CHARACTERISTICS OF RECREATIONAL BOAT WAKES

by

ROBERT SHUSTER

DOUGLAS J. SHERMAN, COMMITTEE CHAIR

LISA DAVIS
MARK LORANG

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ABSTRACT

The applicability of using a boat's size and speed to predict the energy in its wake was studied. A portion of the Georgiana slough, a tributary of the Sacramento River, was instrumented with a data logger, camera, and KPSI 720t pressure transducer to record boat passages and the resulting wake. The camera was set to record when triggered by a motion sensor and the data logger to save data only during daylight hours. The instruments were left in place for roughly the month of September 2009. The data gathered were then grouped into wake categories based on size, speed, and boat type. Distance from shore for each boat creating a wake was assumed to be the same for all boats in the relatively narrow channel. A low statistically significant correlation (linear regression) was found between boat speed, size and type with measures of shoreline wake heights. This surprising result may have been caused by several factors to be discussed but mainly due to boat length not actually capturing boat displacement which when combined with speed creates disturbance we see in the form of a boat wake. Using a double reciprocal regression model $boat\ size^3$ was found to have the strongest correlation to index wave energy with an r^2 value of 87, and a $p < 0.0001$. Boat size was raised to the third power as a surrogate measurement of boat length, width, and hull depth to better capture a metric more closely associated with disturbance force. These results suggest that a boat's size, which can be obtained remotely from cameras, can be used to help predict the energy content of the wake it can produce. This could be used to help assess possible erosion impacts due to boat wakes and possibly help to establish no wake zones for sensitive water bodies.

DEDICATION

This thesis is dedicated to everyone who helped me and guided me through the trials of creating this manuscript; particularly, my family, close friends, and work colleagues who stood by and supported me throughout the time it has taken to complete it.

LIST OF SYMBOLS AND ABBREVIATIONS

cosh	Hyperbolic cosign
D	Depth
Df	Degrees of freedom: number of values free to vary after certain restrictions have been placed on data
E	Energy
FS	Full scale
g	Acceleration due to gravity
h	Total water column depth
H	Corrected wave height
HD	High definition
Hz	Hertz
k	Wave number calculated
kph	Kilometers per hour
Km/h	Kilometers per hour
K_p	Pressure response factor
kgm^2/s^2	Kilograms per meter squared per second squared
L	Shallow water wave length
L	Wave length
L_∞	Deep water wave length calculated
m	Meters

mph	Miles per hour
m/s^2	Meters per second squared
m/y	Meters per year
PWC	Personal Watercraft
r^2	Variance statistic
SSC	Suspended Sediment Concentrations
T	Wave period
tanh	Hyperbolic tangent
V	Volts
z	Calculated pressure transducer reading
z_c	Water surface fluctuations
ρ	Density of water

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INTRODUCTION

Wakes that are generated by recreational boats have the potential to cause erosion along unprotected shorelines (Figure 1). On a global scale, the size, speed, and traffic of large vessels are increasing. Interest in shoreline ecological impacts due to boat wakes has risen over the past decade (Gabel et al. 2008, Gabel et al. 2011, Gabel et al 2011, Gabel et al. 2017). Increased boat traffic has the potential to redistribute large amounts of sediment or contaminates (Rapagila et al. 2010). While it is accepted that large commercial ship wakes can be the cause of significant erosion (Houser 2011), less work has been done on smaller recreational boats and the wakes they create. The focus of many studies is to quantify and record the impacts that boat passages have had at a specific location (eg. Bauer et al. 2002, Castillo et al. 2000, Ellis et al. 2002, Houser 2011, McConchie and Toleman 2003, Osborn and Boak 1999, Rapaglia et al. 2010, Schwimmer 2001, Soomer et al. 2009). These studies are helpful in recording how the processes involved in wake erosion take place by recording location specific interactions. These data can then be used to infer about other locations that share characteristics, but few studies have been conducted that directly study the relation between boats and the wakes created by their passage (Laderoute and Bauer 2013).

This study examines the relationship between recreational boats and the wakes they produce in a river channel. Using data obtained from a pressure transducer, data recorder, and video camera, wakes are matched to the boats that made them. While research about this topic is increasing, there are few data linking boat characteristics to their wakes; likely owing to the conditional nature of a boat's wake. Depending on variables such as water depth, hull type, and boat speed, the wake characteristics produced by any one boat can be difficult to predict. This study is aimed at filling this knowledge gap by trying to answer two questions: 1) can a boat be linked to the wake it creates using a pressure transducer and video camera, and 2) how is a recreational boat's wake controlled by the characteristics of a boat and its passage?

Figure 1. Picture of a river bank after a boat passage, the resulting wake caused mud erosion along the unprotected shoreline. Photo courtesy of Douglas Sherman.

BACKGROUND

Very few studies have related boats to the wakes they create, and most of those studies have focused on large ships or commercial vessels and their impacts instead of recreational boats (Garel et al. 2008, Houser 2011, Kurennoy et al. 2009, Osborne et al. 1999, Parchure et al. 2001, Soomere et al. 2009). With the operation of watercraft in sheltered waters, the hydrodynamic energy in a system increases (Ailstock et al. 2002). When this increased energy surpasses the shear stress needed to entrain sediment, erosion or re-suspension can occur.

Anderson (2002) found that the turbidity of a river rises significantly after the passage of a personal watercraft (PWC). The PWC speed and weight of passengers also affects the turbidity after each passage. With higher speeds, the boats plane out of the water and with increased passenger weight the boats sat lower in the water causing greater displacement and greater waves. Immediately following a boat passage, suspended sediment concentrations (SSC) increase above normal background levels (Osborne and Boak 1999). McConchie and Toleman (2003) found that SSC in a wave train produced by boats were as much as 100 times higher than background levels and could remain elevated for long periods of time after an event. Some studies, like the one by Villard et al. (2000), were conducted in laboratory wave tanks to control conditions. While the focus was on the wakes, Villard et al. (2000) were researching the interactions of the wave train and how it re-suspended sediment from the bed. Working in a flume with controlled wave generation allowed better observation of individual waves in the wave train and the resulting re-suspension of sediments. They found that the highest SSC occurred in tandem with the largest wave, and that above roughly 0.10 m from the bed, SSC lagged behind the wave train by about two or three waves.

Bauer et al. (2002) identified most boat wakes as having a leading trough. Following that, the first three waves (referred to as the wave packet) in any boat wake are usually large and easily identifiable before interaction with the shoreline. Along with depth gauges, they also had an array of optical back-scatter sensors to measure suspended sediment concentrations (SSC). Their study found that the leading three waves each increased the SSC, peaking as the last wave of the packet passed by the sensors. It was also found that water depth played a large role in the SSC and the wakes' interaction with re-suspending sediments from the bed. Several of the sensors in deeper water showed little to no rise in SSC because of the boat passage, but the instruments closer to shore showed large increases in SSC with each boat passage.

Ellis et al. (2002) conducted a study on the Georgiana Slough, a tributary of the Sacramento River. Focusing on the impacts of brush bundles installed as a form of erosion prevention, they measured water depth, boat passages, and suspended sediment concentrations both before and after the installation of the brush bundles. They concluded that these bundles do work as a form of erosion control, as well as being less expensive than other forms of control, such as rip-rap, and were better aesthetically for the area. While the bundles did affect wake energy, reducing it as much as 60%, erosion potential still varied with water depth. These observations support the idea that recreational boats may cause more erosion than commercial vessels due to the location which they operate.

Several studies have recorded the impacts of boat wakes on shorelines and suspended sediment concentrations. McConchie and Toleman (2003) found during their study on the Waikato River, New Zealand, the erosive potential of any given wake depends on factors such as water depth and current speed/direction, and that vessel-generated wakes have more erosive potential than the wind-driven background waves. Schwimmer (2001) conducted a study at Rehoboth Bay, Delaware, and found that the marsh shoreline was eroding rapidly due to wave attack. After surveying sections of shoreline over three years, he found that they were eroding at rates from 0.14 m/y to 0.43 m/y. Soomere et al. (2009) reported from the Aegina Isle, Baltic Sea, that even though ships contributed only a small percent to the beach energy, ship wakes still prevented the beach from reaching a morphologically “stable” form because of the angle at which they struck the shore. Rabaud and Moisy (2013) studied the angle at which a wake is produced, likening it to the Mach cone produced by jet airplanes. The faster the boat was traveling, the closer to parallel to the path of travel the waves became. When a boat changes speed, the angle of wake relative to the shoreline changes. This means that boat wakes rarely match the angle in which natural wind driven waves strike the shore. Researching salt-marsh erosion in southwest Spain, Castillo et al. (2000) found that boat traffic through the marsh led to a drastic increase in the rate of undercutting of the bank (Figure 2).

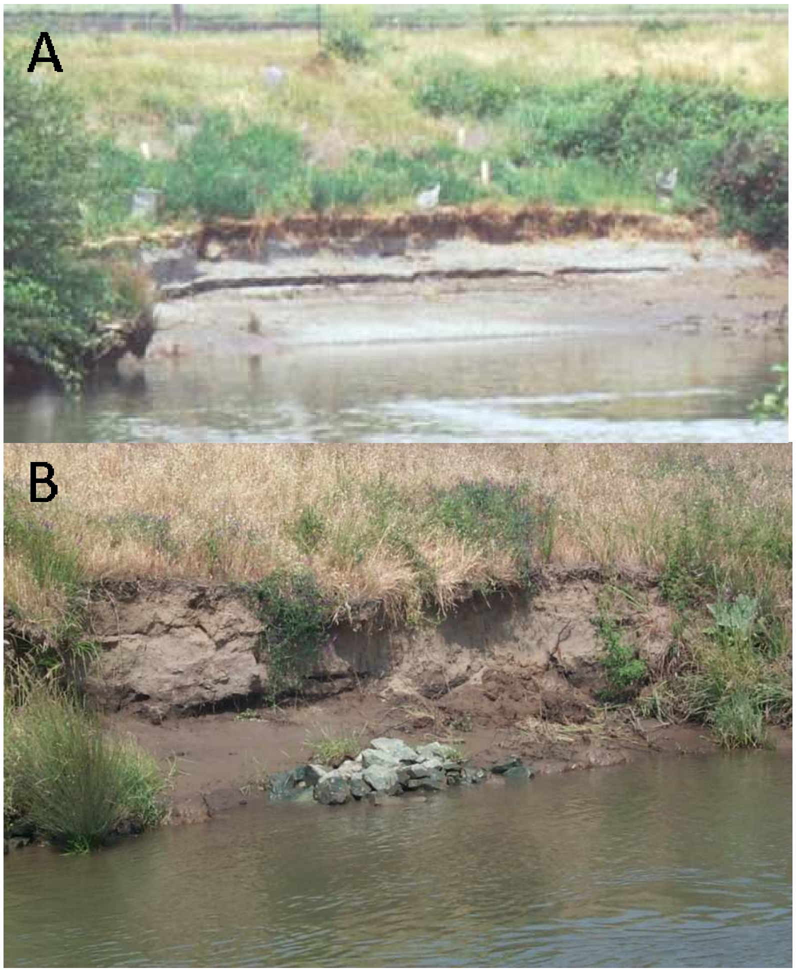

Figure 2. A/B River banks suffering from wave attack, mainly from boat wakes, resulting in undercutting of the bank. Photos courtesy of Douglas Sherman.

