



Optimizing the location of watercraft inspection stations to slow the spread of aquatic invasive species

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Abstract The accidental spread of aquatic invasive species (AIS) by recreational boaters is a major concern of state and county environmental planners in the USA. While programs for watercraft inspection to educate boaters and slow AIS spread are common practice, large numbers of boats and waterbodies, together with limited budgets, make program design difficult. To facilitate program design, we developed an integer programming model for allocation of scarce inspection resources among lakes. Our model uses species-specific infestation status of lakes and estimates of boat movement between lakes. The objective

is to select lakes for inspection stations to maximize the number of risky boats inspected, where risky boats are ones that move from infested to uninfested lakes. We apply our model in Stearns County in central Minnesota, USA, to prioritize lakes for inspection stations and evaluate alternative management objectives. With an objective of protecting uninfested lakes within and outside Stearns County, the optimal policy is to locate stations at infested lakes having the most boats departing for uninfested lakes inside and outside the county. With an objective of protecting only Stearns County lakes, the optimal policy is to locate stations at both infested and uninfested lakes having the riskiest boats arriving from within and outside the county and departing to in-county lakes. The tradeoff between these objectives is significant.

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Introduction

The spread of aquatic invasive species (AIS) among waterbodies in the Great Lakes Region of the United States is a major social, environmental, and economic concern (Escobar et al. 2017). Invaders such as zebra mussel (*Dreissena polymorpha*) and Eurasian watermilfoil (*Myriophyllum spicatum*) are known to

damage fisheries (Vanderploeg et al. 2002; Hansen et al. 2020), interfere with raw water usage (Leung et al. 2002), decrease property values (Halstead et al. 2003), extirpate native species (Strayer 1999), and threaten human health (Vanderploeg et al. 2001). Economic impacts of zebra mussel alone are estimated to range from hundreds of thousands to billions of dollars annually, depending on the scope of the study (Lovell et al. 2006). In Minnesota, the number of newly detected zebra mussel and Eurasian watermilfoil infestations increased annually since their discovery in the 1980s (Kanankege et al. 2018) so that by September 2020, the proportions of Type 5 waterbodies (inland open fresh water) that are at least 0.04 km² in size and invaded by these species were 237/9,182 (2.58%) and 357/9,182 (3.89%), respectively, and included many of the state's most popular recreational lakes (Minnesota Department of Natural Resources 2020a).

An important mechanism of AIS spread is the accidental transport of organisms on recreational boats as they are moved among waterbodies (Johnson et al. 2001; Rothlisberger et al. 2010; Cole et al. 2019). Organisms may be carried in bilge water, live wells, bait buckets, or attached to boat exteriors or other entangled organisms such as plants (Johnson et al. 2001). Thus, every time a boat is transported overland after use in an invaded waterbody, it has the potential to transfer AIS to uninvaded waterbodies. In response, state and county agencies have invested in boat inspection and education programs to slow the spread of AIS. Boat inspections at points of entry to or exit from waterbodies allow discovery and disposal of AIS, education of watercraft users about the impacts of AIS, and collection of information about boater movements. For example, the Minnesota AIS Prevention Aid program provides \$10 million a year to counties to prevent the introduction and limit the spread of AIS (Minnesota Department of Natural Resources 2020b), and much of this money is spent on watercraft inspection (e.g., inspectors were located on 550 waterbodies in 40 counties in 2019) (Minnesota Department of Natural Resources 2020c).

While watercraft inspection is an important component of AIS prevention, the sheer number of recreational boats moving across the landscape, combined with the large numbers of waterbodies that can be sources or recipients of AIS, make watercraft inspection a particularly difficult program to manage.

In addition, inspection stations are costly to operate, and planners must design their programs under budget constraints. Program design is facilitated with knowledge about the current infestation status of waterbodies (e.g., infested or likelihood of infestation) and watercraft movement between lakes. When these kinds of data are available, they can be used in models to help design inspection strategies.

Research efforts with implications for the design of boat inspection strategies have focused on modeling AIS transport, establishment, survival, and spread (e.g., Vander Zanden and Olden 2008; Hyytiäinen et al. 2013; Robertson et al. 2020). Important results from those studies emphasize the need to account for spatial patterns in boater movement between infested and uninfested lakes (Buchan and Padilla 1999) and adjustments in boater behavior in response to inspection strategies (Timar and Phaneuf 2009). Intervening early in the invasion process by removing organisms from transportation pathways and lowering the probability of introduction is economically superior to post-establishment control or eradication (Leung et al. 2002; Lodge et al. 2006; Adams and Lee 2012). Further, when the invasion is in its early stages and eradication is unlikely, the most effective intervention is an offensive strategy of boat inspections at source lakes to curtail the spread of the invader to uninfested destination lakes (Drury and Rothlisberger 2008). Protecting destination lakes is the best strategy late in the process because it yields lower per destination introduction rates at protected sites than containment at the same number of sources (Drury and Rothlisberger 2008). These analyses focus on protecting a single lake from introduction or slowing the spread from a set of infested lakes to uninfested lakes, assuming equally likely contacts among them. Expanding these analyses, Fischer et al. (2021) developed an integer programming model to optimize locations and operating times of roadside watercraft inspection stations while accounting for temporal variations in movement along routes between sets of infested and uninfested lakes. Their objective was to maximize the number of boaters that pass at least one inspection station along their routes, subject to a budget constraint. Applying their model in the Canadian province of British Columbia, they found inspection stations are best placed near border crossings, which funnel incoming movement. Integer programming models like those developed by Fischer

et al. (2021) have emerged as valuable tools for developing optimal spatial-dynamic surveillance and control strategies for invasive species when information and models of invasive species spread are available (e.g., Epanchin-Niell and Wilen 2012; Büyüktaktakin and Haight 2018; Kılış et al. 2020).

