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An Economic Model for Evaluating Zebra Mussel Management Strategies

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Abstract

Zebra mussels present an imminent threat to the water resources in Lake Okeechobee in Florida. The lake is vitally important to consumptive water uses and recreational anglers and provides a host of ecosystem services. We employ a probabilistic bio-economic simulation model to estimate the potential impact of zebra mussels to wetland ecosystem services, consumptive water users, and recreational anglers under alternative public management scenarios. Without public management, the expected net economic impact from zebra mussels is -$244.1 million over 20 years. Public investment in prevention and eradication will yield a net expected gain of +$188.7 million, a superior strategy to either prevention or eradication alone.

Key Words: Invasive species, cost transfer, surface water, fishing, wetlands, probability transition matrix

JEL Classifications: C63, Q25, Q52, Q57, Q58

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Zebra mussels (*Dreissena polymorpha*) are a small freshwater species native to Southeastern Europe. In suitable water, zebra mussels become successful invaders. Mature females can produce up to one million eggs per year (USCACE, 2003). The zebra mussel most likely crossed the Atlantic Ocean as larvae on a transatlantic ship (Hebert et al., 1989; Griffiths et al., 1991; Thorp et al., 2002) and disembarked into the Great Lakes. The mussels multiplied rapidly and began spreading. Today populations are found in twenty-four states as shown in the map in Figure 1 (USGS, 2007).

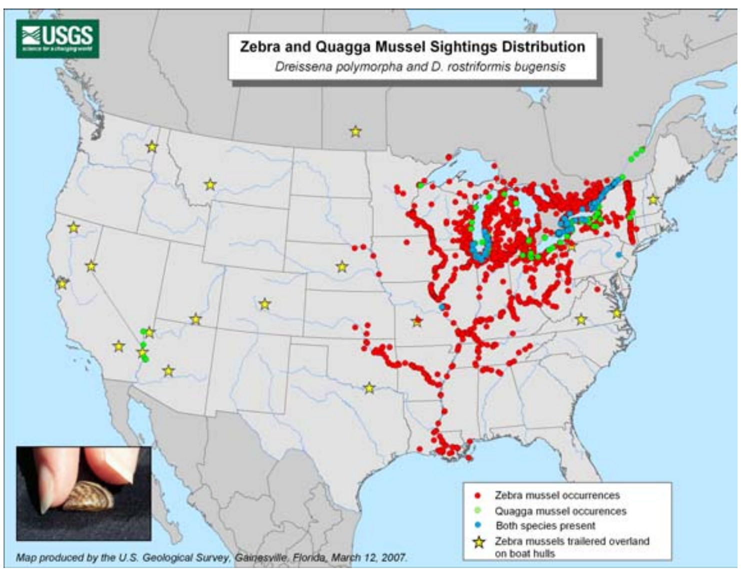

Figure 1. Zebra mussels in the United States (USGS 2007)

The problem with zebra mussels is that they colonize on any submerged surface including boat hulls, navigational buoys, bridge abutments, and water intake pipes. Their dense mats will accelerate the rate of corrosion, sink navigational buoys with their weight, and obstruct water flow in pipes. United States' expenditure for the upkeep required to maintain boat bottoms, docks pilings, locks, gates, and pipes is estimated to be $60 million per year (USGAO, 2002). Because zebra mussels are spreading, damages are expected to rise. Future damages are estimated to be between $3.1 and $5 billion for the period 2002 to 2011 (USGAO, 2002 and USGS, 2000).

Zebra mussels compete with native flora and fauna for food and space, alter the composition of the water column, and transform lake bottoms. They will bio-foul rocks, logs, submerged plants, and the shells of other mussels. In the U.S. more than half of all native freshwater mussel species are either threatened or endangered. Recovery efforts are significantly hindered by the presence of zebra mussels (Ricciardi et. al.,1998; USGAO, 2002)

Will Zebra Mussels Invade Florida?

Zebra mussels were first sighted in Florida in 1998 during an inspection of a bait and tackle shop (University of Florida, 1998). Fortunately a fast acting official collected and destroyed the animals before they could spread. No other sightings have occurred since, but in the last decade zebra mussels have made their way south creeping ever closer to the Florida border. Populations are thriving in Arkansas, Alabama, Kentucky, Louisiana, Mississippi, Missouri, Tennessee, and West Virginia (USGS, 2007). According to estimates by Drake and Bossenbroek (2004) zebra mussels are bound to reappear in Florida. The authors estimate that in the coming years there is a "high" likelihood that zebra mussels will reach north Florida and a "moderate" likelihood that zebra mussels will reach south Florida. Suitability of Florida's warm waters was examined by Hayward and Estevez (1997). They judged the rivers in the Florida panhandle (north Florida) to be unsuitable for zebra mussel propagation because the water is acidic and contains few minerals. The St. Johns river in north central Florida and Lake

Okeechobee in south Florida both have low acidity and high mineral content and are judged suitable for sustaining zebra mussels.