Not all shorelines suffer negative impacts from the passage of boats. Examining a sand and gravel beach, Curtiss et al. (2009) found that ship-generated waves had a unique relation with the other driving forces at Bainbridge Island, Puget Sound. Erosion was mostly driven by winter storms. In non-storm intervals, a combination of vessel waves and tidal flows was responsible for most sediment transport. During these conditions, tidal flows and ship waves would help re-establish the beach recovery after each storm interval. In Venice Lagoon, Italy, Rapaglia et al. (2010) studied a shipping channel by recording the wakes produced by large container ships and the SSC created by their passage. They found that if the cargo ships kept below a critical speed, the wakes produced would not create suspended sediment concentrations exceeding background levels.

In fetch limited environments, such as rivers, recreational boat traffic may be the primary source of wave energy. Comparing the wakes created by boats to those of background wind waves, Fonseca and Malhotra (2012) piloted two boats with similar hull shapes but varying sizes of 7 m and 16 m, and at varying speeds of 3, 10, and 20 knots (about 3.5, 11.5, and 23 mph respectively) past an instrumented shoreline. Using only the top 5% of background wind generated waves, they found that boat wakes still contained more energy with an increased chance of sediment suspension. They also stated that vessels over 7 m in length frequently generated wakes strong enough to create sediment suspension regardless of the speed at which they were travelling.

Garel et al. (2008) obtained measurements (pressure, currents, and turbidity) taken at 4 Hz by instruments and recorded the impacts of two large commercial vessels. Combined with the analysis of currents and sediment suspension, anthropogenic bank erosion was predicted at their location. Houser (2011) found that the wakes caused by pilot boats on the Savannah River, GA, caused a net sediment transport offshore, although the direction of transport from some individual waves in the wave train was landward. Kurennoy et al. (2009) used recordings of wakes caused by fast moving sea ferries. The data were used to create functions of different wake properties, such as maximum height, wake energy, and energy flux, and found that an appropriate estimation of the wave variables could be based on wave height. While not linking a wake to the boat that made it, this article helped validate the use of an index wave to represent the wake. At the Waikato River, New Zealand, McConchie and Toleman (2003) conducted controlled studies to quantify the impacts of boat wakes at several locations along the riverbank.

After picking locations for differences in bank morphology, three boats were piloted past recording instruments at each location at two speeds, fast (50 km/h) and slow (10 km/h). Results showed that erosion potential depended more on the location characteristics, such as the presence of vegetation or bank material, than on the boat's size or speed. This illustrated that more studies need to be done linking boats to the wakes they create and the energy potential in those wakes. The energy content of the wake could then be compared to a survey of the shore, bank material, and any other factors to determine how much if any erosion might occur (Figure 3).

Figure 3. A boat wake about to strike the river bank. Photo courtesy of Douglas Sherman.

Some studies have found wave impact on bank erosion to be insignificant. Osborn and Boakt (1999) found that while large amounts of sediment were re-suspended with the occurrence of wakes, the movement of the sediment away from its origin was mitigated by a shoreward flow which resulted from the wake's interaction with the shore. So, any sediment suspended would not move from its original location by a significant amount.

Lack of data linking a boat to its wake causes a gap in the understanding of river processes. By primarily looking at wave to shore interaction, past studies have greatly increased our understanding of what happens when a wave interacts with the shoreline. However, the characteristics that create these usually high-energy waves still need to be studied and understood. If a link between boat characteristics and wake energy is made, it could predict areas with high erosion potential. Preventative measure could then be taken to mitigate any issues that arise before becoming a greater burden either financially or environmentally. Measures could also be passed on boat characteristics prohibiting boats of certain sizes from traveling smaller waterways. While no-wake zones already exist, speed zones based on boat size may also help alleviate erosion pressures on high risk areas, and this could be made based on the boats characteristics and their interactions with the wave produced.

STUDY LOCATION

My study site is located near Walnut Grove on the Georgiana Slough, a tributary of the Sacramento River in California (Figure 4). Much of the Sacramento-San Joaquin Delta is at or below sea level. Land subsidence as well as sea level rise have placed large amounts of land in the area at great risk of flooding and inundation. To help mitigate this risk of flooding over 1,000 miles of levees have been built up to protect the human population in the area. These levees are built to prevent overflow or failures of a 100-year flood event, but many locations suffer from chronic and acute erosion effects that could reduce the levees integrity. This degradation poses a threat to the long-term stability of the structures. The Georgiana Slough is also a significant boat-traffic corridor, as well as substantial river discharge and tidal influences. Many of the levees on the Georgiana Sloughs are unarmored or are poorly maintained. The selection of this site as the study location was guided by several factors such as no recent signs of bank armoring or maintenance, a lack of vegetative cover, and the presence of a vertical cut bank. The semi-linear section of riverbank also helped prevent complications from wave refraction or secondary flow effects. The section that was instrumented is roughly 40 m wide (Figure 5). While there are tidal influences, this is a predominantly fluvial system. Water depth at the instrument location ranged due to these tidal influences from the lowest point of .48 m, recorded during wake #117 on 9/12/2009 at 8:31 AM, to the highest of 1.01m, recorded during wake #137 on 9/13/2009 at 14:52 (Figure 6). The camera, transducer, and data logger were in place for one month, September 2009. During that month 187 boats and their wakes were recorded.

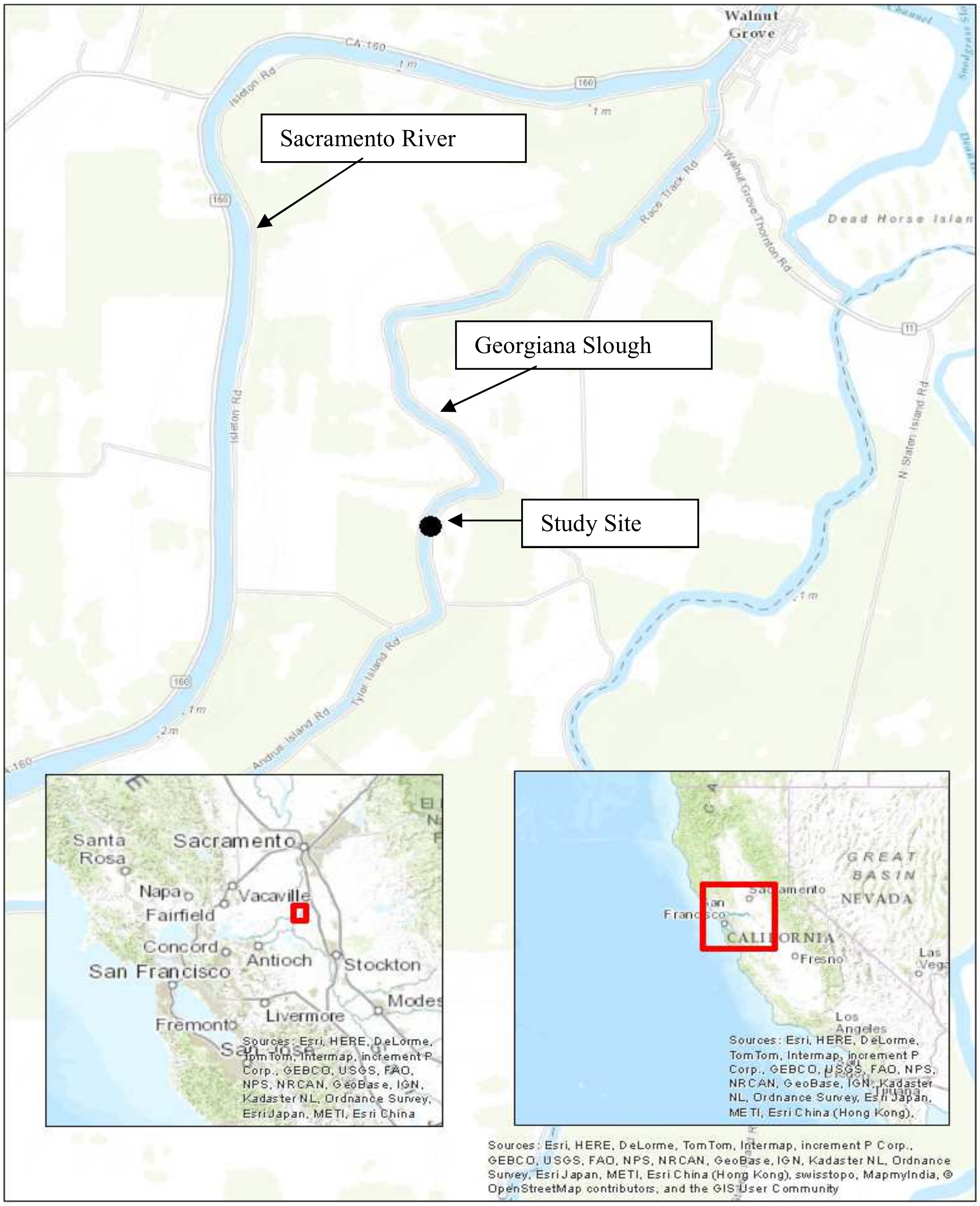

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Figure 4. The study site in California, as well as the location of instruments for this study represented by the black dot in the image.

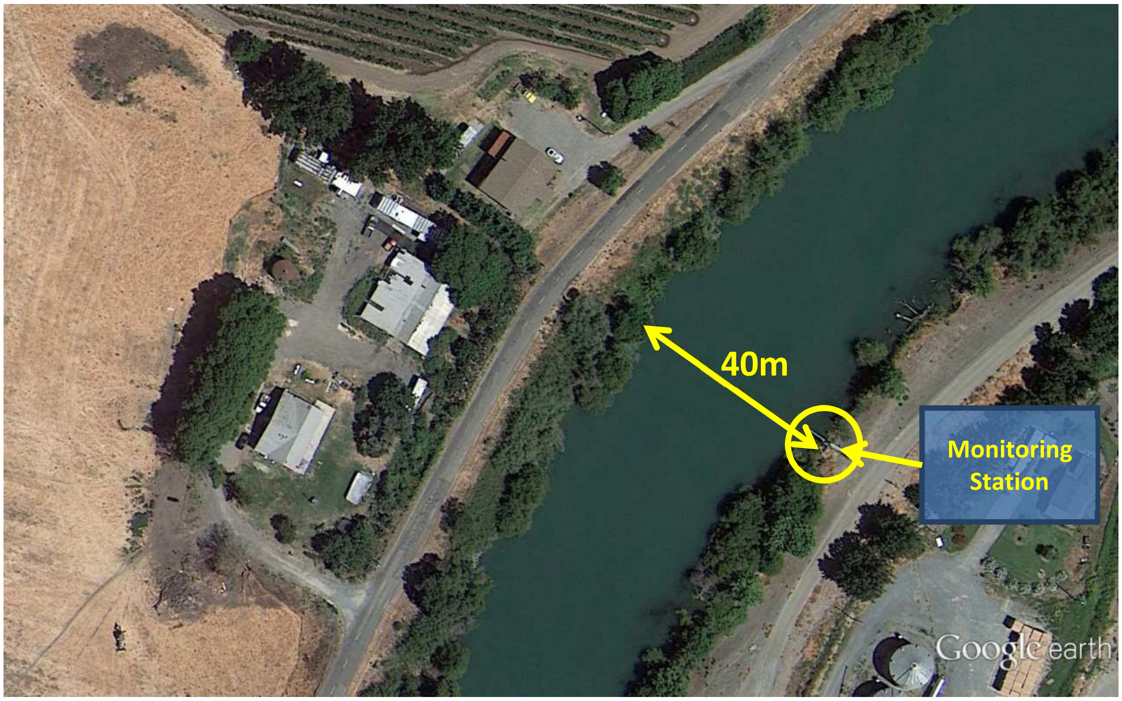


Figure 5. Aerial image of the study site showing characteristics and location where instruments were installed

