Quantifying the Relative Importance of Boat Wakes in Fetch-Limited Environments

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Quantifying the Relative Importance of Boat Wakes in Fetch-Limited Environments

by

Abigail Carswell

A Thesis
Submitted to the Faculty of Graduate Studies
through the School of the Environment
in Partial Fulfillment of the Requirements for
the Degree of Master of Science
at the University of Windsor

Windsor, Ontario, Canada

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Quantifying the Relative Importance of Boat Wakes in Fetch-Limited Environments

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DECLARATION OF ORIGINALITY

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ABSTRACT

Wind waves and wave-generated currents are known to contribute to shoreline change, but there is increasing evidence that vessel-generated waves (i.e., boat wakes) may be responsible for erosion of shorelines in fetch-limited environments. Depending on vessel type and speed of operation, boat wakes have also been shown to be capable of resuspending sediment, degrading habitat, and water quality, and causing damage to shoreline infrastructure. The number of cottages and recreational boats on inland lakes has been steadily increasing in recent decades in Ontario, Canada, which has resulted in a growing perception that boat wakes are detrimental to the environment, infrastructure, and the shoreline. The Muskoka Lakes region (i.e., Lake Joseph, Lake Rosseau, and Lake Muskoka) is colloquially known as the center of “Canadian Cottage Country,” with approximately 7,000 cottages along 480 km of shoreline. Using low-cost wave and water level sensors developed and built at the University of Windsor, the purpose of this study is to assess the relative contribution of boat wakes to total wave energy at ten sites across the Muskoka Lakes and to assess the perception of boat wakes among the region’s cottage owners. Results collected from the ice-free cottage season of 2022 (June - September) suggest that on average 66% of the total wave energy at the shoreline is due to vessel-generated wakes. The relative contribution of wake energy to the total wave energy is inversely related to the fetch length, while the length of time that wakes are present at the shoreline is directly related to the fetch length. While boats wakes have been linked to shoreline erosion in many environments, results of this study suggest that the impact is perceived or assumed, further research is required to determine when and where they may be detrimental, and not simply a nuisance.
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BACKGROUND

There are three primary factors that determine the height and period of wind-waves: 1) wind speed, 2) wind duration, and 3) fetch length (Davidson-Arnott et al., 2019). As wind speed increases, more energy is transferred to the water surface leading to increasingly larger waves with longer periods, such that the size and period of the wave depends on the wind speed, and duration in an open unrestricted sea. In small basins and waterways, wave height and period are limited by the fetch, the distance over which the wind blows (Glamore, 2005; Davidson-Arnott et al., 2019), meaning that waves are still within the area of active generation and are ‘choppy’ (e.g., large height to wavelength ratio) due to the lack of dispersive sorting. Whether limited by wind speed, duration or fetch, wind waves are generated through the transfer of turbulent energy from the wind to the water surface, leading to an undulation that is restored through either gravity or capillary forces, which is gradually dispersed as the waves reach the shoreline. A gust of wind with adequate energy applied to the surface of the water will encounter a restoring force caused by surface tension, leading to a trough that in turn results in the development of small and high frequency capillary waves otherwise known as ‘ripples’ (Holthuijsen, 2007). Capillary waves have a period of 0.25 seconds and a wavelength of less than a few centimeters and they are responsible for a rippled surface on the water that is restored (to flat water) by capillary forces (Davidson-Arnott, et al., 2019). Larger and lower frequency surface gravity waves, generated by strong and consistent winds, have a period between 1 and 200 s, with the water surface restored by the force of gravity. Because the speed of a wave is directly dependent on wave period, gravity waves with different periods can lead to wave interaction resulting in a superimposed long wave with a period between 12-15 s in fetch-limited areas and 25-200 s in
fetch-unlimited environments, resulting in a different degree of impact to the shoreline. Infragravity waves are released at the point of wave breaking and continue to travel unbroken towards the shoreline, where they are either reflected offshore (leaky wave) or trapped through refraction along the shoreline (edge wave). There is limited to no development of infragravity waves in fetch-limited lacustrine environments due to the lack of dispersion and the limited distribution of wave heights and periods. In this respect, most waves in fetch-limited environments are gravity waves.

The cottage country lakes of north-central Ontario are primarily on the Canadian Shield, and as a result can have a range of shapes and sizes dependent on geologic structures (e.g., faults, flowlines), leading to either long narrow lakes with multiple arms composed of bedrock shorelines and widths ranging from 10s of meters to several hundred meters. Other lakes within the region were created with the placement of navigational or power-generating dams (e.g., Lakes Muskoka, Rosseau and Joseph), leading to relatively large lakes with a central basin several kilometers wide surrounded by multiple arms associated with either geologic features or old river channels. Depending on their age and fetch lengths, these shorelines have a combination of vegetated and bedrock shorelines. Regardless of whether the lake is natural or artificial, the complex and narrow shape of lakes may not align with winds from a wide range of directions, leading to fetch limited conditions. Assuming that the wind is directly aligned to a fetch of ~3 km, a frontal wind of ~30 km h⁻¹ over 6 hours (possible with the passage of a frontal storm) creates gravity waves with heights of ~0.58 m and periods of ~2.43 s (USACE, 1984). However, most winds in this region are lake breezes (<10 km/h) that develop through the day in response to the differential heating of the land and water surface. For a fetch of 3 km, the resulting wave heights and periods will be 0.07 m and 1.2 s respectively. Given that most fetch
lengths in this region tend to be only < 1 km, wind-generated waves tend to be <0.05 with periods of ~1 s. In comparison, vessel-generated waves in these environments can be >0.10 m with periods of 3-4 s (Houser et al., 2021). Given that there are ~7000 cottages throughout cottage country in Ontario (pers. Comms Mansion Global, 2020), it is reasonable to assume that the wakes generated by recreational boats may be a source of greater wave energy compared to wind-generated waves in these fetch-limited environments.

1: Vessel-Generated Waves

Cottage and property owners on inland (fetch-limited) lakes in Ontario and elsewhere around the world operate a wide range of vessels including bowriders, cabin cruisers, deck boats, personal watercrafts, fishing boats, and pontoon boats (Walters, et. al, 2021). The weight of the vessel causes water to be displaced, whether a recreational boat (Houser, et. al, 2021) or a large Panamax or post-Panamax cargo ship (Houser, 2011; Yildirim, 2015), creating a series of wave packets commonly referred to as a wake (Soomere, 2007). For recreational boats in particular, the size of the wake additionally depends on the speed of the vessel, which determines if a vessel is operating in displacement, transition, or planning mode (Figure 1). Displacement occurs at the slowest speeds, when the bow is parallel to the waterline of the vessel leading to a wake that is proportional to the weight of the vessel and amount of water displaced. As the boat speed increases, the bow rises and the stern ‘plows’ water at the sailing line leading to a transitional displacement and a large wake (Maynord, 2001). A further increase in speed will lead to a planing speed in which the bow of the boat settles back towards the sailing line and the boat rides on top of the water. While planing, the vessel will create a larger wake than at displacement speed, but smaller than the transition speed (Bilkovic, et al., 2017). High-velocity planing hulls create the smallest wake in planing mode, while high-velocity displacement hulls vessels
creating the largest wake due to the length of bow in contact with the water and the inability to achieve planning speeds (Maynard, 2001; Hill et al., 2002; Fonseca & Malhotra, 2012; Houser, 2021). Some of the largest wakes are created by boats that are purposely constructed with a wide displacement hull and operated with a heavy ballast at slow speeds to create large consistent wakes for wakeboarding and tubing (Carson, 2004).

The ability to reach planing speed depends on the structure and weight of the hull, the number of hulls and the horsepower of the motor(s) (Kelvin, 1887; Hovgaard, 1909; Johnson, 1957). For example, dual-planing-hull vessels, such as speed boat catamarans, produce a larger number of waves when compared to a speed boat with a monohull, due to diverging waves propagating from each of the catamaran's hulls (Kirk, 1989; Osborne & Boak, 1999). Other vessels, such as commercial (cargo) vessels and sailboats, are unable to reach the planing speeds because of their displacement hulls that in turn limit wake generation and friction (Baldwin, 2008). While the drawdown and wake of a cargo vessel can be large, Houser (2010) determined that displacement hull pilot boats on the Savannah River, Georgia operating in plow mode generated the largest wakes compared to (Panamax) container ships (not found within recreational lakes), cabin cruisers, recreational boats, tugs, and a casino boat that were either in planing or displacement modes.
Figure 1: Recreational boat being operated in displacement (a), plowing (b) and planing (c) modes. Photos courtesy of C. Houser.

An important aspect regarding wake size is the dependency on the interaction of the transverse and diverging waves generated by the stern and the bow, respectively. The different waves intersect at a distance from the vessel (the cusp line; Figure 2) leading to a maximum in
the wake height along the sailing line (Froude, 1877; Johnson, 1957; Dorava & Moore, 1997). The interaction of the diverging and transverse wakes and the size of the largest wave are dependent on the dimensionless depth- (Fr_d) and length-based (Fr_l) Froude Numbers:

\[ Fr_l = \frac{v_b}{\sqrt{gl}} \]  \hspace{1cm} (1)

\[ Fr_d = \frac{v_b}{\sqrt{gh}} \]  \hspace{1cm} (2)

where \( v_b \) is the vessel speed, \( g \) is the gravitational acceleration, \( l \) is the vessel length, and \( h \) is the water depth (Sorensen, 1973). When \( Fr_d = 1 \), the vessel’s power is continuously converted to wave energy because the vessel speed is identical to the speed of the wake (i.e., \( v_b = \sqrt{gh} \)) it is generating, leading to the largest bow wake (Soomere, 2005). However, the transfer of energy is practically limited, and wake heights are smaller when the bow wake travels faster than the vessel (\( Fr_d < 1 \)) or the vessel breaks through the wake (\( Fr_d > 1 \)). At the critical \( Fr_l = 0.5 \), the bow and stern waves merge (at the cusp) to create the largest constructive wave possible for the vessel.

Long vessels (\( Fr_l << 0.5 \)) have limited to no interaction between the bow and transverse waves, while the bow and transverse waves for short vessels (\( Fr_l > 0.5 \)) are not in-phase (i.e., destructive) leading to a cusp of limited height. The largest wakes generated by recreational boats are produced by wake boats that displace more water due to their ballast weight.

