The Effects of Wake Boats on Lake Ecosystem Health:

A Literature Review

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*This publication is an update from our February 2024 report of the same title.

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Editor's Note:

This Wisconsin's Green Fire special report is an update to our original literature review "The Effects of Wake Boats on Lake Ecosystem Health: A Literature Review," released in February 2024. This updated version, published in May 2024, includes corrected and expanded information. While most of the conclusions in this report are similar to the recommendations we provided in our February 2024 report, our conclusions here more fully and accurately represent the scientific literature. Here, we also include more Wisconsin-specific community strategies for regulating wake boats and provide an expanded and updated set of references.

Executive Summary

Wisconsin's Green Fire examines the effects of wake boats on lake ecosystem health with this updated literature review based on peer-reviewed research, published reports, and personal communications with topical experts. We have summarized the current research findings and acknowledge that future studies will improve understanding and build upon our conclusions.

While all motorized boats can impact lake ecosystems, our work suggests that wake boats are causing profound ecological issues for lakes. Research on wake boats has primarily focused on the effects of waves on shorelines, deep-reaching propeller turbulence, and the spread of aquatic invasive species. Throughout this document, wakes generated for recreational activities such as wakeboarding or wakesurfing will be referred to as "recreational wakes."

Based on scientific literature, this review focuses on how wake boats affect: 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 critical topic of human safety* regarding wake boats and other lake uses such as swimming and kayaking.

Summary Effects of Wake Boats on Lake Ecosystems

1) **Aquatic Invasive Species (AIS)**
    - Wake boats can retain up to 23 gallons of water inside ballasts and bilge *after* being drained with electric pumps. The transport of this water spreads AIS (e.g., Eurasian watermilfoil, spiny water flea, zebra mussel) between waterbodies.
2) **Shoreline Erosion**
    - Wake boats can produce wakes that are 2–3 times larger than motorized non-wake boats and transfer up to 12 times more power to shorelines, requiring more than 600 ft to dissipate.
    - Armoring shorelines with riprap to repair or reduce erosion has high environmental and financial costs, reducing biodiversity and habitat quality, exacerbating AIS issues, and increasing nutrient runoff into lakes.
3) **Aquatic Plants**
    - Recreational wakes, propeller turbulence, and direct damage from deep hulls and propellers can disturb and destroy aquatic plant communities, worsening erosion and habitat loss.
    - Native aquatic plants help secure shorelines and lake bottoms and are essential cornerstones of food webs. Manoomin (wild rice) is especially susceptible to intense turbulence and is of serious concern because of its cultural significance.
4) **Sediment Resuspension**
    - Wake boats can resuspend lake sediments at deeper depths than other watercraft, reducing water quality and clarity. The resuspension of lake sediment can also reintroduce stored and previously inaccessible phosphorus back into the water column, fueling algal growth.
5) **Birds and Fish**
    - Enhanced wakes, noise levels, and turbulence can negatively impact wildlife, including near-shore nesting birds (e.g., common loons), and fish.

Summary Community Strategies

This review includes examples of community strategies from Wisconsin, other U.S. states, and Australia to mitigate effects of wake boats. These strategies typically include restrictions such as increasing no-wake distances from shore, speed limits, limiting wake boat use during fish spawning periods, and free AIS inspection stations. Some communities are restricting or banning the use of wake boats, or equipment used to create recreational wakes, on any waterbody.

Summary Conclusions:

These conclusions are derived from our review of the scientific literature and best professional judgment of the available information. It is important to state that there are notable gaps in the scientific understanding of the full effects of wake boats on lake ecosystems. We intend these conclusions to be considered and applied together, not taken separately.

1. Wake boating activities that create recreational wakes should be done **only in areas that meet the following criteria:**
    a. At least 20 feet deep,
    b. At least 600 feet from any shoreline.
2. To limit the spread of aquatic invasive species (AIS), exterior surfaces and internal ballast systems of wake boats should be sanitized with hot water (≥140°F) before accessing other lakes.
    a. Inspections for AIS and aquatic plants must include internal and external ballasts.
3. Consider restricting timing of wake boat access to lakes until after fish spawning and common loon reproduction.
4. Create and require online training for wake boat users about proper use and risks involved with wake boating and environmental impacts.
5. Make informational signs and documents about the environmental risks of wake boating available at boat launches and dealerships.
6. Encourage lake users to document and report inappropriate behavior by wake boat operators to the Wisconsin Department of Natural Resources and conservation wardens.

Summary Data Gaps and Research Recommendations:

Researchers, policymakers, and lake users are just beginning to understand the effects of wake boats on Wisconsin lakes. Scientific research focused on wake boats is scarce and significant knowledge gaps exist. This literature review often includes information on motorboats that has been extrapolated to wake boats. To better understand wake boat effects on lakes, future studies must focus on determining recreational wake-to-shore distances, mixing depth of single and multiple boats, AIS sanitation protocol for ballasts, and effects on plants and animals. In addition to initial research on these topics, studies must be repeated consistently so our knowledge of ecological impacts is concurrent with the yearly incremental changes of wake boats (i.e., size, weight, speed, and ability to create wakes).

Introduction

What are Wake Boats?

The popularity of wake boats for recreational activities has surged. Over 13,000 units were sold in the United States in 2020, marking a 20% increase from the previous year ("U.S. Boat Sales Reached 13-Year High," 2021). Wake boats range in length from 18–25 ft. They are designed to displace large quantities of water with their deep V-shaped hull, 200+ horsepower (hp) engine, internal ballast systems, and wake shaping attachments such as wake plates and wedges (i.e., wake shapers) (Wallace, 2022). The most distinctive features of wake boats are the ballast system and wake shapers. Ballasts are containers that can be filled with water to increase the boat's total weight, lowering the boat deeper below the water's surface. The deeper a wake boat sits in the water column, the more water is available to displace, creating taller wakes. The wake wedge allows wake boats to displace more water, amplifying the already tall wake. Wake plates create a smoother and steeper wake, but not necessarily taller.

Wakeboarding and wakesurfing are similar activities performed using wake boats, albeit with important differences. When wakeboarding, a rider on a wakeboard is towed behind a wake boat, enabling the rider to jump from the wakes and perform tricks while airborne. Wakesurfing is similar in that a rider is initially towed while on a longer board. However, the rider moves to the top of the tall wake created by the wake boat and releases the tow line, resembling ocean surfing. Wakeboarding is usually done above 15 mph, while wakesurfing generally occurs between 10–12 mph. Wakesurfing occurs while the bow of the boat is angled approximately 15 degrees above the waterline and requires full ballasts (or several passengers) to create wakes large enough for surfing. Throughout this document, wakes generated for recreational activities such as wakeboarding or wakesurfing will be collectively referred to as "recreational wakes."

