# The Effects of Wake Boats on Lake Ecosystem Health:

## A Literature Review

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## About this Work:

This report was prepared by David A. Ortiz, PhD candidate at the University of Wisconsin–Madison, Center for Limnology, for Wisconsin's Green Fire (WGF) in his work as a Conservation Fellow for WGF from 2023-2024.

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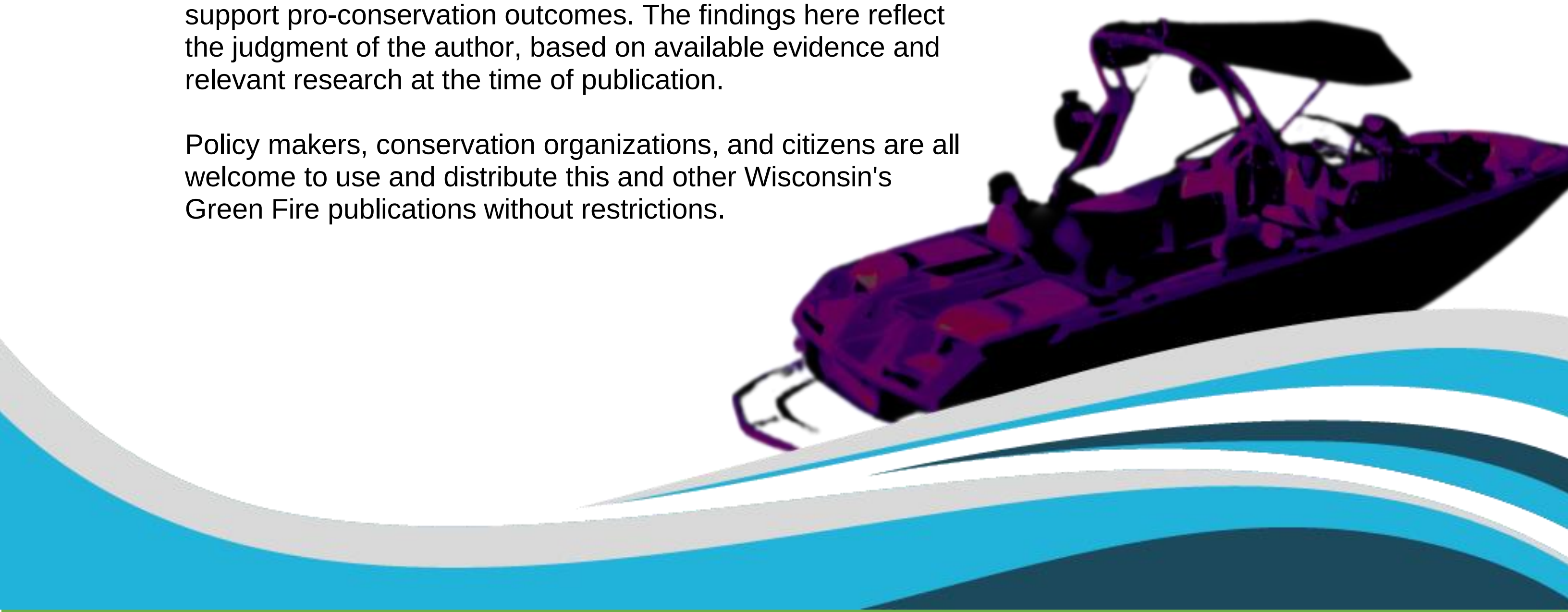

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# Effects of Wake Boats on Lake Ecosystem Health

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VOICES FOR CONSERVATION

- As wake boats become increasingly popular, their impacts on Wisconsin's lakes intensify.
- We've reviewed the science to prepare these pro-conservation recommendations, supporting recreational uses of lakes while protecting the health of lake ecosystems.*

## Concerns

### Aquatic Invasive Species (AIS)

Wake boats spread AIS like zebra mussels and Eurasian milfoil between lakes in their ballast and bilge water, degrading ecosystem health.

### Shoreline Erosion

With wakes 2-3 times bigger than regular boats and up to 12 times more energy from wave action, wake boats accelerate shoreline erosion even at extended distances (<600 ft) from shore.

### Sediment Resuspension

Wake boats resuspend sediment from lake bottoms >15 feet below the surface, reducing water clarity and habitat quality.

### Impacts to Aquatic Plants

Deep hulls and propellers (30" below the waterline), powerful engines, and large wakes can damage and uproot plants and impair plant growth.

### Impacts to Birds and Fish

Proximity, noise, direct wave strikes, and turbulence can disturb nesting waterfowl like loons and negatively affect fish populations.

## Recommendations

**40 ac**

Wake boating requires at least 40 contiguous acres (that are >600 ft from shore & >20 ft deep) to minimize impacts.

+

**↕ 20'**

Water depth of entire contiguous area must be at least 20ft to minimize sediment resuspension.

+

**600'**

Any point of the contiguous area needs to be at least 600ft from any shoreline to minimize shoreline erosion and impacts to plants.

+

**4 days**

At least 4 days between visiting unconnected waters with full wash and dry to limit spread of AIS

+

**i**

Informational signs and trainings for wake boaters and other lake users on best practices

*Read the full report "The Effects of Wake Boats on Lake Ecosystem Health" by David Ortiz for Wisconsin's Green Fire.