Manufacturers suggest that the best (or largest) wakes for wakeboarding are generated when water depths are >20 ft (~6 m; pers. Comm., Luxuo 2020). While not directly related to Fr, longer vessels tend to be heavier and displace the water as they pass. This drawdown is typically restricted to cargo vessels (Parchure, et. al, 2001; Houser, 2010), and is negligible for short vessels (e.g., recreational boats).
Figure 2: Sketch illustrating the propagation of transverse and bow wakes from a recreational vessel.

As the wake moves away from the sailing line, the longer period waves travel faster than the smaller period waves leading to dispersion of the wave field and a decrease in wake height as the waves separate. As a result, a wake nearing the shoreline begins with a lower frequency (longer period) wave followed by increasingly short period waves. (Figure 3). The farther the sailing line from the shoreline, the more dispersed the wave field and the smaller the individual wave heights. Wake heights also decay in response to energy dissipation through viscous forces and interaction with the bottom when the wave is in shallow water \( (1/2 \lambda; \lambda=\text{wavelength}) \). Over the relatively short distance between the sailing line and the shoreline, wave decay through dispersion tends to be greater than viscous and frictional dissipation. Ultimately, the height of the wake at the shoreline depends on the distance to the sailing line, and the initial size of the wake determined by the type of vessel, speed, and operation (Soomere, 2007; Houser, 2010; Bilkovic et.al, 2017). This means that wakes generated in wider channels should have smaller heights and periods over a greater length of time, while wakes in narrow channels should be larger in height and period (Galmore, 2008). At the shoreline, the wave begins to shoal resulting in a slower wave speed and an increase in height. An increase in height due to shoaling tends to happen in dissipative (gently sloping) environments (e.g., sandy beach) and little to no shoaling...
occurs in reflective (steeply sloping) environments (e.g., bedrock shoreline). Consequently, wakes generated in deep water with steep shorelines tend to have larger wave heights (Galmore, 2008), with properties at the shoreline that are directly dependent on how the vessel is operated (displacement, plowing, or planing) and by Fr_d and Fn (Soomere, 2007). In contrast, wakes propagating into small embayments tend to be smaller due to frictional losses across the typically terraced bathymetry and due to the presence of submerged or semi-emergent vegetation (Houser et al., 2015).

![Figure 3: Measured wave profile showing the initial small height and long period of the boat wake, followed by waves of large height and moderate period.](image)

The wake height (H) and energy (∼H^2) reaching a shoreline is also dependent on the number of vessels that pass a specific section of shoreline (Ahmed et al., 2011). Shorelines fronting wide sections of the lake may experience a greater number of passages and recreational activities (e.g., waterskiing, tubing), although the wakes are likely to be dispersed and limited in height and period. In contrast, shorelines fronting narrow channels may experience larger wakes but relatively limited boating activity, unless that waterway is used to move between different
sections of the lake or to a specific destination (e.g., marina, boat launch). To limit wake height and energy at the shoreline, narrow waterways in Ontario and elsewhere in Canada have limits on vessel speeds for safety reasons, with speeds limited to 10 km/h within 30 m of the shoreline (Canadian Legislature, SOR/2008-120, Schedule 6). However, this does not necessarily limit wake heights since a vessel can be driven slowly in plowing mode leading to large waves reaching the shoreline. In areas where there is shoreline infrastructure or sensitive ecosystems, lake associations or individual cottage owners will place ‘no wake’ signs to try and limit the size of the wakes reaching the shoreline (Figure 4). This is particularly common in narrows that are not necessarily captured by the speed limits given their short length and open water on either end.

![Figure 4](image)

**Figure 4:** No wake signs placed by local cottage owners on Whitestone Lake, Ontario in one of the narrowest sections of the lake that is commonly used to transit between the north and south ends of the lake. Note that the MOT notice on the first sign is not official and was added by the cottage owner to deter wakes. Photos courtesy of C. Houser.

2: Vessel-Generated Wake Impacts

With the exception of shoreline erosion studies in marine environments (e.g., Soomere, 2005), there have been relatively few studies to document the impact of vessel-generated wakes on water quality, safety, and damage to infrastructure in fetch-limited lacustrine environments.
In this respect, this review of wake impacts includes both published studies and the perception of cottage owners collected in a parallel but independent and unpublished study conducted in 2023 (REB #42885).

2A: Shoreline Erosion

As noted, most studies of boat wake impacts have been conducted in marine environments or on large inland lakes and the results of these studies suggest that wakes represent a significant amount of the total wave energy and are responsible for shoreline erosion (e.g., Zabawa & Ostrum, 1980; Stumbo et al., 1999; Glamore, 2008). For example, wakes generated by Panamax cargo ships and the associated pilot boats on the Savannah River were found to be responsible for sediment resuspension and associated shoreline retreat that threatened culturally significant structures at Fort Pulaski National Monument along with the recorded frontal storm activity (Houser, 2010, 2011). Similarly, the increasing frequency of both commercial and recreational vessels was identified (with the acknowledgement of the difficulty of measuring boat wake induced erosion) as being responsible for the erosion of ~15% of the 9000 km of shoreline within Chesapeake Bay (Bilkovic, et al., 2019). On the Sacramento Delta in California, Bauer et al. (2002) found that recreational boats were responsible for bank erosion that threatened to undermine levees protecting local agricultural land and the city of Sacramento. Similar results have been identified along the banks of the Kenai River in Alaska (Dorava & Moore, 1997), Tallinn Bay, Estonia (Soomere, 2005), Rich Passage (Osborne et al., 2006, 2007; Curtiss et al., 2009) and Torpedo Bay, New Zealand (Osborne & Boak, 1999). In the latter study, the wakes and prop-wash reached the bottom and were responsible for significant sediment resuspension and increased turbidity: “The annual mass of sediments resuspended by long ship waves is by one order of magnitude greater than the annual mass of sediment brought into
motion by wind waves” (Pg. 316). Combined, these studies suggest that boat wakes are for a major contributor to shoreline erosion and reduction in water quality in fetch-limited environments, along with damage to shoreline infrastructure (Parnell & Kofoed-Hansen, 2001; Soomere, 2005).

In the absence of wakes, the shoreline will trend towards a morphology that is in equilibrium with the amount of wind wave energy (Davidson-Arnott et al., 2019), which as noted is dependent on the length of the fetch, and the frequency, strength, and duration of storm winds. Areas with limited wave activity may have unconsolidated sediments and vegetation extending to and lakeward of the waterline, while larger fetch environments will have greater wind-wave energy leading to a dissipative unvegetated nearshore that is backed by a sand beach or bedrock depending on the availability of sediment and local geology. The addition of boat wakes to the total wave energy, increases the amount of sediment resuspension and shoreline retreat that in turns limits the development of vegetation along the nearshore or results in marsh scarping (Houser, 2010; 2011; Figure 5). While it is reasonable to expect that boat wakes can be attenuated by submerged and emergent vegetation, there is limited field data to document the effectiveness of the vegetation to reduce wave heights. Most studies have shown that vegetation is dislodged directly by the force of the wake and/or the vegetation is undermined by the retreat of the marsh front in tidal environments (Schwimmer, 2001; Bauer et al., 2002).
Results from Houser et al. (2021) suggest that ~60% of total wave energy on Whitestone Lake, Ontario is associated with recreational boat wakes. However, within Whitestone Lake, given that the wakes were reflected off the largely rocky shoreline, the wakes persisted, and the combined wake energy (direct + reflected) represented ~80% of the total wave energy (House, et. al, 2021). Wake reflection can be a particular problem in narrow waterways with bedrock shorelines, and the slow dissipation of the wakes can lead to residual waves and a continuously disturbed water surface (i.e., Figure 5). Other freshwater studies suggest that boat wakes have the potential to resuspend bottom and bank sediment (Baldwin, 2008), limit the growth of vegetation (Mosisch & Arthington, 1998), alter water temperatures through mixing (Reid, 2007), and possibly damage shoreline infrastructure (Houser, et. al, 2021).
Given the increasing number of cottages and recreational vessels in northern Ontario, Canada (colloquially known as Cottage Country), there is increasing concern about the impact of boat wakes leading to the establishment of advocacy groups such as “Safe Quiet Lakes” who advocate for the introduction of local management strategies. Since the number of studies has been limited, there is a further need to determine the relative importance of the addition of the presence of wakes as a baseline. The additional data would help assess impacts and support the development of improved policies and regulations. Based on an understanding of the boat wake energy within sensitive environments, new regulations, and increased enforcement to limit wake damage have been implemented in Denmark (Danish Maritime Authority, 1997) and within riverine environments of New Zealand (Parnell & Kofoed-Hansen, 2001).

Figure 6: Disruption of the water surface by boat wakes on Whitestone Lake, Ontario adjacent to the measurement site of Houser et al. (2021). Visible in the image are wakes recently generated by recreational vessels, wakes reflected by the largely bedrock shoreline and residual wake waves. Photo courtesy of C. Houser.
2B: Sediment Resuspension and Shoreline Erosion

Sediment resuspension at the shoreline is dependent on the size distribution of the shoreline material, level of consolidation, and the height and period of the waves that determine the orbital velocities at the sediment interface (Mehta, 1988). Maximum landward- and lakeward-directed orbital velocities occur at the crest and trough of the wave respectively, leading to a combination of onshore and offshore transport depending on the asymmetry of the wave and the addition of any reflective wakes. The ability of wakes to resuspend sediment depends on the size of the shoreline type, sediment size, distance from sailing line, wake energy and frequency (Hequette & Barnes, 1990; Solomon, et al.,1994; Dallimore, et al.,1996; Obu, et al., 2017). An increase in wave activity due to the presence of recreational boats, can lead to an increase in sediment resuspension, particularly if the wakes have longer wavelengths and faster orbital velocities at the bed. It is important to note that sediment resuspension may not be directly associated with the wake alone but may also be associated with the propeller wash and turbulence reaching the lake bottom (Liao et al., 2015).

