Evaluating the Potential for Technology Adoption in Mitigating Invasive Species Damage and Risk: Application to Zebra Mussels

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Introduction and background

Invasive species hinder ecological goods and services; they may be the primary cause of biodiversity loss (Mack et al., 2000) and they significantly reduce nature-based recreation (e.g., Lee et al., 2009). They also erode the functionality of natural systems, and can impede irrigation, flood control, and other critical services. Control of invasive species in tropical and sub-tropical areas is a constant and growing drain on scarce resources. In Florida, agriculture and silviculture sectors spend over $265 million per year controlling invasive pests (Kim et al., 2007); public spending by State government was $103 million in 2006 (FLDEP, 2006).

A new threat to the State of Florida is the zebra mussel (*Dreissena polymorpha*). Because of the interconnectedness of Florida's waterways, fragility of Florida's freshwater ecosystems, and high level of dependence on surface water, vigilance will be needed to prevent zebra mussels (ZM) from colonizing Florida waters. ZM first entered the Great Lakes over 10 years ago and have already spread thousands of miles infesting U.S. waterways, altering ecosystems, and generating in excess of $60 million per year in economic damages to water intake systems, water front properties, bridges and infrastructure. Lake Okeechobee in Florida is vulnerable to a ZM invasion and susceptible to ZM establishment and spread. A ZM infestation would significantly erode the valuable ecosystem goods and services that the lake provides: surface water for irrigation to Florida's Everglades Agricultural Area, recreation, fishery activity, and other ecosystem services, like habitat for wildlife.

A study by Lee et al. (2007) estimated that the probability of a severe infestation in Lake Okeechobee ranges from 2% to 98%, depending on the level of monitoring, arrival prevention, and response planning. The authors found that with an overall management strategy that included an annual prevention and monitoring program costing $152,000 per year, the net gain in avoided damages and eradication costs would total $188 million over 20 years. Despite creation of an aquatic nuisance species task force in 1999, the State of Florida has no plan for preventing, monitoring, or responding to a ZM invasion. Lack of a State management plan could be explained by (1) uncertainty of ZM arrival, rate of spread, and likely damages; and (2) public funding scarcity, fiscal constraints, and high opportunity costs. With technologies that promise to lower avoidance costs, increase the effectiveness of control, and raise the certainty of management outcomes, the decision to implement a management plan could soon be on the agenda. This study aims to inform that decision.

The threat to Lake Okeechobee from ZM

Lake Okeechobee is a 448,000 acre lake located in South Florida (FDEP, 2001). The lake is an important resource for drinking water, irrigation, and a variety of ecosystem goods and services in and around the five counties that surround the lake. ZM would significantly impact the value of Lake Okeechobee for a variety of uses.

The lake is currently ZM-free, but ZM-infested lakes are within a day's drive (approximately 750 miles away) (Lee et al., 2007). ZM transmission to Lake Okeechobee is expected to occur very rarely. For viable ZM to arrive in the lake, they would have to travel overland from the nearest-known ZM-infested waters, survive the extreme stresses of overland transportation, and be transported in sufficient numbers to effectively reproduce upon arrival. ZM have high expected mortality rates from overland transportation (Ricciardi et al., 1995) and low numbers of ZM are expected for a single dispersal (Johnson and Padilla, 1996). However, ZM can survive for long periods of time out of water, and researchers in the Great Lakes region found live ZM attached to aquatic weeds on roughly 1/275 boats preparing to launch into uninfested lakes (Johnson and Carlton, 1996). Given the popularity of Lake Okeechobee for out-of-state anglers, and the current distribution of ZM in the United States, it is assumed that ZM transmission into the lake would occur via out-of-state boaters from states with ZM infestations.

The role of new technologies

A 2007 study by Lee et al. examined the use of early detection, boater education/awareness, anti-fouling paint, and potassium chloride. For a detailed description of these management tools, see Lee et al. (2007). We investigate the value of adopting two emerging technologies to help manage ZM under the same conditions explored by Lee et al.: hot wash stations and Zequanox.

Washing potentially-infested boats and boating equipment with hot water has been found to be effective at killing ZM veligers and removing aquatic macrophytes that may be transporting adult mussels (e.g., Rothlisberger, 2009). Hot wash stations are made available to boaters in Nevada, South Dakota, Maine, Massachusetts, Minnesota, Wisconsin, Vermont, New Hampshire, and elsewhere for voluntary use to prevent transport of ZM to uninfested lakes. Use of the technology in Florida would require anglers travelling from *out-of-state* to clean their boats *before* entering Florida waters. Together with boater education and awareness campaigns, hot wash stations are expected to be 91% effective at preventing the arrival of ZM.

The pesticide Zequanox has been tested in closed systems and is expected to be 70% to 100% effective at eradicating ZM in open systems (e.g., lakes and ponds). Prior to Zequanox, potassium chloride had been used to eradicate ZM in small systems, but untested in large lakes. With a surface area of 730 square miles, Lake Okeechobee is one of the largest lakes in the United States. The new pesticide offers a lower cost option for rapid reaction to a ZM infestation in Lake Okeechobee. Zequanox is currently being formulated for open water, and is expected to be highly effective at eradicating ZM.

