We thank the individual boat owners for their generosity in providing the test boats, as well as their time and effort in planning and preparing the boats. We thank the Christmas Lake Homeowners Association for the use of their work pontoon for the duration of the field study. We are grateful to Dr. Omid Mohseni of Barr Engineering Company for officiating the independent technical review process and two external reviewers, Dr. Gregory Cox and Dr. Gregor MacFarlane, who provided thorough and constructive comments that greatly improved this report.

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EXECUTIVE SUMMARY

The lakes in Minnesota are considered among the state's most valuable natural resources and are utilized by many visitors and citizens throughout the year. The protection and preservation of surface water resources, lake and shoreline ecosystems, and lakeshore property are shared goals for many in Minnesota. Recreational boating is a highly popular activity and includes motorized and non-motorized watercraft. In recent years, with the growth of recreational activities including the emergence of the sport of wakesurfing, there has been growing concern over the impacts of boat-generated waves and propeller wash on these natural resources. The research reported here was motivated by a need to better understand the characteristics of wakes and waves produced by recreational boats common on lakes and rivers, in particular, in the state of Minnesota.

In the summer of 2020, the University of Minnesota (UMN) launched a program titled "Healthy Waters Initiative" through the St. Anthony Falls Laboratory, an interdisciplinary research laboratory associated with the College of Science and Engineering. The mission of the initiative is to establish multi-year research efforts focusing on issues that have the potential to adversely affect Minnesota lakes and rivers. The Initiative is an independent research program focused on producing targeted, unbiased, peer-reviewed publications of data and research findings.

The initial research performed under the Healthy Waters Initiative was focused on the characterization of boat-generated waves. Funded by a crowdfunding campaign launched in the summer of 2020, the program carried out a six-week, field-based research study examining the wake characteristics of four boats. This report is the first product of the Healthy Waters Initiative.

The field component of the research was conducted in September and October 2020 on Lake Independence, Maple Plain, MN. A study site was selected on the north-eastern shoreline of the lake that provided ideal conditions for a field study of this magnitude. The lake depth increased gradually with distance from shore and was easily accessible from the lake's boat launch. Five, fixed-sensor positions were established at the site to measure wave height – two of these sensors

were submerged Acoustic Doppler Current Profilers attached to pads that rested on the bottom of the lake and three were submerged pressure sensors fixed to masts.

Four boats were evaluated. Two of the boats were typical recreational boats (i.e., non-wakesurf) that are commonly operated (e.g., tubing, waterskiing, wakeboarding) on Minnesota lakes and the two additional boats were wakesurf boats designed specifically for the sport of wakesurfing.

Testing involved operating each boat at four distances from the shoreline (225 ft, 325 ft, 425 ft, and 625 ft) under various conditions (e.g., speed, ballast weight, trim setting, etc.). Test boats were selected based on their size, operational characteristics, typical usage, and availability, and were evaluated under three operating conditions - Condition 1a, Condition 1b, and Condition 2. Conditions 1a and 1b included boat speeds of 10-11 mph and boat configurations that yielded either the largest wake wave possible or settings that are typically used for wakesurfing. Condition 2 included speeds of 20 mph and configurations that resulted in the boat planing on the water surface. Each condition and distance were repeated four times and average wake wave characteristics (i.e., maximum wave height, total wave energy, and maximum wave power) were computed.

An on-board Inertial Navigation System (INS) with an integrated Global Navigation Satellite System (GNSS) was mounted to each test boat and recorded boat attitude (i.e., roll, pitch, and yaw), location, and speed during each pass. The boat positions and mast/pad locations were analyzed to determine the precise location of boat passes and their associated operational distances.

Maximum wave height and maximum wave power within each wake wave packet and the total wave energy content within the packet were calculated for each sensor location and for each boat pass. The wake wave packet is defined as the series of individual waves produced by a single boat pass. These wake wave characteristics were computed for each boat condition at each of the four distances from shoreline. The data from the sensors at each mast/pad location were aggregated and evaluated. The results from this research provide new information on the characteristics of boat-generated waves and reveal interesting and potentially important differences between non-wakesurf and wakesurf boats. The key findings are summarized here:

- The two Malibu Wakesetter (wakesurfing) boats produced the largest waves under all the conditions studied- Condition 1a (largest wave/surfing) and Condition 2 (planing). The longer and heavier of the wakesurf boats, the Malibu Wakesetter MXZ, produced the highest waves with the greatest total wave energy and maximum wave power.
- The smallest maximum wave heights, lowest total wave packet energies and lowest wave powers occurred when boats were planing on the water surface (Condition 2). This was true for all four test boats.
- For an individual boat, the difference in maximum wave height, total wave energy, and maximum wave power between Condition 1a (largest wave/surfing) and Condition 2 (planing) was largest for the wakesurf boats. The Larson LXI 210 and the Malibu Response LX also showed increases in these wave characteristics, however, the magnitude of the changes was smaller for these boats. This is attributable to the large and energetic waves produced by the wakesurf boats under Condition 1a, which is the primary design feature of these boats.
- The decrease (attenuation) in maximum wave height, total wave energy, and maximum wave power over distance was well-characterized by the data and indicate longer operational distances (e.g., distances from shore, other boats, etc.) are required for larger and more energetic wakes to reach the same heights, energies, and powers of smaller wakes.
- Operating with full ballast tanks (Condition 1a) versus empty ballast tanks (Condition 1b) had little impact on maximum wave height, total wave energy, and maximum wave power for the two Malibu Wakesetter boats at operational distances greater than 100 ft.
- The aftermarket wake shaper attached to the Malibu Response LX had a measurable impact on the wave characteristics, resulting in increased maximum wave height, total wave energy, and maximum wave power. This suggests aftermarket products installed on non-wakesurfing boats can create wake waves similar to wakesurfing boats.
- Based on the data and our example method for determining recommended operational distance, we show that when operating under typical wakesurfing conditions, wakesurf boats required distances greater than 500 ft to attenuate wake wave characteristics

(height, energy, and power) to levels equivalent to non-wakesurf boats operating under typical planing conditions. A second example, in which the largest wave was used as reference for the non-wakesurf boats (Condition 1a), an operational distance of 425 ft or greater was required. These results are summarized in the table below.

Results for required operational distance illustrating how data from this study may be used

Reference condition	Operational distance required by wakesurf boat to attenuate to reference condition levels
Example 1 non-wakesurf boat planing at an operational distance of 200 ft (Condition 2 - planing)	Maximum Wave Height: >500 ft. Total Wave Energy: >575 ft. Maximum Wave Power: >600 ft.
Example 2 non-wakesurf boat transition to planing at an operational distance of 200 ft (Condition 1a - largest wave)	Maximum Wave Height: >425 ft. Total Wave Energy: >425 ft. Maximum Wave Power: >425 ft.

In addition to these conclusions, this document offers a summary of research priorities pertaining to the topic of boat-generated waves on lakes and rivers.

INDEPENDENT TECHNICAL REVIEW PROCESS

This report has undergone an independent technical review by subject matter experts not affiliated with the University of Minnesota. The review was facilitated by Dr. Omid Mohseni of Barr Engineering Company, Minneapolis, Minnesota. Two independent experts with backgrounds in naval architecture and vessel wake waves reviewed this work and provided detailed feedback to the review facilitator and authors. The reviewers were Dr. Gregory Cox and Dr. Gregor MacFarlane.

The authors addressed all comments provided by the reviewers and incorporated recommended changes into the final version presented here. UMN responses were shared with the review facilitator who concurred that the updated final report has sufficiently considered and incorporated feedback from the reviewers. UMN responses have also been shared with the reviewers. A draft of this report was submitted for external review on September 29, 2021 and the final version was produced and published through the University of Minnesota's Digital Conservancy on February 1, 2022.

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TERMINOLOGY

Acoustic Doppler Current Profiler (ADCP) – sensor system that uses pulsed, high-frequency sound to measure the velocity field in the water column and vertical position of the water surface.

Boat Wake – surface water waves produced by a boat as it travels on the water surface.

Crest – highest water surface elevation of a single wave.

Dispersion – spreading out or lengthening of the wake wave packet with increasing distance from the source (boat).

Mast – rigid structure used to deploy submerged pressure sensors during testing. Above the water surface, the masts held a datalogger, 12v battery, charge controller, solar panel system, GPS receiver, and wind speed and direction sensors.

Operating Condition – set of boat parameters selected and used within a test. The parameters included: speed, trim setting, ballast setting, hydrofoil setting, wake shaper setting, and number of people aboard.

Operational Distance – distance maintained between the boat and another watercraft, shoreline, dock, lift, raft, or person(s)/animal(s) in the water. For this study, operational distance is the perpendicular distance measured from the boat track line to the object/sensor.

Pad – Acoustic Doppler Current Profiler (ADCP) deployment structure, which sat on the bottom of the lake during testing.

Pass – single instance of a test boat driven along a track line (e.g., 225 ft from shore) under one of the operating conditions.

Trough – lowest water surface elevation of a single wave.

Track Line – line marked by two buoys that ran parallel to the shoreline and perpendicular to the masts/pads. There were four track lines distanced at 225 ft, 325 ft, 425 ft, and 625 ft from shore, that the test boat followed while making a single pass.

Trim – angle of the boat in relation to the water surface measured in the direction of travel.

Wake Wave Packet – series of individual waves generated by a single boat pass. The group of waves within the packet moves outward from the boat track line.

Wave attenuation – decrease in wave height, energy, and power as the operational distance increases from the boat track line.

Wave Energy – a quantifiable attribute of a single wave or series of waves that represents the ability of the wave(s) to do work or make change. In physics, work is often quantified as force applied over a distance.

Wave Height – vertical distance measured from trough to crest of a wave.

Wave Power – the rate at which energy is transferred or used. For wake waves, it is the rate at which energy is transferred away from the track line.

1.0 INTRODUCTION

The state of Minnesota, located in the north central United States, is recognized for having the largest number of natural, inland freshwater lakes and pristine river systems of any state in the lower 48 states of the US (MNDNR 2021). It follows that access, usage, and management of surface waters are highly important subjects within the state. This report is motivated by a need for science-based information on the impacts of motorized recreational boats on surface water resources.

Motorized recreational boats (referred to hereafter as boats) are prevalent on Minnesota waters. In all its forms, including cruising, tubing, waterskiing, wakeboarding, wakesurfing, fishing, or just anchoring to sunbathe and swim, recreational boating is enjoyed by young and old, state residents and visitors, individuals and groups, families, neighbors and friends. Boating and associated activities also represent measurable components of the state's economy.

Those tasked with managing the state's public surface waters face the difficult challenges of balancing public access, long-term protection and preservation of the resources, ensuring protection of property, and public safety. As the popularity of recreational boating continues to grow in Minnesota, so too does the size of boats and their motors. Moreover, new designs of watercraft, specifically, boats engineered to create large wakes for the primary purpose of wakesurfing, are elevating concerns around impacts to safety, lake and river health, shared-use accessibility, and degradation of property. Research to address these concerns is currently lacking or difficult for managers/practitioners to access and apply.

All boats generate wakes associated with the displacement of water by the boat hull. The wake and associated waves produced by a boat are complex hydrodynamic phenomena that have been the subject of research for over a century and have been examined from both fundamental and applied perspectives (see Section 2.0). In this report, we include a brief overview of the salient aspects of boat-generated waves, referred to hereafter as wake waves, however our main focus is on a more pragmatic investigation of common recreational boats operated under typical usage conditions.

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2.0 BACKGROUND

Many books, research reports, theses, and journal papers have been published examining various aspects of boat-generated wake waves. This section provides a summary of the relevant literature on boat wake waves.

2.1 Fundamental research on surface waves, wave energy and power, coastal engineering, and marine architecture

Fundamental research on surface waves and wave attenuation extends back 150 years including fluid mechanics, analytical model development, field investigations, laboratory experiments, and numerical simulations (Lord Kelvin (Thomson) 1887; Stoker 1957; Lighthill 1978; Dingemans 1997; Madsen et al. 2006). This body of fundamental research and theory yields physics-based understanding and mathematical relationships that have enabled practical fields such as naval architecture and coastal and marine engineering. Development of linear wave theory, for example, elements of which are employed in this project, as well as more complex, non-linear wave theories and advanced numerical simulation of waves, continue to be expanded upon today by researchers across the world. In addition, technical guides for the management of coastal areas, such as the Shore Protection Manual (USACE 1984) and Coastal Engineering Manual (USACE 2012) provide useful information and practical equations for computing and modeling surface water waves and applying these to coastal and shoreline engineering problems.

Our study utilized two published doctoral theses in the design of the project (i.e., MacFarlane 2012 and Cox 2020). MacFarlane (2012) is a comprehensive document that provides important and clear summaries of the fundamental theories to the problem of vessel-generated wake waves and the impacts of waves on shoreline environments. This thesis provides insights, among other topics, into the treatment of wave height and practical methods for calculating total wave energy, as well as guidance on proper field deployment of sensors and post-processing methods to field data. Similarly, Cox (2020) offers a wealth of information relevant to this study, such as vessel characterizations, description of surface wave dynamics and classifications, and wave energy dispersion and attenuation.

2.2 Field studies on the impacts of boat-generated wake waves on water quality and shorelines

There are a significant number of published reports and journal articles examining the impacts of boat-generated wake waves on shorelines and near-shore environments. We focused on papers examining transportation vessels, like high-speed or conventional ferries, and on papers examining recreational watercraft. For research published prior to about 2014, wakesurf boats and the sport of wakesurfing were not specifically identified. Several reports and papers after 2014 focused on wakesurfing, which will be discussed in Section 2.3.

The University of New South Wales, Water Research Laboratory, developed a management support tool for boat wake impacts on shoreline zones using standardized field-based measurements of boat-generated wake waves and assessment of impacts on shorelines (Glamore 2008; Glamore and Badenhop 2013). The papers summarized field experience and detailed data collection conducted by the authors and outlined a standardized approach to conduct wake wave assessments including post processing of wave height measurements and calculation of wave energy. Glamore et al. (2013) extended the work to riverbank erosion as well.

We reviewed many field-based studies that focus on assessing boat wave impacts on specific lakes or water bodies. Many of these projects were motivated by anecdotal observations that: 1) boat activity appeared to be increasing, and 2) the increased activity was associated with shoreline erosion and reduction in water quality. A study commissioned by the Maryland Department of Natural Resources (Zabawa and Ostrom 1980) used measurements of wave height and wave energy density for wind-driven and boat-generated waves at five popular boating sites within the project area. The work was performed long before the invention of wakesurfing and wakesurfing watercraft; however, impacts from recreational boating were a concern. In this study, wind wave and storm events appeared to have larger impacts on shoreline erosion than boat wave impacts; however, erosion from boat waves was determined to be significant where wake waves were large and the boats consistently passed within 200 ft or less of the shorelines.

Gourlay (2010) is a similar site-specific field study on the boat waves produced by nine different watercrafts measured at three locations on the Swan River in Perth, Western Australia. The report detailed an approach to wave characterization that was largely adopted in our project. Details on the relationships for correcting attenuation in pressure measurements and computing wave energy in deep water and transitional depths were also provided.

Recent research on boat wake wave impacts within the Chesapeake Bay utilized surveys and existing data to analyze boat wake wave impacts (Bilkovic et al. 2017, 2019). While the research did not involve direct measurement of wave height or wave energy, the authors provided novel approaches to estimating boat activity and locating where impairment/mitigation of shoreline erosion was occurring. Long records of turbidity (a surrogate for suspended sediments) were used to correlate against weekend and holiday lake usage (high boater usage) and weekday usage (low boater usage). The research concluded that boat activity was linked to elevated turbidity and shoreline erosion and this was especially true in regions that were not armored or were not subject to long-fetch wind waves.

While our study focuses on wake waves from recreational boats, observations from studies on wake wave impacts from commercial ferries operating on large marine bays can provide context. Parnell et al. (2007) summarizes research of ferry wave impacts in New Zealand with propagation distances of over 7 km. The authors demonstrated linkages to geomorphic changes on regions they defined as “low wave energy shorelines” meaning shorelines that had not experienced large wind-driven waves and had not become self-armored. Self-armoring refers to a natural process where the waves, over time, mobilize and wash away clays, sands, and gravels up to a certain grainsize. Eventually, only larger grainsizes that are not easily eroded by the waves remain, which serve to protect or ‘armor’ the shoreline. Several papers examined the wave impacts in Tallin Bay, Estonia, which is located within the Gulf of Finland (Parnell et al. 2008; Kurennoy et al. 2009; Kelpšaite et al. 2009). This body of research examined the role of boat operational characteristics, vessel type, wave height, and wave energy on sediment resuspension. The approaches and methods described in these papers informed our research methods.

Boat-generated wake wave impacts on river banks were explored in a number of studies from around the globe and several were informative for this project. USACE (1994) is a final report for a larger research study that provided a comprehensive look at a specific surface water system -

the Fox River and Chain O'Lake public waterway. The findings from the study indicated a nearly instantaneous response in water quality to high boating activity. MacFarlane and Cox (2003a, 2003b, 2005) describe detailed investigations of vessel wake wave characteristics and impacts on bank erosion on the Brisbane, Noosa, and Maroochy Rivers in southeast Queensland, Australia. The authors utilized field measurements of wave height and period to establish threshold criteria that can be used to inform management decisions on these systems. Shoreline erosion was studied on the Waikato River in New Zealand for two recreational watercraft and a personal watercraft (McConchie 2003). The study relied on field measurements of wave height using submerged pressure sensors and the data were used to calculate wave energy. Suspended sediment samples were also collected in an attempt to link wave characteristics to bank erosion. Similarly, Maynord et al. (2008), studied boat-generated wave erosion on the river banks of the Kenai River, Alaska. Here, wave heights were measured with a capacitance-based system but the approach for determining wave heights and energy were the same approaches adopted in our study.

2.3 Field studies on the impacts specific to wakesurf boats

We identified a small number of research reports that specifically focus on wakesurfing conditions (e.g. relatively slow speeds ~10-12 mph, internal ballast tanks and wake enhancing technologies). We were not able to find any journal articles within the peer-reviewed literature. Ruprecht et al. (2015) is a conference paper that compared measured wake height and energy of a boat described as a "wakeboarding vessel" that was operated under wakesurfing, wakeboarding, and waterskiing conditions. The research reported a four-fold increase in wave energy under wakesurfing conditions. In addition, the authors offered an approach for developing empirical equations relating maximum wave height to wake wave energy, which may be a useful and practical approach to adopt in upper Midwest US lakes and rivers. Wakeboarding and waterskiing operational conditions yielded similar wave heights and energy, but were both lower than wakesurfing conditions.

Two research reports from Canada examine impacts from the wake wave and propeller wash of wakesurf boats. Mercier-Blaise and Praire (2014) is a research report from the University of

Québec, Montreal, that details a field-based study of wake wave impacts on shorelines. The researchers used a single wakeboarding boat operated at various speeds and ballast conditions. The report defined 10 mph speed and biased ballasting to be the wakesurfing condition. A unique aspect of the project involved using an Acoustic Doppler Velocimeter (ADV) to record turbulent wave energy (turbulence kinetic energy or TKE) at a specific location in the nearshore environment. The researchers also collected water samples during testing and analyzed for suspended solids concentration. Results from the work showed an increase in TKE from boat-generated waves with the largest impacts resulting from the 10 mph wakesurf boat conditions. Raymond and Galvez-Cloutier (2015) was published by Laval University, Quebec, and focused on the impacts of wakeboat propeller wash on velocities and turbidity. As in Mercier-Blaise and Praire (2014), a single wakeboarding boat was used and operated under three conditions to simulate wakesurfing, wakeboarding, and waterskiing. An Acoustic Doppler Current Profiler (ADCP) was deployed on the lake bottom at a water depth of approximately 16 ft (5 meters) and recorded the velocity field within the water column as the boat traversed over the sensor. The effects of propeller wash appeared to have penetrated up to 16 ft (5 meters) deep for the condition associated with 10 mph and biased ballasting (i.e., wakesurfing). It should be noted that both Mercier-Blaise and Praire (2014) and Raymond and Galvez-Cloutier (2015) were pilot studies and the authors suggest more research is required. Regardless of the preliminary nature of the work, the two projects introduce the use of advanced sensors (ADV and ADCP) and incorporate environmental monitoring (turbidity), which are important for future research in this area.

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3.0 MATERIALS AND METHODS

3.1 Study location and site

This study took place on Lake Independence, Maple Plain, Minnesota, USA (45°1'37"N 93°38'53"W) (Figure 1). Lake Independence is 832 acres (425 littoral acres) with a shoreline length of 7.47 miles. The main basin of the lake is bowl shaped with water depths gradually increasing to the lake's maximum depth of 58 ft. The lake is a popular recreational destination. For example, Baker Park Reserve, owned and operated by Three Rivers Park District, offers 2,700 acres of natural landscape that abuts to the lake via 4,000 ft of southeast shoreline (Figure 1). The park includes a swimming beach, boat launch, RV park, and hiking trails that attract many people to the lake to recreate. Having Baker Park Reserve on the southeast shoreline was integral to the success of this study because it was near our study site and Three Rivers Park District allowed us to use the park's boat rental facility and docks, which drastically increased our efficiency. Our study site was located along the northern shoreline of the lake's southeast quadrant (Figure 1). In addition to having Baker Park Reserve nearby, this site was chosen because a lake property owner graciously granted our team access to their dock and shoreline. The lake bathymetry at the study site had a moderately gradual slope 5.1% (Figure 2) and bottom substrate was measured to be primarily sand and gravel. The shoreline directly abutting the study site was protected with large riprap stones with minimal vegetation present.

Figure 1. Lake Independence, Maple Plain, Minnesota, USA. The red box depicts the study site located along the northern shoreline of the lake's southeast quadrant.

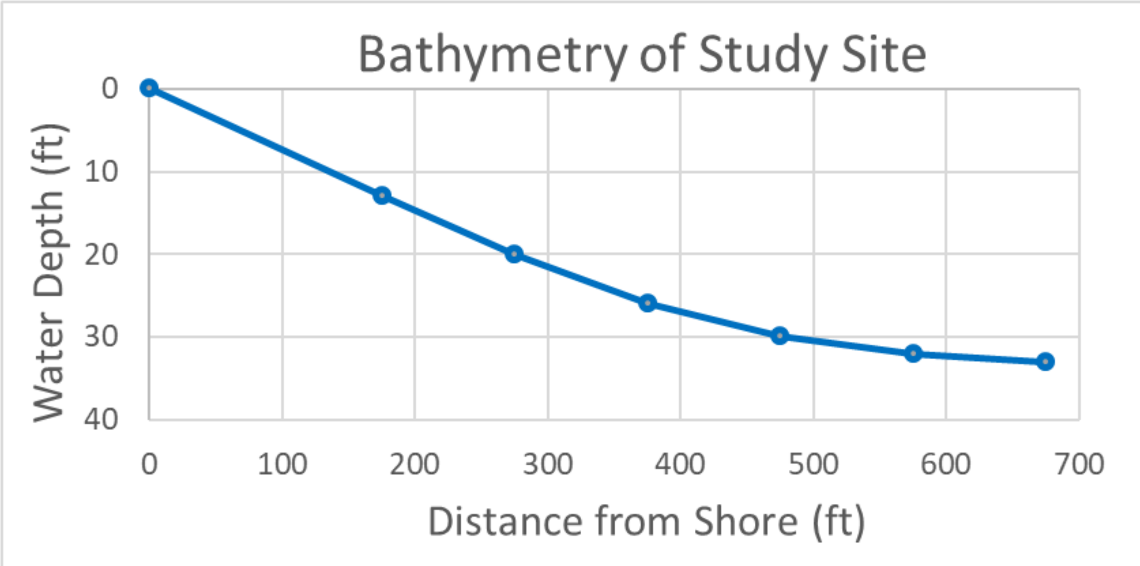


Figure 2. Typical bathymetry at the study site showing a gradual increase in water depth with distance from shore. The maximum depth was 33 ft at 675 ft from shore.

3.2 Layout of the study site

Figure 3 illustrates the layout of the study site and is described hereafter. Using bathymetric and Global Position System (GPS) data, three masts (Section 3.4) and two pads (Section 3.5) that held data sensors, were installed in a straight line approximately perpendicular to the shoreline at known depths and distances (Table 1). The line of masts/pads was also in an alignment that was roughly perpendicular to local bathymetric contour lines.

Four boat tracks were defined in a straight line approximately parallel to the shoreline and perpendicular to the masts and pads at approximately 225, 325, 425, and 625 ft from shore. Each track line was marked by a pair of taut-moored inflatable buoys that helped to visually guide the boat operator during testing (see Section 3.8 for more detailed description).

Table 1. The distances of masts and pads from shore and their respective water depths.

Station	Distance From Shore	Water Depth
Mast A	16 ft (5 m)	1.8 ft (0.6 m)
Mast B	114 ft (35 m)	6.1 ft (1.9 m)
Mast C	142 ft (43 m)	8.5 ft (2.6 m)
Pad 1	219 ft (67 m)	14.0 ft (4.3 m)
Pad 2	311 ft (95 m)	22.0 ft (6.7 m)

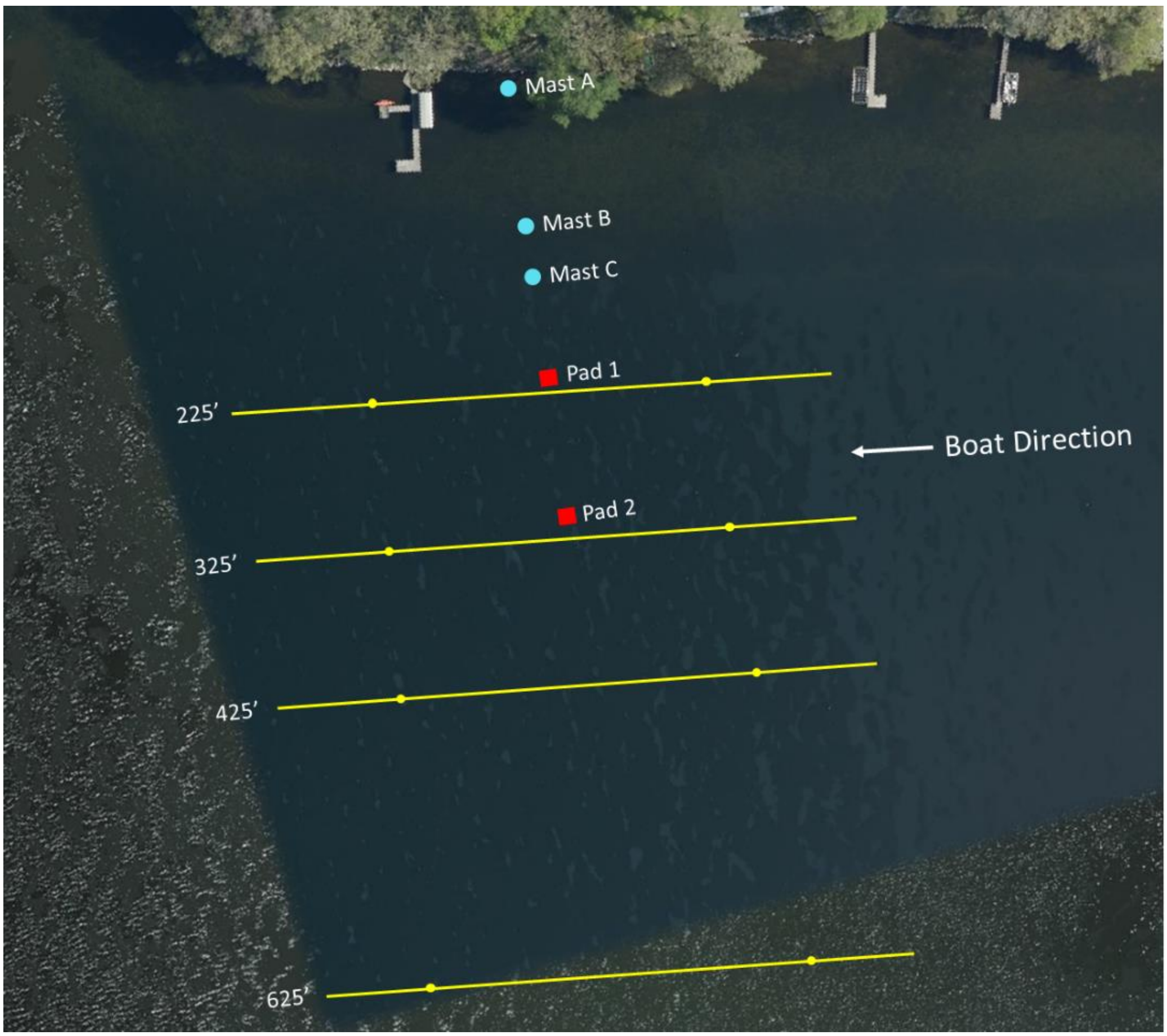


Figure 3. Layout of the study site. The three blue circles and two red squares indicate the locations of the masts and pads, respectively. The yellow lines show the distance of the boat track lines from the shoreline.

3.3 Description of masts and attached data sensors

The three masts were designed and fabricated to hold various types of data sensors. The masts were tripod structures composed of 2 in steel pipe (Figure 4a). To increase sturdiness, three 1-5/8 in steel struts along with three 3/16 in cable wires (made taut via turnbuckles) connected the legs to the center pipe. Because the masts were installed at different water depths, each mast was a different height. However, once deployed each mast had approximately 6 ft of center pipe emerging from the water surface, which was where equipment that needed to remain dry was attached (Figure 4b). With the assistance of a diver, the masts were installed, leveled, and secured to the lake bottom via 330 lbs of steel plate. The masts were installed in relatively shallow water (< 10 ft) and remained in their respective positions for the duration of the study (Table 1, Figure 3). Because Masts B and C were positioned further from shore in deeper navigable water, strobe lights were added to warn approaching watercraft of the hazard at night. Reflectors were also attached to all masts to further increase visibility.

Each mast was equipped with various data sensors, both above and below the water surface. Above the water surface, each was equipped with a water-resistant enclosure that housed a Campbell Scientific datalogger (CR1000X) powered by a 12v battery, charge controller, and solar panel system. A data acquisition program was written and installed on each data logger that collected data from various hardwired sensors. A GPS receiver with integrated antenna (GPS16x-HVS by Garmin International) that provided position, velocity, and timing information was fixed to each mast. Specifically, the GPS receiver allowed the data logger clocks to be synchronized to the highly accurate GPS time, and allowed post-processing synchronization between all sensor systems. Finally, Masts B and C were outfitted with wind speed and direction sensors. A single Campbell Scientific vented pressure transducer (CS431 PS9805 5PSI) was installed on each mast between 8-11 in (0.20-0.28 m) below the water surface. As the wake wave packet (i.e., series of waves produced by the boat) passed above the sensor, the water column height, and thus pressure at the sensor varied. This information was captured at 10 Hz (i.e., 10 samples per second) by the sensor and stored on the datalogger for later post-processing to determine maximum wave height, total wave energy, and maximum wave power of the wake wave packets.

Per the manufacturer’s specifications, this model of pressure transducer has a repeatability of ± 0.1% FSO or ± 0.14 in of water.

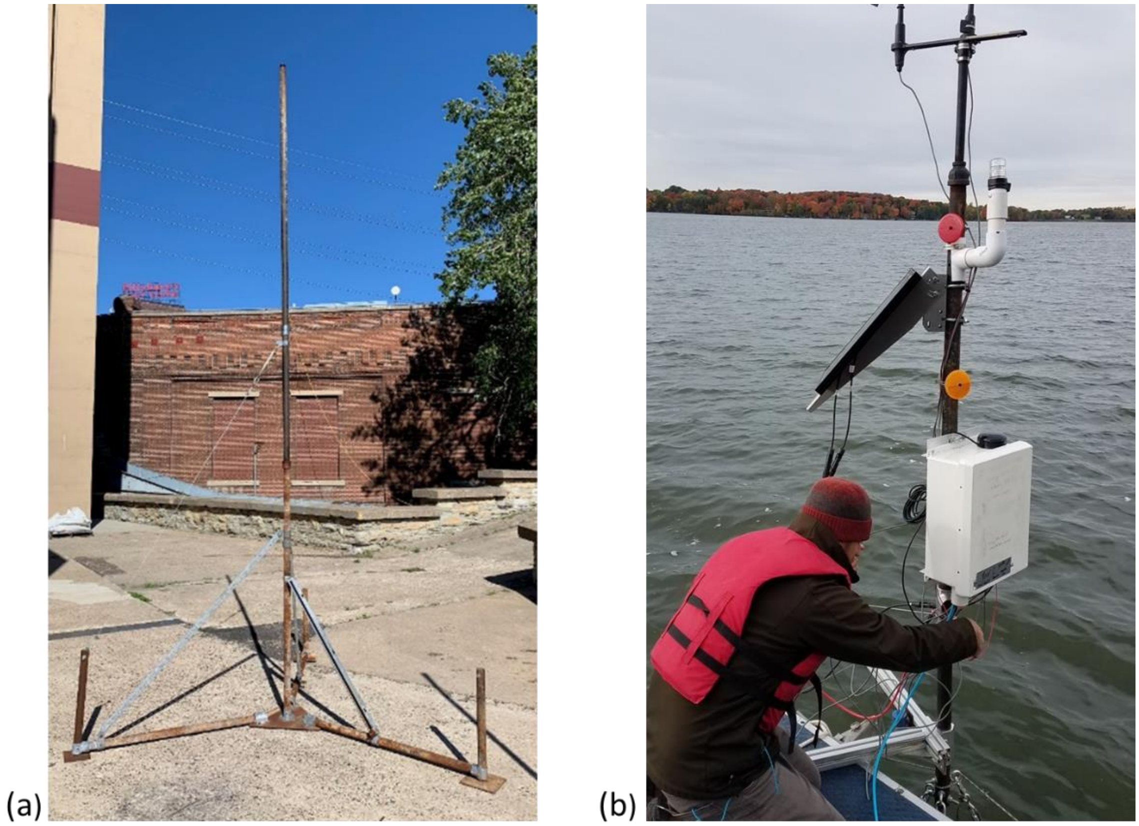


Figure 4. (a) Mast on land prior to being equipped with data sensors, (b) mast deployed and equipped with data sensors.

3.4 Description of pads and attached data sensor

Deployment of a mast system equipped with cabled data sensors was not practical in deeper waters (>10 ft). Instead, two pads were designed and custom-built to be easily deployed and retrieved from deeper waters (Table 1). The pads were rectangular structures made of 1-5/8 in steel strut with 12 in legs (Figure 5) that partially sunk into the substrate upon deployment and prevented the pad from moving. At each corner of the structure, a 4 ft x 3/16 in wire rope was secured. The four wire ropes were joined at a single lifting point and a nylon rope was attached to the lifting point and used to lower and lift the pad during deployment. The other end of the nylon rope was secured to a small buoy at the water surface. Because of the simplicity of this system, we were able to easily retrieve the pads and detach the data sensor and download data after each day of testing.

An Acoustic Doppler Current Profiler (ADCP; Nortek Signature 1000), capable of collecting data on the velocity fields within the water column, was secured to the center of each pad (Figure 5). Specifically, the ADCPs were used to collect high-resolution data on surface wave height. For water surface elevations (referred to as altimeter data by Nortek), the device records the two-way travel time of a single “ping” that is reflected off the water surface. The ADCPs are autonomous units with an internal clock, battery, and data logger. The clock on the ADCPs were set to match the internet time via a tethered laptop prior to deployment. The sampling rate of the ADCPs were set to 4 Hz for all tests.

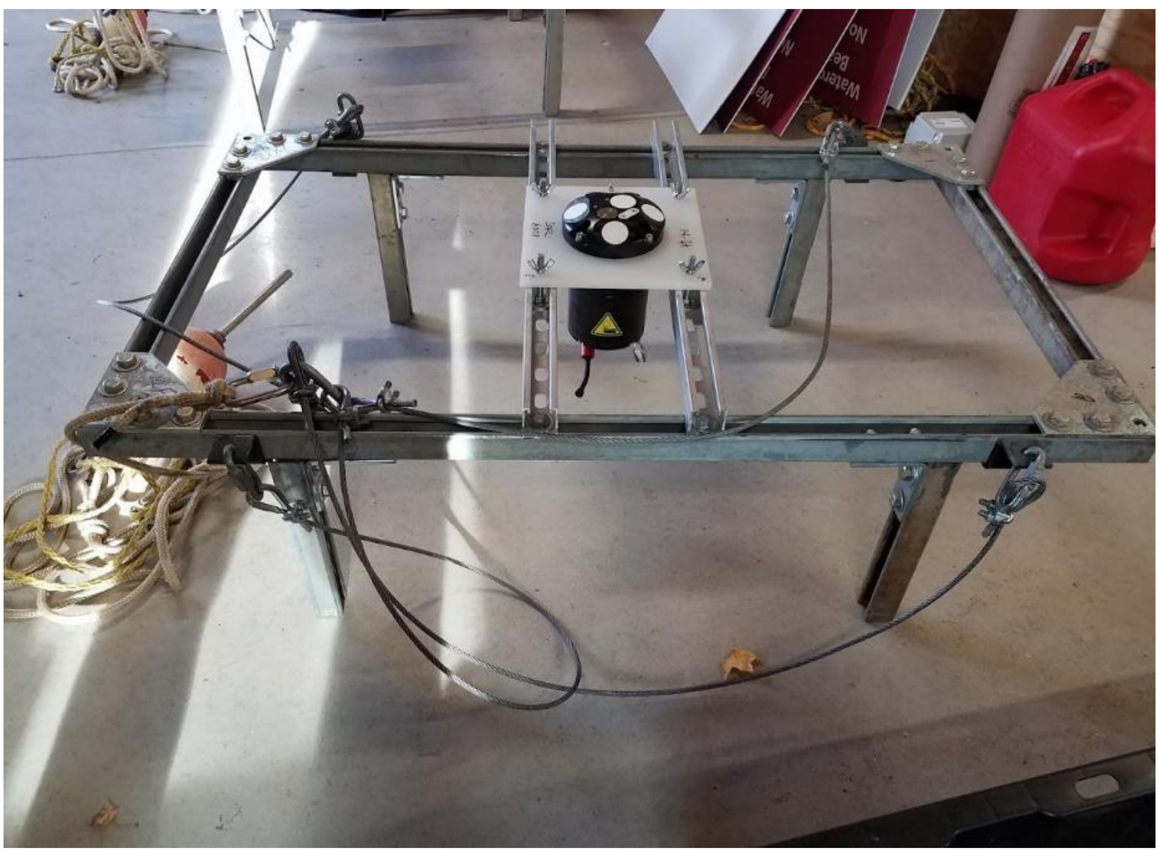


Figure 5. An ADCP secured to the custom-built pad and ready for deployment. The four lifting cables and lift rope can also be seen in the image.