Here, we develop an integer programming model for the allocation of inspection resources among lakes to prevent or slow the spread of AIS. Our model is based on information about the species-specific infestation status of lakes and estimates of boat movement between lakes. The objective is to select lakes for inspection stations to maximize the number of risky boats inspected, where a risky boat is one that moves from an infested lake to a lake that is not infested with one or more of the AIS present in the lake where the boat came from. This objective serves to minimize the propagule pressure on uninfested lakes. From a methodological standpoint, our model expands the work of Fischer et al. (2021) by accounting for potential species-specific transport as well as the frequency of boat movement among lakes. As a result, our model optimizes the location of lakeside inspection stations where boats enter and leave lakes and accounts for species-specific differences in infestation status between pairs of lakes. Like the model of Fischer et al. (2021), our model facilitates the detailed analysis of tradeoffs between management objectives and the effects of cost constraints. We apply our model in Stearns County in central Minnesota, USA. We use the model to prioritize lakes for inspection stations under different levels of budget and analyze tradeoffs between management objectives that differ in their protection of lakes within and outside Stearns County.

Methods

Multi-species boat inspection optimization model

Suppose we have information about the location of infested and un-infested lakes and estimates of the number of boats moving between each pair of lakes. For each lake, we know the presence or absence of each invasive species and we want to locate a fixed number of boat inspection stations at lakes to maximize the number of risky boats that are inspected, where a risky boat is one that moves from a lake with one or more invasive species to a lake that does not

have one or more of the invasive species that are present in the source lake.

Defining notation, we first let I be the set of lakes and n_{ij} be the number of boats that move from lake i to lake $j, \forall i, j \in I$. Further, we let K be the set of invasive species and f_{ik} be a binary parameter for whether or not lake i is infested with species k (i.e., $f_{ik} = 1$ if species k is present in lake i ; $f_{ik} = 0$ otherwise). From these infestation parameters, we compute the parameter b_{ij} , where $b_{ij} = \sum_{k \in K} f_{ik}(1 - f_{jk})$, which is an integer counter for the number of invasive species that may be moved from infested lake i to infest lake j . For example, if lake i has three invasive species and lake j has one of those species, then a boat moving from lake i to lake j is at risk of carrying two invasive species from infested lake i to lake j , which is currently not infested with those species. We define binary decision variables $x_i, \forall i \in I$, for whether lake i is selected for an inspection station (i.e., $x_i = 1$ if lake i is selected; $x_i = 0$ otherwise). Further, we define binary decision variables $u_{ij}, \forall i, j \in I$, for whether or not risky boats that move from lake i to lake j are inspected at either lake i or lake j or both. Finally, we define the budget B as the upper bound on the number of lakes selected for inspection stations. Using these definitions, we formulate the following optimization problem to select lakes for inspection stations:

$$\max_{x_i, \forall i \in I} \sum_{i \in I} \sum_{j \in I} n_{ij} u_{ij} \quad (1)$$

Subject to:

$$b_{ij} = \sum_{k \in K} f_{ik}(1 - f_{jk}) \quad \forall i, j \quad (2)$$

$$u_{ij} \leq (x_i + x_j) b_{ij} \quad \forall i, j \quad (3)$$

$$\sum_{i \in I} x_i \leq B \quad (4)$$

$$x_i \in [0, 1] \quad \forall i; u_{ij} \in [0, 1] \quad \forall i, j \quad (5)$$

The objective (1) is to select lakes for inspection stations to maximize the number of risky boats that are inspected, where a risky boat is one that moves from infested lake i to lake j , which is not infested with one or more of the species that are present in lake i . Constraint (2) is the integer counter for the number of species that may move from infested lake i to uninfested lake j . Constraint (3) defines the value of

the 0–1 decision variable u_{ij} for whether risky boats are inspected: $u_{ij} \leq 1$ only if one or both of the lakes i or j is selected for inspection (i.e., $x_i + x_j \geq 1$) and lake i is infested with at least one species k that is not present in lake j (i.e., $b_{ij} \geq 1$). Note that, since the objective function maximizes the sum of the products $n_{ij}u_{ij}$, constraint (3) will set as many $u_{ij} = 1$ as possible. Constraint (4) sets the upper limit B on the number of inspection stations. Equation (5) includes the binary restrictions on the decision variables x_i and u_{ij} .