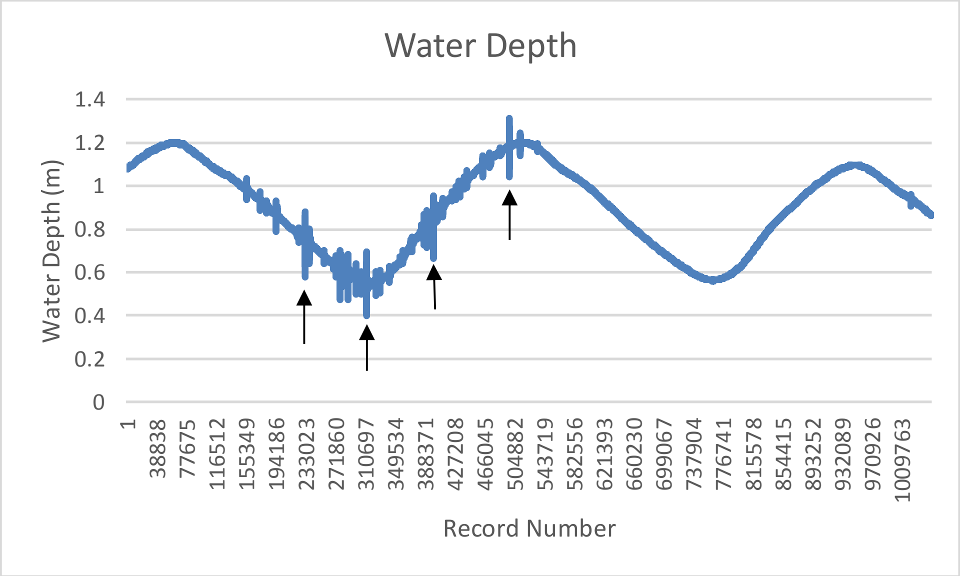


Figure 6. Water depth measurements taken 10 times a second for 9/6/2009 starting at 5:20 AM going until 10:30AM illustrating the tidal influences. The disturbances in the water depth (marked by arrows) are boat passages that caused wakes during this time.

METHODS

Camera footage and pressure transducer measurements from the study site were obtained for analysis. Water depth measurements were taken to measure wave height and wave period. To get these measurements a KPSI 720T transducer sampling at 10Hz with an accuracy of ±.25% FS (percentage of full scale) was installed 0.15 m above the river bed and connected to a data logger. The camera was set to record continuously during daylight hours and to include a time and date stamp on the bottom corner of the footage for reference. The data logger however only saved the footage when triggered by a motion sensor. The saved footage began 10 seconds before the triggering event and went for 30 seconds after it had passed. A video editing program was used to delete footage associated with false triggers or boats with wakes disturbed by other factors, such as a visibly small wake, high winds, or multiple boats passing within quick succession preventing a definitive match with any records (Figure 7).

To remove the footage the video was watched in the editing program and anytime a false record was seen it was clipped from the footage. Further editing of videos was also done to trim the videos to the moment the boats appeared in the footage until the wakes they created hit the shore line to make matching video footage and transducer records easier.

Figure 7. (A) Example of a boat producing a "usable" wake, (B) Boat producing an un-usable wake because it is too small. (C) Multi-pass as two vessels can be seen passing the instrument preventing a wake from being assigned to either boat, (D) A false wake in this case caused by high winds and rain.

The time stamp from the video footage and the timer on the transducer were out of sync. To correct this, the first day of video was used to find the time between the first five wakes for that day. The transducer measurements were then matched to these intervals using the time between each wake as a guide. It was found that the transducer measurements were three minutes and forty seconds ahead of the video time stamp. Video footage and transducer values were then matched so each value could be linked to the footage of the boat that made it.

The transducer recorded its measurements in voltage but was converted to depth equivalents using $\mathrm{D} = \mathrm{V}/0.01504$ where D is depth of water above the transducer and V is volts.

The converted data were plotted and the wave height and length were obtained using an index wave measurement. The index wave used for each wake was the largest in the series and was used to estimate the maximum wake energy (Bauer et al. 2002). The down crossing method (Figure 8) was used to find the wave height and period for each index wave (Sobey 1992).

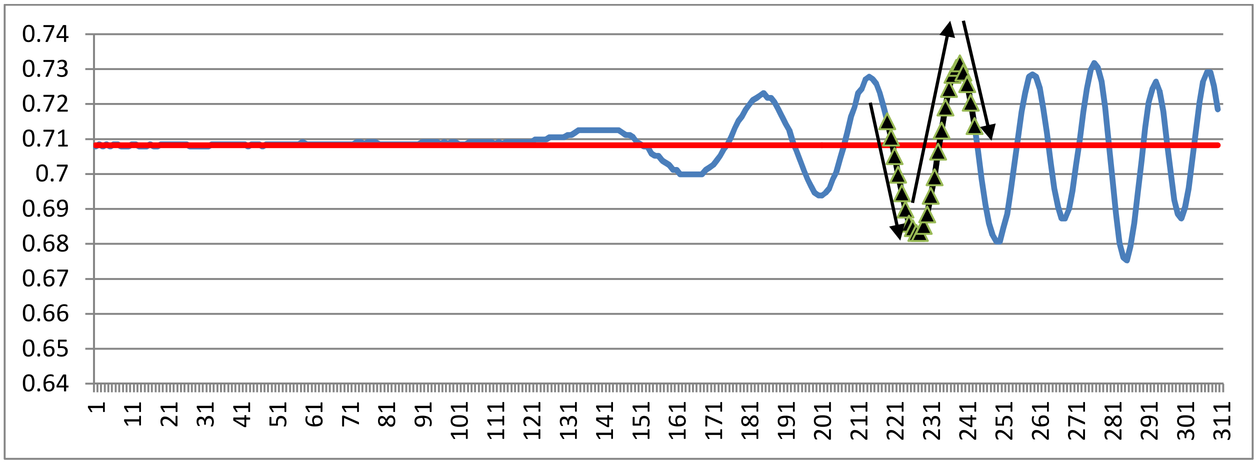


Figure 8. Example of the down crossing method using Wake #5 from 9/5/2009 at 2:07:05 PM. The black section represents the index wave for this wake and the red line showing the average depth. Crossing the mean line going down (point A), the index wave starts there until it crosses the mean line going down again (point B).

Wave length and wave period from the index wave were used to calculate estimates in water surface elevations, z_c, using the same method as Ellis et al. (2003) where:

$$z_c = \frac{z - \bar{z}}{K_p}$$

where z is the calculated pressure transducer reading, the over bar indicates a time average, and K_p is the pressure response factor.

$$K_p = \frac{\cosh k(h - z)}{\cosh(kh)}$$

where h is the total water column depth and k is the wave number calculated using:

$$k = {}^{2\pi}/_{L}$$

where L is wave length, and is calculated using:

$$L = L_{\infty}[\tanh\frac{2\pi h}{L_{\infty}}]^{1/2}$$

where L_{∞} is deep water wave length calculated using:

$$L_{\infty} = \frac{gT^2}{2\pi}$$

where g is acceleration due to gravity (9.8 m/s^2) and T is wave period.

The index wave energy was then calculated using:

$$E = 1/8\rho g H^2 L$$

where E is energy (kgm^2/s^2), ρ is the density of water (1,000 kg/m^3), g is acceleration due to gravity, H is the corrected wave height, and L is shallow water wave length.

The video footage was used to determine the size and speed of each boat. The footage was watched and general characteristics for each boat were recorded including size, speed, basic hull shape, and distance from the camera. For measurements of size and speed, a "known" distance was not found on the video; so other methods were used to create estimates. For the creation of the estimates, PWC, such as jet skis, Skidoos, etc. were used.

Video footage was found of the PWC as they passed the camera in each segment of the river channel (near-camera, mid-channel, and far-bank) to help with scaling based on distance (Figure 9). The typical sizes of these PWC are 1.83-2.7 meters (6-9ft). A standard size of 2.4 m (8 ft) was used because only single rider craft were used to make the size estimations. The sizes of these craft were used to estimate the size of other boats according to their location in the river channel. As boats passed the camera their general location in the river was noted. The appropriate length measurement based from the PWC was used to get a length estimate for larger boats.

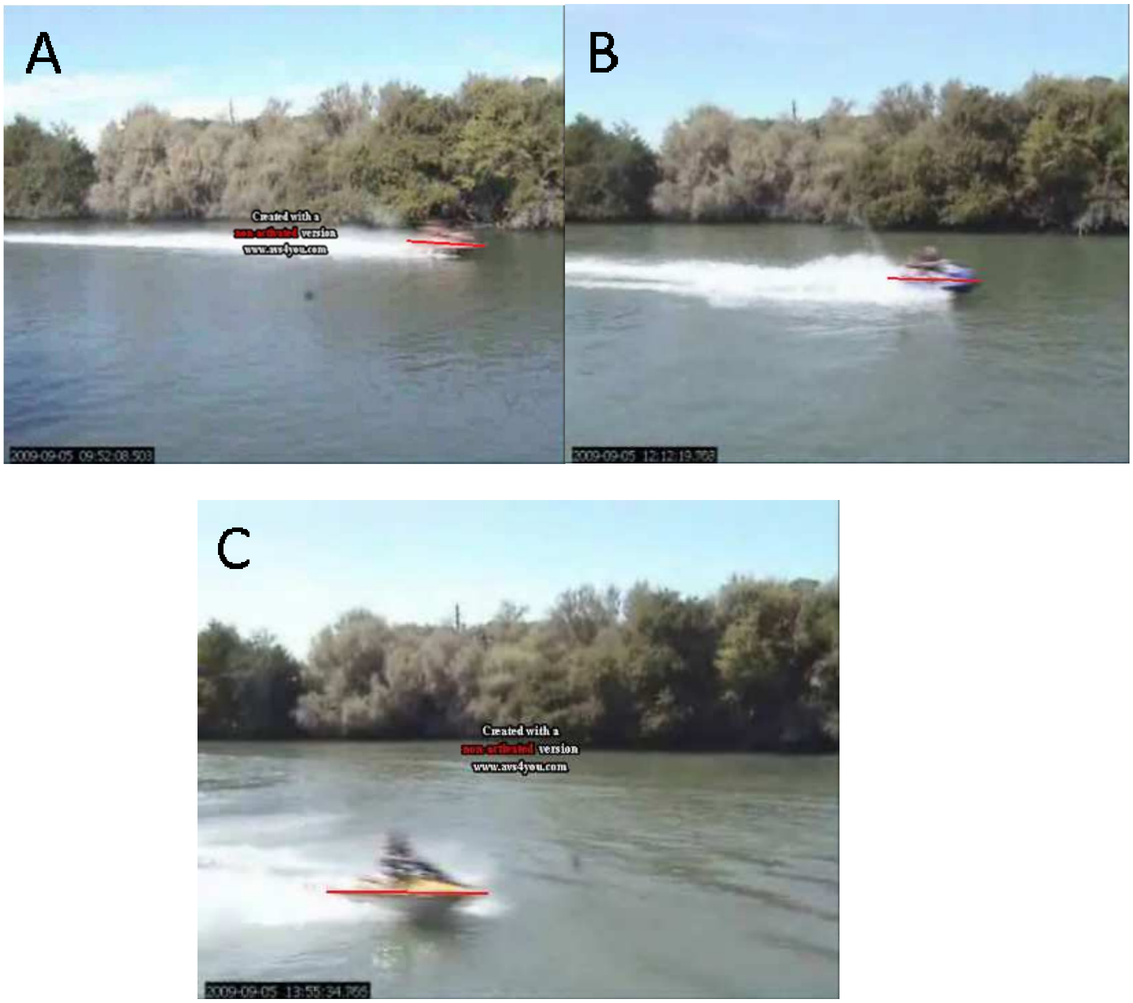


Figure 9. Photo examples of personal watercraft used to create the size estimate for (A) far-, (B) mid-, and (C) near- portions of the channel with the red line denoting the measurement taken to show 2.4m (8ft).