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# Executive Summary

**Wisconsin's Green Fire (WGF) examines the effects of wake boats on lake ecosystem health** with this literature review based on up-to-date scientific research. This review was prepared by David A. Ortiz, PhD candidate at the University of Wisconsin–Madison.

While all motorized boats can impact lake ecosystems, wake boats can cause especially negative ecological issues for lakes. Scientific research on wake boats has primarily focused on the effects of **waves on shorelines** and deep reaching **propeller turbulence**. Generally, studies show that these two consequences of wake boat properties have **negative impacts** on the ecosystem. Water quality worsens and aquatic plants, fish, and birds are negatively impacted. These issues are often amplified when shorelines are armored (lined with large boulders, i.e., riprap).

**Based on scientific literature,** this review focuses on how wake boats effect: 1) aquatic invasive species, 2) shoreline erosion, 3) aquatic plants, 4) sediment resuspension, and 5) birds and fish. It is important to note that *this report does not address the important topic of safety* regarding wake boats and other lake uses like swimming, kayaking, and fishing.

1) **Aquatic Invasive Species (AIS)**
    - Wake boats can carry up to 8 gallons of water inside ballasts and bilge *after* being drained with electric pumps between uses. The transport of this water spreads aquatic invasive species (e.g., zebra mussels, Eurasian watermilfoil, carp) between waterbodies, disrupting and damaging lake ecosystems.
2) **Shoreline Erosion**
    - Wake boats produce wakes that are 2-3 times larger than regular boats and transfer up to 12 times more energy to shorelines. These studies suggest wakes generated by wake boats that wake-boarding modes require up to 600 ft to dissipate while wake-surfing.
    - Armoring shorelines with riprap to repair or reduce erosion has high costs economically and environmentally, reducing biodiversity and habitat quality, exacerbating AIS issues, and increasing nutrient runoff into lakes.
3) **Aquatic Plants**
    - Wave action, propeller turbulence, and direct damage from hulls and propellers can disturb, destroy, and contaminate aquatic plant beds, worsening erosion and habitat issues (the plants help secure shorelines and lakebeds and provide the basis of food webs). Culturally important plants like manoomin (wild rice) are sensitive to impacts from wake boats.
4) **Sediment Resuspension**
    - Wake boats can disproportionately resuspend lake sediments compared to other watercraft, reducing water quality and clarity including releasing phosphorus from sediments into the water column and changing how water mixes in lake strata.
5) **Birds and Fish**
    - Proximity of wake boats and noise levels can disturb wildlife like nesting birds (i.e. loons) and fish. In addition to the effects of wake boats on lake habitats, turbulence and direct wave strikes negatively impact fish and other aquatic animals.

## Mitigating Wake Boat Impacts on Lakes: Community Strategies

**Wake boats and their effects are not unique to Wisconsin**. This review includes examples of community strategies from around the United States of America and Australia. These strategies typically include restrictions such as no-wake lakes, no-wake distances from shore (200−700 ft from shore), limitations on wake boat use during fish spawning periods, AIS inspection stations, and speed limits.

## Recommendations:

These recommendations are based on the current scientific literature. We intend them to be applied together, not taken separately, especially the recommendations regarding minimum contiguous acres, distance from shore, and minimum water depth for areas with wake boat use.

1. Wake boating activities should be done in areas that are **at least 20 feet deep**, providing a buffer around the 15 ft depth reported in Yousef, 1974, and this area has to be at least **40 contiguous acres**. Wake boating areas need to be **at least 600 feet from any shoreline**.
   a. If there is no bathymetry data to accurately assess if a lake meets requirements, then wake boating should not be allowed.
   b. On lakes that are just large enough for wake boats, consider restricting wake boat access early after ice off to increase success of fish spawning and loon reproduction.
2. Institute a **carrying capacity** of number of wake boats on lakes **that meet area and depth requirements** for wake boating. Baud-Bovy and Lawson (1977) recommend that each wake boat have 10 acres providing enough space to comfortably enjoy the lake without disturbing others, reduce the risk traveling over shallow areas, and minimize boating only over a small area.
3. To limit spread of AIS, require a **minimum of four days** before wake boats can access an unconnected waterbody, after being hot pressure washed or treated with bleach and left to dry. This includes hull, trailer, ballast systems, and bilge (Elwell & Phillips, 2021).
   a. Boat and trailer inspections for AIS/macrophytes need to include internal and external ballast tanks.
4. Provide **online training** about proper use and risks involved with wake boating and the environment (Kinsley et al., 2022; Seekamp et al., 2016).
5. **Informational signs and documents** about environmental dangers with wake boating should be available at boat launches and at boat dealerships.
6. Encourage other non-wake boat users to **document and report** inappropriate behavior by wake boat users to the Department of Natural Resources and game wardens, potentially set up a specific hotline for volunteers to document incidences of wake-zone violations.

## Introduction

Wakesurfing and wakeboarding using wake boats have become popular recreational activities, but they can lead to detrimental ecological consequences. Wake boats generally serve three functions: wakeboarding, wakesurfing, and cruising in water. These three activities vary by the speeds that the boat travels in the water: wakeboarding (15-25 mph) being the fastest and cruising being the slowest and done with a minimal wake. This report focuses on the use of wake boats on freshwater lakes, but they can also function in river systems and marine ecosystems.

