Good Afternoon Chair Sollman, Vice-Chair Brock Smith, and members of the committee,

My name is Heidi Hinrichs. I am an avid boater and a waterfront property owner in the Newberg Pool. Thank you for the opportunity to speak this afternoon.

My family and I enjoy the Newberg Pool whether we are swimming, fishing or boating. Prior to the implementation of 1589, we were in the middle of a wake zone. There were multiple heavy wake boats passing our shorelines during this time. When they did pass, our dock shook so violently from the resultant waves that we fell. If we happened to be on our paddle board, we fell. Even in our 2500 pound motorboat, we had to immediately maneuver for safety. The point is that only those in these large wake boats can enjoy the river, nobody else can.

There are other large waterways nearby where these large wake boats can tow. These waterways include the lower Willamette River north of the Hawthorne Bridge, the lower Willamette River south of Waverly to Oregon Falls, the Columbia River, Henry Hagg Lake, and Green Peter Lake, to name a few.

I hear those in support of this bill say their boats should be allowed on all public waterways. Yet we do not allow motorcycles or ATVs on hiking trails. Why is this different when there are alternative waterways nearby that are safe for these large wake boats to tow?

SB 1589 passed with substantial time and effort by Oregon lawmakers. They heard over 21 hours of testimony and educational information on wake boats in the Willamette River. Approximately 40% of that was provided by Oregon State University professors. Only two studies (Poor et al and Macfarlane et al) on wakes generated by boats in the Newberg pool have been published in peer reviewed journals. Macfarlane's 2025 publication, attached, concludes that at least 500 feet is required for the wake boat wave energy to dissipate to that of a water ski boat wave. The Newberg Pool is not wide enough for this to occur. Surprisingly, he also concluded that wake boats, ballasted or unballasted, when operating around 10-12 mph, generally generate significantly higher and more energetic waves than "conventional" recreational craft. So, the peer reviewed science we do have today does not support increasing the boat weight restrictions for towed water sports in the Newberg Pool.

In summary, SB 1589 is working and already has a process in place to modify boat weight for towed sports in the Newberg Pool. Please reject SB 301.

River Research and Applications

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Wakesurfing, Wakeboarding, and Waterskiing: A Comparison of Wake Characteristics

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ABSTRACT

Waterskiing has been a commonplace and generally well-accepted activity on inland waterways for many decades. More recently, there has been a significant increase in wakeboarding and wakesurfing, with the latter relying heavily upon "enhanced" boat wake. This has seen an increase in issues such as shoreline erosion and damage to public and private property, often resulting in additional complications for those tasked with the management of sheltered waterways. This is most prevalent in situations where lateral distance is limited, such as rivers and small lakes, where there may be insufficient distance for the larger boat-generated waves to disperse and attenuate. This has become a hot topic, with disputes occurring at many locations—for example, the author is aware of disputes occurring in at least 20 states in the USA over the past 7 years. This paper investigates the key differences in the characteristics of the waves generated by typical waterski and wake boats, with and without wake-enhancing devices. Measurements of the waves generated by a variety of recreational and wake boats were acquired from full-scale field trials. Results are presented graphically and compared with data from other published studies of a similar nature. It is confirmed that there are significant differences in both the height and energy of the maximum wave generated by the three different water sports (and, to a lesser extent, wave period). Data are acquired at multiple locations over a relatively large lateral distance from the sailing line of the test boats, which should assist regulators in identifying management options for waterways with sensitive shorelines and vulnerable property.

1 | Introduction

1.1 | Background

Shoreline or riverbank erosion caused by vessel-generated waves is a common problem in sheltered waterways that would otherwise experience minimal wave action. Erosion can, of course, be linked to other sources, such as wind waves, floods, regulated river flows, and livestock access; however, there are growing incidences where the waves from commercial and recreational boating have exacerbated erosion levels (Nanson et al. 1994; Novak et al. 2021; Fenton et al. 2023; Fleit et al. 2019; Macfarlane and Cox 2003; Maynord et al. 2008; Macfarlane et al. 2008; WEC 2021). Towed water sports, such as waterskiing, have been a common and accepted activity for many decades, but there has been an increase in the frequency of boats specifically designed to enhance the wake for activities such as wakeboarding and wakesurfing. This latter activity requires the boat to generate a large wave that can be surfed without the aid of a tow rope.

There are clear and notable differences in several aspects of these three water sports, particularly the speed at which they operate, but also the characteristics of the boat used and the optimum depth of water beneath the boat, all of which can heavily

FIGURE 1 | Wakesurfing in the enhanced and tuned wave a short distance aft of the transom of a typical wake boat. *Note:* The asymmetry of the wake and the long, high, clean, and steep wave face (Nautique Boats 2024). [Color figure can be viewed at wileyonlinelibrary.com]

influence the characteristics of the waves generated. This, in turn, will influence the lateral distance that may be necessary for the boat-generated waves to disperse and attenuate sufficiently to minimize the likelihood of shoreline erosion or damage to property.

Manufacturers of wake boats have sought to innovate their designs by adopting several methods to create an "ideal" wave for surfing, which will typically have a long and steep wave face (the first smooth section of the wake, which is generally the preferred region for surfing) leading to a plunging wave, where the crest curls over the front face and falls to the base of the wave. Commonly adopted "wake-enhancing devices" (WED) used to achieve ideal wakesurfing conditions include large internal (and/or inflatable) ballast tanks, hydrofoils, and surf gates or plates typically located at or near the transom of the vessel to further increase the height and shape by adjusting the dynamic trim and heel of the vessel. It is standard practice to impose a notable heel angle, resulting in an asymmetric wake that is surfable on just one side of the boat where the quality of wave has been maximized for surfing, as seen in the photograph provided in Figure 1.

The Water Sports Industry Association (WSIA) in the United States actively promotes three core recommendations for wake surfers to "Wake Responsibly" (WSIA 2023). The first is to stay at least 200 ft (~60 m) from the shoreline, docks, or other structures. The appropriateness of this specific distance is regularly raised and may be considered a focus of the present study. The second rule is to play music at reasonable levels and have respect for the surroundings (i.e., time of day, explicit lyrics, etc.). The third rule is also quite pertinent: to minimize repetitive passes on any one portion of the shoreline.

1.2 | Quantifying Boat Waves

It is common to assess vessel wave wake by quantifying the height, period, and energy (per unit crest width) of a single wave in the complex wave train, usually the highest (or "maximum"). As the wave energy content is per unit width and averaged per wave, this represents an average energy content per surface area (Dean and Dalrymple 1991). Wave energy in deep water is proportional to both the square of the wave height and wave period (refer to Equation 1), so any change in either height or period will result in a significant change in wave energy.

$$E = \frac{\rho g^2 H^2 T^2}{16\pi} \tag{1}$$

Linear wave theory is applicable where the wavelength is less than 3.5 times the water depth: a condition at which a wave's orbital velocity at depth h is only 3% of that at the surface (Lighthill 2001). The length of the waves generated by recreational craft will typically be limited such that they can operate in fairly shallow water before their wakes become depth-affected. Cox (2020) refers to this as "practically deep."

There are two further parameters that may be considered more relevant when identifying when the characteristics of the waves generated by moving vessels may be affected by water depth: the depth Froude number ($Fr_h = V / \sqrt{gh}$, where V is vessel speed in m/s) and the water depth/vessel waterline length ratio (h/L). For the former, limited water depth can affect the form of the vessel-generated wave pattern, such as altering the wave propagation angle (e.g., further details are covered by Cox (2020) or Macfarlane (2012)). A subcritical depth Froude condition (typically "deep" water) occurs when Fr_h is less than approximately 0.7, which is preferred for wakesurfing. A trans-critical zone occurs between $\sim 0.7 < Fr_h < 1.0$ where the waves may become depth affected. Froude depth numbers in excess of 1.0 are generally considered super-critical.

The water depth/vessel length ratio can indicate when waves "feel the bottom" (the orbital motion beneath a wave becomes increasingly elliptical) and the wave transforms, slowing their speed and eventually leading to refraction and shoaling. An of $h/L = 1.77$ identifies the point where the waves are simply not long enough to be depth affected, regardless of vessel speed (i.e., there is zero super-critical effect in any condition). An effect on the waves becomes measurable around $h/L = 1$ and the effect can potentially be substantial when h/L is less than 0.5.

Cox and Macfarlane (2019) state that whatever energy is contained in a wave system must eventually be expended at shore. Close to the vessel, the energy is contained in only a few large waves. As lateral distance is increased, dispersion leads to the same energy shared across many more waves. This is why the most commonly adopted technique to mitigate wave wake impacts is to increase lateral distance; the total energy has not been reduced, just spread across more waves. What this increase in distance cannot do is reduce wave period to any notable extent.

When attempting to avoid or minimize erosion, the key task is to identify the threshold below which the waves are not going to alter the state of equilibrium for the specific shoreline/bank type and composition. For example, in regions with highly sensitive shorelines, experiments that quantify turbidity (sediment movement) can identify threshold limits of wave height and wave period (Cox 2020; Macfarlane et al. 2008). Alternatively, the threshold may be determined by quantifying the naturally occurring (prevailing) wind-generated waves or by identifying vessels that have proven through successful operation over time that the waves they generate are acceptable for the region of concern. This is effectively what has occurred in many "hot spots." For example, by setting the characteristics of the waves generated by adopting waterskiing activities as a benchmark (at a relevant lateral distance) and assessing other activities, such as wakesurfing, by identifying the lateral distance where their waves are considered approximately "equivalent" in terms of erosion potential.