This literature review focuses on using wake boats on freshwater lakes, but they can also operate in rivers and marine ecosystems. We provide a general overview of the ecological consequences of wake boats on lakes, a review of responses from communities to minimize those negative effects, conclusions from the literature that could be implemented to lessen the ecological impacts, and current knowledge gaps about wake boats.

Ecological Issues that Wake Boats Present

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 motorized boats on lakes (Yousef, 1974; Yousef et al., 1980). Although all motorized boats have negative ecological consequences in aquatic ecosystems (Mosisch & Arthington, 1998), wake boats present novel risks to lakes. While wake boats bring enjoyment to users, the lake ecosystems where wake boats are used are not sterile or isolated pools. These ecosystems have complex and delicate water quality and habitat conditions. Lakes are also areas of cultural and spiritual importance to many communities. Major issues of concern from wake boats and recreational wakes include elevated risks of spreading aquatic invasive species, accelerating shoreline erosion, damaging aquatic plants (macrophyte) communities, resuspending lake sediment, water column mixing, and disturbing fauna (birds and fish).

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). Since 1971, global entities have spent $345 billion on containing, controlling, and monitoring AIS, with the U.S. spending $166 billion (Cuthbert et al., 2021). The State of Wisconsin spends approximately $4 million yearly on efforts to minimize the effects of AIS on waterbodies (Campbell, 2018). Removing established AIS from a system is nearly impossible without intense trapping, use of chemicals, or extreme modification of aquatic ecosystems (Escobar et al., 2018; Lawson et al., 2015; Lund et al., 2018; Nico & Walsh, 2011). The establishment of AIS in an aquatic ecosystem is often associated with a reduction in overall ecosystem health and increased vulnerability to future AIS invasions (Havel et al., 2015). AIS have disrupted and restructured ecosystems ranging in size from ponds to Lake Michigan (Vander Zanden et al., 1999, 2010). Should AIS effectively establish itself in a waterbody, they can alter lake ecosystem functions, appearances, and ways humans interact with the lake.

Given Wisconsin's location along one of North America's main AIS ports of entry, the Great Lakes, several invasive organisms warrant careful attention (Davidson et al., 2021). Some species of concern to freshwater lakes include zebra, quagga, 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; Martin et al., 2022), rusty crayfish (Olden et al., 2006), various species of carp (Bajer & Sorensen, 2010; Wittmann et al., 2014), microbes (Kelly et al., 2013), and diseases/viruses (Thiel et al., 2021). Each of these AIS has been documented to negatively alter aquatic ecosystems. For example, zebra mussels are responsible for outperforming native mussel communities (Strayer & Malcom, 2007), and overconsuming zooplankton, which can incite algal blooms (Boegehold et al., 2019). Spiny water fleas are large predatory zooplankton that can outcompete native zooplankton and, in some cases, even limit food availability to fish species that consume zooplankton (Walsh et al., 2016; Yan et al., 2002). Eurasian watermilfoil and purple loosestrife outcompete native plants with rapid growth rates, displacing vital habitats to birds, fish, and invertebrates that depend on native flora (Brown et al., 2002; Buchan & Padilla, 1999). In addition to the ecological effects that AIS can cause in waterbodies, there are real societal and economic impacts like losing recreational opportunities (Eiswerth et al., 2000, Halstead et al., 2003), clogging pipes at water treatment and electric power generation facilities (Connelly et al., 2007), and impeding water navigation and industry (Lovell et al., 2006; O'Neill, 1997). The negative ecological effects of AIS are numerous. Therefore, minimizing the risk of new introductions and spread of AIS is a global priority.

The risk of new AIS introductions in Wisconsin lakes is not limited to species that have already invaded the state but those inhabiting a large geographical area (Collas et al., 2021). Motorized boats are often kept and transported on trailers between unconnected waterbodies. Boat owners have been documented traveling long distances to recreate on pristine or popular waterbodies (Buchan & Padilla, 2000; Johnson et al., 2006). Transportation of AIS via boat trailers has been well documented despite significant efforts to minimize this mechanism of spreading AIS (Minchin et al., 2006; Rothlisberger et al., 2010). For example, one study observed that 45% of boaters exiting a lake had aquatic plants (AIS and native) and invertebrates attached to the hull or trailer (Rothlisberger et al., 2010). Wisconsin boaters who moved between unconnected lakes often (more than once every 5 days) were categorized to be at a greater risk of transmitting AIS (Witzling et al., 2016).

Aquatic plant fragments can survive up to three days while completely dry and up to 36 days if constantly damp with minimal access to nutrients (Madsen & Boylen, 1988). Zebra mussels can survive more than three days out of water and even longer if kept moist (Paukstis et al., 1999; Ricciardi et al., 1995). Quagga mussels, on the other hand, can survive up to 27 days (Choi et al., 2013). Infrequent boaters can also transmit AIS because of the longevity of several AIS outside of waterbodies. Rinsing trailers, boat hulls, decks, and equipment with pressurized hot water can dramatically reduce the risk of spreading AIS to the next water body (Comeau et al., 2011; Elwell & Phillips, 2021; Sims & Moore, 1995). Hot water can kill most AIS within 10 seconds of contact with water ≥140°F. In contrast, spiny water flea (*Bythotrephes longimanus*) eggs are much more resilient than most other AIS (Comeau et al., 2011), requiring 10 minutes of exposure to water of ≥122°F to prevent hatchings (Branstrator et al., 2013). While hot water can efficiently prevent AIS from spreading via boats, only 56% of boaters and approximately 80% of trained professionals successfully removed all AIS during a controlled study (Angell, 2023).

Wake boats pose unique risks of spreading AIS because of their capacity to hold large volumes of water within their internal ballast systems (Doll, 2018). Internal ballasts can hold over 6,000 pounds (2,722 kg or 718 gal) of water. Ballasts are emptied and filled with stationary electric pumps. Currently, pumps cannot completely drain internal ballasts, leaving behind an average of 8.37 gallons (31.7L), but in some cases, up to 22.9 gallons (86.8L) (Campbell et al., 2016) (Figure 1*).*