Research Methodology

We employ a stochastic dynamic bio-economic model of ZM to examine the expected economic value of prevention, control, and eradication alternatives for the freshwater mussel in Lake Okeechobee in Florida. Results from Lee et al. (2007) are extended and compared with two recent additions to the management portfolio for zebra mussels: (1) Zequanox, and (2) hot wash stations at boat ramps.

Data for the analysis was collected from the water management district, phone surveys, prior work, and technology manufacturers. Methods used include: static cost transfer estimation, econometric cost estimation, and stochastic-dynamic simulation. The bio-economic model is used to simulate plausible management scenarios to compare costs, damages, and risks with and without the new technologies and to draw inferences regarding the likelihood of technology adoption.

Management Alternatives

Effective management and prevention of AIS requires knowledge of introduction pathways, ecological processes, and impacts of invasion. Few of the ZM policy alternatives have been assessed for effectiveness of prevention, costs, and other salient features needed for decision-support. We extend the work by Lee et al. (2007) to include emerging ZM management technologies.

Prevention using hot wash stations

Targeted species prevention, for example by focusing on species transmission choke points, has been found to be more effective than non-targeted prevention. There are roughly 13 million registered boaters in the US, providing numerous opportunities for AIS spread. Recreational boats are suspected to be the primary cause of ZM spread for non-connected waters, which has led to the creation of programs that specifically target recreational boaters, including public awareness and education campaigns. For example, information campaigns (e.g., Protect Your Waters, http://www.protectyourwaters.net/) educate boat owners and the general public about steps they can take to prevent and detect AIS (Protect Your Waters, 2010).

Boat washing stations are a tool for preventing the spread of ZM. Boat washing stations employ high-pressure and often very hot water spray to kill and remove AIS from boat hulls, trailers, and related equipment. For example, the University of Wisconsin's Clean Boats Clean Waters program (http://www.uwsp.edu/cnr/uwexlakes/CBCW/) suggests that boaters "spray/rinse with high pressure, and/or hot tap water (above 104º F or 40º C), especially if moored for more than a day; Or dry for at least five days" (Clean Boats Clean Waters, 2010).

Several versions of boat washing are available to boaters: (1) commercial car washes, (2) home cleaning, (3) portable sprayer or drive-through systems, and (4) permanent stations at boat ramps (Jensen, 2009). States have opted for mandatory or voluntary washing after boating in or near ZM-infested water bodies. Both permanent and portable "hot wash" stations have been installed at lake ramps in New York, Minnesota, and Ontario (Canada).

There is little empirical work analyzing the costs of boat wash stations in the US. However, recent work by Jensen (2009) provides an overview of costs from case studies in the Great Lakes region. Portable sprayer systems cost approximately $3,200 for initial purchase, and access is typically provided either free or through coin-operation. Permanent stations typically charge $10 (compared to $15 launch fee). Total costs for boat wash stations on a given water body depend on use. For example, boat wash stations on Lake Mead, NV would need to wash 5,000 boats per day. Assuming 15 minutes per boat, this would require 39 stations costing approximately $11 million initially.

There are critical information gaps on the cost of wash stations (Jensen, 2009; Colorado River 100th Meridian Team meeting, Jan. 30, 2007). An example station would cost $36,675 to install. This includes a treatment system ($15,600), staff training ($700), new concrete wash pads ($3,950), settling tanks to capture and clean runoff ($8,325), plumbing and electrical work ($3,800), and engineering work ($4,300) (Jensen, 2009; Colorado River 100th Meridian Team meeting, Jan. 30, 2007). One recent estimate put average hot wash costs at about $40 for a small boat and up to $200 for a houseboat (Milwaukee Journal Sentinel, 2009).

There has been little empirical work done to evaluate the effectiveness of AIS mitigation strategies, including boat washing stations. However, one recent study in the Great Lakes region found boat washing and visual inspection/manual removal to be effective. For small-bodied organisms (like ZM veligers) and plant seeds, boat washing was highly effective: 91% ± 2% removal rate for high-pressure wash, 74% ± 6% for low-pressure wash, and 65% ± 4% for manual removal (Rothlisberger, 2009). These methods were also effective for aquatic macrophytes, which can harbor ZM. Hand removal following visual inspection can reduce aquatic plant material by 88% ± 5%; high-pressure wash was similarly effective (83% ± 4%), but low-pressure wash was considerably less effective (62% ± 3%) (Rothlisberger, 2009).

In practice, the effectiveness of boat wash stations will be greatly influenced by participation rates. One mail survey (n=396) of registered boaters in Wisconsin and Michigan found that only 57% always 'remove aquatic weeds attached to your boat or trailer' and only 27% 'clean your boat by rinsing, pressure washing, or drying." Further, these boaters visited an average of 2.66 different waterways in the two weeks prior to the survey (Rothlisberger, 2009:79).

A survey of boater attitudes in the Twin Cities area of Minnesota found that 63% agree that boat washing should be mandatory on infested waters, while the remaining 37% agree that it should be voluntary (Jensen, 2009). Both costs and time are serious constraints to voluntary boat washing. Only 45% would be willing-to-pay for boat washing (and an additional 25% were uncertain). Of those indicating a willingness-to-pay, 64% would only pay $1-2, 29% would pay $3-4, and a mere 7% would pay $5-6 (Jensen, 2009). Respondents also indicated an unwillingness to spend a lot of time washing their boats; 69% would be willing to wash their boat if it took five minutes, while only 26% would do so for 10 minutes, and five percent would do so if it took 15 minutes (Jensen, 2009). The author indicated other problems with boat washing: costs might need heavy subsidization for voluntary programs, washing would cause delays and congestion at boat ramps, and washing did not remove all aquatic vegetation. Further, to be most effective, a wash station would need a staff person to operate or help operate the wash equipment.