The existence of erosion thresholds suggests that the magnitude of energy is less important than the form in which it is delivered. Cox (2020) provides a useful analogy to describe annualized (or totalized) energy by considering the dropping of a small coin from a height of 50 mm (2 in.) every second for 1 year, which would be analogous to the effects of wind waves. That annualized energy as a single event would be equivalent to dropping a 1-t vehicle from a height of about 4.5 m (~15 ft). One could be regarded as inconsequential and the other catastrophic, yet both have the same total energy (over the time the energy is computed). Similar applies to the use of total wave energy rather than the energy of a single maximum wave, albeit to a lesser degree.

Given these potential flaws in methods that attempt to summate or annualize wave energy, it is believed that such comparisons of boat wave energy and/or wind wave energy can be meaningless when comparing the impacts of different wave regimes. The author prefers to quantify the energy of the maximum wave as this aligns with the use of benchmarks that can compare the characteristics of discrete waves against erosion thresholds that can be quantified for specific shoreline types. One complication comes if the erosion threshold is exceeded; then the height and/or energy of the maximum wave alone may not be an indication of how many waves exceed that threshold, suggesting an approach that assesses this cumulative effect may be more appropriate (Macfarlane 2012). There are many other factors that must also be considered if attempting to quantify bank erosion from boat waves (beyond the scope of the present study).

1.3 | Relevant Studies

In an effort to better understand the waves created by wakesurfing activities and their potential to result in bank erosion or other issues, several teams have published technical reports describing full-scale experiments designed to quantify the characteristics of these waves. The following three particular studies are the most commonly cited studies:

- Goudey and Girod (2015): Commissioned by the Water Sports Industry Association (WSIA).
- Macfarlane (2018): Australian Maritime College, University of Tasmania (AMC).
- Marr et al. (2022): St. Anthony's Falls Laboratory, University of Minnesota (SAFL).

This paper presents the most salient results from the research performed by AMC in 2018 and compares these against relevant results presented in the WSIA and SAFL reports. The author would have preferred to present all results in metric SI units; however, both the WSIA and SAFL reports (and the original 2018 AMC report) present (most of) their results in imperial units, which have been adopted in this paper to allow easier and more direct comparison between all three studies. Wave heights are reported in inches, lateral distance in feet, wave energy in lb ft/ft, and vessel speed in miles per hour (mph).

Several other studies have also attempted to quantify the characteristics of the waves by recreational craft on sheltered waterways in recent years. For example, Water Environment Consultants (WEC 2021) evaluated the potential impacts of recreational boats on lakes in Northeast Georgia, which included their own site-specific full-scale trials to validate data from Goudey and Girod (2015). The WEC test program focused on a single wake boat (2017 Air Nautique G22) at three load conditions and speeds corresponding with the three operational modes of skiing/cruising (displacement ~6000 lb; speeds 20, 25, 30 mph), wakeboarding (~8000 lb; 21, 22, 23 mph), and wakesurfing (~10,000 lb; 10, 11, 12 mph). The averaged height and period of the maximum waves from five replicate tests at each speed are presented. As measurements were only acquired at two locations (162 and 267 ft from the vessel sailing line), WEC adopted a power-based equation from Macfarlane and Renilson (1999) to create wave attenuation curves to assess wave height over a broader range of lateral distances. This approach relies heavily on the wave decay exponent, which experience has shown can be risky when defined from such a limited number of data points (Macfarlane 2012), as is evident with the comparison of their wakesurfing extrapolations against WSIA data.

Houser et al. (2021) quantified boat-generated waves on a lake regularly used for recreational boating, but unlike the AMC, WSIA, and SAFL studies, boating activity was incidental (unplanned), so none of the key information, such as boat details, speed, or lateral distance, was recorded; just the resultant wave traces to summate cumulative wave energy. An interesting finding from their analysis suggests that up to 47% of the wave energy following a boat wake is associated with the waves reflecting from adjacent shorelines; thus, the cumulative wake energy may be underestimated. A more recent study by Houser et al. (2024) includes a survey of local residents on the perception of boat wake impacts. It is felt that the measurements presented in both studies suffer from a data sampling rate that is too low (1 Hz) to accurately quantify the waves created by the type of boating activities of interest in the present study, which is acknowledged by the authors (and confirmed in later sections of this study).

Fay et al. (2022) describe a numerical simulation of the waves and propeller wash from a wake boat. There are numerous flaws in this study, most notably, the computational fluid dynamics model is not calibrated or validated, leaving questionable results, and there are several claims made in the abstract and conclusion that are not supported by the material presented.

2 | Details of Three Experimental Studies

2.1 | Effect of Water Depth on Wakesurfing Waves

Before presenting details and comparing results from the AMC, WSIA, and SAFL studies, it is helpful to recall that the depth of water beneath a moving vessel can have a significant effect on the characteristics of the waves generated. This is well reported elsewhere, for example, Cox (2020). It is generally known that it is best to wakesurf in "deep" water, where a depth of at least 12 ft (but deeper is better) is suggested by manufacturers of wake boats (Malibu Boats 2024). At shallower depths, the boat will not generate a fully formed wave. This has been confirmed by a series of physical scale model experiments performed at equivalent full-scale water depths of 3, 6, 9, 12, and 18 ft (Buchanan 2019). Time-series data of the wake close to the boat at each water depth are shown in Figure 2, where it is clearly evident that the largest and steepest wave is found at the deepest depths, and this degrades with decreasing water depth.

The next three subsections provide background and details for each of the three key studies identified in Section 1.3. The

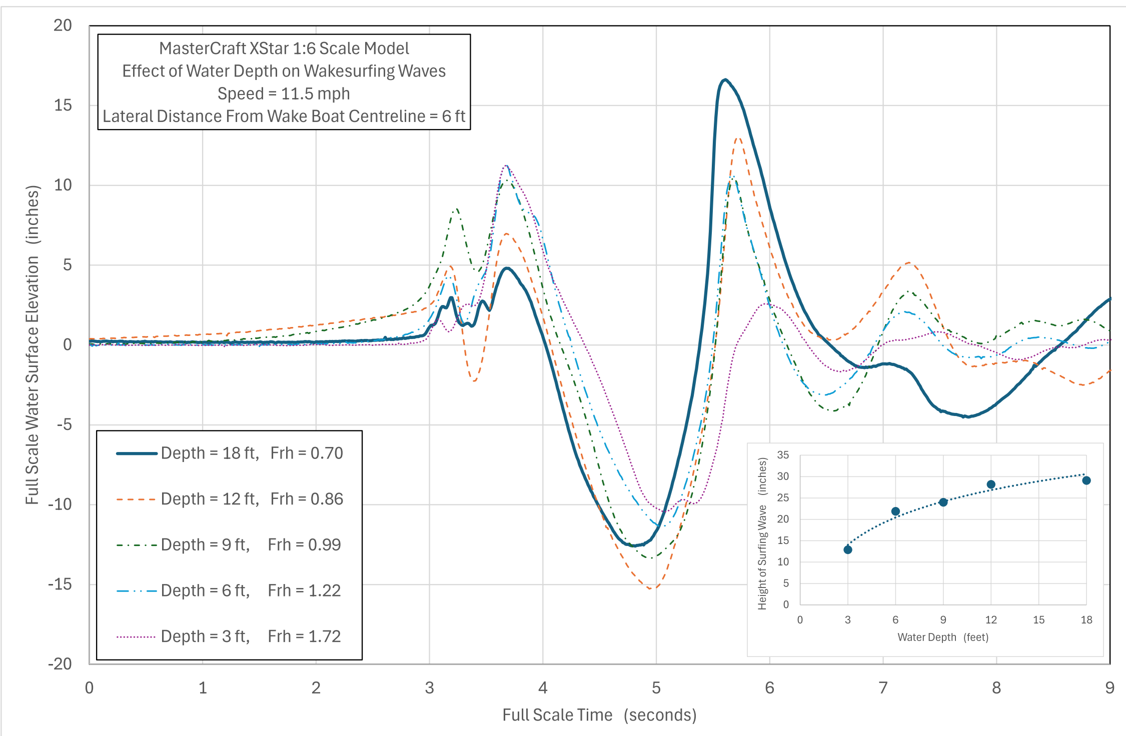

FIGURE 2 | Time-series plots from experiments of the wake close to a 1:6 scale model of the MasterCraft XStar wake boat to investigate the effect of water depth. The largest and steepest wave of approximately 30″ is found at the deepest water depth of 18 ft. Both the height and steepness degrade with decreasing water depth. The inset (bottom right) highlights the decrease in wave height with decreasing water depth. [Color figure can be viewed at wileyonlinelibrary.com]

results from these studies are directly compared and discussed in Section 4.

2.2 | WSIA

The WSIA was the first to recognize the paucity of reliable experimental data quantifying the characteristics of waves created by wake boats operating at wakesurfing speeds. WSIA commissioned Goudey and Girod (2015) to conduct research primarily to achieve the following primary objectives:

- Develop methods and instrumentation to accurately measure waves generated by the passage of a wake boat.
- Measure the wakes produced by a wake-sport boat at cruising, wakeboarding, and wakesurfing speeds and loading conditions at deep and shallow test sites.
- Determine the wave energy from these wakes and how it varies with the mode of operation and distance from the boat track.
- Compare the experimental findings with the wave energy associated with wind waves.
- Use the findings to assist WSIA in developing guidelines for wake boat operation to minimize any negative impacts of wake sports.

Their investigation focused on a single wake boat and two test sites, one considered "deep" where the wake boat operated in water depths around 23–30 ft, and the other "shallow" where the boat operated in depths around 10 ft. The water depth/vessel length ratio for the shallow and deep sites was ~0.44 and between 1.0 and 1.4, respectively. From Section 1.2, we know that the boat-generated waves were likely affected at all speeds of interest at the shallow water site, especially at the higher vessel speeds. The waves created at wakesurfing speeds at the deep-water site will be largely unaffected by water depth (where $Fr_h \sim 0.5–0.6$), while the situation becomes more complex at the higher wakeboarding speeds where $Fr_h \sim 1.0–1.2$, and up to $Fr_h \sim 1.5$ for cruising speeds. As a result, the vessel wake characteristics from this study will likely be influenced, to varying degrees, by the water depth in all but one case: wakesurfing speeds at the "deep" site. This is not unusual, nor does this make the data invalid; it just needs to be acknowledged that this may lead to additional data scatter due to small variations in speed and/or depth affecting the waves created.