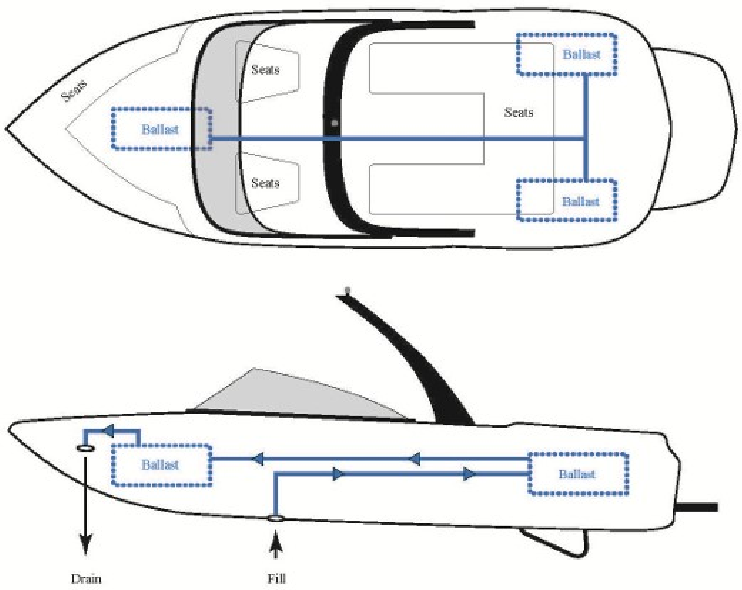

Figure 1. Adapted from Campbell et al. (2016) for general layout of wake boat internal ballasts. This figure is only used as a visual aid to help communicate that the pumps of internal ballasts are generally placed in locations that cannot effectively drain the entire tank. The relative size, number, and placement of ballast tanks will vary depending on the make, model, and owner.

As the volume of water on board boats increases, so does the number of AIS found (Kelly et al., 2013). In addition to holding a large quantity of water internally, placing external ballast bags on the deck is common practice and further increases the amount of water onboard. External ballast bags range between 15–206 gals (56–781 L) of additional water. Zebra mussel veligers (larval stage, 0.002–0.0078 in) and round goby larvae (*Neogobius melanostomus*) have also been found in small outboard motor cooling systems (Bussmann et al., 2022); however, that risk is trivialized by the vast difference in water volume held by wake boats versus small outboard motor systems (De Ventura et al., 2016). Fishing boats with holding wells are also a source of AIS but are easier to rinse with hot water than internal ballast systems (Davis et al., 2016).

Properly sanitizing the internal ballasts of wake boats is essential for reducing spread of AIS. To effectively sanitize internal ballast systems with hot water (≥122°F), repeated flushing is likely required, as large quantities of cold lake water left in the ballast systems will lower the hot water temperature to below effective thresholds. Owner's manuals of wake boats suggest that flushing an unspecified volume of hot water (120°F or 49°C) for a few seconds in their ballast systems is sufficient to prevent spreading AIS. Using a basic thermodynamics equation of heat transfer, the volume of hot water needed to bring the remaining ballast water up to a temperature fatal to all AIS can be calculated:

Eq.1 $$Q_1 +(-Q_2) = 0$$

Eq.2 $$Q_x = m_x{*}c_x{*}\Delta T_x$$

In equations 1 and 2; Q is the amount of heat transferred in joules (J), m represents the mass of the material in grams, c is the specific heat capacity (J/g) of the material, and ΔT is the change in temperature that the material will undergo in degrees Celsius.

We set Equation 1 to zero, assuming that all heat will transfer from the hot water (Q2) to the colder water in the ballast (Q1), achieving the desired equilibrium temperature. The temperature goal is to bring all the ballast water up to 122°F (50°C) to create an environment that is fatal to all known AIS. For this exercise, we assume that the specific heat capacity (c) of water is held constant at 4.18 J/g. We also assume that the ballasts are holding 23 gal (87 L) of water at 68°F (20°C) and that the temperature of the hot water being added to the ballast is known to be 131°F (55°C). Bringing the 23 gal of unpumped ballast water up to 122°F from 68°F would require 138 gals (522 L) of water at 131°F. This exercise also assumes that no heat is lost while hot water is added to the tank and that the tank is a perfectly insulated container. Realistically, more than 138 gals of hot water would be required to create an environment inhospitable to all AIS. Even if wake boat owners follow manual instructions to flush ballasts, it still may not be sufficient to eliminate the risk of transmitting AIS to new waterbodies.

Because of how internal ballasts of wake boats are designed, they present a new and unique risk of spreading AIS compared to traditional motorboats. The large amount of water stored in internal and external ballasts increases the odds that AIS will be onboard and transmitted. This risk is also amplified by the increased complexity of properly decontaminating the large volumes of remaining water inside ballast tanks. If ballasts of wake boats cannot be decontaminated, they are likely violating state laws of transporting AIS. Wisconsin's "invasive species rule," makes it "illegal to possess, transport, transfer or introduce certain invasive species in Wisconsin without a permit," (Wis. Admin Code NR § 40, 2022).

Shoreline Erosion

Shoreline erosion refers to the loss of soil and other material along the shores of a waterbody. Shoreline erosion is associated with increased turbidity from the removed shore material entering the water column and releasing nutrients (Lemieux et al., 2024). There are two major components in shoreline erosion: the composition of the shoreline and the active forces removing material (Alavinia et al., 2019; Allen & Tingle, 1993). Shoreline composition includes characteristics such as the material (e.g., mud, sand), slope, and the amount (or lack) of natural protection from waves (Kobayashi et al., 1987). Active shoreline erosion forces include waves, frost thaw, precipitation runoff, lake level, ice, and wind. Understanding the baseline potential for shoreline erosion is essential when assessing new erosion risks to waterbodies.

Shoreline erosion rates in lakes and reservoirs throughout the Midwest have an average recession rate between 0.35–5.9 ft per year (Eco-Resource Consulting, Inc., 2018; Gatto & Doe, 1996). These high erosion rates are likely driven by past forest clearcutting practices, the removal of lake-fringe wetland ecosystems, the installation of dams, and streamlining hydrology within watersheds (Alverson et al., 1988; Bodensteiner & Gabriel, 2003; Brock & Brock, 2004; Reinartz & Warne, 1993; Steen-Adams et al., 2007). These environmental changes, along with relatively recent shoreline development on Wisconsin lakes, have primed shorelines to be sensitive to any new erosion force.

All motorized boats create wakes and can contribute to eroding lake shorelines, but those that create larger and more powerful wakes have a greater impact (Amin & Davidson-Arnott, 1997; Bauer et al., 2002; Bilkovic et al., 2019; Nanson et al., 1994; Priestas et al., 2015; Reid, 1984). Over a summer of monitoring on an 877-acre Canadian lake, 72% of all total wave energy was attributed to recreational boats; monitoring occurred at approximately 902 ft from a main sailing line and 1,640 ft from allocated wakeboarding areas (Houser et al., 2021). Wake boats can produce recreational wakes that are 5–13 inches taller than wakes from motorized non-wake boats (2–3 times taller) and can generate 9–12 times more power (energy transferred over a distance) at 100 ft (Marr et al., 2022). The total wave power produced by recreational wakes 600 ft away from where the wake was created is equivalent to the wave power produced by a motorized non-wake boat's wake at 200 ft (Marr et al., 2022, p. 90). Ray (2020), Goudey and Associates (2015), and Marr et al. (2022) suggest that recreational wakes need more than 600 ft (180 m) to dissipate. However, no study has yet identified the distance at which a recreational wake ceases to have a measurable influence on nearby shorelines.

