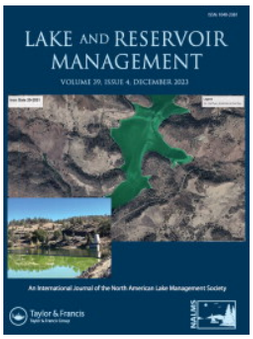

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A comparison of boat cleaning systems: invasive species removal, boater outreach and engagement, and cost

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ABSTRACT

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The movement of recreational boats is an overland transport pathway that places lakes at risk of invasion by aquatic invasive species. Lake organizations, governments, and conservation organizations may choose to install boat cleaning systems that use heated water, pressurized water, hand tools, vacuums, or a combination, to kill or remove attached organisms. Here we present a comparison of these various cleaning systems in terms of decontamination effectiveness, outreach effectiveness, and cost. We reviewed published literature and interviewed 12 invasive species experts representing 7 boat cleaning programs located in Michigan (each program owns 1 to 5 boat cleaning systems, for a total of 15). Our analysis indicates that there is no single best boat cleaning system. Selection of the most effective system for a particular situation should be guided by local invasion risk, management goals, and location and budget constraints of that situation.

KEYWORDS

Boat access site; decontamination; invasive species; Michigan; outreach

Many aquatic invasive species (AIS) initially arrive in North America via transatlantic shipping (Tucker et al. 2017), then spreading to inland lakes and streams when transported by recreational boaters who visit multiple waterbodies. Recreational boats are a significant pathway for AIS to access inland freshwater; AIS establishment is predicted by proximity to boat access site ramps (Tucker et al. 2017, Rodríguez-Rey et al., 2021). AIS can survive overland transport in residual water in the bilge, ballast, engine system, or live wells of boats, or can be transported on the hull or tangled on the trailer or propeller (Johnson et al. 2001, Rothlisberger et al. 2010). AIS may also be introduced through transport on fishing or boating gear (Connelly et al. 2014).

Five of the top 10 US states in number of watercraft registrations are located in the Great Lakes region, as are 33% of the total recreational watercraft registrations in the country (Tucker et al. 2017). Over the past several decades the Great Lakes region has been a test site for policy and management related to AIS (Rothlisberger et al. 2010). Located in the heart of the Great Lakes region, and with approximately 11,000 inland lakes and reservoirs over 2.02 ha (5 acres) in surface area, the state of Michigan is heavily impacted by the spread of AIS by recreational boaters (Tucker et al. 2017).

Eradication of established AIS is often not feasible; success rates are low, control measures are expensive, and the process must be repeated for each new invasion event. These high costs support prevention as the most effective form of control (Ruiz and Carlton 2003, Lovell et al. 2006). Invasive species pathway management provided by boat cleaning systems or cleaning stations targets many species at once. Therefore, resource managers in Michigan encourage boaters to engage in preventative behaviors by providing outreach and access to boat cleaning equipment. Boater surveys indicate that many boaters intend to clean their boats, but lack of equipment is a significant barrier, while easily available equipment

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may be a strong motivator, especially for boaters who are also anglers (Prinbeck et al. 2011, Seekamp et al. 2016, Donnelly 2018, Campbell et al. 2020, Joffe-Nelson et al. 2022).

We describe 2 main approaches to boat cleaning (Fig. 1). Waterless systems typically include some combination of grabber tools, plug wrenches, a vacuum, or a high-pressure air wand. These tools allow the user to remove visible AIS, drain any accumulated water, and dry the boat. Waterless systems are relatively new and have to date been the focus of few studies. On the other hand, water-based systems are an established method of boat cleaning and are sometimes referred to as "boat washes." Boat washes use water spray to remove AIS from the boat and may use heated water to kill AIS. Hot water treatments have been the focus of several studies and are often referred to as the best current technology for boat decontamination (Zook and Phillips 2012, Otts and Nanjappa 2016). Chemical decontamination, hot water immersion, and steam treatment fall outside the purview of this study as they are not applicable to, or practical for, rapid decontamination of recreational boats at boat access sites (Beyer et al. 2011, Crane et al. 2019, De Stasio et al. 2019).

In this article, we present information to assist resource managers in determining which type of boat cleaning system will best serve their needs. We compare waterless systems and water-based systems (which may be heated, pressurized, or both) in terms of decontamination effectiveness, boater outreach and engagement effectiveness, and cost. We include results from a review of published literature and interviews with 12 professionals who have experience installing or operating a boat cleaning system. We compile cost information and community usage of Michigan boat cleaning programs that manage at least one boat cleaning system. We conclude with recommendations on factors to consider when selecting a boat cleaning station for a particular situation.