3.5 Summary of test boat characteristics

The wake waves generated by four boats were evaluated in this field study (Table 2). The 2004 Larson LXI 210 is a common recreational boat powered by a 260 horsepower inboard/outboard (I/O) engine, otherwise known as a sterndrive. The engine is positioned at the stern of the boat, with the drive unit protruding through the transom. The boat operator can trim the drive unit up or down to change performance during various operating conditions. Moreover, when the steering wheel is turned the entire drive unit turns, making the boat more responsive to maneuvering at slower speeds than boats steered by a rudder.

There are two primary types of inboard powertrain configurations, D-Drive (direct drive) and V-Drive, and both were tested in this study. These powertrains are equipped with a system that includes a propeller that protrudes through the hull (i.e., under the boat) via a shaft and rudder that provides the steering. These types of powertrains are presently preferred for many tow sports because of increased safety with the propeller set forward of the transom. As the propeller pushes water past the rudder, the boat direction responds in accordance with the rudder position, which is controlled by the steering wheel. The 2004 Malibu Response LX had a 310 horsepower D-Drive inboard engine, meaning the engine was housed in the center of the boat. The D-Drive powertrain is mechanically simpler and also places the boat's center of mass forward, which allows the boat to transition to planing more efficiently. D-Drive inboards are popular among waterskiing enthusiasts because of this attribute.

Both the 2019 Malibu VLX and 2019 Malibu MXZ had 450 horsepower V-Drive inboard powertrains, meaning the engines were positioned at the rear of the boat beneath the transom seating. Having the weight of the large engine at the back of the boat creates greater aft trim for the boat, thus creating the bigger wakes needed for watersports like wakesurfing. In addition to the type of powertrain, boat manufacturers and independent businesses have developed methods to manipulate boat-generated wakes (e.g., height, length, shape, direction) that include: boat size and weight, hull design, ballast systems, and surf systems (e.g., hydrofoils and wake shapers).

It is important to state that this study was limited to examining only four boats. We selected watercraft that were representative of non-wakesurfing and wakesurfing boats; however, there are many other boat manufacturers and models not considered. The boat selection was based on the boats that were available to us within the short window of field work for this study. This research is not intended to highlight any specific watercraft manufacturer, but recreational boats in general.

In the next sections, we discuss specifics of the four boats tested in this study.

3.5.1 Larson LXI 210

The 2004 Larson LXI 210 had a length of 21 ft, a beam of 8.25 ft, and weighed 2,925 lbs dry (Table 2). The size, weight, and modified V hull design of this boat are common among all-purpose recreational boats (i.e., cruising, fishing, boat watersports). The boat used did not have any additional wake manipulating systems and created a symmetrical wake, meaning the wake waves produced was similar off both sides of the boat.

3.5.2 Malibu Response LX

The 2004 Malibu Response LX was the smallest and lightest of the test boats with a length of 20 ft, a beam of 7.5 ft, and a dry weight of 2,450 lbs (Table 2). Again, the hull design was a modified V shape. This boat was equipped with a manually operated transom mounted hydrofoil. When not in use the hydrofoil gets locked in the stow position (Figure 6a). When in use the hydrofoil is lowered to a single fixed position (Figure 6b). The principle of operation of this hydrofoil is to provide a downward force at the stern of the boat, creating greater aft trim. According to the manufacturer, the hydrofoil produces up to 1,000 lbs of equivalent aft ballast to the stern of the boat.

An aftermarket wake shaper (Wakesurf Creator 2.0 by Swell Wakesurf) was attached to the boat during one of the test conditions (i.e., Condition 1a, see Section 3.6.2). The wake shaper is a paddle-like baffle that was attached via suction cups to the port quarter of the hull just below the water surface (Figure 6c). When installed, the wake shaper increases the size and smoothness of the wake on the opposite side of the boat, making an asymmetric wake that is surfable on one side. The hydrofoil and wake shaper can be used in tandem to create wake conditions that are suitable for wakesurfing.

3.5.3 Malibu Wakesetter Boats: VLX and MXZ

Malibu's line of Wakesetter boats are specifically designed for wakesurfing. The 2019 Malibu VLX Wakesetter was the smaller of the two Wakesetters with a length of 21 ft, a beam of 8.2 ft, and an approximate dry weight of 4,200 lbs (Table 2). To make the wake larger by displacing more water, the boat can be made heavier via its ballast system that can hold up to an additional 3,690 lbs of water weight. The larger 2019 Malibu Wakesetter MXZ was 24.5 ft long, 8.5 ft beam, and weighed approximately 5,500 lbs dry (Table 2). This boat also had a ballast system that could hold up to an additional 4,885 lbs of water weight.

Both boats were equipped with Malibu's proprietary control system called the Integrated Surf Platform. The system combines an array of technologies to create and maintain a desired wake condition. The hydrofoil, termed Power Wedge III by Malibu, functions in the same principle manner as the aforementioned hydrofoil, where according to the manufacture, the Power Wedge III can produce up to 1,500 lbs of downward force, which is equivalent to 1,500 lbs of equivalent aft ballast (Malibu Boats 2020). The Power Wedge III had adjustable settings that range from "lift" to "stow" (Figure 8a). When in lift mode the Power Wedge is in position #1 and fully deployed down (Figure 7a). In this position, the foil creates an upward lift force that allows the boat to reach planing quickly. As the Power Wedge is raised from lower numbered settings to higher numbered settings (Figure 8a), the size, shape, and surface roughness of the wake changes. This control over the wake is desirable because it allows surfing conditions to be adjusted to the skill and preference of the surfer. Finally, when in stow mode, the Power Wedge is not in use (Figure 7b).

The Wakesetters also have factory installed wake shapers (Malibu Surf Gate) on either side of the transom, just below the water surface (Figure 7c). When deployed on one side, the wake shaper produces an asymmetric wave with a larger and smoother surfing wave on the opposite side of the boat.

Table 2. Summary of the four test boats.

Manufacturer	Model	Year	Drive	Horsepower	Beam (ft)	Length (ft)	Dry Weight (lbs)	Ballast (lbs)	Hydrofoil	Wake Shaper
Larson	LXI 210	2004	Sterndrive (I/O)	260	8.3	21	2925	No	No	No
Malibu	Response LX	2004	Direct Drive (I)	310	7.5	20	2450	No	Yes	Yes -aftermarket
Malibu	Wakesetter VLX	2019	V-Drive (I)	450	8.2	21	4200	3690	Yes	Yes
Malibu	Wakesetter MXZ	2019	V-Drive (I)	450	8.5	24.5	5500	4885	Yes	Yes

Notes:

(I/O) - inboard outboard or sterndrive powertrain

(I) - inboard powertrain

Figure 6. Malibu Response LX hydrofoil in the (a) stow position and (b) deployed down position. (c) Installed aftermarket wake shaper (Swell Wakesurf- Wakesurf Creator 2.0).

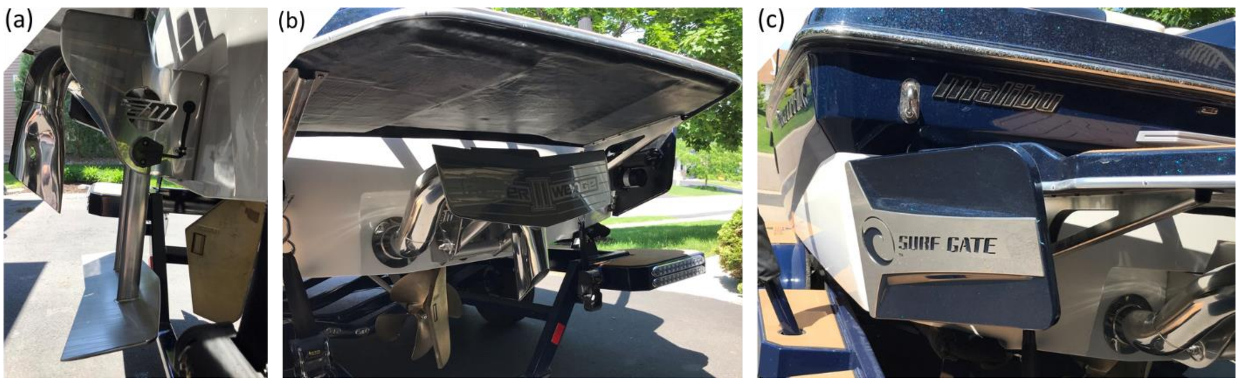


Figure 7. Malibu Wakesetter hydrofoil (Power Wedge III) set to (a) lift and (b) stow. (c) Malibu Wakesetter wake shaper (Surf Gate) in the off position.

3.6 Summary of operating conditions tested for each boat

The operating conditions used during testing of the four watercrafts are summarized in Table 3 and were defined by weight, operating speed, ballast condition (if applicable), hydrofoil (if applicable), and wake shaper (if applicable), and sought to represent typical recreational boating activities.

3.6.1 Larson LXI 210 operating conditions

During testing of the Larson LXI 210, two people were aboard the watercraft that added a combined weight of approximately 330 lbs. The passenger sat in the seat next to the boat operator to keep weight evenly distributed. Condition 1a created the largest wake wave possible without the addition of wake manipulating methods (Table 3). The boat speed was held at 10 mph and the propeller trim was adjusted to achieve the greatest aft trim possible. This propeller trim position was found to be the 50% position.

Condition 2 modeled typical operating conditions of the boat for tow sports like tubing, waterskiing, and wakeboarding (Table 3). The boat traveled at 20 mph with the propeller trim set to 100% (i.e., completely down) and was in a planing condition. Because no wake manipulating methods or technologies were used, the wake waves were symmetrical for both Condition 1a and 2.

3.6.2 Malibu Response LX operating conditions

During testing of the Malibu Response LX, two people were aboard the watercraft, which added approximately 330 lbs of weight. Condition 1a created the largest wake waves possible with the operating conditions tested (Table 3). The boat traveled at 10 mph. The hydrofoil was in the down position, which created an estimated downward force of 1,000lbs, equivalent to 1,000 lbs of equivalent aft ballast (Section 3.5.2, Figure 6b). To increase aft trim further, the passenger (175 lbs) sat in the stern seating area. The aftermarket wake shaper was installed on the outside surface of the port quarter of the hull, just beneath the water surface (Section 3.5.2, Figure 6c), which produced an asymmetric wake with the larger and less turbulent side forming starboard. We chose to have the larger wake on the starboard side because, during testing, the boat traveled from east to west and approximately parallel to the shoreline, which directed the wake towards shore where our data sensors were installed (Figure 3).

For Condition 1b (Table 3), the aftermarket wake shaper was removed so its effects on the wake characteristics (e.g., height, energy, power) could be measured (i.e., device on vs. device off).

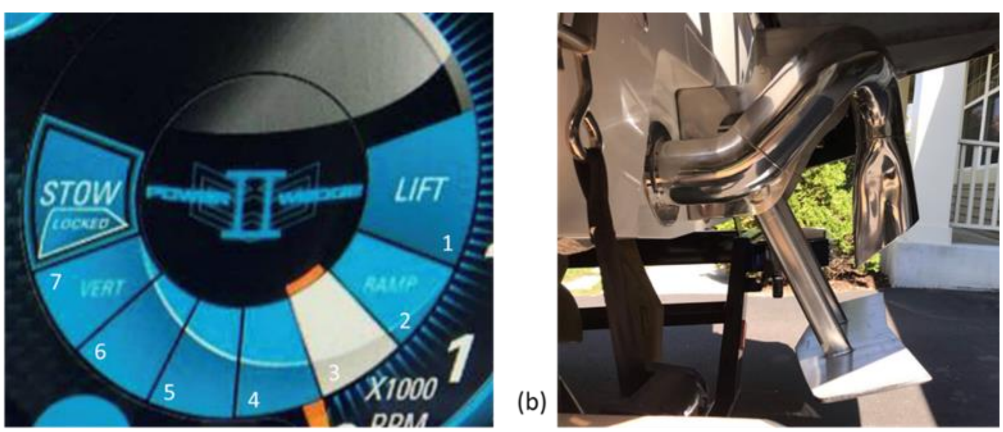
The Condition 2 variables were set to model conditions commonly used during tubing, waterskiing, and wakeboarding (Table 3). The boat traveled in a planing condition at 20 mph with no wake shaper attached (symmetric wake). The passenger sat in the middle of the boat next to the boat operator to evenly distribute weight. The hydrofoil was placed in the downward position creating downward force and additional aft trim.

3.6.3 Malibu Wakesetter Boats: VLX and MXZ operating conditions

Both the Malibu VLX Wakesetter and Malibu MXZ Wakesetter were tested using the same two conditions (Table 3), with the only difference being the manufacturer's boat characteristics (Section 3.5.3, Table 2). Four people were aboard with a combined weight of approximately 740 lbs. To keep the weight in the back half of the boat and evenly distributed, one passenger sat in the passenger seat next to the boat operator and the other two passengers sat in the rear transom seating area. Condition 1a modeled the conditions and settings commonly used by the boat owners when they wakesurf (Table 3). During this condition, the boats traveled at 11 mph with the ballast tanks 100% full. The Power Wedge III was set to setting #3 (Figure 8), with the portside Surf Gate on (asymmetrical wake). Again, this formed a large surf wake on the starboard side of the boat that traveled towards the shoreline and our data sensors (Figure 3).

All variables remained the same for Condition 1b, except for the ballast tank setting (Table 3). The ballast water was completely drained so its effects on the wake characteristics (e.g., height, energy, power) could be compared (i.e., full vs. empty).

The variables in Condition 2 were set to model conditions commonly used during tubing, waterskiing, and wakeboarding (Table 3). The boat traveled at 20 mph with the ballast tanks empty, the Power Wedge III remaining in setting #3, and the Surf Gate off (symmetric wake).

(a)


(b)

Figure 8. (a) Power Wedge III settings that range from lift to stow. Lift is noted as position #1, with the white highlight indicating that setting #3 is selected. (b) Power Wedge set to setting #3.

Table 3. Summary of the operating conditions for each boat tested. The only difference between Conditions 1a and 1b for the Malibu Response LX was the wake shaper setting (i.e., on vs off). The only difference between Conditions 1a and 1b for each Malibu Wakesetters was the ballast setting (i.e., full vs empty).

Boat	Condition #	Speed (mph)	Trim Setting (%)	Ballast (% filled)	Hydrofoil/Power Wedge III	Wake Shaper/Surf Gate	People Aboard	Approx. People Weight (lbs.)
Larson LXI 210	1a	10	50 (middle)	N/A	N/A	N/A	2	330
	2	20	100 (down)	N/A	N/A	N/A	2	330
Malibu Response LX	1a	10	N/A	N/A	Down	On – Port Side	2	330
	1b	10	N/A	N/A	Down	Off	2	330
	2	20	N/A	N/A	Down	Off	2	330
Malibu VLX Wakesetter	1a	11	N/A	100	Down – Setting #3	On – Port Side	4	740
	1b	11	N/A	0	Down – Setting #3	On – Port Side	4	740
	2	20	N/A	0	Down – Setting #3	Off	4	740
Malibu MXZ Wakesetter	1a	11	N/A	100	Down – Setting #3	On – Port Side	4	740
	1b	11	N/A	0	Down – Setting #3	On – Port Side	4	740
	2	20	N/A	0	Down – Setting #3	Off	4	740

3.7 Generating boat wake waves

Test boats were driven approximately from east to west along designated track lines set at 225, 325, 425, and 625 ft from shore, with the shoreline on the starboard side of the boat (Figure 3). The track lines were deployed in a straight line approximately parallel to the lake's measured bathymetry contours, which were also approximately parallel to the shoreline, and perpendicular to the mast/pad alignment. Using GPS coordinates, each track line was marked by a pair of taut-moored inflatable buoys that helped to visually guide the boat operator during testing. Moreover, the buoy locations were marked as waypoints on an onboard GPS unit (Humminbird Helix 10) that charted real-time boat position, further helping the boat operator navigate consistent and repeatable passes along the track lines. To ensure the wake waves that reached the mast/pad sensors were generated under steady conditions, the boat operator maintained test speed and alignment with the track line well before and after the track line buoys.

For each operating condition evaluated (Section 3.6, Table 3), the test boat made four passes along each track line. An observer was stationed onshore to notify the boat operator (via two-way radios) when it was clear to make the next pass, which was made only after the previous wake wave packet had made landfall in its entirety. This ensured that the wake wave packet generated by a single pass would be easily identifiable (i.e., clear start and end of each wake packet) during data post-processing.

3.8 Boat positional data

Instrumentation was mounted on each of the test boats to continually measure the boat's GPS position, velocity, yaw, pitch (trim) and roll. The on-board instrumentation utilized a mobile Raspberry Pi-based interface running Python to query the data from a VectorNav VN-200 inertial navigation sensor (INS)[1], which was positioned mid-boat. The sensor system included a L1 global navigation satellite system (GNSS) module, 3-axis accelerometers, 3-axis gyros, 3-axis magnetometer, barometric pressure, and an on-board processor. An INS Kalman filter reported position, velocity, and orientation at high frequencies after coupling GNSS location information with other on-board sensors used to record hull submergence (not discussed in this report). The

[1] (https://www.vectornav.com/)

stated accuracies of the VN-200 system after coupling with GNSS data are 1.0 m root mean square (RMS) for horizontal position, <0.05 m/s for velocity accuracy, 0.2-degree RMS for heading, and 0.03-degree RMS for pitch and roll. Additionally, the system data continuously reported uncertainties for attitude, position, and velocities, which included measured outliers in those reported values. The data were recorded at ~5Hz and collected within a single data file. To eliminate any potential velocity inconsistency between boats (e.g., different speedometer accuracies), we used the real-time velocity readings of this system during passes. The positional data for each pass were later imported into AutoCAD and used to estimate operational distance (Section 4.1).

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4.0 DATA ANALYSIS

4.1 Computing operational distances

The boat positional data (Section 3.8) were imported into AutoCAD and plotted (Figure 9). The perpendicular distances between each boat pass and each of the masts/pads (i.e., measurement sensors) were then calculated; these distances were defined as operational distances (Figure 9). For each of the four passes along a track line, an operational distance average and standard deviation were calculated. The passes along the track lines were highly repeatable, as the standard deviations for the averaged operational distances were <4 ft. The data and results presented in Section 5.0 are plotted against operational distance.

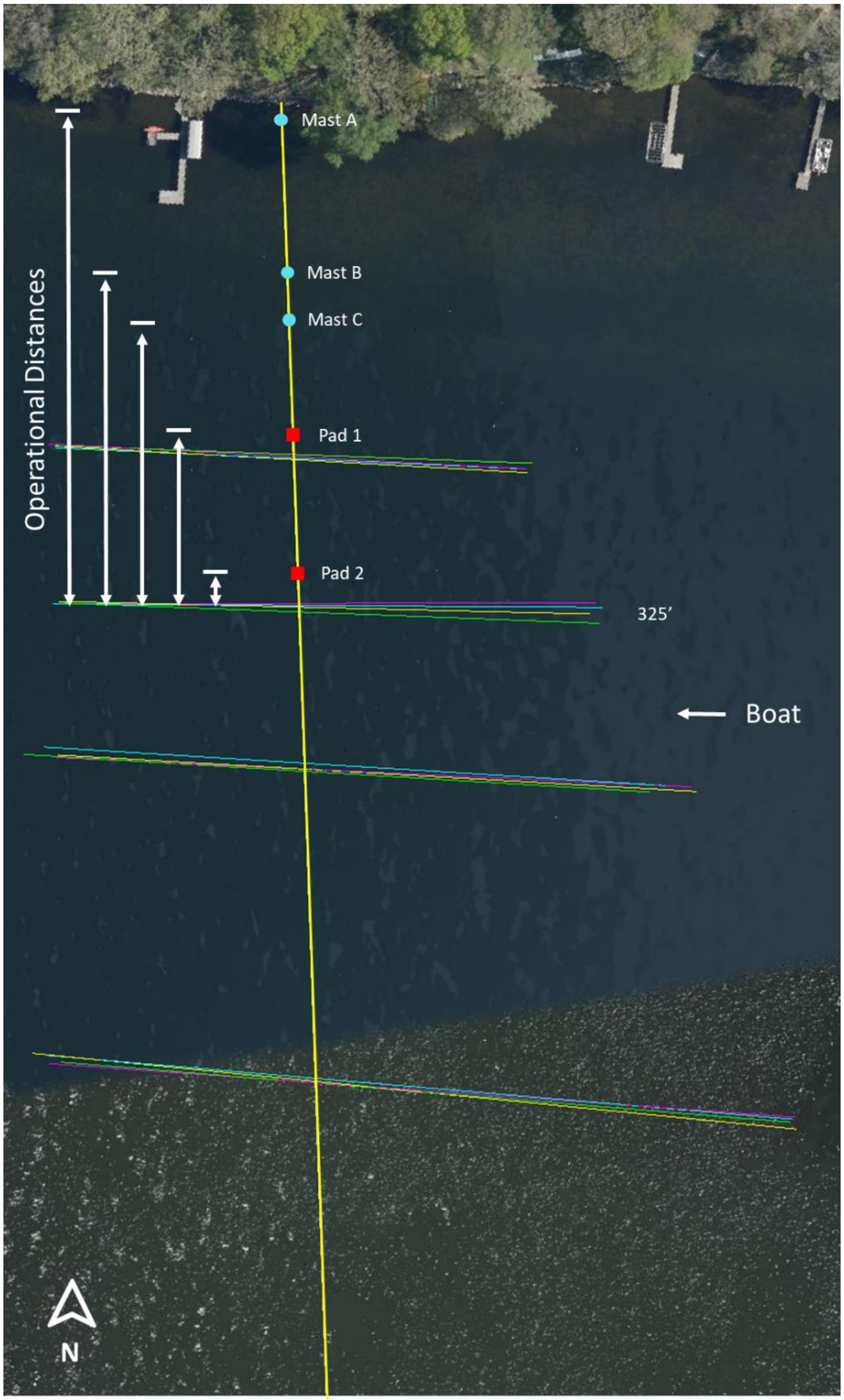

Figure 9. Example of the boat position data imported into AutoCAD for each of the four passes along the four track lines of the Malibu Response LX under operating Condition 1a (colored lines). The operational distance measurements were taken along the yellow line between each track line pass and each mast/pad. The white arrowed lines illustrate the various operational distances from the 325 ft track line.

4.2 Wave Height, Energy and Power

The primary wake wave parameters evaluated in this report are maximum wave height, total wave energy, and maximum wave power produced by the various test boats and how these varied with test conditions and operational distances. This section discusses our approach for collecting and analyzing these data.

4.2.1 Experimental time and wave height data collection – raw data

As previously discussed in Sections 3.3 and 3.4, the change in the water surface elevation was measured at the masts and the pads and was used to record the wave height as a function of time. Time zero (t=0.0) was set as midnight of the day tests were performed and all recorded times were converted to minutes from midnight.

The collected wave height time series data were the raw data sets that served as the bases for further calculations. The first post-processing step was to isolate the wake wave packets of each individual boat pass by manually identifying the first wave peak within the wake wave packet and noting the experimental time that this occurred. We then selected a window 0.3 minutes ahead and 2.0 minutes after this time (2.3 minutes total duration). Selection of these up-time and down-time duration windows was based on trial and error and was set based on the durations needed to fully capture the longest wake wave packet event. From this method, each boat pass yielded three, 2.3-minute duration data clips from the three masts and two, 2.3-minute clips from the two ADCP pads. These data clips were the inputs to further analyses of maximum wave height, total wave energy, and maximum wave power.

4.2.2 Attenuation correction of the mast pressure sensors

Because the pressure sensors were mounted a discrete distance below the water surface (i.e., 8-11 in (0.20-0.28 m)), it was necessary to apply a correction for attenuation of the pressure fluctuations (Tucker and Pitt 2001; Gourlay 2010; Shuster 2017). In many published applications, the pressure sensors were mounted near the bottom of the water body and in deep-water settings where the attenuation corrections were quite large. In our deployment however, the sensors were placed near the water surface slightly below the minimum wave trough elevation and so the correction was fairly minor (<22%). The attenuation correction method used was based on the approach described by Tucker and Pitt (2001) and coded into MATLAB by Neumeier (2020). The formulation applies an attenuation correction over a defined range of wave frequencies (0.05 – 0.8 Hz) that we selected based on a spectral analysis of each boat pass time series. Figure 10 is an example of typical raw and corrected wave height data collected from the pressure sensors plotted against time.

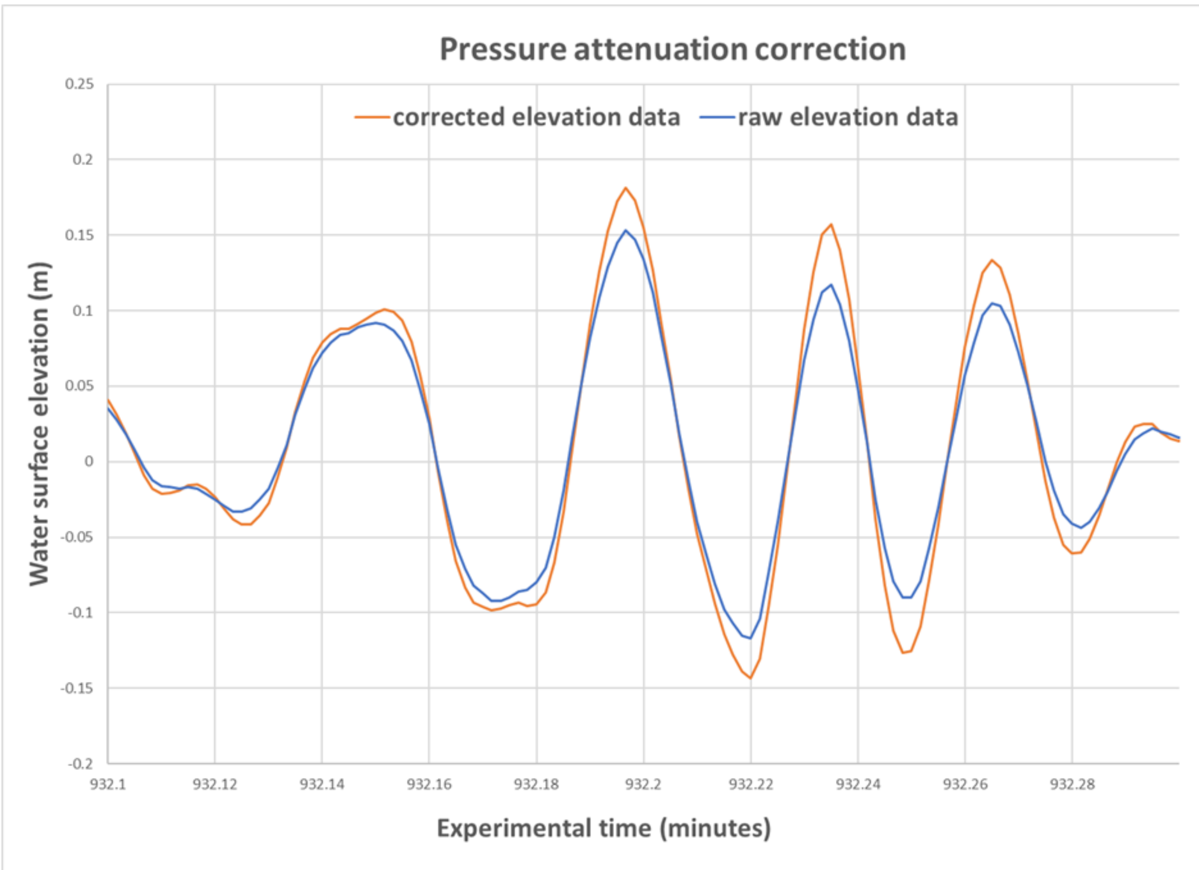

Figure 10. Plot showing an example of pressure attenuation correction applied to raw data of wave height.

4.2.3 Maximum Wave Height

Each corrected data clip was segmented into individual waves by locating the zero-crossing down locations within the 2.3-minute time series. Zero-crossing down refers to the point in time when the detrended water surface passed the zero or mean water surface elevation as it moved from crest to a trough (Figure 11). For each wave in the wake wave packet, the minimum and maximum water elevations were determined and the wave height, H_i, was calculated, where *i* is an integer value representing the sequential number of a wave within the wake wave packet. The duration of a wave or wave period, T_i, was also calculated. In this way, each boat pass wake wave packet was broken down into its individual waves characterized by the H_i and T_i of each wave.

Maximum wave height was simply determined by locating the maximum wave height, H_{max}, that occurred during the pass. H_{max} was the largest single wave that occurred within the wake wave packet.

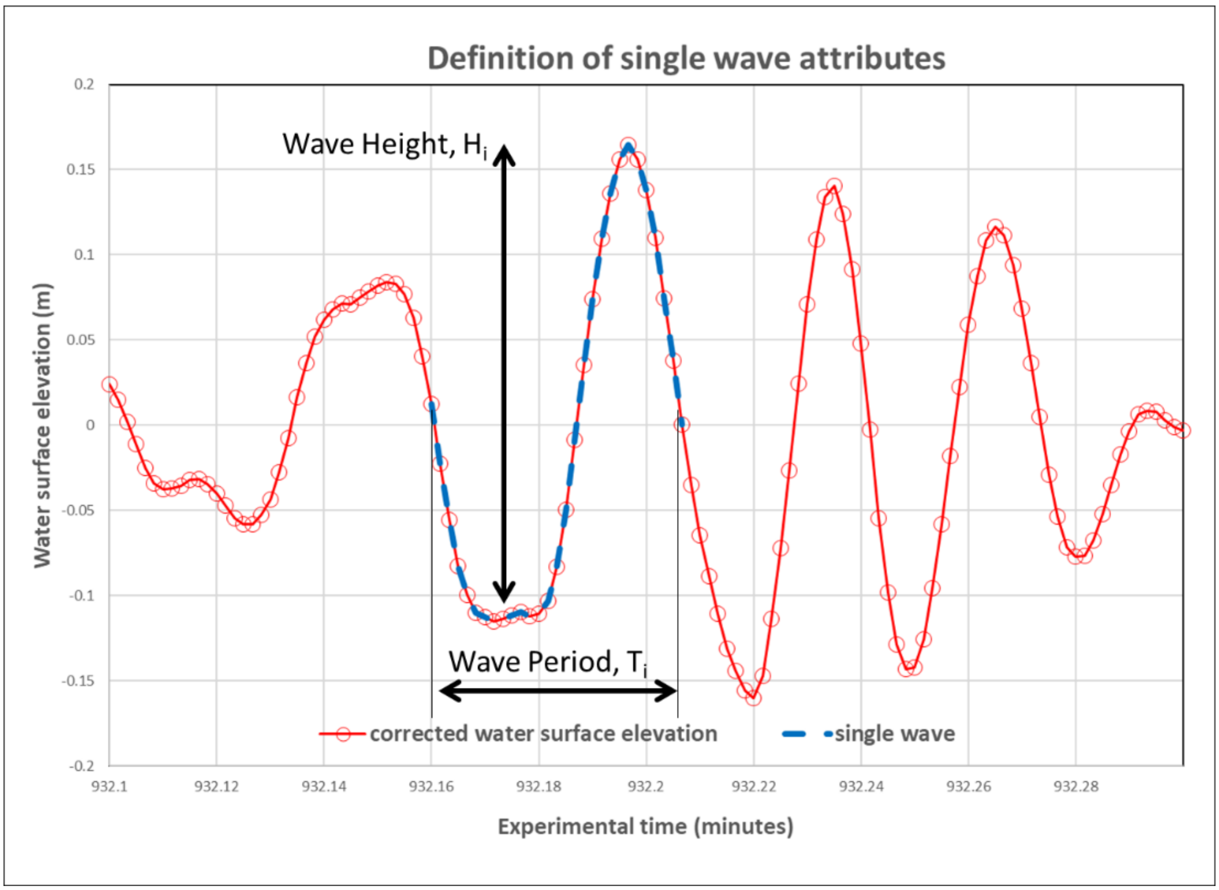

Figure 11. Definitions of zero-crossing down (blue dashed line) as well as wave characteristics of wave height, H_i and wave period T_i, where subscript *i* is an integer representing the sequential number of a wave within the packet.

4.2.4 Total Wave Energy

Energy is a quantifiable attribute and, for waves, is a measure of the ability of the wave or packet of waves to do work such as apply force on the lake bottom or shoreline. The total wave energy within each wake wave packet was determined. Here, we document the formulation used in this calculation.

Equation (1) is the form of the total potential and kinetic energy within a water wave per unit crest length derived from linear wave theory or Airy wave theory (USACE 1984; Dingemans 1997; Stumbo et al. 1999).

$$E_i = \frac{\rho g {H_i}^2 \lambda_i}{8} \quad (1)$$

In this report, we adopt metric SI units for energy and power calculations where, ρ is the density of water (kg/m^3), g is the gravitational acceleration constant (m/s^2), H_i is the wave height (m) and λ_i is wavelength (m). Equation 1 indicates that the total energy per unit crest length within a single wave is related to the density of the water (ρ), the square of wave height, and the wavelength of the wave.

It is important to point out that the data collected in this study was wave height versus time. We did not collect direct measurements of wavelength, λ_i, so it was not possible to evaluate (1) directly; however, we have measurements of the wave period, T_i, which we used in combination with functional relationships between wavelength and wave period to estimate λ_i.

The wavelength and wave period have a complex relationship that required consideration of the local water depth and whether the wave's vertical extent interacted with the lake bottom or not. If the water depth is sufficiently deep, waves are not influenced by the bottom of the lake. Borrowing from the classification adopted by USACE (1984), deep water waves are defined as having wavelengths that are less than twice the water depth. For example, a single wave with a wavelength of 20 ft (6.1 m) is considered a deep wave in depths of 10 ft (3.0 m) or greater. The wave is considered an intermediate wave, meaning some interactions with the lake bottom, if depths are between ½ and $^1\!/_{25}$ of the wavelength. Below $^1\!/_{25}$ wavelength, the wave is considered a shallow water wave. For the example given, a wave with a wavelength of 20 ft would be an intermediate wave between 10 ft and 0.8 ft of depth and a shallow wave below 0.8 ft of depth. These definitions become important as the functional relationship between wave period and wavelength for intermediate and shallow waves are influenced by water depth (Dingemans 1997).

Equation (2) is a general form of a relationship for the phase velocity of a wave (Cp) and is applicable for deep and intermediate depths (USACE 2012). In Equations (3) and (4) we introduce standard definitions for angular frequency, ω, and wave number, *k*. Substituting (3) and (4) into (2) and rearranging terms, we derive Equation (5), which is a general relationship for the wave period, T_i, and wavelength, λ_i, at a specific water depth, d_i.

$$C_p = \frac{\omega}{k} = \sqrt{\frac{g}{k} tanh(kd_i)} = \sqrt{\frac{g\lambda_i}{2\pi} tanh(\frac{2\pi}{\lambda_i} d_i)} \qquad (2)$$

$$\omega = \frac{2\pi}{T} \qquad (3)$$

$$k = \frac{2\pi}{\lambda} \qquad (4)$$

$$\left(\frac{2\pi}{T_i}\right)^2 = \left(\frac{2\pi\, g}{\lambda_i}\right) tanh\left(\frac{2\pi\, d_i}{\lambda_i}\right) \qquad (5)$$

To utilize (5), recall that the data collection and initial analysis resulted in determining wave height, H_i, and wave period, T_i, for all waves in a wake wave packet for each boat pass. We also recorded the water depth at each mast (d_{MastA} = 0.56 m; d_{MastB} = 1.86 m; and d_{MastC} = 2.63 m). Using this information in Equation (5), we solved for the wavelength, λ_i, for each of the waves measured in a wake packet (USACE 1984; MacFarlane 2012).

With the wavelength calculated for each wave, we then evaluated (1) and determined the total energy per unit crest width for each wave by summing all the waves in the wake wave packet generated by a single boat pass (Equation 6). The variable, *n*, represents the total number of individual waves within a wake wave packet.

$$E_{total} = \sum_{i=1}^{i=n} E_i = \sum_{i=1}^{n} \frac{\rho g {H_i}^2 \lambda_i}{8} \quad (6)$$

An important and likely obvious observation is that a single boat passage generated a series of waves that we refer to in this report as the wake wave packet. Because of wave dispersion, the number of individual waves occurring in a wake wave packet increases with distance. For example, at Mast A we observed 8 or 9 individual waves arriving from a ~225 ft pass distance, and greater than 20 individual waves from a ~625 ft pass distances. In addition to the increase in the number of individual waves, we also observed a longer duration of time for the wake wave packet to fully make landfall. Finally, the height of the waves decreased with distance from the boat, defined as wave attenuation. In general, closer to the boat, a smaller number of larger waves will reach the observation point and as the boat distance increases, a larger number of smaller waves will reach the same observation point over a longer duration of time.