An increase in turbidity within a waterway can have an impact on the water quality (Bhowmik et al., 1991), including a reduction in light at lake bottom and increase in nutrient loading that can promote the development of algal blooms (Chen et al., 2003). Conversations with local cottage owners as part of a parallel but separate study of boat wakes suggests that water quality is a significant concern: “The weekend boat traffic has increased dramatically in the past five years……silty water from boat wake is very evident.” (Respondent from Fairy Lake, 2023). Similarly, a resident of Lake Rosalind, near Hanover Ontario, noted that “We have parts of our lake that are less then 20 meters wide and less than 8 feet deep and these boats are generating cutouts on the bottom of the lakebed which of course stirs up silt from the floor bed
and harms water clarity…. ". In many cases, sediment resuspension is associated with or attributed to shoreline erosion in environments with shorelines composed of unconsolidated sediment (Baldwin, 2008; FitzGerald et al., 2011; Bilkovic et al., 2017). Except for embayed marsh environments and artificial sand shorelines, most shorelines in natural Cottage Country lakes are dominated by bedrock. However, artificial (dam-controlled) lakes within this region (including Fairy Lake and Lake Rosalind) tend to have unconsolidated and vegetated shorelines, particularly in narrow sections where there is limited wind-wave activity. Anecdotal evidence from Lake Manitouwabing, a dam-controlled lake northeast of Parry Sound, suggests that vessel generated waves are responsible for shoreline retreat to the underlying bedrock and increasing suspended sediment concentrations that are believed to be contributing to algal blooms that are increasingly common on that lake (pers Comm. MLCA, 2022). Similar concerns have been raised by residents of Kashagawigamog Lake (Respondent, 2023), a natural (undammed) lake southeast of Huntsville, Ontario.

2C: Impacts to Wildlife and Ecosystem Health

Boat wakes have been associated with the uprooting and removal of aquatic vegetation (Schafer, et. al, 2003) that alters shoreline habitat (Bilkovic, et. al, 2019). Conversations with cottage owners in 2023 further revealed concerns regarding the impacts to local wildlife and the health of the shoreline ecosystem: “We have many wakeboard boats on the lake since 2019 (covid times) and our shoreline and nesting birds including our most beloved loons are being negatively affected, our lake is very narrow and not appropriate for these types of boats.” (Respondent from Long Lake). Wakes have been found to cause waves capable of destroying the nests of loons and other waterfowl (Sidor, et al., 2003; Siera Club, 2023).
In addition to the impact of wakes, recreational boats have also been associated with direct trauma to wildlife (Mosisch & Arthington, 1998; Bulté, et al., 2010; Heinrich, et al., 2012; Bennett & Litzgus, 2014). Within the Mosquito Lagoon in Florida, vessel propellers caused damage to the shells of between 13 and 28% of freshwater turtles due to the high traffic of 51.4 vessels per hour within the lagoon (Walters, et al., 2020). Other studies suggest that ~25% of manatee deaths are caused by collisions with aquatic vessels and propellers (Calleson & Frohlich, 2007; Bassett, et al., 2020), and trauma is responsible for 52% of loon mortality (Sidor, et al., 2003). These impacts are in addition to the transportation and deposition of invasive aquatic plants and animals by way of ballast water (Kumaraswamy, et al., 2020) and the intentional or accidental release of waste (Bhat, et al., 2018) or engine lubricants (Kumaraswamy, et al., 2020).

### 2D: Damage to Shoreline Infrastructure

According to the residents and owners in Muskoka, there has been noticeable changes due to wave activity over the years, “Our shorelines are eroding, and docks and moored boats tied to them are being damaged.” (Respondent from Long Lake, 2023). Although it is assumed that wakes can damage or destroy shoreline infrastructure (e.g., piers, docks, buildings, etc.), there is a limited number of studies to make a direct connection. Of the few studies that investigated this took place in New Zealand and Denmark, focusing on the high-speed ferries that frequent their bodies of water (Parnell & Kofoed-Hansen, 2001). The findings provided evidence that vessel generated wakes cause changes to the shoreline morphology, particularly within environments that exhibited a lower level of wind generated waves (Parnell & Kofoed-Hansen, 2001). Additionally, a review of the vessel generated impacts and potential solutions, found that
the infrastructure required to mitigate wakes would be similar to the protection of the shoreline against wind generated waves (Bilkovic, et al., 2016).

2E: Noise Pollution

Even if wakes do not have a direct impact at the shoreline, they are the physical manifestation (a reminder) of ‘disruptive’ boating activity that conflicts with another person’s desired use of the lake. Mosisch & Arthington (1998) suggest that above-water noise pollution from recreational boats represents a significant annoyance for lake users (see also Di Franco, E., et al., 2020; Solomon, et al., 1994; Luczkovich, et al., 2016). Noise and disturbance were primary reasons for the establishment of the Safe Quiet Lakes Association, which has a mission to assure that “The enjoyment of safe, quiet waterways will be ensured for all – boaters, non-boaters, wildlife, aquatic life, businesses and communities – for generations to come”. Noise pollution caused by recreational boats is also addressed within Cottage Life, a popular magazine highlighting the cottage experience in northern Ontario (2022). The article includes an interview with Dr. Barry Truax of Simon Fraser University who highlights the health benefits of nature sounds and the degradation in health that occurs with sounds of human activity including vessel motors, music, and loud voices. As noted by a cottage owner on Fairy Lake, “The one new regulation we need is about quiet enjoyment... boaters and renters are either unaware or do not care about the fact the whole lake has to listen to their blaring choice of music... totally unfair to those of us who want to hear the water and the birds”. Another cottage owner noted that “There are still ocean-going type boats that are intentionally loud enough that they stop conversation on shore when they go by. It makes sitting by the water quite unpleasant and is dramatically different from a ski boat going by, or someone pulling a tube. There are also other boats that
have an extremely high engine noise due to their muffler systems” (Respondent from Lake Joseph).

2F: Personal Safety

Boating regulations tend to be based on safety with a focus on the occupants on the vessel or other vessels (Wright, 1985; McKnight et al., 2007), with limited to no consideration of the potential for wakes to be a safety hazard for people at the shoreline (Bhowmik & Demissie, 2002; Parnell & Kofoed-Hansen, 2001). A respondent from Fairy Lake highlighted the potential safety concerns related to boat wakes: “The shore is eroding. I’m losing land and trees into the water. The water is murkier than ever before, and the constant large waves makes it unsafe for my kids to swim at times”. Another respondent noted that “Kayakers, canoers, paddle boarders and swimmers are at risk when a wakeboard boat passes them, as the large waves can overtake their vessels or cause a swimmer to drown” (Long Lake), or that wakes represent a “High safety risk to other people (swimmers, kayakers, and canoers)” (Lake Rosalind). It is reasonable to assume, however, that concerns that wakes create a safety hazard is also related to conflicting use of the water: “High speed of personal watercraft zigzagging through boat wakes is very dangerous. Very little OPP enforcement especially on the weekends” (Fairy Lake, 2023). Another resident of Lake Rosalind (2023) noted that the biggest safety issue was “Seadoos playing chicken, following too close to other boats jumping their wakes, & generally going anywhere & everywhere – not following the lake direction”.

3: Perception of Boat Wake Impacts

Results of a 2021 survey of cottage owners suggests that the biggest issues with recreational boating was power boats and personal watercraft (PWC) not following the “rules of the road” followed by powerboats and PWCs traveling at high speeds (Spears, 2021; Table 1).
This focus on speed and boating behavior suggests that the primary concern about wakes is conflict in lake usage and is not necessarily the wakes themselves. In comparison, the direct impact of wakes to shoreline erosion and damage to infrastructure was noted by 46% of respondents. However, the survey did not include open-ended questions and a thematic analysis to determine whether shoreline erosion and damage to infrastructure was real or simply perceived.

**Table 1:** Results from “Your Lakes, Your Views,” 2021 survey distributed by SQL to local cottage owners to gain perspective on their views on the harmful use of water vessels and their potential impact on the shoreline.

<table>
<thead>
<tr>
<th>In Agreement</th>
<th>Topic in Question</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 %</td>
<td>Power boats and PWCs that do not follow “the rules of the road”</td>
</tr>
<tr>
<td>59 %</td>
<td>Power boats and PWCs travelling at high speed</td>
</tr>
<tr>
<td>46 %</td>
<td>Erosion of shorelines</td>
</tr>
<tr>
<td>46 %</td>
<td>Damage to docks and moored vessels</td>
</tr>
</tbody>
</table>

Cottage owners and permanent residents from across Ontario have reported shoreline erosion in interviews with news outlets such as CBC Canada and CTV News London. In one instance, a drone photographer, David Piano captured erosion that is “swallowing cottages and eating away at the shoreline” along Lake Erie (Lupton, 2022). Boat wakes have also been the focus of discussions on social media including “Wake Up: Paddlers, environmentalists concerns mounting on Muskoka’s lakes” (Muskoka Region News, 2022) or “Are really loud boats a problem on your lake or river?” (Safe Quiet Lakes Email Prompt, 2022) and photographs with hashtags such as “#WakeAware” (Safe Quiet Lakes, Instagram, Figure 7). Additional examples include cottagers and residents using Facebook to discuss their concerns, suggestions, and assumptions about boat wakes in a public forum about Whitestone Lake, Ontario (Figure 8). The problem with these anecdotal reports is that they tend to focus on individual incidents and
boaters and may have biased assumptions that the wakes are solely responsible for observed erosion and damage to infrastructure.

Be #WakeAware
Did you know? Boat wake can cause shoreline erosion, damage docks and moored boats, topple inexperienced swimmers or smaller craft including canoes, and drown nesting birds and loon chicks. Please learn more, and pledge to Be #WakeAware.

Figure 7: Screenshot of social media posts by Safe Quiet Lakes regarding vessel safety. This photograph exhibits the attempt by locals to understand how they may curve the impacts of boat wakes and their perspective on the damage they create.
Figure 8: Complaints/commentary found on a Facebook cottage owner page ("I Have a Cottage on Whitestone Lake") regarding vessels (personal information redacted). Whitestone Lake is where the Houser et al. (2021) was conducted.
STUDY PURPOSE AND OBJECTIVE

Cottage Country lakes in northern Ontario tend to be fetch-limited such that vessel-generated wakes (herein referred to boat wakes or wakes) may represent a significant source of wave energy at the shoreline. Apart from Houser et al. (2021), there have been no published studies on the relative contribution of recreational boat wakes on the total wave energy of inland lakes, and most evidence is anecdotal or assumed by residents (Safe Quiet Lakes, 2021). To provide baseline data on whether vessel-generated wakes may have an impact in fetch-limited lakes, the purpose of this study is to quantify the relative contribution of boat wakes and wind-generated waves to the total wave energy for sites with a range of fetch lengths within the Muskoka Lakes (Joseph, Muskoka and Rosseau). The specific objectives of this study are to:

1. Quantify the relative contribution of boat wakes and wind generated waves to total wave energy at sites representing different combinations of fetch-length, boating activity, depth, and shoreline configuration.