Application to Stearns county, Minnesota

Stearns County covers 3,600 km² in the central part of the U.S. state of Minnesota (Fig. 1). The terrain consists of low rolling hills dotted with lakes and ponds. The Mississippi River flows southeast along the northeast border of the county, and the Sauk River drains the central part of the county into the Mississippi River in the city of St. Cloud. The county is largely rural with a population of 150,642 people according to the 2010 U.S. Census.

Waterbodies are among Stearns County's greatest assets, including 280 lakes (Stearns County 2018). Lakeshore properties exceed \$1.6 billion in value, and the tourism industry, which depends on lake-based recreation, exceeds \$11 billion in revenues (Stearns County 2018). Preventing and limiting the spread of AIS is critical to maintaining the quality of the County's lakes and the value of their services.

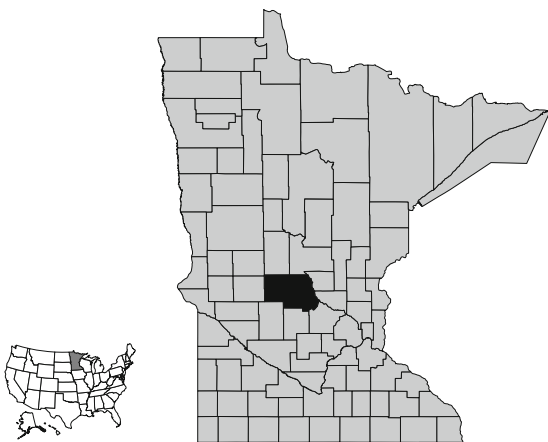


Fig. 1 Stearns County, Minnesota

To slow the spread of AIS, the Stearns County Board of Commissioners first approved the Stearns County AIS Plan in 2015 (Stearns County 2018). As part of the plan, Stearns County entered into an agreement with the Minnesota Department of Natural Resources, which gave the county authority to require inspection of watercraft prior to launching into public waters and to deny launch if the watercraft threaten to spread AIS. County inspectors visually and tactily search for AIS or anything else that could potentially spread AIS (e.g., water, mud, plants, and other debris) on equipment entering or exiting the waterbody at the access point. In addition, the inspectors complete a survey with the access user that details the results of the inspection, while educating access users about AIS issues and the state's AIS laws. During the 2019 boating season (May–October), the County used \$230,000 in AIS Prevention Aid from the State of Minnesota and spent 76 percent (\$175,000) of that aid on watercraft inspections (Stearns County 2019). The funding was used to employ 45 inspectors who performed over 12,000 watercraft inspections at nine lakes.

Lake infestation and boat movement parameters

We focus our analysis on 192 Stearns County lakes that are at least 0.04 km² (10 acres) in size. According to the MNDNR wetland classification, these lakes are Type 5 surface water (inland open fresh water), including shallow ponds and reservoirs, which provide floodwater detention, wildlife and fish habitat, and recreation (Minnesota Department of Natural Resources 2020d). While this definition excludes smaller lakes and wetlands, it does include most lakes relevant to recreational boating and risk of AIS movement through this pathway. We used the infestation status of lakes reported in the MNDNR Infested Waters List, as of May 1, 2020 (Minnesota Department of Natural Resources 2020a). Each of the 192 lakes was classified as infested or uninfested. Twenty-five lakes were infested with one or more AIS, including zebra mussels (zm) ($n = 15$), starry stone-wort (ss) ($n = 4$), and Eurasian watermilfoil (ew) ($n = 7$).

We used estimates of annual boat movement among lakes within and outside Stearns County (Kao et al. 2021). The estimates were based on responses from boaters to questions during the watercraft inspection

process and aggregated by the MNDNR for the period 2014–2017. Boaters were asked to recall and identify the previous lake visited and identify the next lake they planned to visit. Using these responses, Kao et al. (2021) employed an extreme gradient boost analysis to estimate the annual number of boats moving between each pair of lakes in MN. The authors accounted for variation in inspection effort and extrapolated the survey information to estimate movement among all lakes in MN, including lakes that were not surveyed. The estimates did not include movement of boats to or from lakes outside of MN.

Using these estimates, we created a 192 by 192 matrix of annual number of boat movements from each source lake (row) to each destination lake (column) in Stearns County. A total of 11,111 boat movements were estimated to occur annually between all pairs of lakes represented in the matrix. In addition, we added eight columns for estimates of the annual number of boat movements from each source lake in Stearns County to lakes outside the county. These outside-county lakes were aggregated into eight categories according to the AIS present (e.g., none, zm, ss, ew, zm/ss, zm/ew, ss/ew, zm/ss/ew). A total of 70,968 boat movements per year were estimated from lakes in Stearns County to lakes in these eight categories outside the county. Finally, we added eight rows to the matrix for estimates of the annual number of boat movements into Stearns County lakes from each of the eight categories of lakes outside the county. An estimated 70,831 boat movements occurred to lakes within Stearns County from lakes outside the county.