Compared to motorized non-wake boats, recreational wakes can transfer more energy to the shore and accelerate shoreline erosion (Goudey & Associates, 2015; Ray, 2020; Ruprecht et al., 2015). Conservative modeling efforts by the boating industry suggest that the influence of wake boats on shorelines is minimal at distances as near as 200 ft (61 m) from shore (Fay et al., 2022). However, these methodologies and analyses have been questioned by several topical experts; see link to: collection of critiques via the Vermont Department of Environmental Conservation. Critiques include serious issues with modeling effort, height of modeled wakes, depth of propellers, and referencing highly uncommon wind speeds to draw comparisons to recreational wakes. Without adequate distance for recreational wakes to dissipate, these effects can result in the loss of ecologically, financially, and culturally important ecosystems.

Shoreline erosion has driven lake managers and residents to pursue methods to minimize shoreline losses. Installing riprap is a common approach to minimize erosion, involving the placement of large rocks or concrete on shores of concern (Gittman et al., 2015; Scyphers et al., 2015). While riprap stabilizes shorelines against erosion, it has environmental consequences and high financial costs. Environmental consequences of hardened shorelines include new habitat for AIS (Roche et al., 2021), loss of overall biodiversity (Brauns et al., 2011), relocating erosion to unhardened areas and near shore lake bottoms (Strayer & Findlay, 2010), and increased nutrient runoff into lakes (Wetzel, 1993). The installation of riprap smothers native riparian and macrophyte habitats by the heavy machinery and the armoring material itself, causing the loss of vital shoreline habitat (Lee et al., 2003; Schoonover et al., 2005; Gabriel & Bodensteiner, 2012; Wensink & Tiegs, 2016). Commonly, after the installation of riprap near the shoreline, habitats are homogenized. Riparian habitat is often converted to non-native grasses and macrophyte beds are lost, resulting in a loss of the overall diversity of plants and the organisms that depend on the habitat (O'Connell et al., 1993; Cole et al., 2020), and what was an efficient filter of nutrients from the watershed (Bornette & Puijalon, 2011; Ostendorp et al., 1995). Reduced nearshore plant habitats have been related to lakes supporting less young-of-year fish and lowered diversity (Quigley & Harper, 2004). Replacing vital native macrophytes and riparian vegetation with riprap can open niches for AIS to invade and establish themselves (Patrick et al., 2014).

While an important ecological issue, shoreline erosion also has economic consequences, such as decreased property values. Decreasing water clarity, an effect of shoreline erosion can decrease properties by nearly $600 per foot of shoreline for every lost meter in clarity in the lake (Krysel et al., 2003). In some instances, the reduction of water quality (clarity, algae, smell) has decreased overall nearshore property values by up to 20% (Nicholls & Crompton, 2018). The loss of shoreline health due to riprap and shoreline erosion can also drive away recreational users from those impacted waterbodies (Landry et al., 2003).

Shoreline erosion varies from lake to lake, but the historical priming that Wisconsin has undergone makes its lake shores more susceptible to new erosion risks, including recreational wakes. The installation of riprap and its negative ecological effects include increased nutrient runoff, increased habitat for AIS, and opening niches for invasive aquatic and terrestrial plants. Lakeshore stabilization efforts are often more successful when native riparian and aquatic plants are restored to act as a buffer from waves and to stabilize lake sediment, even if timelines for projects are longer and require more upfront effort (Eerdt, 1985; Elias & Meyer, 2003; Hartig et al., 2011; Manis et al., 2015; Scyphers et al., 2015).

Aquatic Plants

Aquatic plants (i.e., macrophytes) have several ecological roles. Aquatic plants stabilize lake bottoms and shorelines with their root systems (Madsen et al., 2001), dampen the effects of wind-generated waves (Augustin et al., 2009), oxygenate littoral zones through photosynthesis (Hartman & Brown, 1967), uptake and sequester nutrients (Chen & Barko, 1988), promote decomposition of organic matter (Brix, 1994), and keep the water column cool with shading effects (Carpenter & Lodge, 1986). Aquatic plant beds are also nurseries for most fish species, the home of smaller fish species, and the primary habitat for aquatic invertebrates (Randall et al., 1996; Schultz & Dibble, 2012).

While aquatic plants can help stabilize lake bottoms and reduce shoreline erosion, they have structural limits. Aquatic plants are susceptible to being run over, cut, or uprooted by boats, which can hinder their growth and survival (Asplund & Cook, 1999; Liddle & Scorgie, 1980; Sagerman et al., 2020). Several species of aquatic plants native to Wisconsin have high light requirements, such as chara (*Chara vulgaris*) and Manoomin (wild rice, *Zizania palustris*) (David, 2018; Santamaría, 2002). Long term sediment resuspension or shoreline erosion can negatively affect such light-sensitive species. Areas with constant boat traffic resuspending sediment or damaging aquatic plants can create bare sediment patches on lake bottoms, commonly referred to as "propeller scars" (Burfeind & Stunz, 2006; Dawes et al., 1997).

Wake boats present elevated levels of disturbance to aquatic plants from the recreational wakes, depth of propellers, and turbulence generated (Zhang et al., 2017; Sagerman et al., 2020). Recreational wakes are several times more powerful than other motorized boats, and those wake effects are felt at extended distances (>600 ft), either physically damaging aquatic plants or limiting the amount of light they receive (Asplund & Cook, 1997). Wake boats have deep hulls whose propellers can be as deep as 3 ft (0.9 m) when creating recreational wakes, doubling the depths of most motors used in freshwater systems. This deeper propeller and greater turbulence can cut and uproot aquatic plants if wake boat operators are not carefully monitoring their speeds and water depth. The relatively steep bow angle (15°) while creating recreational wakes directs propeller turbulence more toward lake sediments and plant roots. Non-wake boats generally operate with their bow parallel to the water's surface, minimizing the effect of their prop and turbulence on the lake bottom. Lakes without aquatic plants are more likely to be algae-dominant systems (i.e., eutrophic) (Canfield Jr. et al., 1984; Le Bagousse-Pinguet et al., 2012).

Aquatic plants are also important to Indigenous communities, specifically the Ojibwe people with Manoomin (Barton, 2018). Manoomin is highly valued within Ojibwe culture as a high-calorie and nutrient-dense food source, an essential source of income, and central to Ojibwe origin stories. Manoomin has relatively shallow root systems and is submerged underwater in its early life stages, making it difficult to spot while boating. When driven over, Manoomin is especially susceptible to being damaged or uprooted (Preiner & Williams, 2018). Manoomin is one of several species sensitive to water clarity (David, 2018), which could be affected by shoreline erosion or sediment resuspension.