The WSIA study compares the measured wave characteristics of a single wake boat against wind waves predicted for various combinations of wind velocity and fetch. The WSIA report includes some valuable data. However, the report itself may be tainted by bias, as a number of the conclusions are not supported by the data presented. It appears that the consulting engineers commissioned by WSIA performed the study, but the WSIA may have made their own interpretation of the results from which they based their recommendations—most notably that wakesurf activities stay at least 200 ft from the shoreline, docks, or other structures. The following statement was available on the WSIA website: "*In 2015, Ocean Engineer and Naval Architect Clifford Goudey scientifically studied and collected wave energy data on the characteristics of boat wakes. WSIA analyzed the data to develop recommendations to protect shorelines, docks and other personal property*" (WSIA 2023).

2.3 | SAFL

Also motivated by a need to better understand the characteristics of wakes and waves produced by recreational boats common on lakes and rivers, the SAFL performed full-scale trials on four different boats, where two were typical recreational boats (i.e., non-wakesurf) that are commonly used for tubing, waterskiing, and wakeboarding, and two boats designed specifically for the sport of wakesurfing (Marr et al. 2022). For these latter two boats, tests were performed with and without WEDs, where the configuration was determined by the wakeboat owners. This allowed a direct comparison of measured wave characteristics of the more traditional non-wakesurf boats against ballasted and unballasted wake boats. No attempt was made to compare against wind-generated waves.

2.4 | AMC

The origins of the present paper stem from a series of full-scale trials performed by the author in 2018. The need for an independent study comparing the wave characteristics for a wider range of recreational and sport boats was recognized. The study includes boating activities covering waterskiing, wakeboarding, tubing, wakesurfing, and fishing. Some results were provided in an unpublished but freely available report (Macfarlane 2018). The experiments were conducted in collaboration with the Oregon River Safety and Preservation Alliance (ORSPA 2024), which organized the test vessels and provided valuable assistance in setting up equipment. All test data were acquired and analyzed solely by the author, who contributed time and equipment pro bono. The brief 2018 unpublished report provided details of the experiments and presented limited results but deliberately refrained from making conclusions or guidelines for wake boat operation.

This paper presents the most salient data from the full AMC study, including data that is not included in the 2018 report and directly compares this with data published in both the WSIA and SAFL reports.

2.5 | Common Traits Between the Three Studies

All three studies adopted test crafts that was considered representative of those typically used for waterskiing, wakeboarding, and/or wakesurfing (and other recreational activities such as tubing and fishing). They also provided details of each craft, most importantly the total displacement of each vessel, which at times included significant ballast and other WEDs deployed.

All three studies also covered the two speed zones of most interest: wakesurfing (10–12 mph) and wakeboarding/tubing (20–24 mph). The AMC study also included a higher speed range commonly used by experienced water-skiers (30–32 mph).

FIGURE 3 | Right—Location of the test site on the Willamette River. The water depth at the wave sensor was 15 ft and approximately 40 ft at each of the vessel track paths (100, 200, 300, 400 ft from the sensor at $y = 0$ ft). Top left—Wave sensor attached to a rigid vertical pole. Bottom left—Test vessel passing the wave sensor. [Color figure can be viewed at wileyonlinelibrary.com]

As previously noted, of particular interest to this study is the effect lateral distance has on the characteristics of waves created by various recreational/sport boats. To cover a wide range of lateral distances in their respective field trials, all three studies adopted a similar approach whereby one or more wave sensors were located at fixed locations, while the (straight) track line of the test vessel was set at multiple lateral distances. This provided the desired result of acquiring data at multiple locations, but also introduced additional variables that may lead to further scatter in the experimental results (refer to Section 4.5).

Each report presents a small sample of their time-series data and confirms the equipment and sample rates used when acquiring time-series wave measurements. These are summarized below:

- WSIA—30 Hz capacitance two-wire wave probe and pressure sensor
- SAFL—10 Hz for pressure transducers; 4 Hz for Acoustic Doppler Current Profiler (ADCP)
- AMC—200 Hz capacitance two-wire wave probe

Note that the sample rate of 4 Hz for the SAFL ADCPs is considered low when attempting to quantify wind and boat waves with periods in the range of 1.2–2.5 s.

Conveniently, all three studies recognize the relevance of both wave height and wave energy, and all three present the height of the maximum wave from each complete wave train. However, both WSIA and SAFL present the *total* wave energy in the wave train. For reasons noted in Section 1.2, the author believes the energy of the maximum wave to be a better indicator of the potential to cause bank erosion due to the ability to compare this against appropriate erosion thresholds for different shoreline types. To obtain the energy in the maximum wave, both the height *and* period must be known—unfortunately, both WSIA and SAFL fail to present wave period data. As a solution, in this paper, AMC wave period data are used to determine typical average periods for each of the three-speed zones of interest, which are used to calculate indicative values of energy for the maximum waves presented in the WSIA and SAFL reports.

3 | Methodology for AMC Field Trials

3.1 | Full-Scale Trials, Test Site, and Instrumentation

The full-scale trials for the AMC 2018 study were conducted on a selected section of the Willamette River near Coalca Landing, Oregon City, Oregon, USA, as indicated in Figure 3. The site provided a straight reach with a roughly constant "deep" water depth beneath the test vessel in the region of 40 ft. The water depth at the probe was confirmed as 15 ft, which is sufficient to also be considered "deep" (refer to Section 1.2). Several images related to the test site are shown in Figure 3: the "zero" starting point of the white line shown in the aerial image indicates the approximate location of the wave sensor. The test vessels ran track paths perpendicular to the white line at each of the four nominal lateral distances of 100, 200, 300, and 400 ft from the wave sensor. Buoys were deployed at appropriate locations to guide the boat operator to maintain a consistent distance/track path.

It is important to select a test site where the wave probe will not be subjected to boat-generated waves that reflect off the surrounding shore or any bluff structure, as these reflected waves may contaminate the traces and lead to misleading results (as noted by Houser et al. 2021). For example, gently sloping beach-type banks are less reflective than levee-type banks. The site selected had a sufficiently nonreflective shoreline, including considerable vegetation, resulting in minimal reflection.

Water surface elevation was measured using MK-VI salt/freshwater capacitance wave probes manufactured by Manly Hydraulics Laboratory. The signal from the wave sensor was digitized and radio telemetered to a custom data acquisition unit that was located approximately 50–75 ft distant on a stationary support vessel. Each run was recorded using a Dell laptop computer that was accessed by Labview acquisition software. The wave sensor was calibrated both within the AMC laboratory and checked in situ multiple times. The calibration factors compare well against those obtained under laboratory conditions prior to departing and upon return to AMC.

At the commencement of each test session, the wave sensor and data acquisition equipment were set-up on the test site. The wave sensor was fixed to a vertical post that was driven into the riverbed and supported by three equispaced ropes that were anchored to the riverbed to minimize any lateral movement of the wave sensor. If the support structure moves laterally during field experiments, the resulting wave periods will be contaminated. Similarly, any vertical movement will result in variations in wave height. A photograph of the wave probe set-up is shown in the top-left image in Figure 3. The umbrella was deployed to minimize overheating due to direct sunlight on the yellow case that contains the wave sensor power supply and signal transmitter.

The AMC test matrix (refer to Table 1) provided reasonable coverage of different and relevant recreational boat types, including a variety of WED and a range of operational speeds, but there was a possible weakness that needed to be considered. In short, the wakesurfing boats on the Willamette, when run at wakesurfing speeds, were sometimes driven by individuals with significant waterskiing experience but potentially lacking in the nuances associated with fine-tuning the WEDs to achieve optimum waves for wakesurfing. It was observed that large waves were generated (as expected), but they were occasionally broken or spilling. It is likely that further fine-tuning of the asymmetric ballasting and wedges/trim tabs by more experienced practitioner/s would likely have produced a “cleaner” and unbroken wave for wakesurfing. It is suspected that these waves would likely have been higher, which was the case observed during the physical scale model experiments that produced the deep-water data shown in Figure 2.

3.2 | Test Program and Procedure

It is highly recommended that a systematic approach be adopted for any experimental campaign involving several variables. The test program undertaken in the present study involved various recreational crafts, multiple load conditions (including ballast options and number of passengers), several lateral distances, and boat speeds. The recreational crafts and their respective load conditions are summarized in Table 1. There are 18 AMC cases listed in this table that form the primary part of the test program (Cases 1–10 and 17–24). Cases were run at the three key boat speeds representing wakesurfing (10–12 mph), wakeboarding/tubing (20–24 mph), and waterskiing (30–32 mph). The vast majority of these cases were run at each of the four lateral distances (100′, 200′, 300′, and 400′). The other cases shown in Table 1 are the tests performed by WSIA in 2015 (Cases 11 and 12) and SAFL in 2022 (Cases 13–16 and 25–28). Their published results are compared to the AMC data in Section 4.