Methods

We used the snowball method as described by Wohlin (2014) as a basis for our systematic literature study and review, relying on 3 search tools: Web of Science, Google Scholar, and Citation Gecko. We compiled the starting set of 3 pieces of peer-reviewed published literature and 10 white papers and internal reports using our keywords (below) and including literature from multiple journals, universities, and state and federal agencies. Unlike Wohlin (2014), we did not examine the complete list of referenced papers, but instead identified in-text citations that supported important relevant information, which we then compiled into an abbreviated list of referenced papers. We first examined candidate papers' titles for our keywords ("decontaminat*"; "clean"; "invasive

Figure 1. (A) A boater uses the vacuum tool of a waterless cleaning system (Credit: CD3 Systems). (B) A student uses the Michigan State University Mobile Boat Wash cleaning system, a high-pressure, hot water system. (Credit: J. Latimore).

species"; "recreation"; "boat access site"), for the relevance of the publication venue, and for status of the authors in the AIS management field, based on our combined professional experience in the field. If the candidate had not yet been excluded, we read the abstract, using the same methods to continue excluding candidates, and then the full paper. At the point where no new papers were found in the iterations of backward and forward snowballing, our review was completed. This yielded 37 peer-reviewed publications and 21 white papers ranging from 1994 to 2022, where 79.3% (46) were located in the United States, 12.1% (7) in the United Kingdom, 3.4% (2) in Canada, and 5.2% (3) in other countries. Of the 18 studies that empirically tested efficacy of cleaning systems, 6 reviewed only water-based systems, 10 reviewed only waterless systems, and 2 reviewed both. We also reviewed boater survey data we collected through our Michigan State University (MSU) Mobile Boat Wash outreach and education program at outreach events at 50 Michigan waterbodies from 2017 to 2019.

We compiled a list of 13 professionals with experience managing the recreational pathway of AIS in the Great Lakes states (Table 1), and 2 additional names were suggested by interviewees. All interviewees hold a professional role in managing AIS in their communities. Twelve of the interviewees scheduled an interview, all of which were conducted in the summer of 2020. We designed 2 questionnaires of open-response questions. Nine of the interviewees had purchased, installed, and/or managed at least one boat cleaning system, and they received a questionnaire that consisted of 22 questions. They represent a total of 7 boat cleaning programs that consist of 6 waterless and 9 water-based boat cleaning systems. Only 3 professionals had not purchased, installed, and/or managed a boat cleaning station, and they received a separate questionnaire of 9 open-response questions. Both questionnaires are available in the Supplement (Table S1 and Table S2). We interviewed 6 by phone and 4 by video-conference, while 2 responded to the questionnaire by email. We informally analyzed the notes taken during interviews for common opinions, experiences, and beliefs. We include in this article the expert responses that directly relate to our cited literature and the responses that provide anecdotal information that may help maximize the effectiveness of a cleaning system.

Table 1. Affiliations of 12 total interviewees.

Affiliation	Number of interviewees
Lake association governance member	3
DNR (state Department of Natural Resources)	1
Private AIS management	1
Federally recognized tribes	3
Government AIS manager	1
University outreach	3

Results and discussion

Decontamination effectiveness

Decontamination refers to the removal or destruction of AIS that are on or in a boat, trailer, or gear. Some groups reserve the word "decontamination" for a mandatory boat-cleaning check station with trained staff and use the word "cleaning" to describe the approach of a typical boater. In this article, we use the terms interchangeably to refer to any attempt to remove or destroy AIS. Approaches can include rinsing the hull with water, removing organisms with hands, brushes, or grabber tools, or flushing the engine with hot water. Boat cleaning systems may make the process of decontamination easier to perform and possibly more effective but are not necessary. A 3-step decontamination process is promoted by AIS control programs with the slogan "Clean, Drain, Dry": Clean the boat surface and trailer of any aquatic plants or animals, drain any accumulated water, and dry the boat before launching in a new waterbody.

Mohit et al. (2021) reviewed 37 published papers to assess current decontamination treatments used by water recreationists for effectiveness. They noted that complete removal or destruction of all AIS is difficult to achieve. We summarize their conclusions here and add 7 additional studies about decontamination from our own literature review.

Water-based cleaning systems

Heated water: Hot water treatments at boat access sites are applied with either a spray gun or hose connected to a heated water tank. Boaters can rinse the hull and boat trailer and may choose to flush the engine or ballast tanks with hot water,

although temperatures above 54 C may damage ballast tank pumps and bladders when present (Zook and Phillips 2012). The literature indicates that for hot water spray, temperatures ≥ 55 C for 1 to 10 s are required to yield 90% mortality of most plants and invertebrates (Mohit et al. 2021). To kill AIS on contact, water must be heated significantly above the target temperature, since pressurized water used at 30 cm distance or farther can cool by about 20 C (Bradbeer et al. 2021).