To estimate speed, the same process was used to get a “known” distance for each section of the river channel. Using the length estimate to measure the distance covered by each boat, the time stamp from the video showed how long it took to cover the distance, and was converted into distance per second and then ultimately into kilometers per hour (km/h).

Statgraphics, a data analysis program, was downloaded from www.statgraphics.com and used for analysis of the data. Simple regressions were run using this program to explore what relation might exist between boat size, speed, and other factors to the index wave energy.

RESULTS

After removing any records deemed un-usable due to double passes, false records, small wakes, or other factors such as weather, 147 wakes were left. The depth correction equations increased the index wave heights of these remaining wakes by an average of 0.03 m. The largest increase was wake #134 which was increased by .12 m, and the smallest was wake #126 which was increased by 0.01m (Figure 10).

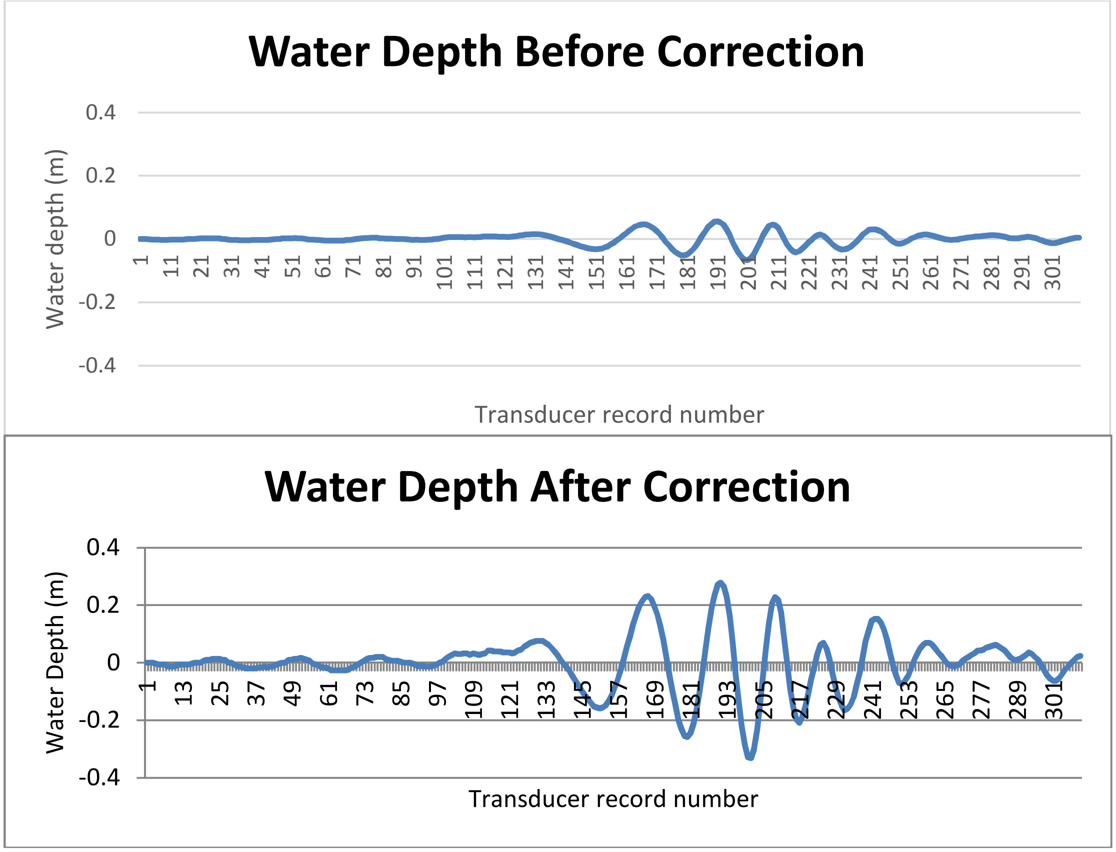


Figure 10. Example of wake #5 from 9/5/2009 at 2:07:05 PM graphed before and after water depth correction. Index wave height for this sample increased by 0.023m.

An exploratory simple linear regression was run in the Statgraphics data analysis program using all the boat records. This was run for boat size compared to index wave energy, and separately for boat speed to index wave energy, to explore any relationships that the two factors might have (Table 1). During these regressions boat size was raised to the 3rd power to create a crude approximation of volume.

Data	Variable	r^2	*p* value
All	speed	-5.6	0.0001
All	size	+7.7	0.0001
Core boat types boats	speed	-5.7	0.0001
Core boat types boats	size	+10.4	0.0001
Types and size	speed	-5.6	0.0001
Types and size	size	+13.0	0.0001
Types, size, and speed	speed	-9.5	0.0001
Types, size, and speed	size	+26.5	0.0001
Fully trimmed data using Comparison of models	speed	-12.1	0.0001
Fully trimmed data using Comparison of models	size	+87.4	0.0001

Table 1. Regression results from all stages of analysis comparing both $boat\ size^3$ and boat speed to index wave energy independently.

Boat size shows a positive correlation with wave energy meaning as a boat gets larger the energy in its wake increases. Boat speed has a negative correlation meaning that as a boat speeds up the energy in the wake will tend to decrease. This matches a boat as it planes on top of the water. With less of its hull in the water the boat's displacement decreases making a less energetic wake. Both aspects have a statistically significant impact, each with a p value <0.0001, but the r^2 for each factor is still low. With a large standard error, this was thought to be due to the wide variability in the boat types, sizes, and speeds included in the data. After the initial regression, boat types were edited to include only what was deemed "normal" so all pontoon, houseboats, PWC, cigarette boats, etc. were removed. The regression was then re-run with boat size and speed compared to index wave energy.

The p value for each factor remained <0.0001. The r^2 value did increase slightly, but the standard error did not improve noticeably. Data standerdizing was done based on boat sizes, removing any records with boats smaller than 3.048 m (10 ft.). Any boats smaller than that tend to be PWC. Boats larger than 15.24 m (50 ft.) were removed, as these tend to be larger luxury cruisers or house boats. Boats of this size are less common and are almost always producing a wake due to water displacement of hulls that large.

With p values remaining <0.0001, the r^2 increased by a small amount for boat size, but decreased by .16% for boat speeds. Another standerdizing was done to boat speeds to refine the data further. Boats going slower than 16 kph (10mph) were cut. Speeds for no wake zones are usually defined as operating at a minimum speed required to steer and make headway, usually around 5 mph (Mehta 2014, Oregon State 2015). This speed is supposed to allow just enough power to the boat for navigation, but not enough to affect anything around it. At this speed, boats are not going fast enough to produce a substantial wake, and have not begun to rise out of the water. That slow speed makes any impact inconsequential. The average boat does not begin to plane on top of the water until around 24-32 kph (15-20 mph) (Abj87 2009, Tashasdaddy 2009). Boats going faster than 87 kph (55 mph) were also cut. Boats are completely planning on top of the water after reaching this speed.

The last regression raised the r^2 value for boat size to 26.26%, but further decreased the $r^2$for speeds to 9.47%. With the final trimming, the number of wakes included in the analysis is 88. After the depth correction equations and measurements based on the index wave of each wake, the average energy was 96.71 $\mathrm{kgm^2/s^2}$, and the sum wave energy for the wakes is 8,316.8

kgm^2/s^2. The weakest of the remaining wakes was caused by boat passage #109 with index wave energy of 2.76 kgm^2/s^2, and the strongest index wave energy is from passage #38 with 1021.79 kgm^2/s^2 (Table 11 and Figure 11).

With all standardizing finished, Statgraphics was used to run an exploratory statistical analysis. The regression was re-run in Statgraphics using the fully edited data, with output showing which regressions models created a strong statistical relationship. For $boat\ size\ (m)^3$, the best relation was created using the model IWE=1/(-0.012276+8,90461/boatsize^3), a double reciprocal regression (Figure 11). For boat speed, the best relation IWE==(17.9041-1.61407*sqrt(speed))^2, a double square root regression (Figure 12).

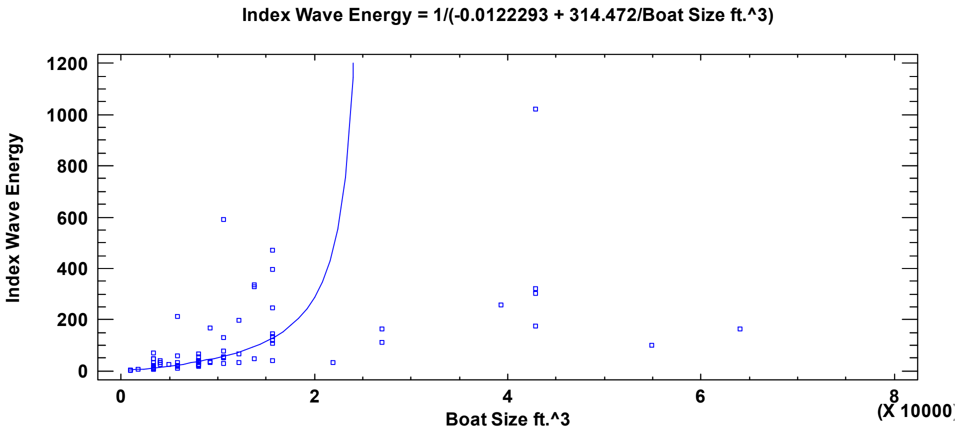


Figure 11. Double Reciprocal regression graphed with boat size^3 with a best fit line.