Wake boats are vessels that range in length between 18-25 feet. They are specifically designed to displace large quantities of water with their deep V-shaped hull, 350+ horsepower (hp) engine, ballast systems, and wake plate and wedges (i.e., wake shaper) (Wallace, 2022). The most distinctive features of wake boats are the ballast system and wake shapers. Ballasts are tanks or containers that are filled with water to increase the total weight of the boat, to lower the boat further below the water surface. The deeper a wake boat is in the water column, the more water is available to displace into tall wakes. The wake wedge allows for larger amounts of water to be displaced, amplifying the already tall wake, while wake plates create smoother and steeper wake.

Wake boats have recently increased in popularity due to the draw to extreme water sports, with an increase of 20% to approximately 13,000 wake boats sold in 2020 ("U.S. Boat Sales Reached 13-Year High," 2021). This popularity is despite some research indicating increased rates of boating accidents associated with wake boats (Hostetler et al., 2005). According to the U.S. Bureau of Economic Analysis in 2022, approximately 710 million dollars were spent on boating and fishing activities in Wisconsin. Wake boats are here to stay on Wisconsin waters and across the nation.

While wake boats bring enjoyment to users, lakes and rivers are not sterile or isolated pools. These ecosystems are alive and exist in a delicate state of stability in terms of water quality, habitat for flora and fauna, as well as areas of cultural and spiritual importance to many communities. This report provides a general outline of the ecological consequences of wake boat usage in lakes, a review of responses from communities to wake boat effects, and some recommendations moving forward for the State of Wisconsin.

## Ecological Issues that Wake Boats Present

Although all motorized boats create ecological issues in lakes, rivers, and streams, wake boats specifically have an excessively negative influence on lakes. Since the 1970s, aquatic scientists and government agencies, such as the United States Environmental Protection Agency (EPA,) have been monitoring and quantifying the influence of boats on lakes (Baud-Bovy & Lawson, 1977; Yousef A. Yousef, 1974; Yousef et al., 1980). Major issues of concern span from elevated risk of boats being a vector for spreading aquatic invasive species (AIS), accelerating shoreline erosion from large wakes, destroying macrophytes communities (aquatic plants), resuspension of lake sediment which leads to a reduction in water clarity and quality, and disturbing fauna (fish and birds).

## Aquatic Invasive Species

Aquatic invasive species (AIS), also referred to as non-native species, are major concerns in all aquatic systems (Leppäkoski et al., 2002). The removal of AIS in systems larger than a small pond is nearly impossible (Escobar et al., 2018; Lund et al., 2018; Nico & Walsh, 2011), so the introduction of AIS is often an indication of reduced ecosystem health, and greater vulnerability to future invasion by other AIS (Havel et al., 2015). AIS have ruined and restructured ecosystems ranging in size from Lake Michigan to as small as Lake Wingra in Madison, WI (Vander Zanden et al., 1999, 2010). AIS completely change how an ecosystem functions, looks, and how humans interact with the lake.

Given Wisconsin's location along one of North America's main AIS ports of entry, Lake Michigan, there are several invasive organisms that warrant careful attention. To list a few species: zebra mussels, quagga mussels, and golden mussels (Belz et al., 2012; Benson et al., 2023; Boltovskoy et al., 2006; Johnson et al., 2006; Strayer, 2009; Zhu et al., 2006), Eurasian watermilfoil (Buchan & Padilla, 2000), purple loosestrife (Reinartz et al., 1987), spiny water fleas (Kerfoot et al., 2011), rusty crayfish (Olden et al., 2006), various species of carp (Bajer & Sorensen, 2010; Wittmann et al., 2014), zooplankton (*Daphnia lumholtzi, Hemimysis anomala*), microbes (N. E. Kelly et al., 2013), and diseases (Thiel et al., 2021). Each of these organisms have been documented to negatively alter aquatic ecosystems.

Motorized boats, including wake boats, are often kept and transported on trailers. Transportation of AIS via boat trailers has been well documented as have significant efforts to limit new AIS introductions into lakes (Minchin et al., 2006; Rothlisberger et al., 2010). Boat owners have been documented traveling up 300 miles (482 km) to recreate on popular or pristine waterbodies (Buchan & Padilla, 1999; Johnson et al., 2006). This means that AIS risks are not limited to species that have already invaded Wisconsin, but also boaters from Illinois, Indiana, Upper and Southern Peninsulas of Michigan, Minnesota, and Iowa that flock to Wisconsin lakes (Collas et al., 2021). Up to 33% of boats and boat trailers have macrophytes on them when exiting a waterbody and these macrophytes can harbor zebra mussels and other AIS.

Macrophyte fragments can survive up to three days completely while dry and up to 36 days if the boat lake is kept in a nutrient poor lake (Madsen & Boylen, 1988). Zebra mussels have been documented to survive past 36 hours out of water and even longer if exposed to moisture (Paukstis et al., 1999; Ricciardi et al., 1995) while quagga mussels can survive up to 27 days (Choi et al., 2013). Rinsing trailers, boat hulls, and boat decks with a heated pressure washer or a handheld pump sprayer with diluted bleach can dramatically reduce the risk of spreading AIS to the next water body, especially if boaters allow for their entire boat sit to dry for two to three days before use (Elwell & Phillips, 2021; Sims & Moore, 1995).