At the commencement of each run, the test vessel was accelerated to a nominal steady speed and achieved some distance prior to being perpendicular to the wave sensor (typically at least 200–500 ft) to ensure the waves recorded were generated when the vessel was operating at a “steady-state.” Recording of the water surface elevation signal from the wave sensor was triggered manually, dependent upon the lateral distance between the sailing line of the boat and the wave sensor. This provided a baseline measurement of the ambient conditions prior to the arrival of the wake waves at the wave sensor. The water surface elevation continued to be recorded until all significant waves generated by the test boat had passed the wave sensor (this generally lasted for approximately 60–120 s). The sample rate was set at 200 samples per second (200 Hz), which is more than adequate for clearly defining the full form of each wave. Figure 3 (bottom left) shows a photograph taken during a typical run (R70) involving the 2015 Ski Nautique 200 at a speed of 12 mph and a lateral distance of 100 ft (Case #20). Yellow marker buoys were used to guide the boat skipper to the desired lateral distance (these buoys were located using a hand-held GPS).

At the end of each run, the test vessel paused until the waves generated had dissipated and conditions were considered calm enough for the next test run. The vessel then sailed past the wave sensor in the opposite direction to the original starting location. Approximately 220 individual runs were performed in the AMC trials.

Each test run has been individually analyzed within an Excel macro worksheet, which imports the data file created during each test run and from the discrete samples collected plots a wave elevation time history. The macro then determines the characteristics of height and period of the maximum wave (and any other selected waves). Other quantities, such as wavelength, celerity, energy, and power for the maximum wave can then be readily computed.

4 | Results and Discussion

4.1 | Comparison of Wave Characteristics

As previously noted, the large number of variables involved can lead to a huge amount of data to process, so a logical and considered approach is often necessary to achieve meaningful outcomes when comparing and presenting the characteristics

TABLE 1 | Summary of test vessels and details. The 18 gray-shaded cases are from the test program performed by the author (AMC) on the Willamette River in 2018. Data from the AMC study are compared to data extracted from the WSIA and SAFL reports (unshaded cases). The three speed zones are color-coded. Additional speeds were tested at $y = 100$ ft for Cases 1, 2, 3, and 4 (refer to Figures 5 and 6).

Case no.	Boat type	Speed range (mph)	Boat description	Length overall (ft)	Ballast condition and/or wake-enhancing devices	Boat displacement: Dry (lbs)	Boat displacement: Ballast (lbs)	Boat displacement: PAX	Boat displacement: PAX/Misc (lbs)	Boat displacement: Total (lbs)	Water depth (ft)	Data origin
1	Wake	10–12	2006 Malibu V-Ride	21′	Ballast	3000	900	9	1620	5520	40	AMC
2	Wake	20–24	2006 Malibu V-Ride	21′	Ballast	3000	900	9	1620	5520	40	AMC
3	Wake	10–12	2014 Nautique G21	21′6″	Ballast	5500	2850	9	1620	9970	40	AMC
4	Wake	20–24	2014 Nautique G21	21′6″	Ballast	5500	2850	9	1620	9970	40	AMC
5	Wake	10–12	2014 Nautique G21	21′6″	No ballast	5500	0	9	1620	7120	40	AMC
6	Wake	20–24	2014 Nautique G21	21′6″	No ballast	5500	0	9	1620	7120	40	AMC
7	Wake	10–12	2018 Axis T23	23′6″	Ballast	4500	900	9	1620	7020	40	AMC
8	Wake	20–24	2018 Axis T23	23′6″	Ballast	4500	900	9	1620	7020	40	AMC
9	Wake	10–12	2018 Axis T23	23′6″	No ballast	4500	0	9	1620	6120	40	AMC
10	Wake	20–24	2018 Axis T23	23′6″	No ballast	4500	0	9	1620	6120	40	AMC
11	Wake	10–12	2015 Nautique G23	23′	Ballast	5720	4250	1	180	10,150	8–10	WSIA
12	Wake	10–12	2015 Nautique G23	23′	Ballast	5720	4250	1	180	10,150	22–30	WSIA
13	Wake	10–12	2019 Malibu Wakesetter VLX	21′	Ballast, hydrofoil, wake shaper	4200	3690	4	740	8630	15–30	SAFL
14	Wake	20–24	2019 Malibu Wakesetter VLX	21′	Hydrofoil	4200	0	4	740	4940	15–30	SAFL
15	Wake	10–12	2019 Malibu Wakesetter MXZ	24′6″	Ballast, hydrofoil, wake shaper	5500	4885	4	740	11,125	15–30	SAFL
16	Wake	20–24	2019 Malibu Wakesetter MXZ	24′6″	Hydrofoil	5500	0	4	740	6240	15–30	SAFL
17	Fishing	10–12	2004 Thunder Jet Alexis	21′	N/A	4100	0	6	1080	5180	40	AMC

(Continues)

TABLE 1 | (Continued)

Case no.	Boat type	Speed range (mph)	Boat description	Length overall (ft)	Ballast condition and/or wake-enhancing devices	Boat displacement Dry (lbs)	Ballast (lbs)	PAX	PAX/Misc (lbs)	Total (lbs)	Water depth (ft)	Data origin
18	Fishing	20–24	2004 Thunder Jet Alexis	21′	N/A	4100	0	6	1080	5180	40	AMC
19	Fishing	30–32	2004 Thunder Jet Alexis	21′	N/A	4100	0	6	1080	5180	40	AMC
20	Ski	10–12	2015 Ski Nautique 200	20′	N/A	2850	0	6	1080	3930	40	AMC
21	Ski	30–32	2015 Ski Nautique 200	20′	N/A	2850	0	6	1080	3930	40	AMC
22	Ski	10–12	2008 Reinell Ski Boat	20′	N/A	2900	0	6	1080	3980	40	AMC
23	Ski	20–24	2008 Reinell Ski Boat	20′	N/A	2900	0	6	1080	3980	40	AMC
24	Ski	30–32	2008 Reinell Ski Boat	20′	N/A	2900	0	6	1080	3980	40	AMC
25	Ski	10–12	2004 Larson LXI 210	21′	N/A	2925	0	2	330	3255	15–30	SAFL
26	Ski	20–24	2004 Larson LXI 210	21′	N/A	2925	0	2	330	3255	15–30	SAFL
27	Ski	10–12	2004 Malibu Response LX	20′	Hydrofoil; wake shaper	2450	0	2	330	2780	15–30	SAFL
28	Ski	20–24	2004 Malibu Response LX	20′	N/A	2450	0	2	330	2780	15–30	SAFL

of the waves generated by multiple vessels. This is the primary reason why it is recommended that the present study focuses on the height and energy of the highest wave from each wave train/run.

Typical wave elevation time-series records from four individual runs are plotted in Figure 4. These wave profiles are all for Case #3 (refer Table 1): 2014 Nautique G21 with ballast and a nominal forward speed of 10 mph; the four records represent each of the lateral distances, starting with the closest of 100 ft, then 200, 300, and 400 ft. The primary purposes of this figure are to provide examples of the time-series wave traces and illustrate how dispersion over increasing lateral distance leads to a reduction in wave height and an increase in the number of waves. Note that the start/arrival times for each of the four records, relative to each other, are not displayed correctly in this figure (separated for clarity).

The Excel macro used to analyze each run determines the start of each successive wave by the change in wave elevation above the still water level from positive to negative (or vice versa)—this is the definition of a zero-crossing point. The maximum wave height is defined as being the single greatest distance from a trough to a successive crest (or crest to trough) recorded anywhere within the sample. The period of the maximum wave is obtained from the time between consecutive zero up-crossings (or down-crossings).

For two of the test wake boats, the 2006 Malibu V-Ride (Cases 1 and 2) and 2014 Nautique G21 (Cases 3 and 4), additional runs were performed to provide a better-defined curve to investigate the effect that speed has on the height, period, and energy of the maximum wave. The wave height and period for both boats as a function of vessel speed are presented in Figure 5 (these data are for the constant lateral distance of 100 ft). As expected, there is a very rapid increase in the height of the maximum wave between 8 and 12 mph. After reaching a peak, the wave height generally reduces gradually with increasing speed, except for a bit of a "hump" around 20–24 mph, which may be due to depth-critical speed effects or due to the dynamics of planing craft with extremely low slenderness ratios as they transition to a semi-planing condition. More work in this area is needed.

Wave period reaches a peak around 12–14 mph, and similar to wave height, it also generally reduces gradually with increasing speed. The resultant energy of the maximum wave, calculated using the wave heights and periods in Figure 5 and Equation (1), is shown in Figure 6. Not surprisingly, with the maximums of both height and period (of the maximum wave) occurring around 12 mph, there is a pronounced peak in energy at or around this speed. The general trends seen in Figures 5 and 6 were evident in the results for all boats tested by AMC.