The variation in wake wave packet duration with distance noted above had implications for how we determined the endpoint of the packet and calculations for total cumulative wave energy, E_{total} for a boat pass. To determine this point in time, t_{end}, we established a threshold criterion, ε, defined as the point in time when the incremental change in total cumulative wave energy dropped below 1% of the total cumulative wave energy (Equations 7 and 8). Figure 12 shows an example of a cumulative total wave energy plot measured for one boat pass. The total duration of the analysis was ~130 seconds (2.3 minutes); however, in general, the main contribution of the wake wave packet occurred over 35-40 seconds from the start of the packet. Once t_{end} was located, it was used to determine the total energy of the wake wave packet.

$$\varepsilon(t) = \left(\frac{E_{total(t)} - E_{total(t-1)}}{E_{total(t-1)}}\right) * 100 \quad (7)$$

$$t_{end} = \varepsilon(t) < 1.0 \quad \text{\{threshold criteria\}} \quad (8)$$

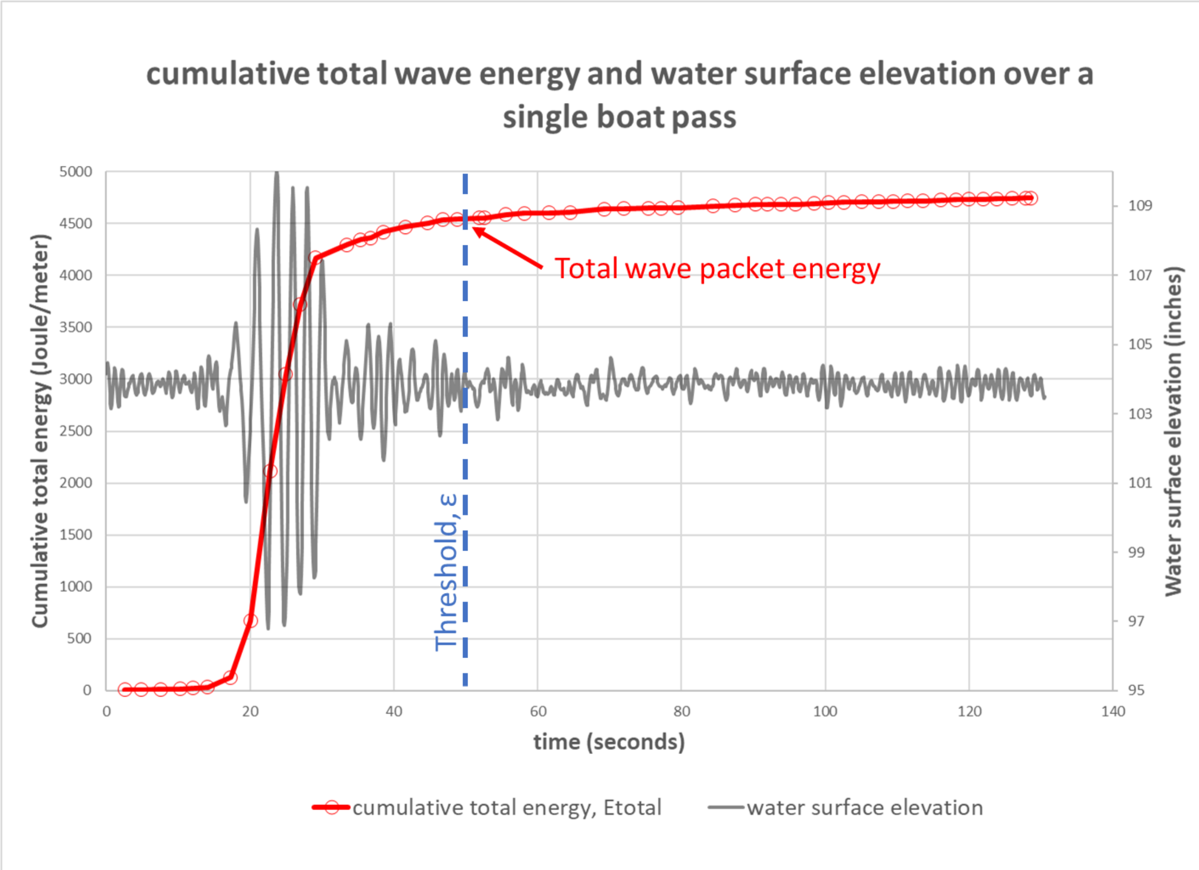

Figure 12. Example of a wake wave packet measurement and equivalent cumulative wave energy computed for the packet. The blue dashed line represents the end of the wake packet as defined by the threshold criteria, ε.

4.2.5 Maximum Wave Power

Another characteristic commonly computed for water waves is the wave power, also referred to as wave energy flux (Equation 9), which is calculated as the product of wave energy density, $\bar{E}$ (Equation 10) and group velocity, C_g (Equation 11) (USACE 1984 and 2012, MacFarlane 2012). The wave power quantifies the rate at which energy within a wave is delivered to a shoreline or object, and is another measure of the ability of a wave to impact the near-shore environment. We estimated that the majority of wake waves produced in the study were deep-water waves and we therefore employed the deep-water formulation of group velocity (11).

$$\bar{P} = \bar{E}C_g \quad (9)$$

$$\bar{E} = \frac{\rho g H^2}{8} \tag{10}$$

$$C_g = \frac{g T_{max}}{4\pi} \tag{11}$$

Our analysis involved determining the wave energy flux associated with the largest wave within the wake wave packet and its associated wave period. Maximum power, P_{max}, was calculated using Equation 12.

$$P_{max} = \left(\frac{\rho g (H_{max})^2}{8} C_g\right) \tag{12}$$

5.0 RESULTS

The maximum wave height, total wave energy and maximum wave power were analyzed as a function of operational distance for each boat and operating condition. Each data point shown in the following figures is the mean value of the four passes at a given distance and under the same conditions, with the error bars depicting the standard deviation. Data points obtained from the masts (i.e., pressure transducers) and pads (i.e., ADCPs) and are represented as closed circles or squares and open triangles or diamonds, respectively. The vertical axis is either the maximum wave height (in), total wave energy (J/m), or maximum wave power (J/m-s). The horizontal axis is the operational distance (ft), which again is defined as the perpendicular distance from the boat track line to the masts/pads. A best fit power-law trendline is fit to all data points greater than one boat length from the track line (20-24-ft). The equation of this best-fit relationship and the corresponding R^2 correlation is provided on each graph. Data within one boat length had greater variability and was subject to influence from both transverse and divergent waves produced by the boat. We include these data points in the following figures, however, we do not include them in the regression analyses. Further, a power-law regression is adopted here based on the fact that it provides a reasonable fit to the observed data trends and also because of the long history of describing wave parameter decay using power law formulation. A thorough summary of many of these methodologies can be found in MacFarlane (2012). It should be noted that we were not able to collect data within the first 100 ft of operational distance for the Malibu Response LX because of technical issues with the ADCP sensors on the test day.

The results discussion relies heavily on the reader being familiar with the various test conditions (Conditions 1a, 1b and 2) for each boat tested. For convenience, we provide Table 3 again for quick reference.

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Table 3. Summary of the operating conditions for each boat tested. The only difference between Conditions 1a and 1b for the Malibu Response LX was the wake shaper setting (i.e., on vs off). The only difference between Conditions 1a and 1b for each Malibu Wakesetters was the ballast setting (i.e., full vs empty).

Boat	Condition #	Speed (mph)	Trim Setting (%)	Ballast (% filled)	Hydrofoil/Power Wedge III	Wake Shaper/Surf Gate	People Aboard	Approx. People Weight (lbs.)
Larson LXI 210	1a	10	50 (middle)	N/A	N/A	N/A	2	330
	2	20	100 (down)	N/A	N/A	N/A	2	330
Malibu Response LX	1a	10	N/A	N/A	Down	On – Port Side	2	330
	1b	10	N/A	N/A	Down	Off	2	330
	2	20	N/A	N/A	Down	Off	2	330
Malibu VLX Wakesetter	1a	11	N/A	100	Down – Setting #3	On – Port Side	4	740
	1b	11	N/A	0	Down – Setting #3	On – Port Side	4	740
	2	20	N/A	0	Down – Setting #3	Off	4	740
Malibu MXZ Wakesetter	1a	11	N/A	100	Down – Setting #3	On – Port Side	4	740
	1b	11	N/A	0	Down – Setting #3	On – Port Side	4	740
	2	20	N/A	0	Down – Setting #3	Off	4	740

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5.1 Condition 1a

This section discusses the results of the data analyses for maximum wave height, total wave energy, and maximum wave power for each of the four boats tested under operating Condition 1a. Detailed descriptions of the boat operating conditions are provided in Section 3.6 and Table 3.

5.1.1 Maximum Wave Height

The maximum wave height is defined as the highest single wave measured within a wake wave packet and this value was computed for each pass. The average maximum wave height was then computed from these data and is presented in the following figures. For simplification, we refer to these values as maximum wave heights with the understanding that they are averages of all passes at a given distance.

All boats showed a nonlinear decrease in maximum wave height with operational distance (Figures 13 and 14). The most rapid decline in wave height occurred over the first 100 ft of operational distance where, for all boats, the maximum wave height decreased by half. The initial maximum wave heights recorded for the Larson LXI 210, Malibu VLX, and Malibu MXZ were 22 in, 34 in, and 39 in, respectively, which occurred within 4-6 ft of the boat track line.

All the data from Figures 13 and 14 are presented together in Figure 15 for easier comparison. The Larson LXI 210 attenuated from a maximum wave height of 22 in to 10 in at 84 ft of distance. The Malibu Response LX recorded a 10 in maximum wave height at 120 ft of distance. At 600 ft, both the Larson LXI 200 and Malibu Response LX had maximum wave heights of roughly 5 in. The Malibu VLX had a maximum height of 34 in that attenuated to 10 in after 210 ft. At 600 ft, the maximum wave height had decreased to approximately 5 in. Of the four boats tested, the largest boat in terms of length, total weight, and ballast water weight was the Malibu MXZ. The Malibu MXZ's maximum wave height attenuated from 39 in to 8 in after 400 ft. Finally, by ~600 ft of operational distance the maximum wave height had decreased to roughly 6 in.

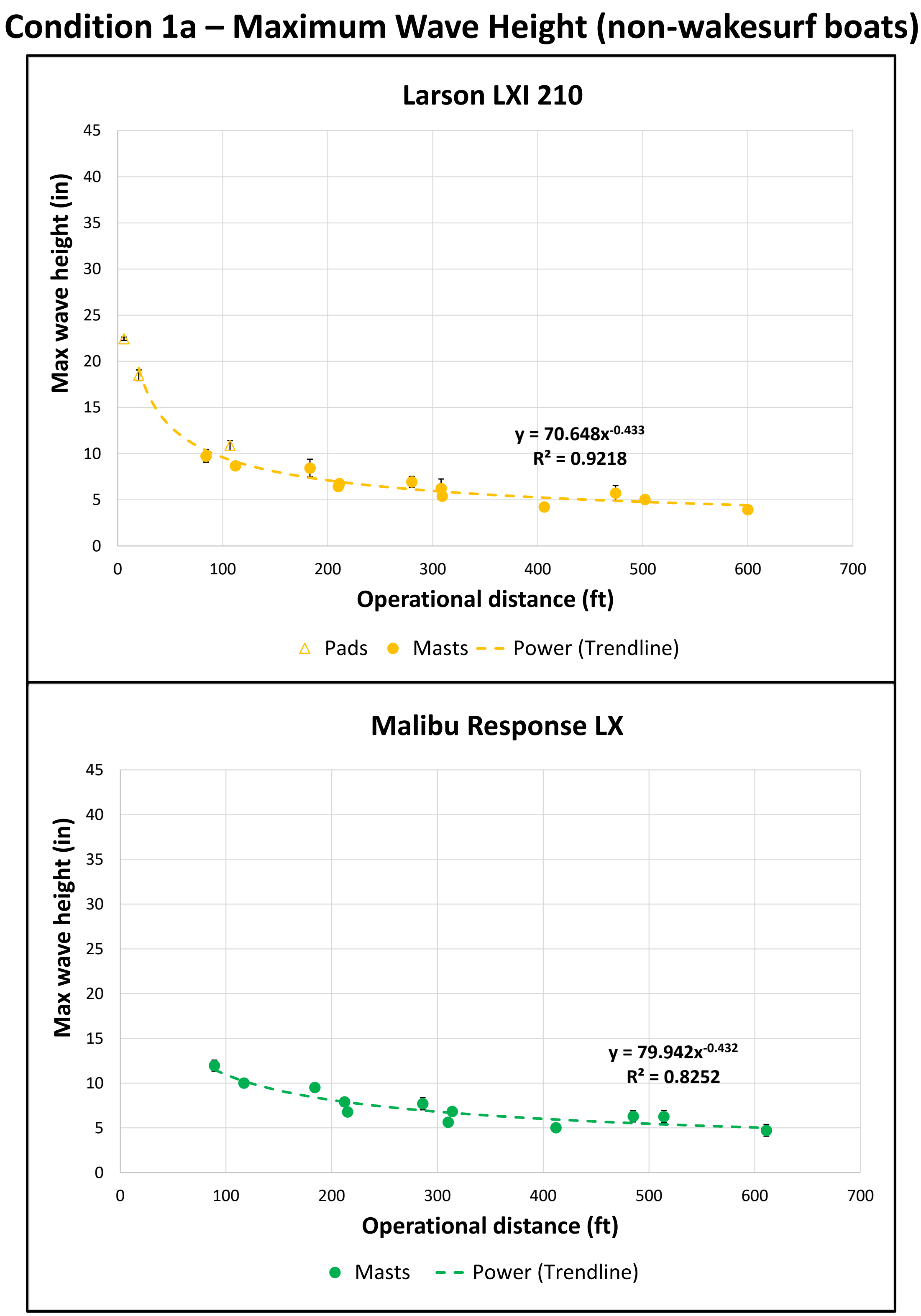
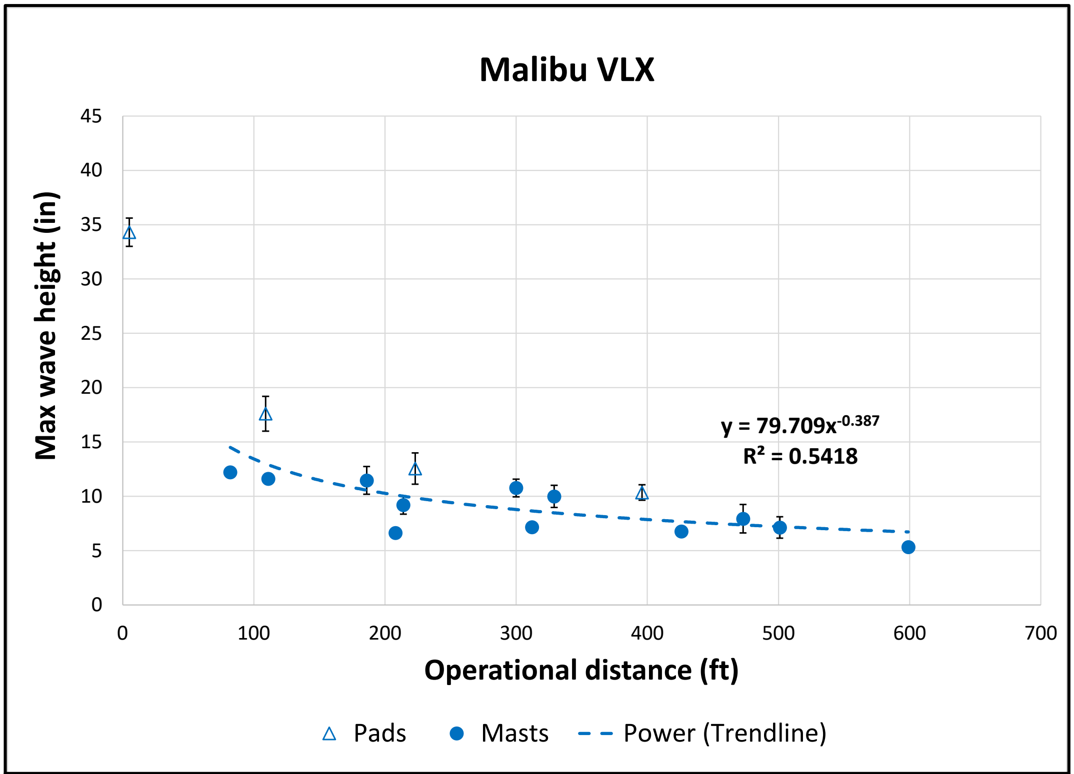


Figure 13. Maximum wave height as a function of distance for the two non-wakesurf boats tested under Condition 1a. The error bars represent the standard deviation. There are no data for the Pads for the Malibu Response LX due to technical issues with the ADCP on test day. Data points less than one boat length from the track line were not included in the regression analysis.

Condition 1a – Maximum Wave Height (wakesurf boats)



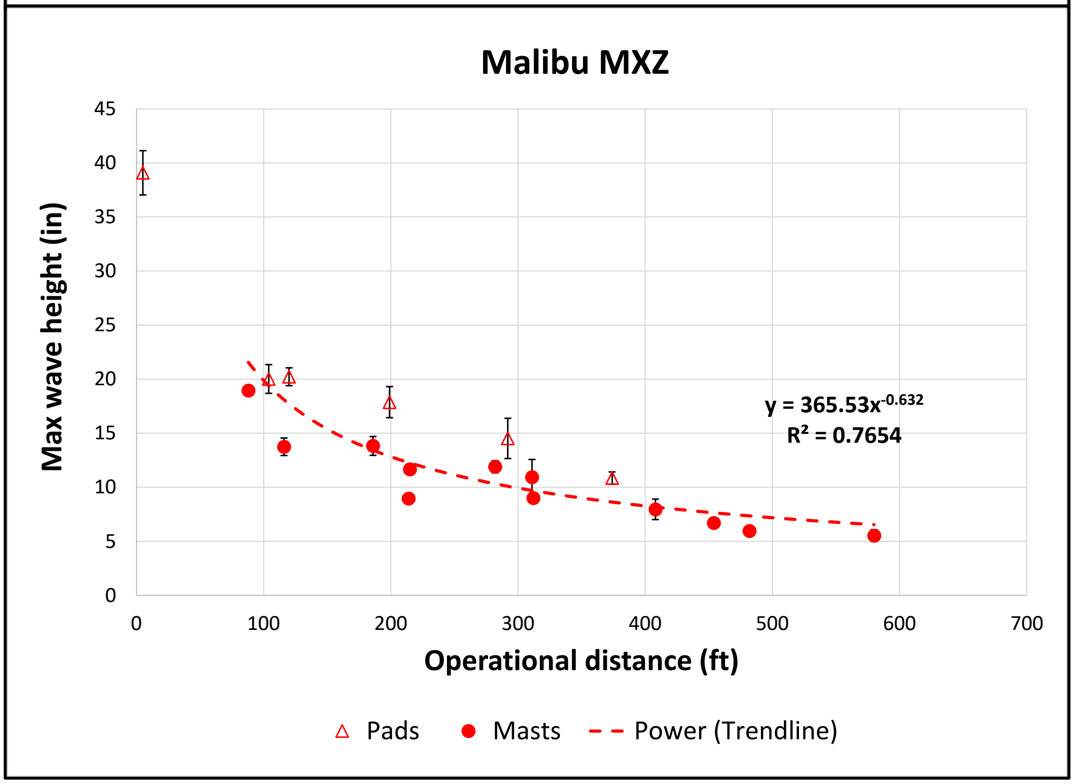


Figure 14. Maximum wave height as a function of distance for the two wakesurf boats tested under Condition 1a. The error bars represent the standard deviation. Data points less than one boat length from the track line were not included in the regression analysis.

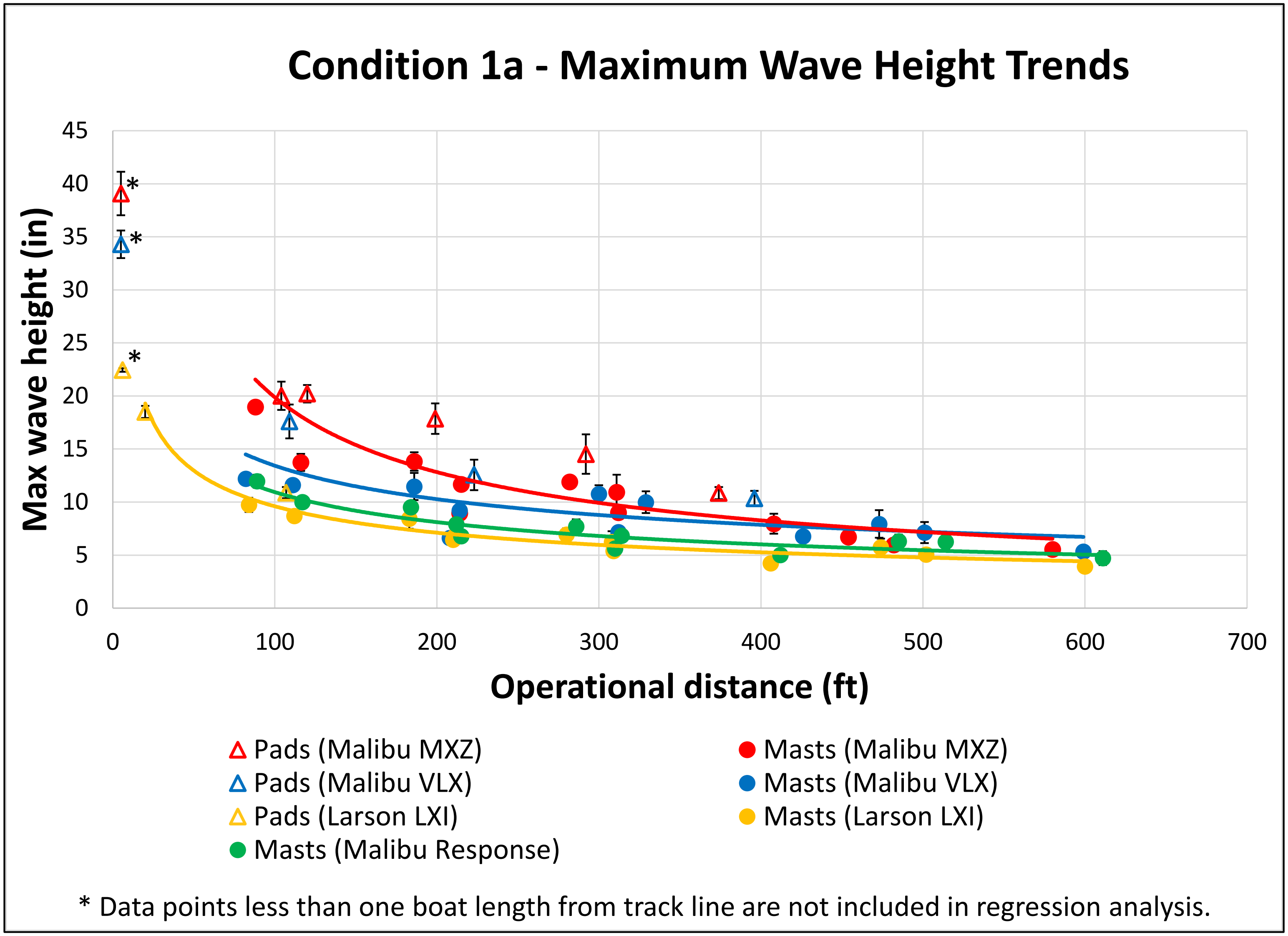


Figure 15. Condition 1a best-fit power law trendlines of the four test boats showing maximum wave heights over operational distance.

5.1.2 Total Wave Energy

All four test boats showed a nonlinear decrease in total wave energy with increasing operational distance (Figure 16 and 17). The maximum total wave energy recorded for the Larson LXI 210, Malibu VLX, and Malibu MXZ was 5,400 J/m, 12,200 J/m, and 16,300 J/m, respectively, which occurred within 4-6 ft of operational distance.

Figure 18 compares all the data and trendlines for the four boats. The Larson LXI 210 and Malibu Response LX had nearly identical total wave energies and attenuation rates. At 120 ft of operational distance, their total wave energies had attenuated to 2,000 J/m, and by 600 ft they had decreased to roughly 700 J/m. The Malibu VLX had the second greatest total wave energy at all distances, with a maximum level of 12,200 J/m that attenuated to 2,000 J/m around 400 ft of operational distance. At 600 ft, the total wave energy had decreased to around 1,000 J/m. Of all the boats tested, the Malibu MXZ produced the greatest total wave energy at all distances, with an initial maximum of 16,300 J/m that, like the Malibu VLX, decreased to 2,000 J/m around 400 ft. At 600 ft of operational distance, the total wave energy had attenuated to roughly 1,000 J/m.

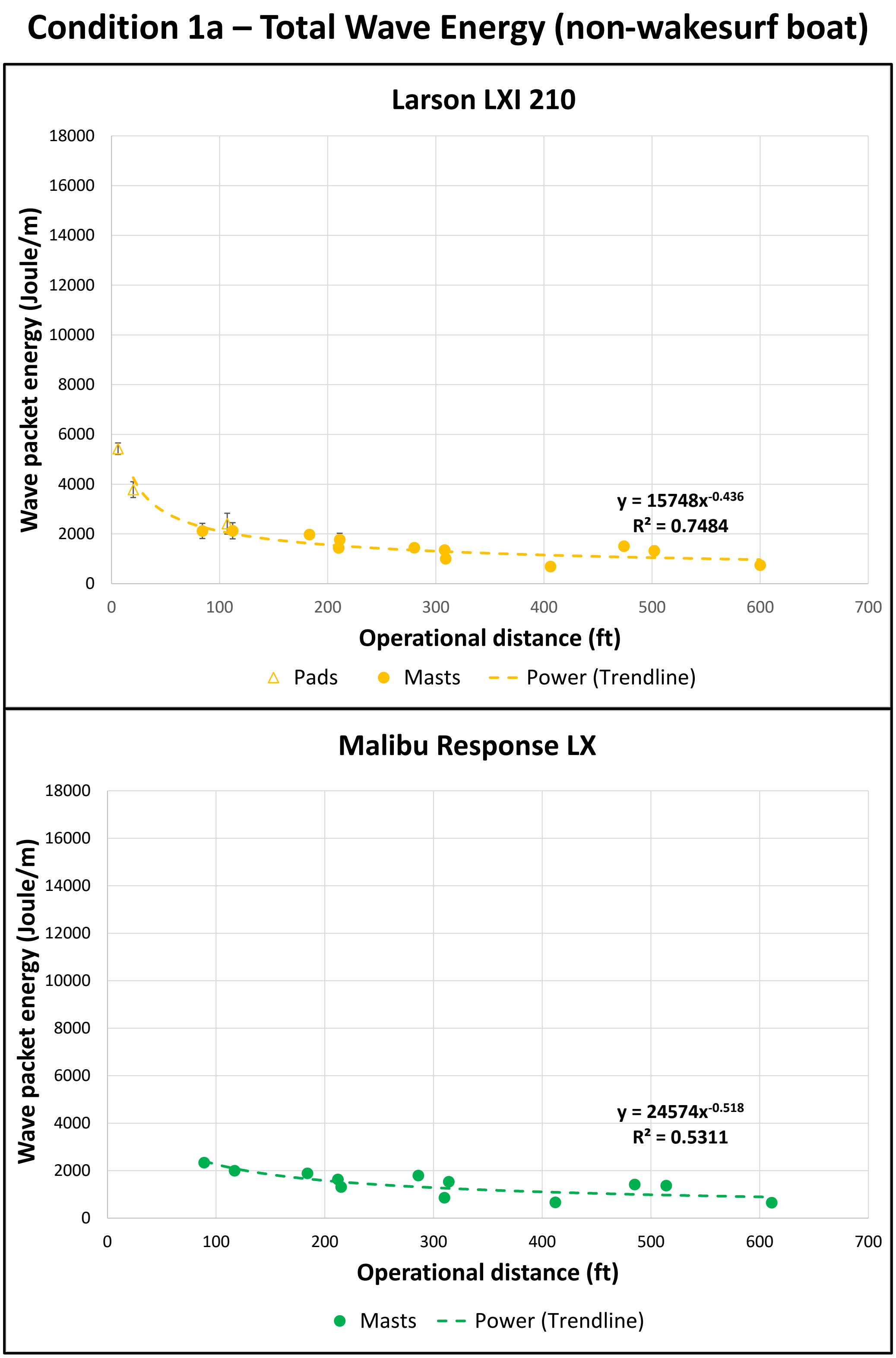


Figure 16. Total wake packet energy as a function of operational distance for the two non-wakesurf boats tested under Condition 1a. There are no data for the Pads for the Malibu Response LX due to technical issues with the ADCP on test day. Data points less than one boat length from the track line were not included in the regression analysis.

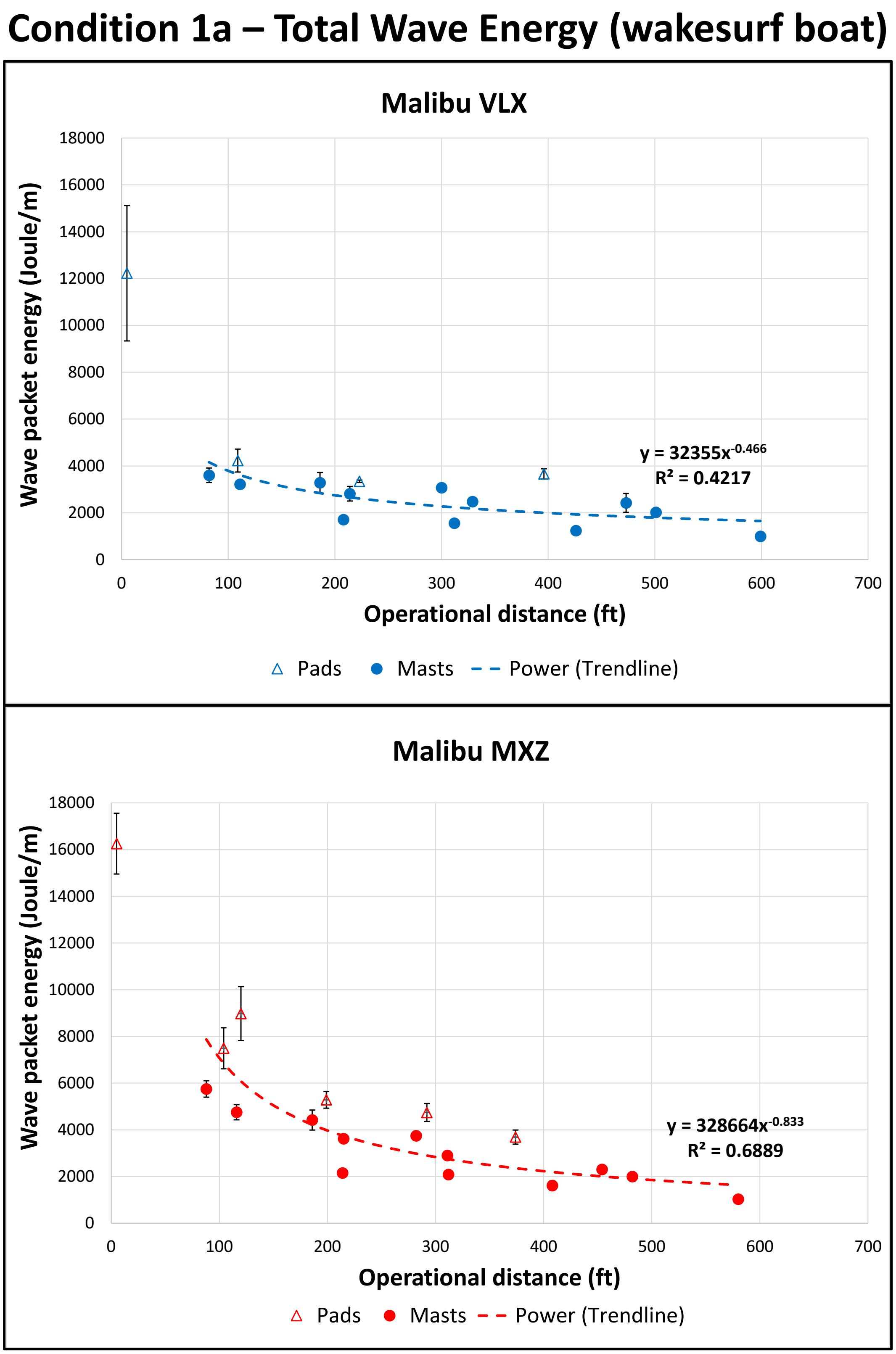


Figure 17. Total wake packet energy as a function of operational distance for the two wakesurf boats tested under Condition 1a. Data points less than one boat length from the track line were not included in the regression analysis.

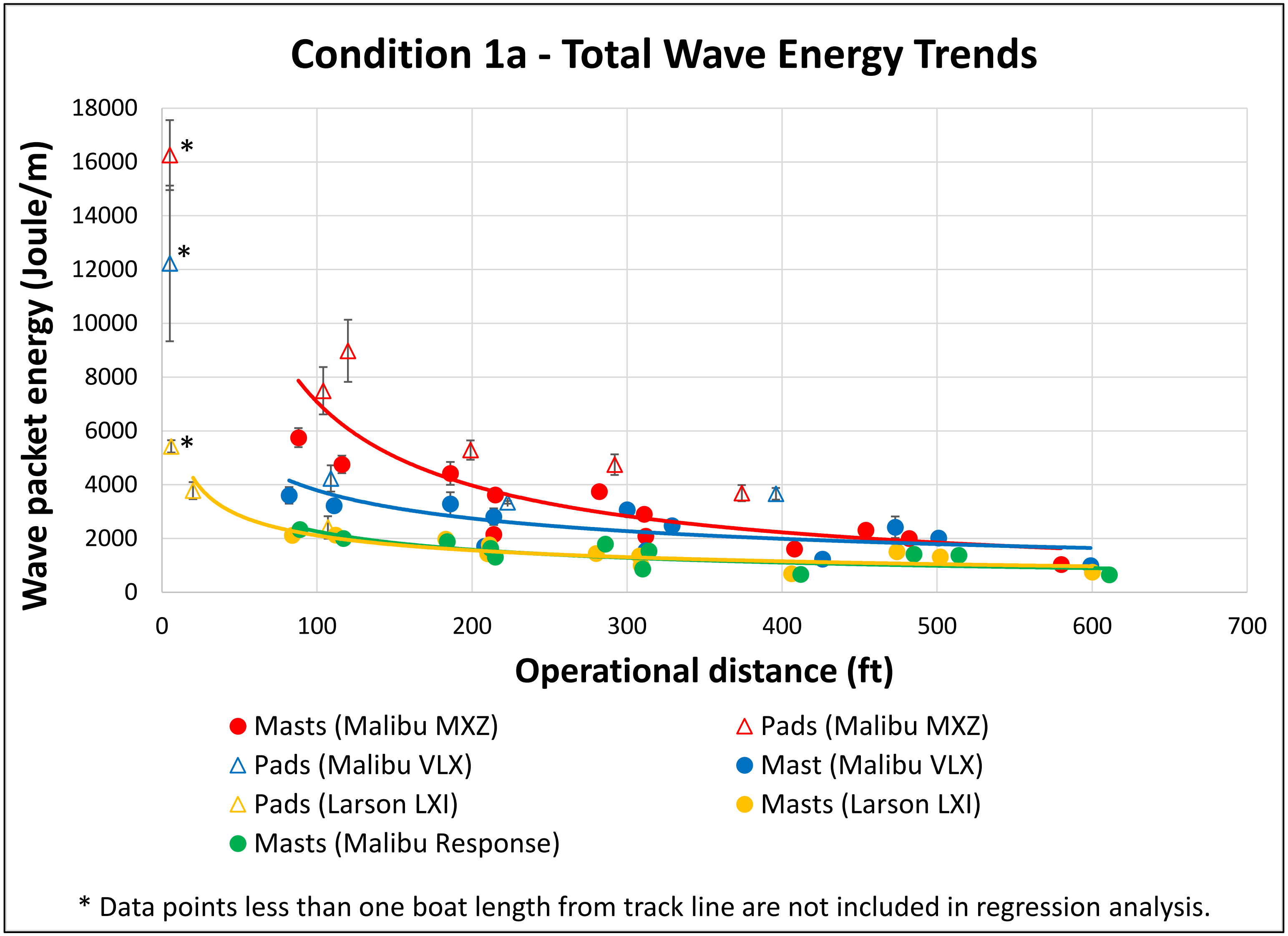


Figure 18. Condition 1a trendlines for the four test boats showing total wave energy over operational distance.

5.1.3 Maximum Wave Power

Like maximum wave height and total wave energy, the maximum wave power showed a well-defined, nonlinear decrease as operational distance increased (Figure 19 and 20). The initial maximum wave powers recorded for the Larson LXI 210, Malibu VLX, and Malibu MXZ were 860 J/m-s, 1,970 J/m-s, and 2,370 J/m-s, respectively, which occurred within an operational distance of 4-6 ft.

A comparison of all data and trendlines for each boat is presented in Figure 21. The Larson LXI 210 attenuated from an initial maximum wave power of 860 J/m-s to 50 J/m-s over the first 110 ft of operational distance. For operational distances greater than 210 ft, the maximum wave power for the Larson LXI 210 and Malibu Response LX were nearly identical, and by 600 ft they had decreased to roughly 10 J/m-s. The Malibu VLX had an initial maximum wave power of 1,970 J/m-s that attenuated to 100 J/m-s at an operational distance of 300 ft. By 600 ft, the maximum wave power decreased to roughly 40 J/m-s. Finally, the Malibu MXZ produced the greatest maximum wave powers at all operational distances, with an initial maximum wave power of 2,370 J/m-s that decreased to 100 J/m-s at approximately 400 ft, and 50 J/m-s by 600 ft of operational distance.

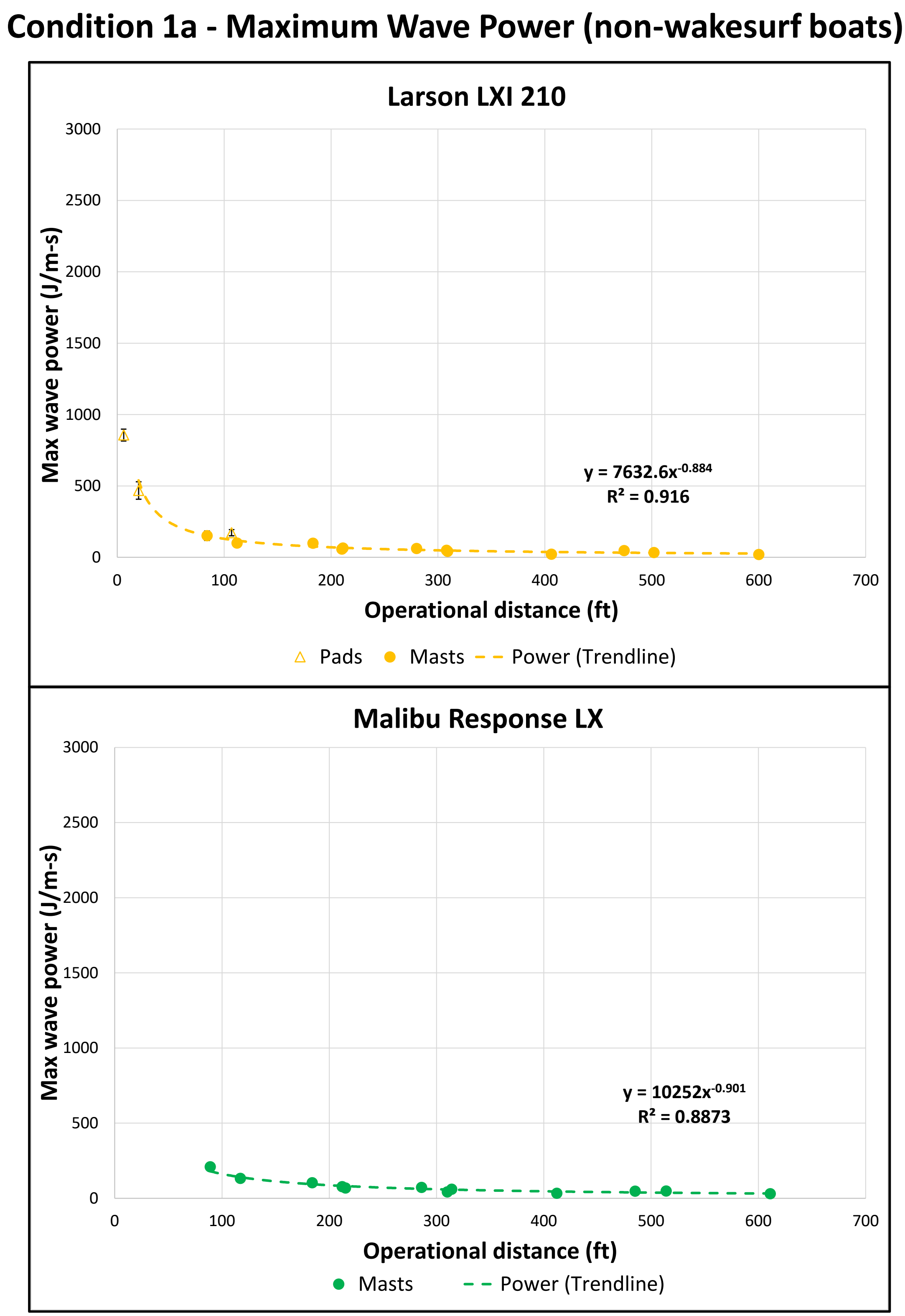


Figure 19. Maximum wave power as a function of wave propagation distance for the two non-wakesurf boats tested under Condition 1a. There are no data for the Pads for the Malibu Response LX due to technical issues with the ADCP on test day. Data points less than one boat length from the track line were not included in the regression analysis.