Wake boats are unique risks when it comes to AIS because of their capacity to hold so much water on board with their ballast systems and bilge (Doll, 2018). The ballasts themselves are often nearly double the total weight of the boat, holding approximately 5,000 pounds (2,267 kg or 599 gallons). Wake boats often come with electric pumps to make filling and emptying ballasts straight forward, as they need to be filled with each use. Currently, ballasts found in wake boats are not designed to completely drain, leaving behind on average 8.37 gallons (31.7L) of internal ecosystem capable of harboring AIS (Campbell et al., 2016) *(see Figure 1).*

In addition to holding a large quantity of water internally, there are several companies that sell ballast bags that can be filled in addition to the internal system, further increasing the risk of transporting AIS. Ballast systems are the reason zebra mussels were introduced into North America (Escobar et al., 2018). Since 2004 incoming international ships ensure they abide by higher precautions (emptying ballasts mid-ocean or installing internal ballast filtering systems) to minimize the spreading of AIS invasions globally (Gerhard & Gunsch, 2018; Tsolaki & Diamadopoulos, 2010).

Wake boats ballast systems are not designed to completely drain or be easily cleaned, which would reduce their risk of being vectors of AIS. Wake boats manufacturers do not offer internal filtering or decontamination systems for ballast tanks to remove AIS. Furthermore, most large powerboats (including wake boats) also have a large bilge system, which are seldom drained or cleaned by owners, but have also been found to harbor AIS. As the volume of water onboard boats increases so does the number of AIS found on boats (N. E. Kelly et al., 2013).

Compared to other vessels, wake boats present a greater risk of spreading AIS. While zebra mussel veligers (larval stage, 70 – 200µm or 0.002 – 0.0078in) have been found in small outboard motor cooling systems, that risk is trivialized by the vast difference in water held by wake boats (De Ventura et al., 2016). Although fishing boats with holding wells are also a source of AIS, especially diseases and smaller organisms, they are easier to rinse and sanitize than internal and external ballast systems but still require attendance and effort (Davis et al., 2016). These large ballast systems, hard to reach bilge areas, and holding wells are all areas where clippings of invasive macrophytes, zooplankton, microbe, or disease could be located.

Figure 1. Internal ballast system of 2023 Malibu 26 LSV model wake boat. Image from 2023 Malibu Boats product guide. The image highlights the large volume of water held within the internal ballast system with minimal access to decontaminate.

## Shoreline Erosion

Shoreline or bank erosion is a slow and naturally occurring process found in any aquatic ecosystem. Major drivers of shoreline erosion on lakes are divided into two categories, passive and active. The passive category of shoreline erosion includes characteristics of the shoreline or the lake like material composition, slope, exposure to direct sunlight, lack of natural protection from waves, lack of vegetation, water flow rates and lake level change. Active shoreline erosion drivers include waves, frost thaw, precipitation runoff, groundwater when at or above the lake levels, lake ice, and wind (Alavinia et al., 2019; Allen & Tingle, 1993).

Lake shoreline erosion was estimated for the Great Lakes region to have been as high as 0.7 m per year (May et al., 1983; Swenson et al., 2006). These high erosion rates are likely driven by forest clear cutting practices that ended around 1915 and the removal of wetland ecosystems (Alverson et al., 1988; Brock & Brock, 2004; Reinartz & Warne, 1993; Steen-Adams et al., 2007). This clearing of established forest and draining of wetlands completely and permanently altered the flora, fauna, hydrology, and soils of Wisconsin. These environmental changes and relatively recent shoreline development in Wisconsin have left lakes primed for elevated rates of shoreline erosion. Wakes created by wake boats amplify shoreline erosion rates especially when paired with unscientific recommendations of boating distances from lake shores.

All motorized boats create wakes and are all contributing to eroding lake shorelines, but the differences in magnitude and influence on eroding shorelines are distinct between non-wake and wake boats (Bauer et al., 2002). Several studies have shown that larger waves and wakes erode shorelines at faster rates (Amin & Davidson-Arnott, 2023; Bilkovic et al., 2019; Nanson et al., 1994; Priestas et al., 2015; Reid, 1984). Wake boats when compared to fishing boats, speed boats, jon boats, trolling motors, or paddle-powered watercraft, or regular wind conditions create waves that are transferring more energy to the shore expediting erosion (Alexander & Wigart, 2013; Baud-Bovy & Lawson, 1977; Goudey & Associates, 2015; Houser et al., 2021; Marr et al., 2022; Ray, 2020; Roberts et al., 2019; Ruprecht et al., 2015).

Wake boats produce wakes that are 2-3 times larger than regular boats and transfer up to 12 times more energy to shorelines. These studies suggest wakes generated by wake boats that wake-boarding modes require up to 600 ft (180 m) to dissipate while wake-surfing. While some modeling efforts and boat industries suggest that the influence of wake boats on shorelines are minimal at distances as near as 200 ft (61 m) from shore (Fay et al., 2022), but these methodology and analyses seem to be flawed (see collection of critiques via the Vermont Department of Environmental Conservation).