We counted the annual number of boat movements from infested to uninfested lakes and identified the infested lakes with the greatest number of risky boat departures. An estimated 32,782 departures occurred from the 25 infested lakes in Stearns County annually and headed to uninfested lakes inside or outside the county. The vast majority (88 percent) of those boat movements (28,993) were to uninfested lakes outside Stearns County, while 12% (3789) were to uninfested lakes within the county. The ten busiest infested lakes each had between 1000 and 6000 risky boat departures annually for uninfested lakes (Fig. 2).

We also identified the uninfested lakes with the greatest number of risky boat arrivals. There were an estimated 23,661 boat movements to uninfested lakes in Stearns County annually from infested lakes; 16%

(3789) of the boat movements occurred from infested lakes inside the county, and 84 percent (19,872) occurred from infested lakes outside the county. The ten busiest destination lakes each received 400–800 boats annually from infested lakes (Fig. 3). Note that three of the destination lakes in Fig. 3 are infested with starry stonewort. Those three lakes (Koronis, Rice, and Grand) are listed as uninfested destination lakes because they do not currently have zebra mussel or Eurasian watermilfoil and they receive boats from lakes infested with those species.

Finally, we identified the Stearns County lakes with the greatest numbers of risky boats arriving from infested lakes inside and outside the county plus risky boats departing for uninfested lakes within the county only (Fig. 4). These lakes are likely to be high priority for inspection stations when the objective is to maximize the number of risky boats inspected, where risky boats are those that arrive at uninfested lakes within the county from infested lakes within and outside the county plus those that depart from infested lakes within the county and move to uninfested within the county. The 11 busiest lakes according to this measure had 600–1200 risky boat movements annually (Fig. 4). Four of the lakes are uninfested (Big, North Brown's, Big Spunk, and Long), and for those lakes we only count boat movements arriving from infested lakes inside and outside the county. The other seven lakes are infested with one or two AIS, and for those lakes we count boat movements arriving from lakes that are infested with a species that is not currently known to be present, and we count departing boat movements to lakes that are not infested with AIS that are currently present.

Analysis

Our analysis focused on the evaluation of and tradeoff between two management objectives that differ in how they account for boat movements from lakes infested with AIS within Stearns County to uninfested lakes outside of Stearns County. In Problem 1, the management objective is to select lakes for inspection stations within Stearns County to maximize the number of risky boat movements that are inspected subject to an upper bound on the number of lakes selected for inspection stations. Problem 1 accounts for risky boat movements from infested lakes outside Stearns County to uninfested lakes within the county and

Fig. 2 Annual boat movements from the ten busiest infested lakes inside Stearns County to uninfested lakes within and outside the county

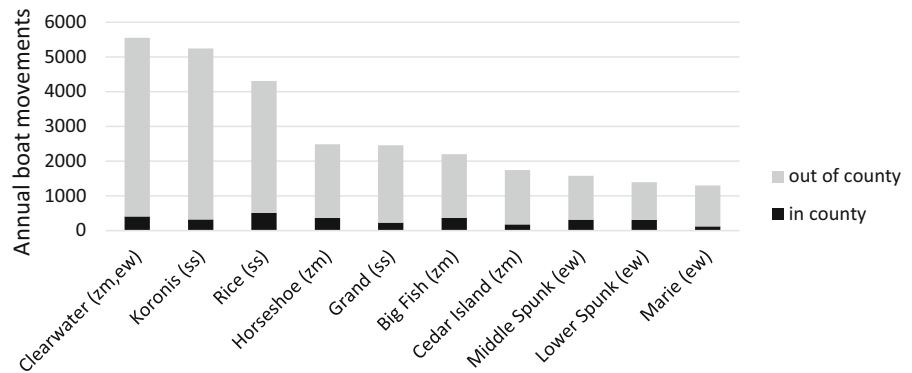


Fig. 3 Annual boat movements to the ten busiest uninfested lakes in Stearns County from infested lakes inside and outside the county

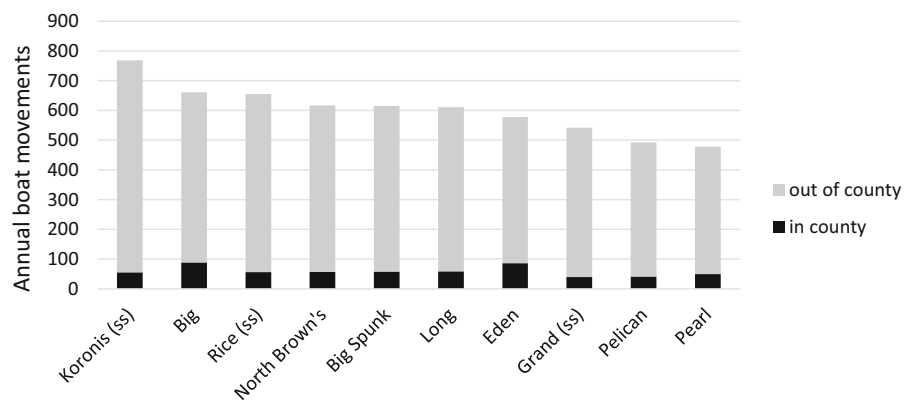
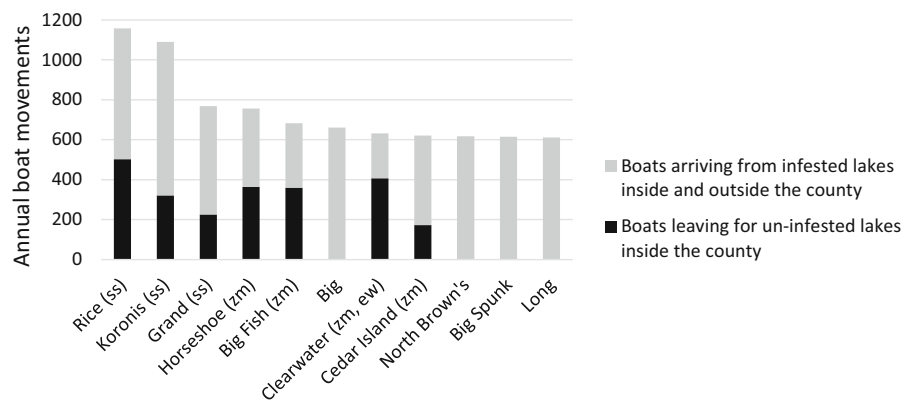