There are three key features that can be observed from this study: (1) the relative differences in the maximum wave height, period, and energy between the different water sports activities; (2) how much the height and energy of the maximum wave alter (reduce) with increasing lateral distance, and (3) comparing the full-scale experimental data from three similar but independent

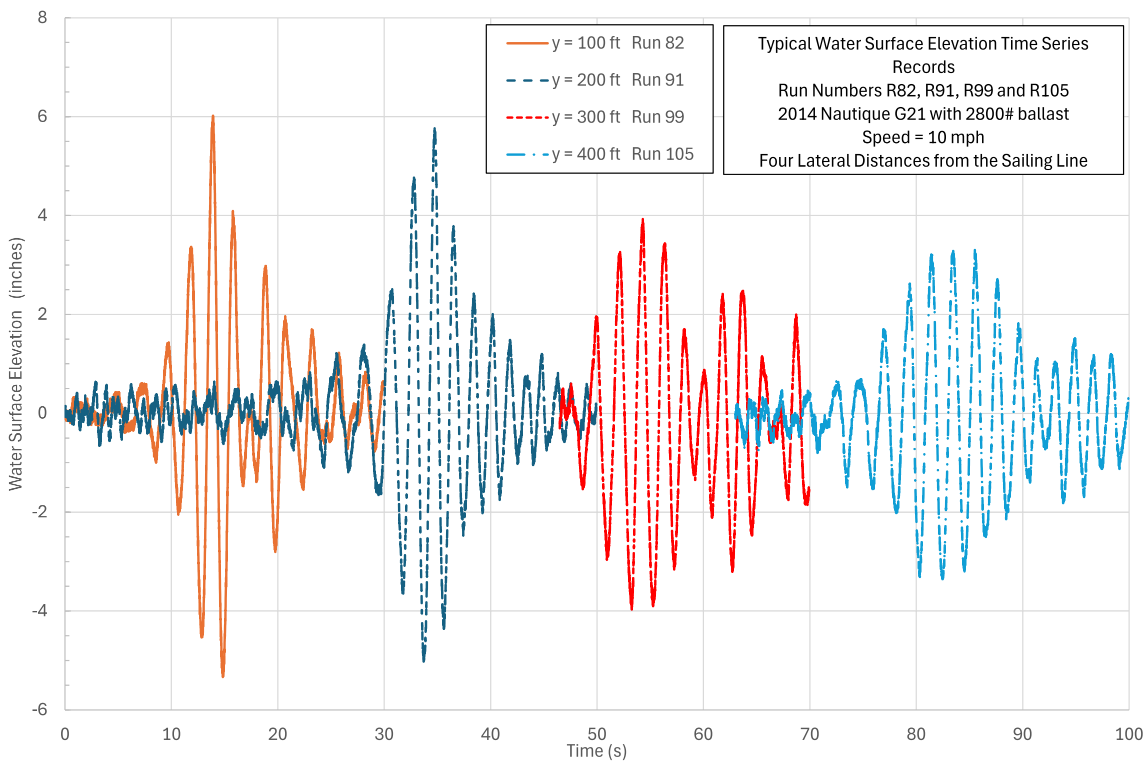

FIGURE 4 | Typical wave elevation time-series records from four individual runs for 2014 Nautique G21 with ballast at 10 mph (Case #2). The four records are for lateral distances of 100, 200, 300, and 400 ft. It can be observed how dispersion leads to a reduction in wave height and an increase in the number of waves with increasing lateral distance. The start/arrival times for each of the four records, relative to each other, are not displayed correctly (separated for clarity). [Color figure can be viewed at wileyonlinelibrary.com]

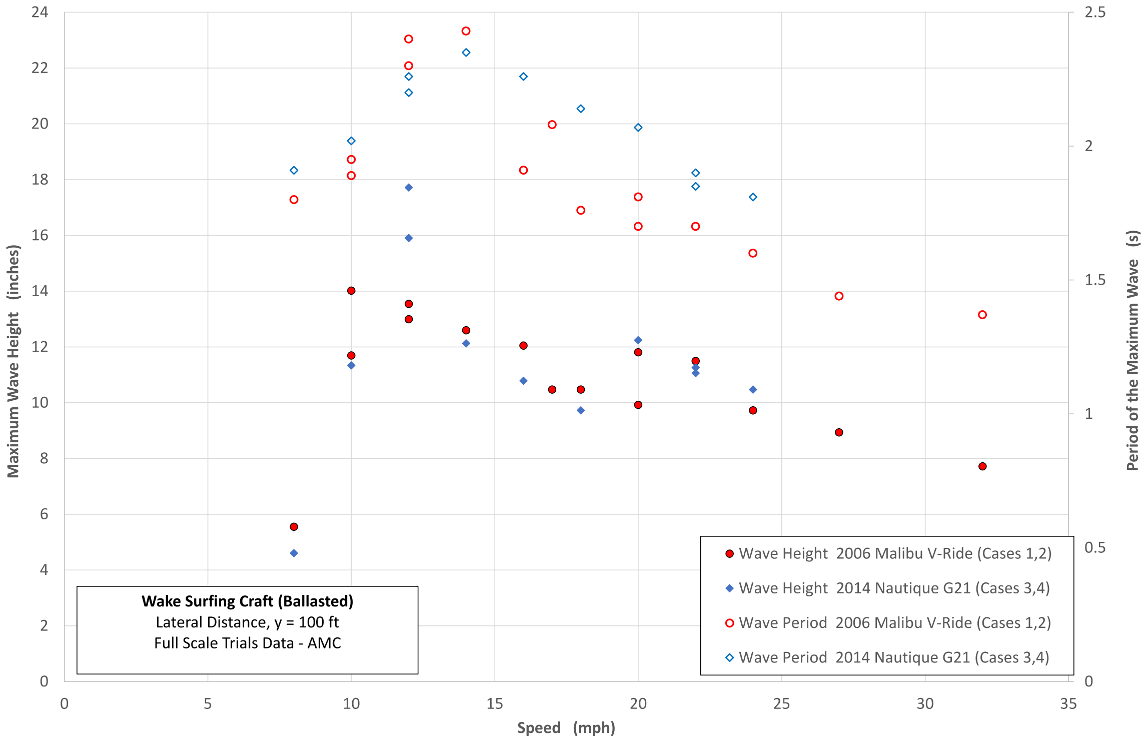

FIGURE 5 | Maximum wave height and period as a function of vessel speed for two wake boats: 2006 Malibu V-Ride (Cases 1 and 2) and 2014 Nautique G21 (Cases 3 and 4) at a lateral distance of 100 ft. The peak wave height occurs around 10–12 mph and the peak wave period around 12–14 mph. [Color figure can be viewed at wileyonlinelibrary.com]

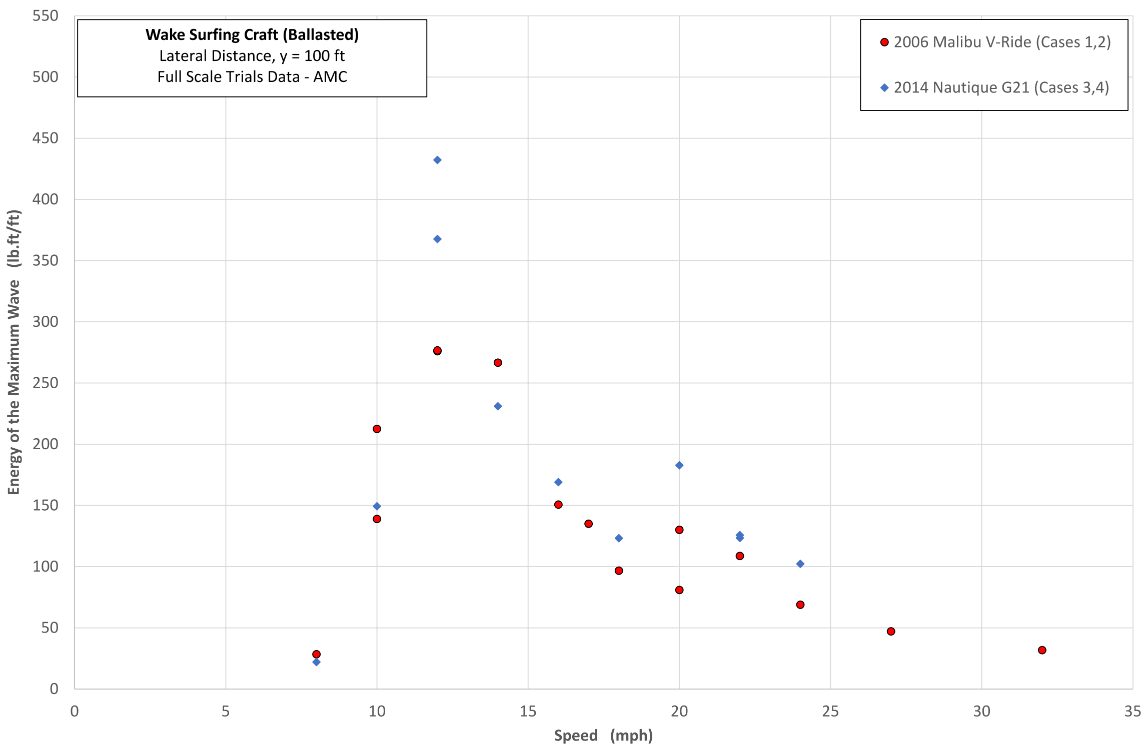

FIGURE 6 | Energy of the maximum wave as a function of vessel speed for two wake boats: 2006 Malibu V-Ride (Cases 1 and 2) and 2014 Nautique G21 (Cases 3 and 4) at a lateral distance of 100 ft. Similar to the wave height and period, the peak wave energy occurs around 12 mph. [Color figure can be viewed at wileyonlinelibrary.com]