Shoreline erosion has driven lake managers to pursue several different methods to minimize losses. In Wisconsin this generally results in riprap (hardening shorelines with large rocks or concrete) (Gittman et al., 2015; Scyphers et al., 2015). While riprap is a solution to stabilizing shorelines to erosion risks, it often comes with several environmental consequences and high economic cost. These consequences include loss of overall biodiversity, increasing hard surfaces for invasive zebra mussel populations, wakes being reflected and traveling downstream to unhardened shorelines, increased decomposition rates, and increased nutrient runoff into lakes (Kobayashi et al., 1987; Roche et al., 2021; Strayer & Findlay, 2010). Riprap displaces valuable macrophyte and riparian areas (Gabriel & Bodensteiner, 2012; Wensink & Tiegs, 2016). These have consequences of reduced young and small fish habitat which are the cornerstones of aquatic food webs (Quigley & Harper, 2004). Removing vital native macrophytes with placing of riprap opens ecosystems to invasions of AIS (Patrick et al., 2014). During installation of riprap, native riparian buffers are often smothered by riprap and heavy machinery, leading to increased nutrients running off into lakes from nearby areas (Lee et al., 2003; Schoonover et al., 2005). Use of riprap can also lead to loss of habitat for various organisms as shoreline areas behind riprap are often converted to non-native lawns (Cole et al., 2020; O'Connell et al., 1993). Lake shore stabilization efforts are more often successful with restoring native riparian and aquatic flora, even if timelines for projects are longer and require more up-front effort (Eerdt, 1985; Elias & Meyer, 2003; Hartig et al., 2011; Manis et al., 2015; Scyphers et al., 2015).

## Aquatic Plants

Aquatic plants (macrophytes) have several ecological roles. They stabilize lake bottoms and shorelines with their often long and dense root systems (Madsen et al., 2001) and dampen most organically formed waves (Augustin et al., 2009). Macrophytes serve in several other functions in waterbodies like oxygenating littoral zones through photosynthesis (Hartman & Brown, 1967), consuming nutrients (Chen & Barko, 1988), promoting aeration and decomposition with their root systems (Brix, 1994), and keeping the water column cool with shading effects (Carpenter & Lodge, 1986). Macrophyte beds can be nurseries for fish, homes for smaller fish, and are the primary habitat for aquatic invertebrates (Randall et al., 1996; Schultz & Dibble, 2012).

Macrophytes serve in the important role of housing the bottom layers of fisheries food webs, studies have shown a decrease in macrophytes lead to a decrease in fish populations (Hansen et al., 2019; Hawkins et al., 1983). The effects of macrophyte populations on fisheries stability are difficult to monitor but loss of macrophytes could lead to ecosystem instability without us noticing (Mrnak et al., 2023). Macrophytes have been important to Indigenous communities, specifically the Ojibwe people with wild rice (manoomin, *Zizania palustris*) (Barton, 2018). Manoomin is highly valued within Ojibwe culture as both calorically and nutrient dense food source but also as an important source of income.

While macrophytes can help stabilize lake bottoms and reduce shoreline erosion, they do have their structural limits. Macrophytes are susceptible to being run over and cut, reducing ability to photosynthesize, reproduce, and survive (Sagerman et al., 2020; T. Asplund, C. Cook, 1999). Several species of macrophytes native to Wisconsin have high light requirements such as chara and sago pondweed (Santamaría, 2002), so any long-term sediment resuspension would negatively affect those light sensitive species. With constant boat traffic, areas can be void of all macrophytes leaving behind “scars'' on lake bottoms (Dawes et al., 1997).

Wake boats present elevated levels of disturbance to macrophytes based on wake sizes and depth of propellers and turbulence (Zhang et al., 2017). Wake boats generate wakes that are several times more powerful than other motorized boats and those wake effects are felt at extended distances (>600 ft) and either knock down macrophytes or limit the amount of light they receive (Asplund & Cook, 1997). Wake boats have deep hulls that house propellers up to 30 inches (0.76 m) below the waterline, almost double the depths of most motors used in freshwater systems. This deeper propeller and turbulence are primed to uproot and cut macrophytes if boaters are careless with their speeds and water depth. According to Preiner &

Williams in 2018, wake boat influences are major concerns for the Ojibwe people, as manoomin has relatively shallow roots and growth early in the spring is just under the surface making it difficult to notice.

Heavy boat usage also comes with contaminants entering the water and consequently into a vital food source for the Ojibwe people, these can include hydrocarbons, metals, antifreeze, acids, and solvents (United States Environmental Protection Agency Office of Water, 1994). Boat manufacturers recommend that wake boat ballasts are winterized with antifreeze, but because of ballast design, antifreeze will enter lakes during critical moments of growth for manoomin. According to United States and Wisconsin law, this is illegal even including products labeled as environmentally friendly (Clean Water Act, 1977; Wisconsin Administrative Code, 2020; Hunt et al., 1996; LaKind et al., 1999). In addition to simply being uprooted or cut, there is also a reduced growth rate of manoomin that grows in turbid waters associated with areas of wake boat use (David, 2018).

## Sediment Resuspension

Sediments on the bottom of lakes accumulate over many centuries and store large quantities of nutrients (generally nitrogen and phosphorus) from the watershed. This report focuses mainly on phosphorus (P), as it is mainly the limiting factor for algal growth in Wisconsin lakes (Schindler, 1977). In the Anthropocene, there is evidence that fertilizers used within watersheds are collecting into lake sediments, further increasing the already large pool of nutrients (Arbuckle & Downing, 2001; T. Mayer et al., 2006; North et al., 2015). While on the lake bottom, these nutrients remain generally unavailable to a majority of primary producers, like algae, plants, and microbes (Forsberg, 1989). There are a few exceptions when the surface waters have access to the nutrient storage of the bottom waters; during lake destratification in the spring or fall, if thermoclines deepen, or if sediment are disturbed (Bengtsson & Hellström, 1992; Orihel et al., 2015, 2017).