2. Document local perspectives on the impacts of vessel-generated waves through an online survey distributed with the support of Safe Quiet Lakes (SQL).

Results of this study will contribute to our understanding of boat wake impacts in fetch-limited environments and can be used to inform educational programs and local management strategies.
**STUDY SITES**

This study was completed in the Muskoka Lakes region of Ontario, ~220 km north of Toronto, Ontario (Figure 9). Wind- and vessel-generated waves were measured in summer 2022 at 10 sampling sites around Lakes Muskoka, Rosseau, and Joseph. According to a 2020 Mansion Global report, the approximate number of cottage properties is 4,500 on Lake Muskoka, 1,500 on Lake Rosseau, and 1,300 on Lake Joseph. Lake Rosseau and Joseph are connected to Lake Muskoka by way of Muskoka River and the Port Carling Dam, which was constructed in 1873. The specific locations of the sampling sites were based in part on the willingness of SQL members to have sensors placed at their shorelines, with the final section of sensor locations based on shoreline type (sand versus bedrock, considered for varying erosion potential), orientation, fetch-length, boating activity, water depth, and accessibility (Table 2; Figure 10 A&B).
Figure 9: Study site map (each letter coincides with a site) with a local wind rose showing hourly records over the study period and inset map illustrating the region the sites reside in within Ontario.

Table 2: Site specific controls on potential wave/wake generation and shoreline response, including fetch length, orientation (direction facing), shoreline material and average depth offshore in the vicinity of the sailing line. Water depth was determined by historic data provided by Environment Canada. Water depths determine wake size through energy dissipation.

<table>
<thead>
<tr>
<th>Site</th>
<th>Average Fetch (km)</th>
<th>Shoreline Material</th>
<th>Orientation</th>
<th>Average Depth (m)</th>
<th>Site Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>2.32</td>
<td>Sand to Bedrock</td>
<td>E</td>
<td>35.7</td>
<td>Open</td>
</tr>
<tr>
<td>C</td>
<td>0.53</td>
<td>Sand to Bedrock</td>
<td>S</td>
<td>16.7</td>
<td>Narrows</td>
</tr>
<tr>
<td>E</td>
<td>2.52</td>
<td>Cobble to Bedrock</td>
<td>NE</td>
<td>37.2</td>
<td>Bay</td>
</tr>
<tr>
<td>F</td>
<td>2.03</td>
<td>Cobble to Bedrock</td>
<td>NW</td>
<td>9.6</td>
<td>Bay</td>
</tr>
<tr>
<td>G</td>
<td>0.63</td>
<td>Bedrock</td>
<td>SE</td>
<td>16.1</td>
<td>Open</td>
</tr>
<tr>
<td>H</td>
<td>0.58</td>
<td>Sand</td>
<td>SE</td>
<td>2.7</td>
<td>Narrows</td>
</tr>
<tr>
<td>I</td>
<td>2.11</td>
<td>Sand to Bedrock</td>
<td>NW</td>
<td>22.8</td>
<td>Open</td>
</tr>
<tr>
<td>J</td>
<td>2.19</td>
<td>Bedrock</td>
<td>W</td>
<td>21.1</td>
<td>Open</td>
</tr>
</tbody>
</table>
Figure 10: Images of shorelines of sites A through J.
METHODS

Pressure transducers measuring wave height, wave period and water level were deployed at 10 sites during the week of June 1st, 2022. The sensors were mounted on a cement block to ensure that it remained stationary, placed at a depth of ~1 m, and marked with a discrete buoy for easy retrieval. Every 3 to 4 weeks, sensor batteries were replaced, and the data was downloaded. If a sensor malfunctioned or batteries were observed to be drained rapidly, the sensor was either fixed or replaced with another pre-tested sensor. All sensors were removed during the week of September 29th, 2022. Although all sensors were maintained, there are certain gaps in data due to various reasons including lost or damaged sensors.

1: Wind Activity and Fetch Length

Fetch length was calculated using satellite photographs (Google Earth) by measuring and averaging the distance to the adjacent shoreline along 16 compass directions at each sensors location (Figure 11). Fetch lengths ranged between 0.44 km and 2.34 km, creating a variety of fetch limited environments for the generation of wind waves. The distribution of wind wave heights and periods generated at each site was predicted using the past two years of historical wind speed and direction from the Muskoka Airport. Using standard nomograms, the wind speed, direction, and fetch length were used to estimate the range of wind-generated wave heights and periods expected during the study period.
Figure 11: Fetch length measuring technique shown at site C, the measurement is represented as the yellow line, 0.15 km at 315° or NW, which is repeated every 22.5 degrees facing away from the shoreline (the fetch length is found by averaging these values).

2: Pressure Transducers

Commercial wave instruments (e.g., RBR Wave & Tide Sensor) are often cost prohibitive for projects requiring multiple sensors, and there is a significant risk of them being lost or damaged in high energy wave environments. Recent advances in low-cost ‘Do It Yourself’ (DIY) pressure transducers have increased accessibility to highly accurate instruments at a significantly lower cost (Temple et al., 2020; Lyman, et al., 2020; Beddows & Mallon, 2018). The transducers are also capable of measuring high-frequency (<20 s) variations in water level with the passage of individual waves, allowing for measurement of wave height, period, and energy. If corrected for changes in atmospheric pressure, the DIY transducers also record change in water levels at low frequencies (> 20 s) including tide, seiche and hydrology-driven changes.
This study uses a modified DIY design that incorporates various aspects of previously published models (Table 3). The main housing of the transducer consisted of a 32 cm long and 12 cm diameter PVC pipe fitted with a 5-cm diameter cap on one end, with a hole in one of the caps for the pressure sensor (Figure 12 B). The sensor is held in place using epoxy putty, and liquid epoxy is used to create a waterproof seal around its electronics, leaving only the transducer port exposed. The other end of the housing is sealed with a gripper cap, which can be loosened to open the sensor. The electronics include a pressure sensor, a real time clock, an SD card, and a microcontroller board that are assembled on a custom circuit board to connect and hold everything together (Figure 12 A).

The accuracy and precision of the DIY transducer was compared to a commercial RBR Wave and Tide Sensor (Model TWR 2050) following similar experimental approaches used in other DIY transducer studies (Temple et al.,2020; Lyman, et al.,2020; Beddows & Mallon, 2018). The RBR has a depth full-scale resolution of <0.001%, an accuracy of ± 0.05%, and a clock accuracy of ± 32 seconds/year, according to the manufacturer. The offset between the DIY sensors and the RBR sensor can be accounted for by adjusting any constant error offset while processing the data (Figure 13). Prior to deployment in the field, the sensors were placed together in a 15” x 60” tub at a depth of 72” and tested for both mean water level and high-frequency oscillations similar to what would be produced by a recreational vessel. As described in the previously mentioned studies, a field test took place within Whitestone Lake, comparing the offset between the commercial sensor and the DIY sensor. The root-mean square error (RMSE) between the commercial grade and calibrated DIY sensor was 1cm, indicating the high accuracy and precision of results presented in this study.
**Figure 12:** Images of pressure transducer construction; A) electronics, B) outer dimensions, C) deployment structure.

**Figure 13:** The offset between DIY and RBR sensors, which was accounted for during data processing.
Table 3: A comparison of DIY data loggers and pressure transducers from other studies to the DIY design used in this study.

<table>
<thead>
<tr>
<th>Research Paper Citation</th>
<th>Key Features</th>
</tr>
</thead>
</table>
- PCF8523 real time clock  
- MS5803-14BA pressure sensor  
- Arduino Uno microcontroller  
- Fast sampling and Data stored on SD  
- Powered by a 6600 mAh Lithium-Ion battery which lasts approximately 5.5 days |
- DS3231 real time clock  
- MS5803-14BA pressure sensor  
- Arduino-based custom microcontroller  
- Samples at a modifiable frequency and saves data to SD card  
- Powered by 3 x D Cell batteries which last more than 14 months |
| Beddows PA, Mallon EK. Cave Pearl Data Logger: A Flexible Arduino-Based Logging Platform for Long-Term Monitoring in Harsh Environments. Sensors. 2018; 18(2):530. | - Multiple housing designs  
- DS3231 real time clock  
- Many types of sensors, including the MS5803 series  
- Arduino microcontrollers- Samples at modifiable frequency and saves data to SD card- Typically powered by 3 x AA batteries which last more than 1 year depending on the sensor |
| DIY Pressure Transducer used in this study | - Large housing design (Temple et al.,2020)  
- DS3231 real time clock  
- MS5803-05BA  
- ESP32 FireBeetle microcontroller  
- Samples at 1 Hz and saves data to SD card  
- Powered by 3 x AA batteries, which last more than 8 months on the most updated microcontroller code |
3: Deployment

As noted, sensor deployment and data collection took place from June to September 2022 (Table 4), with brief sampling gaps due to changing batteries and downloading of data once a month. To avoid data loss due to battery shortage or unforeseen technological mishaps, two DIY transducers were assigned to each site. An RBR pressure transducer was deployed at Whitestone Lake (see Houser et al., 2021) as a ‘control’ sensor for examining interannual variations in boating activity. The locations of the sensors were not publicly disclosed to avoid potential damage or theft, and to ensure that there were no changes in boating activity based on knowledge of the sensor location. An additional transducer was placed within an open boat house at Site B to provide a continuous measure of atmospheric pressure for water level corrections. Unfortunately, two sensors (Site I) were lost due to strong wave activity and loose bindings, and some sensors (Site B and Site J) had gaps in data due to delayed deployment or sensor failure. It is recognized that potential bias may be introduced over the course of the study in response to battery voltage, algae build-up on the sensor and age of the sensor. These variables remain untested for the sensors used in this study or other studies involving DIY sensors.

Table 4: Details of sensor deployment, deployment lake, and data collection dates for Summer 2022.

