A Scientific Literature Based Review of What is Currently Known About the Adverse Impacts Attributed to the Operation of Wake Enhanced Boats on Inland Lake Ecosystems

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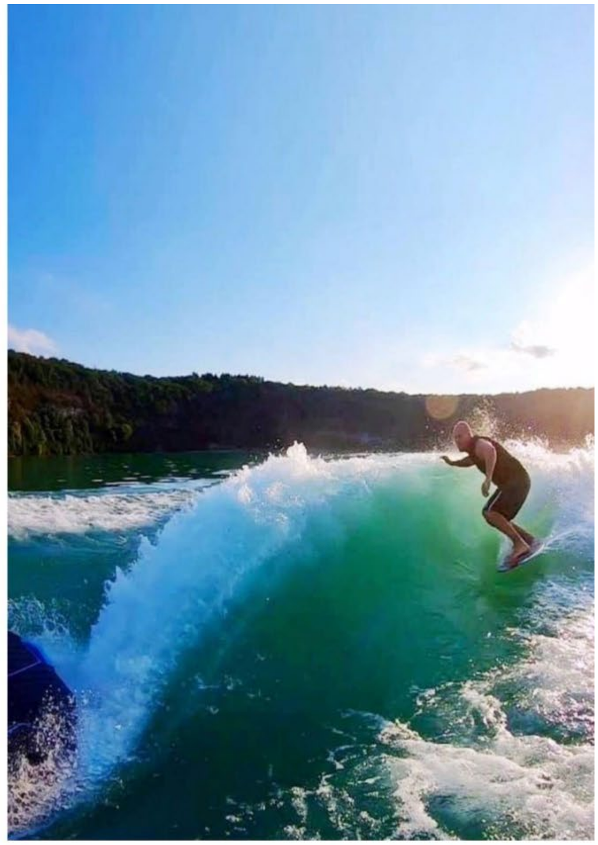

The substantive findings of several peer reviewed scientific investigations that have been conducted in recent years clearly demonstrate that the upsurge in the number of wake enhanced boats operating on the inland lakes of the Laurentian Great Lakes region are likely responsible for rendering an array of adverse impacts on frequently exposed aquatic ecosystems. A dramatic increase in sales of recreational vessels that are designed and operated for the sole purpose of enabling enhanced wake dependent water sports by generating wakes that possess kinetic energy levels that greatly exceed those that occur naturally has helped gain the attention of state and local government officials, law enforcement agencies, lake managers, lake conservation advocacy groups, and the news media. In addition to their significant potential to have a negative impact on vulnerable aquatic ecosystems, regularly occurring, well publicized incidents involving high energy wake perpetrated over turned kayaks, swamped fishing boats, hazardous swimming conditions, and damage to moored boats, piers, and docks have served to help focus public attention on the frequently disruptive watercraft. Heated discussion regarding the difficult public policy question of whether operation of the increasingly popular though controversial water craft should somehow be restricted, or even banned in some cases, has now migrated from marinas to state capitols where legislators, and lobbyists representing the special interests of a powerful group of stakeholders remain deeply divided on the issue (Orenstein, 2020).

Wake boats, also referred to as wake enhanced boats, are designed to generate the high energy wakes that are required to enable wake surfing and wakeboarding (Ruprecht *et al*., 2015; Goudey and Girod, 2015). Wake surfing, the significantly more popular of the wake enabled water sports due to the fact that it is safer and much easier for most people to master than wake boarding (Ray, 2020), involves riders who surf the substantial wake that results from shifting ballast water to the aft (rear) corner on the side of the boat that is to be surfed (Mercier-Blais and Prairie, 2014; Ruprecht *et al*., 2015). Enabled by operating speeds ranging from 8 - 13 mph (13 - 21 km/h), wake surfers are not attached to their boards, and are not supported by tow ropes (Ruprecht *et al*., 2015). In contrast, wakeboarding, whose rise in popularity began in the late 1990's, usually involves more athletically inclined participants who strive to perform acrobatics while airborne during high jumps that are achieved by using the enhanced wakes produced by their supporting water craft as transient 'launch' ramps (Ruprecht *et al*., 2015; Boyd, 2016). Engaged at speeds ranging from 18 - 30 mph (29 - 48 km/h) (Ruprecht *et al*., 2015), wakeboarders are attached to their board, and pulled along well behind their supporting boat by a tow rope of up to 85 feet (26 meters) in length (Allen *et al*., 2019).

Driven by a precipitous increase in popularity of enhanced wake enabled water sports, sales of wake boats have surged over the course of the past decade. Ranging in price from $80,000 USD to well over $200,000 USD, wake boats represent the fastest growing and most profitable segment of the thriving recreational boating industry. According to a recent report issued by the National Marine Manufacturers Association (NMMA), sales of new wake boats in the United States were up a significant 13% in 2020 to a total of 13,000 units (NMMA, 2021).

In contrast to conventional styles of water skiing that are supported by recreational water craft capable of planing-out on the surface of the water at high speeds due to the fact that they are designed to minimize water displacement and drag, enhanced wake dependent water sports are enabled by water craft that have been specially designed to produce high energy wakes at relatively slow speeds as a result of their inordinate capacity to displace large volumes of water. Driven by the simple truth that "more water displacement equals bigger wakes" (Allen *et al*., 2019), wake boat manufacturers design their water craft to achieve maximum water displacement at slow to intermediate operating speeds with their disproportionally heavy sterns sitting low in the water. The overall capacity of wake boats to displace large volumes of water, and to consequently generate high energy wakes, is primarily a function of grossly asymmetric weight distribution in addition to the overall proportion of their stern that sits below the water line (Allen *et al*., 2019).