Fig. 4 Annual boat movements from infested lakes inside and outside Stearns County to uninfested lakes within Stearns County



from infested lakes within Stearns County to uninfested lakes both within and outside the county. Problem 2 has the same management objective as Problem 1—select lakes for inspection stations within Stearns County to maximize the number of risky boat movements that are inspected—except that Problem 2 does not count risky boats moving from infested Stearns County lakes to uninfested lakes outside the county.

Using the lake infestation status and boat movement estimates, we solved the two optimization problems while increasing the upper limit on the number of lakes selected for inspection stations. The results allowed us to determine the effects of increasing the inspection budget on each problem's objective value. To assess the tradeoff between management objectives in Problems 1 and 2, which differ in their accounting of risky boat movements from Stearns

County lakes to lakes in other counties, we performed a loss analysis where we computed the loss in objective function value for Problem 1 using the solution from Problem 2, and vice-versa using the following expressions:

$$Loss_1 = \frac{O_1(S_1) - O_1(S_2)}{O_1(S_1)}$$

$$Loss_2 = \frac{O_2(S_2) - O_2(S_1)}{O_2(S_2)}$$

where O_1 and O_2 are the objective functions of Problems 1 and 2, S_1 and S_2 are the optimal solutions of Problems 1 and 2, $O_1(S_1)$ and $O_1(S_2)$ are the objective function values of Problem 1 evaluated with solutions S_1 and S_2 , and $O_2(S_2)$ and $O_2(S_1)$ are the objective function values of Problem 2 evaluated with solutions S_2 and S_1 .

We used the General Algebraic Modeling System (GAMS v27.3) to formulate and solve the optimization problems. GAMS is a high-level modeling system for mathematical programming and optimization, consisting of a language compiler and a set of integrated high-performance solvers. We used CPLEX, a solver for the mixed-integer programming problem. The problems proved to be tractable using an everyday laptop computer: solutions to each problem were found in seconds on an HP840G3 Laptop running Windows 10 64-bit operating system.

Results

Problem 1—inspections to prevent the spread of AIS within and outside Stearns County

With an objective of maximizing the number of risky boats inspected while accounting for boat movements within Stearns County and to lakes outside the county, and with an upper bound of ten lakes for inspection stations, the optimal solution is to select the top ten infested lakes having the most (1000–6000) boats departing for uninfested lakes, which are mostly outside of Stearns County (Fig. 2). For comparison, the seven busiest uninfested lakes in Stearns County each received fewer than 700 boats from infested lakes (Fig. 3) and were therefore lower priority for selection.

As we increased the upper bound on the number of lakes selected from one to ten, the proportion of risky boats inspected increased rapidly from 11 to 61 percent (Fig. 5). Increasing the upper bound from ten to 50 lakes, we found that the curve flattened and increased inspection to 88 percent of the risky boats.

We found that the priority order of lake selection with incremental increases in the upper bound largely followed the ranking of lakes according to the number of outgoing risky boats, but with some differences (Table 1). For example, with an upper bound of one inspection station, the optimal solution is Lake Koronis, which has fewer outgoing risky boats than Clearwater Lake (Fig. 2). However, because Lake Koronis has over 700 risky boat arrivals (Fig. 3), its total number of risk boat movements (arrivals plus departures) exceeds the total for Clearwater Lake making Lake Koronis a higher priority. The same logic holds for Grand Lake and Horseshoe Lake, which are the fourth and fifth lakes selected. Although Grand Lake has fewer risky boats departing than Horseshoe Lake (Fig. 2), Grand Lake has more incoming boats from infested lakes than Horseshoe Lake (Fig. 3), which gives Grand Lake higher priority for selection. With each incremental increase in the upper bound on the number of inspection stations from six to ten, the optimal solution involves selecting the lake with the next highest number of risky boats departing.