Eradication using Zequanox

Zequanox is a microbial product derived from the dead cells of *Pseudomonas fluorescens*. In high doses, the product effectively kills zebra mussels as they filter-feed, causing the epithelial lining of their stomachs to hemorrhage (Sarahann Dow, 2010 [pers. comm.]). Although the microbe is toxic to zebra mussels, it is one of the most common bacteria found in water and soil, with no acute toxicity to mammals (as required for US EPA registration; Dow, 2009).

Marrone Bio Innovations, owners of Zequanox, have not yet released pricing information; however early indications are that it would be priced comparable 20-times the cost to treat invasive aquatic plants in open water. From 1998-2002, the average annual per-acre cost to control hydrilla in Florida was $561, and to treat water hyacinth and water lettuce it was $107 (Adams and Lee, 2007). By these estimates, at 20-times the cost to treat invasive aquatic plants, Zequanox is expected to cost between $2140 and $11,220 per acre to treat ZM in open water.

Although this will likely make it as expensive or more than potassium chloride (potash), as was used in Milbrook Quarry, Virginia to eradicate ZM, Zequanox would likely be preferred for its lack of non-target species impacts. Marrone is currently working with SePro (a company with expertise in applying aquatic herbicides to control invasive plants) to develop a cost of treatment on a per-acre basis for Zequanox in open water.

To achieve a high level of effectiveness against ZM, Zequanox levels must be kept at about 25-50 parts per million in the target area for 6-10 hours (Sarahann Dow, 2010 [pers. comm.]). It is expected that Zequanox would be >90% effective against adult and 100% effective against veliger ZM at 50-100ppm for 6 hours. At 10 hours and 50ppm, 100% effectiveness has been achieved in lab settings (Dow, 2010 [pers. comm.]). Zequanox attenuates naturally in the water (which is desirable from an environmental perspective), so site-specific formulation may be required and will depend on environmental factors such as flow rate.

The product is not yet approved for commercial release, but the Bureau of Reclamation has granted a section 18 emergency use permit for Zequanox in two Colorado water bodies. These will provide the first data of Zequanox effectiveness and other evaluation metrics for open water use.

Bioeconomic model

Mathematical model

We use a stochastic dynamic programming approach (i.e., transition probability matrices in a Markov chain) to evaluate the expected net benefits under several feasible policy alternatives. We follow an approach similar to Leung et al. (2002), Finoff et al. (2005), and Buhle et al. (2005) who used a stochastic dynamic programming approach to model the impact of invasive mussels and mollusks.

We simulate the impacts of policy alternatives that include the use of existing management strategies as well as new technologies that show promise for mitigating invasive species damage. The following model is adapted from Lee et al. (2007).

Four distinct ZM-related states (s_i) for the lake are: (1) uninvaded, (2) arrived, (3) growing/spreading, and (4) at carrying capacity. For any time period t, we calculate the probability that the lake is in each of the four ZM states:

(1) $$S_t = \begin{bmatrix} s_1 \\ s_2 \\ s_3 \\ s_4 \end{bmatrix}_t \quad \textit{where} \quad 0 \le s_{it} \le 1 \quad \textit{and} \quad \sum_{i=1}^{4} s_{it} = 1.$$

At time t=0, the lake is not invaded, such that the state is:

(2) $$S_0 = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}_{t=0} .$$

At time t+1, S_{t+1} is given by:

(3) $$S_{t+1} = A_0 S_t .$$

where A_0 is a matrix of transition probabilities:

(4) $$A_0 = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix}.$$

where a_{ij} is the probability of transitioning from state j to i in a single time period. Arrival of ZM is assumed to follow a gravity model of jump dispersal based on boater behavior (Lee et al., 2007). The lake is not directly connected to any waterways that are suspected to be infested by ZM, and ZM arrival would likely occur when a recreational boater arrives with live ZM veligers and/or adult mussels on boating equipment (e.g., on trailers, on fishing equipment, in live wells). Given the high habitat suitability index for ZM on Lake Okeechobee (Hayward and Estevez, 1997), we assume a high probability (1.0) of ZM reproducing and reaching carrying capacity within a short period of time. Once carrying capacity is reached, significant economic and environmental damages will occur.