When lakes are stratified (warm top layer, cold bottom layer) they essentially become two pools of resources as surface level mixing cannot penetrate the thermocline (layer of water with the greatest change in temperature and density). Thermocline depth varies for different lake sizes, shape, and latitude (Boehrer & Schultze, 2008), but areas with a shallower thermocline are susceptible to mixing and sediment disturbance. The bottom waters (the hypolimnion zone) are generally oxygen poor, and the top is well oxygenated top water (epilimnion zone). Because of how the density of water changes with temperature, these two layers do not mix (Sommer et al., 2012). This phenomenon drives the differences in P concentrations between the epilimnion and hypolimnion. As P enters the well oxygenated portion of a waterbody, some proportion of it is quickly consumed by primary producers (Currie & Kalff, 1984; Istvànovics et al., 1994; Schindler & Fee, 1974). The P that is not consumed in the epilimnion will likely bind to calcium, manganese, aluminum, or iron depending on element availability and pH (Eckert & Nishri, 2014; Jensen & Andersen, 1992; Mortimer, 1942).

Regardless of the element that P binds to, it becomes biologically inaccessible and will eventually sink to the bottom of the lake. Additionally, P can be transported to the sediment in organic matter of phytoplankton, macrophytes, and fish (Yu et al., 2022). Under hypoxic (low oxygen) conditions in the hypolimnion, P can dissociate from the element it formed a bond with and become biologically available again (Albright et al., 2022). Concentrations of P in the hypolimnion can become high as consumption demand is low under low light and cold temperatures.

Regular conditions can cause some of the P rich hypolimnetic waters to be mixed with the epilimnion; again, lake turnover, deepening of thermocline, or sediment disturbances. Lakes in Wisconsin can have thermoclines that are about 8-9 ft from the surface and are generally dimictic (lakes where water columns only mix in the fall and spring) (Lewis, 1983). Lakes that are not at least 10 ft in max depth are likely to be polymictic, meaning they mix several times throughout the year. These mixing events fuel a large portion of a dimictic lake primary production need for P (Hanson et al., 2020). If lakes have a large enough area that is below or near the thermocline and have a long enough disturbance (strong winds), this can cause enough mixing of the epilimnion to dip into and pull up some of the nutrient rich water in the hypolimnion (Bennett et al., 1999; Roberts et al., 2019).

If the lake is shallow enough, wind can be enough to resuspend sediment. Additionally, if the pH in the more oxygenated water is near 9 (which commonly happens in the summer), there is a risk of P being released from element bonds (Bengtsson & Hellström, 1992; Dunn et al., 2017; Kelton & Chow-Fraser, 2005; Koski-Vahala & Hartikainen, 2001). This movement of nutrient rich bottom water is often credited to incite algal blooms in lakes (Orihel et al., 2015). This can also occur from sediment disturbances of organisms that dig into the sediment for food or shelter; several species of carp are notorious for resuspending enough sediment to turn lakes turbid (Gautreau et al., 2020; Lin & Wu, 2013; Wittmann et al., 2014).

Motorboats in general have increased the sediment disturbance and resuspension in lakes, streams, and rivers (Nedohin & Elefsiniotis, 1997). This is one reason for no wake zones and speed limits, restricting wave influences on shorelines and propeller turbulence to shallow lake bottoms (Beachler & Hill, 2003). Some studies suggest that boat disturbances are minimal and only influence the very top layers of sediment, but a majority of P is found to be in the top centimeter (0.39in) of sediment (Doig et al., 2017). This has implications for wake boats potentially having a disproportionate and unregulated impact on resuspending P-rich lake sediment. Fine silt particles that are disturbed can take days to settle back to the bottom of the lake when the lake experiences no further disturbances, reducing water clarity for extended periods of time (Douglas et al., 2003; Yousef et al., 1980).

An early study on boat effects on lakes found that the mixing depth of boats was linearly related to the horsepower of the motor and showed that 50 hp motors are capable of disturbing lake sediment while in 15 ft (4.57 m) of water (Yousef A. Yousef, 1974). While in 1974 there were not as many power boat motors readily available for commercial consumption or testing, one can only assume that depth has only increased as motors found on wake boats commonly exceed 300 hp in the present day.

A more recent study compared various motorized boats and their influence on lake bottoms and found that wake boats had the largest disturbance of sediment and release of nutrients when compared to various other non-wake boats after driving past sampling locations once (Daeger et al., 2022). Unfortunately, the Daeger et al. (2022) study did not include trials of wake boats with wake wedges or wake shapers which increase the wake and potentially the turbulence created from crashing wakes (Ruprecht et al., 2015). Some studies also suggest that the effect of boating is strongly dependent on boating in a single area, which wake boats are discouraged from doing (Abu Hanipah & Guo, 2019; Alexander & Wigart, 2013; Sagerman et al., 2020).

Wake boats are often seen repeating the same path patterns on lakes, increasing the impact on the lake bottom and near shorelines. Wake boats may sometimes be operating at a depth where sediment resuspension is not a concern but pushing down the thermocline and allowing some of the hypolimnion water to escape in the epilimnion. While an intense and thorough study has yet to definitively map wake boats mixing depth or how much sediment they can disturb, there is evidence to support the idea that wake boating reduces water clarity and quality by resuspending P-rich lake sediments more than other motorized boats.