Intense competition between at least a dozen North American wake boat manufacturers has led to the development of rapidly evolving wake enhancing technology. A multitude of wake enhancing devices, as illustrated by operator adjustable hull attitude wings, gates, tabs, plates, and wedges, to cite manufacturer specific examples, have been designed for the sole purpose of optimizing the capacity of wake boats to generate high energy wakes by maximizing their ability to displace large volumes of water (Ruprecht *et al*., 2015). Wake boat design engineers have also learned how to optimize the amplitude and shape of the wakes created by their increasingly elaborate water craft by effectively integrating rapidly advancing technology with "old fashioned" wake enhancing methods such as increasing the capacity and on-board location of ballast water storage tanks and bladders, shifting increasingly powerful in-board motors toward the rear of the watercraft, improving the efficiency of propellers, and by altering hull design (Boyd, 2016). Steady improvements to ballast systems and wake enhancing devices that have enabled the capacity of wake boats to produce wakes whose amplitude and shape are optimal for wake surfing, the most popular of the wake boat associated water sports, are primarily responsible for the dramatic increase in sales and market growth that has occurred within the enhanced wake enabled water sport industry over the past ten years (Ruprecht *et al*., 2015). Recently deployed wake enhancing technology allows their operators to easily shift the wake produced by the craft from side to side without shifting ballast, and to maintain concise control over both size and shape of the enhanced wakes produced by their increasingly sophisticated boats (Allen *et al*., 2019). In contrast to wake boats produced prior to 2012 that required their operators to turn in continuous wide circles in order to create and sustain significant wave action, modern wake boats are capable of generating wakes that are optimal for engaging enhanced wake enabled water sport participants by simply travelling in a straight line while operating at slow to intermediate speeds (Armitage, 2019).

Ranging from 20 - 26.5 feet (6 - 8 meters) in length, and weighing up to 13,000 pounds (5,897 kg), the United States Coast Guard cautions that inordinately heavy wake boats are essentially incapable of safely navigating the volatile open waters of oceans, or of the Great Lakes. Accordingly, safe operation of even the largest, well-equipped wake enhanced water craft is primarily restricted to the relatively calm waters of inland lakes, wind protected bays, and large rivers (Ruprecht *et al*., 2015). Steadily escalating occurrences of natural shoreline degradation, and shallow water habitat disturbance, in addition to an increasing number of safety related incidents, and reports of damage to waterfront property, have occurred primarily as a direct consequence of the fact that many wake boat operators often irresponsibly operate their extraordinarily heavy, ballast water laden water craft within waters that are too shallow, too close to shore, and/or dangerously close to vulnerable swimmers, paddle boaters, fisherman, and other quiet water users (Ray, 2020; FitzGerald *et al*., 2011). The myriad of ecological impacts that are likely occurring due to a dramatic increase in popularity of enhanced wake dependent water sports, and in particular wake surfing, have been exacerbated by the fact that protracted periods of often intense near shore, and/or shallow water incursion by multiple wake boats simultaneously operating on popular lakes on weekends, results in an unrelenting barrage of high energy wave action (TOTMWC, 2007).

Even though the high energy wakes produced by a single wake boat passage are classified as periodic disturbances, they crest at greater heights, and possess substantially more kinetic energy than wakes that occur naturally (Goudey and Girod, 2015; Ruprecht *et al*., 2015; Mercier-Blais and Prairie, 2014). Creating waves that are substantially greater in magnitude than those that occur naturally as a result of the interaction of wind and water, Goudey and Girod (2015) found that wake boats operating on lakes in support of wake surfers are capable of generating maximum wave heights of 27.83 inches (.71 meter). The Goudey and Girod (2015) study also indicated that in contrast to conventional watercraft operating at 'cruising' speeds that generate kinetic energy levels of as low as 305 joules/meter, wake boats operating in support of wake surfers are capable of generating maximum wave energy in excess of 2,500 joules/meter. Investigators Mercier-Blais and Prairie (2014) observed that the wakes created by wake boats operating in support of wake surfers enabled by operating speeds ranging from 8 - 13 mph (13 - 21 km/h) while the boat is operating in a pronounced lopsided manner that results from shifting much of the craft's ballast water to a single rear corner, possessed an average of 1.7 times greater kinetic energy than the wakes created by wake boarding that occurs at speeds ranging from 18 - 30 mph (29 - 48 km/h). Corresponding to the findings of Goudey and Girod (2015) and Mercier-Blais and Prairie (2014), research conducted by Ruprecht *et al*. (2015) revealed that the highest average wake crest and kinetic energy values occur while wake boats operate at a speed of 11.5 mph (10 knots) while enabling wake surfers. It is important to note that Ruprecht *et al*. (2015) also found that kinetic energy levels generated during optimal wake surfing conditions were four times greater in magnitude than the kinetic energy produced during nominal wakeboarding conditions, and two times greater in magnitude than the level of kinetic energy produced during ideal "maximum wave height" enabled wakeboarding conditions.

Coinciding with the findings of research conducted by Goudey and Girod (2015), and Mercier-Blais and Prairie (2014), investigator Ray (2020) found that wake boat generated wakes originating 300 feet (91.5 meters) from shore are capable of a height of 7.75 inches (19. 38 cm) by the time they reach shore; enhanced wakes created 135 feet (41 meters) from shore are capable of a height of 9 inches (22.5 cm) by the time they reach shore; and that enhanced wakes created 1,000 feet (305 meters) from shore are capable of a height of 4 inches (10 cm) by the time they impact the shoreline. Research focused on the impacts of enhanced wakes on shorelines conducted by Ray (2020) also served to reaffirm the observations of Mercier-Blais and Prairie (2014) in regards to the ability of wake boat enhanced wakes to contribute significant energy to naturally occurring waves when they occur within distances of up to 984 feet (300 meters) from shore. The Mercier-Blais and Prairie (2014) study indicated that by an "average of a factor of four times", wakes produced by wake enhanced boat passages cause a significant increase in the amount of wave related kinetic energy that ultimately reaches the shoreline. The significant potential for wakes generated by passing boats to harm nearby shorelines has also been clearly demonstrated by the fact that Zabawa and Ostrum (1980) discovered that even small outboard motor propelled aluminum fishing boats passing at moderate speeds within 500 feet (152 meters) or less of shore are capable of creating wakes of sufficient magnitude to inflict damage to shoreline property and natural habitat. This observation was also reaffirmed by Dorava and Moore (1997) who observed that the wakes created by small fishing boats navigating Alaska's Kenai River were capable of inducing accelerated rates of erosion along the river's banks.