Prevention measures reduce the probability that ZM will be introduced and propagate. Let f_1 be the effectiveness of prevention efforts. When *only prevention* is undertaken, S_{t+1} is given by the transition probabilities in matrix A_p:

(5) $$A_p = \begin{bmatrix} a_{11} - a_{21} f_1 & a_{12} & a_{13} & a_{14} \\ a_{21}(1 - f_1) & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix}.$$

Alternatively, the state could pursue a policy of *only eradication*. Here, we assume that there would be no spending on prevention or early warning, and ZM would only be detected once economic damages begin to accrue in state 4. Eradication is achieved by using either potassium chloride or Zequanox to kill all ZM veligers and adult mussels in the lake. Under this policy, S_{t+1} is given by transition probability matrix A_r:

(6) $$A_r = \begin{bmatrix} a_{11} & 1 & 1 & 1 \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & 0 & a_{33} & a_{34} \\ a_{41} & a_{42} & 0 & 0 \end{bmatrix}.$$

Following eradication, the lake is assumed to be free from ZM for n years, and during this time the transition probability matrix is A_n:

(7) $$A_n = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}.$$

When both prevention and eradication measures are pursued, prevention measures reduce the probability of arrival and propagation, and when ZM are discovered in state 3, they are eradicated before significant damages occur. This policy modeled using transition probability matrix A_m:

(8) $$A_m = \begin{bmatrix} a_{11} - a_{21} f_1 & 1 & 1 & 1 \\ a_{21}(1 - f_1) & a_{22} & a_{23} & a_{24} \\ a_{31} & 0 & a_{33} & a_{34} \\ a_{41} & a_{42} & 0 & 0 \end{bmatrix}.$$

ZM management choice is defined as matrix X, comprised of x_p and x_r:

(9) $$X = \begin{bmatrix} x_p & x_p & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & x_p x_r & 0 \\ 0 & 0 & 0 & x_r \end{bmatrix}$$

Prevention only is given as x_p=1 and x_r=0; for eradication only, x_p=0 and x_r=1; and for both prevention and eradication, x_p=1 and x_r=1. Depending on the scenario being considered, prevention may include hot wash stations, and eradication includes either potassium chloride or Zequanox.

The two management choices (prevent, eradicate) yields four management alternatives:

(10) $$u(X) = \begin{bmatrix} (1 - x_p)(1 - x_r) \\ x_p(1 - x_r) \\ (1 - x_p)x_r \\ x_p x_r \end{bmatrix}.$$

Direct public costs of prevention and eradication are c_p and c_r which comprise the management cost vector q.

(11) $$q = \begin{bmatrix} c_p \\ 0 \\ c_r \\ c_r \end{bmatrix}.$$

Three policy scenarios are considered: (1) prevention without boat wash stations and eradication with potassium chloride, (2) prevention with boat wash stations and Zequanox (at a low cost estimate), and (3) prevention with boat wash stations and Zequanox (at a high cost estimate).

Costs for the standard technology scenario 1 are given as:

(12) $$q_1 = \begin{bmatrix} c_p \\ 0 \\ c_{rk} \\ c_{rk} \end{bmatrix}$$

where c_p is the cost of arrival prevention and monitoring per year, without hot wash stations, and c_{rk} is the annualized cost of eradication using potassium chloride.

The costs of new technologies – hot wash stations and Zequanox – are given as two possible scenarios:

(13) $$q_2 = \begin{bmatrix} c_p + c_{wL} \\ 0 \\ c_{rzL} \\ c_{rzL} \end{bmatrix}$$ and

(14) $$q_3 = \begin{bmatrix} c_p + c_{wH} \\ 0 \\ c_{rzH} \\ c_{rzH} \end{bmatrix}$$

where c_{wL} (c_{wH}) is the cost of prevention with the low-cost (high-cost) estimate for hot wash stations, and c_{rzL} (c_{rzH}) is the annualized low-cost (high-cost) estimate for Zequanox.

In each year of the simulation, the cost of management C_t is a product of unit cost (q), management (X), and ZM state:

(15) $C_t = q'X\, S_t$.

A ZM infestation is expected to cause economic damages *d*, an *X*-dependent variable that captures the increased private costs by surface water users (anti-fouling paint). Environmental damages *e* includes reduced wetland function, habitat loss, etc in state 4. Increased water clarity, due to ZM clearing the water column, is expected to improve angler catch rates. The benefit to anglers from ZM infestation is *b*.

We specify an objective function, where management strategy *X* is chosen to maximize the present value net benefits *Z* of the threat of ZM infestation:

(16) $$\max\ Z = \sum_{t=0}^{T} (1+r)^{-t} \left(q'X\, S_t) + (e' + b')S_t + u(X)'d(X)'S_t \right) .$$

where *r* is the discount rate and *T* is the planning horizon in years.

Empirical Model

ZM arrival probabilities are taken from Lee et al. (2007), who calculated the probability of ZM being introduced to Lake Okeechobee from out-of-state boats. They examined registration data from national fishing tournaments on the lake from 2006-2007, applied transmission probabilities from the Great Lakes region (Bossenbroek et al., 2001), and arrived at a 3.5% annual probability of ZM being introduced to the lake ($a_{21} = 0.035$).

Probability of survival is assumed from Hayward and Estevez (1997), who computed habitat suitability indices (HSI) for ZM in Florida waters. Based on the high HSI for ZM in lakes with biophysical attributes similar to Lake Okeechobee, we assumed that ZM would rapidly establish, propagate, and reach carrying capacity with 100% probability ($a_{32} = a_{43} = a_{44} = 1.0$). This assumption is consistent with numerous studies that indicate ZM reaching carrying capacity within two to three years after initial detection (Lee et al., 2007). We assume that ZM begin to cause environmental damages after two years following introduction, so that the time from state 2 to 3, and from 3 to 4 is one year each.