As integral components of aquatic ecosystems and cultures, the value of aquatic plants plays a crucial role in fisheries. Fisheries science has identified that aquatic plants are essential in recruiting and sustaining fish populations (Jeppesen et al., 1997; Perrow et al., 1999;

Radomski et al., 2019). The relationship between aquatic plant communities and fisheries is so strong that altering aquatic plant communities can directly affect fish growth rates (Olson et al., 1998; Wiley et al., 1984). Increased diversity of aquatic plants also leads to greater species richness of fishes (Slagle & Allen, 2018). Studies have shown that decreases in aquatic plants in lakes can lead to negative cascading effects, ultimately causing decreases in fisheries (Hansen et al., 2019; Hawkins et al.,1983) and potential for ecosystem instability (Mrnak et al., 2023). Minimizing the loss of overall aquatic plant populations and native species has important implications for more stable and diverse fisheries.

Motorized boats have also introduced contaminants into the waterbodies and consequently into a vital food source for local and Indigenous communities. These contaminants include hydrocarbons, metals, antifreeze, acids, and solvents. Emerging worries surround the potential harm posed by chemicals, which may be absorbed by aquatic plants or fish and consequently ingested by humans (Amoatey & Baawain, 2019; Bennett et al., 2000; Brungs et al., 1978). Boat manufacturers recommend winterizing wake boat ballasts with antifreeze to prevent damage to tanks and pumps during long-term cold storage. With current internal ballasts that do not fully drain, residual antifreeze will likely enter lakes after the first use after winterization. Allowing antifreeze to enter a waterbody is illegal under federal and state laws, even if the antifreeze is labeled as "environmentally friendly" (Clean Water Act, 1977; Hunt et al., 1996; LaKind et al., 1999; US EPA, 2023; Wis. Admin Code NR § 661 Appendix VIII, 2020).

Deep propellers, intense turbulence created by powerful motors, and recreational wakes causing erosion all contribute to wake boats likely having a more profound effect on aquatic plant communities than other motorized watercraft. While focused research has not quantified the differences in effects between wake boats and motorized non-wake boats on aquatic plants and their cascading consequences, wake boats are likely to cause more damage to these delicate organisms.

Sediment Resuspension and Water Column Mixing

Sediments on the bottom of lakes accumulate over centuries and store large quantities of nutrients (generally nitrogen and phosphorus) from the watershed (Macintosh et al., 2018). This report focuses mainly on phosphorus (P), which is usually considered the limiting factor for algal growth in lakes (Schindler, 1977). Fertilizers used within watersheds collect in lake sediments, increasing the already large and old pool of nutrients (Arbuckle & Downing, 2001; Mayer et al., 2006; North et al., 2015). These nutrients remain unavailable on the lake bottom to most primary producers, such as algae and plants (Forsberg, 1989). There are a few exceptions when the surface waters have access to the nutrient storage of the bottom waters: during lake destratification (i.e., turnover) in the spring or fall, if thermoclines are weakened, or if sediments are disturbed (Bengtsson & Hellström, 1992; Orihel et al., 2015; Orihel et al., 2017).

When lakes are stratified (warm top layer, cold bottom layer) (Figure 2), the layers essentially become separate resource pools separated by a thermocline (layer of water with the greatest change in temperature and density) (Sommer et al., 2012).

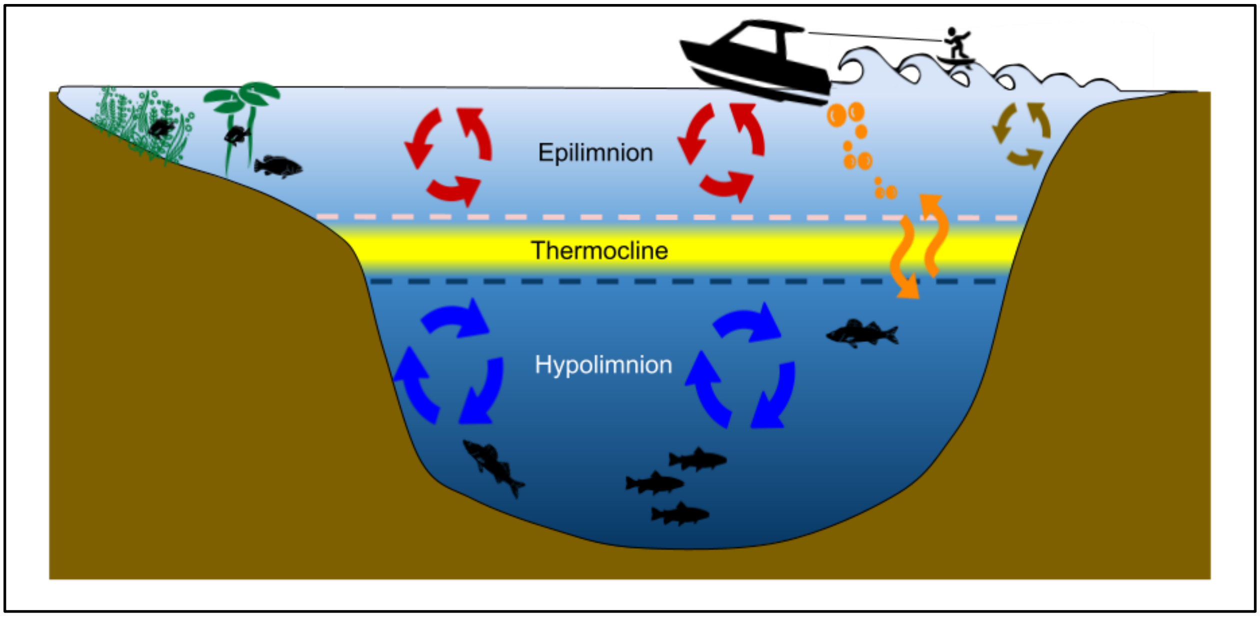

Figure 2. Illustrated cross-section of a stratified lake showing potential effects of recreational wakes. The yellow gradient represents the thermocline, which prevents the epilimnion and hypolimnion from mixing. The orange icons represent turbulence and destabilization of the thermocline. The brown cycling arrow represents sediment resuspension and erosion.