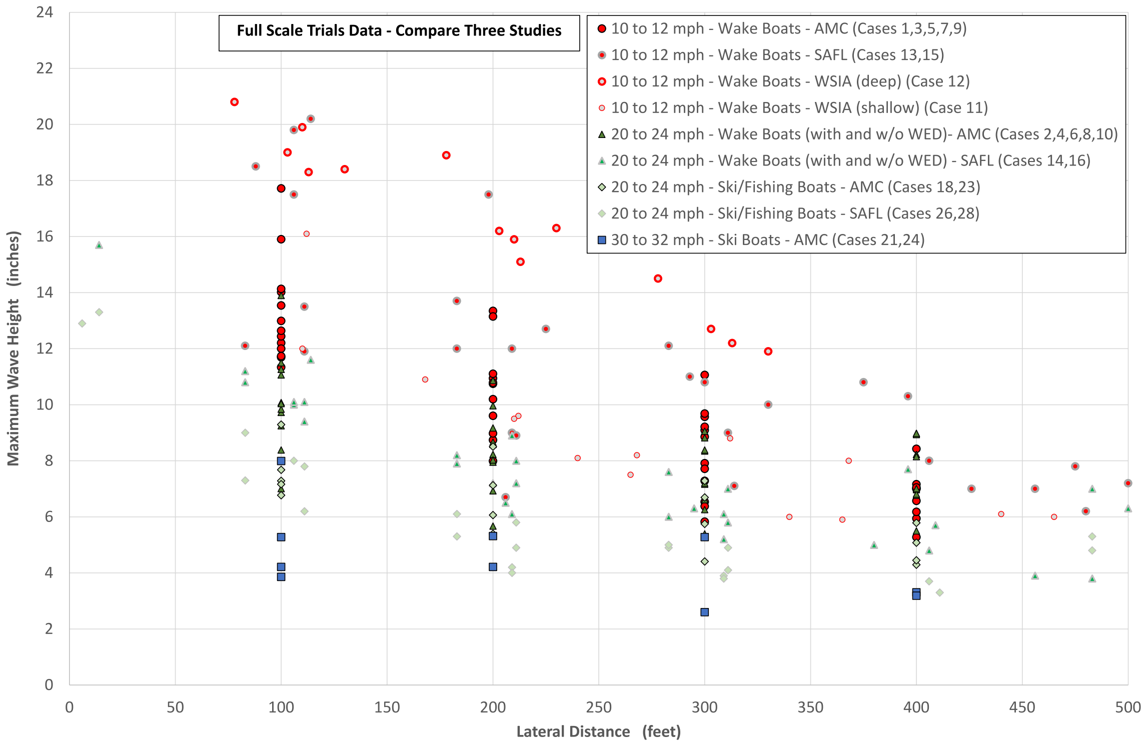

FIGURE 7 | Maximum wave height as a function of lateral distance for each of the three nominal speed ranges: 10–12 mph (red), 20–24 mph (green), and 30–32 mph (blue). Where appropriate, the data have been sub-categorized into each of the three studies (AMC, WSIA, and SAFL). [Color figure can be viewed at wileyonlinelibrary.com]

studies (AMC, WSIA, and SAFL). This comparison commences with Figure 7, where the maximum wave height measured from most of the cases listed in Table 1 is presented as a function of lateral distance from the track path of the test vessels. Importantly, the data from each of the three studies are presented as separate data series for the categories of wake boats (at speeds of 10–12 and 20–24 mph), ski/fishing boats (at 20–24 mph), and ski boats (at 30–32 mph).

There is a lot of data in Figure 7, so the following key is designed to assist in the identification of each category: All data symbols from each of the four data series at wakesurfing speeds (10–12 mph) have different symbols but share the common base color code of red and a secondary color/feature to distinguish between each of the wake boat data series at this speed. Similarly, the four data series at wakeboarding/tubing speeds (20–24 mph) have a green base color code. The symbol for the single data series of ski boats traveling at the highest speed zone (30–32 mph) is a blue square (both are from the AMC study, Cases 21 and 24).

There is a stark difference between the highest waves, which are predominantly from wake boats at wakesurfing speeds (10–12 mph), and the lowest wave heights from the ski boats at waterskiing speeds (30–32 mph). The mix of all craft (wake, ski, fishing) operating at the intermediate wakeboarding/tubing speeds (20–24 mph) generally lies between the wakesurfing and waterskiing categories. This trend generally applies at all lateral distances presented. It is worth noting that the WSIA data for the wake boat case that was run in shallow water (Case 11) lies on the lower bound of all wake boats, which is to be expected, as per the earlier discussion about the effect of shallow water and the results presented in Figure 2. Interestingly, the data for the WSIA wake boat case that was run in deep water (Case 12) lies on the upper bound of all wake boats. It is hypothesized that the WSIA deep-water data may be more representative of "true" wake boat waves, assuming they engaged more experienced practitioners to tune the operation of their boat to produce a "cleaner" unbroken wave for wakesurfing, as discussed in Section 3.1. It is noted that the SAFL tests were the only one of the three studies that adopted WEDs to induce a heel angle to obtain an asymmetric wake, suggesting that a further increase in wave height is likely for much of the wake boat data presented in Figure 7.

As previously mentioned, the WSIA or SAFL reports did not present data for the period of the maximum wave, so (almost) all wave period data presented in Figure 8 are from the AMC study. As for wave height, wave period data are distinguished for each speed category. As expected, the wave period is largely unaffected by lateral distance. Ruprecht et al. (2015) presented limited wave period data for wakesurfing and wakeboarding boats, which have been added to Figure 8 (listed as WRL for Water Research Laboratory). There may only be a few data points from WRL, but they are a close match to the AMC data, helping to validate these measurements. Importantly, there is a small but clear difference in the average period at each of the three key speed zones (refer to the inset table in Figure 8), which also agrees with the data presented in Figure 5.

As covered in Section 2, the present study prefers to compare the energy in the maximum wave (rather than the total energy in the wave train), which requires both the wave height

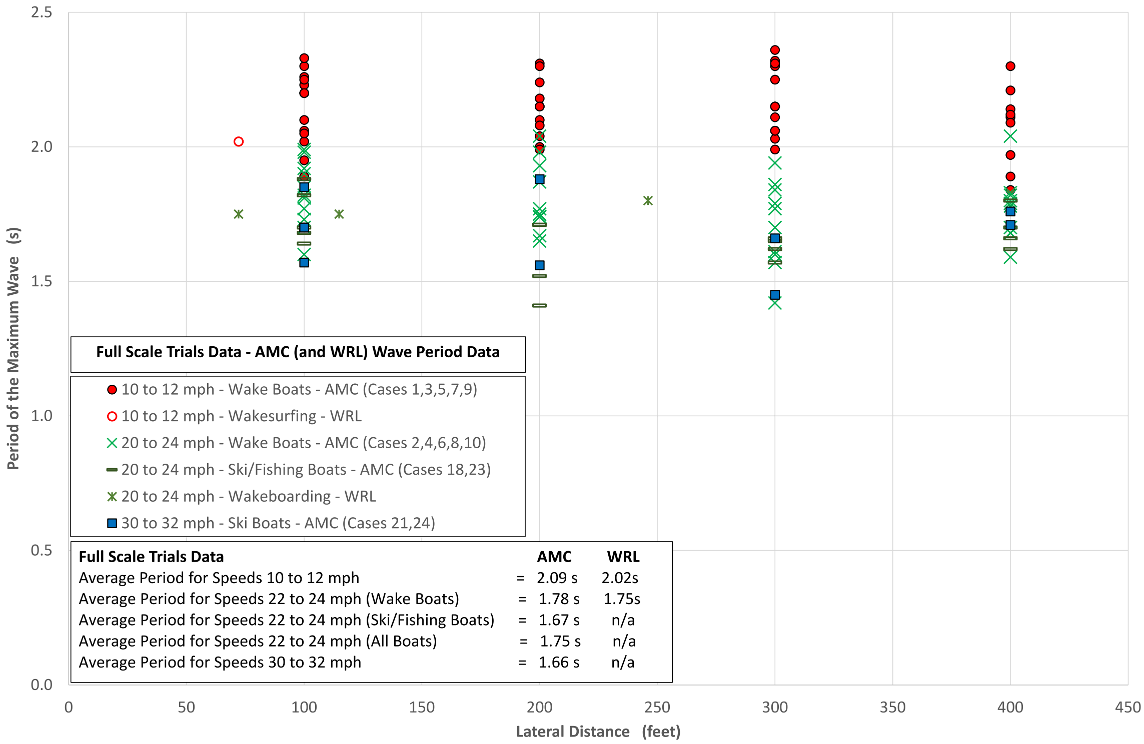

FIGURE 8 | Period of the maximum wave as a function of lateral distance for each of the three nominal speed ranges: 10–12 mph (red), 20–24 mph (green), and 30–32 mph (blue). Also shown (inset) are the average values for each speed range, which were used to estimate the energy in the maximum waves for the WSIA and SAFL studies. A few additional points from WRL (Ruprecht et al. 2015) are added to help validate the AMC data. [Color figure can be viewed at wileyonlinelibrary.com]

and period to be known. The average values obtained from the AMC wave period data (from Figure 8) have been used with the wave height data from the WSIA and SAFL studies (Figure 7) to calculate indicative values for the energy of their maximum waves. For wakeboarding/tubing speeds (20–24 mph), the average period of all boats (1.75 s) has been adopted, noting that this may result in conservative estimates of energy for ski/fishing boats. The resultant values for the energy of the maximum wave are plotted in Figure 9, adopting the same categories as used for wave height in Figure 7. Similar trends are visible to those for wave height, but here, the differences are even more pronounced.

Both the WSIA and SAFL studies conducted runs where they had wave sensors close to the boat, where the lateral distance between the track path and sensor was approximately 6–14 ft. The maximum wave heights measured by these sensors ranged between 26 and 39 in. The vertical *y*-axis in Figure 7 was limited to 24 in. to improve the clarity of the more relevant data at greater lateral distances. The SAFL study also measured some cases at greater distances around 600 ft (not included), where wave heights continued the declining trend. Similarly, for clarity, the plot of energy data presented in Figure 9 is limited to 550 lb ft/ft. There are four WSIA and SAFL measurements close to the boat (6–14 ft) that significantly exceed this, ranging from 850 to 1900 lb ft/ft.

4.2 | Benchmarks

In the original AMC report, potential benchmarks were included in the plots for maximum wave height and energy of the maximum wave (figs. 10 and 11 in Macfarlane 2018). These values, ~7.2 in. and 43 lb ft/ft, respectively, were representative of the highest values measured at a distance of 100 ft for a 20 ft runabout/ski boat operating at wakeboarding/tubing speeds (22–24 mph), which for the local sheltered waterway was considered typical of accepted practice. These example benchmarks were included to help identify the approximate lateral distance that the waves generated by wake boats may be considered equivalent to these more "accepted" water sports activities.