An outstanding water science focused website entitled **Exploring our Fluid Earth**, created and administered by the **University of Hawaii's Teaching Aquatic Science as Inquiry** program, and aptly referenced by Ray (2020), serves to emphasize the fact that kinetic energy associated with water waves, whether created naturally as a by-product of the interaction of water and wind, or by wake boats, grows exponentially in response to linear increases in wave height. A wave defined by a height of 8-inches (20 cm), for example, possesses four times greater kinetic energy than a 4-inch (10 cm) wave, and sixteen times greater kinetic energy than a 2-inch (5 cm) wave.

Research conducted by Ray (2020) on Lake Payette, a 5,000 acre (2,023.4 hectares), 300 feet (91.46 meters) deep glacial lake located in central Idaho, revealed that the potential for wake boat generated enhanced wakes to impact shorelines is exacerbated by the fact that their wavelengths are significantly longer than wind produced waves. Supported by a significant quantity of field sensor collected data, advanced modeling techniques utilized by Ray (2020) indicated that in contrast to commonly occurring 4-inch (10 cm) wind induced waves defined by wavelengths of approximately 6 feet (1.93 meters), and 8-inch (20 cm) high wind induced waves defined by a wavelength of approximately 10 feet (3.04 meters), wake boat generated enhanced waves are capable of achieving wavelengths ranging from 15 feet (4.57 meters) to 25 feet (7.62 meters). In addition to the fact that wake boat created waves possess greater levels of kinetic energy due to the fact that they often crest at significantly greater heights than wind generated waves, their overall capacity to affect vulnerable natural shorelines is enhanced by the fact that they also possess greater levels of kinetic energy due to their significantly longer wavelengths (Ray, 2020).

It is important to note that Mercier-Blais and Prairie (2014) also observed that wakes created in areas of the lake's basin defined by deep, steeply sloping bottom contours are capable of sustaining higher energy levels for longer periods of time in contrast to wakes generated in shallow, gently sloping areas of the basin whose energy levels are much more likely to dissipate before having a harmful impact on ecologically sensitive habitat. The findings of research conducted by Mercier-Blais and Prairie (2014) also indicate that wakes abruptly impacting steeply sloping banks are capable of inflicting significantly greater erosive force than those whose kinetic energy gradually dissipates while travelling over shallow, gently sloping shorelines. Waves travelling through gently sloping, shallow areas gradually reduce their energy due to contact with the bottom which causes them to rise up, and eventually collapse in water depths that are less than 1.3 times their height, resulting in near instantaneous dissipation of their remaining kinetic energy (Biello, 2014).

In light of the observation of Mercier-Blais and Prairie (2014) that all wake boat passages occurring within 984 feet (300 meters) of the shore are capable of contributing significant energy to naturally occurring waves, it is important to note that the height, frequency, and duration as well as the kinetic energy levels associated with wind generated waves are primarily determined by wind speed, wind duration, and fetch (Ray, 2020). Fetch is defined as the length of the span of open water that wind blows across, and is directly related to the magnitude of wind waves that are capable of being formed by a given wind speed (Ray, 2020; Clawson, 2017). Lakes defined by relatively small areas of open water are considered to be fetch limited (Ray, 2020). The important influence of fetch in determining the magnitude of wind generated waves is effectively demonstrated, for example, by the fact that Ray (2020) recorded a maximum wave height value of 7.4 inches (18.5 cm) induced in response to a 15 mph (24 km/h) wind blowing for a duration of one hour over a fetch of 2.5 km (1.55 miles) in contrast to the creation of a wave with a maximum wave height of only 4.7 inches (11.75 cm) created by a 15 mph (24 km/h) wind blowing for a duration of one hour over a fetch of 1 km (.62 miles). The most significant natural waves occur in response to sustained high winds emanating from a compass heading that serves to maximize both the distance and duration of their interaction with large unobstructed areas of open water (Ray, 2020; Clawson, 2017).

In addition to the potential for high energy waves created by wake boats to have a negative impact on shorelines from distances of up to 984 feet (300 meters) (Mercier-Blais and Prairie, 2014), research conducted by Raymond and Galvez (2015) discovered that turbulence generated by wake boats operating in support of wake surfers is capable of disturbing ecologically sensitive habitat situated in relatively deep areas of the lake's basin. Assessing the potential for turbulence generated by wake boats operating at slow, intermediate, and fast speeds to disturb benthic habitat as indicated by the occurrence of bottom sediment resuspension at various depths, the study revealed that turbulence generated by wake boats operating at very slow speeds (3 mph; 5 km/h), or less, and at high speeds (33 mph; 53 km/h), is capable of resuspending sediments to depths of up to 3.28 feet (1 meter). Representing the most important finding of the study, however, Raymond and Galvez (2015) observed that the jet engine-like turbulence generated by wake boats operating at a speed of 12 mph (19 km/h) while engaging wake surfers is capable of disturbing lake bed sediments situated in water depths of up to 16.4 feet (5 meters). The findings of Raymond and Galvez (2015) in regards to the capacity of turbulence generated by wake boats to disturb sediments situated in relatively deep waters have been complimented by the results of a recent study conducted by Ray (2020) which observed that in contrast to wind generated waves that are capable of disturbing lake bed sediments occupying depths of up to 5 feet (1.5 meters), enhanced wakes generated by wake boats are capable of disturbing lake bed sediments situated in water depths of up to 12 feet (3.65 meters).