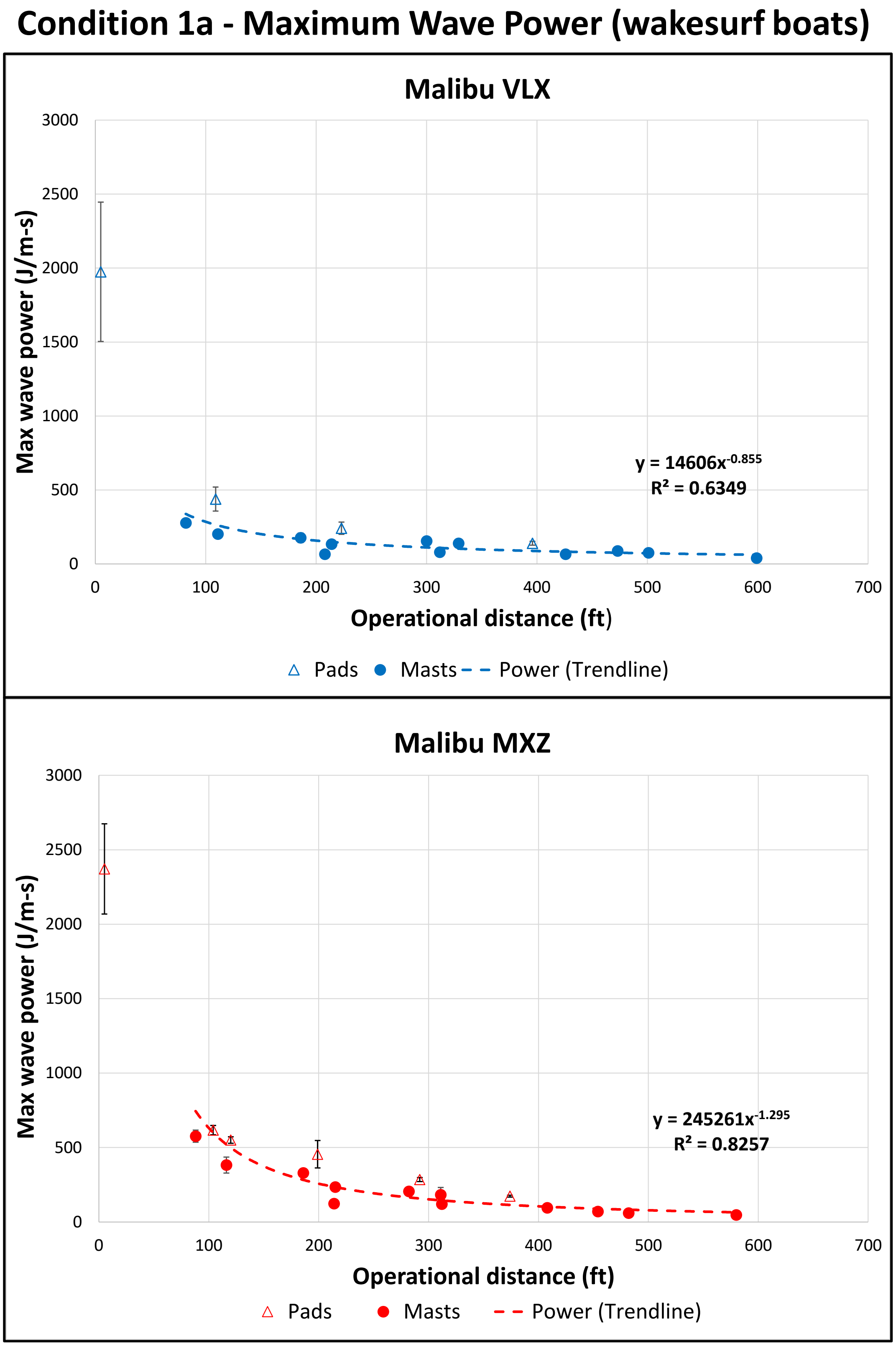


Figure 20. Maximum wave power as a function of wave propagation distance for the two wakesurf boats tested under Condition 1a. Data points less than one boat length from the track line were not included in the regression analysis.

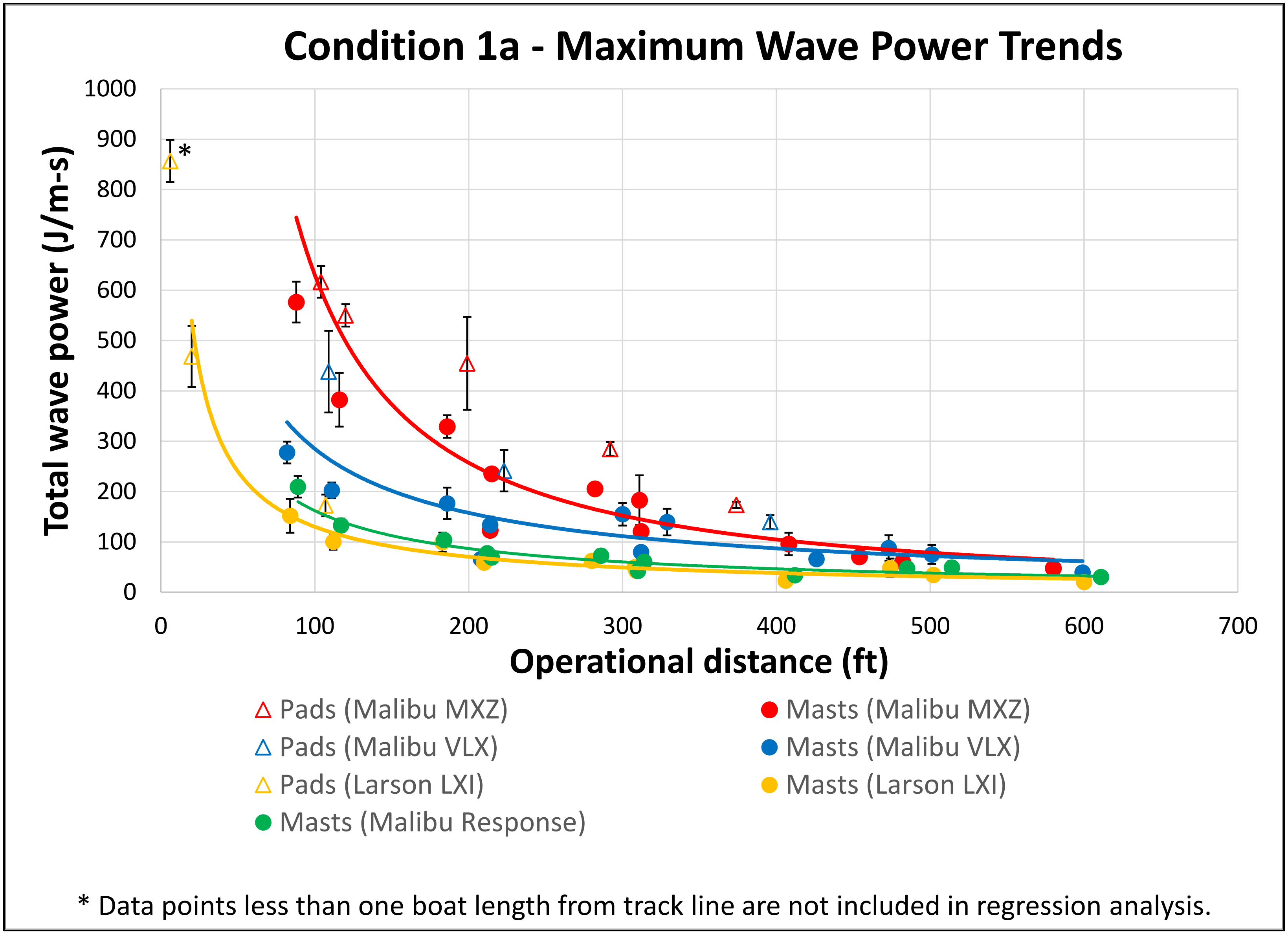


Figure 21. Condition 1a trendlines for the four test boats showing maximum wave power over operational distance.

5.2 Condition 2

This section discusses the results of the data analyses for maximum wave height, total wave energy, and maximum wave power for each of the four boats tested under operating Condition 2. Detailed descriptions of the boat operating conditions are provided in Section 3.6 and Table 3. It is important to note that the magnitudes of wave height, energy, and power were much smaller when the watercraft was planing. It is also important to note that the ADCP data at operational distances less than 100 ft for the Malibu MXZ under Condition 2 were noisy and thus eliminated from this analysis (see Section 6.2.1 for more details).

5.2.1 Maximum Wave Height

In general, all boats follow the same nonlinear decrease in maximum wave height with increasing operational distance (Figures 22, 23 and 24). The initial maximum wave height recorded for the Larson LXI 210 was 13 in at a distance of 9 ft. The maximum wave height was 6 in at roughly 150 ft, and continued decreasing to less than 4 in at operational distances greater than 600 ft. The Malibu Response LX recorded a maximum wave height of 8 in at 100 ft that attenuated to 6 in by 200 ft of propagation. At roughly 425 ft of operational distance, the maximum wave height had decreased to 4 in. The Malibu VLX produced an initial maximum wave height of 16 in at 10 ft, and attenuated to approximately 11 in at 100 ft of operational distance. By 500 ft of operational distance the maximum wave height decreased to 6 in. Like the Malibu VLX, the Malibu MXZ produced a maximum wave height of 11 in at roughly 100 ft. At 300 ft of operational distance, the maximum wave height was 6 in, and by 500 ft had decreased to 4 in.

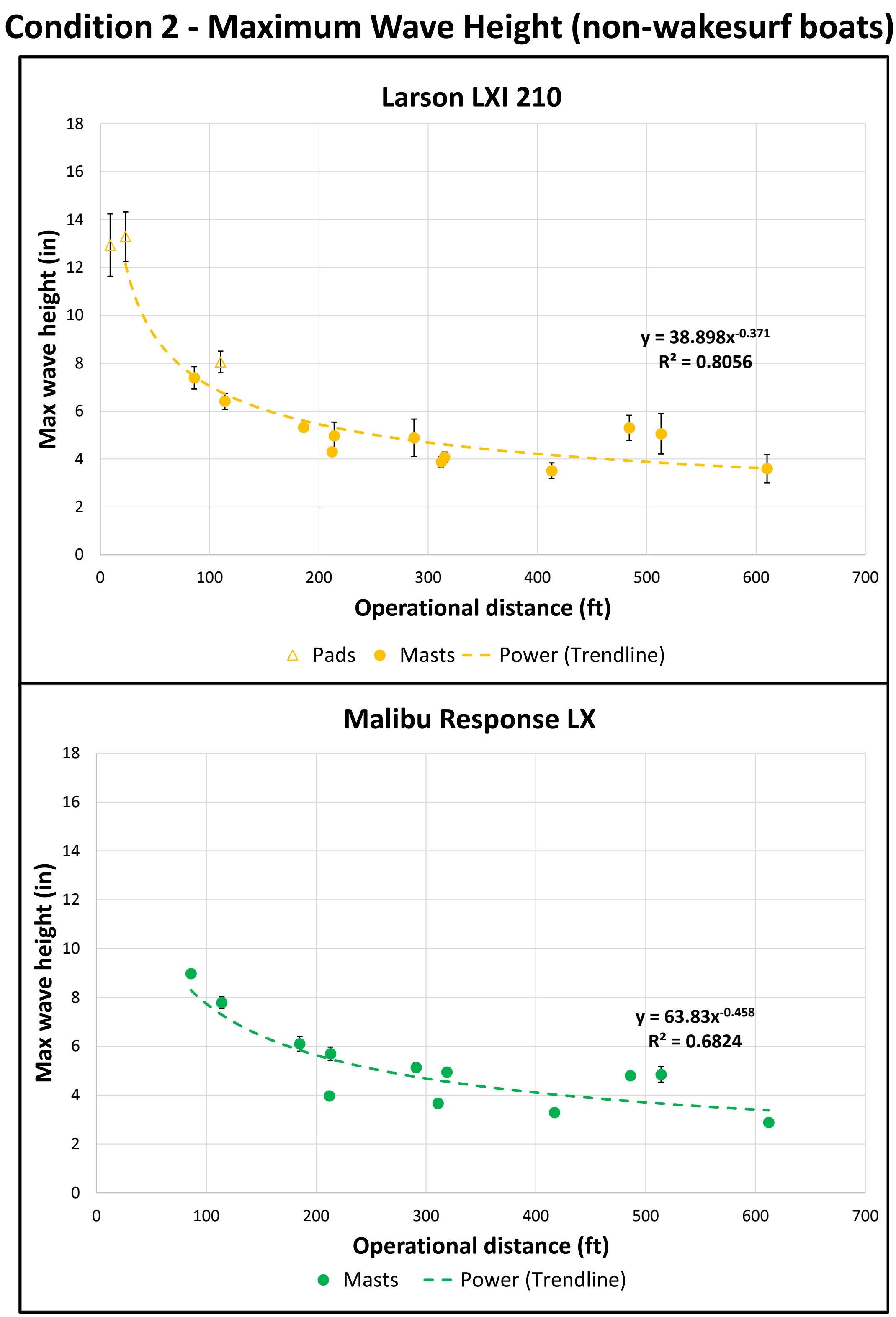


Figure 22. Maximum wave height as a function of operational distance for the two non-wakesurf boats tested under Condition 2. There are no data for the Pads for the Malibu Response LX due to technical issues with the ADCP on test day. Data points less than one boat length from the track line were not included in the regression analysis.

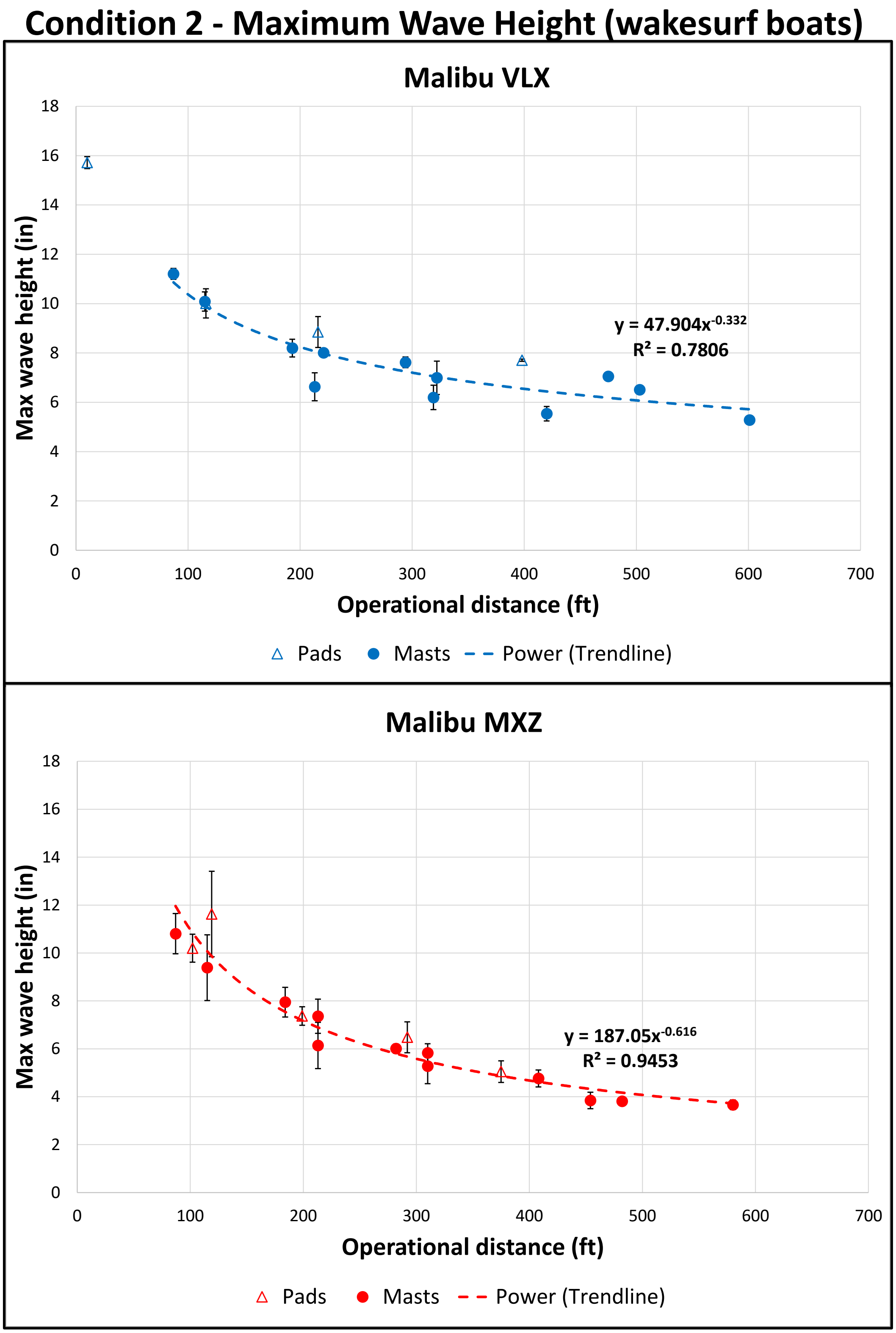


Figure 23. Maximum wave height as a function of operational distance for the two wakesurf boats tested under Condition 2. The Pad data at distances less than 100 ft for the Malibu MXZ were noisy and thus eliminated from this analysis. Data points less than one boat length from the track line were not included in the regression analysis.

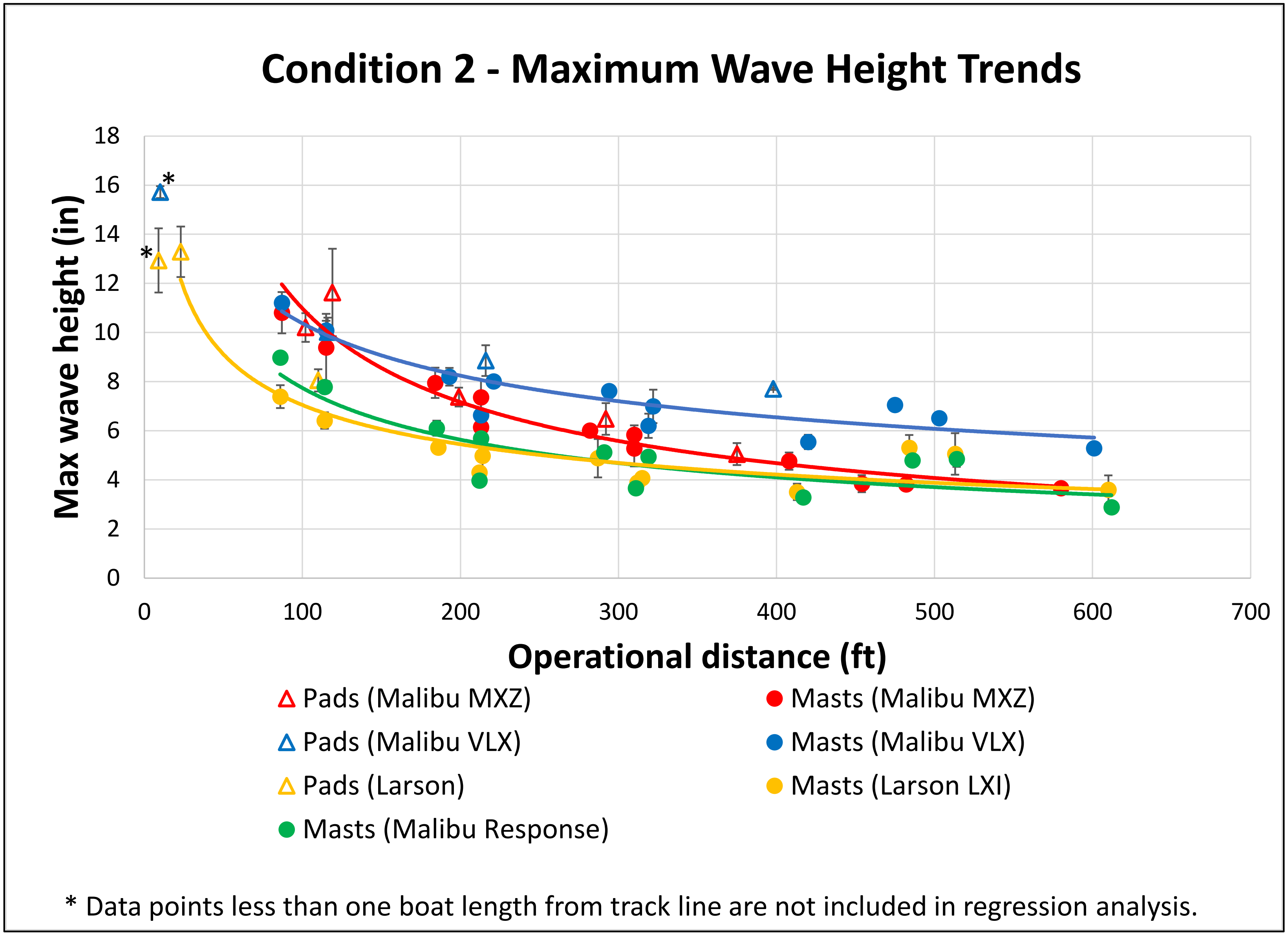


Figure 24. Condition 2 trendlines of the four test boats showing maximum wave heights over operational distance.

5.2.2 Total Wave Energy

The attenuation of the total wave energy as a function of operational distance shows a nonlinear decreasing trend for all test boats (Figures 25, 26 and 27). The Larson LXI 210 and Malibu Response LX had little change in total wave energy with operational distance, with the data only slightly varying between 1,500 J/m and 700 J/m. Likewise, the Malibu VLX had little change in total wave energy attenuation, as the magnitudes were between 2,500 J/m and 1,000 J/m over the full range of operational distances. The Malibu MXZ data show a wider range of total wave energies between 2,800 J/m and 900 J/m.

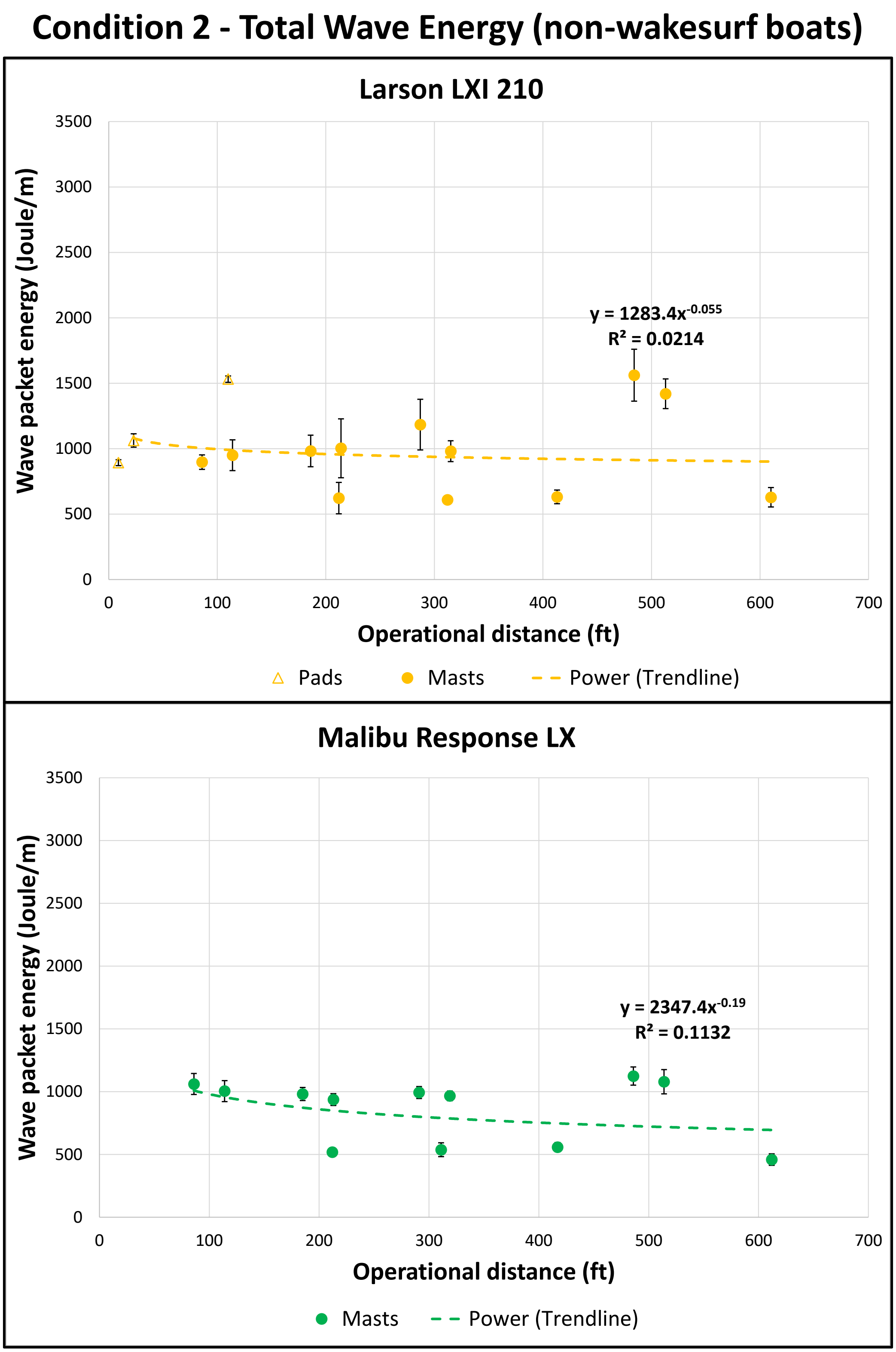


Figure 25. Total wake packet energy as a function of operational distance for the two non-wakesurf boats tested under Condition 2. There are no data for the Pads for the Malibu Response LX due to technical issues with the ADCP on test day. Data points less than one boat length from the track line were not included in the regression analysis.

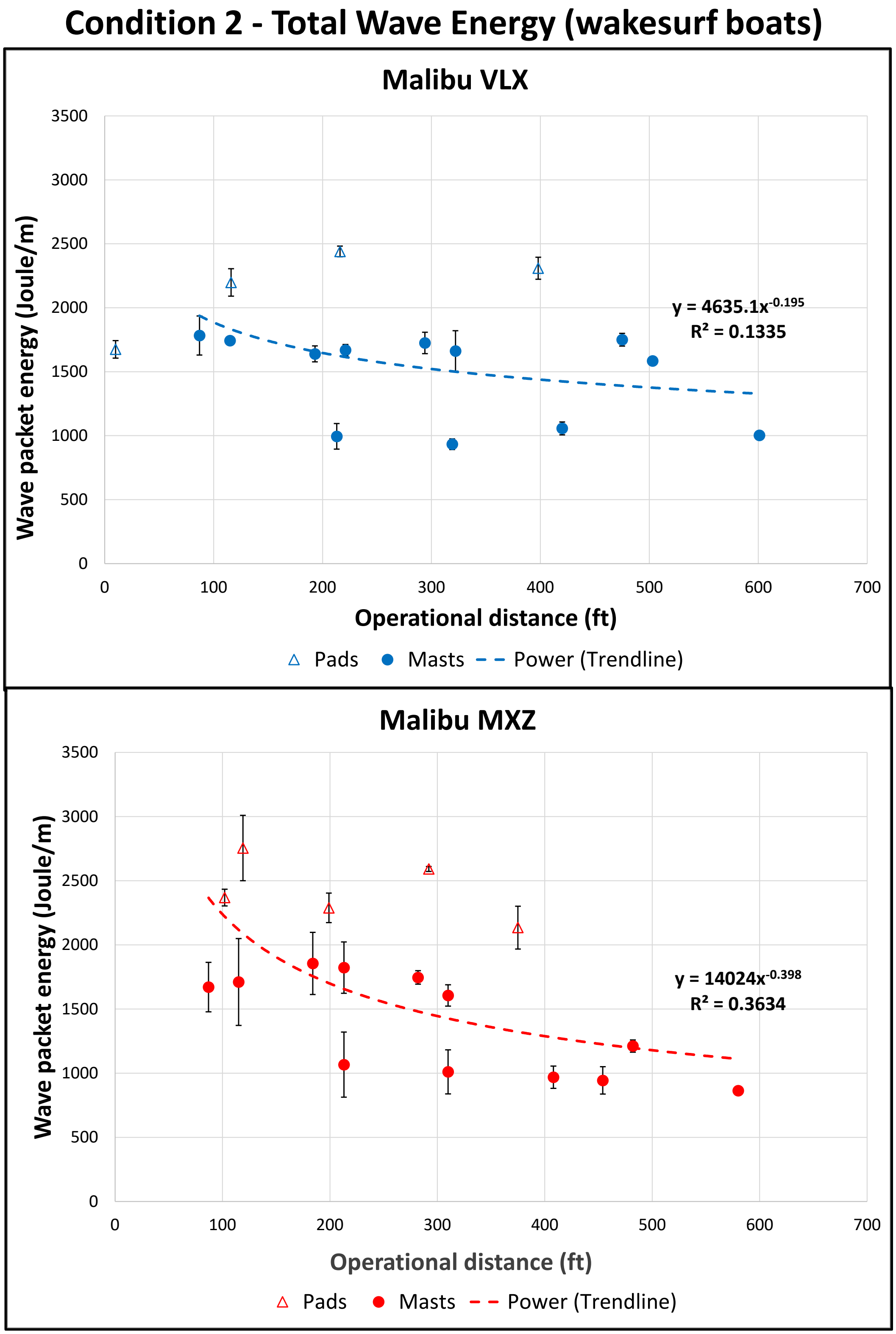


Figure 26. Total wake packet energy as a function of operational distance for the two wakesurf boats tested under Condition 2. The Pad data at distances less than 100 ft for the Malibu MXZ were noisy and thus eliminated from this analysis. Data points less than one boat length from the track line were not included in the regression analysis.

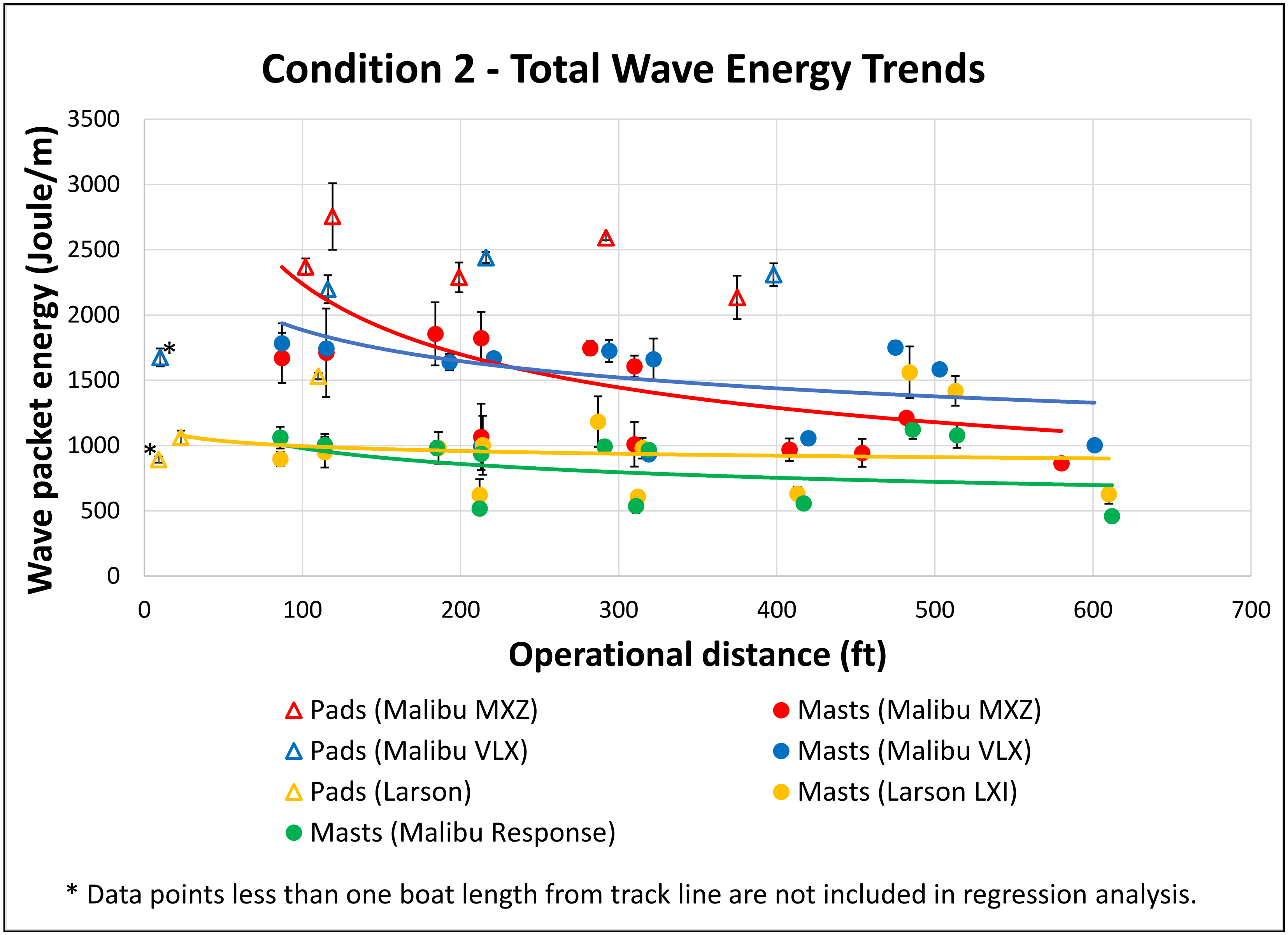


Figure 27. Condition 2 trendlines for the four test boats showing total wave energy over operational distance.

5.2.3 Maximum Wave Power

Attenuation of the maximum wave power with operational distance shows a decreasing nonlinear trend for all boats tested (Figures 28, 29 and 30). The initial maximum wave power for the Larson LXI 210 was roughly 180 J/m-s at a distance of 20 ft. The Malibu Response LX recorded a maximum wave power of approximately 80 J/m-s at 100 ft of operational distance. After a distance of roughly 300 ft, the maximum wave power for the Larson LXI 210 and Malibu Response LX were nearly identical at <25 J/m-s. The Malibu VLX produced an initial maximum wave power of about 270 J/m-s at 10 ft, which attenuated to approximately 30 J/m-s at 600 ft. The Malibu MXZ recorded a maximum wave power of 140 J/m-s at 100 ft, which decreased to roughly 40 J/m-s at 300 ft and 20 J/m-s at 600 ft.

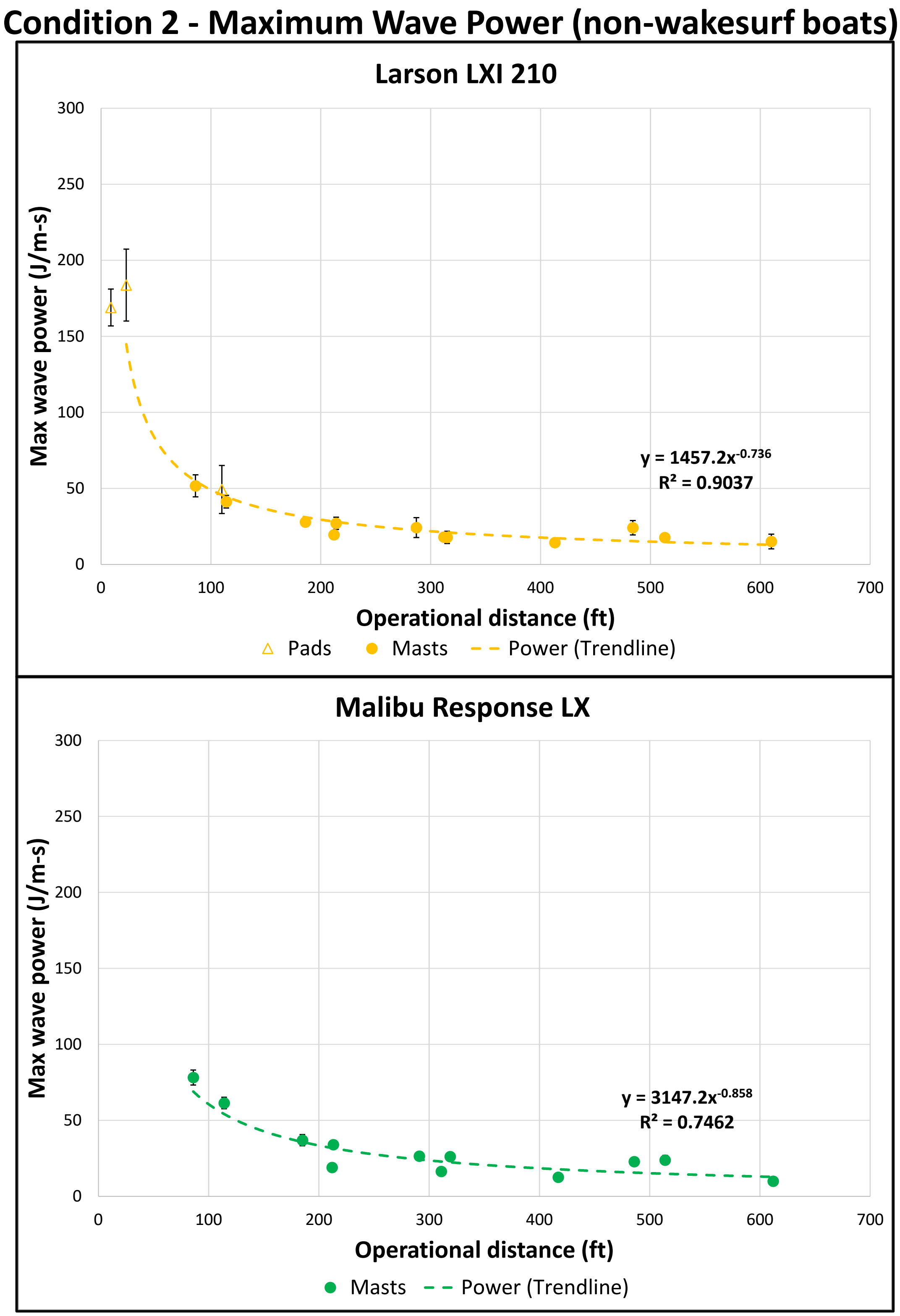


Figure 28. Maximum wave power as a function of operational distance for the two non-wakesurf boats tested under Condition 2. There are no data for the Pads for the Malibu Response LX due to technical issues with the ADCP on test day. Data points less than one boat length from the track line were not included in the regression analysis.