Mohit et al. (2021) reviewed 12 hot water treatment studies and found that all methods reported significantly higher mortality than the control for invertebrates and some plants. Pressurized hot water is more practical than hot water immersion for watercraft, but there are obstacles. First, water spray does not directly contact the places where many AIS can settle (Morse 2009). Comeau et al. (2011) noted that temperature and contact time found to cause 100% AIS mortality only apply to the hull, while longer contact times would likely be necessary for the motor and ballast tanks due to conduction across metal and other materials. Second, the necessary amount of contact time is an obstacle. The temperature and contact time required to achieve 95% mortality range from 50 to 80 C and from 1 to 10 s (Mohit et al. 2021). Bradbeer et al. (2021) noted that 15 s spray applications with a focal point of 10 cm^2 would require a total of 25 min to apply treatment to a 1 m^2 area of a boat hull. To treat the hull of an average 4.07 m boat at this speed, excluding interior areas, with a height and width of 1.62 and 0.61 m, we estimate 139 min are needed. We estimate a treatment of 1 s per 10 cm^2 would last 9.3 min, but only the 2 studies described above investigate the efficacy of this contact time, and the treatments used ≥80 C water (Morse 2009, Comeau et al. 2011). Despite the challenges, 3 experts and one paper report that hot water spray is recommended by many federal and state agencies (Morse 2009, and references therein). Thermal control of AIS is currently recommended by federal and Western state agencies as an economical, quick, and environmentally benign treatment, especially when compared to chemical treatments (Stebbing and Rimmer 2014).

Pressurized water: Pressurized water is provided at boat access sites by a water pump, spray gun, or hose. This treatment alone is unlikely to kill many AIS, even when used at close range (25 cm), so its effectiveness relies on physical removal (Stebbing and Rimmer 2014, Bradbeer et al. 2021). Rothlisberger et al. (2010) is the only study we found that compares high-pressure (1800 psi), unheated water to other decontamination treatments (low-pressure [40 psi] water and hand removal of organisms). They found that all 3 treatments removed at least 60% of aquatic fragments, seeds, and small-bodied organisms (SBOs; for this experiment, the spiny waterflea, *Bythotrephes longimanus*, an invasive cladoceran, was used). However, high-pressure water was significantly more effective than low pressure and hand removal at removing seeds and SBOs (91% vs. 74% and 65%, respectively). This implies that it is a good choice at boat access sites where boats are fouled with small invertebrates or small plant seeds, and we hypothesize that it will be effective against any AIS lodged in mud. Due to water retention, AIS in mud can survive for longer overland journeys than they would otherwise (De Stasio et al. 2019). Note that is important to remove even the smallest plant fragments; Coughlan et al. (2021) clipped 3 invasive plant species 10 mm below the apical bud, and all grew new roots when returned to water. It is not known whether pressurized water removes encrusted mussels, since there are no published empirical studies demonstrating this use (Morse 2009, Bradbeer et al. 2021).

Waterless cleaning

Waterless cleaning systems may include one or several tools: grabber tools for removing hard-to-reach aquatic plants, a brush to remove mud and SBOs, a plug wrench for pulling the boat's drain plug, a wet/dry vacuum for collecting water from low points, and/or a compressed air wand for drying.

Visual inspection and hand removal: Visual inspection and hand removal can be done with or without the aid of a waterless cleaning system and is effective in some situations. Rothlisberger et al. (2010) found that hand removal removed

about as many plant fragments as pressurized water (88% vs. 83%, respectively), but that hand removal was less effective at removing plant seeds and SBOs (65% vs. 91%). Campbell et al. (2020) compared hand removal of multiple species of AIS to the use of a waterless cleaning system toolset and found that the toolset did not provide a significant advantage for removing plant fragments ($P = 0.18$) or SBOs ($P = 0.14$). The authors pointed out that cleaning was done by a trained inspector and suggested that the general public would likely benefit from access to tools to help them access difficult-to-reach areas, allowing them to decontaminate their boats more thoroughly.

Air drying: Most aquatic plants and animals will not survive long without being immersed in water. Mohit et al. (2021) reviewed 26 studies about desiccation of AIS and found that AIS removed from water and left exposed to air resulted in much higher and faster mortality than controls. They also found that relative humidity weakly predicts the treatment duration needed to reach 100% AIS mortality ($P = 0.04$), but that air temperature does not predict duration. Overall, they concluded that 7 days of drying may be enough to kill 90% of the AIS present on watercraft in most environments and for most AIS, including many aquatic plants, zebra mussels (*Dreissena polymorpha*) and quagga mussels (*Dreissena rostriformis bugensis*), crayfish, and some snails. Spiny water flea is another species that does not survive 7 days of drying (Branstrator et al. 2013). There are several exceptions: Large snails such as Chinese mystery snails (*Cipangopaludina chinensis*) and applesnails (Ampullariidae), adult golden mussels (*Limnoperna fortunei*), killer shrimps (*Dikerogammarus villosus*), New Zealand pygmyweed (*Crassula helmsii*), and parrot's feather (*Myriophyllum aquaticum*) can survive weeks of desiccation (Evans et al. 2011, Barnes et al. 2013, Mohit et al. 2021). Also, coiled plant fragments, which occur when plants wrap around a propeller, survive longer than uncoiled fragments (Mohit et al. 2021). Many "Clean, Drain, Dry" outreach campaigns recommend 5 days, but this may be too long to be widely adopted by boaters who visit lakes more frequently. Nearly 40% of Wisconsin boaters and 64% of UK anglers reported they visited more than one body of water within a 5 day period (Anderson et al. 2014, Witzling et al. 2016). Only 5 days of drying may be too brief to ensure 90% zebra mussel mortality; however, most recreational boats that move between inland waterbodies are not kept in the water long enough to have encrusted mussels (Anderson et al. 2015, Mohit et al. 2021). Adult mussels are much more likely to be spread by attaching to aquatic plants, which then become tangled on the boat propeller or trailer and are carried to new waterbodies (Johnson et al. 2001).