Stearns County and the North Fork Crow River Watershed District planners selected ten lakes for inspection stations in 2019 based on several criteria, including risk of invasion, boat movement, and matching funds available from local organizations (Stearns County 2019). Six of the lakes selected—Clearwater, Rice, Horseshoe, Grand, Big Fish, and Middle Spunk—are consistent with the lakes selected by the optimization model (Table 1); three are not—Big Watab, Pleasant, and Two Rivers. The tenth lake selected for an inspection station is Big Birch Lake, which straddles the border between Stearns and an adjacent county and is counted outside of Stearns County in our analysis. Using these nine Stearns County lakes, we computed the value of the objective function of Problem 1 and found that this solution inspected 22,004 (42%) of the 52,654 risky boats moving into and out of Stearns County lakes (see black dot for Problem 1 in Fig. 5). For comparison, the optimal set of nine lakes inspected 30,448 (58%) of the

Fig. 5 Proportion of risky boats inspected for increasing upper bounds on the number of lakes selected for inspection stations. The black triangles show the performance of Stearns County's current inspection station locations using the objective functions of Problems 1 and 2

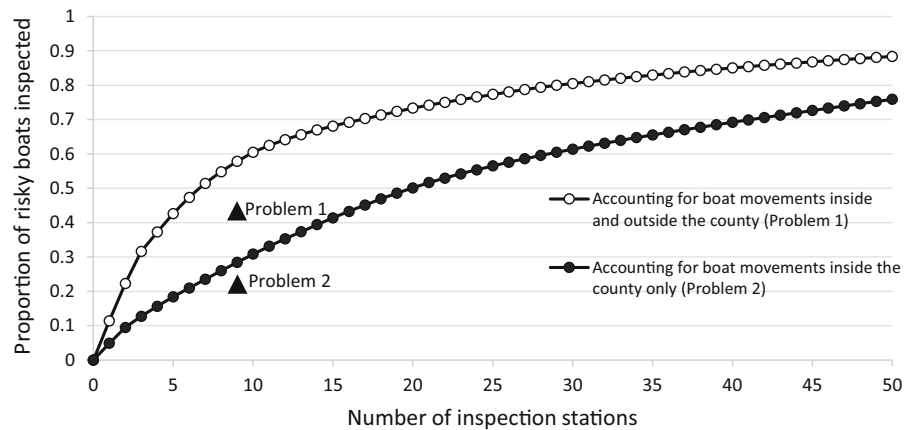


Table 1 Optimal lake selection for increasing number of inspection stations accounting for boat movements inside and outside of Stearns County (Problem 1)

Lake (AIS present)	Number of inspection stations									
	1	2	3	4	5	6	7	8	9	10
Clearwater (zm,ew)		X	X	X	X	X	X	X	X	X
Koronis (ss)	X	X	X	X	X	X	X	X	X	X
Rice (ss)			X	X	X	X	X	X	X	X
Horseshoe (zm)					X	X	X	X	X	X
Grand (ss)				X	X	X	X	X	X	X
Big Fish (zm)						X	X	X	X	X
Cedar Island (zm)							X	X	X	X
Middle Spunk (ew)								X	X	X
Lower Spunk (ew)									X	X
Marie (ew)										X
Proportion boats inspected	0.11	0.21	0.32	0.37	0.43	0.47	0.51	0.55	0.58	0.61

risky boats. As a result, the optimal solution to Problem 1 provides a more cost-effective use of resources than current practice. By changing the location of three of their inspection stations, Stearns County could inspect an additional 8,444 risky boats, thereby reducing by 8444 the number of potential vectors of AIS moving into and out of Stearns County.

Problem 2—inspections to prevent the spread of AIS within Stearns County

In problem 2, we restricted the objective function by excluding risky boats that move from infested lakes within Stearns County to uninfested lakes outside of the county. Using this restricted definition of risky boats, we selected lakes for inspection stations to maximize the number of risky boats inspected subject to an upper bound of ten lakes selected. The optimal

solution is to select nine of the ten lakes with the highest numbers of risky boats arriving and departing (Fig. 4). Clearwater Lake is the exception that is not selected, and it is replaced with an inspection station at Long Lake, which is uninfested. Clearwater Lake is infested with zebra mussel and Eurasian watermilfoil and has a higher proportion of risky boats departing for uninfested lakes in Stearns County (Fig. 4), many of which are already selected for inspection stations because they have large numbers of incoming risky boats. As a result, Long Lake is a more effective location for an inspection station.

Among the ten lakes selected for inspection stations (Table 2), six are infested and consistent with the selections made in Problem 1 (Rice, Koronis, Grand, Horseshoe, Big Fish, and Cedar Island). The other four (Big, North Brown's, Big Spunk, and Long) are not currently infested and differ from the selections made

Table 2 Optimal lake selection for increasing number of inspection stations accounting for boat movements inside of Stearns County only (Problem 2)

Lake (AIS present)	Number of inspection stations									
	1	2	3	4	5	6	7	8	9	10
Rice (ss)	X	X	X	X	X	X	X	X	X	X
Koronis (ss)		X	X	X	X	X	X	X	X	X
Grand (ss)			X	X	X	X	X	X	X	X
Horseshoe (zm)				X	X	X	X	X	X	X
Big Fish (zm)					X	X	X	X	X	X
Big						X	X	X	X	X
Cedar Island (zm)										X
North Brown's								X	X	X
Big Spunk							X	X	X	X
Long									X	X
Proportion boats inspected	0.05	0.09	0.13	0.16	0.18	0.21	0.23	0.26	0.28	0.31

in Problem 1. Because we restricted the objective function in Problem 2 by excluding risky boats that move from infested lakes within Stearns County to uninfested lakes outside of the county, many of the infested lakes with large numbers of boats departing for uninfested lakes outside of Stearns County were no longer a high priority for selection.