Thermocline stability varies throughout the year and is generally weakest during early spring and late fall. The thermocline varies in depth for different lake sizes, shapes, and latitudes (Boehrer & Schultze, 2008). However, lakes with a shallower or weaker thermocline are more susceptible to mixing events and sediment disturbance. Lake stratification creates a difference in P and oxygen concentrations; the epilimnion (top layer) is generally P-poor and oxygen-rich, while the hypolimnion (bottom layer) is P-rich and oxygen-poor. As P enters the well-oxygenated portion of a lake, some proportion is quickly taken up by primary producers (Currie & Kalff, 1984; Istvànovics et al., 1994; Schindler & Fee, 1974). In most lakes, the P 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 unavailable and will eventually sink to the bottom of the lake. Additionally, P can accumulate in the sediment when organic matter from phytoplankton, aquatic plants, and fish settle to the bottom (Yu et al., 2022). Under hypoxic (low oxygen) conditions in the hypolimnion, P can dissociate from the element and become biologically available again (Albright et al., 2022, Koski-Vähälä & Hartikainen, 2001). Concentrations of P in the hypolimnion can become high as uptake rates are low under low light and cold temperatures.

Regular conditions can cause some P-rich hypolimnetic waters to be mixed with the epilimnion, such as the lake turning over, weakening of the thermocline, or sediment disturbances (Dunn, et al., 2017, Gautreau et al., 2020). Wisconsin lakes generally have thermoclines about 8–9 ft from the surface and are dimictic (lakes where water columns only mix in the fall and spring) (Lewis, 1983). Lakes less than 16 ft (5 m) in maximum depth are likely polymictic, meaning they mix several times throughout the year (Padisák & Reynolds, 2003). These mixing events can be a large portion of a lake's primary producers' P requirements

(Hanson et al., 2020). If lakes have a shallow or weak thermocline, a prolonged disturbance (strong winds or boats) can cause mixing and entrain hypolimnionic water and biologically available P (Bennett et al., 1999; Roberts et al., 2019). This movement of nutrient-rich bottom water to the epilimnion can incite algae blooms in lakes (Orihel et al., 2015).

Motorboats have generally increased sediment disturbance and resuspension in lakes, streams, and rivers (Nedohin & Elefsiniotis, 1997). Efforts to limit sediment disturbance and shoreline erosion are the primary reasons for no-wake zones in shallow areas near shores. Beachler & Hill (2003) suggest that motorized non-wake boat turbulence from propellers is minimal and only influences the very top layers of sediment, but the majority of P is found in the top centimeter (0.39 in) of sediment (Doig et al., 2017). The minimal sediment resuspension by motorized non-wake boats used in Doig et al. (2017) likely had relatively shallow propeller angles. When disturbed, fine silt particles found in lake sediment can take days to settle back to the bottom of the lake, reducing water clarity for extended periods (Douglas et al., 2003; Yousef et al., 1980).

Early studies on boat effects on lakes found that the mixing depth of boats was linearly related to motor horsepower (hp) (Yousef, 1974) and dependent on sediment material composition (Yousef et al., 1980). Yousef (1974) reported that a 100 hp motor was able to mix the top 10 ft (3 m) of water of a 62-acre lake within 20 minutes. Yousef (1974) also provides evidence that a 50 hp motor could resuspend sediment 15 ft (4.5 m) below the surface. The material composition of the lake bottom determined resilience to resuspension; sandy bottoms were more resistant than those made of organic matter (i.e., muck). In 1974, there were no common power boats with horsepower capabilities comparable to today's powerful watercraft. The linear relationship between horsepower and depth presented by Yousef (1974) suggests that mixing depths have only increased with greater horsepower capabilities seen in modern wake boats.

Compared to motorized non-wake boats, wake boats had the largest disturbance of sediment and release of nutrients after driving past sampling locations once (Daeger et al., 2022). Unfortunately, Daeger et al. (2022) did not include trials of wake boats with wake wedges or wake shapers to quantify a more robust estimate of mixing depth and concluded that wake boats could not disturb sediment when in water deeper than 10 ft (3 m). Terra Vigilis Environmental Services Group (2022) provides evidence to support that wake boats creating recreational wakes were found to disturb water 20 ft (6 m) below the surface. This evidence supports the increased potential of wake boats to reduce water clarity and quality by resuspending P-rich sediment and weakening the thermocline.

Sediment resuspension caused by boating can be more pronounced if intense boating occurs in a small area (Abu Hanipah & Guo, 2019; Alexander & Wigart, 2013; Sagerman et al., 2020). This effect is likely to also apply when nearby boats create a deeper cumulative mixing depth, extending their influence to the thermocline depths of larger lakes. Wake boat owner manuals and websites discourage repeated use of small areas to limit adverse effects. However, studies have yet to focus on measuring the distances in proximity or areas at which cumulative effects occur. Without published area requirements for wakesurfing or wakeboarding, we turn to the related sport of waterskiing to understand spatial needs. The Maryland Department of Natural Resources (2020) recommends that water skiing should occur in an area of at least 14 acres. Baud-Bovy and Lawson (1977) recommend that the area be 25 acres. Based on the area recommendations for waterskiing, a reasonable starting range for allocating space for each wake boat creating recreational wakes is 14–25 acres. If we assume that wake boat recreation requires a similar area (it has not yet been quantified in the literature), this area would also need to be at least 20 feet deep and the entire activity would need to occur at least 600 feet from shore to minimize wave impacts and water column mixing.

Wake boats and their enhanced ability to resuspend sediment and weaken thermoclines compared to motorized non-wake boats raise serious ecological concerns. Mixing depths of wakesurfing are estimated to be as deep as 20 ft. At this depth, thermoclines (especially during early spring or late fall) and sediments will likely be disturbed at locations far from shore. Not all wake boats or equipment have the same ability to create recreational wakes (Ruprecht et al., 2015); the same is likely true for their mixing depth. Deep water mixing is more concerning than sediment resuspension in shallow areas because the increased turbidity is visually apparent and a signal to relocate the boat. When mixing occurs in deeper areas, leading to sediment resuspension or the influx of P-rich water into the epilimnion, the resulting consequences, such as algae growth, will require time to become apparent. These adverse effects are likely enhanced when wake boats create recreational wakes near each other, but the distance or area specifically for wake boats is currently unknown.

Birds and Fish

The presence and behavior of humans in nature can disturb nearby wildlife (Bird, 2015; Inkpen, 2017). Over the past one hundred and fifty years, our disturbances have increased as combustion engines have become more central to our daily lives. While humans have embraced this new trajectory, aquatic organisms have not been as quick to adapt to the new soundscape and effects from combustion motors.