It is important to acknowledge that with the exception of the previously discussed findings of seminal studies conducted by Ray (2020), Goudey and Girod (2015), Raymond and Galvez (2015), Ruprecht *et al*. (2015), and Mercier-Blais and Prairie (2014), relatively little scientific inquiry has thus far been devoted to the study of the myriad of ecological impacts that are likely occurring as a result of the increasingly intense levels of wake boat activity that is taking place on a steadily escalating number of lakes, bays, and rivers. It is also important to note, however, that scientific research motivated by the myriad of adverse impacts associated with frequent exposure to wakes generated by conventional recreational water craft has been ongoing for several decades (Bilkovic *et al*., 2017). Many of the significant impacts that are likely occurring as a consequence of frequent exposure to the wakes and turbulence created by wake boats have also been 'unequivocally' attributed to near shore and shallow water operation of increasingly powerful conventional watercraft whose negative influences have been previously explored within the context of a plethora of peer reviewed scientific journal articles.

In contrast to wakes created by vessels operating in deep, open waters located a great distance from shore that are unlikely to disturb shallows and shoreline habitat, wakes created in close proximity to shore, and/or within shallow waters are not allotted the distance, time, and/or depth that is necessary for their kinetic energy to dissipate before disturbing vulnerable benthic habitat, and/or natural and developed shorelines (Ray, 2020; Bilkovic *et al*., 2019; Raymond and Galvez, 2015; FitzGerald *et al*., 2011). In addition to distance, time, and depth, the overall impact of enhanced wakes on shallows and shoreline habitat is dependent upon the boat's displacement weight, ballast storage system configuration and capacity, the design and configuration of wake enhancing devices, hull and propeller design, and operating speed as well as upon the bottom contour of the affected waterway (Allen *et al*., 2019; Goudey and Girod, 2015; Glamore, 2008). The frequency of occurrence of near shore, and/or shallow water boat passages is also a critical factor in evaluating the potential for high energy wakes to render harm to aquatic flora and fauna (Bilkovic *et al*., 2019; Goudey and Girod, 2015; Glamore, 2008; Zabawa and Ostrom, 1980).

Whether generated by wake boats, or by increasingly powerful conventional water craft, high energy wakes generated in close proximity to shore possess the greatest potential to impact ecologically sensitive aquatic habitat (Ray, 2020; Bilkovic *et al*., 2019; Mercier-Blais and Prairie, 2014). In an assessment of the impact of boat wakes on Chesapeake Bay shoreline stability, Bilkovic *et al*. (2019) observed that wakes tend to be most harmful in narrow waterways where their kinetic energy has only limited potential to dissipate in response to increasing distance from the originating vessel. Mercier-Blais and Prairie

(2014) concluded that the impact of wakes created during boat passes is “directly and inversely” related to the distance between the passage and the shore. Capable of having a profound impact by significantly reducing the stability and bio-productivity of ecologically sensitive habitat (TOTMWC, 2007), accelerated rates of shoreline erosion that occur as direct result of frequent exposure to high energy wakes are widely recognized as one of the most difficult and expensive to remediate of any of the harmful impacts that are likely occurring as a result of the increasingly popular wake enabled water sports. It is also important to note, however, that the surge in popularity of all forms of recreational boating has led to a sharp increase in occurrences of severe erosion caused by water craft passing too close to shorelines (Bilkovic *et al*., 2019).

In contrast to the long-term effects of natural erosion that take place over geologic versus human time frames (TOTMWC, 2007), frequent exposure to high energy waves induce rapid rates of erosion that often results in exposing the roots of shoreline plants and trees, and degradation of critical plant and animal habitat (Allen *et al*., 2019; Bilkovic *et al*., 2017; Mercier-Blais and Prairie, 2014; TOTMWC, 2007). Particularly in the substantially deforested areas that often surround northern temperate inland lakes, accelerated rates of shoreline erosion serve as a major source of growth stimulating nutrients (Keenan and Kimmins 1993). The shorelines most susceptible to accelerated rates of erosion are located in low lying areas, and in wind protected areas that normally experience only low energy waves (Bilkovic *et al*., 2019). Although the ‘erodibility’ of a particular shoreline is a function of the magnitude of erosive energy that ultimately reaches the shore, steeply sloping shorelines composed of bare soil, or those consisting of peat or mud, are the most vulnerable to accelerated rates of erosion (TOTMWC, 2007). High energy wakes striking the steeply sloping banks of inland lakes are capable of causing accelerated rates of severe erosion that often leads to the total collapse of the bank (Bilkovic *et al*., 2017; TOTMWC, 2007). Although gradually sloping shorelines hosting vegetation are capable of partially mitigating the erosive influences of natural waves, the capacity of natural shorelines to absorb frequent exposure to the powerful erosive influences of high energy wakes is limited (Bilkovic *et al.,* 2019; Bilkovic *et al*., 2017).

Representing an important indicator of their vulnerability to near shore wake boat operation, shorelines surrounding many of the thousands of lakes distributed throughout the Laurentian Great Lakes region are comprised of a highly erodible mixture of sand and clay that is referred to as glacial till (TOTMWC, 2007). The most significant shoreline erosion occurs during periods marked by high water levels due to the fact that wakes are capable of travelling closer to shore before they break (Harwood, 2017). Causing extensive damage to waterfront property and natural shorelines, frequent near shore wake boat activity is likely to intensify the desire of waterfront property owners to construct seawalls or other forms of shoreline armoring to protect their property from the highly erosive influences of unrelenting wake energy (Harwood, 2017). The overall importance of increased rates of natural shoreline habitat destruction is exacerbated by the fact that the 2012 United States Environmental Protection Agency National Lakes Assessment found that over 50% of the inland lakes in the fresh water resources inundated region have experienced significant natural lakeshore and physical habitat complexity loss.