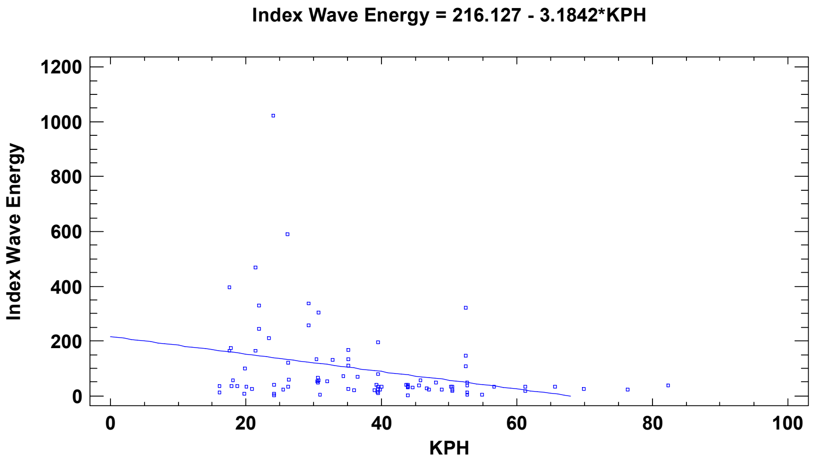


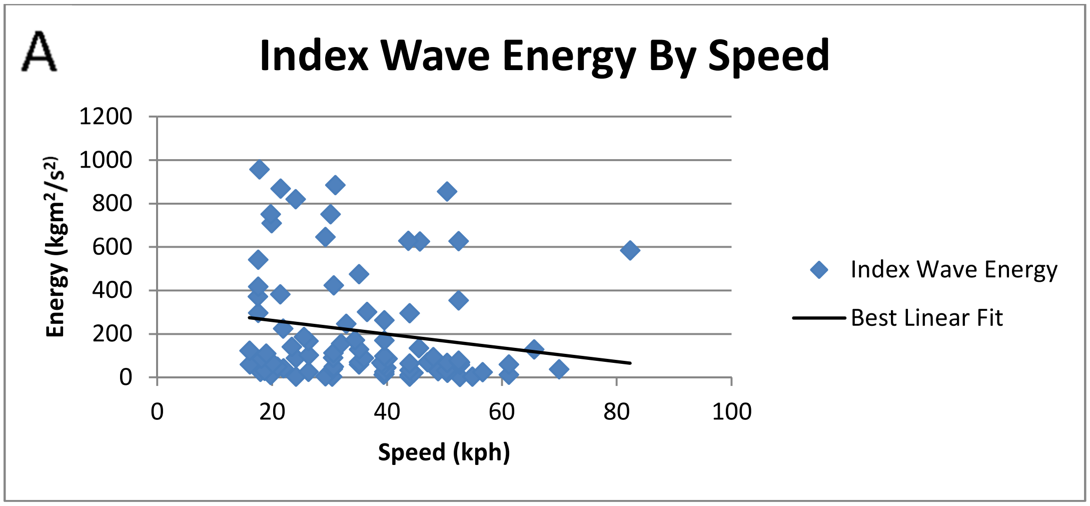
Figure 12. Double square root regression using boat speed with a best fit line.

The new regression showed $boat\ size^3$ to have a p value< 0.0001, and an r^2value of 87.38%. meaning that boat size has a statistically significant impact on the energy in the index wave of a wake, and that boat size also explains much of the variability in index wave energy. Boat speed also has a *p* value <0.0001, but an r^2 of only 12.06%. While it may be statistically significant the variability is still too large for boat speed to mean much.

Wake #	Date	Wake Start Time	Description	Total Water Depth (m)	Wave Height (h) After	Shallow Water Wave Length	Boat Size (m)	KPH	Index Wave Energy
1	9/5	12:09:35	PB,O,SA	0.67	0.08	5.65	7.32	52.67	47.55
5	9/5	12:23:42	PB,SA	0.64	0.18	3.81	7.62	52.46	145.30
6	9/5	12:28:15	PB,O,SA	0.64	0.10	5.53	7.01	36.51	67.78
7	9/5	12:35:55	G,O,SA	0.63	0.06	5.22	5.49	35.92	20.66
11	9/5	13:19:38	DFS,DA	0.57	0.15	6.52	10.67	17.77	174.58
17	9/5	14:03:07	PB,O,SA	0.57	0.04	5.01	5.49	52.67	12.24
18	9/5	14:14:54	PB,SA,O	0.59	0.04	5.35	4.57	16.09	12.76
19	9/5	14:22:51	PB,SA,F	0.60	0.07	5.14	6.10	65.57	32.07
21	9/5	14:30:31	PB,DSF,O,DA	0.62	0.28	6.01	6.71	26.09	590.55
22	9/5	14:48:12	O,SA,F	0.67	0.05	5.07	6.10	50.45	17.12
23	9/5	14:53:40	O,SA,F	0.68	0.12	4.81	6.71	39.50	79.61
24	9/5	14:54:10	PB,DA,B2	0.68	0.14	6.55	9.14	21.47	164.58
26	9/5	15:02:21	SA,O,PB	0.70	0.08	5.18	6.10	45.53	37.68
27	9/5	15:13:13	SA,PB,O,F	0.74	0.07	4.97	6.10	39.50	31.88
28	9/5	15:14:30	SA,PB,O,F	0.75	0.06	5.30	5.49	39.03	20.22
29	9/5	15:17:54	SA,CC,O,F	0.76	0.15	5.95	6.40	35.11	166.58
31	9/5	15:24:23	SA,F,PB	0.78	0.07	6.32	6.10	16.07	36.56
32	9/5	15:34:04	SA,S,O,F	0.80	0.06	5.10	5.49	47.03	23.22
33	9/5	15:35:58	SA,O,PB	0.81	0.09	5.13	6.71	31.97	52.79
34	9/6	9:38:13	S,SA,O	0.99	0.12	6.58	9.14	35.11	109.89
35	9/6	10:21:40	PB,O,SA	0.91	0.06	6.39	6.40	56.61	32.85
36	9/6	10:42:38	PB,DA,IN,B2	0.87	0.16	7.92	7.62	21.92	245.01
38	9/6	11:43:53	PB,DA,IN	0.76	0.37	5.96	10.67	24.09	1021.79
39	9/6	11:49:01	PB,B2	0.75	0.13	5.31	7.62	52.46	108.66
41	9/6	12:25:15	SA,O,F	0.68	0.07	5.11	4.88	50.29	32.21
44	9/6	12:57:35	SA,PB,O	0.63	0.05	4.67	5.49	61.20	16.62
45	9/6	13:01:09	SA,PB,O	0.62	0.27	5.21	7.62	21.38	469.39
46	9/6	13:02:35	PB,F,SA	0.62	0.19	4.64	5.49	23.38	211.40
47	9/6	13:06:24	S,O,SA	0.60	0.06	5.15	6.10	76.43	23.11
49	9/6	13:17:23	SA,PB,F	0.60	0.10	4.84	6.10	30.72	55.61
50	9/6	13:18:26	SA,PB	0.60	0.25	5.11	7.62	17.52	397.41
51	9/6	13:20:02	S,SA,F	0.59	0.05	4.83	4.57	39.42	14.05
53	9/6	13:43:55	SA,O,F	0.56	0.06	5.24	5.49	50.47	22.28
55	9/6	14:07:21	SA,O,F	0.55	0.03	4.15	3.05	54.86	3.54
56	9/6	14:15:53	SA,O,F	0.55	0.02	3.90	3.05	43.89	2.92
58	9/6	15:00:12	SA,S,F	0.61	0.03	2.82	3.05	52.67	3.39
60	9/6	15:16:49	SA,F	0.66	0.07	5.62	6.10	43.89	35.23
65	9/6	16:04:26	DA,PB	0.80	0.18	5.09	7.01	39.50	196.14
67	9/7	10:44:15	S,F,O,SA	0.83	0.03	6.18	3.66	24.14	7.65
69	9/7	10:56:49	DA,PB,O	0.81	0.10	5.12	6.10	30.66	65.73
72	9/7	11:49:25	SA,PB,O	0.71	0.14	5.19	7.62	26.28	119.63
73	9/7	12:05:55	DA,CC	0.68	0.21	5.68	10.67	52.46	320.87
74	9/7	12:13:12	SA,S,O	0.67	0.07	4.78	6.10	69.95	25.01
78	9/7	12:48:58	O,SA,F	0.60	0.07	5.12	4.88	20.08	34.05

Wake #	Date	Wake Start Time	Description	Total Water Depth (m)	Wave Period (t)	Wave Height (h) After	Shallow Water Wave Length	Boat Size (m)	KPH	Index Wave Energy
80	9/7	12:57:25	SA,PB,O	0.58	1.70	0.10	3.69	6.10	43.89	41.60
81	9/7	13:15:12	B3,DA,CC	0.55	1.90	0.18	4.17	12.19	17.53	165.22
85	9/7	13:57:21	SA,PB	0.50	2.30	0.06	4.97	4.57	39.83	21.36
86	9/7	14:10:37	DA,PB,O	0.49	2.20	0.11	4.69	4.57	34.39	70.65
89	9/7	14:24:20	DA,DFS	0.49	2.20	0.24	4.67	7.32	29.26	336.99
91	9/7	14:29:54	SA,F,O	0.49	1.90	0.07	3.97	6.10	35.11	25.92
92	9/7	14:30:40	SA,F,PB	0.49	2.30	0.09	4.92	4.57	48.06	47.53
94	9/7	14:50:43	PB,SA,O	0.51	2.20	0.08	4.77	7.62	24.14	39.85
95	9/7	15:11:35	SA,F,O	0.55	2.20	0.07	4.93	6.10	20.88	25.94
96	9/7	15:18:16	DA,PB	0.56	2.00	0.15	4.47	6.71	32.85	130.31
98	9/7	15:55:30	SA,O,PB,DFS	0.68	2.20	0.09	5.40	6.71	18.08	55.15
99	9/7	16:10:07	PB,DA	0.72	2.50	0.07	6.41	6.10	52.67	37.12
100	9/7	16:33:32	PB,DA	0.78	2.30	0.07	6.03	6.10	17.92	36.29
101	9/7	16:35:53	PB,F,SA	0.79	2.10	0.07	5.40	6.71	44.60	29.15
104	9/8	11:44:43	DA,PB	0.76	2.50	0.19	6.55	10.67	30.72	303.39
105	9/8	14:00:04	FB,F,O	0.53	2.20	0.04	4.88	4.57	19.73	7.42
106	9/8	14:19:52	FB,F,O	0.52	2.20	0.04	4.81	4.57	39.50	10.15
107	9/9	11:38:58	DA,PB,O	0.90	2.10	0.07	5.67	7.01	26.28	31.99
108	9/9	12:49:23	DA,PB,IN	0.79	2.40	0.09	6.37	5.49	26.33	57.69
109	9/9	13:57:55	SA,O,F	0.69	1.90	0.02	4.52	3.05	24.14	2.76
110	9/9	14:44:23	SA,O,PB	0.64	2.20	0.06	5.28	6.10	48.90	21.85
112	9/9	16:42:21	SA,F	0.83	2.00	0.08	5.15	6.10	18.66	35.68
114	9/11	11:41:04	PB,SA,O	0.86	2.50	0.07	6.91	6.10	39.34	40.93
115	9/11	12:51:58	PB,SA,O	0.92	2.10	0.06	5.70	5.18	39.50	25.46
120	9/12	12:35:21	O,S,SA	0.95	2.50	0.07	7.21	4.88	43.72	41.21
121	9/12	13:33:51	O,SA,S	1.02	2.20	0.07	6.28	6.10	50.45	34.15
122	9/12	14:37:17	B2,DA,CC	1.04	1.90	0.13	5.10	11.58	19.91	100.44
125	9/12	15:20:10	SA,S	1.01	2.40	0.06	7.02	6.10	46.75	26.94
126	9/12	15:23:21	F,SA,O	1.01	2.80	0.02	8.45	4.57	30.97	5.51
127	9/12	15:24:40	DA,PB	1.01	2.30	0.08	6.64	6.71	45.72	55.44
128	9/12	15:45:45	DA,S,PB	1.00	2.40	0.07	6.98	6.40	82.30	37.18
129	9/12	15:51:07	FB,O,S	0.99	2.50	0.19	7.33	7.32	21.95	330.28
131	9/12	16:40:15	PB,S,DA	0.95	2.40	0.06	6.86	8.53	61.20	32.27
132	9/13	11:43:01	SA,PB	0.82	2.30	0.08	6.16	4.57	30.60	47.73
135	9/13	14:17:45	SA,O,F	1.08	2.10	0.07	5.97	4.57	43.89	31.14
137	9/13	14:52:17	DA,CC	1.10	2.20	0.18	6.41	10.36	29.26	255.96
139	9/13	15:54:03	SA,PB,O	1.07	2.10	0.09	5.97	6.71	30.54	52.94
140	9/13	16:51:37	SA,O,F	1.00	2.30	0.05	6.62	4.88	25.52	23.57
141	9/14	10:24:32	DA,PB	0.54	2.00	0.16	4.39	7.62	35.11	133.05
142	9/14	11:52:32	DA,BP,IN	0.69	1.80	0.16	4.21	7.62	30.42	133.45
145	9/15	13:27:28	SA,PB,F,IN	0.79	2.00	0.07	5.08	6.10	40.05	32.79
147	9/15	16:26:43	SA,S,IN	1.08	2.40	0.06	7.17	5.49	43.89	34.11