Motorized boats can disturb birds from distances up to 778 ft (237 m), but on average, this distance is closer to 197–262 ft (60–80 m) (Burger, 1998; Mayer et al., 2019; Ortega, 2012; Rodgers & Smith, 1997). Several factors influence the distance at which birds are flushed, including the boat size, speed, noise, bird species, and seasonal behaviors (such as breeding or chick rearing) (Rodgers & Smith, 1997). Noise levels of boats sold and operated in Wisconsin are not to exceed 86 decibels (Wis. Stat. § 30.62(2)(b), 1987). Although wake boat manufacturers typically target noise levels below 86 decibels while idle or cruising, these noise requirements are met while the engines operate at only a fraction of their capacity. When creating recreational wakes, wake boat motors have to move full ballasts (combined weight of >13,000 lbs.) with a high bow angle (~15 degrees above the water). Under usual recreational wake-creating conditions, wake boats are likely exceeding the noise limitations in Wisconsin with motor revolutions per minute (RPM) near 4000 RPM. Wake boats, being larger and louder than most other boats on lakes, are likely to disturb birds over long distances. (See link to: detailed noise levels by boat makes and models via Boating Magazine.)

Human disturbance of common loons (*Gavia immer*) has been a primary focus of study in Wisconsin. The common loon has been described as an apex predator and an indicator species, living up to 30 years (McIntyre, 1994; Strong, 1990). Common loons are territorial and prey on many organisms, from crayfish to small walleye. Because of their high position in the food web, loons reflect the health of lake ecosystems over their long lifespans. Loons face several environmental risks aside from effects of wake boats; these risks include accumulation of mercury in their bodies (Mitro et al., 2008; Scheuhammer et al., 2016), lead poisoning (Michael, 2006; Pokras, 1992), lake acidification (McNicol, 2002), warming climates (Piper et al., 2024), and fluctuating water levels (Desorbo et al., 2007; Fair & Poirier, 1993). If loons can overcome these obstacles, they generally become sexually mature between four to six years of age. Loons have been found to successfully reproduce when nests are on shorelines of lakes larger than 25 acres and more likely to nest on lakes with minimal development (Piper et al. 2012). Successful loon nests are generally found within one foot (~ 0.3 m) of the water's edge and on small islands (Bianchini et al., 2020; Heimberger et al., 1983; Kelly, 1992; Lindsay et al., 2002; Spilman et al., 2014; Tischler, 2011). Loons also tend to create nests on shores close to the direction of the dominant wind to minimize fetch effects on nests (Kelly, 1992). Loons are selective with nest location relative to the lake because they struggle to walk on land.

Approaching boats can disrupt nesting loons (Kelly, 1992). Any boat producing wakes close enough to shore can scare loons off their nests, flood them, or erode prime nesting locations. These disturbances can increase the time that incubating loons are away from nests or chicks and increase the chances of a clutch being abandoned (McIntyre & Olson, 1998), increasing predation risks (Cooley et al., 2019; McCarthy & DeStefano, 2011), and increasing the caloric need for adults (Kahl, 1993). If elevated noise or recreational wakes from wake boats flush adult birds enough times, it can force them to spend almost twice the amount of time foraging for food away from nests or chicks (Rodger & Smith, 1997). These nests are especially vulnerable to tall and powerful recreational wakes across long distances. When loon nests are flooded, the nest structure and potentially any eggs or chicks are damaged or injured. After approximately 30 days of incubating, mostly ending in late July (W. Piper, personal communication, March 8, 2024), loon chicks hatch and spend the following eight weeks within 490 ft of shore in lake areas that are less than 10 ft in depth (Barr, 1996; Desorbo et al., 2007; Jung, 1991). Until young loons achieve independence, they remain vulnerable to recreational wakes, predation (especially if nearby adults flush), and direct strikes from boats (Bianchini et al., 2020). These negative effects are not exclusive to the common loon but are likely to affect several birds that spend time in shallow areas and nest near shorelines (Bowles, 1995).

Fish have been impacted by motorized boats through turbulence, physical collisions, noise disturbances, and introductions of AIS. Turbulence from boats has negatively affected fish eggs, young fish, and benthic invertebrates (Bozek et al., 2011; Gabel et al., 2011; Hawkins et al., 1983; Neuswanger et al., 2015; Zajicek & Wolter, 2019). Boat-generated turbulence and wakes can move eggs away from bedding areas like during storms (Raabe & Bozek, 2015; Wolter & Arlinghaus, 2003). Wakes can also move smaller and young fish away from their desired habitat, exposing them to a higher predation risk (Becker et al., 2013). Turbulence from recreational wakes can also increase the risk of egg predation by displacing or limiting a fish's ability to guard its nest (Mueller, 1980).

Turbulence can move benthic invertebrates from their habitat, potentially changing resource availability for fish (Gabel et al., 2011). Boats have an increased risk of disturbing flora and fauna while navigating shallow waters (Heinrich et al., 2012; Lima et al., 2015). As previously described, the loss of aquatic plants can result in a feedback loop with declining water clarity and sediment resuspension. Reduction in water clarity has been shown to limit fishes' ability to hunt using their vision, such as walleye (*Sander vitreus*) and other species (Nieman et al., 2018; Nieman & Gray, 2019). Recreational wakes from wake boats, if not operated at least 600 ft from shorelines, may be an unaccounted factor contributing to the reduced future sustainability of fisheries across Wisconsin as described by Hansen et al. (2017) and Rypel et al. (2018).

Studies focusing on noise generated by boat motors found that this noise can hinder fish communication, cause physical damage to their internal ears, and increase stress (Popper & Hastings, 2009; Slabbekoorn et al., 2010). Fish are more sensitive to combustion boat motor noise than canoe or electric motor noises. Fish were found to have increased stress hormone (cortisol) concentrations in their bodies up to 40 minutes after exposure to the noise generated from a 9.9 hp combustion motor for only 60 seconds (Graham & Cooke (2008). The effect of motor noise was demonstrated in an observational study in a lake, showing that boating had a larger effect on smaller fish species (Jacobsen et al., 2014). There were lasting adverse effects on poor-conditioned fish if constantly exposed to boat engine noise, such as reducing swim distances and increasing predation (Harding et al., 2020).

In addition to noise stress, boat motors can muffle sounds from fish that vocalize. Freshwater species that communicate with sound include freshwater drum, catfish, perch, and some minnows (Bass & Chagnaud, 2012; Codarin et al., 2009; Pieniazek et al., 2020). Their communication strategies have been observed to be changed by anthropogenic noises, mainly by boat motors. This includes shifting when they vocalize to times during the day when loud noises occur less frequently and resorting to visual cues (Radford et al., 2014). In addition to fish altering their communications due to boating, there is evidence that species with sensitive internal ears can experience hearing loss (Popper & Hastings, 2009). The unnoticed consequences of loud motor noise on fisheries (Venohr et al., 2018) can be minimized by increasing the distance from shorelines and depths at which boats operate, but wake boats likely need to be further away.