<table>
<thead>
<tr>
<th>Deployment Date Range</th>
<th>Deployment Lake</th>
<th>Sensor Type</th>
<th>Site Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>07/11/22 to 09/24/22</td>
<td>Lake Muskoka</td>
<td>DIY Pressure Transducer</td>
<td>J</td>
</tr>
<tr>
<td>06/03/22 to 09/24/22</td>
<td>Lake Rosseau</td>
<td>DIY Pressure Transducer</td>
<td>E, F, G, H &amp; I</td>
</tr>
<tr>
<td>06/03/22 to 09/24/22</td>
<td>Lake Joseph</td>
<td>DIY Pressure Transducer</td>
<td>B &amp; C</td>
</tr>
</tbody>
</table>
4: Data Correction & Processing

The DIY pressure transducers were set to record water temperature and water level every second (1 Hz) over the course of Summer 2022. The data from each sensor was downloaded once a month and the data was examined to determine if there were errors, outliers (large spikes), missed readings and/or duplicate measurements. These actions were taken in addition to those mentioned in the Pressure Transducer Feasibility section, where offsets between the DIY and RBR sensors were made. The ‘clean’ data was then corrected for atmospheric pressure, which was subtracted from the pressure measured by the sensors in the water (Figure 14).

![Wave Activity Before Adjusting for Air Pressure (2022-08-01)](image)

**Figure 14:** Section from Site B and Site J on a civic holiday, August 1st, 2022, to highlight the effects of air pressure on the signal.
Figure 15: Section from Site B and Site J on a civic holiday, August 1st, 2022, to exhibit accounting for air pressure then converting water pressure to depth. Numbers 1-5 on the orange dataset are examples of boat wake packets. Numbers 1 and 2 on the blue dataset are examples of what is most likely storm activity due to the consistent nature of the high peaks without the flux seen in boat wake.

The atmospherically corrected pressure \( p \) (Pa)) was converted to water depth \( h \) (m), by:

\[
h = \frac{p}{g \rho}
\]  

(3)

where \( g \) is the acceleration of gravity 9.81 m s\(^{-1}\), \( \rho \) is the density of freshwater \( \sim 1,000 \) kg m\(^3\) (Figure 15). The data was then segmented into 20 min periods and detrended with a 2\(^{nd}\) order polynomial to remove the effect of unsteady winds that alter the size of the background wind waves. To isolate the segments into boat wakes and wind waves, a continuous wavelet transform (CWT) was used to determine the variation of the recorded to a synthetic signal generated using a Morlet wavelet across multiple scales. Given the normal distribution of the CWT coefficients, values exceeding 99% confidence in (~2.57 standard deviations from the population mean) at
scales corresponding up to a 5s wave period were interpreted as boat wakes given the increased magnitude of wave height and period in comparison to the background signal or wind generated waves (e.g., Figure 16). Quality controls were implemented to remove isolated peaks within the signal, and areas identified to be statistically significant must have a length of 12 s (i.e., approximately three or more recorded waves) to be considered a boat wake packet. Once discrete sections of each segment were identified, the wave height ($H$) for boat wakes and wind waves were found using the zero-up crossing method that measures the height between a successive trough (-) and crest (+). Wave energy ($E$ ($J \ m^2$)) was then calculated as:

$$E = \frac{1}{8} \rho g H^2$$

Identification of the period of the waves allows for further understanding of the percent occurrence of the waves and the associated percent of total wave energy seen at our sites (see Houser et al., 2021). Additional published (Houser et al., 2021) and unpublished data from Whitestone Lake and Lake Rosalind collected in 2022 are used to explore the relationship between the fetch length and the wake energy and time fraction. Afterwards, the processed data was tested utilizing the non-parametric Kolmogorov-Smirnov test to understand the distribution of wake energy in comparison to the local wind wave energy at each site, which is used to determine if distributions are statistically similar (Massey, 1951; Table 6).
Figure 16: Example of extracted vessel generated wake, from June 11th at Site B; wake activity within boxes and wind activity outside of boxes.

5: Accuracy of Wake Estimates

The ability to separate wakes varied with the size of the wind waves. Examples of varying wind-wave activity from Sites B, I, and G are presented in Figure 17. At Site B (large fetch and westward orientation), wind-wave activity on Saturday, June 11th, 2022, was moderate leading to wind wave heights of ~ 0.025 m and periods of 12s. A total of 7 individual wakes were identified over a four-hour period, with significant wake heights ($H_{sw}$) of between 0.03 and 0.04 m and periods ranging from 12 to 15s. The wind-generated waves in this example increased in height due to the increase in wind speeds (from 4 to 28 km/h) over that time. It is possible that some of wind-waves are reflected waves from adjacent shorelines, but those are difficult to accurately extract across all sites due to variations in shoreline type and the width and depth of the waterway. A relatively straightforward separation of wakes and wind waves is presented in Figure 17b from Site I (medium fetch and westward orientation) on Sunday, June 6th, 2022. On this day, there were low and consistent wind speeds, leading to limited wind-wave activity.
(H_s=0.015 m) and easily identifiable wake packets (H_{sw} = 0.037 m) over a 4-hour timeframe. An example in which it was difficult to separate wind waves and boat wakes is presented in Figure 17c for Site G (small fetch and southward orientation) when it was experience strong wind speeds on Sunday June 19^{th}, 2022. While it is reasonable to assume that few boaters would be out during such a storm (H_s = 0.037 m), it is not possible to identify wakes from the record such that vessel-generated wake energy may be underestimated.
Figure 17: Example Vessel Generated Wakes, Site B, Saturday, June 11th, 2022; Vessel Generated Wakes, Site I, Sunday, June 6th, 2022; Storm Wave Activity, Site G, Sunday June 19th, 2022; all over a 4-hour timeframe.
In addition to the direct measurement of wake energy, a perception survey (REB #42885) was distributed with the support of SQL to all members on Lakes Muskoka, Joseph and Rosseau in 2023. The purpose of the survey was to understand the perception of landowners and lake users on fetch-limited lakes in the northern region of Ontario, as well as the perceived impact of how boat wakes vary by lake that vary in size, shape and orientation, and the potential implications for regulations. The survey (Appendix A) included questions related to lake characteristics (fetch, depth, etc.), boating usage, and perceptions of boat wake impacts. Additional open-ended questions asked respondents to consider “What changes have you noticed in the past 5 years on your waterbody and how much have they impacted your experience, safety, and/or the environment,” and “In your opinion, are additional regulations and restrictions required on your waterbody?” No identifying information is collected through the survey and the identity and location (e.g., IP address) of the respondent. The email distributed by SQL contained both a URL link to the survey and a QR Code with an explanation of the research study (Figure 18). The estimated completion time of the survey was between 15 and 20 minutes.

Figure 18: QR code that was distributed for survey participants.
RESULTS

A total of 2735 hours of data and 251,573 boat wake waves were captured across all sites. The cumulative sum of wake energy was 139,912. J/m² or 65.9% of the total wave energy across all sample sites, while the cumulative sum of the background wind-wave energy was 72,364 J/m² or 34.1% of the total wave energy across all sample sites. Across all sample months, wake energy was greater than the wind-wave energy (Table 5), despite frontal storms recorded during the study period (Figure 19). While the relative amount of wake energy varied across the sites, wakes also accounted for most of the wave energy despite variations in the total number of wakes, orientation, and fetch length (Table 5). In general, the total wake energy and period were similar for the sites with longer fetch (Sites B, E, F, I, & J), due to greater activity in open sections of the lake. The greater activity was, however, balanced by a decrease in wake height and period due to the distance of the sailing line from the shoreline. In contrast, wake heights and periods were greater at sites with a shorter fetch, while the wake time fraction (Sites C, G, & H) are lower. Relatively few wakes were observed at site G due to few vessels passing through this area, while Sites C and H exhibited greater activity because they were at the narrow sections of the lake that were key to transiting from one section to another.

Table 5: Site specific characteristics, including number of wakes and average wake energy and time fractions.

<table>
<thead>
<tr>
<th>Site</th>
<th>Number of Boat Wakes</th>
<th>Average Energy Fraction of Wakes (%)</th>
<th>Average Energy Fraction of Background Waves (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>25,148</td>
<td>70</td>
<td>30</td>
</tr>
<tr>
<td>C</td>
<td>17,097</td>
<td>66</td>
<td>34</td>
</tr>
<tr>
<td>E</td>
<td>31,568</td>
<td>70</td>
<td>30</td>
</tr>
<tr>
<td>F</td>
<td>35,085</td>
<td>70</td>
<td>30</td>
</tr>
<tr>
<td>G</td>
<td>19,483</td>
<td>73</td>
<td>27</td>
</tr>
<tr>
<td>H</td>
<td>32,388</td>
<td>75</td>
<td>25</td>
</tr>
<tr>
<td>I</td>
<td>29,407</td>
<td>69</td>
<td>31</td>
</tr>
<tr>
<td>J</td>
<td>20,264</td>
<td>69</td>
<td>31</td>
</tr>
</tbody>
</table>
Figure 19: Comparison of RBR data gathered during both Summer of 2020 and Summer of 2022, providing evidence that there is consistent vessel activity during the Summer season, with a slight decrease during Summer 2022.

I: Variation in Wake Energy

Peak wave and wake activity varied with day of the week, Wednesdays and Saturdays were found to be the days with the greatest boating activity, the trend is typically an increase in wake energy from Monday to Saturday with the outliers being Site B and I (Figure 20). Additionally, there is a visible variation between each site, which is likely due to the variation in shoreline type (some narrow and others open). The holiday dates during Summer 2022 were often Monday dates, which is a potential reason for the peak of activity on Wednesdays, as cottagers frequently increase vessel use during the weeks of holidays.
Figure 20: Weekly average variation of vessel generated wake at each study site, exhibiting the increased usage during the weekend days in comparison to the weekdays.
Wave and wake energy also varied over the summer sampling season due to holidays and the passage of frontal storms (Figure 19). There were four frontal storms observed during the study period with average wind speeds of 22 km/h, maximum wind gusts of 22-30 km/h, and typical directions of west or northwest. Sites B and I are the sites with the highest levels of frontal storm activity, likely due to their fetch-aligned exposure to west winds. The frontal storm wind-wave energy ranged from 100 to 250 J/m², which were smaller than the cumulative energy of the wake energy on weekends (Average of 200 J/m²) and during holidays such as Canada Day, Civic Holiday, Labor Day 300 J/m²) when boating activity was markedly greater. Between frontal storms, wind waves are largely diurnal in response to differential heating creating a lake breeze that is equivalent to a sea breeze in marine environments. These diurnal winds were typically ~5 km/h with wave generation oriented to the longest fetches and reaching a maximum in late afternoon. Little to no wind-wave activity was observed overnight, leading to the strong diurnal signal and the cumulative sum of wake energy being greater than the wind-wave energy at all sites (Figure 14). The largest amount of cumulative boat wake energy was observed at Sites F, I, and B due to their location to commonly used sailing lines, while the longer fetches of Sites C, G, and H resulted in lower cumulative wake energy compared to the wind-wave energy.