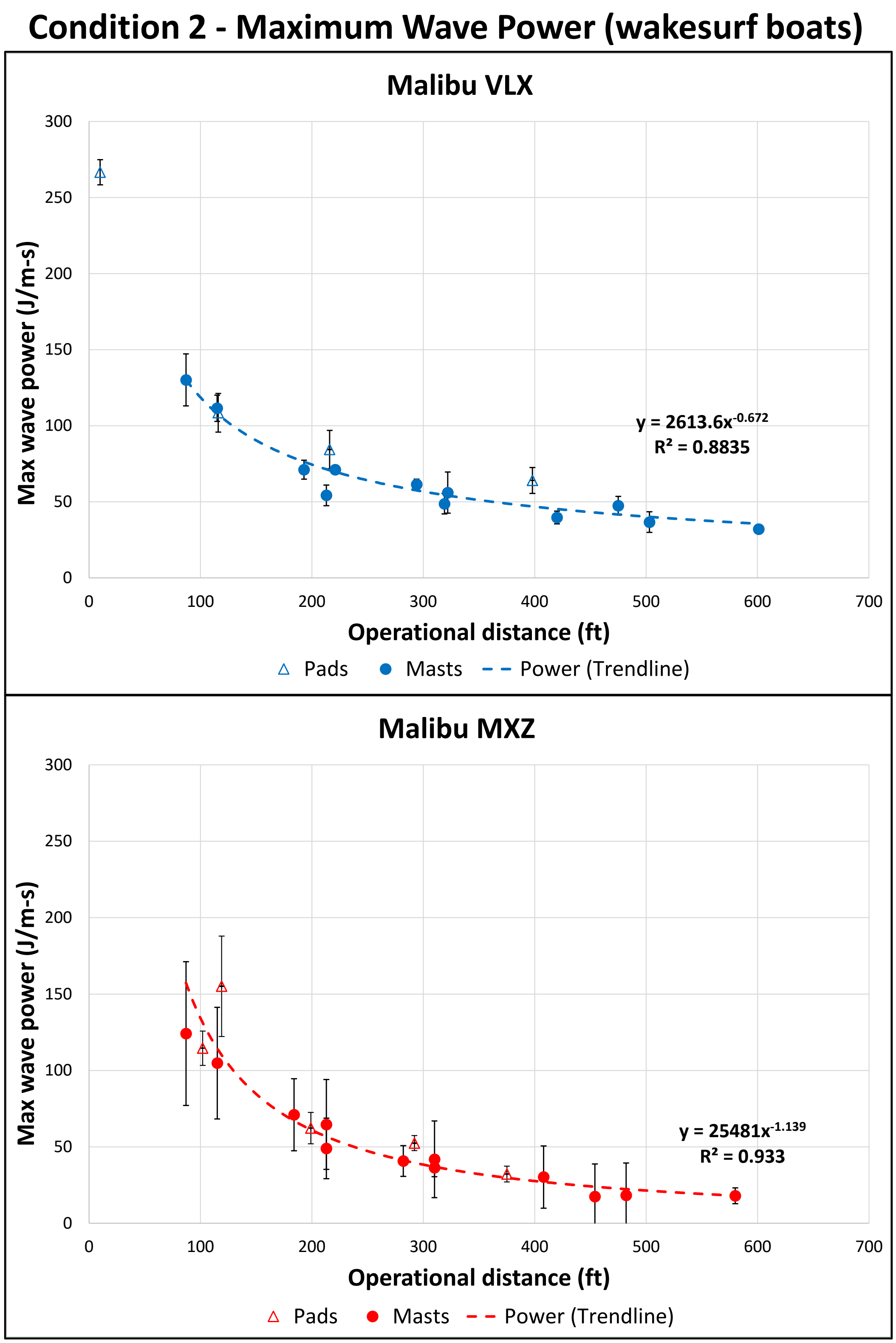


Figure 29. Maximum wave power as a function of operational distance for the two wakesurf boats tested under Condition 2. The Pad data at distances less than 100 ft for the Malibu MXZ were noisy and thus eliminated from this analysis. Data points less than one boat length from the track line were not included in the regression analysis.

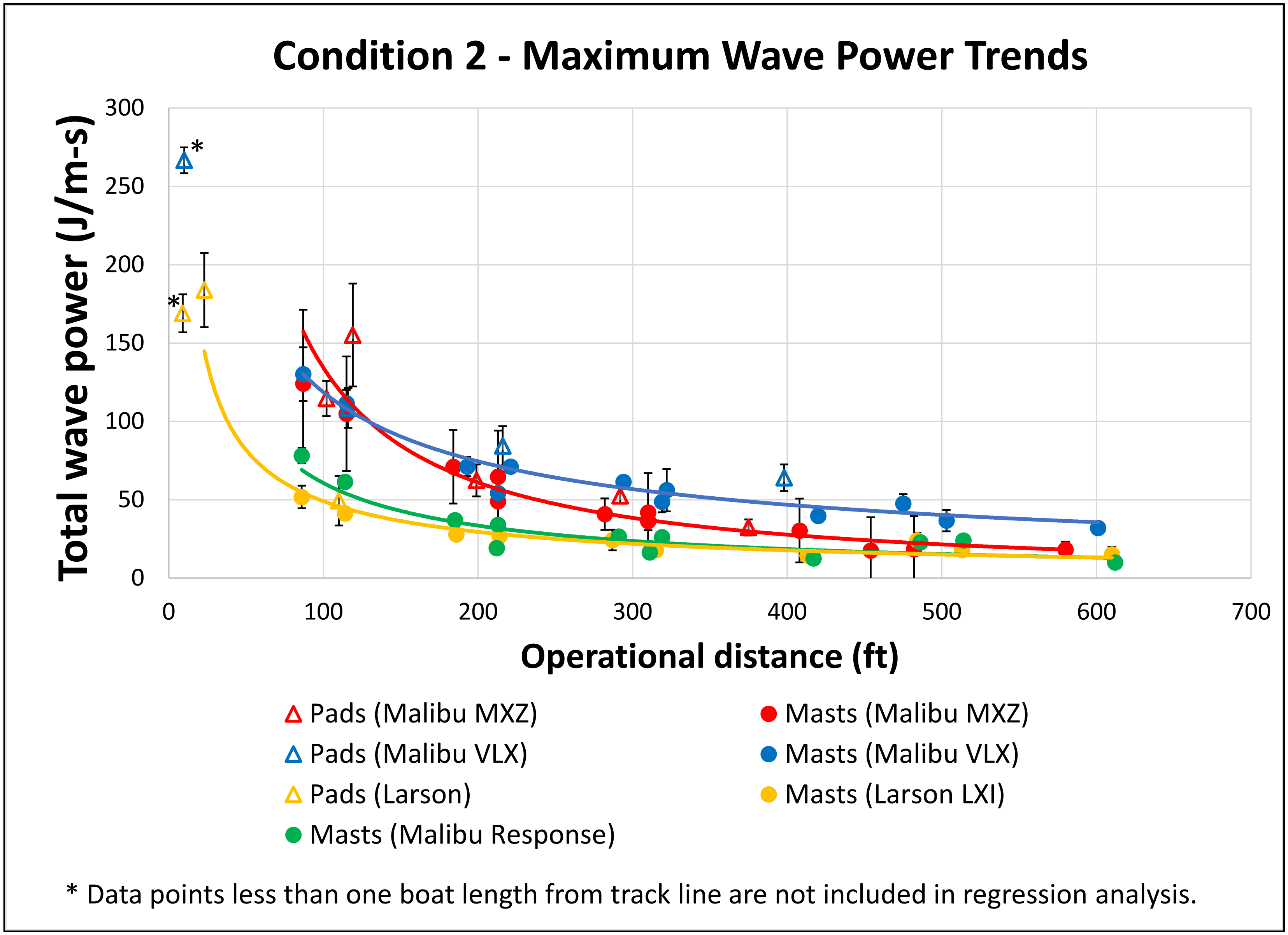


Figure 30. Condition 2 trendlines for the four test boats showing maximum wave power over operational distance.

5.3 Condition 1a (ballasts full) versus Condition 1b (ballasts empty)

Condition 1a for the Malibu VLX and Malibu MZX included operating with the ballast tanks completely full (results in Section 5.1). For Condition 1b, all variables remained the same except the ballast tanks were completely empty (Section 3.6.3, Table 3). Removing just the ballast water variable allowed for the comparison of its effects on measured wake wave characteristics (i.e., maximum wave height, total wave energy, and maximum wave power).

5.3.1 Malibu VLX

Overall, Condition 1a results (i.e., ballasts full) are very similar to Condition 1b results (i.e., ballasts empty) when maximum wave height, total wave energy, and maximum wave power are compared (Figures 31, 32 and 33). In the first 100 ft of operational distance, there appears to be an influence of the ballast weight on the measured wake wave characteristics. At a distance of 5 ft, the initial maximum wave heights were 34 in for ballasts full and 27 in for ballasts empty. However, by 100 ft the maximum wave height of both conditions had attenuated to approximately 14 in. At operational distances greater than 100 ft, the attenuating rates were very similar and had decreased to roughly 6 in by 600 ft. At an operational distance of 5 ft, the initial total wave energy was 12,200 J/m when the ballasts were full and 10,000 J/m when the ballasts were empty, however, it should be noted that the standard deviations for these data points were quite large. Again, by 100 ft of distance, the total wave energy of both conditions had attenuated to nearly identical values of approximately 3,900 J/m. Beyond this distance, the total wave energy continued to be very similar and eventually decreased to roughly 1,900 J/m at 600 ft. Finally, at 5 ft of operational distance, the initial maximum power was almost 2,000 J/m-s and 1,600 J/m-s for ballasts full and ballasts empty, respectively. Again, like initial total wave energy, the standard deviations for these data points were quite large. The maximum wave power for both conditions had attenuated to near identical values of roughly 250 J/m-s by 100 ft, and continued to attenuate to roughly 50 J/m-s at 600 ft.

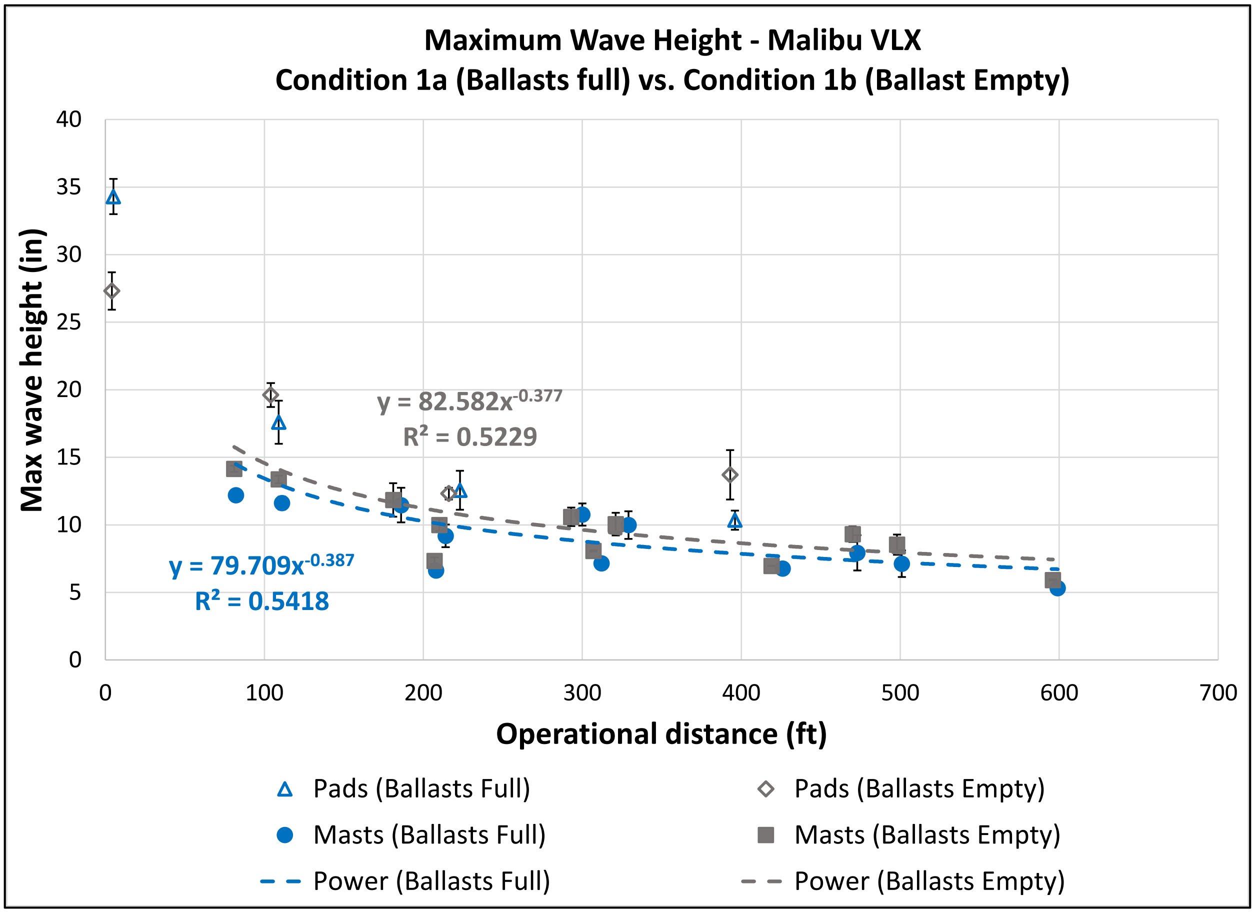


Figure 31. Comparison of the maximum wave height of the Malibu VLX when the ballast tanks were full and empty. Data points less than one boat length from the track line were not included in the regression analysis.

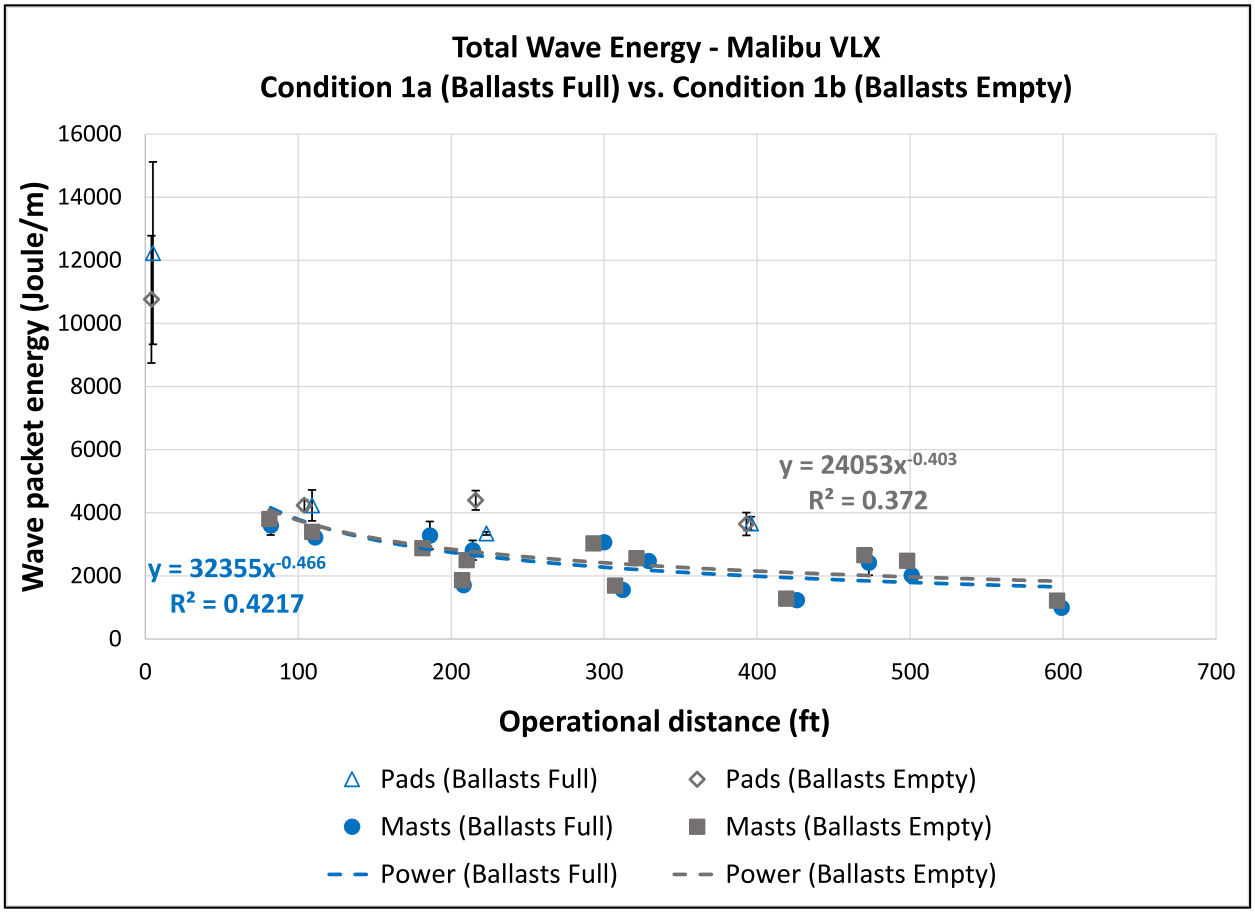


Figure 32. Comparison of the total wave energy of the Malibu VLX when the ballast tanks were full and empty. Data points less than one boat length from the track line were not included in the regression analysis.

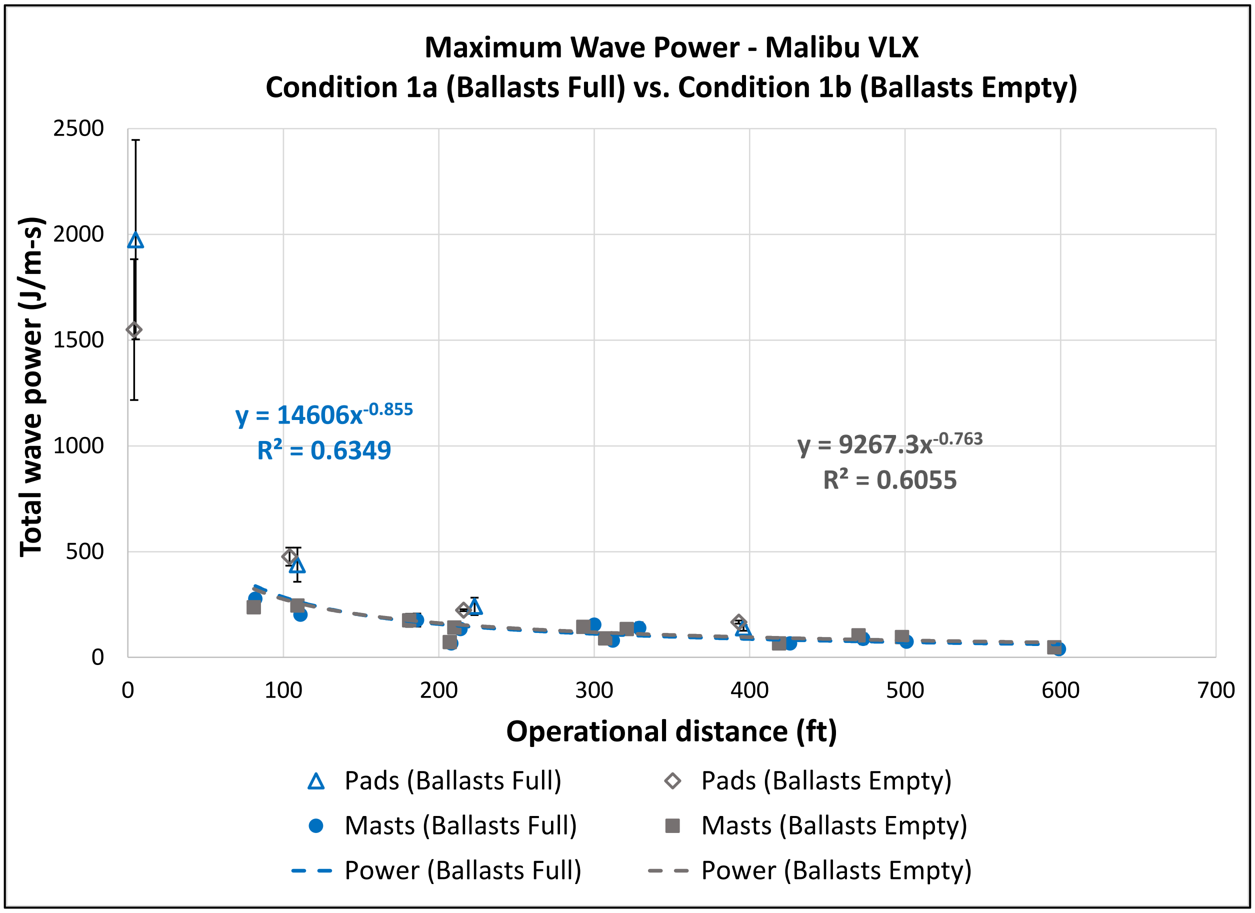


Figure 33. Comparison of the maximum wave power of the Malibu VLX when the ballast tanks were full and empty. Data points less than one boat length from the track line were not included in the regression analysis.

5.3.2 Malibu MXZ

Like the Malibu VLX, the Malibu MXZ has very similar results when Condition 1a (ballasts full) was compared to Condition 1b (ballasts empty) (Figures 34, 35 and 36). The data suggest there is an influence on the initial maximum wave height when the ballast tanks were full. At an operation distance of 5 ft, the initial maximum wave height was 39 in with the ballasts full and 31 in with the ballasts empty. However, the data and best-fit trendlines are nearly identical along the entire operational distance. By 590 ft the maximum wave heights attenuated to roughly 8 in. The total wave energy averaged roughly 1,000 J/m higher in the first 200 ft when the ballast tanks were full versus when they were empty. Between 200-400 ft, the influence of the ballast water could still be seen, however, the difference was less than ~500 J/m. After 400 ft, there was no discernable difference in total wave energy. Considering maximum wave power, the initial maximum measured at an operational distance of 5 ft was almost 2,400 J/m-s when the ballast tanks were full, and 1,900 J/m-s when the ballast tanks were empty. However, the standard deviations for these data points were quite large. By 100 ft the maximum wave power was approximately 500 J/m-s and this continued attenuating to about 40 J/m-s by 580 ft for both conditions.

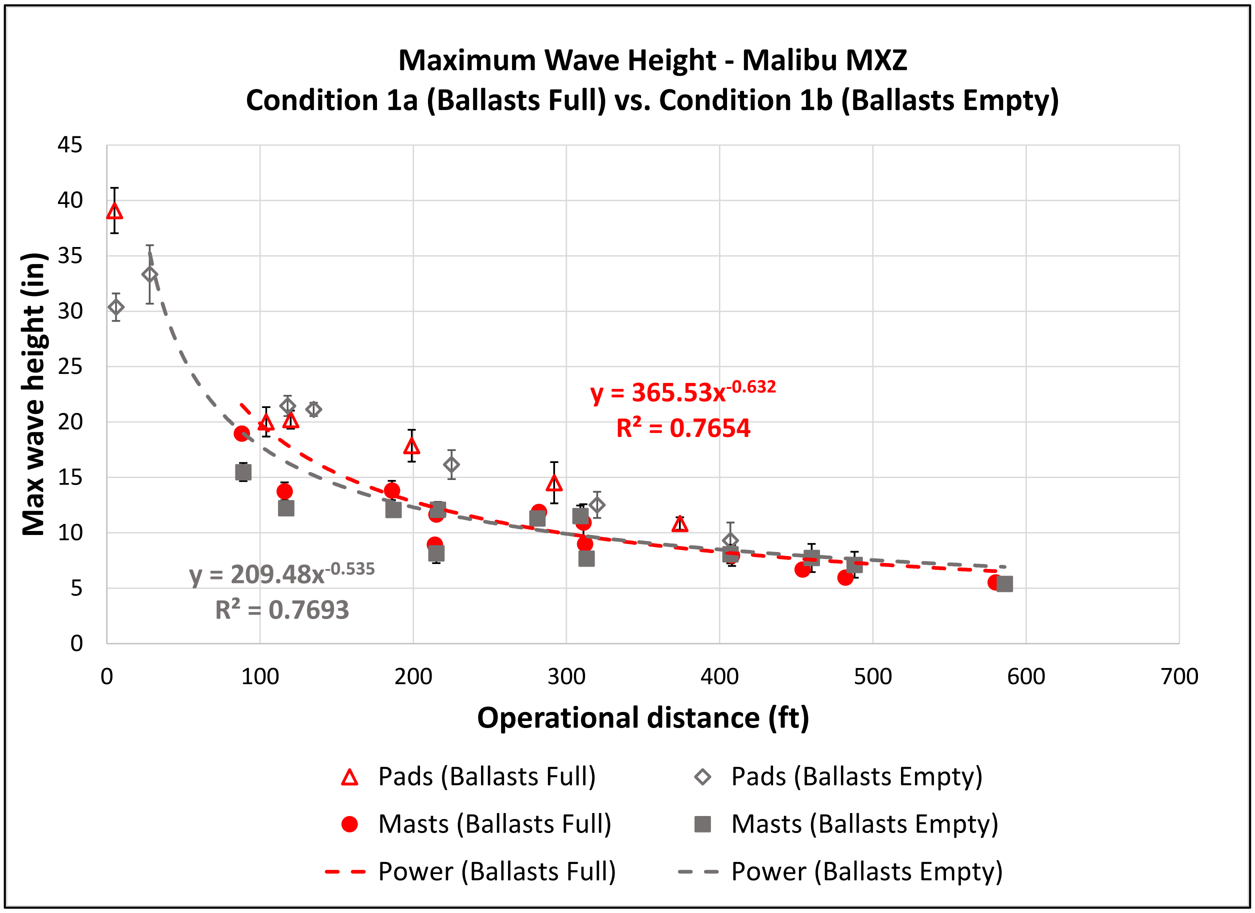


Figure 34. Comparison of the maximum wave height of the Malibu MXZ when the ballast tanks were full and empty. Data points less than one boat length from the track line were not included in the regression analysis.

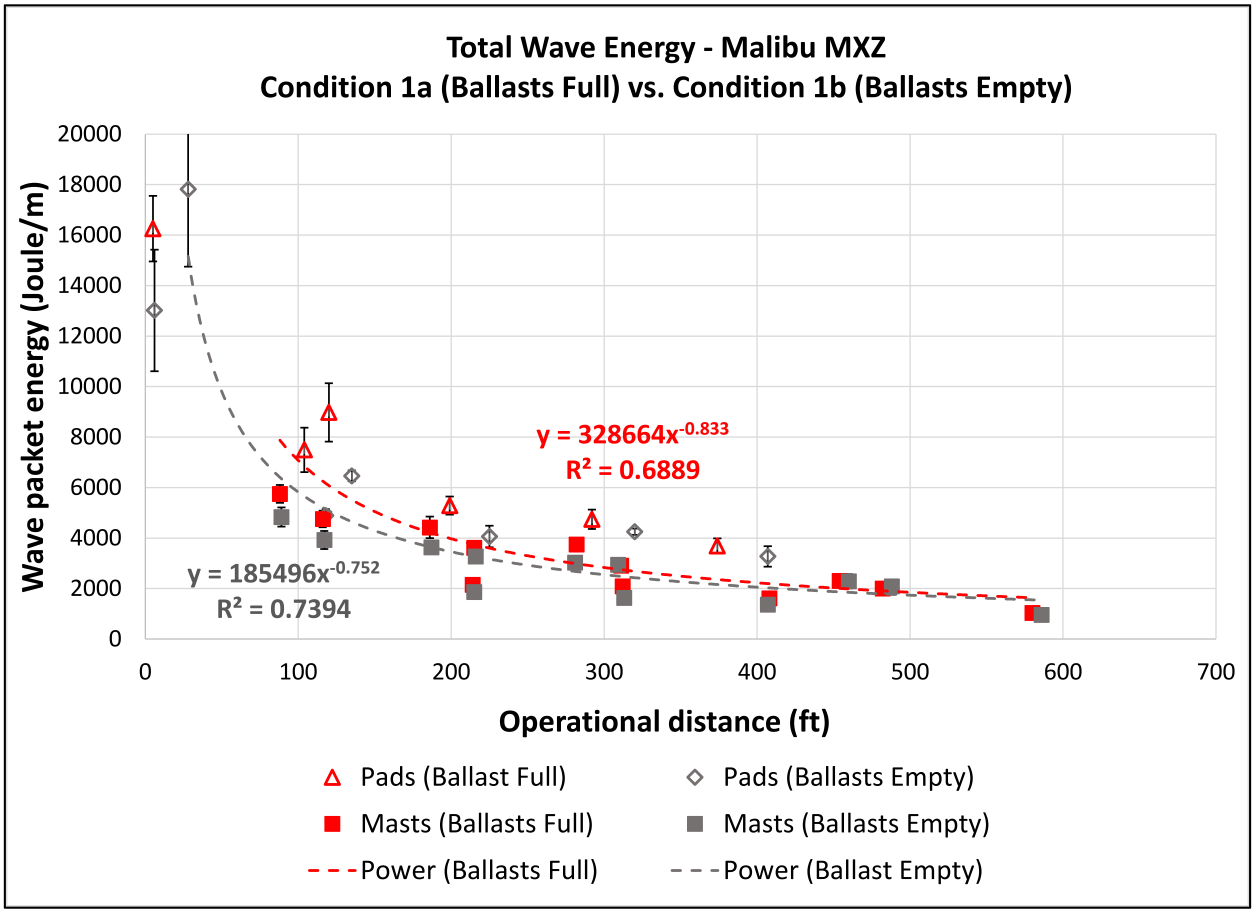


Figure 35. Comparison of the total wave energy of the Malibu MXZ when the ballast tanks were full and empty. Data points less than one boat length from the track line were not included in the regression analysis.

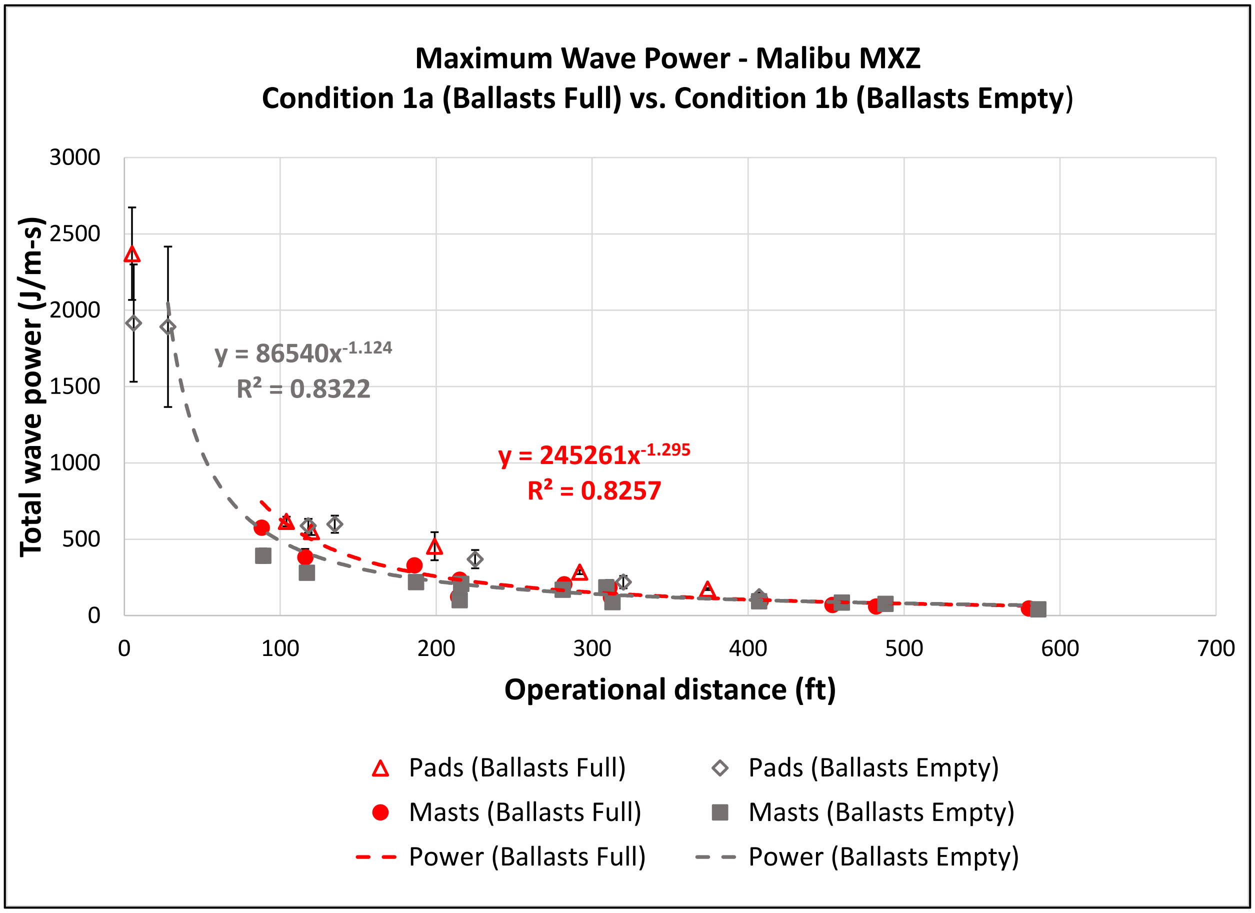


Figure 36. Comparison of the maximum wave power of the Malibu MXZ when the ballast tanks were full and empty. Data points less than one boat length from the track line were not included in the regression analysis.

5.4 Condition 1a (wake shaper on) versus Condition 1b (wake shaper off)

Condition 1a for the Malibu Response LX included an aftermarket wake shaper that was mounted just beneath the water surface on the port quarter of the hull (Section 3.6.2, Table 3). The wake shaper was removed from the boat during Condition 1b, while all other variables remained the same (Section 3.6.2, Table 3), allowing for the comparison of its influence on measured wake wave characteristics (Figures 37, 38 and 39).

The maximum wave height attenuation rates were similar for both conditions. However, the addition of the wake shaper resulted in a maximum wave height that was on the order of two inches higher over the entire operational distance. Just prior to 100 ft, the presence of the wake shaper created a maximum wave height of 12 in that attenuated to roughly 5 in after 600 ft. With the wake shaper removed, the maximum wave height was 10 in just prior 100 ft, and decreased to roughly 4 in after 600 ft. Like maximum wave height, the total wave energy attenuation rates were very similar between conditions. With the wake shaper attached, the total wave energy recorded over the entire operational distance was higher by roughly 200-500 J/m. The total wave energy was 2,300 J/m just prior to 100 ft and attenuated to approximately 650 J/m after 600 ft. With the wake shaper removed, the total wave energy was 1,900 J/m just prior to 100 ft, and by 600 ft it had decreased to roughly 430 J/m. Finally, attenuation rates for both conditions were nearly identical for maximum wave power. There was an increase in maximum wave power of around 20-40 J/m-s with the wake shaper attached. Just prior to 100 ft of operational distance, the maximum wave power was about 200 J/m-s, that attenuated to approximately 30 J/m-s at 600 ft. Without the wake shaper, the maximum wave power just prior to 100 ft was 160 J/m-s, which decreased to 10 J/m-s by 600ft.