Table 2. Boat wake data used in the final regression. Wake # is the record number from all wakes recorded during the study. Date and start time refer to the video time stamp when the wake is seen to first hit instruments. Description refers to a visual analysis made using the video footage and is explained in appendix 2. The remaining columns show the relevant data used during the different steps of depth correction and regressions.



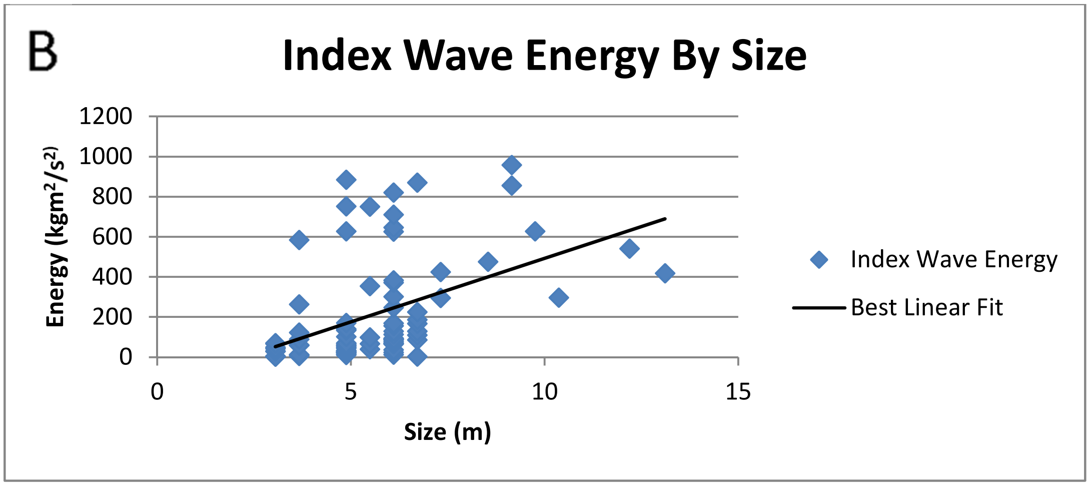


Figure 13. (A) Index wave energy graphed by boat speed. With speed (kph) on the X axis, and index wave energy on the Y axis. (B) Index wave energy graphed by boat size. With size (m) on the X axis, and index wave energy on the Y axis.

DISCUSSION

Using the methods described in this paper, a link was made that could successfully connect and relate individual recreational boats with the wakes they made as they passed an instrumented river section. With the p values < 0.0001 the two characteristics of boat passages examined likely have an impact on the energy of the wake a boat makes with its passage. While this study was unable to determine why boat speed did not have a strong correlation to the index wave energy, a strong link was found between $boat\ length^3$ and index wave energy, meaning recreational boat characteristics do have an impact on the wake created by passage. To help examine impacts a boat's speed has on its wake another study with a single boat piloted past instruments at different speeds could be conducted. Comparing the wakes produced by one boat at different speeds could help explain why a strong correlation between speed and wake energy could not be found in this study. Although it needs some refining, making this connection means the method of matching boats to their wakes using a pressure transducer and a video recording camera will work, and that we have a meaningful model for predicting wake energy based on $boat\ length^3$.

Other studies discussed the variability of wakes based on different environmental factors, such as current speed and water depth, than those associated with the boats characteristics. However, many of these characteristics are present only minimally in this location. Tidal influences are minor in the area so do not affect the current in a substantial way. Background wind driven waves at the study location are minimal. In this fetch-limited environment, the wind does not have the open space to exert enough force to create substantial waves. This means that the largest, and usually sole, source of waves to strike the river bank is from boat passages (Figure 12). This supports the idea that boats can raise the wave energy present along a stretch of shoreline.

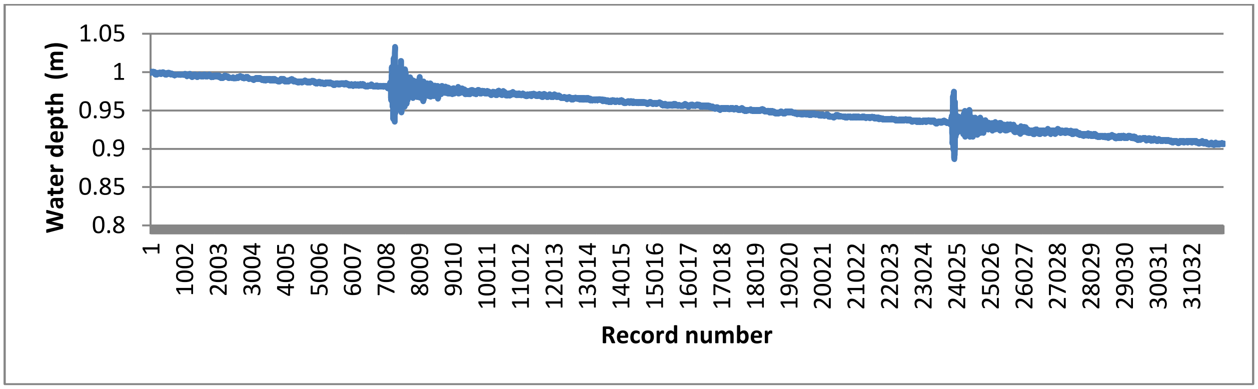


Figure 14. The continuous reading of transducer records over the course of an hour on 9/6/2009 starting at 9:41AM. In this time two boats passed the transducer causing a noticeable increase in wave fluctuations with their passage as opposed to any background wave activity.

The focus for this study was to look at the most common recreational boat types at this location and the energy in the wake they create. While this does narrow the focus to a specific type of craft, it allows for a more accurate review of the characteristics involved. This limited focus on boat types, and the large number of records (86 usable records), lends the results a great deal of assurance to the accuracy of this model.

Areas that have a wide diversity in the type of boats present, such as very affluent areas or larger harbors, may not find this tool to be as reliable for energy estimates. However, as a predictive tool it would still help identify areas at risk from wave impacts. Other areas with vessels of one common type could use this model to help predict the amount of energy affecting the shore with greater accuracy. With the focus on wave energy and not erosion this tool could also be easily adapted to work in many situations. In areas surveyed by Castillo et al. (2000), where salt marsh erosion was the focus, it was found many areas suffered from undercutting of the bank. These areas would have the typical boat types examined in this study, making this tool much more accurate for wake energy estimates. Once the amount of energy in a wake is known, and a survey completed to find the shear strength of the banks accounting for any vegetative cover or bank armoring, this model could be adapted for any location. It could also be used to help in understanding the impacts on local species. With the energy content of the wake, the disturbance to local flora and fauna could be assessed to see what impacts boat traffic is having. Paired together this would allow for a manager to monitor boat wake energy and what type of boats would have the greatest impacts to both physical and biological aspects.

Several steps could be taken to further increase the accuracy of this model. A known distance could be found and recorded prior to camera installation. This would provide more accurate boat length estimates. The addition of an overhead camera could also be used to get boat width measurements as boats pass below. This would allow a better approximation of volume for each vessel giving a better measure for water displacement. An overhead camera could also provide a location in the river to help account for distance decay of the wake to instruments. New HD cameras could help refine any estimates made from possible “fuzzy” pictures and allow direct identification of boat model numbers, thus hull characteristics. The introduction of a “speed gun” or similar device to record boat speeds could also strengthen the relation of speeds to index wave energy by improving estimates about the vessel speeds.

CONCLUSIONS

This study examined the correlation between a boat’s size, speed, and the wake it creates using a pressure transducer and a video camera. Using video footage and transducer records obtained during the month of September 2009, on the Georgiana Slough in California, numerous boats and the wakes resulting from their passages were recorded with the analysis demonstrating that a boat’s size does have an impact on the wake it creates, and that its speed explained little of the variability in wave energy. The relationship between a boat and the wake it makes is quite complicated which is an issue that most of the boat wake experiments have not quantified to the extent that was undertaken in this study.

These data were used to create a table of each boat that had passed the instruments, and analyzed with a regression analysis between the size and speed of the boat and the energy of the wake created by its passage. Using a pressure transducer, video camera, and data logger an individual boat wake was paired with the boat that made it. A statistically significant correlation was found between a boat and the energy in the wake it made.

With *p* values consistently less than 0.0001, a boat’s characteristic has significant impact on the wake it creates. A positive correlation with size means the larger the boat, the more energy will be in its wake. With a larger boat, there is more water displacement. The negative correlation with boat speed means that the faster a boat goes the less hull is in the water hence the less energy its wake will have. As a boat increases in speed it will partially rise out of the water into a planning position. This lifts some of the hull out of the water causing less displacement and hence less energetic wakes.

Further studies could be used to help understand boat characteristics and wake interactions. Other studies could be done focusing on “non-conventional” boat types to add to the diversity of the data available for erosion prediction based on this process. As boat traffic increases predictive studies will help find areas of high erosive potential so steps could be taken to prevent issues before they arise. Linking boat characteristics to wake energy will help create predictive models as information about recreational boats can be collected remotely.