Private damages and mitigation costs for surface water users are taken from Lee et al. (2007). Private damages are assumed to be a function of mean water withdrawal (USGS, 2006) and a unit cost to clear clogged intake pipes from Deng (1996) and O'Neill (1996), equaling \$2.76 million in annual damages.

Mitigation costs are for application of anti-fouling paint on surface water intake pipes. Adams (2007) calculates the average surface area of intake pipes and estimates the number of major water users to arrive at $3.87 million in private mitigation costs, based on a $25.56 per square foot application cost (Phillips, 2005) and a survey of Lake Okeechobee surface water use and intake pipe inventory. Given that the paint is effective for 10 years on average, the annualized private mitigation cost is $0.387 million. Further, we assume that anti-fouling paint is effective at reducing maintenance costs by approximately 22%; that is, with a ZM infestation, additional total maintenance costs faced by surface water users would be $3.37 million per year.

Losses to ecosystem services are captured by the value of nearly 60,000 acres of wetlands surrounding the 448,000-acre lake. Costanza et al. (2003) estimates per-acre wetland services to be worth $1,083 per year. Using the wetlands as a proxy for total loss of services on the lake following a ZM infestation yields $64.98 million per year in ecosystem damages.

Recreational fishing is a major use of the lake. Each year, anglers spend about 1.57 million hours fishing on Lake Okeechobee (FFWCC, 2003). Assuming an average per-trip expenditure of $20.65 per hour for freshwater fishing in Florida (FFWCC, 2003), Lee et al. (2007) approximate the value of the lake to anglers to be $32.5 million annually. We assume a 1% increase in fishing effort due to ZM infestation, which would increase water clarity and is expected to improve fishing catch rates. This yields a $0.325 million per year increase in anger benefits for ZM in state 4.

Management costs are taken from Lee et al. (2007) for ZM monitoring by the US Army Corps of Engineers to inspect structures, sample waterways, and educate boaters and others about ZM at a cost of $152,800 annually. The cost of eradication using potassium chloride comes from the singular instance of ZM eradication in the United States in Milbrook Quarry, VA. The total cost to eradicate was $365,000 to apply 174,000 gallons of a potassium chloride solution (VDGIF, 2007). At the same per-acre cost as Milbrook Quarry, it would take $1.32 billion to eradicate ZM in Lake Okeechobee using potassium chloride. The annualized cost is $55.03 million per year, and the treatment is assumed to be 100% effective.

The cost of hot wash stations is estimated from non-resident boat launches on Lake Okeechobee and cost estimates for hot wash stations from the Great Lakes region. The number of freshwater fishing trips to

Lake Okeechobee by non-residents we estimate to be 46,288 per year based on a composite of boat launch statistics, angler profiles, and characteristics of nonresident fishing trips (Wiggin et al., 2009:186-7). Assuming the majority of fishing occurs during the non-summer months, we estimate an average of 143 to 191 non-resident boat launches per day. Assuming the non-residents would be required to wash their boats only before the first launch of their trip, the number of required hot boat washes for Lake Okeechobee comes to 128 to 170 per day. A hot wash station that can handle 12 boats per hour via 3 working stalls would cost about $36,675. Assuming the station operates 12 hours per day the station capacity would be 144 boats per day. We estimate that Lake Okeechobee would need a minimum of 1.18 hot wash stations at a cost of $43,361.

The feasibility of a single operating station would require that it be centrally located and provide boaters with a certification or stamp that can be used to show proof of washing before being allowed to enter the Lake. Alternatively, 5 hot wash stations could be constructed (one per county surrounding Lake Okeechobee) at a cost of $183,375. We amortized the capital cost over 10 years at 2% annual interest to get an annual cost of $4,827 to $20,415 per year. The operation and maintenance cost of hot washing all out of state boats was estimated to be $10 per boat or $462,875 per year. Hot wash effectiveness at removing live zebra mussels is assumed to be the same as high pressure wash, 91%.

The cost of eradicating with Zequanox we estimated to be between $2,140 and $11,220 per acre, based on the relative cost of applying aquatic herbicides (Adams, 2007) and discussions with the makers of Zequanox (Dow, 2010). The cost of disseminating Zequanox over 448,000 acres of Lake Okeechobeee is $958,720,000 to $5,026,560,000. Amortized over 33 years at 2% we obtain an annual cost of $39,965,711 to $209,539,850 per year. Zequanox is highly effective in lab tests, and we assume 100% effectiveness in Lake Okeechobee when the entire lake is fully treated. We provide a summary of the parameter values in Table 1.

Table 1. Parameter values for ZM model.