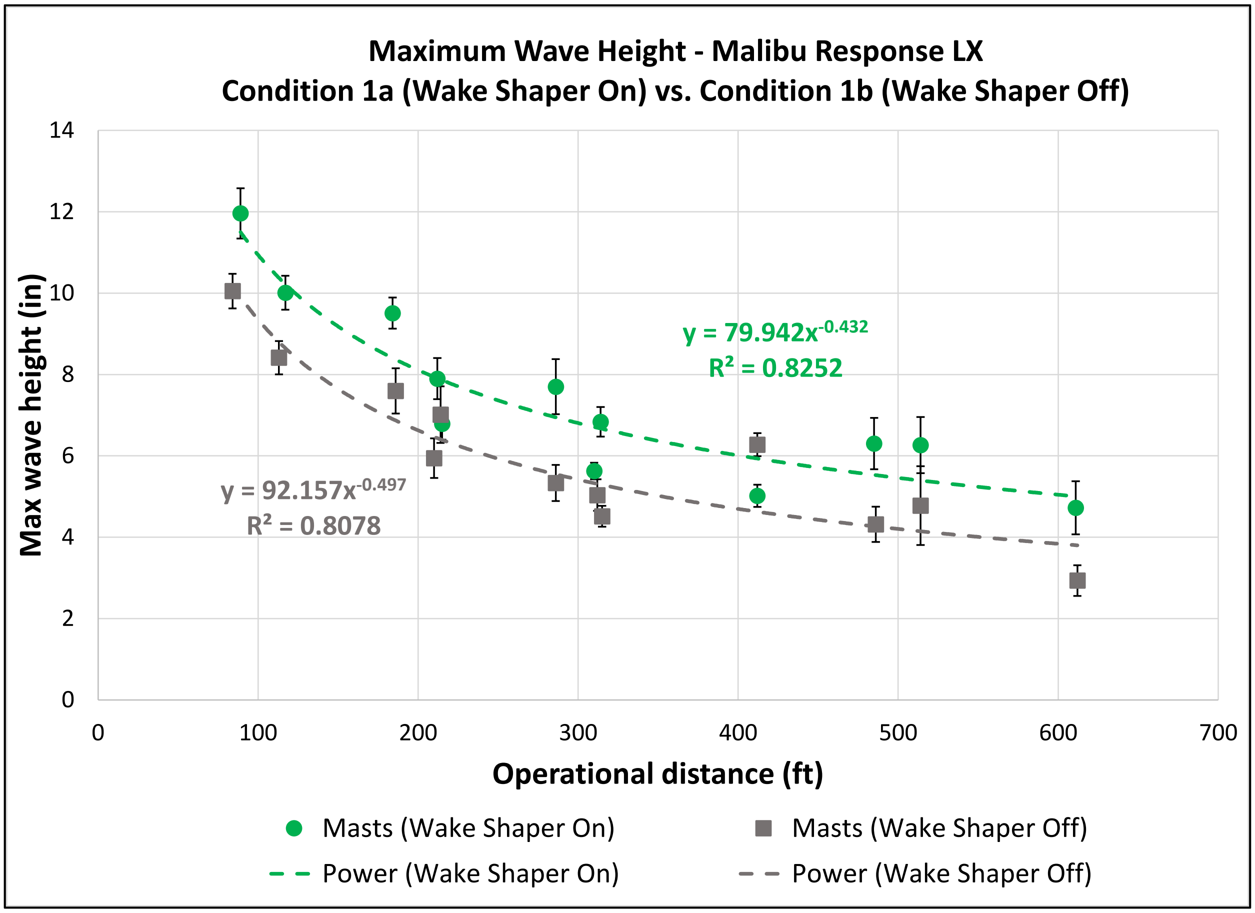


Figure 37. Comparison of the maximum wave height of the Malibu Response LX when the wake shaper was on and off. There are no data for the Pads for the Malibu Response LX due to technical issues with the ADCP on test day.

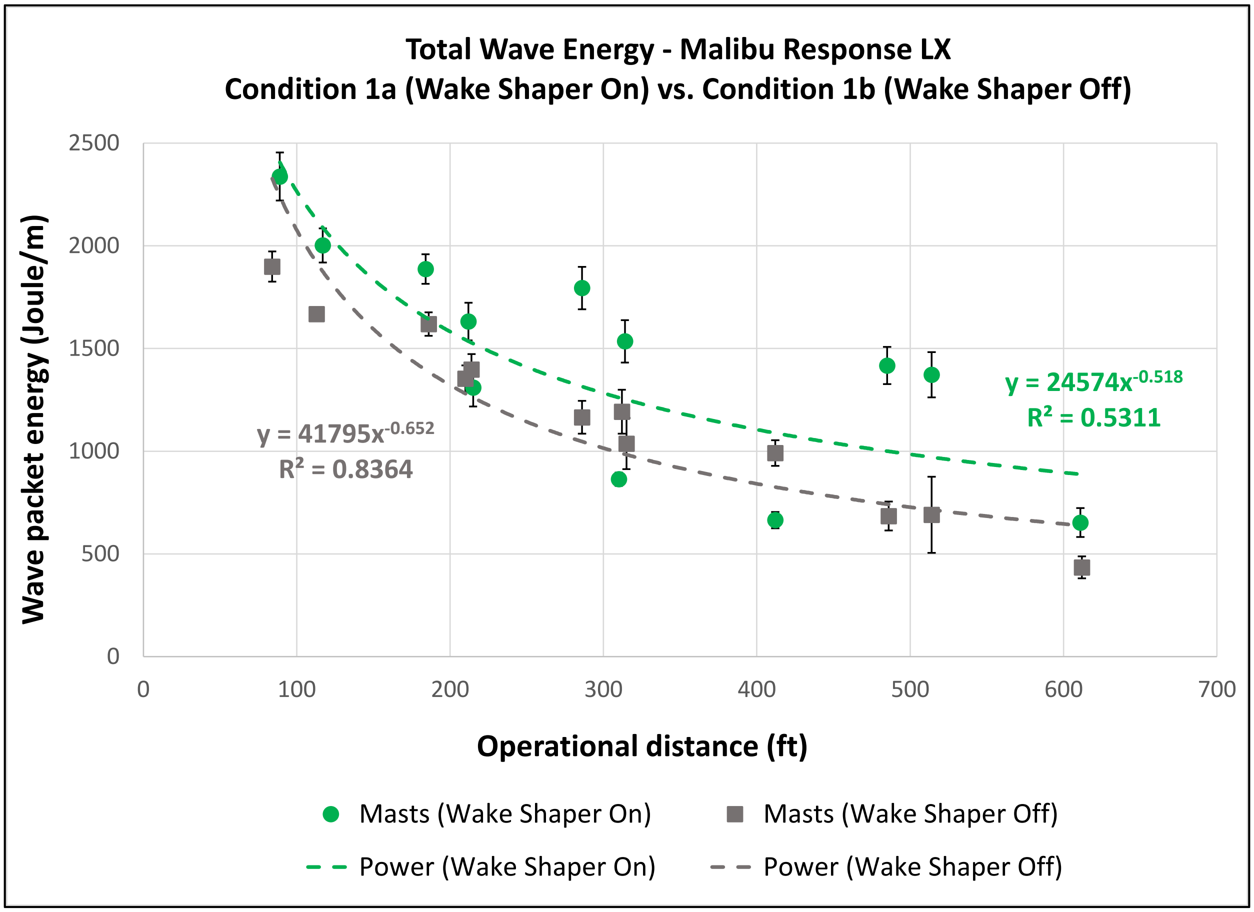


Figure 38. Comparison of the total wave energy of the Malibu Response LX when the wake shaper was on and off. There are no data for the Pads for the Malibu Response LX due to technical issues with the ADCP on test day.

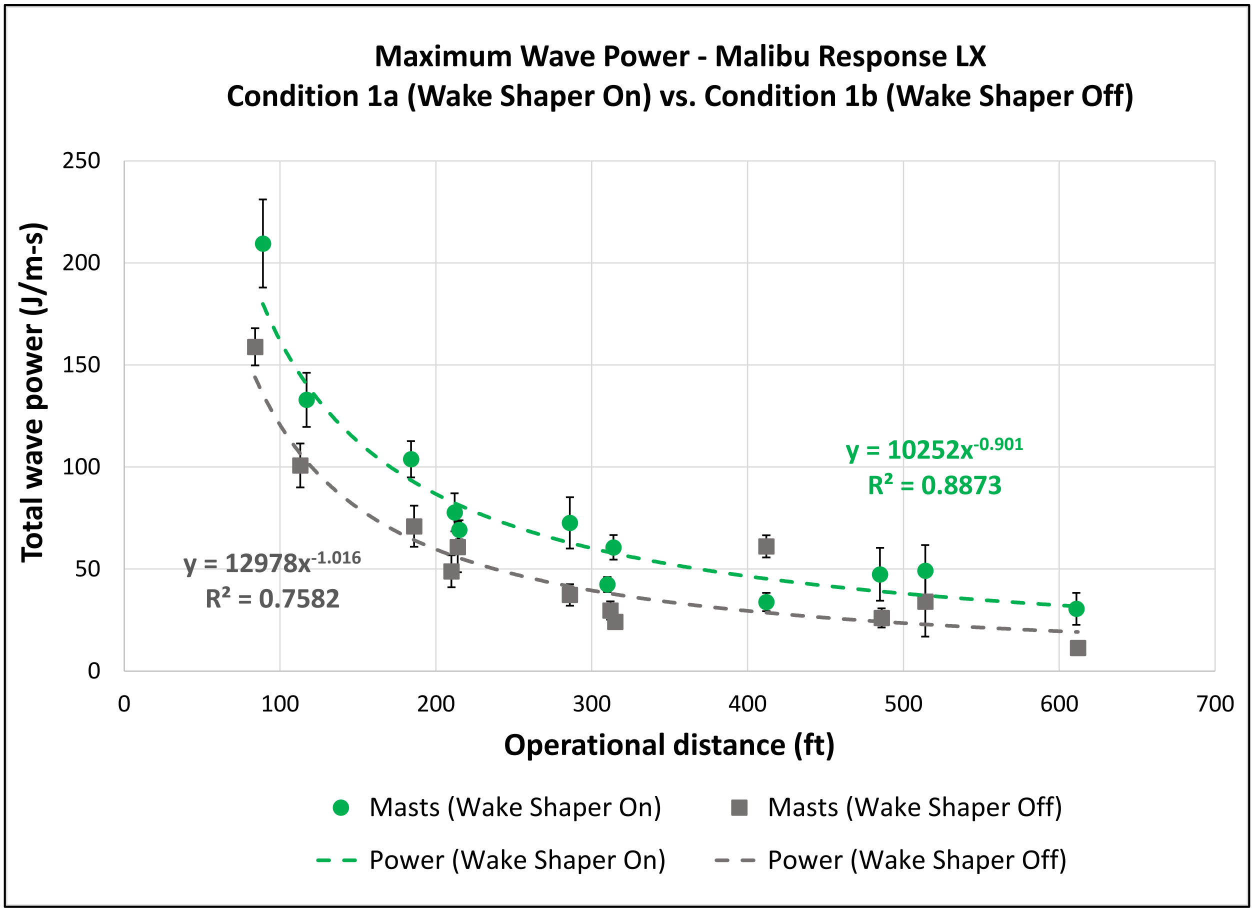


Figure 39. Comparison of the maximum wave power of the Malibu Response LX when the wake shaper was on and off. There are no data for the Pads for the Malibu Response LX due to technical issues with the ADCP on test day.

6.0 DISCUSSION

This section provides a discussion of the key observations and findings made in this study. We also provide guidance on how the information can be used by stakeholders in shaping future research efforts, managing lake and river resources, and providing education for boat operators. Finally, we end this section with a description of priority research needs related to boat-generated wake waves and their impacts.

6.1 Summary of observations

6.1.1 The maximum wave height, total wave energy, and maximum wave power produced by the four test boats were different between operational Condition 1a and Condition 2

The Larson LXI 210 is an all-purpose recreational boat that is typically operated at higher speeds where the boat is planing on the water surface. Typical usages include cruising or tow sports like tubing, waterskiing, and wakeboarding. Similarly, the Malibu Response LX is a recreational boat with a specialized design (e.g., D-Drive) for waterskiing and other tow sports that are performed at higher planing speeds. Figure 40 shows data for the Larson LXI 210 and Malibu Response LX comparing the total wave energy produced by Condition 1a (largest possible wake) and Condition 2 (planing). The data show a higher total wave energy under Condition 1a, which was also true for maximum wave height and maximum wave power. Although the Malibu Wakesetters can be operated on-plane for the same aforementioned tow sports, they are designed primarily to be operated at slow speeds that maximize water displacement and produce large wakes suitable for wakesurfing. Figure 41 shows the same data collected for the Malibu VLX and Malibu MXZ under Conditions 1a (wakesurfing) and Condition 2 (planing). Both boats showed significantly larger changes in total wave energy levels between Condition 1a and Condition 2. Again, the same trend was true for maximum wave height and power.

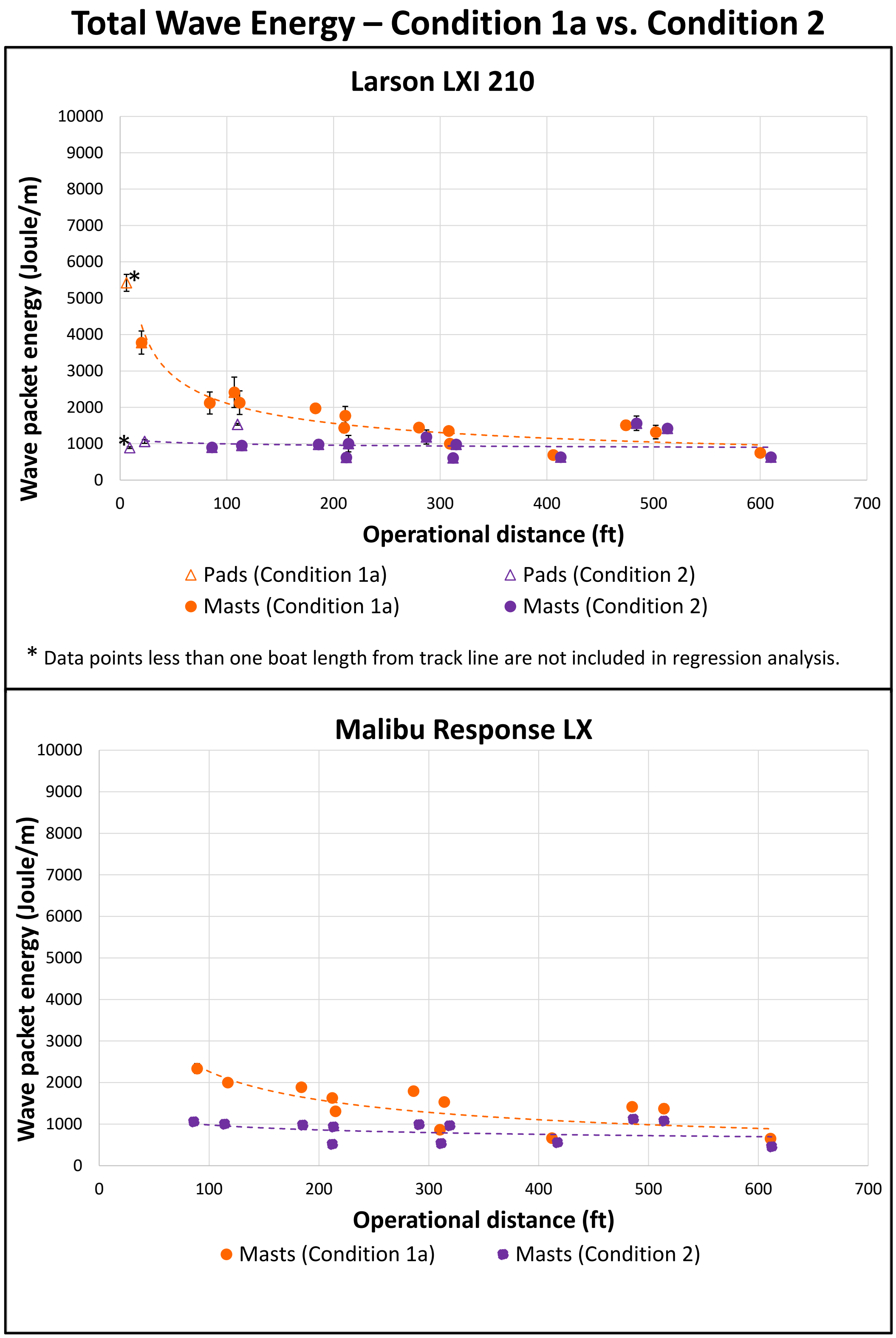


Figure 40. Comparisons of the total wave energy for the Larson LXI 210, Malibu Response LX Condition 1a (largest wave/surfing) and Condition 2 (planing). There are no data for the Pads for the Malibu Response LX due to technical issues with the ADCP on test day. Note the maximum y-axis value is 10,000 J/m.

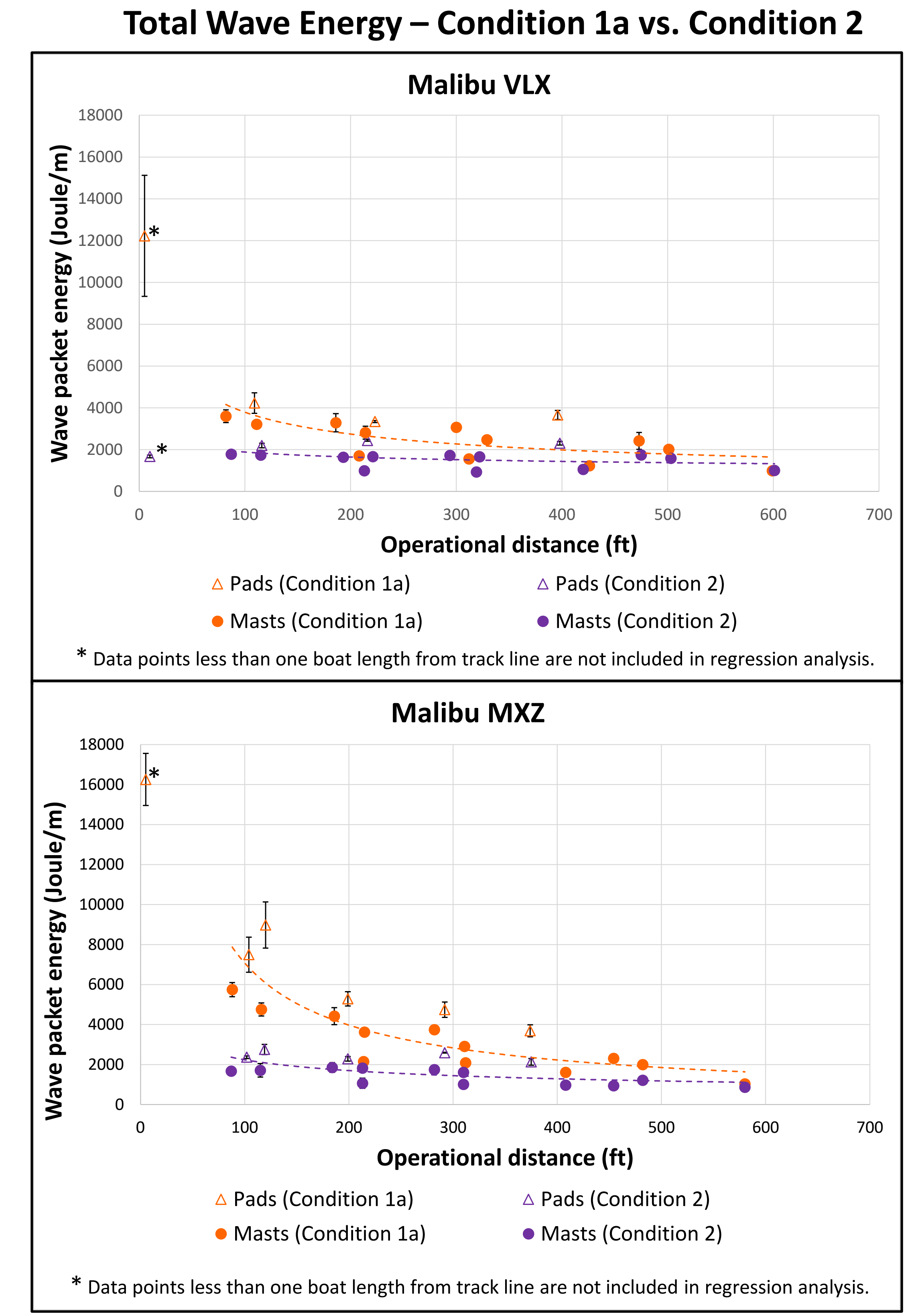


Figure 41. Comparisons of the total wave energy for the Malibu VLX, and Malibu MXZ Condition 1a (wakesurfing) and Condition 2 (planing). Note the maximum y-axis value is 18,000 J/m.

6.1.2 When operated under their most typical operating conditions, wakesurf boats were capable of producing larger wake waves that contain more energy and power than non-wakesurf boats

During boating water sports, the Larson LXI 210 and Malibu Response LX are typically operated in a planing mode (Condition 2), while the wakesurf boats studied here are engineered to operate, amongst other configurations, at Condition 1a. This is the condition associated with the sport of wakesurfing and it is safe to assume that this is the most common operational condition for these boats. Therefore, a useful comparison to consider is the maximum wave height, total wave energy, and maximum wave power under the conditions that are most common for the boat's operation (Figures 42, 43 and 44).

Under this comparison, the two wakesurf boats produced substantially higher (~2-3 times) maximum wave heights than the non-wakesurf boats at 100 ft and ~2 times higher after 600 ft. The wakesurf boats had maximum wave heights between 12-20 in at 100 ft of operational distance, that attenuated to 5-7 in around 600 ft. Maximum wave heights for non-wakesurf boats decreased from 7-9 in at 100 ft of distance to 4 in or less at 600 ft. Total wave energy showed a similar pattern, with the two wakesurf boats producing ~3 to 9 times more energy than the non-wakesurf boats after 100 ft of operational distance and ~3 times at 500 ft. At roughly 100 ft of operational distance, the wakesurf boats had total wave energies that ranged between 3,200-9,000 J/m, which attenuated to ~2,000 J/m by 450-550 ft. Both non-wakesurf boats had initial total energy levels of roughly 1,000 J/m with minimal attenuation over 600 ft of distance. Maximum power for the non-wakesurf boats was 50 J/m-s at 100 ft and attenuated to around 10 J/m-s at 600 ft of operational distance. The wakesurf boats had measured maximum powers that ranged from 280 to 620 J/m-s at 100 ft (~6 to 12 times more power) and attenuated to 40 J/m-s at 600 ft (4 times more power).

While Figures 42, 43 and 44 focus on assumed typical operations, it is important to note that wakesurf boats are multipurpose boats designed to also operate at Condition 2 where they can be used for cruising and other recreational tow sports. Similarly, with the addition of wake manipulating technology (e.g., hydrofoil and wake shaper), non-wakesurf boats like the Malibu Response LX can be operated as a wakesurf boat (i.e., Condition 1a). Finally, it is technically possible for the Larson LXI 210 to be operated in Condition 1a for long periods of time, however, it is our experience that boats of this type spend very little time in this condition; normally they would transition quickly through Condition 1a as they accelerate to planing operation.

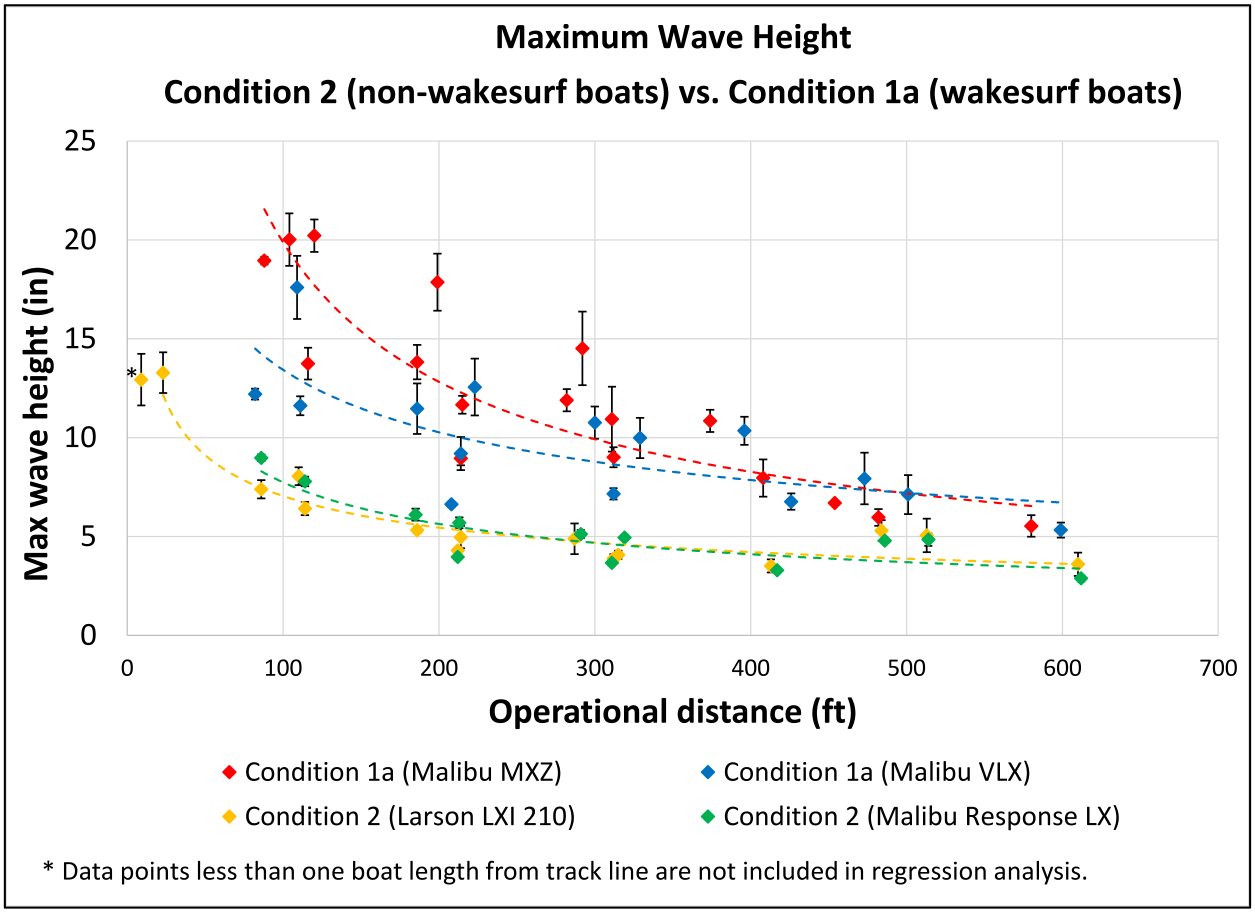


Figure 42. Comparison of maximum wave height of the test boats under their typical operational conditions.

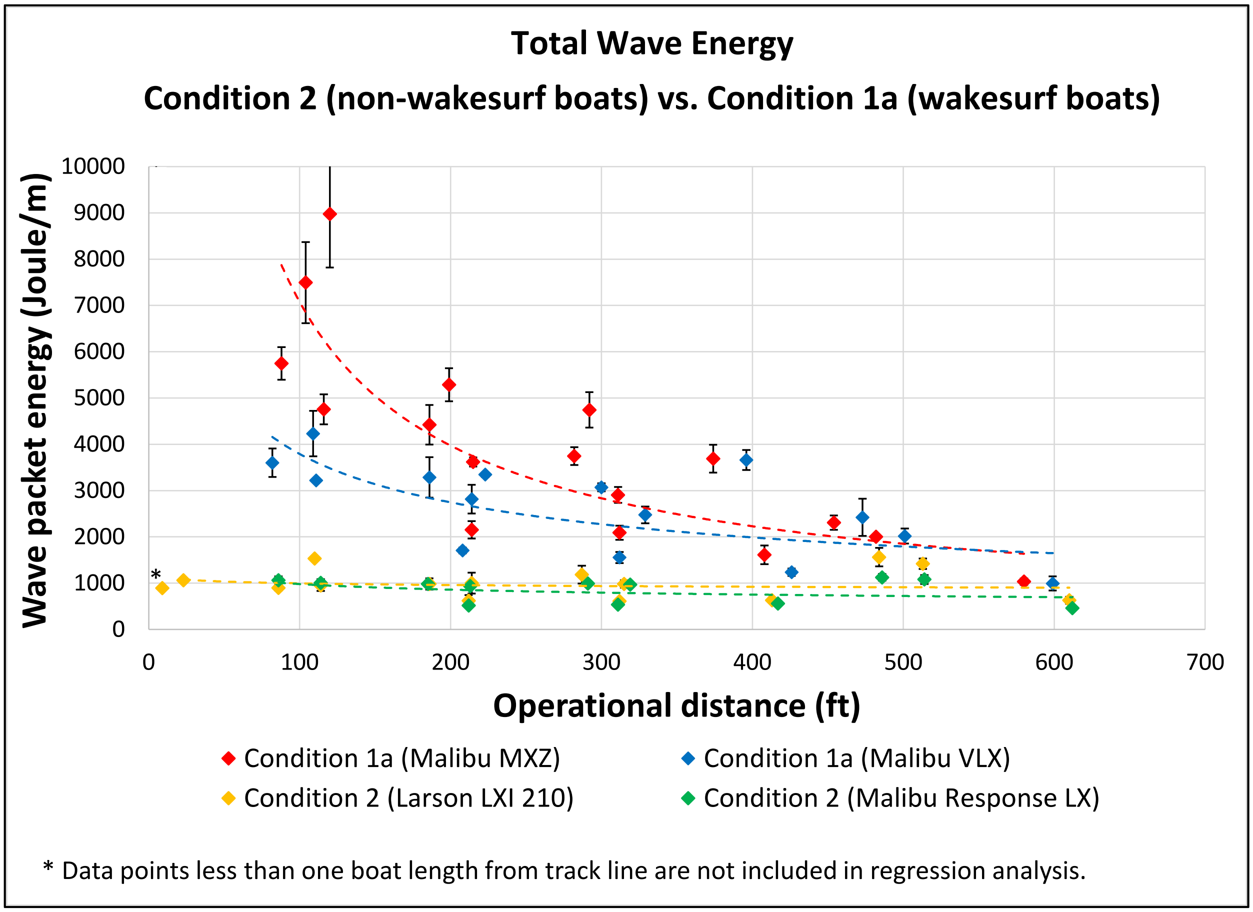


Figure 43. Comparison of total wave energy of the test boats under their typical operational conditions.

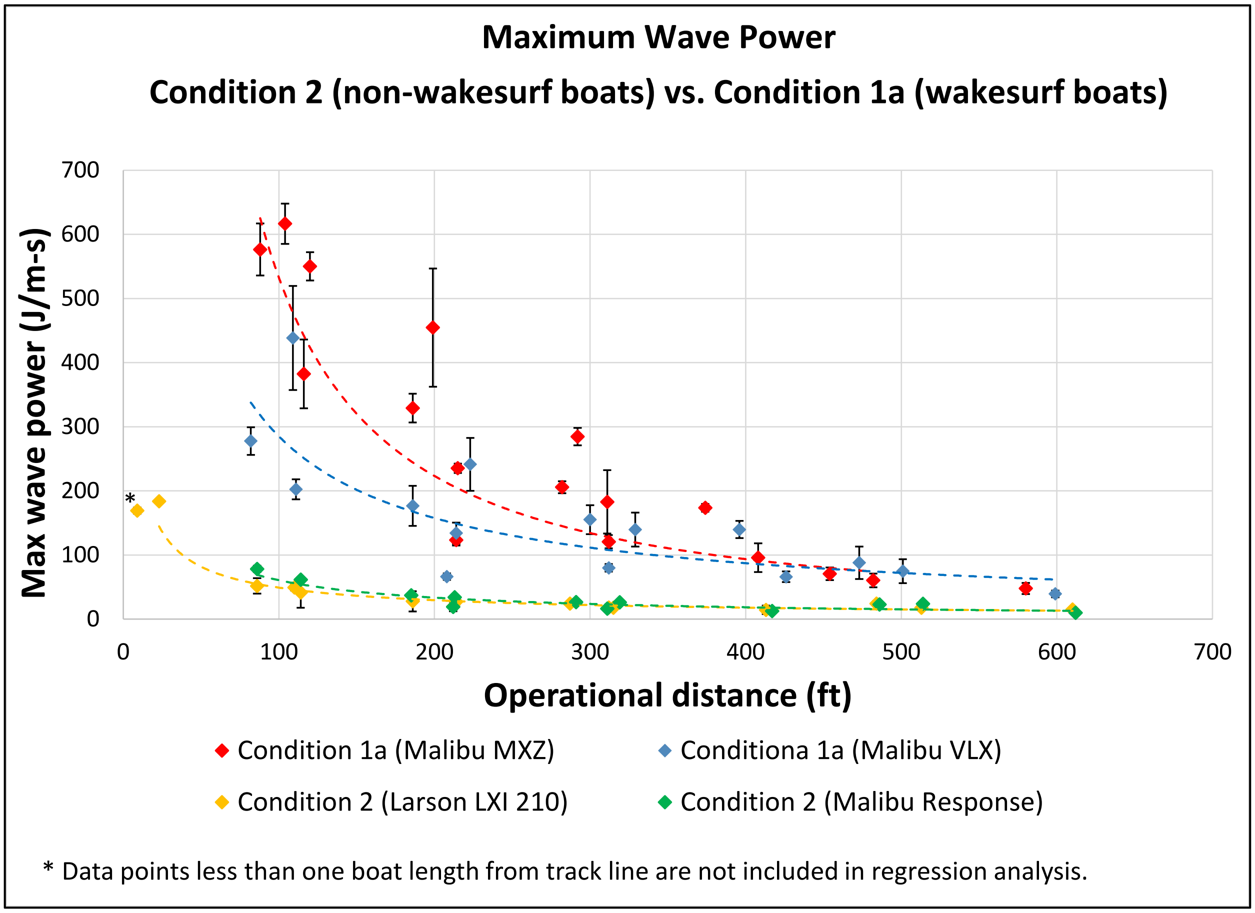


Figure 44. Comparison of maximum wave power of the test boats under their typical operational conditions.

6.1.3 Full ballast tanks had a minor impact on the wake wave characteristics of the Malibu Wakesetters at distances greater than 100 ft from the boat

An unexpected finding was the relatively small influence the added weight of the ballast water had on the maximum wave height, total wave energy, and maximum wave power for the Malibu Wakesetters. As shown in Table 2, completely full ballast tanks increased the total boat weight by 3,690 lbs (47% increase) and 4,885 lbs (47% increase) for the VLX and MXZ, respectively. Our expectation was that the increased water weight, and thus greater hull submergence equating to more water being displaced, would result in an increase in the magnitude of the measured wake wave characteristics over the entire operational distance. Although there were increases in the maximum wave height, total wave energy, and maximum wave power in the first 100 ft of operational distance for both boats when the ballast tanks were full, the differences quickly decreased with distance and were no longer discernible after approximately 200 ft (Figures 31-36). This observation motivates further investigations.

6.1.4 Addition of the aftermarket wake shaper to the Malibu Response LX resulted in larger maximum wave heights, increased total wave energy, and greater maximum wave power

The wake shaper attached to the Malibu Response LX altered the wake by creating an asymmetric wake that increased the measured maximum wave height, energy, and power. When compared to the Malibu Wakesetters, the wake wave characteristics were smaller (Figures 15, 18, and 21). Interestingly, when considering the Malibu Response LX individually, the aftermarket wake shaper resulted in notable increases in the wake wave characteristics, not only near the boat (i.e., first 100 ft), but at all operational distances (Figures 37, 38, and 39). This observation, along with those discussed in Section 6.1.3, suggest the wake shaper may have more influence on the measured wave characteristics than the addition of ballast water at greater operational distances. Nevertheless, the implications are that aftermarket products can effectively modify the wave characteristics of recreational boats.

6.1.5 A potential method for establishing guidance for boat operational distances based on measured wake wave characteristics (height, energy, power)

We conducted a review of the relevant laws, regulations, and recommendations for the state of Minnesota and the surrounding upper Midwest states regarding the operational distances that boats have to maintain between other watercrafts, shorelines, docks, etc. No consistent guidance has been adopted by these states (Table 4). Operational distances range between 100 ft and 300 ft, vary in the type of specification, and pertain to all types of motorboats. In Minnesota, for example, there is presently no law that prescribes an operational distance between boats, shorelines, docks, other watercraft, etc., rather there is a recommended distance of 200 ft. Iowa, Michigan, North Dakota, and Wisconsin have developed laws stating specific distances of 300 ft, 100 ft, and 100 ft, respectively. We could not locate operational distance criteria for South Dakota.

The data produced in this study can be used to inform boat operational distances necessary to attenuate maximum wave height, total wave energy, and maximum wave power to levels deemed acceptable. To illustrate this approach, we provide two examples below. In both examples, we select the Minnesota recommendation of 200 ft as the reference operational distance (Table 4). In principle, the point at which the various wake wave characteristic data cross a selected reference distance, defines the recommended threshold criteria for that characteristic.

In the first example (Figures 45, 46 and 47), we reference Figures 42, 43, and 44 from Section 6.1.2, where the boats were compared under their typical operational conditions: Condition 2 (planing) for the non-wakesurf boats and Condition 1a (wakesurfing) for the wakesurf boats (Section 3.6, Table 3). Because Condition 2 for the non-wakesurf boats are typical recreational operating conditions seen on Minnesota inland lakes, it was used as the reference condition. Moreover, the non-wakesurf boats produced the lowest overall values of wave height, energy, and power and were nearly identical to one another after 200 ft of distance. The results in Figures 45, 46 and 47 suggest, based on both the actual data points and best-fit power law regressions, that operational distances greater than 500 ft are needed to attenuate the wake wave characteristics of the wakesurf boats to the selected reference condition levels, which were roughly 6 in, 1,000 J/m, and 35 J/m-s for maximum wave height, total wave energy, and maximum wave power, respectively.

In the second example, (Figures 48, 49 and 50), we reference Figures 15, 18, and 21 from Section 5.0, where all boats were compared under Condition 1a (i.e., largest wave/surfing). Again, the non-wakesurf boats are the reference. The results in Figures 48, 49, and 50 suggest, based on the actual data points and best-fit regressions, that operational distances greater than 425 ft are needed to attenuate the wake wave characteristics of the wakesurf boats to the selected condition reference levels, which were approximately 7 in for maximum wave height, 1,600 J/m for total wave energy, and 80 J/m-s for maximum wave power. Table 5 summarizes the results from both examples.

Table 4. Summary of state laws/recommendations regarding operational distances between recreational boats and shoreline, docks, other watercraft, etc.