Boater failure to fully drain a boat or to leave compartments open and drain plugs removed can delay desiccation and allow AIS to survive for several days after a boat is taken from the water (Kappel 2012, Bruckerhoff et al., 2014, Anderson et al. 2015). A survey of 2 lakes in Minnesota found that boats operated in the last 24 h contain a median of 4945 mL of residual water in their sterndrive engine and an average of 13 zebra mussel veligers per boat (Doll 2018). Some boats with ballast tanks harbor large volumes of residual water (1.0 to 86.8 L), even after their tanks are drained with a pump (Campbell et al. 2016, Doll 2018). Another study found that boaters who believed that their boat's bilges were empty actually had >13 L of water, and boats with more standing water were found to carry more pelagic zooplankton (Kelly et al. 2013). A proactive boater can remove residual water with the vacuum, towel, or sponge, and the pressurized air wand can then blow the boat dry.

Outreach and engagement effectiveness

Effective boat cleaning stations will facilitate AIS prevention actions. There is no clear threshold on when outreach can be labeled "effective." In most cases, more investment in well-planned outreach will yield more prevented AIS invasions.

Ease of use

The most effective cleaning system is the one that the boaters engage with and use correctly and consistently. While aquatic plants can be removed by hand, grabber tools and pressurized water allow cleaning without requiring the boater to kneel or

crawl under the boat trailer, which makes cleaning behavior more likely. Staffed stations do not require the boater to operate the station themselves and therefore are the easiest to use, as long as the staff are present when the cleaning system is needed. In the case of heated, high-pressure systems, the purchasing party may want to hire staff to protect users from burns and themselves from liability issues. Unheated pressure washers do not warrant as many safety precautions, but high-pressure water can potentially damage unprotected skin (Morse 2009, Stebbing and Rimmer 2014). A survey of 3900 North American boaters conducted in the western United States reported on a 1 (very unlikely) to 5 (very likely) scale that they were on average very likely (4.5) to participate in removing visible organisms and draining the bilge, but on average they were only likely (4.0) to use pressurized or heated water, indicating that it is perceived as cumbersome (Kyle et al. 2022).

Waterless systems are designed to be boater-operated and require no safety training. Furthermore, users confirm that the design is self-explanatory. In a Minnesota survey of boaters who had just used a waterless system, 78% of respondents reported that the waterless stations were "easy" or "very easy" to use, and among second-time users the agreement was nearly unanimous ($n = 46$). When asked about vegetation, 78% of users said the waterless station provided "much" or "very much" help at removing vegetation and 60% of users said it offered "much" or "very much" help for drying the boat or trailer (Three Rivers Park District 2018).

Outreach approaches

While educational outreach to boaters may take many forms, and the approach is not dictated by the type of equipment at a boat cleaning station, we chose to focus on signage and staff-delivered outreach because those approaches are most often associated with individual boat cleaning stations. Insights regarding other outreach approaches, such as mass media, online methods, and word of mouth, can be found elsewhere (e.g., Prior 2005, Nathan et al. 2014, Howell et al. 2015, Donnelly 2018).

Signage: Signage at boat access sites makes AIS information and prevention regulations and recommendations available to boaters at any time. Signage is consistently cited as a main source of information by water recreationists (Armson 2004, Witzling et al. 2016, Hammond et al. 2019, Kyle et al. 2022). Boat access sites operated by the state of Michigan are required to have signage including relevant AIS prevention regulations (NREPA 1994). The installation or redesign of signage can positively influence boater behavior. Inconspicuous observers on 4 lakes in Hennepin County, Minnesota, noted that lakes with multiple, large signs and digital signs had fewer boat cleaning violations than lakes with fewer, nondigital signs (Fortin Consulting 2020).

Access site managers must maintain signage visibility for it to be an effective outreach tool. One study found that only 25% to 32% of visitors remembered seeing signage at a boat access site, noting that distance and vegetation may have interfered (Cimino and Strecker 2018). One of our interviewees described a survey of signs in northwestern Wisconsin that found many to be hidden behind grass or bushes. Road stencils are a type of signage that places messaging directly in the boaters' path, designed to be easy for boaters to see. We have observed stencils reading "Clean Drain Dry" or "Clean In, Clean Out" at launch facilities in Michigan. However, we have also encountered many boat access sites where signage is absent or out of date and thus not reflecting current AIS regulations.