The wind-wave and wake period, energy and time fraction are presented by month in Figure 21 A through 21 D. On average across all sites, the wake energy was 67% of the total wave energy during the study period ranging from 69% at Sites B and H to 60% at Site C (Table 6; Figure 21 A through 21 D). This indicates that the wakes are the primary source of wave energy across the sites. A Kolmogorov-Smirnov (KS) comparison of the sites suggests that the distribution of wake energy is significantly greater than wind-wave energy at the 95% confidence level across all sites (Table 6). No statistically significant relationship was observed
between the period of the wind-waves ($\bar{T} = 3.0$ s) and boat wakes ($\bar{T} = 3.1$ s), but there was a statistically significant difference in the time fraction of boat wakes compared to wind waves based on a Z-Test (Table 6). On average, boat wakes accounted for 11% of the study period, while wind-generated waves and calm water accounted for 83% and 6% respectively (Table 6). The KS test is for non-parametric, and that Z is for parametric (normally distributed) data.

**Table 6:** Comparison of Average Hourly Wind-wave and Wake Energy (E), Ratio of Wake Energy to Wind-wave energy, D- and Z-score of hourly energy distributions, wind-wave and wake time fraction, Z-score of hourly time fraction distributions, and the time fraction of no waves. Statistically significant z-scores are shaded.

<table>
<thead>
<tr>
<th>Station</th>
<th>Wind E</th>
<th>Wake E</th>
<th>Wake/Wind</th>
<th>D-Score</th>
<th>Wind Time</th>
<th>Wake Time</th>
<th>Z-Score</th>
<th>No Waves</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>0.0062</td>
<td>0.0135</td>
<td>2.18</td>
<td>0.11</td>
<td>0.84</td>
<td>0.12</td>
<td>153.30</td>
<td>0.04</td>
</tr>
<tr>
<td>C</td>
<td>0.0003</td>
<td>0.005</td>
<td>1.52</td>
<td>0.06</td>
<td>0.86</td>
<td>0.10</td>
<td>223.30</td>
<td>0.04</td>
</tr>
<tr>
<td>E</td>
<td>0.0034</td>
<td>0.0067</td>
<td>1.98</td>
<td>0.18</td>
<td>0.81</td>
<td>0.11</td>
<td>122.80</td>
<td>0.07</td>
</tr>
<tr>
<td>F</td>
<td>0.0020</td>
<td>0.0038</td>
<td>1.88</td>
<td>0.09</td>
<td>0.85</td>
<td>0.11</td>
<td>283.24</td>
<td>0.04</td>
</tr>
<tr>
<td>G</td>
<td>0.0017</td>
<td>0.0031</td>
<td>1.79</td>
<td>0.08</td>
<td>0.75</td>
<td>0.09</td>
<td>74.59</td>
<td>0.17</td>
</tr>
<tr>
<td>H</td>
<td>0.0014</td>
<td>0.0031</td>
<td>2.26</td>
<td>0.15</td>
<td>0.86</td>
<td>0.09</td>
<td>136.78</td>
<td>0.05</td>
</tr>
<tr>
<td>I</td>
<td>0.0042</td>
<td>0.0084</td>
<td>2.02</td>
<td>0.19</td>
<td>0.82</td>
<td>0.13</td>
<td>132.34</td>
<td>0.05</td>
</tr>
<tr>
<td>J</td>
<td>0.0027</td>
<td>0.0059</td>
<td>2.16</td>
<td>0.36</td>
<td>0.84</td>
<td>0.12</td>
<td>221.38</td>
<td>0.03</td>
</tr>
</tbody>
</table>

The site with the highest sum of energy is Site E and the lowest is Site I. This is due to two main factors; fetch length and vessel activity, which determine the buildup of local wind energy and the exposure of vessel wake, respectively. Finally, the period of the wake was consistently higher than the period of the wind waves, frequently a 1 second difference. However, the site with the largest average period was Site H and the lowest was Site E, which is likely due to the fetch length at each site.
Figure 21 A: Plot representing all sites and the cumulative wave energy from both the vessel-generated wake and background waves, the dates of frontal storms, and the dates from holidays.
Figure 21 B: Plot representing all sites and the cumulative wave energy from both the vessel-generated wake and background waves, the dates of frontal storms, and the dates from holidays.
Figure 21 C: Plot representing all sites and the cumulative wave energy from both the vessel-generated wake and background waves, the dates of frontal storms, and the dates from holidays.
Figure 21 D: Plot representing all sites and the cumulative wave energy from both the vessel-generated wake and background waves, the dates of frontal storms, and the dates from holidays.

2: Fetch-length Relationships

Fetch length is the primary control on wind-wave energy in the fetch-limited lakes of cottage country in Ontario. A comparison of the % wake energy with the average fetch length reveals an inverse relationship (r² = 0.34; <0.05) in which wake energy decreases with increasing fetch (Figure 22). However, there is no statistically significant correlation between the total wake energy and fetch length, suggesting that the decrease in % wake energy with fetch is largely associated with an increase in wind-wave energy. The deviation of % wave energy
from the observed relationship with fetch appears to be associated with the type of shoreline, with sites within narrows having a negative deviation (less energy than expected) and closed/bay sites (i.e., Lake Rosalind) having a positive deviation (more energy than expected). Similar to % wake energy, the time fraction of wakes exhibited a statistically significant relationship ($r^2=0.46$; $p<0.05$) with the fetch length. Open sites with the longest fetch experienced the greater time fraction of wakes, while sites with shorter fetches (bays and narrows) had a shorter time fraction. No statistically significant relationship was observed between the average wake period and the fetch length.

Figure 22: Wake energy (A) and time fraction (B) versus fetch length for the Muskoka Lake sites (circles) and the data from Whitestone Lake in 2020 and 2022 (open squares).
3: Perception of Boat Wakes in the Muskoka Lakes’

The perception survey was distributed in Summer 2023 with the support of SQL. A total of 97 cottage owners from Lakes Muskoka, Joseph and Rosseau participated in the survey, out of an approximate total of >7000 cottages on the lakes (~1%). However, not all residents on the lakes are members of SQL, it is assumed that the response rate was stronger, stemming from potential responses across a broader region as SQL has over 6,200 members (ranging from Georgian Bay to Lake of Bays regions). When asked about the emerging issues related to watercraft on your waterbody, many respondents (n=38) noted issues with the types of boats, their operation, and the lack of experience amongst drivers:

*Ocean sized racing boats should not be allowed on the Muskoka lakes.*
*The boat design industry is producing boats (and PWC) with annoying unintended consequences such as large wakes and noisy sound systems because these boats look fancy, sexy and appeal to a small but affluent water toys segment of the population.*

*Increased activity with noisy boats that remind me of episodes of Miami Vice.*
*How are they appropriate in the environment of Muskoka?*
high speed boat races and jet skis as well as surfing on boat wakes

Lake powered motorboats and sea-dos moving too quickly close to shore and the boat operators not always focusing on driving the boat.

Increased popularity of weak, surf boats. These boats create significant Wakes, even when not being used as surf boats.

Increasing boat size, horsepower, and the number of outboard engines on boats.

More wakeboats, more load music on motorized boats.

One issue would be an increase in inexperienced boat drivers. It takes half an hour to get your boat smart card which qualifies you to drive a boat but absolutely no hands-on experience. Driving a boat is totally different from driving a car.

1. More and more inexperienced boat operators. 2. More renters. Right now, a person can simply rent a boat, pay for a temporary boat license, and off they go. How does that make any sense? THAT is an accident waiting to happen. 2. People purchasing faster boats. 3. Engines continuing to increase in size and speed. 4. No regulations in place to regulate or monitor activity or ensure safety and impact on the environmental impact.

In comparison, very few respondents (n=7) noted issues related to shoreline erosion, safety, and/or habitat loss:

environmental damage, property damage, safety of swimmers, noise

Environmental ruining the habitat of the wildlife

Disappearing shoreline and animal species

Someone being seriously hurt or killed. Shoreline destroyed. Nature Loons disappearing and other ducks.

Increased environmental damage and shore erosion. Increases number of boats as our lakes become more developed and lack of REAL enforcement and education relating to the damages that unsafe and reckless, thoughtless boating habits have.

Accidents and continued damage to wildlife and property

It is not a coincidence we have not had loons nesting on our point for 10 years since our channel became a busy wake surfing mecca.

And only one respondent noted directed evidence of erosion:
Our shoreline has eroded approximately 6 feet in the last 10 years causing trees and shoreline to collapse into lake.

All but one of those respondents described their shoreline as being vegetated (with and without rock) or sandy, but this appears to be contradictory as only 17% of respondents who identified having a vegetated or sandy shoreline. Only one respondent noted shoreline erosion, safety and/or habitat loss in response to the final question Q24 to raise additional questions:

There is an urgent need to curtail and prevent further shoreline erosion. Real action must be taken Immediately. The time to act is now, not 10 years from now after massive damage is done.

A small number of respondents (n=3) to Q23 noted that boating activity was not an issue including single responses (“none”):

I love the sound of the boats. To me it is a cottage noise. During the week it is very quiet. The noise is usually only on weekends.

Safe Quiet folk need to relax more and enjoy the summer.

One respondent to Q23 noted that the primary issue was not about activity or impacts but was associated with water quality:

“With increased density of cottages in commercial settings all needing a boat I think we will see a lot more full day cruising boats. Without washrooms and areas for anchoring there will be more and more floaters, swimmers dipping for various reasons etc.”