Wake facilitated accelerated rates of severe erosion are also known to lead to proportional increases in the rate of deposition and accumulation of sediment (TOTMWC, 2007). Resulting from the dislodgement and transport of soil due to the powerful influences of wave action, flowing waters, gravity, and/or ice (Brooks *et al*., 1997; Pitt *et al*., 2007), sedimentation occurs as eroded soil is transported, and later deposited into affected waterways (TOTMWC, 2007). Depending on the physical characteristics of affected sites, high volume sediment deposition is capable of rendering a harmful array of ecological impacts. The impacts of sediment deposition and accumulation includes loss or degradation of fish spawning areas, less desirable fish species, loss of fish foraging habitat, impaired or destroyed adjoining wetlands, and a reduction in the overall capacity of affected lakes, rivers, and wetlands to support diverse recreational opportunities (Johnstone *et al*., 2010). Sedimentation is also known to be a major contributor to the steep decline in both the diversity and abundance of North American aquatic organisms, and in particular aquatic insects, that has occurred over the course of the past one hundred years (Henley *et al*., 2000).

Resulting in the ‘filling-in’ of the basins or channels of affected water bodies, persistent high-volume sediment deposition also affects the viability of navigation channels, and areas supporting water craft related infrastructure by rendering them incapable of handling deep draft boats due to the gradual onset of shallower waters. Sediment deposition may also contribute to the degradation of desirable natural features such as firm sandy bottoms situated in shallow gradually sloping beach areas of inland lakes that have been designated for public swimming by covering the bottom in a thick layer of easily resuspended soft sediment (TOTMWC, 2007). Having a major impact on national water infrastructure, state and federal agencies have been pro-actively engaged in large scale efforts to control erosion and sedimentation for many decades. Considered the most significant form of water pollution in the United States, severe cases of sediment deposition affecting hydroelectric dams and coastal maritime ports, to cite two important examples, often require extensive dredging in order to maintain their capacity to operate (TOTMWC, 2007).

In addition to causing accelerated rates of shoreline erosion, and sediment deposition, Bilkovic *et al*. (2017) observed an “unequivocal” correlation between shallow water recreational boat operation and high-volume sediment resuspension. Derived from an array of both natural and manmade sources, some degree of resuspended sediment consisting of both organic and inorganic particulate matter is considered by limnologists to be an integral component of freshwater ecosystems (Birtwell, 1999). Within most northern temperate glacial lakes, suspended sediment consists of particulate matter that is primarily derived from organic sources as well as fine, easily resuspended inorganic particulate comprised of silt and clay (TOTMWC, 2007). Although Wetzel (1990) indicates that episodic sediment resuspension due to windy weather is considered a natural component of lake ecology, the sheer volume of sediment resuspension that often occurs during intense wave action, and/or protracted periods of shallow water recreational boat operation is capable of having a significant impact on aquatic ecosystems (Henley *et al*., 2000). Research conducted by Garrad and Hey (1987) indicates that sediment resuspension may occur as an undesirable by-product of the passage of a single watercraft. Moreover, research conducted by Asplund (1996) and Anthony and Downing (2003) strongly suggests that particularly in lakes defined by relatively shallow basins, recreational boating induced high volume sediment resuspension is capable of contributing to significant increases in phytoplankton production, increased turbidity, decreased water clarity, suppression of aquatic macrophyte and fish communities, and overall decreases in water quality.

Wake and propeller induced turbulence associated with passing watercraft is widely considered to be a major factor in facilitating sediment resuspension (Hayes *et al*., 2012). In an era defined by a sharp upsurge in popularity of wake surfing, however, unprecedented rates of sediment resuspension are likely occurring as a direct result of the extraordinarily large wakes, and jet engine-like turbulence created by wake boats that have been configured to maximize their capacity to displace high volumes of water by shifting large volumes of ballast water to a single aft corner of the boat, and operating at an intermediate speed of approximately 19 km/h (12 mph) (Ruprecht *et al*., 2015). In line with this observation, Raymond and Galvez (2015) reported that the greatest potential for high volume sediment resuspension occurs at depths of up to 5 meters (16.4 ft.) while wake boats operate at intermediate speeds in support of wake surfers. Moreover, a recent study conducted by Ray (2020) found that in contrast to wind generated waves that are capable of resuspending lake bed sediments situated in depths of up to 5 feet (1.5 meters), enhanced wakes generated by wake boats are capable of resuspending sediments situated in water depths of up to 12 feet (3.65 meters).

Occurring primarily on summer weekends on popular inland lakes since the now one-hundred-year-old advent of motorized recreational boating, enhanced wave energy facilitated high volume sediment resuspension causes the rapid onset of increased turbidity (USACE, 1994; Asplund, 1996), and commensurate decreases in water clarity (Lloyd *et al*., 1987). A reliable bio-indicator of the trophic status of a particular inland lake (Asplund, 2000), water clarity is considered the most important water quality attribute due to its prized aesthetic qualities as well as its important role in supporting diverse recreational uses, and enhanced lakefront property values. Water clarity is also widely perceived to be a critical surrogate measure of how safe lake water is for swimming, and for other full contact water sports (Angradi *et al*., 2018). Depending upon the volume of sediment that is vulnerable to resuspension, shallow water recreational boat activity is capable of temporarily rendering the clear, blue-green waters that are a treasured quality of many northern temperate inland lakes into an undesirable state defined by turbid, pale brown waters.