Symbol	**Definition**	**Model Value**
a_{11}	Probability of zebra mussel not being introduced to Lake Okeechobee	0.965
a_{21}	Probability of zebra mussel being accidentally introduced to Lake Okeechobee	0.035
a_{32}	Probability of zebra mussel moving from state 2 to state 3	1
a_{43}	Probability of zebra mussel moving from state 3 to state 4	1
a_{44}	Probability of zebra mussel remaining state 4	1

all other a_{ij}		0
b	Economic benefits from zebra mussel	\$0.325 mil
c_p	Cost of arrival prevention (through education) and monitoring (per year)	\$0.1528 mil
c_{wL}	Cost of hot wash stations, low (1.18 stations) estimate (annualized)	\$0.0048 mil
c_{wH}	Cost of hot wash stations, high (5.0 stations) estimate (annualized)	\$0.0204 mil
c_{rk}	Cost of eradication with potassium chloride (annualized)	\$55.03 mil
c_{rzL}	Cost of eradication using Zequanox, low estimate (annualized)	\$39.97 mil
c_{rzH}	Cost of eradication, high estimate (annualized)	\$209.54 mil
d_1	Private economic damages without mitigation expenditures (per year)	\$3.37 mil
d_2	Private economic damages with mitigation expenditures (per year)	\$2.76 mil
d_3	Private mitigation expenditures (annualized)	\$0.387 mil
e	Value of wetland services lost with zebra mussels in state 4 (per year)	\$64.98 mil
f_{pp}	Effectiveness of arrival prevention and monitoring	0.75
f_{pw}	Effectiveness of hot wash	0.91
f_r	Effectiveness of eradication measures	1.00
r	Discount rate	0.02
t	Year	0,...,19
T	Planning horizon	20 years

Simulated Policy Scenarios

We simulate the net benefits of the policy alternatives using several simulated policy scenarios. Four scenarios are considered: (1) *Do nothing*, in which direct public spending on ZM prevention and eradication are zero; (2) *Only prevention*, in which the state of Florida funds an early warning and prevention program that includes boater awareness/education, early warning, and hot wash stations; (3) *Only eradication*, which holds spending on prevention at zero for all years, and eradicates ZM using Zequanox or KCL if they arrive; and (4) *Prevention and eradication*, which is a combination of policies [2 – 3] above. See Table 2.

For all scenarios, ecosystem losses (e) and public recreation benefits (b) accrue for each year that the ZM are in state 4. Surface water users face private damages d_1 for the year that ZM are in state 4.

For the *do nothing* management alternative, public spending on ZM is zero. Surface water users are assumed to be unaware of newly-established ZM until the year they reach state 4 and cause d_1 damages.

The next year, these water users apply anti-fouling paint that mitigates ZM damages d_2 and private mitigation costs d_3 in following years.

Under *prevention only*, public direct costs are c_p for each year that ZM are in states 1 or 2. If ZM reach states 3 or 4, prevention costs are suspended (c_p=0). Early warning allows private users to apply anti-fouling paint while ZM are in state 3 at a cost of d_3. In subsequent years, private users face damages and mitigation costs $d_2 + d_3$.

With *eradication only*, public direct costs for arrival prevention and monitoring at zero (c_p=0). When ZM reach state 4, ZM eradication is attempted using Zequanox or potassium chloride. The cost of eradication is given by c_{rk} for potassium chloride. Zequanox is not yet approved for market, and costs are not yet available; however, discussions with the makers of Zequanox indicate that per-acre application prices are expected to be roughly 20-times the cost of controlling invasive aquatic plants (Dow, 2010 [pers. comm.]). We assume two feasible costs for Zequanox based on the relatively low per-acre cost of floating plants (e.g., water hyacinth and water lettuce), c_{rzL}, and the relatively high per-acre cost of controlling hydrilla, c_{rzH}. Post-eradication, private damages and costs d_1 drop to zero.

Prevention and eradication relies on a combination of prevention and eradication efforts. Under this policy, public direct spending is c_p during ZM states 1 and 2, c_r when the system is in state 3 (to achieve eradication) for the standard technologies. For new technologies, direct spending would be c_p plus either c_{wL} or c_{wH} during ZM states 1 and 2, and c_{rzL} or c_{rzH} during state 3. This combination prevents ZM from reaching state 4, thus avoiding private damages to surface water users, changes in public recreation benefits, and loss of ecological services.

Table 2. Policy scenarios.

	Strategy	**Scenario I (Standard technologies)**	**Scenario II (New technologies – low cost)**	**Scenario III (New technologies – high cost)**
Early warning	Prevention/ Eradication	Yes	Yes	Yes
Boater education/awareness	Prevention	Yes	Yes	Yes
Hot wash stations	Prevention	No	Yes (~1 station)	Yes (5 stations)
Potassium chloride	Eradication	Yes	No	No
Zequanox	Eradication	No	Yes (low cost)	Yes (high cost)

The empirical zebra mussel model was run with GAMS software (GAMS, 2009).

Results

We simulated the four management alternatives under three scenarios (Standard technologies, New technologies – low cost, and New technologies – high cost), and report the results in Table 3. Under the standard technologies scenario and a *do nothing* approach, ZM are expected to cause $244.09 million in present value net losses; $219.48 million are from loss of ecosystem services, $25.71 million are related to private water users' damages and mitigation costs, and $0.10 million in additional benefits occur as a result of improved fishing on the lake. An *only prevention* management approach costs $2.48 million in public expenditures, but significantly reduces the value of lost ecosystem services and private damages and mitigation costs. Under this approach, ecosystem service losses are valued at $62.43 million, and private damages and mitigation costs are just $7.25 million. Benefits to anglers also increase to $0.31 million. The expected net present value of ZM infestation under this approach is -$71.85, or +$172.24 more than *do nothing*. *Only eradication* costs significantly more than all other approaches, $185.87 million, but improves on *only prevention* in terms of private damages and mitigation costs, and ecosystem service losses. This approach reduces ecosystem service losses to $23.78 million, substantially reduces private losses to $1.23 million, but reports fishing benefits at just $0.12 million. The present value net benefit of ZM infestation with this approach is -$210.77 million, or +$33.32 million more than *do nothing*, but $138.92 million less than *only prevention*. Finally, *prevention and eradication* is the preferred approach under this scenario. While this approach reports the second-highest total cost, $55.35 million, it reduces ecosystem service losses and private damages and mitigation costs to zero. Changes in benefits to anglers also remain at zero. The approach has a present value net benefit from ZM infestation of -$55.35, and it improves over *do nothing* by +$188.74 million. Under this scenario, *prevention and eradication* is both effective and efficient, and is the preferred policy option from a social welfare perspective.