In response to Q14, one respondent noted identified infrastructure damage as part of a longer response focused on environmental impacts:

I’ve watched a boat wake wipe out a sun fish nest. We don’t have the same number of fish around the dock as we did 30 years ago. Our dock is aging more quickly because of the wake from boats.

Too many wake boards. There is a cottage who runs lessons. We even put out a red buoy. They are up and down our shoreline. We had to put in lifts because they put our boat up on the dock with their wake.
No wakeboarding within 300 feet of shore. Destroys docks.

The wakeboard waves are so big they swamp our boats in the boathouse and is destroying our shoreline.

When asked about specific policy and regulation change, they would like to see, respondents concerned about boats (including type of vessel, operation, erosion, etc.) tended to highlight the need for additional regulations and education:

“More signage around the lake reminding those of speed limits, shore restrictions, and ‘No Wake’ zones”.

“Teach boaters they are responsible for the damage caused by their wake.”

“More studies to create awareness and education of how we can better help our environment.”

One respondent who also noted that wakes were not an issue, noted that not all boats are the issue and not all shorelines are sensitive:

It is about people respecting the current regulations. It is not just wake boats that create wake. Many classic boats create significant wake as do any powerboats that cruise slowly and push a large wake as opposed to settling to produce no wake in sensitive area. Not all areas are sensitive to wake so a blanket rule negatively affects those where there is no concern.

Others (n=3) who did not believe that wakes were an issue simply stated, “Absolutely Not”, “No” or “No but current ones need to be enforced”.

3A: Relative Importance of Impacts

In Q8 of the survey, respondents were asked to rank the perceived changes in the past 5 years on a scale of 1 (small impact) to 10 (big impact). Impact of boat wakes had the largest average score (7.9) followed by noise (7.1) and level of traffic (6.7). Shoreline change had an average
rank of 6.4 and water quality had an average rank of 4.6. When asked about the top impacts of boat wakes (Q*) from 1 (biggest impact) to 6 (smallest impact), the largest perceived impact was shoreline erosion with an average of 2.5 followed by danger to wildlife and habitat (3.5), danger to swimmers (3.7) and damage to moored boats (3.7). The smallest perceived impact was damage to infrastructure (4.0) and the lowest ranked category was “wakes have no impact” (6.7).

3B: Important Vessel Factors

The results from the survey provided us with the local’s understanding of the various aspects of vessel-generated wake, which factor has the most impact on creating a large wake. This is crucial in determining where education regarding vessel use is lacking, which is a factor that needs to be taken into consideration when enforcing the rules and regulations of vessel use within Cottage Country. Speed, hull shape, and number of hulls were consistent in perceived importance. The survey questions that were open ended also provided the opportunity for these topics to be addressed; “Vessels are often used for water “play” – jumping wakes, racing, sharp turns etc. Those behaviours are in conflict with the other uses of a busy lake. People pulling a tube with kids on it, kayakers, sailors, paddle boarders etc.” (Respondent from Muskoka Lakes).

For instance, when asked about emerging issues related to watercrafts on their waterbody, the cottage owners expressed concerns relating to wake size and speed, and the possible variables at play:

“The presence of people who like to show off on personal watercraft in close proximity to shorelines and people. We have had a runaway seadoo run up on our beach because the rider fell off doing tricks and did not have the safety cable attached to his body..”
“So many wake boats and no controls (we have one but we’re respectful about how close we get to shore/docks). And personal watercraft jumping peoples wakes when people are surfing – so dangerous if surfer falls.”

“So many are renters, and they don’t need a boat license to rent. Likewise with pontoon rentals – people have no clue about boating rules and safety. Crazy that cottagers who have been boating all their lives need a boat license but renters who rarely if ever boat don’t need one.

That’s backwards.”

These variables include the lack of knowledge of the people utilizing the vessels and lack of enforcement regarding the required education prior to using such powerful machines. This is highlighted by question 13 which addresses general regulations, as well as enforcement of local speed limits:

“There are only speed limits of 9kmph, however many folks “request” no wake through personal and some lake association signage.”

“10 km when boating within 30m of the shoreline, otherwise there is no speed limit on our lake.”

“There is a 9kmph limit in restricted zones. No other limits. There are voluntary wake abatement areas but no regulations.”

“Boat speed must be less than 10km/hr 30 m from shore, boats, docks and swimmers. Water-ski, tube, surf and wakeboard 200 meters away from all shorelines. 10 km/hr going through the narrow channel to Lake Kashagawigamog.”

Although speed of the vessel is not the only factor that impacts the wake size, it is an important aspect of wake generation and is lacking regulation from local law enforcement:

“MNR [Ministry of Natural Resources] having more impact on enforcing and educating boaters on impact of wakes on the shoreline, wildlife, and environment with increased notice of no power
boats usages during flood notices and more policing of lower speed on the rivers. Also, more studies to create awareness and education of how we can better help our environment.”

It is important to note that the MNR was replaced by the Ministry of Natural Resources and Forestry in 2014, and that the agency has no jurisdiction over vessel operation. Despite this, other respondents noted similar issues:

“The problems arise from the minority of boats drivers who either don’t care about the effects of their speed and wake, or are completely ignorant of the rules of conduct.”

“Boat operators need to be educated on the negative impact that they have on the environment. Boat operators need to be educated on the appropriate use of their craft. Speed appropriate to the size and depth of the lake should be part of the Boat operator’s licensing. Some of the operators are cognizant of the regulations and deliberately disregarded them. These operators need to have punitive consequences.”

Although the cottage owners may not have an exact understanding of the specific factors involved in maximum wake generation, these results suggest a desire for heightened regulations, enforcement, and education, prior to the use of vessels within their waterbody.
DISCUSSION

The purpose of this study was to determine the relative contribution of recreational boat wakes to the total wave energy on the Muskoka Lakes, and to assess local perceptions of boat wakes and their impact. Across all sites and over the summer of 2022 (June 1-September 23), the cumulative wake energy was 139,912 J/m^2 or 66% of the total wave energy, while the wind-wave energy was 72,364 J/m or 35% of the total wave energy. The statistically significant difference in hourly wind-wave and wake energy suggests that wakes are not simply additive to the (background) wind-wave energy. The energy of wakes, which is an important control on their ability to resuspend sediment and erode shorelines and damage infrastructure (Parnell & Kofoed-Hansen, 2001; Soomere, 2005), is nearly 2x greater than the wind-waves across all sites. This greater wave energy is only present at the shoreline (of the sampled sites) for an average of 11% of the summer, while wind-waves were present for an average of 83% of the summer. This is consistent with the results of Houser et al. (2021) who found that wakes were only present 9% of the summer, but their energy was ~2.3x greater than wind-wave energy where the fetch was 0.93 km.

The relative proportion of wake energy was inversely related to the fetch length, with wakes representing the greater proportion of total wave energy in the most fetch-limited environments. This reflects both the limited ability of wind-waves to develop (Osborne & Boak, 1999), and a shorter distance between the sailing line and the shoreline, which limits wave dispersion and frictional losses (Ulm, et. al, 2020). Sites within narrows tended to have less wake energy than expected (negative deviation), most likely in response to the slower speeds of vessels and the fewer passes of vessels that are moving from one section of a lake to another. In contrast, bays and closed sites had greater than expected (positive deviation) wake energy,
possibly in response to the limited wind-wave development at those sites and the tendency of boaters to turn around within those environments. Bays and closed sites also had a positive deviation in the correlation between time fraction and fetch length, suggesting that the greater wave energy % is associated with operation within the enclosed space, including looping (e.g., “donuts and spraying”). The greater time fraction for open sites may in part be associated with greater boating activity and multiple sailing lines, as well as dispersion that spreads out the wave field as it approaches the shoreline. However, the lack of a statistically significant variation in wave period between sites suggests that the greater time fraction for open sites is associated with greater activity not dispersion.

While wake energy represented the majority of total wave energy, there was no clear evidence of shoreline erosion or damage to infrastructure or shoreline habitat. Most of the sites had bedrock shorelines that would simply reflect the wave energy back offshore, suggesting that the greater wave energy due to wake does not have a significant impact on shoreline erosion. This is consistent with the lack of clear evidence or examples from the online survey of erosion and damage. Only 17% of respondents who reported having vegetated or sandy shorelines listed erosion and damage to the habitat or infrastructure- most of the respondents with these shorelines focused on the types of boats, their operation, and the lack of experience amongst drivers as the biggest issues with boats and the wakes they generate. The lack of direct evidence for shoreline erosion and damage and the limited number of responses to the survey about these issues suggests that the additional wake energy is not necessarily a real threat to shoreline stability. Further data collection, however, is required from lakes without bedrock shorelines, in addition to studies that quantify sediment resuspension, turbidity, etc. in response to wakes (e.g., Rapaglia, et. Al, 2011).
Most respondents noted that the greatest impact of boating was not their wakes, but the types of boats, their operation, and the lack of experience of boaters. One response suggests that biggest issue is conflicting use of the lake:

“Vessels are often used for water “play” – jumping wakes, racing, sharp turns etc.

Those behaviours are in conflict with the other uses of a busy lake.”

Many others noted concerns related to “courtesy [of drivers]”, noise pollution and light pollution that are disruptions:

“Why are so many of us being held hostage to the few who abuse the majority? Loud unmuffled oversized engines have no place on freshwater lakes where cottages are seeking peace.”

Some wake boats do their surfing late in the evening when the bay is calm.

In the absence of direct evidence about the impact of wakes on shoreline erosion, it is reasonable to assume that the wake is simply an annoyance, a physical reminder of the disturbed “cottage country” scene. While the impact of wakes appears to be minimal and isolated, many of the respondents expressed a desire for improved enforcement of pre-existing regulations, updated education, and increased awareness. Other participants suggested more extreme measures including certain types of boats, local enforcement, and additional fines. Some of the answers and solutions rely on stricter speed restrictions and enforcement while others rely on education for renters and a better license system. Specified desired changes regarding the policy and regulations surrounding vessel use were stated by respondents from the study area:

“More signage around the lake reminding those of speed limits, shore restrictions, and ‘No Wake’ zones”;

“Teach boaters they are responsible for the damage caused by their wake.”
“More studies to create awareness and education of how we can better help our environment.”