Sediment resuspension caused by shallow water recreational boat activity may also result in a significant decrease in the amount of photosynthesis enabling sunlight that is capable of penetrating the water column, and of supporting submerged macrophyte communities (Wetzel, 1990; Madsen *et al*. 2011). Substantial reductions in the diversity, abundance, and colonization depth of submerged macrophytes are known to occur in response to the onset of significantly higher levels of sediment and turbidity (Lloyd *et al*., 1987; Canfield *et al*., 1985). In addition to the loss of life sustaining sunlight, submerged macrophytes are also subject to severe shading as resuspended particulate matter rapidly accumulates on stems, shoots, branches, branchlets, and leaves (Madsen *et al*., 2001; Lloyd *et al*., 1987). Accumulation of particulate matter is ultimately capable of causing the pre-mature death of submerged macrophytes (Madsen *et al*, 2001). The significance of the threat posed to submerged macrophytes is emphasized by the fact that aquatic plants are known to play a critical role in fostering and sustaining the health of inland lakes by providing ideal habitat for a diverse array of amphibians, insects, and fish; by storing nutrients, particularly nitrogen, that would otherwise be available for stimulating light attenuating phytoplankton growth; and by preventing the resuspension of water clarity depriving particulate matter (Scheffer *et al*. 1993; Jeppesen *et al*. 1998). Moreover, vibrant submerged macrophyte communities provide an ideal safe harbour to a diverse and often abundant array of phytoplankton grazing zooplankton species such as *Daphnia magna*, for example, that make critical contributions to sustaining moderate levels of bio-productivity, and to fostering and sustaining water clarity (Timms and Moss, 1984; Ozimek *et al*., 1990).

Acting to substantially reduce water clarity, and the amount of light penetrating the water column by providing up to 94% of the nitrogen, and up to 83% of the phosphorus required to stimulate rapid phytoplankton growth (Cowan *et al*., 1996), Fanning *et al*. (1982) observed that resuspension of as little as one millimeter of the upper layer of lake bed sediment is capable of facilitating a doubling of phytoplankton abundance. Lake managers working on lakes suffering from the deleterious influences of intense shallow water recreational boat activity are likely aware of the fact that sediment resuspension is capable of contributing to poor water quality long after external sources of excess nutrient loading have been reduced or eliminated (Anthony and Downing, 2003). Particularly in shallow lake ecosystems, frequent resuspension of sediment hosting high levels of growth stimulating nutrients is capable of contributing to accelerated rates of eutrophication (Anthony and Downing, 2003; Yousef *et al*., 1980). Protracted periods of shallow water boat incursion also act to increase the time it takes for resuspended sediment to eventually settle out of the water column (Alexander and Wigart, 2013). Elevated levels of water clarity diminishing turbidity have also been associated with a reduction of the innate ability of fish, and other foraging aquatic animals to visually locate prey (Gardner, 1981). Research conducted by Levine *et al*. (2005) suggests that prolonged periods of light attenuating sediment resuspension may also have a significant impact on complex aquatic food webs by altering flora and fauna community structure, and by substantially reducing the amount of biotic energy that is available for transfer between lower to upper trophic levels.

Sediment resuspension resulting from intense wave action and turbulence generated by shallow water boat operation has also been associated with degradation of water quality due to the release of sediment-based pollutants such as fecal coliforms, and/or motor boat associated chemical pollutants such as gasoline, diesel fuel, lubricants, and anti-fouling paint (Sagerman, Hansen, and Wikström, 2019; Alexander and Wigart, 2013). Whitfield and Becker (2014) also observed that high energy wakes are capable of facilitating the resuspension of sediments laden with toxic heavy metals, that, depending upon the natural and cultural history of a particular water body, may include arsenic, cadmium, chromium, copper, lead, mercury, nickel, and zinc. High concentrations of heavy metals are known to constitute a major threat to human health (Lambert *et al.*, 2000).

Surges in the availability of growth stimulating nutrients due to high volume sediment resuspension are also known to contribute to conditions that are favorable to the formation of cyanobacteria (NALMS, 2016; Rastogi *et al*., 2015; Merel *et al*, 2013). Even though cyanobacteria are referred to as blue-green algae, their physiological, morphological, and metabolic structures identify them as a form of bacteria (Uduma *et al*., 2017). Occurring on a frequent basis within lakes, reservoirs, and ponds hosting nutrient rich warm waters, cyanobacteria blooms represent a significant threat to human and animal health due to their potential to produce cyanotoxins, one of the most powerful poisons known to man (Rastogi *et al*., 2015). Cyanobacteria are also known for their ability to deprive aquatic flora and fauna of life sustaining resources such as sunlight and oxygen (NALMS, 2016). The frequency, magnitude, and duration of cyanobacteria blooms are gradually increasing due to climate change, and widespread nutrient enrichment (Ho *et al*., 2019). Occurring on a more frequent basis within the Laurentian Great Lakes region, and particularly within the nutrient rich, shallow waters of western Lake Erie, the findings of increasingly well-funded research dedicated to improving the working knowledge and capacity of freshwater resource managers to prevent, and/or manage cyanobacteria blooms are of great importance to public health officials worldwide (Rastogi *et al*., 2015; Merel *et al*, 2013).

The explosive turbulence associated with the high-performance propellers of recreational boats are capable of having a number of destructive impacts on shallow water habitat (Asplund, 2000). Designed to provide “more push out of the hole”, modern large diameter wake boat propellers usually possessing four blades have been engineered to convert the immense mechanical energy produced by wake boat engines into the ability to push the heavy craft through the water at the slow to intermediate speeds that are required to enable wake dependent water sports. Producing jet engine-like thrust that is often referred to as jet wash, wake boat propellers are designed to set dense water in motion at extremely high velocities. Facilitating high volume sediment resuspension, jet wash is capable of causing increased turbidity, loss of water clarity, reductions in the amount of light that penetrates the water, and overall loss of the ability to support light dependent aquatic flora (Symonds *et al*., 2017). Sediment resuspension caused by jet wash has also been associated with extensive lake bottom scouring. Scouring occurs when jet wash causes the loss of the upper most layer of lake bed sediment, resulting in the formation of straight and narrow troughs that align with the trajectory of the water craft, and that appear as dark, thin lines in aerial photo surveys of affected lakes (Harwood, 2017; Symonds *et al*., 2017).