In addition to the negative effects of turbulence and noise on fisheries, the introduction of AIS by wake boats can have negative implications for fish communities in lakes. For example, rusty crayfish (*Orconectes rusticus*) can consume aquatic plant communities, benthic invertebrates, and fish eggs (Hein et al., 2007). The disturbance caused to nearshore habitats and benthic invertebrates has adverse effects on lower trophic fish species, which rely more heavily on aquatic plants for shelter and their primary food resource. As another example, rainbow smelt (*Osmerus mordax*), an invasive fish, has negative effects on native fish populations such as yellow perch (*Perca flavescens*) and cisco (*Coregonus artedi*) (Lawson & Carpenter, 2014). In addition to these visible AIS threats, a highly contagious waterborne virus, viral hemorrhagic septicemia virus (VHSV), has been detected in a wide range of freshwater fish species at all trophic levels and has a high mortality rate (Bain et al., 2010). AIS disruption of fish communities has larger implications for disrupting the entire food web structure and how people recreate on lakes.

Community Strategies for Mitigating Effects of Wake Boats on Lakes

Wisconsin communities are not alone in experiencing the effects of wake boats on lake ecosystems. Communities around the US and abroad have struggled to balance recreational activities with ecosystem protection and protecting delicate ecosystems. This list includes examples from communities who have created stricter boating regulations in an attempt to minimize the adverse effects of wake boats on their lakes.

- **Mequon and Thiensville, Wisconsin:** Banned wake-enhancing equipment; this ordinance applies to two waterbodies and a section of the Milwaukee River (ordinance).
- **Rhine, Wisconsin:** Banned the use of ballasts or wake-enhancing equipment on Crystal and Elkhart Lakes (ordinance).
- **Sawyer County, Wisconsin:** (Town of Hayward, Bass Lake, and Round Lake townships): Prohibit large recreational wakes from being created within 700 feet from shore or dock; combined, these ordinances apply to over 28 waterbodies.

- **Lake Minnetonka, Minnesota:** Adopted a 300 ft no-wake zone from shore (ordinance).
- **Lake Tahoe, California and Nevada:** 600 ft no-wake zone from shore, a 100 ft no-wake zone near swimmers and paddlers, and a 200 ft no-wake from structures. Lake Tahoe also has required boat and internal ballast inspections for AIS. If needed, boaters are responsible for the cost of decontamination. To help their boaters abide by their no-wake laws, they provide online maps and apps for inspection stations and authorized decontamination providers (ordinances).
- **Lake Sunapee, New Hampshire:** No-wake zones up to 500 ft and 700 ft from shore within town boundaries (ordinances).
- **Montana:** Instituted AIS inspection points with free decontamination (AIS laws), lakes with 200–500 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 (wake regulations).
- **South Carolina:** No wakeboarding or wakesurfing within 200 ft from shore (regulations).
- **Tennessee:** No wakeboarding or wakesurfing within 200 ft from shore (regulations).
- **Vermont:** Wakeboating is restricted to defined "wakesport zones" with a "Home Lake Rule" to limit spread of AIS (Wakeboat Rule).

- **Victoria, Australia:** Instituted a 5 knots (7 mph) limit within 50 m (164 ft) of any shore, fixed, or floating structure for all boats and lakes (ordinances).

Conclusions

These conclusions stem from an analysis of the latest peer-reviewed scientific literature, published reports, and personal communications with topical experts in relation to the ecological effects of boating, water skiing, and wake boats. However, it is important to note that there is a sizable gap in our understanding of the full implications of wake boats on lake ecosystems. We intend for these conclusions to be applied together, not taken separately.

1. Wake boating activities creating recreational wakes should be done **only in areas that meet the following criteria:**
    a. At least 20 feet deep (Yousef, 1974; Terra Vigilis Environmental Services Group, 2022). If there is no bathymetry data to assess if a lake meets the depth requirements accurately, then creating recreational wakes should not be allowed.
    b. At least 600 feet from any shoreline, including shorelines of islands (Marr et al., 2022).
2. To limit the spread of aquatic invasive species (AIS) by wake boats (Branstrator et al., 2013; Comeau et al., 2011; Elwell & Phillips, 2021):
    a. Exterior boat surfaces need to be sanitized with hot water (≥140°F) before accessing other lakes.
    b. Internal ballasts should be sanitized by bringing internal temperatures up to at least 122°F.
    c. Inspections for AIS and aquatic plants must include internal and external ballast tanks.
3. Consider restricting the timing of wake boat access to lakes until after fish spawning and common loon reproduction (i.e., late July) (Bozek et al. 2011; Neuswanger et al., 2015; Piper et al., 2012; W. Piper, personal communication, March 8, 2024).
4. Create and require online training for wake boat users about proper use and risks involved with wake boating as well as environment impacts (Kinsley et al., 2022; Seekamp et al., 2016).
5. Informational signs and documents about the environmental risks of wake boating should be available at boat launches and dealerships.
6. Encourage lake users to document and report inappropriate behavior by wake boat operators to the Wisconsin Department of Natural Resources and conservation wardens, and potentially create a specific hotline for volunteers to document incidences of wake-zone violations.

Data Gaps and Research Recommendations:

Researchers, policymakers, and lake users are just beginning to understand the effects of wake boats on Wisconsin lakes. Scientific research focused on wake boats is scarce and significant knowledge gaps exist. Accordingly, this literature review often references information from studies focused on less powerful watercraft. Thus, we attempted to use our best professional judgment when extrapolating these findings to wake boats.

To achieve a more comprehensive understanding of the effects of wake boats on lake ecosystems, we recommend empirical studies on the following topics:

- Visual limitations while creating recreational wakes;
- Safe distance requirements between wake boats and other lake users;
- Minimum distance from shore for recreational wakes to have an undetectable effect on shoreline erosion;
- Average lake area that each wake boat uses while wakeboarding or wakesurfing, so that proper space requirements and allocations can be made per boat;
- Water mixing depth from wakesurfing and wakeboarding and disturbance to thermoclines and lake bottoms;
- Cumulative mixing and wake effects from wake boats operating near each other;
- Effects of recreational wakes on lake biota (plants, birds, fish, mammals, reptiles, invertebrates, etc.);
- Noise from wake boats during actual use conditions (filled ballast, people in the boat, towing, creating recreational wakes, etc.);
- Effectiveness of AIS hot water sanitization protocol of internal ballasts;
- Effectiveness of filters specifically designed for internal ballasts;
- Effectiveness of antifreeze flushing protocols to stop antifreeze from entering lakes;
- Potential unique issues from wake boat use in rivers.

In addition to initial research on these topics (which do not represent an exhaustive list), studies must be repeated regularly. This element of ongoing research is critical for understanding patterns in effects over time, and to keep scientific understanding of the ecological impacts concurrent with ongoing design changes of wake boats (i.e., size, weight, speed, and ability to create wakes).

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