The new technologies – low cost scenario includes hot wash stations as a prevention measure and Zequanox as an eradication option, but assumes that application costs of each are on the low end of the expected range. Under this scenario, *prevention only* costs $7.63 million in public expenditures, which reduces ecosystem service losses to just $23.12 million, private damages and mitigation costs to $2.69 million, and increases fishing benefits by just $0.12 million. The net present value of a ZM infestation under this approach is a much lower -$33.32 million, which provides a substantial improvement over *do nothing* as well as greatly improving on the net benefits indicated by the efficient approach under the standard technologies scenario. Compared to *do nothing*, this approach increases net benefits by +$210.76 million. *Only eradication* posts the highest public expenditures of the four approaches under this scenario, $134.99 million. Ecosystem service losses under this approach are only slightly higher than *only prevention*, at $23.78 million, but private damages and mitigation costs are much lower, at only $1.23 million. Angler benefits are roughly similar to those indicated by *only prevention*. With this approach, the present value of a ZM infestation is -$159.88 million, or +$84.20 million more than *do nothing*, but $126.56 million less than *only prevention*. The preferred approach under this scenario is *prevention and eradication*, as is the case under the standard technologies scenario without hot wash stations and Zequanox. This mixed approach costs $21.85 million in public expenditures, but keeps ecosystem service losses, private damages and mitigation costs, and changes in fishing benefits at zero. The present value of a ZM infestation under this approach is just -$21.85 million, a +$222.24 million improvement over *do nothing*.

In the new technologies – high cost scenario, we allow the use hot wash stations and Zequanox, but assume that unit costs for these management alternatives are on the high end of the expected range. Impacts on ecosystem service losses, private damages and mitigation costs, and fishing benefits are the same as under the low cost scenario, but public expenditures and net benefits for the approaches change significantly. Now *only prevention* costs a slightly higher $7.88 million and net present value of a ZM infestation is slight higher than under the low cost scenario, -$33.58 million. *Only eradication* is now a much costlier approach, costing $707.75 million to implement and significantly decreasing the present value net benefits of a ZM infestation to -$732.64 million. This represents a large reduction in net benefits compared to *do nothing* by $488.56 million. This approach is not cost-effective. *Prevention and eradication* now costs $82.45 in public expenditures and improves on *do nothing* by +$161.64 million. Under this high cost scenario for hot wash stations and Zequanox, *only prevention* is the preferred approach from a social welfare perspective.

The introduction of hot wash stations and Zequanox change the expected impacts of a ZM infestation (Table 3 and 4). For the low-cost scenario, these management alternatives reduce the impacts of *only prevention*. With boat wash stations, public management costs for *only prevention* increase by $5.15 million, but ecosystem losses are reduced by $30.30 million, private damages and mitigation costs fall by $4.56 million, and fishing benefits drop by $0.20 million. On net, hot wash stations improve the net benefits of *only prevention* by +$38.52 million, or 22.37%. Having Zequanox available at $2,140 per acre reduces public management costs and increases net benefits by $50.88 million over potassium chloride.

For *prevention and eradication*, net benefits increase by +$33.50 million when hot wash stations and Zequanox are available at the low cost assumptions. High cost options for hot wash stations and Zequanox change public expenditures and net benefits of the approaches. Now, public expenditures are $5.40 million more for *only prevention*, $521.88 million more for *only eradication*, and $27.10 million more for *prevention and eradication*. While *prevention and eradication* is the preferred policy option under the low cost scenario, under the high cost scenario *only prevention* is the preferred policy choice: compared to *do nothing*, *only eradication* makes ZM infestation $521.88 million more costly, *prevention and eradication* increases the costs of a ZM infestation by $27.10 million, but *only prevention* reduces the present value net negative impacts of a ZM infestation by $38.27 million.

Table 3. Zebra mussel model simulation results ($ million)

Management Alternative	Standard technologies (Lee et al., 2007)				New technologies (low cost)			New technologies (high cost)		
	I[2] Do nothing	II Only prevention	III Only eradication	IV Prevention and eradication	II Only prevention	III Only eradication	IV Prevention and eradication	II Only prevention	III Only eradication	IV Prevention and eradication
Public management cost	0	-2.48	-185.87	-55.35	-7.63	-134.99	-21.85	-7.88	-707.75	-82.45
Public ecosystem loss	-219.48	-62.43	-23.78	0	-23.12	-23.78	0	-23.12	-23.78	0
Private economic damage	-25.71	-7.25	-1.23	0	-2.69	-1.23	0	-2.69	-1.23	0
Private recreational benefit	0.10	0.31	0.12	0	0.12	0.12	0	0.12	0.12	0
NPV	-244.09	-71.85	-210.77	-55.35	-33.32	-159.88	-21.85	-33.58	-732.64	-82.45
ΔNB[1]	0	172.24	33.32	188.74	210.76	84.20	222.24	210.51	-488.56	161.64

T=20 years, r=0.02.