## Birds and Fish

Anthropogenic presence and behavior in any space provides some sort of disturbance to surrounding wildlife (Andrew Inkpen, 2017; Bird, 2015). Over the past one hundred and fifty years, our disturbances have increased with the everyday takeover of combustion engines in our daily lives. While humans have embraced this new trajectory on Earth, the co-inhabitants that share our environments have not been as quick to adapt. Motorized boats have been well documented in disturbing birds from distances up to 237 m (778 ft), but on average this distance is closer to 60-80 m (197- 262 ft) (Burger, 1998; M. Mayer et al., 2019; Ortega, 2012; Rodgers & Smith, 1997).

There are several factors that influence the distance it takes a boat to scare birds, including speed, size, and the season (influencing the behavior of birds, breeding, foraging, loafing, nesting) (Rodgers & Smith, 1997). Noise levels of boats sold and operated in Wisconsin are not to exceed 86 dBA (Wisconsin Statutes, 1987). While a majority of wake boat manufacturers aim to have noise levels near 86 dBA, that is set for a fraction of the potential revolutions per minute (RPM) at 3000 (for a detailed list of make, model, motor combination noise levels: https://www.boatingmag.com/boats). The increased RPM in any wake boat attempting to move 10,000 lbs. would certainly exceed the noise limitations in Wisconsin. Disturbing birds with boats that are larger and faster could lead to birds leaving nests with eggs or young, reducing survival rates and increasing their caloric needs forcing birds to forage longer (Kahl, 1993; McIntyre, 1994).

A major focus of human disturbance has been on common loons (*Gavia immer*). The common loon has been described to be both an apex predator and an indicator species, living up to 30 years (Strong, 1990). Common loons prey on a wide range of organisms, from crayfish to small walleye and other aquatic species. Because of their high position in the food web, they reflect the health of the entire food web of the lake over their long lifespans. Accordingly, loons are subject to mercury accumulation in their bodies (Mitro et al., 2008; Scheuhammer et al., 2016). Loons are also sensitive to lead poisoning, lake acidification, warming climates, fluctuating water levels, and human trash (Desorbo et al., 2007; Fair & Poirier, 1993; McNicol, 2002; Michael, 2006; Pokras, 2023). Often not reproducing until they are about six years of age, they are very territorial and particular about where they nest.

Loons have been found to successfully reproduce when nests are on shorelines of lakes about 250 acres (1.01 km$^2$) or larger with low human development. Successful loon nests are generally found within a foot (~ 0.3 m) from the water's edge and on small islands (Bianchini et al., 2020; Heimberger et al., 1983; L. M. Kelly, 1992; Lindsay et al., 2002; Spilman et al., 2014;

Tischler, 2011). Loons also tend to create nests on shores that are in the direction of the dominant wind to minimize fetch effects on nests (L. M. Kelly, 1992). Loons are selective with their nest locations because they struggle walking on land and want to be close enough to the water to quickly access the water while minimizing predation risks.

The noise from approaching boats has been documented to scare loons while brooding. Boats that produce large enough wakes that hit the shore can also scare loons off their nests, flood their nests, or erode prime nesting locations. These disturbances increase time away from nests, opening the clutch of eggs to predation risks from bald eagles, raccoons, and mink (Cooley et al., 2019; McCarthy & DeStefano, 2011). After approximately 30 days of brooding from May to early June, loon chicks spend most of their time within 150 m from and areas that are 3 m in depth or shallower (Desorbo et al., 2007; Jung, 1991). The effects that wake boats potentially have on reduced reproduction success of loons with significantly larger and more powerful wakes is undeniable, especially because wake boat owners and loons have an interest in both using larger lakes.

A new field of study has been focusing on the effects of motorized boats on fisheries, ranging in consequences from turbulence, physically hitting fish, and noise disturbances. Turbulence from boating has been shown to negatively influence fish eggs, young fish, and benthic invertebrates (Gabel et al., 2011; Hawkins et al., 1983; Zajicek & Wolter, 2019). Boat generated turbulence and wakes can physically move fertilized eggs off beds, as seen with storms (Raabe & Bozek, 2015), as well as moving smaller and young fish away from desired habitat (Becker et al., 2013).

Turbulence can move benthic invertebrates from their habitat, potentially changing resource availability for fish (Gabel et al., 2011). Larger boats and deeper hulls have an increased risk of both creating more turbulence closer to fish, hitting or disturbing fish, mammals, and birds as boats navigate shallower waters (Heinrich et al., 2012; Lima et al., 2015). As described in the aquatic plant section of this report, increased turbulence and wakes can reduce macrophyte populations, which many fish species use as nursery beds (Asplund & Cook, 1997; Hansen et al., 2019). Reduction in water clarity has also been shown to limit walleye (*Sander vitreus*) ability to hunt and as well as other fish species (Nieman et al., 2018; Nieman & Gray, 2019), potentially contributing to their dwindling population in Wisconsin (Rypel et al., 2018). This would also mean difficulty for future tribal harvesters that depend on subsistence fishing practices, which rely on walleye.

Studies focusing on how fish respond to noise, including muting fish communication and physical damage to their ears are relatively new areas of study (Popper & Hastings, 2009; Slabbekoorn et al., 2010). A laboratory study shows that fish size directly influences the effects that boat noise has and how long those effects last. Increased signals of stress in fish have been observed up to 40 minutes after noise generation from a small 9.9 hp motor (Graham & Cooke, 2008). A study in a lake confirmed via laboratory results that boating had a larger effect on smaller fish (Jacobsen et al., 2014). These observed effects could have profound effects on smaller fish species if constantly exposed to boat engine noise even after being exposed to noise, reducing swim distances, and increasing risk of predation (Harding et al., 2020). In addition to stressing fish with noise from boats, they can also muffle those fish that vocalize Freshwater species that communicate with sound include freshwater drum, catfish, perch, and some minnow (Bass & Chagnaud, 2012; Codarin et al., 2009; Pieniazek et al., 2020). As fish are being muted by anthropogenic noises, mainly boats, they have been observed to change how they communicate with each other. This includes changing frequencies they use, shifting when they communicate to times a day where noise is less, and resorting to visual cues (Radford et al., 2014).