Staff-delivered outreach: Educational outreach delivered by people (e.g., facility staff, educators, local volunteers) may connect to boater values and affect attitudes more than signage alone (Henker and Brown 2011, Poudel and Nyaupane 2013). Lake managers that oversee hot water stations and mobile boat cleaning stations typically hire staff to safely operate or transport the systems. The direct interactions between staff and boaters represent outreach opportunities. The presence of outreach specialists or boat inspectors will likely create an incentive to comply with regulations. Incognito observations of 4 boat access sites in Minnesota found that the 2 locations with even an infrequent inspector presence had lower rates of AIS violations than the 2 uninspected sites (11.2% and 14.4% vs. 23% and 27.8%), but variation in signage likely also played a role (Fortin Consulting 2020). Furthermore, staff-led collaborative activities such as weed-removal events

have been shown to help overcome the belief barrier that one person's behaviors make no real difference when so many other factors contribute to the spread of invasive species (Prinbeck et al. 2011).

There are not many studies on the effectiveness of staff-delivered outreach about invasive species, and even fewer studies on aquatic invasive species. However, surveys show that staff-delivered outreach is less commonly cited as a source of AIS information by boaters than signage. In 2 surveys, boaters reported fewer than 25% obtained AIS information from inspection programs or volunteer stations at boat access sites, which could indicate either a lack of efficacy at imparting knowledge, or more likely a lack of investment in staffing (Armson 2004, Hammond et al. 2019).

Our interviews revealed that staff demeanor plays an important role in outreach effectiveness. Four interviewees suggested that staff can set a positive tone for a boater's visit, which ensures that their brief time of receiving AIS and boat cleaning information is enjoyable rather than tedious or uncomfortable. One interviewed expert emphasized the role of hospitality in outreach efforts, which nearly always involve approaching boaters and requesting their time and attention. They observed that staff who greet boaters with a cheerful demeanor, connect with them about a mutual interest, and treat them as a guest will always be more successful and have a more pleasant interaction than those who approach boaters with a serious expression and clipboard in hand. Our field experience supports this suggestion; we find boaters are more likely to engage, listen, and accept a free boat wash when approached conversationally, than when immediately questioned about their prevention behaviors.

Message content

Uninformed audiences may more often notice and remember messages that align with their specific core value. Thus, boaters with more anthropocentric values are more likely to connect with messaging that communicates the economic impacts of AIS rather than the environmental impacts. Examples include framing boat cleaning as an investment in the longevity of an expensive boat, or emphasizing the taxpayer cost of managing AIS invasions (Pradhananga et al. 2015, O'Keefe et al. 2016, Sharp et al. 2017, Kyle et al. 2022). Science-based messaging is reported to likely be effective (e.g., "PREVENT THE SPREAD OF AQUATIC INVASIVE SPECIES. Aquatic invasive species are present in our state's lakes and rivers and can severely impact these ecosystems"; Shaw et al. 2021, Kyle et al. 2022), as well as protection-based messaging (e.g., "HELP PROTECT OUR WATERS. Aquatic invasive species harm our lakes and rivers"; Kyle et al. 2022). This is in comparison to nativist messaging (e.g., "Zebra mussels: Not Native. Not Welcome") or militaristic messaging ("Stop the Invasion" accompanied by an image of a warship), which were seen by some audiences as controversial or off-putting (Shaw et al. 2021). Also, messaging that targets local boaters who only use their boat on one lake (hereafter nontransient boaters) may be effective at encouraging preventative actions. Three of the experts whom we interviewed confirmed that nontransient boaters typically do not use boat cleaning stations. Data we collected through our MSU Mobile Boat Wash program showed that while over half had already cleaned their boat before arriving, among boaters who had not yet, the most common reason for declining a free boat wash was that they only use their boat on one lake (32.95%; Fig. 2). The misconception that locals are exempt from AIS control regulations is common, possibly because nontransient boaters believe their actions present zero risk, or possibly because they do not see many other local boaters using boat cleaning stations, which establishes skipping the station as a social norm. The social norm that the peers of boaters expect them to take cleaning action can influence boater behavior (Connelly et al. 2014, Witzling et al. 2016). For example, boaters at 2 Wisconsin lakes used a waterless cleaning station 38% more often when they saw someone else using it (Three Rivers Park District 2018). Under either scenario, local boaters may be making justifications that allow them to bypass preventative actions while still maintaining a pro-AIS prevention attitude. While only using a boat on one lake is less risky behavior, the risk of transporting AIS to new areas within the lake still exists, and Michigan law requires all boaters to remove aquatic organisms before transporting boats over land or launching them in the water, regardless of whether the boat is being returned to the waterbody in which it was last used (NREPA 1994).

Cost

Our interviews with purchasers and/or managers of boat cleaning systems in Michigan revealed that systems differ by orders of magnitude in their costs, and the available funds for a boat cleaning program will greatly influence the choice of equipment. We provide the total costs of 15 cleaning systems in Michigan according to the interviewees who purchased, installed, operate, and maintain them (Table 2).