[1] Compared with *do nothing*.

[2] Results are the same for all scenarios.

Table 4. Comparison of zebra mussel results under differing scenarios ($ million)

Management Alternative	New technologies (low cost) versus standard			New technologies (high cost) versus standard			New technologies (high cost) versus new technologies (low cost)		
	II Only prevention	III Only eradication	IV Prevention and eradication	II Only prevention	III Only eradication	IV Prevention and eradication	II Only prevention	III Only eradication	IV Prevention and eradication
Δ Public management cost[1]	-5.15	50.88	33.50	-5.40	-521.88	-27.10	-0.25	-572.76	-60.60
Δ Public ecosystem loss[1]	39.30	0	0	39.30	0	0	0	0	0
Δ Private economic damage[1]	4.56	0	0	4.56	0	0	0	0	0
Δ Private recreational benefit	-0.20	0	0	-0.20	0	0	0	0	0
Δ NPV	38.52	50.88	33.50	38.27	-521.88	-27.10	-0.25	-572.76	-60.60

T=20 years, r=0.02.

[1] Positive number indicates *lower* cost, loss, or damage.

Discussion

Our results indicate that new technologies can be cost-effective means for managing a potential ZM infestation in Lake Okeechobee. As a preventative measure, installation of mandatory hot wash stations for out-of-state boats appears to be a cost-effective means for reducing the threat and potential damages of a ZM infestation in the lake. The addition of hot wash stations at the low (~1 station) and high (5 stations) cost estimates increases present value net benefits of the prevention approach by roughly $38 million over 20 years.

We evaluated the potential use of Zequanox for eradication in place of potassium chloride. Two per-acre costs of application were evaluated: (1) $2,140 per acre, roughly 20-times the per-acre cost of controlling water hyacinth and other invasive floating plants; and (2) $11,220, approximately 20-times the per-acre cost of controlling the submersed invasive plant hydrilla. At a cost of $2,140 per acre, eradication of ZM using Zequanox is economically warranted. We estimate that, for an *only eradication* approach, low-cost Zequanox would increase present value net benefits by $50.88 million over 20 years versus potassium chloride. For a *prevention and eradication* approach, low-cost Zequanox would increase present value net benefits of the program by $33.50 million over 20 years. At $11,220 per acre, an *only eradication* approach is not economically warranted, with the change in present value net benefits at -$521.88 million versus use of potassium chloride.

The addition of hot wash stations and Zequanox does not change the policy choice when Zequanox costs are at the low-end of the expected range. As with standard technologies, controlling ZM is cost-effective, and the *prevention and eradication* approach is efficient (highest net benefits). However, when Zequanox costs are high, the optimal policy choice is not *prevention and eradication*; the best approach is *only prevention*, which increases net benefits while approaches that include eradication reduce net benefits.

We also estimate the breakeven cost for Zequanox for whole-lake eradication in Lake Okeechobee. Any price below $3,475 per-acre generates present value net benefits for the *only eradication* scenario. This approach would also be cost-effective even at the high cost of $11,220 per-acre over a partial area of the lake. If eradication can be achieved by applying Zequanox to 138,747 acres or less, the *only eradication* approach is cost-effective.

Conclusion

This study employs a stochastic dynamic bio-economic model of invasive zebra mussels to evaluate the net gain in terms of expected cost savings, damage diminishment, and risk reduction from the addition of two new technologies to the arsenal in the battle against ZM. The costs and benefits of ZM management are assessed for Lake Okeechobee, Florida. The bio-economic model is used to capture the relationship between management activities and the probability of ZM infestation and establishment over time. Alternate management scenarios are simulated and sensitivity tests are conducted.

We find that the adoption of hot wash stations and Zequanox may reduce the expected impacts of a ZM infestation, depending on the assumed costs for these management alternatives. Under a low-cost scenario for hot wash stations and Zequanox, the preferred policy is *prevention and eradication*, but all three active management alternatives were effective. However, when we assume high-range cost estimates for both alternatives, the preferred policy was *only prevention*; *prevention and eradication* was cost-effective, but less so than standard technologies; and *only eradication* was not cost-effective.

Areas for future work include: (1) Estimating the cost of enforcement and monitoring of hot wash requirements for out of state anglers; (2) Examining the impact of fees, duration of boat wash, and congestion on level of fishing activity and decision to fish elsewhere; and (3) Examining other uses of the hot wash stations (e.g., after fishing) that may supplement the costs of the stations. For example, implementation of user fees for the hot wash station, plus paid use by in-state boaters for cleaning up after fishing trips, could more than offset the cost of installing and maintaining the stations and alter the optimal policy choice. Given the potential for tremendous economic and environmental damages from a ZM infestation, prudent investment in prevention, early detection, and rapid reaction provides the highest net benefits over the planning horizon; and with two new lower cost options, the likelihood of public investment in management becomes increasingly more justifiable, depending on cost assumptions for the new technologies.

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