In addition to altering their communications there is also evidence that when fish with developed ears are exposed to loud enough noises fish can experience hearing loss (Popper & Hastings, 2009). The consequences of changing and alternating how fish communicate seem to be unrealized but we as humans should minimize the levels of influence of our fisheries (Venohr et al., 2018). Both with effects of their wake and noise, irresponsible use of wake boats can negatively influence fauna found on and in Wisconsin lakes.

## Mitigating Wake Boat Impacts on Lakes: Community Strategies

Wake boats are not only a Wisconsin issue. Several communities, states, and countries have been struggling to strike a balance allowing people to enjoy their investments and protecting their delicate ecosystems. Below is a list of communities that have decided that enacting stricter boating regulations would help them, and future generations enjoy their lakes.

- **Lake Tahoe, California & Nevada**: 600 ft no-wake zone from shore, 100 ft no-wake zone near swimmers and paddlers, and 200 ft no-wake from structures. Lake Tahoe also has some of the strictest and most thorough boat inspections for AIS with at boaters cost decontamination.
- **Lake Minnetonka, Minnesota:** 300 ft no-wake zone from shore
- **Montana**: AIS inspection points with free decontamination, 200 ft no-wake zone, liability to boaters for damage caused by wake, lakes less than 35 acres (0.14 km$^2$) are no-wake lakes.
    1. Canyon Ferry Reservoir has areas of 300 and 500 ft no-wake zones.
    2. Cooney Reservoir has areas of 300 ft no-wake zones.
    3. Hauser Reservoir has areas of 300 and 500 ft no-wake zones.
    4. Lake Koocanusa has areas of 300 ft no-wake zones.
    5. Several water bodies have no boat usage from March 1 – April 10th to protect fish spawning.
- **Lake Sunapee, New Hampshire:** No-wake zones up to 500 and 700 ft from shore within town boundaries.
- **Tennessee, South Carolina, and Alabama:** all adopted no wake boarding or surfing within 200 ft from shore.
- **Lake Bonney, Australia**: 100 m (328 ft) boating from shoreline restriction of all boats.
- **Lake Hume, Australia:** 5 knot (5.7 mph) limit within 50 m (164 ft) of shore for all boats.

## Recommendations

These recommendations are based on the current scientific literature. We intend them to be applied together, not taken separately, especially the recommendations regarding minimum contiguous acres, distance from shore, and minimum water depth for areas with wake boat use.

1) Wake boating activities should be done in areas that are at least 20 feet (6 m) deep, providing a buffer around the 15 ft depth reported in Yousef 1974, and this area has to be at least 40 contiguous acres (0.16 $km^2$). Wake boating areas need to be at least 600 feet (183 m) from any shoreline.
    a. If there is no bathymetry data to accurately assess if a lake meets requirements, then wake boating should not be allowed.
    b. On lakes that are just large enough for wake boats, consider restricting wake boat access early after ice off to increase success of fish spawning and loon reproduction.

2) Institute a carrying capacity of number of wake boats on lakes that meet area and depth requirements for wake boating. Baud-Bovy and Lawson (1977) recommend that each wake boat have 10 acres (0.04 $km^2$) providing enough space to comfortably enjoy the lake without disturbing others, reduce the risk traveling over shallow areas, and minimize boating only over a small area.

3) To limit spread of AIS, require a minimum of four days before wake boats can access an unconnected waterbody, after being hot pressure washed or treated with bleach and left to dry. This includes hull, trailer, ballast systems, and bilge (Elwell & Phillips, 2021).
    a. Boat and trailer inspections for AIS/macrophytes need to include internal and external ballast tanks.

4) Provide online training (e.g., through the Department of Natural Resources) about proper use and risks involved with wake boating and the environment (Kinsley et al., 2022; Seekamp et al., 2016).

5) Informational signs and documents about environmental dangers with wake boating should be available at boat launches and at boat dealerships.

6) Encourage other non-wake boat users to document and report inappropriate behavior by wake boat users to the Department of Natural Resources and game wardens, potentially set up a specific hotline for volunteers to document incidences of wake-zone violations.

## Final Comments from the Author

The residents of Wisconsin should weigh the pros and cons of unregulated wake boating in their beautiful waterways. This document outlined most of the concerns that wake boats bring to an ecosystem if not done in a responsible fashion. Without proper distance away from shore, water depth, and contiguous areas large enough for wake boats lakes, flora, fauna, and property owners will see likely irreversible negative effects in the near future. The regulators of natural resources and legislators in the state of Wisconsin also have to reflect on what the public trust doctrine means for this issue and consider adopting some if not all of the recommendations listed above.

To continue reading some more detailed information about boating, I urge you to prioritize your readings with Arthington (1998), Havel et al. (2015), Liddle and Scorgie (1980), and Mosisch and Venhor et al. (2018); all of which are included in the literature cited list for this report.

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