Water-based

Overall, high-pressure, hot water boat washes have been documented to incur the greatest

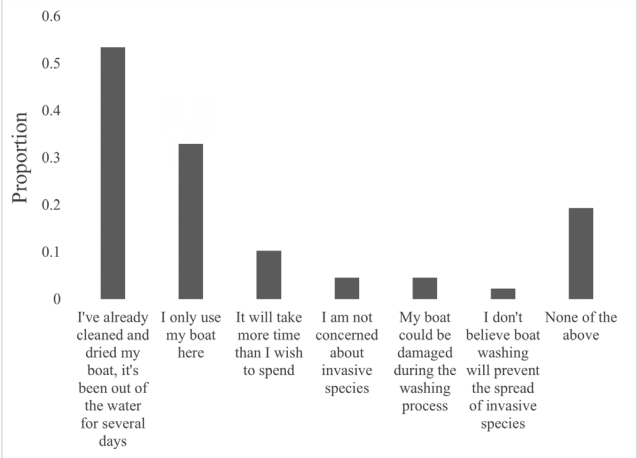

Figure 2. Reasons why boaters at 50 boating access sites throughout Michigan declined the offer of a free boat wash at outreach events held by the Michigan State University Mobile Boat Wash crew ($n = 397$). Note that some boaters gave more than one response. Survey data collected from 2017 to 2019.

Table 2. Approximate installation and operation/maintenance costs (in US$) of 15 boat cleaning systems in Michigan.

Organization or affiliation	Location	Type of cleaning system	Stationary or mobile	Purchase price and initial construction	Annual operation cost	Funding Source
MSU and EGLE	Statewide	Heated and high-pressure (2 systems)	Mobile (2 systems)	$15,000 each	$26,500* ($26,000 staffing)	EGLE and USFWS
Higgins Lake	North Higgins Lake, Crawford County	Unheated and high-pressure	Stationary	$60,000	$2000	HLPOA and the HLF
	South Higgins Lake, Roscommon County	Unheated and high-pressure	Stationary	$70,000	#	#
	North Higgins Lake, Crawford County	Waterless	Stationary	$12,500	$850 for software, $50 for tool repair/replacement	MDNR
	South Higgins Lake, Roscommon County	Waterless	Stationary	$10,735	#	#
	West Higgins Lake, Roscommon County	Waterless	Stationary	$28,450	#	#
Paradise Lake	Paradise Lake, Emmett County	Unheated and high-pressure	Stationary	$174,612	$340	GLRI grant
Glen Lake	Glen Lake, Leelanau County	Heated and high-pressure	Stationary	$12,000 (estimate)	$32,000* (estimate)	Glen Lake Association
Benzie Conservation District	Multicounty	Heated and high-pressure (2 systems)	Mobile (2 systems)	$16,622.00 and $15,517.57	$12,470 total* ($11,500 staffing)	Michigan Invasive Species Grant Program
Gull Lake	Gull Lake, Kalamazoo County	Heated and high-pressure	Stationary	$62,402	$7000–$8000*	Prairieville Township ($10,000) and the Gull Lake Quality Organization ($52,402)
Gun Lake	Gun Lake, Barry County	Waterless (3 systems)	Stationary (3 systems)	$93,000 total including 2 years of software each	$5000* saved most years to replace the solar batteries (5–7 years)	Gun Lake Tribe—GLRI grant

Data collected via interviews. An "*" in the annual operation cost category indicates that the cost includes annual staff expenses; "#" indicates the same information as the box directly above. Acronyms include the Michigan Department of Environment, Great Lakes, and Energy (EGLE), the Great Lakes Restoration Initiative (GLRI), the Higgins Lake Foundation (HLF), the Higgins Lake Property Owners Association (HLPOA), the Michigan Department of Natural Resources (MDNR), Michigan State University (MSU), and the US Fish and Wildlife Service (USFWS).

combined costs for equipment purchase, installation (including engineering and construction, power and water sources, wastewater disposal construction, and all associated permits), operation, maintenance, trash disposal, and staffing (States Organization for Boating Access 2015), although we encountered a few high-pressure, unheated boat washes that cost more than some heated stations in Michigan (Table 2). This is likely due to site-specific engineering costs. High-pressure, unheated boat wash equipment is less expensive, but will incur many of the same installation, operation, and maintenance costs. A garden hose attachment or a gas-powered, high-pressure water machine, such as one intended to clean cars, is a low-cost equipment option that can be purchased for as little as US$100 (Fig. 3A). Note that this tool still incurs costs for water source, wastewater removal, fuel, and maintenance.

Waterless

Waterless systems are often less expensive, although they will still incur maintenance costs, such as tool replacement, waste disposal service, and power source (connection to electrical grid or the replacement of batteries on solar stations). Two experts who opted for waterless systems mentioned that in comparison to water-based systems, the decreased construction expenses and lack of wastewater disposal system installation costs significantly decreased the overall bill. These were the key factors in their decision.