State	Boats	Note	References
Iowa	speeds less than 10 mph at distances less than 300ft from shore	state law/ regulation	http://publications.iowa.gov/15950/1/ia_handbook_entire.pdf
Michigan	slow, no wake speed at distances less than 100 ft from shore (if < 3 ft deep), moored or anchored vessel, dock, raft, swimming area, or person(s) in the water	state law/ regulation	https://assets.kalkomey.com/boater/pdfs/handbook/michigan-handbook-entire.pdf
Minnesota	maintain greater than 200 ft between boat and shore/other structures	recommendation	http://files.dnr.state.mn.us/rlp/regulations/boatwater/boatingguide https://www.dnr.state.mn.us/safety/boatwater/own-your-wake.html
North Dakota	No operation within 100 ft of a person fishing from shore, swimmer, raft, or an occupied, anchored or nonmotorized vessel	state law/ regulation	https://gf.nd.gov/boating/safety-regulations
Wisconsin	slow, no wake speed at less than 100 ft from shore, dock, raft, pier, swimmer, or restricted area	state law/ regulation	https://dnr.wi.gov/files/pdf/pubs/le/le0301.pdf

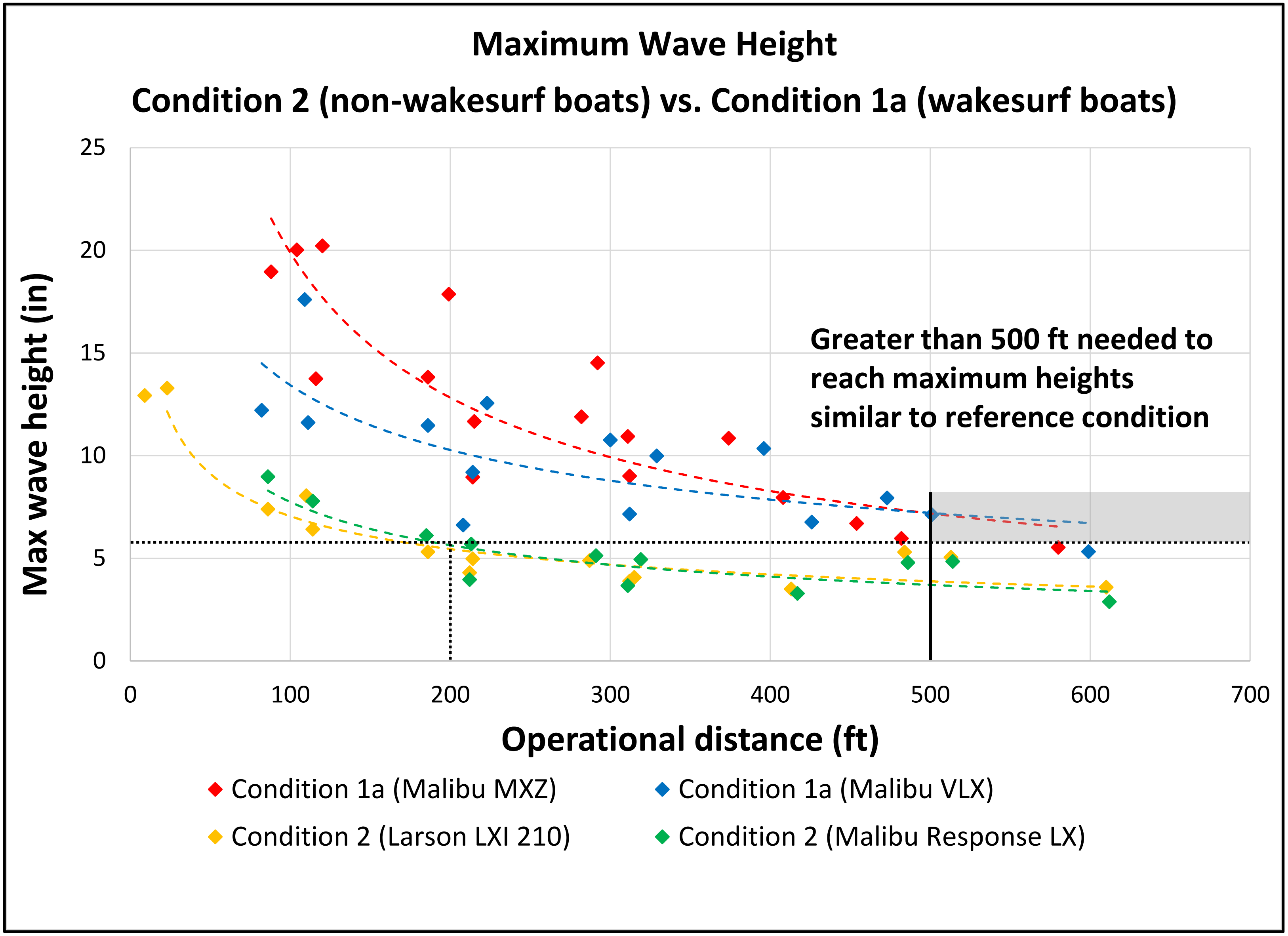


Figure 45. Illustration of a potential method for estimating the operational distance needed to reduce the maximum wave height of the wakesurf boat to reference levels associated with Condition 2 (planing) of the non-wakesurf boats (black horizontal dashed line).

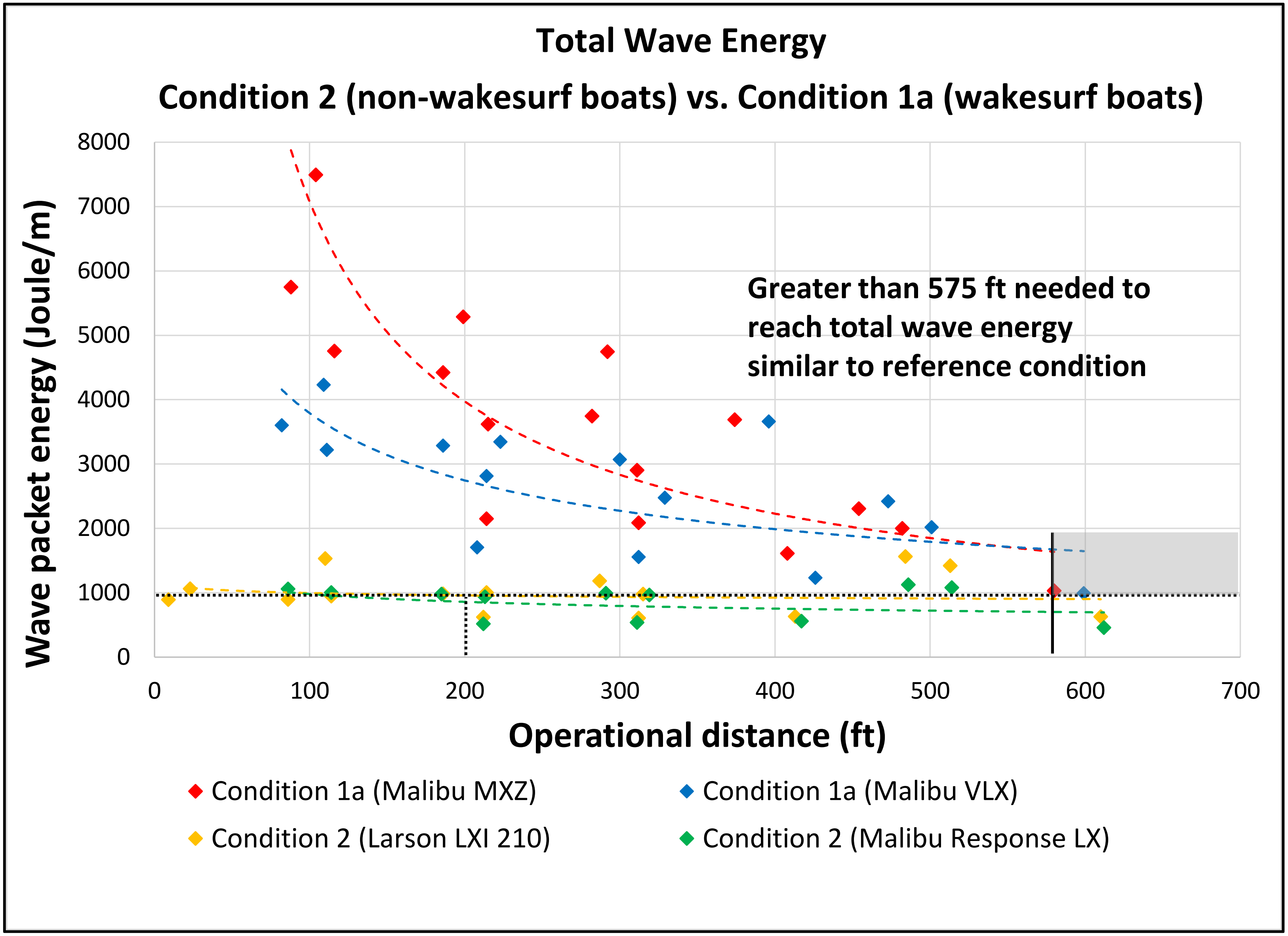


Figure 46. Illustration of a potential method for estimating the operational distance needed to reduce the total wave energy of the wakesurf boat to reference levels associated with Condition 2 (planing) of the non-wakesurf boats (black horizontal dashed line).

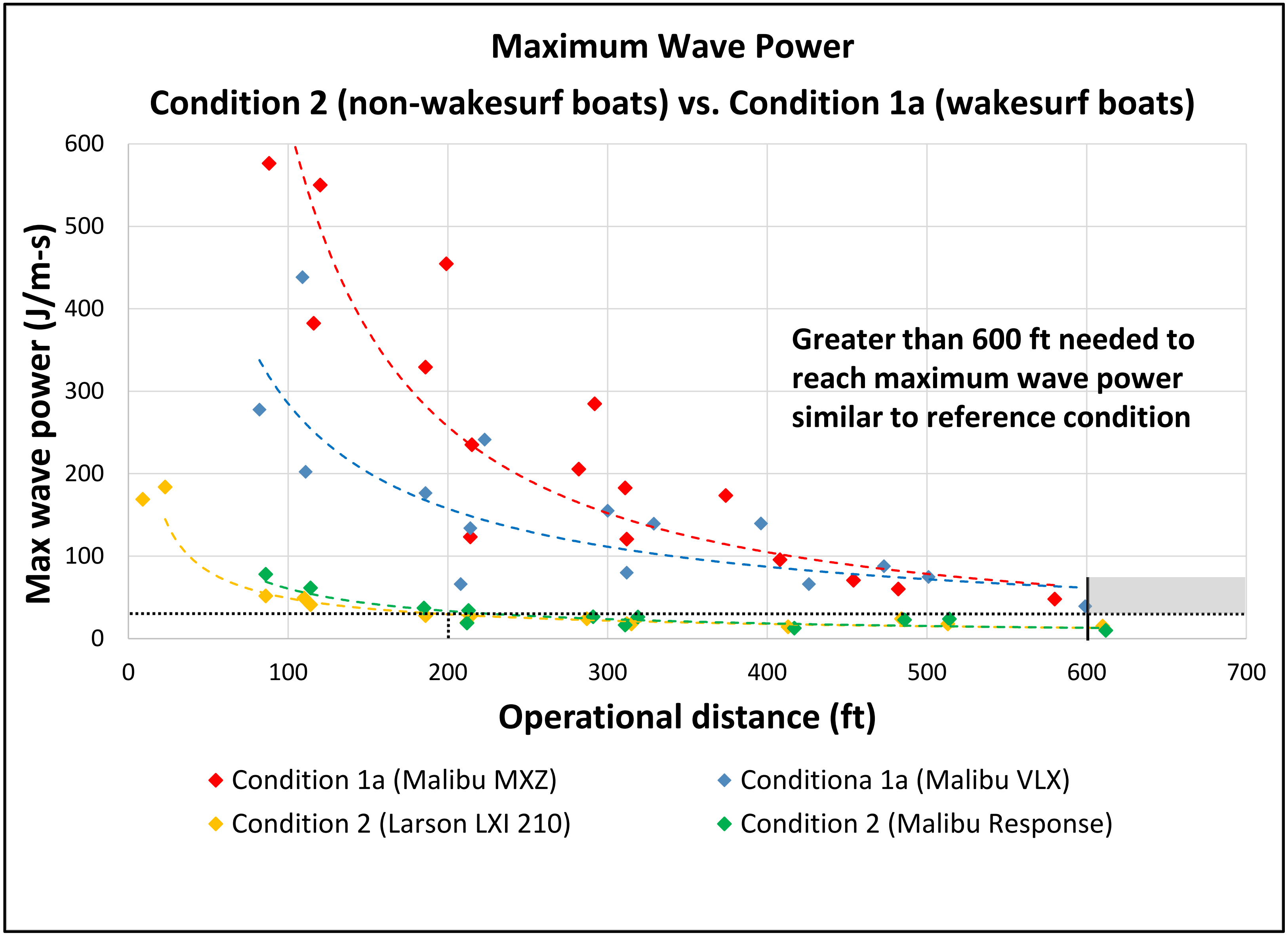


Figure 47. Illustration of a potential method for estimating the operational distance needed to reduce the maximum wave power of the wakesurf boat to reference levels associated with Condition 2 (planing) of the non-wakesurf boats (black horizontal dashed line).

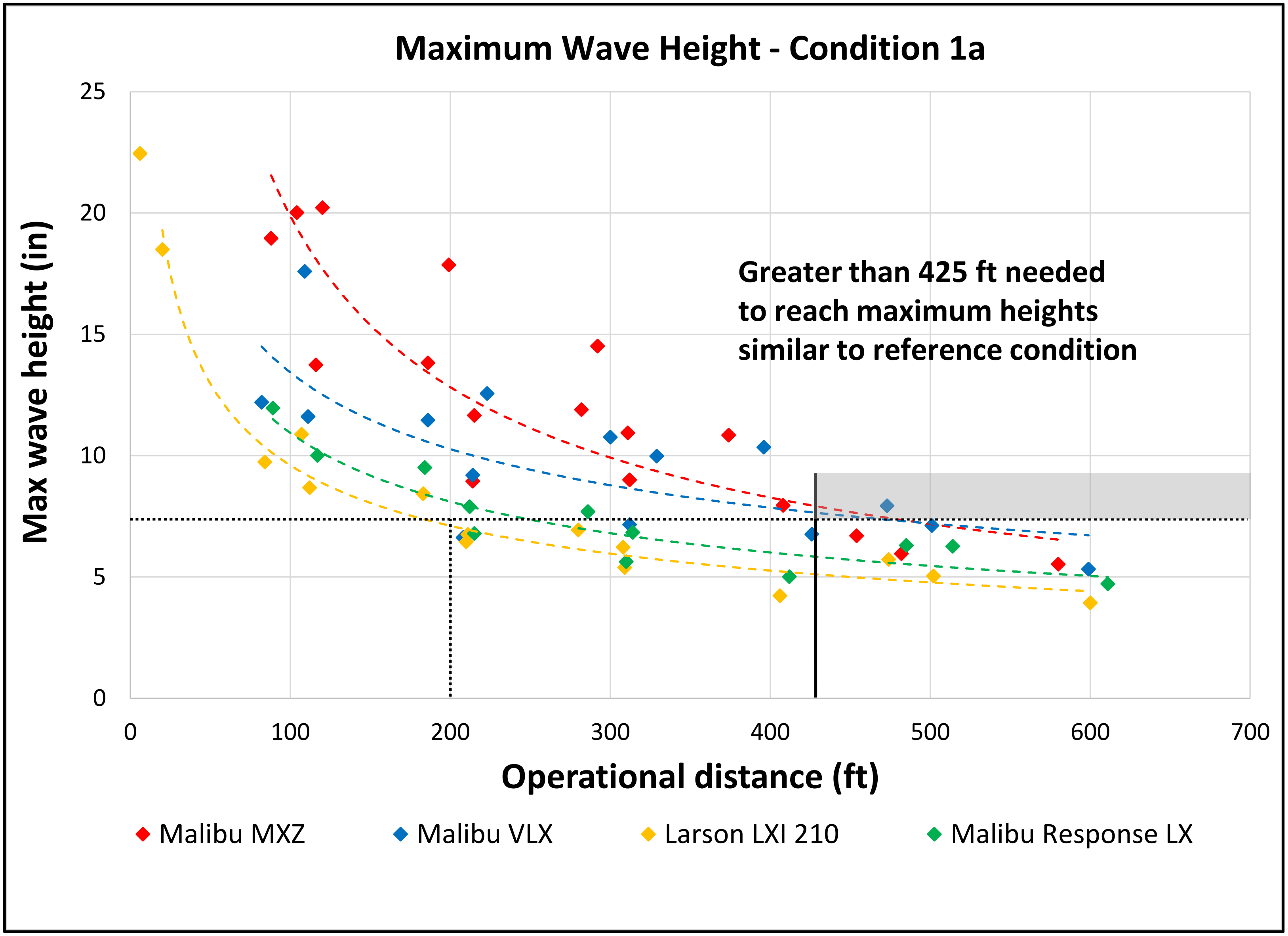


Figure 48. Illustration of a potential method for estimating the operational distance needed to reduce the maximum wave height of the wakesurf boat to reference levels associated with Condition 1a (largest wave) of the non-wakesurf boats (black horizontal dashed line).

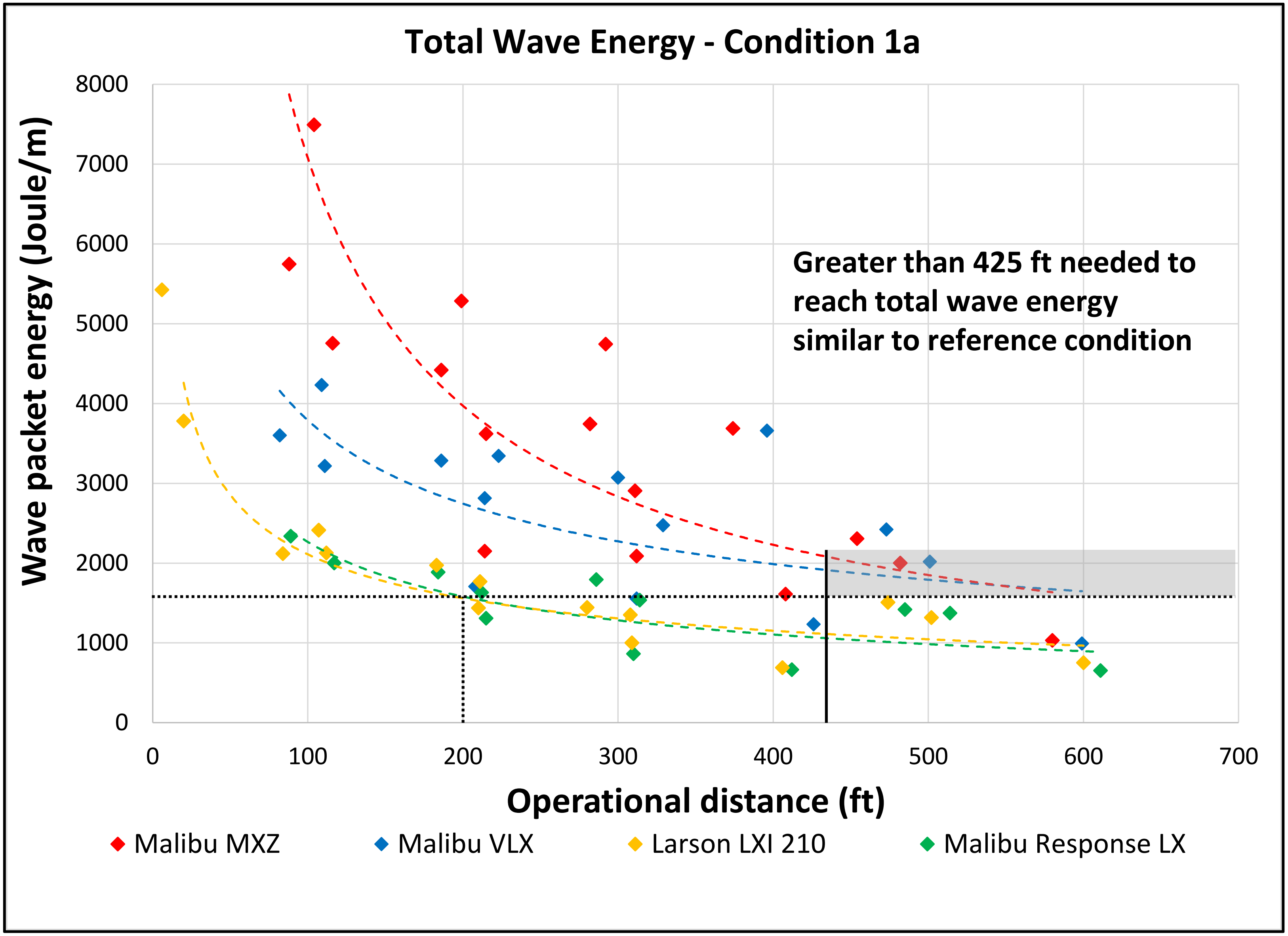


Figure 49. Illustration of a potential method for estimating the operational distance needed to reduce the total wave energy of the wakesurf boat to reference levels associated with Condition 1a (largest wave) of the non-wakesurf boats (black horizontal dashed line).

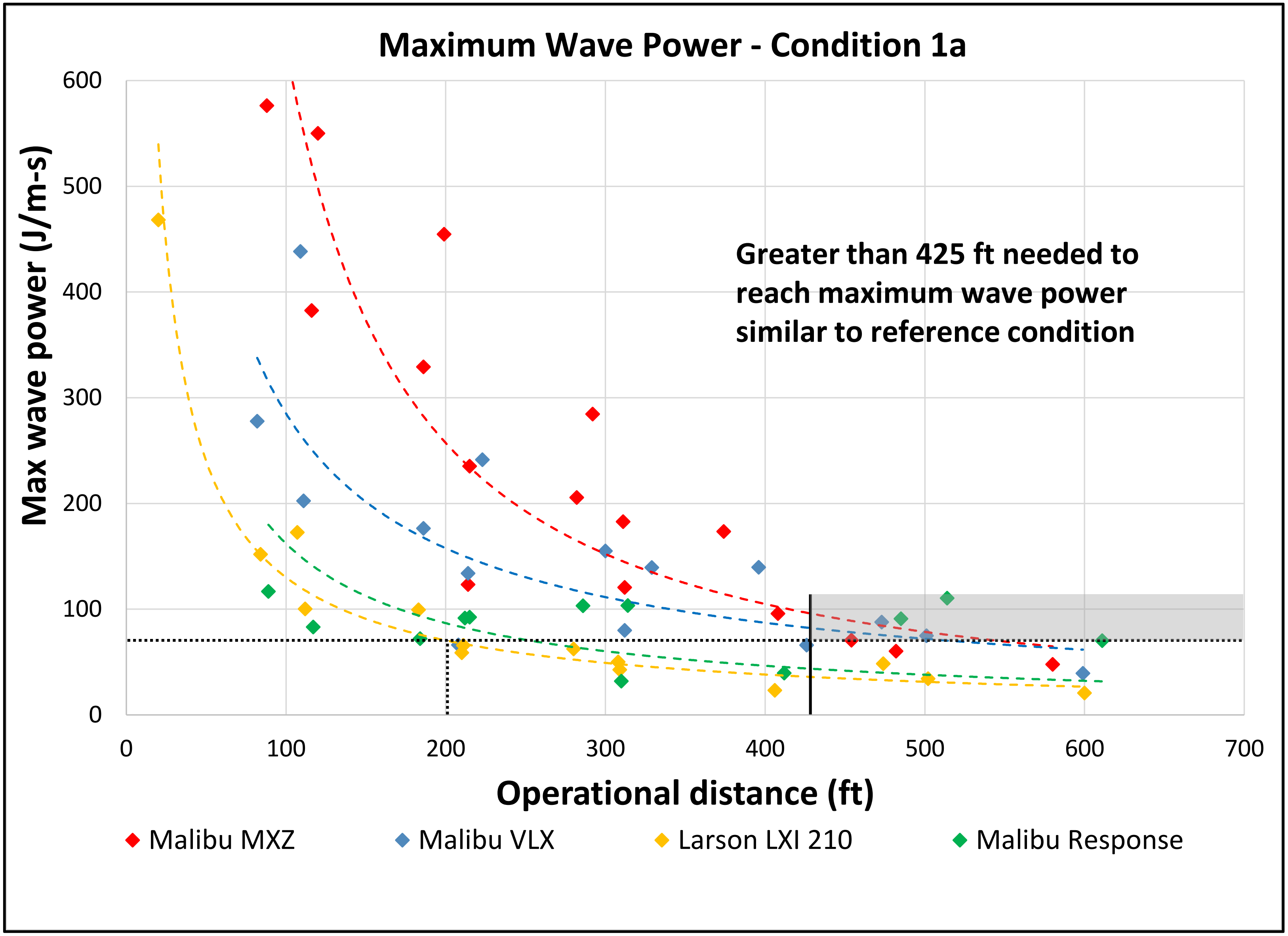


Figure 50. Illustration of a potential method for estimating the operational distance needed to reduce the maximum wave power of the wakesurf boat to reference levels associated with Condition 1a (largest wave) of the non-wakesurf boats (black horizontal dashed line).

Table 5. Summary of the estimated operational distances needed to attenuate the wake wave characteristics (height, energy, and power) of the wakesurf boats to the reference condition levels selected in examples 1 and 2.

Reference condition	Operational distance required by wakesurf boat to attenuate to reference condition levels
Example 1 non-wakesurf boat planing at an operational distance of 200 ft (Condition 2 - planing)	Maximum Wave Height: >500 ft. Total Wave Energy: >575 ft. Maximum Wave Power: >600 ft.
Example 2 non-wakesurf boat transition to planing at an operational distance of 200 ft (Condition 1a - largest wave)	Maximum Wave Height: >425 ft. Total Wave Energy: >425 ft. Maximum Wave Power: >425 ft.

6.1.6. Non-dimensionalization of operational conditions

It is common practice in the fields of fluid mechanics, naval architecture and other engineering disciplines to generalize the physics of a problem using dimensionless variables. For problems involving wake wave physics, the length Froude number (Equation 13) and depth Froude number (Equation 14) can be used. Transforming dimensional values like boat speed, boat length, and water depth into Froude number is a powerful tool for comparing the operational regime of different recreational and commercial vessels. The length Froude number can be used to describe whether the boat is displacing, transitioning to planing or planing. The depth Froude number is an indicator of the type of wake wave pattern that forms behind the boat. We recognize the power of dimensionless variables of the wake wave phenomena studied here, however because this report is focused on practical operational conditions and targets a general audience, we have chosen to present our results as dimensional values.

$$Fr_l = \frac{u}{\sqrt{gl}} \tag{13}$$

$$Fr_h = \frac{u}{\sqrt{gh}} \tag{14}$$

Where,

u = boat speed along the track line

g = gravitational acceleration coefficient

L = wetted length of the boat hull

h = the water depth under the boat.

6.2 Caveats, areas for improvement, and future research needs

6.2.1 Issues encountered with the Acoustic Doppler Current Profiler (ADCP)

The research involved deploying Nortek Signature 1000 ADCPs at Pad 1 and Pad 2. The instruments were used to capture wave height information and velocity profile information throughout the water column. The velocity profile data will be the focus of a second report that stems from this project. The ADCP is an acoustic device that uses the two-way travel time of short bursts of high frequency, narrow bandwidth sound to measure the velocity field and water surface elevation above the instruments. Some of our near-boat data were not usable because the boat passed too close to the sensor causing poor signal quality due to air entrainment and/or motor noise. For the Malibu Wakesetters, the wakesurf wave generated by the boat during these passes was also too steep for the sensor to capture the static water surface. In future tests, the boat should travel no closer than 20 ft (6.1 m) from the ADCP for water surface tracking measurements.

6.2.2 Boats and operational conditions tested

It is important to recognize that this study examined only four boats. We sought to pick watercraft that were representative of non-wakesurfing and wakesurfing boats; however, there are many other boat manufacturers and models that we were not able to study. Three of the test boats were from a single manufacturer (Malibu). The boat selection resulted from the boats that were available to us within the short window of field work for this study and the resulting research is not intended to represent a single manufacturer, but the operation conditions of recreational boats in general.

We also selected operational conditions that were representative of various tow sports for boats with different manufacturing characteristics (Section 3.6, Table 2), combined with the various wave manipulating technologies and settings; however, we recognize that the range of all possible operational conditions and data comparisons were larger than available time and resources.

6.2.3 Sample size of boat tracks

In this study, boats made passes along four track lines that were set at 225, 325, 425, and 625 ft from shore. In hindsight, adding a few more track lines at key distances would have increased the sample size, and thus narrowed the data variance (i.e., greater precision and less uncertainty). For example, few data points fell within the first 20-100 ft of operational distance where there was rapid attenuation of height, energy, and power. These near-field data are less important to informing boat operational distances, which will generally exceed 100 ft, but may be important for understanding processes of energy dissipation nearer the boat track. A similar data collection campaign within the first 100 ft where the wave heights, energy, and power are at their greatest would help to fill in these gaps.

6.2.4 Impacts of propeller wash on vertical mixing, sediment scour/suspension, and aquatic organisms

This project also involved collection of velocity and turbulence data associated with propeller wash from the four test boats. This data will be the subject of a future report. Boats of all sizes produce propeller wash and, at a certain depth the wash begins to interact with the thermocline, lake bottom, vegetation, and aquatic habitats. These complex interactions are not well-studied, and we believe this is a priority area for future research.

6.2.5 Linking wave height, energy and power to environmental impacts

This report only characterizes the wave height, energy, and power of a few recreational watercraft, and does not address potential environmental impacts such as shoreline/riparian erosion, water quality degradation, or alteration to aquatic habitats. Focus of future research will seek to understand the linkages between characteristics of boat-generated waves (e.g., wavelength, wave period, height, energy and power) and the nearshore environment. Future research will focus on: a) wave-induced sediment transport in the near-shore lake environment; b) interactions of wake waves with aquatic vegetation; c) impact of changing wave regimes on natural and armored shorelines. These topics are of great interest and concern to many stakeholders. For the benefit of finding solutions to the long-term protection and shared-used of recreational water resources, it is critical that researchers, funding agencies, and stakeholders prioritize coordinated, multi-year research in these areas.

6.2.6 Comparisons of boat wakes with wind waves for different lakes sizes

The sensitivity of a lake (or river) to boat wakes likely depends on the level of wind-wave energy that the lake experiences. For example, a small lake, with short fetches and relatively small wind-generated waves, is likely to be more sensitive to boat wakes than a large lake. Further work is needed, likely in the form of long-term monitoring, to compare the cumulative impacts of wind- and boat-generated waves on shoreline erosion, lake water quality, and nearshore habitat for different lake sizes, depths, and shoreline characteristics.

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7.0 CONCLUSIONS

This report summarizes the data and results of a field-based assessment of wake wave characteristics (maximum height, total energy and maximum power) produced by four recreational boats operated under a range of conditions and at various distance from data sensors. Two of the boats, Larson LXI 210 and Malibu Response LX, were representative of typical boats used on Minnesota inland lakes over the last several decades. Two of the boats, Malibu Wakesetter VLX and Malibu Wakesetter MXZ, were representative of state-of-the-art wakesurf boats.

The main conclusions of the research are summarized below:

The maximum wave height, total wave energy, and maximum wave power produced by the boats studied were substantially different between two operational conditions tested. For all the test boats studied, the maximum wave heights, total wave packet energy and maximum wave power were greatest under Condition 1a (wakesurfing/largest possible wake) operation. These same wake wave parameters were smallest for all test boats under Condition 2 (planing). Most notably, we document a substantial increase in maximum wave height, total energy, and maximum power between Condition 1a and 2 for the wakesurf boats. This finding is not a surprise, but confirms that the design of wakesurf boats (i.e., weight, hull shape, powertrain, and wake enhancement technologies) enables the creation of large wake waves under wakesurfing conditions.

When comparing the boats under their typical operational conditions, which was Condition 2 for the non-wakesurf boats and Condition 1a for the wakesurf boats, our data documents substantially larger maximum wave height, total wave energy, and maximum wave power for the wakesurf boats (Figures 42-44). At 100 ft of operational distance, the wakesurf boats measured maximum wave heights that were roughly 5-13 in higher than the non-wakesurf boats, an increase of 2-3 times. The total wave energy was 2,200-7,000 J/m higher (~3-9 times higher) for the wakesurf boats at 100 ft. The maximum wave power at 100 ft was also higher for the wakesurf boats by 230-570 J/m-s, a 6-12 fold increase.

Operating the Malibu Wakesetters with full ballast tanks (Condition 1a) appeared to have an observable but smaller than expected impact on maximum wave height, total wave energy and maximum wave power at operational distances less than 100 ft (Figures 31-36). At distances greater than 100 ft, the measured wake wave characteristic values did not seem to be affected by the addition of ballast water. These results were unexpected as we anticipated that the additional ballast water weight and resulting water displacement during travel would generate higher waves with greater total energy; however, this observation was similar for both boats. Clearly, the role of ballast water weight on asymmetric wake wave characteristics is an area where more research is needed.

The aftermarket wake shaper had an observable impact on the wake wave characteristics of the Malibu Response LX, resulting in increased maximum wave height, total wave energy, and maximum wave power (Figure 37-39). With the wake shaper attached and at an operational distance of 200 ft, the data show an approximate increase in maximum wave height of 2 in (33%), total wave energy of 270 J/m (20%), and maximum wave power of 30 J/m-s (20%).

We demonstrate how data collected in this study can be used to inform operational distance for wakesurf boats/wakesufing based on reference conditions derived from non-wakesurf boats. In the first example provided (Figures 45-47) the boats were compared under their typical operational conditions, which was Condition 2 (planing) for the non-wakesurf boats and Condition 1a (wakesurfing) for the wakesurf boats. In this scenario, operational distances greater than 500 ft were needed to attenuate the measured wake wave characteristics of the wakesurf boats to levels equivalent to the non-wakesurf boats at 200 ft (Table 5). In the second example (Figures 48-50), the boats were all compared under Condition 1a (i.e., largest possible wake/wakesurfing). Here, operational distances greater than 425 ft were needed to decrease wave height, energy, and power of the wakesurf boats to levels similar to the non-wakesurf boats at operational distances of 200 ft.

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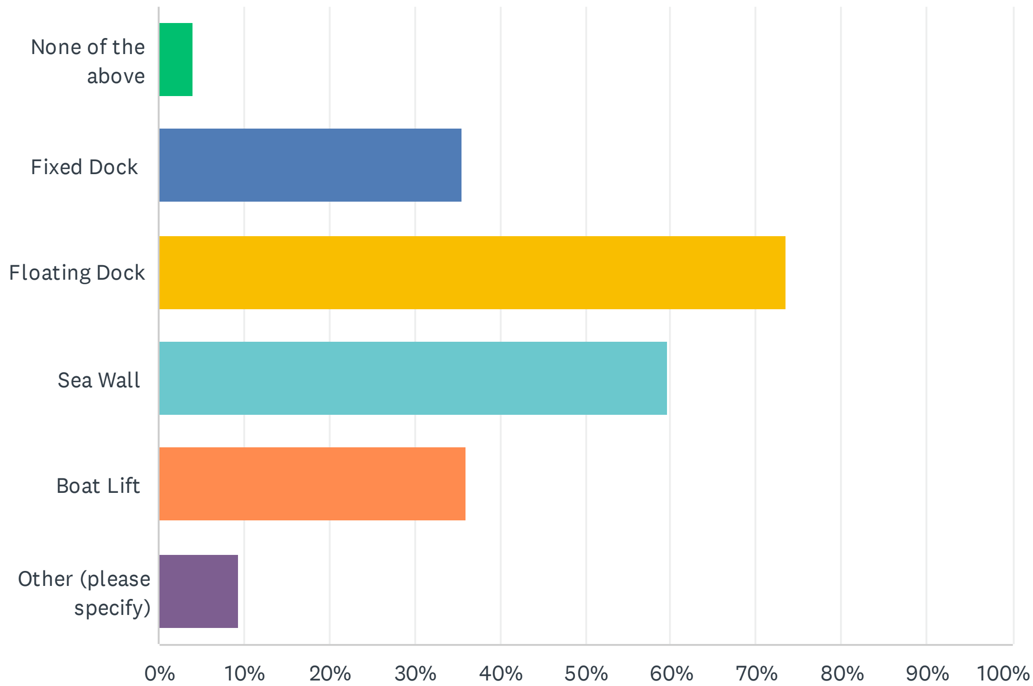
LWPOA Wakesurf Survey Data

Q1 Does your property include a dock, boat lift or sea wall? Please check all that apply.

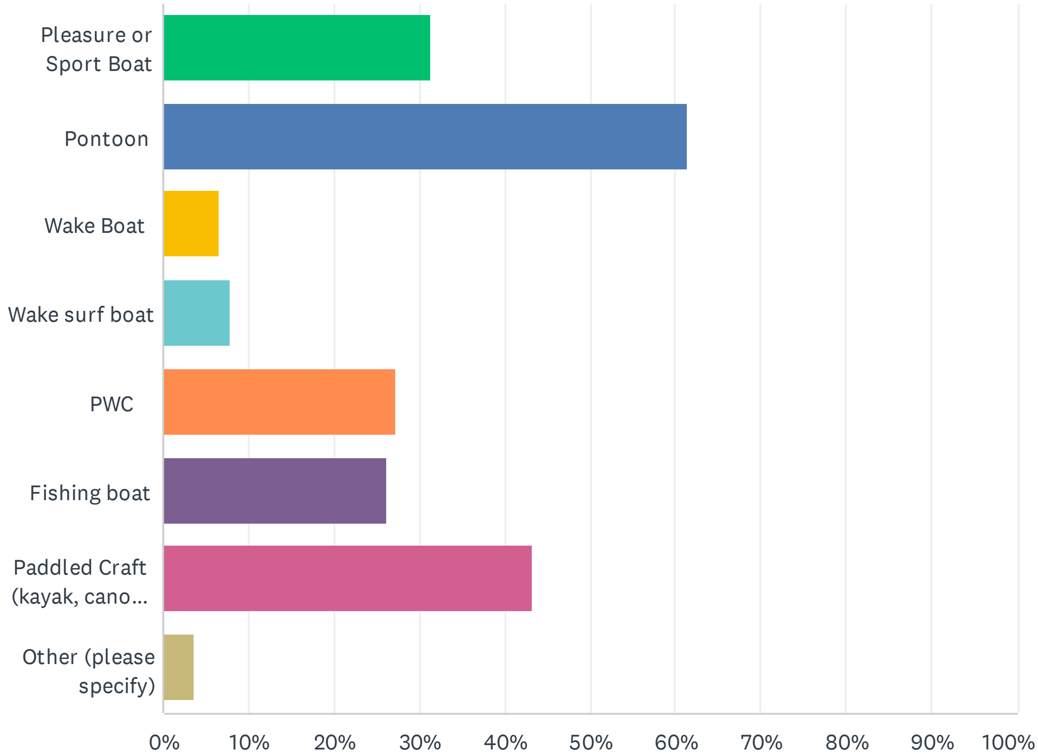
Answered: 363 Skipped: 0



ANSWER CHOICES	RESPONSES	
None of the above	4.13%	15
Fixed Dock	35.54%	129
Floating Dock	73.55%	267
Sea Wall	59.78%	217
Boat Lift	36.09%	131
Other (please specify)	9.37%	34
Total Respondents: 363		

Q2 Do you own a boat? If so please describe, select all applicable.