Similar to the results for Problem 1, the proportion of risky boats inspected increases with the upper bound on number of lakes selected for inspection stations (Fig. 5); however, the curve for Problem 2 is below that of Problem 1. Increasing the upper bound from one to ten lakes selected increased the proportion of risky boats inspected from 5 to 31%. Increasing the upper bound from ten to 50 lakes resulted in decreasing marginal returns, with proportions of risky boats inspected increasing from 31 to 76%.

We found that the priority order of lake selection with incremental increases in the upper bound largely followed the ranking of lakes according to the sum of their outgoing and incoming risky boats, but with some differences (Table 2 and Fig. 4). With each incremental increase in the upper bound on the number of inspection stations from one to six, the optimal solution involves selecting the lake with the next highest sum of risky boats arriving and departing (Rice, Koronis, Grand, Horseshoe, Big Fish, and Big). The next three lakes selected—Big Spunk, North Brown's, and Long—are uninfested and have almost the same numbers of boats arriving from infested lakes (611–617 boat movements each). Their order of selection reflects differences in the frequencies of

boats arriving from infested Stearns County lakes that are already selected for inspection stations. Although the tenth lake selected—Cedar Island—has a higher number of risky boats arriving and departing than other lakes selected, it has a lower priority for selection because it is infested with zebra mussel and has risky boat movements to uninfested lakes already selected for inspection stations.

Four of the nine selected lakes in Stearns County for inspection stations in 2019 were consistent with the optimal solution for Problem 2 (Rice, Grand, Horseshoe, and Big Fish). Using the nine lakes selected in Stearns County, we computed the value of the objective function of Problem 2 and found that this solution inspected 5,619 (24%) of the 23,661 risky boats moving into Stearns County Lakes (see black dot for Problem 2 in Fig. 5). For comparison, the optimal set of nine lakes inspected 6730 (28%) of the risky boats. As a result, the optimal solution to Problem 2 provides a more cost-effective use of resources than current practice. By changing the location of five of their nine inspection stations, Stearns County could inspect an additional 1,111 risky boats, thereby reducing by 1,111 the number of potential vectors of AIS moving into Stearns County lakes.

Tradeoff analysis

The tradeoff between the management objectives of maximizing the protection of lakes both within Stearns County and outside of the county (Problem 1) and maximizing the protection of lakes within Stearns

County alone (Problem 2) is significant (Table 3). Using the 10-lake optimal solution obtained for Problem 2, the value of the objective function for Problem 1 (23,770 risky boats inspected) was 25 percent less than the optimal solution for Problem 1 (31,858 risky boats inspected). This reduction in risky boats inspected in Problem 1 is caused by moving inspection stations away from four infested lakes in the optimal solution for Problem 1 (Clearwater, Middle Spunk, Lower Spunk, and Marie), which together send over 8000 risky boats per year to uninfested lakes outside of Stearns County, and putting them at four uninfested lakes (Big, North Brown's, Big Spunk, and Long). This move increases protection of uninfested lakes inside Stearns County at the expense of protecting uninfested lakes outside of Stearns County.

The tradeoff between the management objectives of maximizing the protection of Stearns County lakes (Problem 2) and maximizing the protection of lakes both within Stearns County and outside the county (Problem 1) is not as great (Table 3). Using the 10-lake optimal solution for Problem 1, the objective function value for Problem 2 (6715 risky boats inspected) was 8 percent less than the optimal solution for Problem 2 (7298 risky boats inspected). This reduction in risky boats inspected in Problem 2 is caused by moving inspection stations away from four uninfested lakes in the optimal solution of Problem 2 (Big, North Brown's, Big Spunk, and Long), which receive over 2400 risky boats from infested lakes inside and outside of Stearns County, and putting them at four infested lakes (Clearwater, Middle Spunk, Lower Spunk, and Marie). This move increases protection of uninfested lakes outside of Stearns County at the expense of protecting uninfested lakes inside Stearns County.

Discussion

We developed an integer programming model for allocating scarce inspection resources among lakes to slow the accidental spread of AIS by recreational boaters. Our model is based on information about the species-specific infestation status of lakes and estimates of boat movement between lakes. The objective is to select lakes for inspection stations to maximize the number of risky boats inspected, where risky boats are ones that move from infested to uninfested lakes. This objective serves to minimize the propagule pressure on uninfested lakes.