An alternative low-cost waterless option is to build a low-tech boat cleaning station by simply affixing a brush and tongs to a large sign at the boat access site (Fig. 3B). One interviewee reported US$100–150 for the cost. The tools facilitate cleaning, and the sign provides space for instructions and information. Six of the 9 experts we interviewed who were familiar with such approaches mentioned that the annual cost of replacing stolen or damaged tools is low.

Mobile systems

A mobile unit, regardless of whether it offers waterless cleaning, heated water, or pressurized water treatment, is generally less expensive than its permanent equivalent, because the potential installation costs described above do not apply. However, a tow vehicle, fuel, staffing, and maintenance will be required. Mobile units can be

Figure 3. (A) A low-budget option for the equipment portion of a water-based cleaning station (Credit: M. Bleitz). (B) A low-budget waterless cleaning station combined with outreach. (Credit: K. Bockelman.)

used to inform and engage boaters throughout a region, and the cost of equipment and staffing can be shared among multiple organizations.

Other factors to consider

Michigan policy

A cleaning station can make it easier for boaters to comply with policy. Michigan law (NREPA 1994) requires that all water be drained from the boat, and that the boat, trailer, and gear are free of all aquatic plants and animals before it is transported or placed into water, so a cleaning station that provides a plug wrench and cleaning tools will help boaters comply with this policy. However, this law does not require visits to active inspection stations, unlike the regulations in many Western states (Tucker et al. 2017). Therefore, use of cleaning stations at most Michigan boat access sites is voluntary. Those who are making the decision of whether to invest in boat cleaning infrastructure must confront the possibility that it may be used by only a small proportion of visitors. A small number of townships and local units of government in Michigan have enacted ordinances that establish mandatory use of cleaning systems before transporting to a new lake, but how well the ordinances are enforced and by whom is ambiguous (Fuller et al. 2016). Uniform statewide regulation that requires use of cleaning systems would be a more consistent approach to introducing mandatory boat cleaning policy (Buchanan et al. 2017).

AIS disposal and wastewater disposal

The organization interested in installing a cleaning station may want to consider how AIS will be dealt with after removal. Trash receptacles or compost bins located next to the cleaning station make disposal convenient for boaters and may provide another structure for educational signage. The available vacuum on some waterless cleaning systems can also serve as a disposal method. Like trash receptacles, it must be emptied periodically. Mobile boat cleaning systems and some permanent systems may collect wastewater in a wastewater holding tank, which can be either emptied into a sanitary sewer system or disposed of pursuant to relevant regulations and permits. Mobile systems also may temporarily contain wastewater on a roll-up containment mat, in which case the visible AIS must be gathered for disposal. In Michigan, mobile boat washes must create a plan and follow regulations for the disposal of wastewater, as it can potentially contain metals, paint chips, oil, grease, and biological material (MDEQ/EGLE 2018). Whether permanent or mobile, anyone considering installing a boat wash in Michigan needs to contact their local Michigan Department of Environment, Great Lakes, and Energy (EGLE) district office to inquire about wastewater disposal options (NREPA 1994).

Placement

The placement of a cleaning station within the boat access site can change its effectiveness. For permanent systems, 2 of our interviewed experts reported that proximity to a water supply and the electrical grid lowered installation costs, depending on the type of equipment selected. Permanent boat washes will connect to a sanitary sewer system much more easily if the station is located near an existing sewer line. More remote boat access areas may be restricted to waterless, mobile, or solar-powered systems. On the other hand, the operational capacities of solar-powered or mobile units may limit their utility at busy sites.

Ideally, the station should be placed near a traffic pinchpoint but should not block the flow of traffic (Stebbing and Rimmer 2014). A manufacturer of waterless cleaning stations recommends stations be located within 30 to 60 m of the water access site so that they are within walking distance and can be easily found by boaters (CD3 Systems 2023). At some boat access sites, water-based boat wash systems may have to be placed farther away due to wastewater regulations and/or insufficient space for a drainage pad (MDEQ/EGLE 2018). There should also be a designated, clearly marked cleaning area that allows boaters to move safely around their boat while cleaning, leaving enough space for other vehicles to pass by. Some boaters believe that boat access sites are too crowded to perform preventative actions; good site design might address that belief (Kyle et al. 2022).

Conclusions and recommendations

This study compares boat cleaning systems for decontamination effectiveness, boater outreach and engagement effectiveness, and cost. There are numerous considerations when choosing a boat cleaning system for prevention of AIS at a boating access site (Table 3). The most effective cleaning system in the world is ineffective if it comes with barriers that prevent boaters from using it. Water spray at high temperatures can be effective, but cost and location constraints may prevent its establishment at many boat access sites. Unheated pressure washers and waterless systems can be effective alternatives that reduce the risk of AIS transport while often costing less and being more accessible to boaters. In addition to ease of use, characteristics of the waterbody and of the managing organization may help determine which system is most effective.