Although our study does not identify the specific impact the vessel generated wake has on the shoreline, studies such as these provide unbiased data to policy makers, who may consider altering current legislation (see Dorava, et al.,1997; Bauer, et al.,2002; Glamore, 2008; Houser, et al.,2021). Current legislation states; “(7) No person shall operate a power-driven vessel at a speed in excess of 10 km/h within 30 m of the shore in the following waters: (a) the waters of Ontario, Manitoba, Saskatchewan and Alberta, (b) the rivers and lakes in British Columbia, (c) Nitinat River and Nitinat Lake, upstream of Nitinat Bar, in British Columbia, (d) the rivers and lakes in Nova Scotia, and (e) Bras d’Or Lake in Nova Scotia, inland of a line drawn between Coffin Point and Red Head in Great Cras d’Or Channel and the inland end of St. Peters Canal.” (Vessel Operation Restriction Regulations, SOR/2008, 120). The results of the study do not suggest a need to revise the regulation, but that this conclusion is based on this study site and that there are some areas that may need additional regulation. A factor lacking representation in this study is vegetation at the shoreline, this is due to the hardened nature of the Muskoka Lake shorelines. Additional lake variations worth researching further are; size, orientation, wildlife, and level of vessel activity. Orientation could represent varying exposure to the historically prominent wind path, which would allow for a deeper understanding of the impact of barriers within fetch-limited environments on wind-wave activity. Also, a lake banned from vessel activity would act as a control in a future study, broadening the comprehension behind wind-wave erosion versus wake erosion.
CONCLUSION

Recreational boat wakes represent the majority of wave energy in Lakes Joseph, Rosseau, and Muskoka. Despite wakes only being present for 11% of the time, they represent nearly 2x as much energy as wind-generated waves. The relative proportion of wake energy is inversely related to the fetch length and varies with the type of shoreline (narrrows, open, bay/closed), while the time fraction is directly related to the fetch length. Despite the additional wave energy resulting from wakes, little no direct evidence of wake impacts (e.g., erosion, damage to infrastructure) was identified through an online perception survey distributed to local members of SQL. Most respondents noted the disruption caused by boating activity and the conflict of boating with other uses of the lake including enjoyment of the “cottage country” scene. Further research is required to determine when and where wakes may be detrimental to shorelines, water quality and safety and are not simply a nuisance.
CONSENT TO PARTICIPATE IN RESEARCH

Title of Study: Perception of boat wakes in fetch-limited environments

You are asked to participate in a research study conducted by Ava Caschera, an undergraduate student in the School of the Environment at the University of Windsor. Ava works under the direction of Dr. Chris Houser, Professor in the School of the Environment at the University of Windsor.

If you have any questions or concerns about the research, please feel free to contact Ava Caschera at cascher1@uwindsor.ca.

PURPOSE OF THE STUDY

The purpose of this study is to assess public perception of boat wakes and their impact on lakes in Ontario.

PROCEDURES

If you volunteer to participate in this study, you will be asked to complete an inline questionnaire about your understanding of boat wakes and their potential impact on your body of water.

POTENTIAL RISKS AND DISCOMFORTS

You may withdraw your participation at any point until you submit the questionnaire by closing your browser or navigating away from this page. You may also skip or decline to answer any question. You may also contact the principal investigator for the study, Ava Caschera at cascher1@uwindsor.ca, if you have any questions or concerns.
POTENTIAL BENEFITS TO PARTICIPANTS AND/OR SOCIETY

There is no direct benefit to participants, but you may benefit from this study by becoming more knowledgeable about the science of boat wakes and their potential impact on your body of water.

CONFIDENTIALLY

Surveys will be submitted online, and your data will be confidential. Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission. Research data will be kept on a password-protected computer in a locked office. The survey results and analyses will be stored and encrypted on a private server maintained by the Coastal Research Group. The records will be maintained for three years encrypted and password protected, upon which time they will be permanently destroyed (i.e., computer files deleted). Furthermore, study participants will not be individually identified in any publications or presentations that may stem from this research; only aggregated data will be presented.

PARTICIPATION AND WITHDRAWAL

You can choose to participate in this research or not. If you choose not to participate, there will not be any consequences to you. If you choose to be in this study, you may withdraw at any time up until survey responses are submitted. You may also choose which questions you wish to answer and still remain in the study. If you participate in the study, and submit a completed survey online, the survey will no longer be able to be withdrawn once it is submitted. Submission of survey responses implies consent for participation in this study. Any incomplete surveys will still be included in the analysis of the results up until the point the participant has decided to withdraw.
RESULTS OF THE RESEARCH

Results of the research will be made available as a report through the Windsor Costal Group website (https://www.windsorcostalgroup.ca/) in 2024. An email will be sent to participating cottage associations to inform them that the report is available for download.

Do you consent to participating in this survey:

Yes

No

What type of water body is your property located on?

Lake

River

Canal

Other

What is the name of the water body?
__________________________

Approximately how many cottages and homes are on your body of water?

<10

10-50

50-100

100-250

>250
Describe your shoreline, what material is your shoreline comprised of? (Select all that apply)

Sandy
Rocky
Vegetated
Armoured
Muddy
Other

What water activities do you participate in? (Select all that apply)

Relaxing on a dock or beach
Swimming
Enjoying nature
Cruising on a boat (touring/site seeing)
Visiting friends and neighbours by boat
Non-motorized boating
Transportation to and from a location
Towing sports (waterskiing, wake boarding, etc.)
Fishing
Other:

________________________
What boats will you use this year? (Select all that apply)

Non-motorized (includes paddle boards)

Power boats below 40 hp

Power boats 40-99 hp

Power boats 100-199 hp

Power boats 200 hp or over

Personal watercraft

Other:

__________________________

None

What is the most common boat used on your waterbody? (Select all that apply)

Non-motorized (includes paddle boards)

Power boats below 40 hp

Power boats 40-99 hp

Power boats 100-199 hp

Power boats 200 or over

Personal watercraft

Other:

__________________________

None

Do you know the speed and/or wake limit(s) of your waterbody?

Yes

No
What are the speed and wake regulations for you waterbody?

In your opinion, are additional regulations required on your waterbody?

What changes have you noticed in the past 5 years on your waterbody and how much have they impacted your experience, safety and/or the environment? (0 = No impact, 1 = Small impact, 5 = Somewhat of an impact, 10 = Large impact).

To answer this question, slide the marker to your selected number for each item.

0 1 2 3 4 5 6 7 8 9 10

Impact of Boat Wakes
Amount of Boat Traffic
Boat Noise
Level of Safety
Shoreline Change and Modification
Water Quality
In your opinion, what is the most important factor to the size of a boat generated wake?

Rank from most important (1) to least important (9). To answer this question, move the different items into the order of most important (top) to least important (bottom).

Water depth
Hull shape
Number of hulls
Position in water
Boat length
Speed
Driver experience
Activity (waterskiing, wake boarding…)
Motor horsepower

On average what is the depth of your waterbody in metres?

<1 m
1-2 m
2-5 m
5-10 m
>10 m
Not sure
In front of your property what is the approximate width of your waterbody in meters?

- <10 m
- 10-30 m
- 30-50 m
- 50-100 m
- >100 m
- Not sure

On your waterbody, what do you think are the top impacts of boat wakes? Rank from most impactful (1) to least impactful (6). To answer this question, move the different items into the order of most important (top) to least important (bottom).

- Shoreline erosion
- Damage to infrastructure
- Damage to moored boats
- Danger to smaller and non-motorized crafts
- Danger to swimmers
- Danger to wildlife and habitat
- They do not have an impact

In your opinion, what is the environmental quality of your waterbody?

1 2 3 4 5

1= Far from ideal 5 = Close to ideal
In your opinion, what is the general level of safety of your waterbody?

1 2 3 4 5

1= Not at all safe 5= Very safe

In your opinion, what are the biggest safety, environmental and experience concerns on your waterbody?

………………………………………………

Are boat wakes an issue on your waterbody and if so, what are the best solutions to minimize the impacts of boat wakes?

………………………………………………

What is the top impact on safety and the environment?

Watercraft not following regulations.

Watercraft travelling at high speed.

Large wakes that endanger small crafts, swimmers, and shorelines.

None, Boat wakes have no impact on safety or the environment on my waterbody.

In your opinion, are the boats on your waterbody a noise nuisance?

Yes

No

Sometimes

What level of enforcement do you want to see on your waterbody?

No changes needed.

Increased patrolling.

Decreased patrolling.
What do you see emerging issues related to watercrafts on your waterbody?

__________________________________

Are there any other comments and issues you would like to raise about boats and boat wakes?

__________________________________

We thank you for your time spent taking this survey.

Your response has been recorded.
Figure 24 A: Energy of Wind Waves (red) and Vessel-Generated Wakes (Blue) Throughout the Summer, with the secondary y-axis reversed for ease of analyzing the graphs.
Figure 24 B: Energy of Wind Waves and Vessel-Generated Wakes Throughout the Summer, with the secondary y-axis reversed for ease of analyzing the graphs.
Figure 24 C: Average Period of Wind Waves and Vessel-Generated Wakes Throughout the Summer, with the secondary y-axis reversed for ease of analyzing the graphs.
**Figure 24 D:** Average Period of Wind Waves and Vessel-Generated Wakes Throughout the Summer, with the secondary y-axis reversed for ease of analyzing the graphs.
Figure 24 E: Energy and Time Fraction of Vessel-Generated Wakes Throughout the Summer, with the secondary y-axis reversed for ease of analyzing the graphs.
Figure 24 F: Energy and Time Fraction of Vessel-Generated Wakes Throughout the Summer, with the secondary y-axis reversed for ease of analyzing the graphs.
REFERENCES


Froude, William (1877). Experiments upon the Effect Produced on the Wave-making Resistance of Ships by Length of Parallel Middle Body. Trans., Inst. of Naval Architects, Vol. 18, pp. 77-87


Parnell, Kevin E. & Kofoed-Hansen, Henrik (2001) Wakes from Large High-Speed Ferries in Confined Coastal Waters: Management Approaches with Examples from New Zealand and Denmark, Coastal Management, 29:3, 217-237, DOI: 10.1080/08920750152102044


Zabawa, C., and C. Ostrom. "The role of boat wakes in shoreline erosion in Anne Arundel County, Maryland." Final Report to the Coastal Resources Division, Maryland Department of Natural Resources (1980).
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