In our application to planning for boat inspections in Stearns County in central Minnesota, we highlight the tradeoffs between management objectives that planners may adopt to account for risky boats that exit the county. The tradeoffs between the objective of maximizing the protection of uninfested lakes inside and outside the county, which accounts for boat movement from infested Stearns County lakes to uninfested lakes outside the county, and the objective of maximizing the protection of uninfested lakes within Stearns County alone, which does not account for boats exiting the county, are significant. With the former objective, the optimal policy is to prioritize infested lakes with the highest levels of boat movement to lakes outside of the county. With the latter objective, the optimal policy is to prioritize both infested lakes that are prime sources of boat movement to uninfested lakes inside the county and uninfested lakes that are prime destinations of boat movement from infested lakes outside the county. The difference in these optimal policies highlights the need for planners to carefully weigh their preferences for protecting uninfested lakes inside versus outside their

Table 3 Objective function values for alternative solutions to Problems 1 and 2 using an upper bound of 10 lakes selected

Problem ^a	Solution		Loss ^b
	Optimal for Problem 1	Optimal for Problem 2	
1	31,858	23,770	0.25
2	6715	7298	0.08

^aProblem 1 maximizes the protection of lakes both within Stearns County and outside of the county, while Problem 2 maximizes the protection of lakes within Stearns County alone

^bFor each problem (row), loss percentage is the difference between the objective function value of the optimal solution for the problem and the objective function value of the alternative solution divided by the objective function value of the optimal solution

county jurisdictions. The difference also highlights the need for cross-county cooperation and statewide coordination of county-level inspection programming.

We use the model to prioritize lakes for inspection stations under increasing levels of budget, expressed as an upper bound on the number of lakes selected for inspection stations. The results showed decreasing marginal returns in the number of risky boats inspected for increasing budgets, especially for budgets greater than ten lakes. When planners have estimates of the cost of inspection stations and the benefits of avoided AIS damages associated with increased boat inspection, then they can use marginal benefit curves in benefit–cost analyses to estimate the optimal budget level for inspection stations.

From a methodological standpoint, our model for optimizing inspection station locations is similar in structure to the integer programming model of Fischer et al. (2021), who determined the location and operating time of roadside inspection stations to maximize the number of risky boats inspected. Their model is based on estimates of the daily variation in boater movement along pre-defined routes that connect infested and uninfested waters. In contrast, our model is based on boater movement between lakes and species-specific infestation status of those lakes. As a result, we model the location of lakeside inspection stations where boats enter and leave lakes and account for species-specific differences in infestation status between pairs of lakes. Like the model of Fischer et al. (2021), our model facilitates the detailed analysis of tradeoffs between management objectives and the effects of cost constraints. Further, our integer programming formulation, with hundreds of lakes and hundreds of thousands of lake connections, can be solved exactly in seconds using commercial software on everyday laptop computers. This capability bodes well for solving expanded formulations that incorporate lakes and boat movement for many counties at once.

There are several ways to improve our formulation to more realistically fit practical AIS management. For example, we assume that Stearns County lakes all have the same likelihood of becoming infested per unit of propagule pressure. Realism could be strengthened by using the bio-physical characteristics of lakes to estimate the likelihood of AIS establishment and incorporating those likelihoods into a model for calculating the expected number of risky boats moving

among lakes. Likewise, incorporating estimates of AIS risk for each boat type, frequency of boat movements by time of day/week/month, variable costs of inspections at different sites, and opportunities to leverage support from stakeholders could improve the realism of the model if those data are collected in the future. Another area of exploration is the uncertainty in the estimates of boat movement among lakes. This uncertainty could be accounted for by developing scenarios representing the distribution of possible boat movement outcomes. Then, these scenarios could be incorporated into the optimization model with an objective of maximizing the expected number of risky boats inspected or an objective of minimizing the cost of maintaining protection thresholds for specified lakes. Examples of these formulations have been developed for management problems with uncertain invasion spread (Yemshanov et al. 2017). It is important to note that improvements to our model like those discussed above may affect optimal resource allocations and alter conclusions about the effectiveness of actual decisions. Lastly, solutions to our model represent the optimal placement of inspectors based on the infestation status of lakes within the study period. We acknowledge that invasion processes are dynamic and the infestation status of lakes will change over time. As a result, the optimal resource allocation based on today's conditions may be suboptimal at a later point in time as invasion status changes. New information about lake infestations could be incorporated into the optimization model over time to obtain solutions that reflect current conditions.

Our formulation applies to a single, local governance unit (i.e., the county). In practice, the governance of AIS interventions and other conservation practices involves collaborative decision making at both the regional and local levels (Armsworth et al. 2020). For example, the State of Minnesota allocates funds to counties for boat inspection and boater education to slow the spread of AIS within the state. County planners, in turn, make decisions to slow AIS spread within their county jurisdictions. Meanwhile, the MNDNR also allocates their own funding for watercraft inspection at a regional scale, that may or may not be coordinated with local planners. An area of future research is to model this bi-level structure of decision making with the goal of improving the cost-effectiveness of regional funding allocations across local jurisdictions and local management decisions.

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Declarations

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

Code availability Yes; however, license for commercial optimization solver is required.

Data availability The datasets analyzed during the current study are available from the corresponding author on reasonable request.

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