A similar exercise can be performed with the more comprehensive collection of relevant wave data presented in this paper. This is attempted using a slightly different approach in Figure 10, where the maximum wave height data presented in Figure 7 is repeated but with the following modifications:

1. This data, plus additional AMC data, are grouped into speed and boat type categories, combining all relevant data from each of the three studies. The following five categories are presented: (i) all wake boats at 10–12 mph; (ii) all ski/fishing boats at 10–12 mph; (iii) all wake boats at 20–24 mph; (iv) all ski/fishing boats at 20–24 mph; and (v) all ski boats at 30–32 mph.

   Power trendlines are fitted for each of the abovementioned data series (dashed or dotted curves), providing an indication of the average for the combined results. Several studies have found that a power-based relationship exists between wave height decay and lateral distance (see, e.g., Robbins et al. 2009; Macfarlane 2012).

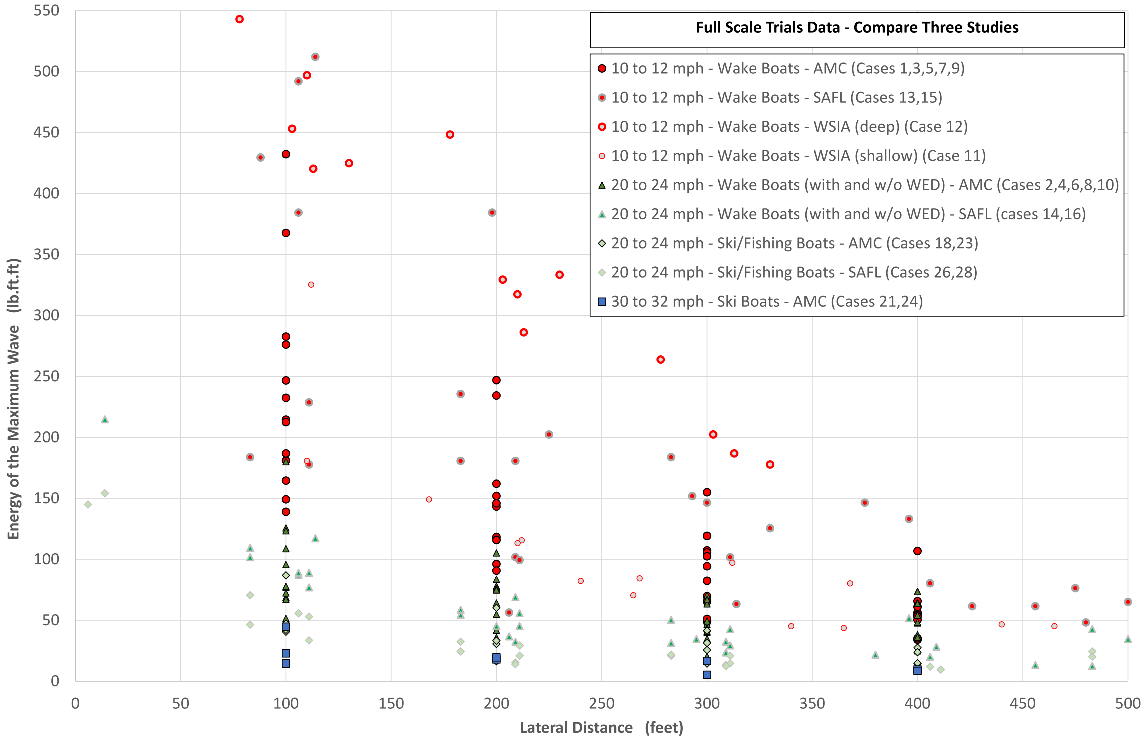

FIGURE 9 | Energy of the maximum wave as a function of lateral distance for each of the three nominal speed ranges: 10–12 mph (red), 20–24 mph (green), and 30–32 mph (blue). Where appropriate, the data have been sub-categorized into each of the three studies (AMC, WSIA, and SAFL). [Color figure can be viewed at wileyonlinelibrary.com]

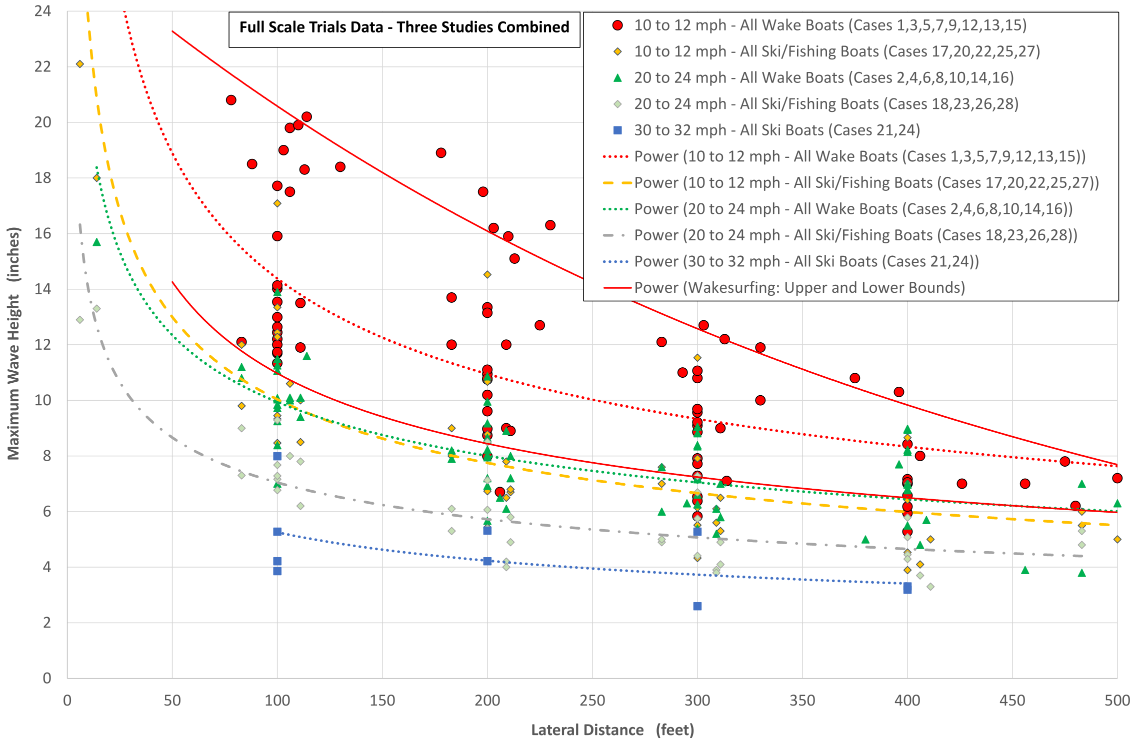

FIGURE 10 | Maximum wave height as a function of lateral distance for each of the three nominal speed ranges (all studies combined): 10–12 mph (red), 20–24 mph (green), and 30–32 mph (blue). Boat categories (wake or ski/fishing) are also identified. Power trendlines are included to assist interpretation. [Color figure can be viewed at wileyonlinelibrary.com]

2. Given the considerable scatter evident from the combined results for wakesurfing, two additional curves are added, providing approximate upper and lower bounds (some outliers fall beyond these "solid" curves).
3. Data for the single "shallow" water case (Case 11, WSIA) is not presented.

A similar comparison for the energy of the maximum wave data (from Figure 9) is presented in Figure 11. Some of the limited WSIA and SAFL data very close to the boat ($y = 6$–14 ft) lie beyond the data presented but are included when applying the power trendlines. As previously mentioned, the focus of the present study is on the more relevant data ranging between $80 < y < 500$ ft.

The abovementioned benchmarks of ~7.2 in. and 43 lb ft/ft from Macfarlane (2018) closely matches the values at which the power trendline for all ski/fishing boats at 20–24 mph cuts the lateral distance of 100 ft (which includes data from both AMC and SAFL studies). The corresponding lateral distance that the trendline for all wake boats at wakesurfing speeds (10–12 mph) meets these benchmarks is just beyond the presented data (~$y = 550$ ft). As noted in Section 1.3, the risk when making predictions that are reliant on a wave decay exponent that is defined by a very limited number of measurements is highlighted here, where the corresponding wave attenuation equation proposed by WEC (2021) suggests the wakesurfing wave height would not attenuate to ~7.2 in. until a lateral distance in excess of 1000 ft.

A second example benchmark could be defined as the value at which the trendline for wake boats at wakeboarding speeds (20–24 mph) cuts the lateral distance of 100 ft. These "benchmark" values would be approximately 10 in. for wave height and 85 lb ft/ft for energy of the maximum wave. The corresponding lateral distance that the trendline for all wake boats at wakesurfing speeds (10–12 mph) draws approximately equivalent to these "benchmark" values is around 250 ft for wave height and 400 ft for the energy of the maximum wave. For both these example benchmarks, the WSIA recommended distance of 200 ft from the shoreline, docks, or other structures would be inadequate.

4.3 | Wind Waves

An alternative benchmark occasionally adopted is to compare boat-generated waves against wind-generated waves. On the surface, using local wind waves as a benchmark may make good sense as each shoreline is presumably in a state of dynamic equilibrium (i.e., no substantial erosion or changes) based on the prevailing weather conditions. However, typical winding rivers and smaller lakes naturally have very limited fetch, plus the local topography and vegetation can attenuate wind speed. As a result, it is likely that the equilibrium of very sheltered shorelines is not impacted by wind waves much, if at all, and it may be that other riverine processes are the dominant causes of change (Cox 2020). In the case of the Willamette River, this may be more due to seasonal flows or floods rather than wind.