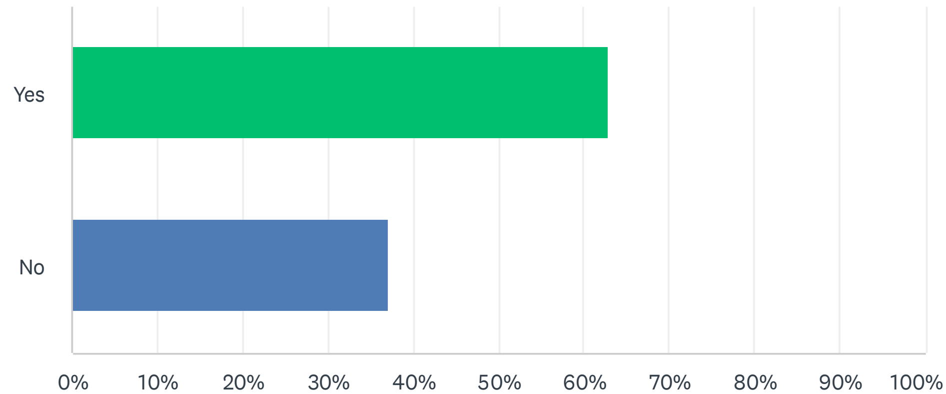
Answered: 363 Skipped: 0



ANSWER CHOICES	RESPONSES	
Pleasure or Sport Boat	31.40%	114
Pontoon	61.43%	223
Wake Boat	6.61%	24
Wake surf boat	7.99%	29
PWC	27.27%	99
Fishing boat	26.17%	95
Paddled Craft (kayak, canoe, paddle board, row boat)	43.25%	157
Other (please specify)	3.58%	13
Total Respondents: 363		

Q3 Have you experienced damage to your property as a result of boat wakes? If so, please describe.

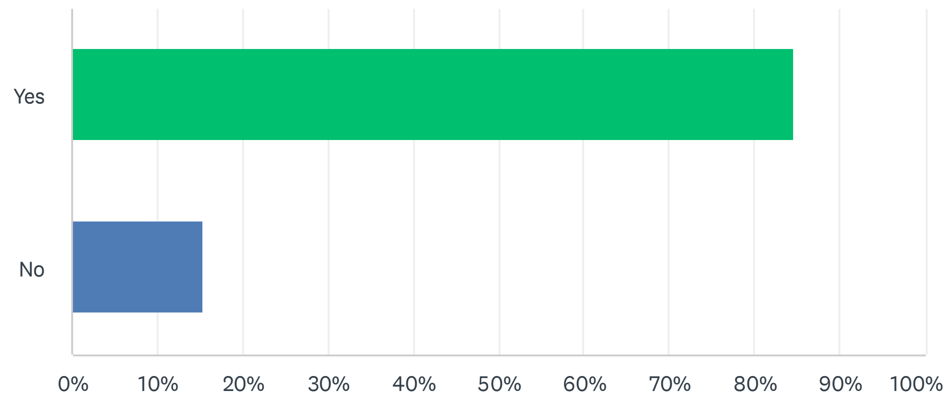
Answered: 363 Skipped: 0



ANSWER CHOICES	RESPONSES	
Yes	62.81%	228
No	37.19%	135
TOTAL		363

Q4 Do you feel wakes from wake surfing craft create a safety hazard?

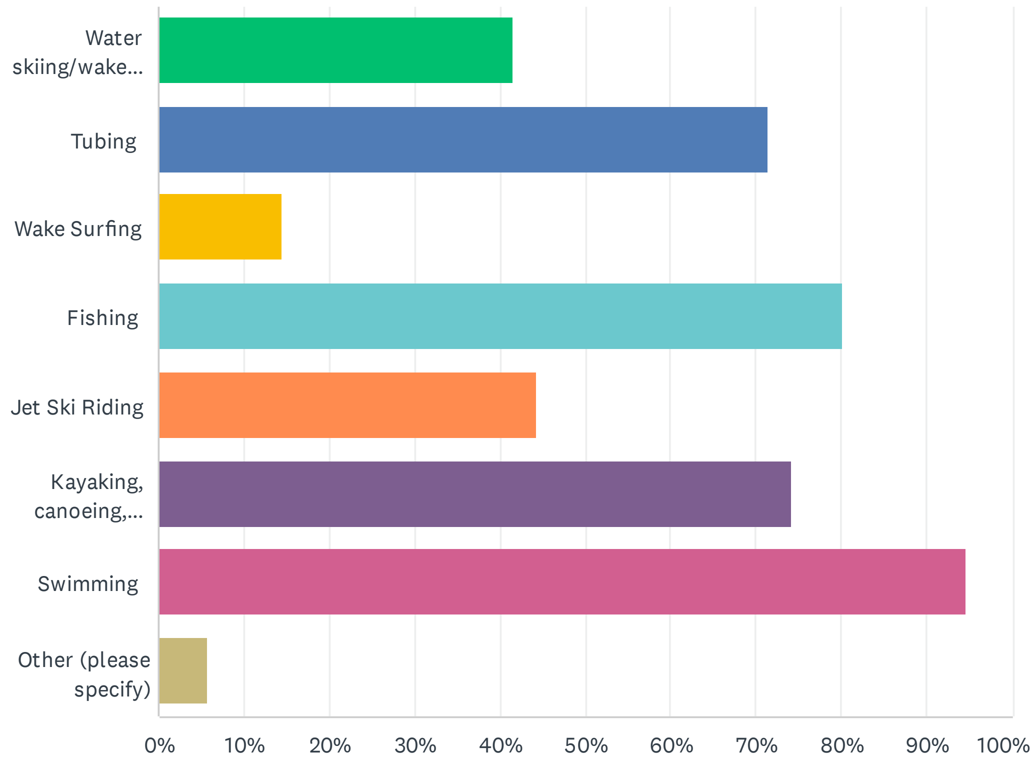
Answered: 363 Skipped: 0



ANSWER CHOICES	RESPONSES	
Yes	84.57%	307
No	15.43%	56
TOTAL		363

Q5 Do you or members of your family participate in any of the activities listed below?

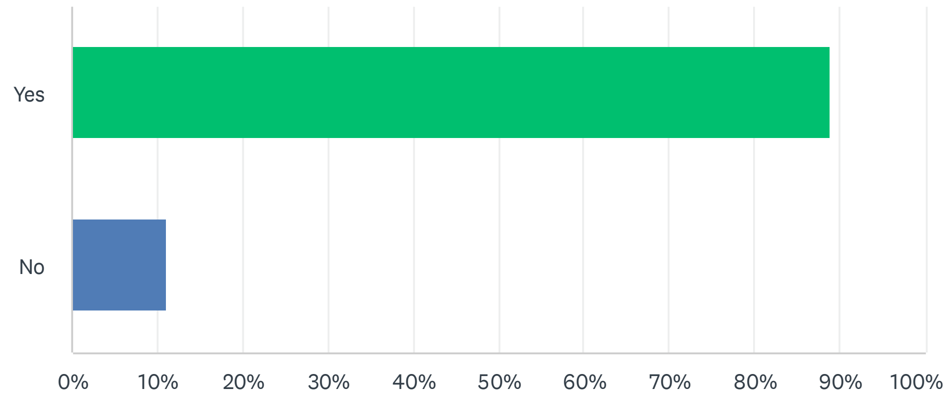
Answered: 363 Skipped: 0



ANSWER CHOICES	RESPONSES	
Water skiing/wake boarding	41.60%	151
Tubing	71.35%	259
Wake Surfing	14.60%	53
Fishing	80.17%	291
Jet Ski Riding	44.35%	161
Kayaking, canoeing, paddle boarding	74.10%	269
Swimming	94.77%	344
Other (please specify)	5.79%	21
Total Respondents: 363		

Q6 Would you support legislation that would regulate wake surfing on Alabama lakes?

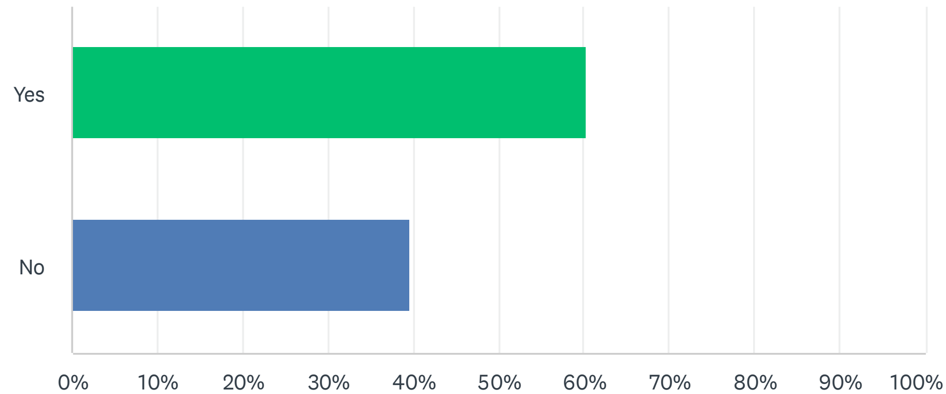
Answered: 363 Skipped: 0



ANSWER CHOICES	RESPONSES	
Yes	88.98%	323
No	11.02%	40
TOTAL		363

Q7 Are you currently a member of Lake Wedowee Property Owners Association?

Answered: 361 Skipped: 2



ANSWER CHOICES	RESPONSES	
Yes	60.39%	218
No	39.61%	143
TOTAL		361

Q8 Please provide contact information

Answered: 363 Skipped: 0

ANSWER CHOICES	RESPONSES	
Name	100.00%	363
Company	0.00%	0
Address	0.00%	0
Address 2	0.00%	0
City/Town	100.00%	363
State/Province	100.00%	363
ZIP/Postal Code	100.00%	363
Country	0.00%	0
Email Address	100.00%	363
Phone Number	0.00%	0

Description of Property Damage

shore line erosion
Broken hinge points on dock   Broken cables on dock
The floats supporting the dock have shifted and tore the anchor points away from the floats. The walkway had to be reinforced at the anchor point of the bulkhead.
One section of our dock split in two. This was due to high lake activity.
Our dock has sustained damage to supports for the roof, which have cost us nearly $1000 to repair over the last year or so.
impacted shore line
Hinges and cables have come loose
A wake boat was traveling so fast it lifted our tritoon boat onto the stationary dock damaging the boat and dock.
Minimal wash out under my boat ramp and seawall
Tension and pressure to boarding. Excessive wake always sloshing on deck boarding.
Hardware connecting the floating dock to the fixed dock was ripped loose and had to be replaced.
Dock needed to be repaired 3 times in the past 3 years due to significant wave damage
Boat dock has had to be repaired several times.
Severe dock damage and boat damage
Absolutely- in fact just this week had dock repairs due to wake damage for the third time. Over $4,000 total.
Walkway was sheared from the dock. Lift was damaged twice
Top blocks get knocked off of seawall every summer. Boat dock is constantly in need of repair. We will easily get 3’-4’ waves lifting and dropping our dock and beating the seawall.
Shredded the welds from our dock and made our sea wall fall in. Caused us to get a new dock and new wall.
Washing along sea wall
Sea wall erosion.   Floating dock requiring structural repairs.   Erosion around and under dock supports.
outside 2x10 on dock broke in half had to repair. had to add support to walk way. bank is washing away.
Our dock was broken due to the extreme waves that occur from the wake boats being so close
Dock and pontoon damage

Broken support braces and cables
Many, many boats drive within feet of our dock. All kinds of boats: pontoons, bass fishing boats, ski boats, come within 25 ft or closer to our dock. Some pontoon boats create as much problems as any boat. It's not the type of boat as much as the way people drive it.
Loosening of the floats
But only because I live in a cove.
Boat crashes into floating dock when in slip when large wakes are made. Sea wall has deteriorated significantly in last few years.
1) Floating dock braces (2) were broken away from dock on one weekend. Wake board waves caused this damage. 2) Pontoon boat was damage when in covered dock. Damage was caused by wa in e board waves.
To my dock
Shore erosion on shoreline not covered by sea wall Jet ski ports pulled loose
We have a steel dock and the gang way to dock, broke off due to the waves from wake boats.
Dock damage, big dent on front of pontoon from wakeboard wave in narrow part of little river.
Loosening of dock boards, erosion of natural shoreline. However, it's hard to pinpoint id it is directly related to wake surfing boats or other boat wakes with people coming to close to docks.
It has broken our additional safety precautions we have taken to secure our floating dock because of all the wake boarding traffic. We are near mile marker 13.
This year, one of our boat lift rag bolts was ripped out of the dock with the boat in it. Last year we had to install / insert metal plate between the gang plate & dock to manage the friction caused by the wakes. We added two stabilizing wires within the last 3 years between gang plank & dock. And we lose almost all of our pine straw around our sea wall from wake water coming up over the wall. Lastly we have replaced the float & stabilizers for our lily pad every year.
Shoreline erosion, damage to our boat due to it hitting hitting our dock with large wakes.
Not yet!
Sea wall is deteriorating much faster
Broke anchor cables to floating dock. Damage to sea wall from wave action. Broke boat tie off cleats from floating dock when a boat was secured. Family members from young to old, have lost balance and nearly thrown off dock from extreme wave action. Have to grab hold of something and hang on for dear life.

Boards and supports on dock have broken loose and had to be replaced. Bolts and screws become loose and have to be tightened or replaced. We live on Wedowee Creek and boats pull tubes in a circle coming dangerously close to our dock while creating a huge wake making it impossible to enjoy swimming, etc. We've owned our property for 10 years and it gets worse each year. Many boaters don't follow safe boating laws and have no respect for the property owner.
Excessive boat traffic
Bank erosion so we built seawall, pontoon ties ripped from dock tie.
Shoreline erosion, to include lost trees.
Not sure...Live in a cove but I get some great waves from time to time....More so on Jet sking
Lift separated from dock.   Dock teathers damaged.
Damaged boat, falling rip rap, and the waves made on small areas such as Wedowee Creek are dangerous because the waves are so big they can rock other boats to the point of taking on water.
People come flying in cove too fast! They don't know the rules! When wake boats come by our cove we always have bad wakes!
Broken catwalks from waves.
In the Fourth of July Boat Parade, wake boats caused a psunami that almost sunk our pontoon! A pontoon in front of us had the same experience. Our boat was flooded and we were terrified. We will Never again participate in a Wedowee Boat Parade. It is not safe... because of wake boats. We also do not feel safe in our canoe for the same reason.
The big waves made by these wake boats are causing erosion on our sea wall and also is causing our floating dock to rock so much it is causing damage to it. Let me add it is the BOATS that causes this not the person wake surfing. These boats need to be banned from our lake.
Dock flotation ripped out from under dock… bent dock ramp… PWC port ripped off dock bracket

Boat damage, floaters bolts come loose,
Dock issues. Due to Large wakes in area to narrow for wake boats.
Damage to both docks and seawall.
The waves are so large it caused our pontoon to be damaged against our dock
Erosion
I'm by Foster's Bridge
Waves are so rough my PWC dock has been damaged as well as my sea wall. It has cost thousands of dollars. I have been on the lake since 1989 and the change to the shoreline has been dramatic since wakeboats became popular.
Had to help neighbor reinforce boards on Seawall. We have rip rap & have to re-stack it every year.
Not a property owner
Shore deterioration. Lost the property the dock was attached to. Had to redo half the dock to fix the issue.
My boat dock sea wall and PWC are getting beat up with the wakes
Had to build my seawall one block higher to stop Erosion.
Bass boat damaged from bouncing on the dock chipped fiberglass in front. Pontoon broke ropes while we were out of town damaged the cowling on the motor.
Boat lift damage on our floating dock. Sea Wall failure.
Wake damage to shoreline
Pieces of dock coming loose
Damage to tie out poles holding boats to dock. Also creating standing water behind sea wall. Washing out gravel behind sea wall.
Damage to floating dock and erosion of shoreline under and around docks. Boat gets beat up due to large wake.
Erosion and also unable to sit on our dock.
We have had extensive damage to our floating and stationary dock, as well as our shoreline. We have 2 plus feet of undermining on the shore. There are several large trees whose roots have such exposure that we expect them to fall at any time. Our boats have been damaged also. Our dock is 30 yards or more in a slough off of Wedowee Creek if it causes this much damage here I really feel sorry for those property owners on the creek. We have filed for a repair permit and will not be able to enjoy our dock as we will be working to repair it.

Because of the waves and wake from these types of boats : had to have my dock completely rebuilt.
We thought our 24’ pontoon was going to sink because of a wake boat. Two wake boats were going in big circles & caused an ocean like wave to come completely over our entire boat. I couldn’t see anything in front of me until after I was slammed by what we describe as an “ocean wave”. We we a good distance from the wake boats but we were still caught up in their waves.
Because of the excessive rocking from the large wakes, the roof supports on my dock are unstable. Also, some of my dock floats have worked loose and I constantly have to put them back under my dock. The rip rap in front of my sea wall has washed away, undermining the safety of the steps into the water.
The sole reason we sold our lake house. We had damage to our dock, boats, and sea wall.
Soil erosion on bank
Loosened and broke mounting bolts.
Hit a big wave with pontoon and the water pushed in the outside of our boat.
Dock starting to come apart from large wakes.
We have lost over a foot of our property due to to the wake from boats. It is a constant problem!! The wake board boats create too much erosion and are a huge safety hazard!!
We replenished the rip rap summer of 2019. When you own property on a lake there is going to be damage and erosion from waves regardless of how the waves are produced. I understand what is being reported; however, what next? It appears to me that a jet ski produces a huge wake. The larger pontoons produce a huge wake. Since I have become aware of this issue, I am paying attention to wakes being produced. I own a point lot. I get waves. I expect to get waves. When lots of water craft are on the lake at the same time, there are enormous wakes. I am bitterly opposed to restricting wake boats!
Supports on dock were broken and had to be replaced. These boats come very close to our Dock and make big waves making it Hazardous to swim. We live on Wedowee Creek and these boats also pull tubes and go around and around coming dangerously close to the docks. It is worse this year than we have experienced in the 10 years we have owned our property.
Not yet but only been there a short period of time
Required to install a fixed dock because the wave action was making it impossible to use our floating dock to dock our boats. Now constantly adjusting the fixed dock to be able to dock boats without damage to them. And you cannot dock if a wake boat has come by because of the waves.
Not damage but aggravation from the huge waves. We have to keep furniture tied down. Lately the wakes are going over the sea wall and the jet ski that is on a pad has to stay tied also because the wakes would wash it off of the pad. Going out for a joy ride is not an option if you see wake boats out. Also tubing small kids is not an option if wake boats are out.

I have a PWC (jet ski) that was damaged while someone was attempting to park the jet ski next to the dock. The wave (wake) from the surfing boat caused the PWC to impack the dock causing fiberglass damage. I have also had to replace many broken bolts on my boat lift. Before we had surfing boats in our area we did not have this issue. We continually see surfing boats with active surfers drive as close as 30 ft. to our dock. I am in the Wedowee Creek area and we believe that active surfers should only be allowed in the main channel of the lake.
Damage to dock and sea wall. Damage to boat bouncing off my dock.
Damage to dock supporting structure.
We have plenty of open areas with no homes or docks- we always go to those areas for surfing. Courtesy is what people need to show
Damage to shoreline and sea wall.
Erosion predicated installation of sea wall. I am at the end of a cove that connects to river.
Excessive shoreline erosion from larger than normal waves
Sea wall as well as damage to boat and jet skis from rocking from waves against dock
We are on the other end of lake, so no damage. However, wake surfing will sink it at least bring water onto my boat. I have been here 5+ years. I do not go out on weekends! I can't take a chance.
Bent the metal frame work connecting walkway to dock.
The metal frame of my dock is cracking several places from the excessive flex of surf boats. The waves they put out are larger than my storm waves I have seen in my 16 years on wedowee.
The waves also go over our sea wall and have eroded around the edges of our sea wall. Our neighbors have had parts of their docks snap due to wake boats.
The wake action from specifically wake boards boats due to 3and 1/2 waves have crumbled my cement bulkhead and snapped the roller pins on gangway. My gangway is now slamming down on my 5th wheel metal plate and is bent. My safety was compromised as I could not get off the dock fast enough and the wake knocked me down injured my ankle. I can not even sit on my dock anymore during wake boats passing through due to waves coming in and then rebound from the sea wall. Worried about new cement block seawall being compromised. My neighbors sea wall has totally torn down due to wake action.
Sea wall damage twice and dock fifth wheel damage anchor cables pulling a lot of stress on anchor post
Violent waves and dock appears to be splitting

The size of the waves constantly hitting our dock created problems with our post and we had to install reinforcements for our JetSki Port
Stationary dock steps boards
Wakes frequently cause the moored pontoon to violently rub against the dock bumpers…resulting in a tearing and sometimes completely ripping the bumpers off the dock.
Our dock is continuously rocked. Our lift unexpectedly failed and our boat and dock sustained significant damage from all the waves when boat was not on lift. The giant waves also make the dock not enjoyable to use and difficult for our children to enjoy swimming.
Dock stairs have been damaged and a lot of shore erosion .
Sea wall almost obliverated.
Damage to the toons from beating the dock
Piers and land and boats are being destroyed by the wakes
our bank is eroding
Gang way came off the pad. Not from wake boats but from boat traffic wake in general.
Shoreline erosion requiring seawall installation. The wake from these boats goes over the wall and causes the dock to rock to the point that it is unsafe to be on. It is impossible to get the boat safely back on the lift when wake boats are running back and forth.
Wooden, covered floating dock has racked.
Securing cable pulled loose
Erosion of areas without rip rap. Deterioration of connections on dock.
I had my pontoon boat moored with mooring whips correctly tied up. During a busy weekend, several wake boats came by and caused the mooring whips to get forced under the Bimini top supports. The front on my pontoon boat then crashed into the boardwalk breaking the left corner off. It also cut the boat cover here the mooring whip rubbed the pontoon boat side rails. It was a very expensive repair.
Screws and bolts have come loose due to the severe rocking when boats come too close. On Memorial Day Saturday we had to get a dock company come and replace a bolt because our pontoon was coming down off the lift and leaning severely to one side.
Shoreline erosion and dock damage.
Wakes caused dock ramp to come loose. Had to repair anchor holding ramp and also ramp.
massive waves smashing boats against dock dock and sea wall being washed out lots of debris floating from big waves smashing shore cant even enjoy floating in the lake without giant waves knocking us around
Boat and Dock damage when boat was pushed up against dock.
Torn boards off boat slips. Boat damage due to excess wake.
Water damage to dock as waves roll over the dock.

NOTE: We have had to contact a welder several times to reinforce the walk way to our dock due to so much wake. It may not be necessarily from wake surfing but from so much wake from people coming so close to our dock.
Wave action snapped rope that was used to secure boat in slip. Boat swamped once by large wave while fishing. There was enough water to float gas tank.
Soil erosion
Ramp brackets coming loose from boathouse due to strong waves, rocks from sea wall washing down
Wear and tear on docks and damage to boats being bounced around due to large wake.
Dents and scratches to my boat from the dock when wake waves hits. I cannot use my dock on the weekends.
damaged lift components, sheared bolts on dock
The constant high waves caused the dock hinges to come loose and our dock ended up separating from the gang plank with our pontoon attached to it.
We have lived on the lake for 24 years. In the last ten years, we have experienced a lot of dock damage...about $9,000. Our solid dock which is connected to our floating dock has been completely knocked down twice, the ramp ripped away once. We had to replace our boat lift, which we had for 20 years, because the waves had gotten so large they kept snapping the lifting cables. Now the surfing boats have gotten deeper and heavier. Just two weeks ago I watched one of these new boats go by and the wave ripped my neighbors jet ski dock away from his floating dock.
We are new homeowners. This is our first summer at the lake. We have not had enough time to assess, however, we have noticed how much wake results from wake surfing.
A few broken ropes that tie the boat to the dock.
We are between 431 and old 431 bridges. It is use for beginners but rocks dock and lift out of sight to narrow
Water over sea wall causing erosion.
floating boat dock gang planks have fallen from excessive waves from wake boats 2 times this year. $3,000 in damage repairs
Broken steel cables on floating dock. Trash washed up on property every weekend. Waves hit 4+ feet past rip rap.
Sea wall erosion
Damage to my seawall. It is PT wood, mostly 2x8s. The huge waves knock the boards loose, and in the fall I have to repair the wall.
Dock pivot pins broken. Boat slamming into the slip walls
The boats slamming around in the dock from the waves are beating them up! We are not on wide water and one wake boat runs by about 4 feet from our seawall. Also when the grandchildren are swimming in the lake near the dock the waves are very dangerous.
Deep erosion that required a new seawall $50,000.00
Sea wall damage

Two years ago added 25 tons of rip-rap to help protect sea wall. After the past two years & popularity of these style boats creating 3-4’ waves on my narrow water way it causes the waves to crash up & over my sea wall, during this past memorial holiday I had to place straps & bracing on sea wall to secure it hoping to keep it standing until the water recedes in October for repair. I also had to remove PWC from the dock due to these waves washing them off their ports.
Damage to the lift
On the Memorial Day holiday in 2020 our previous home in Creek Crossing sustained damage to our walkway (sheared steel bolt loose) which caused the walkway to sag beneath the dock. On the 4th of July weekend our lift was damaged by the sideway torch from the waves and caused a stabilization rod to lodge underneath/between the joists of the dock and the lift could not raise or lower. We repaired the dock on both occasions. We sold that home in 2020and moved to Ginhouse cove which is much better. We are now able to let our grandkids and friends kids to float, paddle board, and kayak without worrying about the waves and our dock has not been damaged by the waves created.
Dock cable broke
But..if the wake boats are moved to larger parts of lake- the probability of issues occurring are high. The problem would just be moving places on the lake.
Mountain Laurel and small trees have been washed into the lake from the force of the waves from these boats crashing against the rock facing.
We have had damage to our dock several times that has required repairs. We have steel cables to attaches our floating dock to the shore, and these steel cables have been broken. We also have had damage to our boat while it was docked at our floating dock due to the wake created from other boats.
Had to install a seawall because of big waves causing erosion on our shore line. These waves also do damage to our dock.
Dock damage. Have an older floating dock and the wakes have caused the hinges between the gangway and dock to wear and loosen. Plan to replace it soon.
The wakes from these boats are much stronger. And even though we are in a cove the waves coming in from the main channel are more powerful. It is hard on floating docks and our rip rap.
Erosion behind sea wall from large wakes and undercutting under the boat ramp
Water splashing over the seawall has eroded the rocks and left holes of dirt
Retaining wall broke in center, and has been scoured behind by excessively large waves in the middle and one end. I've reinforced the wall and raised it six inches. The damage is absolutely caused by the giant wakeboard waves. I sat in my dock and watched a part of it year out when not by oversized waves. Bank erosion has accelerated since wake boats became common.
Waves are coming up & over our Seawall & eroding the backside of our Seawall and also causing blocks to dislodge out of place.
Not yet but planning on replacing the older floating dock with a fixed dock. The floating dock takes a beating during the summer months due to big wake boats and wake surfing.

3 of 4 bolts holding braces to the floating dock were broken off by heavy wave rocking leaving one brace sunk in the lake. Soil is eroding between joints in the artificial logs of the seawall at a rate never seen before. Loss is caused by heavy waves against the seawall
Starting to see some erosion but not serious at this time. The large wakes are beginning to take a toll on our boat dock with cover. We are making additional bracing for the roofline to the post holding it up.
Had to change to a fixed dock as the waves would just about knock us off of our dock. Pontoon boat, not on lift, was damaged from rough waves (hitting against the dock).
Broke cables floats come in bolted on dock and float out so rough can't enjoy your property
Our jet ski port has been rocked so hard that the metal bracket attaching it to the dock actually broke. In addition, our seawall has been compromised due to the high wakes from the wake boats going over the wall!
Shore erosion. Damaged jet ski due to wake. Dock pulled from bank due to wake.
Dirt behind sea wall leaching out from water coming over sea wall.
Sea wall failure in one part
Extensive damage to the shoreline and minor damage to the dock. Unintelligent drivers ride far to close to the docks and it is a massive safety hazard as we use our spot for mainly leisure and floating activities
Bumpers & cleats damaged/broken due to wave boat waves. Wave boats, and other boats come too close and too fast by our dock requiring us to hold on tight to stay on.
I have a floating dock that goes up and down while connected to three post. In the past, I had no problems, but since the larger boats and esp the wake boats have been used on the lake, my dock and seawall takes a severe beating. I have added sleeves to the dock pole frame to reduce the turmoil created by the big waves. I have a walkway that pivots from the permanent dock structure and moves up and down as the lake water level changes. Now this walkway want to walk side ways and I have had to add additional blocks to stop that movement. My crosstie seawall is 20 years old and I have had to add another course of crossties on one side to keep water from washing out that side. I totally agree that limits should be placed on this lake for the bigger size boats and esp the wake boats. Anytime a wake boat goes by, I have water splashing over half of my seawall. I appreciate your interest in this matter and I woould be happy to assists. My family likes to kayak and paddle board and I hesitate to let them because of the big waves.
I am in the back of a cove facing directly to the river. My dock is not damaged, however, it suffers a continuous pounding from wave action during busy periods on the lake. I am not able to leave my 20' boat attached to the dock on weekends or holidays despite using "wake defender" spring arm boat stabilizers as the wave action slams the stern into the dock.
Erosion on shoreline where property meets sea wall. Have to continually fill in with sand
Damage to dock and wall, had to reinforce with riprap. We live on a cove off a finger and are at the very end of the cove. Waves overlapping the sea wall is common when wake boats enter the narrow finger area
A wake boat passed our boat and we were nearrly swamped when wake overtopped the gunwhale of our 22 ft bowrider. We were at idle speed.
Dock damage

1. The connections at the dock end of my ramp from shore to dock have come loose from excessive boat wake. The dock end of the ramp became entirely disconnected and fell, requiring repair by a local dock company. 2. Additionally, the heaving of the boat lift inside my heaving dock housing has destroyed the light on the top of my boat's canvas by smashing it into the underside of the structure overhead. 3. We also had a cable (that connects the dock to an anchor pin on shore) becoming broken by excessive boat wake, thus also requiring replacement by a local dock company. We are located on the main channel of the Little Tallapoosa. There are days that boat traffic is quite wild and excessive, producing continual heavy, quite violent wake that puts great strain on our dock, boat lift and ramp. We've made it a point to avoid using our boat on those heavy traffic days.
Yearly repair on sea wall.
Shore line and rip rap destruction
I am near the back of a cove so my damage is minimal. I have neighbors that have had huge amount of erosion.
Cross-tie cables broken due to excessive wake from inconsiderate boaters traveling too close and too fast.
Wake has washed me ashore and my trolling motor, while fishing, could not overcome the wake. I had to call friends to help get my boat off shore and flotilla g. Had to repair bull from rock damGe.
1. My 19' Yamaha jet boat was thrust onto our dock because of high waves produced by wake boat. It made a 8" gash through the gel coating and into fiberglass. 525.00 to have repaired. 2. Gang plank walkway fitting broke off dock and fortunately cables prevented dock from floating away as walkway and dock were no longer attached. This was called by severe waves.
Boat docks and sea walls damaged. Also boats damaged by waves forcing boats into docks
Completely destroyed my dock. It was a Cherokee two story. Just replaced it at a cost of $60,00.00 plus. Engineer called….diagnosed it as wave damage. We own a wake boat but ONLY use it on big water near the dam.
But the move wake boats on the lake the more damage I will incur.
Have replaced many of the top blocks on the seawall every year, replaced pinestraw, etc. Boat lift requires biannual maintenance to replace bolts, pads, etc from wave action
I cannot point directly to damage but the rip rap at the base of my sea wall has been extensively eroded the past couple of years which I can attribute to the larger waves being generated. However, the lake has experienced a large growth in boat traffic the past few years which has had an impact. I cannot point directly to the waves created by wake boats as a contributor but the number of wake boats has grown dramatically.
Wakes have resulted in damage to the "bumper" of my pontoon boat while parked in the slip of my boat dock. I have had to replace 3 cleats on my bass boat due to damage from excessive wakes while the boat was in its slip
Our dock takes a beating during peak boating times. We have increased shoreline erosion due to constant wave action, especially on the weekends. Our floating dock is a hazard to stand on with large amounts of boat traffic. Many boaters do not respect distancing from the docks and create unsafe conditions for swimming or doing anything on the dock. We have noticed that many other types of boats cause large wakes as well.

The wake boats were moving and shifting out into the water our rip rap rocks. We have spent a fortune on a new sea wall in order to protect the shoreline. I sure would love to charge the folks who come bombing into our cove with their big wake boats for our new wall!! Outlaw them all! Our beautiful shorelines will thank you!
Dock broke loose
Had to replace sea wall because water was coming way over. We were riding in our boat and the wakes were so large that I cracked the third lumbar vertebrae in my back.
Snapped ropes holding boat to dock and boat crashed into dock causing damage to wood and boat It is almost impossible to swim at your dock when they are in the area! Also, waves so large they they overtook our pontoon over the roof and caused us to sink on front of boat with my elderly parents. Very scary!
Erosion over the sea wall.
New owner
In a cove
Excessive erosion to the shore around my property. A wave from someone wake surfing has overtaken the front of my pontoon boat while traveling on the lake causing damage to my boat and scared my entire family on board. This has caused such a fear that some don't like going near anyone wake surfing at all.
Boat damage and lost bumpers. More importantly boats speeding by have created wakes that washed my grandchildren under the dock.
Erosion on the banks
Floating platform has been torn from walkway TWICE
Erosion.
Beats up and cuts away at the shoreline
Damage to fixed dock steps going into lake.
Shoreline major damage and dock minor damage
Increased erosion on our banks. We have a rock wall and need more rock because of the erosion
Sea wall, boat lift
Shortly after purchasing our new Crest I tritoon, someone in a wake boat came within 50 ft. of our dock while we were getting our boat on the lift. Both outer pontoons were scratched, one dented and scratched even with 3 adults trying to hold it steady. This incident occurred in spring 2020. Within the next few months, we had to pay someone to reinforce all the joints in our floating dock due to the damage from extreme turbulence of the waves crashing into it. Our lake house is located on the big curve on the Little Tallapoosa (Andanley Branch). This is a major thoroughfare for boat traffic, but much too narrow for wake boats with ballast.
Beats boat against dock and washing out banks along property they don't follow rules of the lake by coming to close to docks and boats I have been a property owner for 33 years in the last couple of years enjoying the waters have went downhill
Shoreline erosion has laid bare some tree roots, causing potential tree falling hazard.

These yes or no questions should allow for explanation. I support what was originally proposed from the state legislature. There should be guidelines for surfing areas. We surf only south of 48 on the big body of water…no coves, etc, out of respect for homeowners. (I am a lake homeowner.) Potential safety hazard, yes. But then again any stupid boater is a safety hazard regardless of activity. I see more safety issues with boaters pulling water toys than any other activity…erratic driving to sling their riders while not paying attention to other boaters as they approach…even in crowded conditions. I would support legislation in regards to regulation not elimination of wake surfing. I know budgets are limited, but I would support more deputy patrol for ALL boating.
Our boat lift was loose and had to have repaired
Our property on Allen Branch sits on a back water channel where there typically is not much high speed water sport boats.
Sea wall damage
We have made repairs for the last 3 years. I am on Wedowee Creek. The area is NOT wide enough for these wake boats! If we are on the dock when these boats come through, you have to hold on to keep from falling in. They need to be in LARGER areas of the lake. Thank you for helping with this problem
Our floating dock with lift was installed 2 years ago. The waves that come into our cove after a wake boat goes by is tossing our floating dock around like a rag doll. On the side closest to the cove - first to get hit with the waves all the screws sheared off. We had to pay $375 just a month ago to get it repaired. Besides the dock, we have been tossed around in our boat on the lake because the waves were so big. Last summer we thought we may capsize - it was very scary. A lake is a lake and an ocean an ocean. If you want to "surf" go to the ocean. There are plenty of waves.
The waves actually come over the dock and the waves push items on the dock in the water PWC floating dock, which was attached to the dock, was ripped off the dock The metal eye on the fishing pontoon that keeps the boat tied to the dock was bent and broken
Have had a Jon boat pushed off a jet ski port, and had the wake come over the dock and push everything not tied down into the lake.
Dock damaged.
Waves coming over the sea wall. Sheared bolts where the ramp connects to the dock. Wake surfing in our cove!
Bank erosion caused us to build our seal wall.
The large wakes have damaged my seawall
Water washing over sea wall causing erosion. Ski Doo hitting dock, because of waves, scraping paint off Ski Doo. Noise nuisance….several jet skis coming into our cove and going around in circles.
Constant maintenance of my dock because of the wake boat activity.

Aggressive sea wall and dock damage. Our dock is mainly used for lounging & swimming. It is unsafe for me to swim at certain times of day because of watercrafts driving too close to my dock. This is very frustrating as swimming is one of the only reasons we invested in a property on Wedowee in the first place.
Erosion of sea wall, wear on floating dock
I have had to have a large 1/4' thick metal plate 8' long added to the hinge area on my dock where the ramp hooks on due to metal fatigue on the dock. The hinges were were about to rip out on the dock side. Cost $2,500. I also see the same happening to the ramp on the land end and am in line to get that fixed before the dock detaches from land. Do not have a cost on that yet. Also one night I could not see a wake boat wake, hit the wake wrong and my front fishing seats were knocked off the boat into the water. Lost one of them. We had 3-4 inches of water all the way in back of the pontoon boat, everyone got their shoes wet sitting in back of boat. No box for additional comments but I would support the TN law being passed in Alabama. If cannot get the full 200' TN law, then compromise at 150' from docks/shoreline. One hundred feet is not enough in my opinion! I have already personally contacted Bob Fincher about this.
Jet skis have been rocked loose from their ports. And ports have come unattached from dock on one side. Boat has had to be pumped out from wakes throwing water into our boat while it was tied to our dock. Luckily this is all the damage we've sustained so far.
Erosion
Erosion of sea line. Boat damage (dents and scuffs) due to wake shifts
Tore pwc float off dock, Bent pontoon frame
Rip rap experiences significant erosion due to waves and impacts. It is also causing our wall of railroad ties to be compromised due to the waves and force going over them. We are on the main part of the lake.
I have had trouble with the wake boats coming to close to my dock over and over. I have had bolts broke off the lift, steel tubing bent and chairs rocked off the deck. Also have had a few cap blocks loosened on my sea wall. I'm not opposed to the wake boats but they need to respect peoples property.
Have reengineered my anchoring system to account for the new, higher wave impact. Previously, cabling failed, dock was often under water, and it is simply because of all wave creating boats getting too close to my property.
Extensive damage to the shore line & minor dock damage. This is in addition to the irresponsible drivers who are far to close to the shore line and it is a hazard as we use our dock for leisure activities and floating close in. It has been an issue and major safety concern.
Waves due to surf boats have crashed over our sea wall which in time will destroy it. The massive waves from surf boats broke steel plates on my dock which attached to a PWC port. Where we have rip rap these same waves are actually moving the rocks. It's a disaster and these boaters don't care.
My dock is floating and attached to pylons. The bracket has cracked hold the dock to the pylon due to excessive wakes.

We have had massive amounts of erosion to our shoreline (roughly 6 feet), which necessitated a seawall. Our dock has also had damage from the large wakes
Shoreline washing