As indicated by the presence of vegetative mats free-floating on the surface, and/or of significant amounts of aquatic plant remnants piled-up and decomposing on the shoreline, shallow water boat operation also represents a major threat to aquatic plants. Research conducted by Asplund (2000), and

Murphy and Eaton (1983) concluded that in addition to the ability of the propellers of watercraft to chop off, and/or to break aquatic plant stems, shoots, branches, branchlets, and leaves, propeller induced turbulence is capable of completely uprooting floating, emergent, and submerged macrophytes. Frequently occurring shallow water encroachment by recreational boats is capable of substantially reducing both the abundance and diversity of beneficial aquatic macrophyte communities (Madsen *et al*, 2001). The overall impact of wake boat operation is enhanced by the fact that many submerged macrophytes are capable of flourishing at depths that are now known to be vulnerable to exposure to the high level of turbulence that is created during wake surfing. Research conducted by Raymond and Galvez (2015) concluded that wake boat turbulence is capable of extending to critical bottom habitat occupying water depths of up to 16.4 feet (5 meters).

Shallow water wake boat operation is also capable of suppressing the otherwise prodigious reproductive capacity of freshwater sunfish, and in particular the ever popular and widely distributed bluegill (*Lepomis macrochirus*), as a prime example, by damaging late spring and early summer spawning habitat. Appearing on the gradually sloping areas of most moderately productive inland lakes in waters ranging in depth from 1.5 feet (.46 meter) to 4 feet (1.2 meters), bluegill nests are often completely destroyed by shallow water habitat encroachment by wake enhance boats. Bluegill nests are comprised of easily disturbed sediment free small stone and gravel-lined depressions that are formed, groomed, and guarded by the male of the spawning pair in order to provide protective niche to their thousands of fertilized eggs, larvae, and hatchlings. High velocity jet wash produced by wake boats and jet skis is capable of completely destroying dozens of the vulnerable shallow water nests during a single brief pass. Causing instantaneous disbursement of nesting material, and the death of developing eggs, and/or larvae, wake boat operators are likely to be responsible for the loss of tens of thousands of reproductive propagules with each spawning habitat encroachment. The viability of nests not directly impacted by wake boat turbulence may also be compromised as resuspended sediment settle out, smothering the remaining nests in a dense layer of fine particulate matter. Responding to encroachment into their shallow spawning areas, the reproductive cycle of bluegill may also be compromised by the fact that the males, reacting to stress, sometimes abandon their nests, subjecting their eggs and larvae to a high risk of predation.

While the impact of shallow water wake boat operation on the ability of fish to successfully reproduce has not yet been documented within the context of formal scientific inquiry, the findings of a study of the impact of water craft navigating the St. Mary's River (Michigan-Ontario) on the nests of spawning fish conducted by University of Michigan limnologist Jude *et al*. (1998) concluded that along with high volume sediment resuspension induced by the jet wash of the propellers of passing water craft, large quantities of eggs and larvae were simultaneously dislodged from their protective nests, leading to the death of the eggs, and to the premature emergence of highly vulnerable larvae from their protective nests. In addition, fisheries managers working for the National Oceanic and Atmospheric Administration (NOAA) reported that wake boats operating on Oregon's Willamette River "pose a serious risk to threatened salmon and steelhead populations" due to the fact that juvenile salmon and steelhead are increasingly being violently ejected from their protective habitat, and tossed ashore as a direct result of high energy wakes produced by passing wake boats (Profita, 2020). Suggesting the need for much more inland fishery focused scientific research, fish biologists Whitfield and Becker (2014) observed that the overall biological influences of recreational power boating on inland waters have thus far been grossly underestimated.

Just as exposure to the intense jet engine-like turbulence generated by wake boats is capable of destroying the vulnerable, shallow water nests of spawning panfish, enhanced wakes produced by wake boats operating in close proximity to natural shorelines are also capable of abruptly terminating the reproductive cycle of mating loon pairs by destroying their nests and eggs, or by killing their chicks (Similuk, 2020). Migrating in late spring, or early summer from their over-wintering grounds located in the fertile, fish foraging rich habitat found in the near shore waters of the Atlantic and Pacific Oceans, and the Gulf of Mexico, adult breeding common loons begin their annual reproductive cycle by building simple nests on the natural shorelines of inland lakes that are widely distributed across northern tier states such as Michigan, Minnesota, Wisconsin, and the Canadian province of Ontario (Jones, 2020). Preferring large lakes characterized by irregular natural shorelines, coves, and small islands that offer some degree of shelter from the deleterious influences of high winds and waves, loons build their simple nests in areas that provide the nesting pair with a wide, unobstructed view of the area, thus enabling their ability to continuously survey for various forms of pending danger (Similuk, 2020). Returning to the same lake year after year, the reproductive success of loons is widely perceived to represent a reliable indicator of the overall health of the aquatic ecosystems of their respective nesting lakes (Bianchini *et al*., 2020). The validity of this observation is emphasized by the fact that loon breeding pairs, and their annual prodigy of never more than two chicks, feed exclusively on their respective nesting lakes (Jones, 2020). The threat posed to nesting loons by near shore wake boat operation is primarily associated with the fact that high amplitude wakes created by passing wake boats are capable of inducing as much as a six inch (15 cm) temporary rise in water levels, that, particularly in periods marked by record high water levels, dramatically increases the probability of flooded loon nests (Similuk, 2020). Frequent passages by recreational water craft are also capable of disturbing mating loon pairs to the extent that they ultimately abandon their nests, resulting in the death of their eggs, or of their chicks (Genier, 2019). Recognizing this fact, loon conservationists caution those seeking to observe the iconic waterfowl to not operate their water craft any closer than 100 feet (30.48 meters) to avoid disturbing the ultra-sensitive bird species (Adirondack Center for Loon Conservation, 2020).