Outreach is vital to the success of a boat cleaning system. At minimum, some form of outreach is necessary when a cleaning system is first installed. The best outreach programs will be comprehensive in message; they will inform the public why the spread of AIS must be managed, what the new infrastructure is, and how to use it. These programs will also be comprehensive in format; boaters depend on signage, but in-person communication can also result in meaningful engagement. All branding and messaging should be consistent, inviting, and current. We recommend prioritizing well-placed, visible signage and stenciling, contacting local media, and appearing at local events. Once those conditions are met, outreach programs should create targeted

Table 3. Considerations when choosing a boat cleaning system for prevention of AIS at a boating access site.

Category	Questions	Considerations
Space	• How much space is available for the system, including infrastructure (e.g., drainage pad)?	• Systems and the necessary infrastructure vary in size; space for safe operation and traffic flow is crucial.
	• Is there space for boaters to move safely around their watercraft while cleaning it?	
	• Is there space for other vehicles to pass by safely while a boat is parked at the system?	
	• Are electricity, water, and drainage available at the site?	• If not, choose a system that does not require them.
	• Are electricity, water, and drainage located close enough to the system that the cost of construction to connect them is not an obstacle?	
	• How far from the waterbody will the system be placed?	• Systems placed close to a waterbody pose a potential risk of organisms and contaminants washing back into the waterbody, so prevention measures must be in place, but systems can be more easily found by the boater if they are located near the boat launch location.
Cost	• What is the total cost of the system, including infrastructure?	• Both initial and ongoing maintenance and staffing costs must be considered to fund a cleaning system.
	• What engineering or construction costs will be required (e.g., concrete pad, wastewater disposal, a shed for housing equipment, utilities)?	
	• Will paid staff be hired, and if yes, how many hours will the system be staffed each week?	
	• What are the estimated annual maintenance costs (e.g., mechanical, waste disposal, component replacement)?	
	• Will costs need to be shared with one or more organizations from other lakes?	• A mobile system can be shared between lakes.
	• Which outreach formats will be associated with this system?	• Outreach costs should also be considered.
Environment	• Are small-bodied AIS present in the waterbody on departing watercraft, such as invertebrates or invasive plant seeds?	• Small-bodied organisms are more effectively removed by pressurized water than by waterless systems (Rothlisberger et al. 2010).
	• Are plant fragments present on departing watercraft?	• Fragments can be removed effectively by either water-based or waterless methods (Rothlisberger et al. 2010).
	• Are encrusted mussels present on departing watercraft?	• Most mussels can be killed by drying watercraft for >7 d in low humidity, or by using hot water spray >80 C for 1 s per the area of spray.
	• Are boats likely to carry mud?	• Water-based systems are recommended for mud removal.
	• Have any particular AIS been recently discovered, or suspected to be in the area?	• Outreach materials associated with the wash station should make boaters aware of these AIS and where to find them on a boat.
Traffic	• Are most users likely to be waterfront property owners, or transient (travelers from other locations)?	• Nontransient waterfront residents tend to use cleaning systems less often due to lower perceived risk, so outreach associated with the wash station should address the risks and behaviors for both transient and nontransient boaters.
	• Are there likely to be more than 100 users of the system per day?	• Solar-powered units or mobile units may not be able to keep up with high demand.

education that aligns with anthropocentric boater values and also aligns with local and state AIS laws, regulations, and recommendations.

The cost of a cleaning station will vary greatly depending on the equipment selected and the installation, operation, maintenance, and staffing needs specific to the equipment and the site. The available budget therefore places an important constraint on system selection. We recommend careful consideration of the total cost of the various options in the context of site-specific AIS risk and goals.

Additional research would improve our current understanding of the efficacy of cleaning systems. In particular, we believe the following questions should be addressed by future research: (1) Does boater use of a cleaning station at a boat access site increase the likelihood that they will perform AIS prevention actions elsewhere, even in the absence of a cleaning station? (2) When a boat cleaning system is used as intended, does the system sufficiently address the residual water transport pathway (e.g., water remaining in bilges, motors, ballast tanks)? (3) Do most cleaning station users use the station effectively, and from what source do they learn how to use it (e.g., signs, past experience, other boaters, outreach event)?

Also, we noticed some gaps in the literature during our review; suggesting a high likelihood that there are few or no existing studies on the following topics: There are currently no published papers on the cost of boat cleaning systems. A study of the economic return on investment into cleaning systems would be especially interesting and useful to those who are deciding whether to purchase a system. Also, there is only one study on the efficacy of unheated, pressurized water; investigating its ability to remove and possibly kill AIS could inform its usefulness as a cleaning treatment.

The selection of a boat cleaning system for AIS is a challenging decision that depends on many factors. Decision makers must consider their goals, the financial resources available, and the constraints of the boat access site. Further, they must recognize that the choice of cleaning system will only partially determine its effectiveness; success will depend equally or more on how and where it is implemented.

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