The WSIA acknowledges that the wind wave predictions presented in their report are applicable to more exposed waterways than typical narrow, winding rivers or small lakes where the naturally occurring wind wave climate is low due to significantly reduced fetch, as displayed from predictions

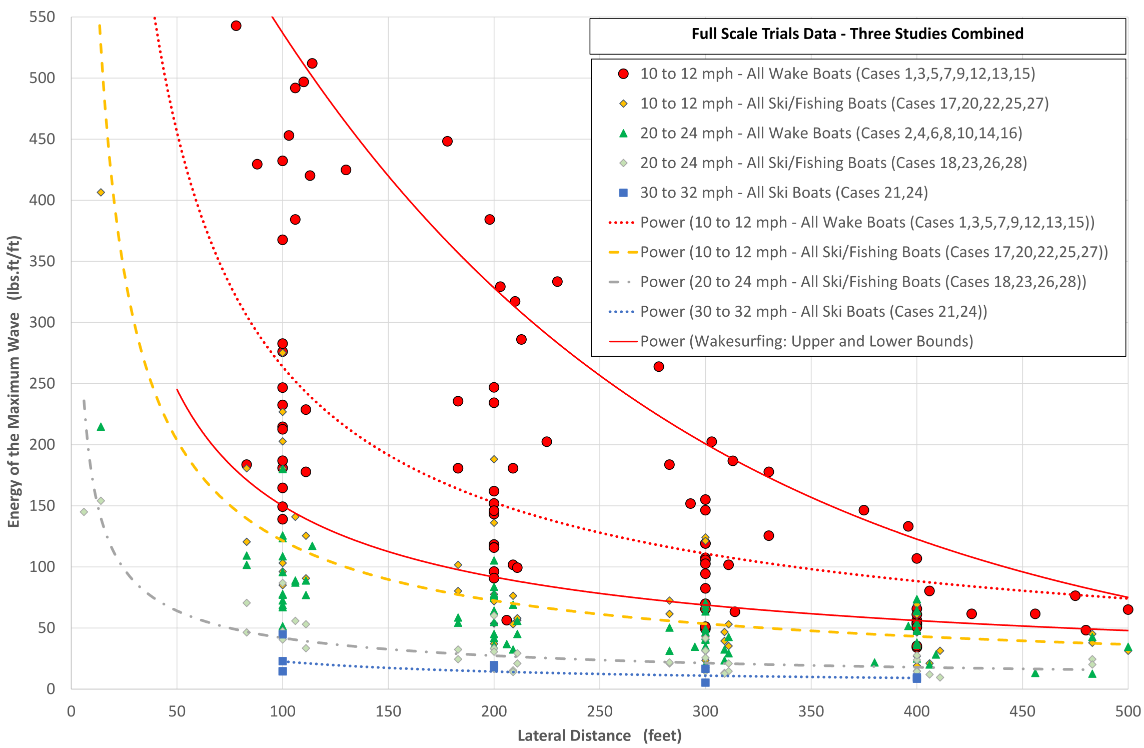

FIGURE 11 | Energy of the maximum wave as a function of lateral distance for each of the three nominal speed ranges (all studies combined): 10–12 mph (red), 20–24 mph (green), and 30–32 mph (blue). Boat categories (wake or ski/fishing) are also identified. Power trendlines are included to assist interpretation. [Color figure can be viewed at wileyonlinelibrary.com]

presented by WEC (2021). The shortest fetch WSIA considered is 1 mile: equivalent to approximately 5280 ft or ~1600 m (tab. 6, Goudey and Girod 2015). To put this into perspective, the test section for the Willamette River (AMC) trials was approximately 1000 ft wide by 3000 ft long, meaning the wind direction would have to be in close alignment with a significantly longer section of river for a lengthy duration and high wind velocity to generate waves of similar energy to those given in the WSIA assessment. It is worth noting that the largest wind waves generated would expend much of their energy at river bends, not straight stretches.

4.4 | Effect of Ballast on Wakesurfing Waves

Additional data presented in the SAFL report investigated both ballasted and non-ballasted conditions for two wake boats, where the results suggest the additional ballast had little effect on either the maximum wave height or total wave energy at lateral distances greater than 100 or 200 ft (refer figs. 31–36, Marr et al. 2022). This finding is unexpected as it is well known that increased displacement will lead to increased wave height/energy (see, e.g., Macfarlane 2012). There may be several explanations for this result. One may be experimental uncertainty, which can affect all similar studies, including those by WSIA and AMC—this is covered in more detail in Section 4.5. Another explanation relates to the steepness of the waves created. It is well understood that wake boats are specifically designed to significantly increase their displacement as this will increase the size of the surfing wave close to the boat (for speeds around ~10–12 mph). However, the added displacement has a negligible effect on the period of this wave, thus increasing the wave's steepness. When the steeper waves break, ideally just beyond the desired "surf zone," they will likely lose considerable energy. It is hypothesized that the steeper "well-tuned" surfing waves generated by a heavily ballasted wake boat may lose a greater level of energy through wave breaking than a lighter, unballasted wake boat.

Two data points presented in the SAFL report provide provisional support for this hypothesis. They acquired measurements for both ballasted and non-ballasted wake boats at a distance of approximately 5 ft from the boat and found, in one case, the maximum wave height was 34 in. when ballasted and 27 in. non-ballasted. The second case found a similar result with 39 and 31 in., respectively. In both these cases, there is a notable increase in maximum wave height for the ballasted boat compared to the unballasted, which is not the case with the data at greater lateral distances. The primary focus of all the WSIA, SAFL, and AMC studies is on the wave characteristics at notably greater distances from the boat track. Thus, further research involving measurements close to the wakeboat is required to confirm this finding.

4.5 | Experimental Uncertainty

As is the case for all in situ full-scale experiments, a level of scatter is present in all trial data presented in this paper. For the AMC study, considerable effort was placed into maintaining consistency during the conduct of the trials. However, the large number of variables and practical realities ensure that there will always be a greater degree of scatter in results from experiments conducted in any uncontrolled environment compared to those performed in the controlled environment provided by specialist hydrodynamic facilities, such as the AMC Model Test Basin (where the data in Figure 2 was acquired).

Guidelines for the conduct of full-scale wave wake experiments provided by Macfarlane (2002) are designed to minimize uncertainty such that reliable conclusions can be drawn from the data obtained. Included is an extensive list of variables and/or external influences that should be considered when planning and undertaking such experimental campaigns. Each of the following factors are known to adversely affect the measurements, so efforts were made to minimize them as much as practical for the experiments at the Willamette River site:

- method/s used to measure the speed of the test vessel and for it to remain as constant as practicable;
- vessel track path to remain straight and at the desired lateral distance;
- minimize ambient conditions, such as wind waves by picking suitable weather window/s;
- selection of a site where the water depth is considered "deep" (and approximately constant) at all lateral distances;
- use of reliable and calibrated wave sensors that are rigidly mounted in sufficiently deep water.

From the author's experience, the factor that possibly created the largest "uncertainty" in this specific study was the likelihood that the WEDs might have been insufficiently fine-tuned to achieve optimum "maximum" waves during some of the wakesurfing trials, as previously noted in Section 3.1. This could potentially mean that the AMC data for wakesurfing cases is conservative (lower than what is possible).

Repeatability was investigated by performing several tests (each test session) where conditions remained as constant as practical, and the resultant time-series wave data was overlaid graphically to assess variability. The accuracy of the measurements of both wave height and period is estimated to be within ±5%. This does not entirely account for variations in vessel speed, water depth, lateral distance, or environmental influences such as wind waves and currents, all of which may result in increased data scatter. Another key factor is the localized interaction between the divergent and transverse wave systems generated by all craft operating at subcritical (deep water) speeds. It is estimated that the combined effect of measurement accuracy and these uncontrolled sources of potential uncertainty may account for up to 10% variation in the experimental results. It is not the aim of studies such as this to identify the effect of small systematic changes, but to obtain a statistically robust number of data points where there are more significant differences in key variables, from which good engineering approximations can be obtained. These can then lead to the proposal of rational and justifiable management or regulatory decisions. It is believed that this study has achieved the key first step of this aim.

5 | Conclusions

A comparison of full-scale trials from three separate studies has confirmed that wake boats, either ballasted or unballasted, when operating around 10–12 mph, generally generate significantly higher and more energetic waves than "conventional" recreational craft operating within higher speed zones of 20 mph and above.

The data presented may assist in defining rational management options for waterways where the waves generated by sporting activities such as wakesurfing may be causing issues related to shoreline erosion, damage to maritime structures, and/or presenting a danger to other users of the waterway.

The leading advocate for the towed water sports industry in the USA, the WSIA, recommends wakesurfers stay at least 200 ft away from the shoreline, docks, or other structures. The appropriateness of this distance can be examined using the presented data from multiple locations from the sailing line of the test boats and compared against a suitable benchmark. It is likely that some rational benchmarks may recommend a greater distance, likely to be in excess of 350 ft when considering wave height and 500 ft when considering wave energy. In the vast majority of cases where vessel wave wake is being assessed, the author believes wave energy to be a notably more appropriate measure than wave height for the reasons presented in Section 1.2.

Acknowledgments

The full-scale experiments on the Willamette River, Oregon, were performed in collaboration with the Oregon River Safety and Preservation Alliance (ORSPA). A special mention is deserving of the tireless efforts of Steve Gregg from ORSPA. The author acknowledges the support of the Australian Research Council via Linkage Project LP150100502, which supported the development of wave measurement equipment. The experimental data on the effect of water depth on the waves from wakesurfing activities presented in Figure 2 were acquired by Robert Buchanan as part of his Honors thesis for his BEng degree in naval architecture, under the supervision of the author. Dr. Gregory Cox reviewed a near-complete draft and provided valuable input. Open access publishing facilitated by University of Tasmania, as part of the Wiley - University of Tasmania agreement via the Council of Australian University Librarians.

Data Availability Statement

The data that support the findings of this study are available from the author upon reasonable request.

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