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APPENDIX A

Wake #	Date	Wake Start Time	Trimming Reasons	Location	Description	Total Water Depth (m)	Period (t)	Wave Height (h) Before	Wave Height (h) After	Shallow Water Wave Length	Size (m)	KPH	Wave Energy
1	9/5	12:09:35		M	PB,O,SA	0.67	2.30	0.07	0.08	5.65	7.32	52.67	47.55
2	9/5	12:10:22	4	M	PB,IN, SA	0.67	2.00	0.10	0.13	4.78	7.62	12.06	105.73
3	9/5	12:12:27	1,2	M	SKI	0.67	1.80	0.04	0.06	4.16	3.05	35.11	17.31
4	9/5	12:19:19	4	M	CC,DA,B3 tow inflatable	0.65	2.20	0.21	0.27	5.30	13.72	14.25	458.26
5	9/5	12:23:42		MF	PB,SA	0.64	1.70	0.11	0.18	3.81	7.62	52.46	145.30
6	9/5	12:28:15		M	PB,O,SA	0.64	2.30	0.08	0.10	5.53	7.01	36.51	67.78
7	9/5	12:35:55		M	G,O,SA	0.63	2.20	0.04	0.06	5.22	5.49	35.92	20.66
8	9/5	12:42:37	4	M	PB,SA	0.61	1.50	0.04	0.08	3.14	6.71	13.14	23.83
9	9/5	12:53:22	4	M	IN,B2,DFS,DA	0.60	1.60	0.11	0.18	3.43	12.19	9.87	131.94
10	9/5	13:04:23	1	M	SA,S,O Cigarette boat	0.59	2.00	0.07	0.10	4.54	7.32	65.57	52.59
11	9/5	13:19:38		M	DFS,DA	0.57	2.80	0.13	0.15	6.52	10.67	17.77	174.58
12	9/5	13:25:52	1	M	P,O	0.56	2.50	0.12	0.14	5.74	7.01	19.73	144.17
13	9/5	13:53:15	1,2,4	M	SKI	0.56	1.40	0.01	0.03	2.76	3.05	15.02	2.39
14	9/5	13:53:59	1,2	M	SKI	0.56	1.70	0.03	0.05	3.64	3.05	26.28	9.21
15	9/5	13:57:49	4	MF	O,PB,B2,DA	0.56	2.30	0.18	0.21	5.25	6.71	5.61	294.51
16	9/5	13:59:35	1	M	O,SO,SA, Cigarettte boat	0.56	2.50	0.03	0.04	5.75	5.49	29.26	9.98
17	9/5	14:03:07		MF	PB,O,SA	0.57	2.20	0.04	0.04	5.01	5.49	52.67	12.24
18	9/5	14:14:54		M	PB,SA,O	0.59	2.30	0.04	0.04	5.35	4.57	16.09	12.76
19	9/5	14:22:51		M	PB,SA,F	0.60	2.20	0.06	0.07	5.14	6.10	65.57	32.07
20	9/5	14:27:34	4	M	PB,B2,DA	0.61	1.60	0.12	0.19	3.45	9.14	7.13	150.98
21	9/5	14:30:31		M	PB,DSF,O,DA	0.62	2.50	0.24	0.28	6.01	6.71	26.09	590.55
22	9/5	14:48:12		MF	O,SA,F	0.67	2.10	0.04	0.05	5.07	6.10	50.45	17.12
23	9/5	14:53:40		M	O,SA,F	0.68	2.00	0.08	0.12	4.81	6.71	39.50	79.61
24	9/5	14:54:10		M	PB,DA,B2	0.68	2.60	0.12	0.14	6.55	9.14	21.47	164.58
25	9/5	14:57:35	4	M	DA,CC	0.69	2.20	0.21	0.28	5.44	10.06	9.14	525.61
26	9/5	15:02:21		MF	SA,O,PB	0.70	2.10	0.06	0.08	5.18	6.10	45.53	37.68
27	9/5	15:13:13		M	SA,PB,O,F	0.74	2.00	0.05	0.07	4.97	6.10	39.50	31.88
28	9/5	15:14:30		M	SA,PB,O,F	0.75	2.10	0.04	0.06	5.30	5.49	39.03	20.22
29	9/5	15:17:54		M	SA,CC,O,F	0.76	2.30	0.11	0.15	5.95	6.40	35.11	166.58
30	9/5	15:21:10	1	MF	SA,S,O Cigarette boat	0.77	2.60	0.04	0.05	6.90	4.57	43.72	18.78

Wake #	Date	Wake Start Time	Trimming Reasons	Location	Description	Total Water Depth (m)	Period (t)	Wave Height (h) Before	Wave Height (h) After	Shallow Water Wave Length	Size (m)	KPH	Wave Energy
31	9/5	15:24:23		M	SA,F,PB	0.78	2.40	0.05	0.07	6.32	6.10	16.07	36.56
32	9/5	15:34:04		M	SA,S,O,F	0.80	2.00	0.04	0.06	5.10	5.49	47.03	23.22
33	9/5	15:35:58		M	SA,O,PB	0.81	2.00	0.06	0.09	5.13	6.71	31.97	52.79
34	9/6	9:38:13		M	S,SA,O	0.99	2.30	0.08	0.12	6.58	9.14	35.11	109.89
35	9/6	10:21:40		M	PB,O,SA	0.91	2.30	0.05	0.06	6.39	6.40	56.61	32.85
36	9/6	10:42:38		M	PB,DA,IN,B2	0.87	2.80	0.13	0.16	7.92	7.62	21.92	245.01
37	9/6	11:30:01	4	MF	PB,DA	0.78	2.40	0.05	0.06	6.34	6.10	14.61	31.49
38	9/6	11:43:53		MF	PB,DA,IN	0.76	2.30	0.28	0.37	5.96	10.67	24.09	1021.79
39	9/6	11:49:01		NM	PB,B2	0.75	2.10	0.09	0.13	5.31	7.62	52.46	108.66
40	9/6	11:51:25	4	M	O,PB,DA	0.75	1.50	0.04	0.08	3.27	7.62	11.67	26.01
41	9/6	12:25:15		M	SA,O,F	0.68	2.10	0.05	0.07	5.11	4.88	50.29	32.21
42	9/6	12:45:02	4	M	PB,B2,DA	0.65	1.80	0.05	0.07	4.13	10.06	10.95	23.55
43	9/6	12:50:55	4	M	B2,PB,DA	0.64	1.80	0.10	0.15	4.10	10.67	13.14	111.60
44	9/6	12:57:35		NM	SA,PB,O	0.63	2.00	0.04	0.05	4.67	5.49	61.20	16.62
45	9/6	13:01:09		M	SA,PB,O	0.62	2.20	0.21	0.27	5.21	7.62	21.38	469.39
46	9/6	13:02:35		M	PB,F,SA	0.62	2.00	0.14	0.19	4.64	5.49	23.38	211.40
47	9/6	13:06:24		M	S,O,SA	0.60	2.20	0.05	0.06	5.15	6.10	76.43	23.11
48	9/6	13:13:04	1	M	P,O	0.60	2.80	0.10	0.11	6.70	9.14	18.97	105.58
49	9/6	13:17:23		MF	SA,PB,F	0.60	2.10	0.08	0.10	4.84	6.10	30.72	55.61
50	9/6	13:18:26		M	SA,PB	0.60	2.20	0.20	0.25	5.11	7.62	17.52	397.41
51	9/6	13:20:02		M	S,SA,F	0.59	2.10	0.04	0.05	4.83	4.57	39.42	14.05
52	9/6	13:35:08	4	M	IN,PB,DA	0.57	1.50	0.13	0.23	3.08	9.75	10.95	192.70
53	9/6	13:43:55		M	SA,O,F	0.56	2.30	0.05	0.06	5.24	5.49	50.47	22.28
54	9/6	13:59:25	1,4	M	Y,B2	0.55	2.80	0.23	0.27	6.41	10.67	8.78	555.04
55	9/6	14:07:21		M	SA,O,F	0.55	1.90	0.02	0.03	4.15	3.05	54.86	3.54
56	9/6	14:15:53		M	SA,O,F	0.55	1.80	0.02	0.02	3.90	3.05	43.89	2.92
57	9/6	14:27:46	4	M	SA,PB	0.56	1.90	0.10	0.14	4.18	9.14	13.15	96.56
58	9/6	15:00:12		N	SA,S,F	0.61	1.40	0.02	0.03	2.82	3.05	52.67	3.39
59	9/6	15:11:21	4	MF	SA,F	0.64	2.30	0.03	0.04	5.56	4.57	11.62	11.45
60	9/6	15:16:49		MF	SA,F	0.66	2.30	0.06	0.07	5.62	6.10	43.89	35.23

Wake #	Date	Wake Start Time	Trimming Reasons	Location	Description	Total Water Depth (m)	Period (t)	Wave Height (h) Before	Wave Height (h) After	Shallow Water Wave Length	Size (m)	KPH	Wave Energy
61	9/6	15:34:55	4	MF	SA,PB,O	0.71	2.30	0.03	0.04	5.80	4.57	6.23	12.35
62	9/6	15:35:30	1	M	S,SA,Cigarette boat	0.71	2.10	0.07	0.09	5.21	6.10	62.40	57.29
63	9/6	15:54:43	1,4	M	P,B2, Houseboat	0.77	1.40	0.01	0.04	2.93	13.72	6.64	5.02
64	9/6	15:57:47	4	MF	PB,SA	0.78	2.10	0.04	0.06	5.38	6.10	9.24	26.34
65	9/6	16:04:26		M	DA,PB	0.80	2.00	0.12	0.18	5.09	7.01	39.50	196.14
66	9/6	16:08:09	4	MF	PB,DA,B2	0.80	2.50	0.17	0.21	6.73	7.62	12.33	380.92
67	9/7	10:44:15		M	S,F,O,SA	0.83	2.30	0.02	0.03	6.18	3.66	24.14	7.65
68	9/7	10:45:04	4	M	DA,PB	0.83	2.00	0.08	0.13	5.16	6.10	13.72	100.80
69	9/7	10:56:49		M	DA,PB,O	0.81	2.00	0.07	0.10	5.12	6.10	30.66	65.73
70	9/7	11:41:30	4	M	B2,DA,CC	0.72	2.60	0.11	0.13	6.72	12.19	12.06	138.01
71	9/7	11:45:32	4	M	DA,DFS	0.71	2.10	0.18	0.25	5.20	9.14	15.96	399.15
72	9/7	11:49:25		M	SA,PB,O	0.71	2.10	0.10	0.14	5.19	7.62	26.28	119.63
73	9/7	12:05:55		M	DA,CC	0.68	2.30	0.17	0.21	5.68	10.67	52.46	320.87
74	9/7	12:13:12		M	SA,S,O	0.67	2.00	0.05	0.07	4.78	6.10	69.95	25.01
75	9/7	12:17:21	4	M	DA,B3,DFS Inflatable in tow	0.66	1.70	0.15	0.24	3.84	12.19	8.76	266.94
76	9/7	12:29:28	4	M	SA,O,PB	0.64	1.50	0.06	0.10	3.17	9.14	11.01	41.27
77	9/7	12:48:05	4	M	DA,B2,CC	0.59	1.80	0.09	0.13	4.00	13.72	14.61	81.43
78	9/7	12:48:58		MF	O,SA,F	0.60	2.20	0.06	0.07	5.12	4.88	20.08	34.05
79	9/7	12:54:15	3	M	DA,B2,CC	0.59	2.00	0.16	0.21	4.56	15.85	17.56	253.36
80	9/7	12:57:25		M	SA,PB,O	0.58	1.70	0.06	0.10	3.69	6.10	43.89	41.60
81	9/7	13:15:12		M	B3,DA,CC	0.55	1.90	0.13	0.18	4.17	12.19	17.53	165.22
82	9/7	13:29:53	4	M	SA,S,O	0.53	1.70	0.04	0.06	3.58	6.10	5.88	16.36
83	9/7	13:38:56	3,4	M	CC,B2,DA,IN	0.52	1.80	0.11	0.15	3.81	15.85	14.61	108.05
84	9/7	13:43:31	4	M	O,DA,B2,PB skiff in tow	0.51	2.30	0.16	0.18	5.03	10.67	12.67	210.22
85	9/7	13:57:21		M	SA,PB	0.50	2.30	0.05	0.06	4.97	4.57	39.83	21.36
86	9/7	14:10:37		M	DA,PB,O	0.49	2.20	0.09	0.11	4.69	4.57	34.39	70.65
87	9/7	14:12:47	4	M	SA,PB,S	0.49	2.10	0.05	0.06	4.45	6.71	10.33	21.81
88	9/7	14:13:28	4	M	SA,PB,O	0.49	2.40	0.08	0.10	5.15	7.62	5.19	58.62
89	9/7	14:24:20		M	DA,DFS	0.49	2.20	0.20	0.24	4.67	7.32	29.26	336.99
90	9/7	14:24:56	4	M	DA,PB	0.49	2.00	0.13	0.16	4.20	7.62	10.53	131.18