Responsible for relocating over 7,000 living animal, plant, and algae species to vulnerable natural habitats distributed across the planet, ballast water transported exotic aquatic invasive species have a long history of harming the environment, affecting human health, and disrupting local and national economies (Surangi, 2019). Designed by manufacturers to store up to 500 gallons (1,893 liters) of water weighing 4,165 pounds (1,889 kilograms), the ballast water systems of wake boats are capable of acting as a vector for the introduction of aquatic invasive species (Doll, 2018). Wake boat owners that tow their water craft to two or more waterways hosting public boating access sites in relatively quick succession are particularly vulnerable to inadvertently contributing to the spread of exotic aquatic invasive species (Doll, 2018). Trailered wake boats are known to be an important vector for spreading aquatic invasive species. Secondary dispersal by recreational boaters engaged in overland transport of their ballast water laden watercraft has been primarily responsible for the increasingly widespread and abundant presence of highly invasive exotic aquatic animals, including species that have managed to achieve a high degree of success in the waters of the region such as the now ubiquitous zebra and quagga mussels (*Dreissena spp*.) (Doll, 2018; Rothlisberger *et al*., 2010).

Literally anything that is small enough to pass through the ballast water intake pump of wake boats, including bacteria, invertebrates, and/or the eggs, cysts, larvae, and veligers of a diverse and potentially destructive array of exotic aquatic species are capable of surviving for long periods of time in ballast water, and of eventually being released into un-invaded waters where they are often capable of flourishing in their new environments (Surangi, 2019). Originally transported from the Ponto-Caspian region of southern Russia to North America's St. Lawrence Seaway within the ballast water of ocean-going freighters (McMahon, 1996), as a prime example, recreational boats transporting ballast water laden with the microscopic veligers of zebra mussels (*Dreissena polymorpha*) are known to be primarily responsible for spreading the rapidly reproducing exotic mollusc from the waters of the Great Lakes to a steadily expanding list of infested inland lakes (Doll, 2018). The significance of the exotic mussel invasion is highlighted by the fact that provincial, federal, and state governments have thus far invested over five-billion-dollars in efforts to manage the destructive influences of *Dreissena* mussels (Surangi, 2019). Ballast water harboring highly contagious fish diseases, such as viral hemorrhagic septicemia (VHS), and transported from one inland lake to another via trailered wake boats, are also capable of having a significant impact on local fish populations (Whitfield and Becker, 2014). Wake boats are also responsible for increases in the coverage area and abundance of exotic invasive macrophytes, such as Eurasian water milfoil (*Myriophyllum spicatum*), that rapidly reproduce via fragmentation caused by propellers, turbulence, and/or intense wave action (Madsen *et al*., 2001).

In addition to wake enhancing technological advances that have enabled the on-going extraordinary surge in the popularity of wake surfing (Ruprecht *et al*., 2015), the rapid growth of the wake boat industry has also been driven by the fact that wake boats are capable of being towed to local and regional waterways (National Marine Manufacturers Association, 2018). The National Marine Manufacturers Association (2018) reports that 95% of all wake boat owners tow their watercraft. Particularly in the freshwater inundated Laurentian Great Lakes region, steadily increasing sales of the high-end recreational boats are driven by the fact that potential wake boat owner/operators are motivated by the awareness that those who tow are capable of operating their wake enhanced watercraft on multiple inland lakes, bays, and/or rivers over the course of a single weekend. In the absence of state laws or local ordinances restricting their operation, the scale of the multi-faceted ecological and environmental issues associated with the operation of a steadily increasing number of wake boats has been exacerbated by the fact that the vast majority of wake boat owners who tow their watercraft are currently only restricted in their choice of thousands of ecologically sensitive lakes, bays, and rivers by the fact that many waterways either do not possess public boating access sites, or possess crude, unimproved sites that are not capable of safely handling the launch and retrieval of heavy trailered recreational watercraft.

In light of the fact that researchers Mercier-Blais and Prairies (2014) observed considerable impact on the shore when (wake boats) passed within 328 feet (100 meters), and that all wake boat enhanced wakes contribute significant energy to naturally occurring waves when they occur within distances of up to 984 feet (300 meters) from shore, it is important to emphasize that the Water Sports Industry Association proposed minimum distance-from-boat-to-shore standard of 200 feet (61 meters), ultimately fails to establish an adequate level of protection to vulnerable natural shorelines, and/or waterfront property. As indicated by investigator Ray (2020), local governments that have previously acted to protect waterfront property, and/or natural shorelines by establishing s minimum-distance-from-boat-to-shore 'no wake' zone of 200 feet (61 meters) are now finding that due primarily to an upsurge in the number of wake boats operating on local waters, minimum protective zones of 200 feet (61 meters) are no longer capable of adequately protecting shoreline property, and/or highly beneficial natural shorelines.

It is also important to note that that the Water Sports Industry Association has yet to make a recommendation in regards to a minimum wake boat operating depth. In light of the findings of Raymond and Galvez (2015) who discovered that the jet engine-like turbulence generated by wake boats is capable of disturbing aquatic habitat occupying water depths of up to 16.4 feet (5 meters), and of research conducted by Ray (2020) that found that enhanced wakes generated by wake boats are capable of disturbing sediments situated in water depths of up to 12 feet (3.65 meters). the importance of the need to establish a requirement for a minimum operating depth that is commensurate with these findings cannot be overstated.

The significant findings of peer reviewed scientific research conducted by Ray (2020), Goudey and Girod (2015), Raymond and Galvez (2015), Ruprecht *et al*. (2015) and Mercier-Blais and Prairie (2014) have helped define the scope and scale of the significant ecological impacts that are likely occurring to many inland lake ecosystems as a result of frequent exposure to the enhanced wakes, and jet engine-like turbulence produced by wake boats. Their research has also provided a cogent, science-based body of knowledge that can be referenced by state legislators, and natural resource and environmental protection agency managers in order to enact laws and formulate policies that should be implemented and enforced by state, county, and local governments in order to help mitigate the harmful influences attributed to frequent exposure to nearshore, and/or shallow water wake boat operation. Science-based legislation written and passed into law in order to establish enforceable minimum distance-from-boat-to-shore, and minimum operating depth standards, for example, would serve to provide a modicum of definitive guidance to wake boat operators and law enforcement agencies, and ultimately contribute to reducing the overall potential for wake enhanced boats to inflict harm to ecologically sensitive inland lake ecosystems.

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