Wake #	Date	Wake Start Time	Trimming Reasons	Location	Description	Total Water Depth (m)	Period (t)	Wave Height (h) Before	Wave Height (h) After	Shallow Water Wave Length	Size (m)	KPH	Wave Energy
91	9/7	14:29:54		M	SA,F,O	0.49	1.90	0.06	0.07	3.97	6.10	35.11	25.92
92	9/7	14:30:40		M	SA,F,PB	0.49	2.30	0.08	0.09	4.92	4.57	48.06	47.53
93	9/7	14:40:04	1	M	DA,B2,Y	0.50	1.90	0.20	0.26	3.99	14.02	17.56	330.24
94	9/7	14:50:43		MF	PB,SA,O	0.51	2.20	0.07	0.08	4.77	7.62	24.14	39.85
95	9/7	15:11:35		M	SA,F,O	0.55	2.20	0.05	0.07	4.93	6.10	20.88	25.94
96	9/7	15:18:16		M	DA,PB	0.56	2.00	0.12	0.15	4.47	6.71	32.85	130.31
97	9/7	15:28:22	1,3,4	M	P,IN,B3,Houseboat	0.59	1.20	0.01	0.03	2.17	15.85	6.57	2.46
98	9/7	15:55:30		M	SA,O,PB,DFS	0.68	2.20	0.07	0.09	5.40	6.71	18.08	55.15
99	9/7	16:10:07		M	PB,DA	0.72	2.50	0.06	0.07	6.41	6.10	52.67	37.12
100	9/7	16:33:32		MF	PB,DA	0.78	2.30	0.05	0.07	6.03	6.10	17.92	36.29
101	9/7	16:35:53		M	PB,F,SA	0.79	2.10	0.05	0.07	5.40	6.71	44.60	29.15
102	9/8	9:58:54	1,4	MF	Y,B2,IN,DA	0.92	1.30	0.01	0.05	2.60	13.72	8.73	6.82
103	9/8	9:59:31	4	MF	DA,PB,IN,B2	0.92	1.20	0.02	0.11	2.23	13.72	8.22	33.14
104	9/8	11:44:43		M	DA,PB	0.76	2.50	0.15	0.19	6.55	10.67	30.72	303.39
105	9/8	14:00:04		M	FB,F,O	0.53	2.20	0.03	0.04	4.88	4.57	19.73	7.42
106	9/8	14:19:52		MF	FB,F,O	0.52	2.20	0.03	0.04	4.81	4.57	39.50	10.15
107	9/9	11:38:58		MF	DA,PB,O	0.90	2.10	0.04	0.07	5.67	7.01	26.28	31.99
108	9/9	12:49:23		M	DA,PB,IN	0.79	2.40	0.07	0.09	6.37	5.49	26.33	57.69
109	9/9	13:57:55		M	SA,O,F	0.69	1.90	0.02	0.02	4.52	3.05	24.14	2.76
110	9/9	14:44:23		M	SA,O,PB	0.64	2.20	0.05	0.06	5.28	6.10	48.90	21.85
111	9/9	16:32:15	4	M	B2,DA,PB,IN	0.80	1.30	0.02	0.05	2.58	10.67	7.07	8.30
112	9/9	16:42:21		N	SA,F	0.83	2.00	0.05	0.08	5.15	6.10	18.66	35.68
113	9/11	10:37:28	4	MF	SA,PB,IN	0.85	2.10	0.04	0.06	5.55	5.49	8.77	26.84
114	9/11	11:41:04		MF	PB,SA,O	0.86	2.50	0.05	0.07	6.91	6.10	39.34	40.93
115	9/11	12:51:58		M	PB,SA,O	0.92	2.10	0.04	0.06	5.70	5.18	39.50	25.46
116	9/12	8:29:53	4	M	DFS,DA,B2	0.48	1.50	0.03	0.05	2.94	9.14	14.59	8.13
117	9/12	8:31:07	4	M	B2,SA,PB,IN	0.48	1.50	0.11	0.17	2.94	7.62	9.19	99.70
118	9/12	12:05:48	4	MF	F,PB,SA,IN	0.91	1.70	0.02	0.04	4.17	4.57	4.39	7.99
120	9/12	12:35:21		MF	O,S,SA	0.95	2.50	0.05	0.07	7.21	4.88	43.72	41.21

Wake #	Date	Wake Start Time	Trimming Reasons	Location	Description	Total Water Depth (m)	Period (t)	Wave Height (h) Before	Wave Height (h) After	Shallow Water Wave Length	Size (m)	KPH	Wave Energy
121	9/12	13:33:51		M	O,SA,S	1.02	2.20	0.04	0.07	6.28	6.10	50.45	34.15
122	9/12	14:37:17		M	B2,DA,CC	1.04	1.90	0.07	0.13	5.10	11.58	19.91	100.44
123	9/12	14:39:45	4	MF	DA,PB,IN	1.03	2.40	0.05	0.07	7.06	9.14	15.10	43.42
124	9/12	14:42:10	4	M	B2,PB,IN,DA	1.04	1.80	0.07	0.15	4.68	9.14	10.52	131.60
125	9/12	15:20:10		MF	SA,S	1.01	2.40	0.04	0.06	7.02	6.10	46.75	26.94
126	9/12	15:23:21		MF	F,SA,O	1.01	2.80	0.02	0.02	8.45	4.57	30.97	5.51
127	9/12	15:24:40		MF	DA,PB	1.01	2.30	0.06	0.08	6.64	6.71	45.72	55.44
128	9/12	15:45:45		MF	DA,S,PB	1.00	2.40	0.05	0.07	6.98	6.40	82.30	37.18
129	9/12	15:51:07		M	FB,O,S	0.99	2.50	0.14	0.19	7.33	7.32	21.95	330.28
130	9/12	16:26:30	4	M	O,F,SA	0.96	1.70	0.02	0.03	4.21	4.57	10.95	5.69
131	9/12	16:40:15		MF	PB,S,DA	0.95	2.40	0.04	0.06	6.86	8.53	61.20	32.27
132	9/13	11:43:01		MF	SA,PB	0.82	2.30	0.06	0.08	6.16	4.57	30.60	47.73
133	9/13	11:46:11	1,4	M	P,O	0.83	2.20	0.06	0.09	5.85	7.62	7.31	53.25
134	9/13	13:28:39	4	M	DA,PB,S	1.01	1.70	0.10	0.22	4.25	7.62	13.36	246.86
135	9/13	14:17:45		MF	SA,O,F	1.08	2.10	0.04	0.07	5.97	4.57	43.89	31.14
136	9/13	14:19:08	1,4	M	P,IN	1.08	2.80	0.11	0.14	8.67	9.14	9.87	206.94
137	9/13	14:52:17		M	DA,CC	1.10	2.20	0.11	0.18	6.41	10.36	29.26	255.96
138	9/13	15:38:45	5	M	SA,PB,O	1.09	1.70	0.02	0.05	4.29	7.62	87.78	14.80
139	9/13	15:54:03		MF	SA,PB,O	1.07	2.10	0.05	0.09	5.97	6.71	30.54	52.94
140	9/13	16:51:37		MF	SA,O,F	1.00	2.30	0.04	0.05	6.62	4.88	25.52	23.57
141	9/14	10:24:32		MF	DA,PB	0.54	2.00	0.12	0.16	4.39	7.62	35.11	133.05
142	9/14	11:52:32		MF	DA,BP,IN	0.69	1.80	0.10	0.16	4.21	7.62	30.42	133.45
143	9/15	11:47:32	4	M	IN,PB,SA	0.53	1.30	0.02	0.04	2.43	12.19	11.94	4.37
144	9/15	11:48:48	4	M	IN,DA,DFS,B2	0.53	1.60	0.13	0.19	3.30	12.19	10.96	143.43
145	9/15	13:27:28		M	SA,PB,F,IN	0.79	2.00	0.05	0.07	5.08	6.10	40.05	32.79
146	9/15	14:24:59	4	MF	SA,PB	0.91	2.50	0.07	0.09	7.09	4.57	5.99	75.23
147	9/15	16:26:43		M	SA,S,IN	1.08	2.40	0.04	0.06	7.17	5.49	43.89	34.11
148	9/15	16:45:35	5	M	SA,PB	1.07	2.10	0.02	0.04	5.97	6.71	87.43	12.62

APPENDIX B

This table lists the abbreviation meanings used during this study. They are also used in the list of full data attached with appendix B under the description and trimming reasons columns.

Boat Type		Hull type	
Symbol	Description	Symbol	Description
PB	Pleasure Boat	DA	Deep Arrow Shaped Hull
F	Fishing Boat	SA	Shallow Arrow Shaped Hull
S	Speed Boat	FBA	Flat Bottom Arrow Shaped Hull
DSF	Deep Sea Fishing Boat		
Y	Yacht	Trimming Reason	
P	Pontoon Boat	1	Boat type
G	Generic Open Boat/Fishing	2	Boat Size to Small
CC	Cabin Cruiser	3	Boat Size to Large
SAIL	Sailboat	4	Boat speed to Slow
Ski	Jet Ski	5	Boat speed to Fast
B2	Bridge on 2nd level		
B3	Bridge on 3rd Level		
IN	Inboard Engine		
O	Outboard Engine		