This study examines the potential for Lake Okeechobee to become infested with zebra mussels, describes a simulation model, proffers a series of management scenarios, presents results, and offers sensitivity tests on key model parameters. Novel contributions include quantification of potential future damages from zebra mussels, economic trade-offs between public management expenditures and public and private gains, and comparisons of management alternatives prevention and eradication.

Lake Okeechobee

Lake Okeechobee is an important commercial shipping route, a valuable source of freshwater, a major recreational resource, and at 448,000 acres, the second largest lake wholly contained in the United States, (FDEP, 2001). Five counties around the lake pump water for irrigation, industry, and household uses. Impacted services from an infestation of zebra mussels would include water supply, water recreation, and wetland ecosystem services.

The Lake Okeechobee waterway is presently free of zebra mussels and the nearest populations are 750 miles away. Most likely zebra mussels will make the journey by clinging to the stems of aquatic weeds entwined in a boat propeller or snagged on a trailer. While the possibility may seem remote, it is worth noting that zebra mussels can survive several days out of water. In the Great Lakes region, aquatic weeds covered with live zebra mussels were observed on 1 out of every 275 boats in parking lots while owners were preparing to launch into non-infested lakes (Johnson and Carlton, 1996).

Lake Okeechobee is a popular destination for local and out-of-state sport fishers, recreational boaters, and host to several major fishing tournaments each year. Out-of-state boaters and returning Florida boaters are likely vectors for transporting zebra mussels to Lake Okeechobee.

Zebra mussel model

In a previous work, Leung, et al. (2002) used stochastic dynamic programming to model the probability of a zebra mussel invasion as a decreasing function of prevention effort. Zebra mussel growth was captured with a logistic function. Damages were expressed in terms of lost productivity due to reduced water flow. The optimal solution was to reduce the probability of arrival by 10% using prevention measures. Finnoff et al. (2005) applied a stochastic dynamic programming model following Leung et al. (2002) to examine the economics of preventing zebra mussel damages in a Midwest lake. They questioned the importance of including feedback links and the conditions under which omission would make a difference. One interesting finding was that over investment or under investment in control could result depending on how the public manager believes the private entity will respond to the invasion. To compare management alternatives for eradicating the oyster drill (*Ocinebrellus inornatus*) an invasive marine mollusk, Buhle et al. (2005) employed a Markov approach. The authors specified a 2x2 transition matrix to capture two of the animals' three life stages and ascertained that control efforts targeting the adult animals would be more cost effective than control efforts targeting the bright egg masses.

For Lake Okeechobee, we assume there is a real threat of zebra mussel introduction. Once introduced, the small critters are unlikely to be noticed until dense mats are formed or piles of razor sharp mussel shells wash up on shore. By the time they are noticed, the economic and environmental damage will already be significant. To characterize this system we use a stylized model comprising the following four "states of nature": (1) none, (2) introduced, (3) propagating, and (4) critical mass. The probability that the Lake will be in any of the four states at time t in the future, is s_{it}. At present, there are no zebra mussels so $s_{1t=0} = 1$ and it follows that $s_{2t=0} = s_{3t=0} = s_{4t=0} = 0$. Some additional description of the variable s_{it} appears in Table 1.

Table 1. Description of Zebra Mussel States in Lake Okeechobee

i	Probability of state i at time t	Description of state i	Economic and ecosystem damages?
1	s_{1t}	No zebra mussels	no
2	s_{2t}	Zebra mussels recently introduced	no
3	s_{3t}	Zebra mussels propagating	no
4	s_{4t}	Zebra mussels at critical mass	yes

The s_{it} state probabilities are brought together to form the elements of vector variable $\boldsymbol{S}_{\mathbf{t}}$:

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

At present the Lake has no zebra mussels, so at t = 0,

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

To derive future state values S_{t+1} we define the transition probability a_{ij} which represents the probability of changing to state i from state j in a single time period. In matrix form, a_{ij} comprise the elements of $\boldsymbol{A_0}$ the 4×4 matrix of transition probabilities under a natural progression of zebra mussels:

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

S_{t+1} is defined as the product of $\boldsymbol{A_0}$ and $\boldsymbol{S_t}$ from equations (3) and (1):

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

Each element of $\boldsymbol{S_{t+1}}$ can be obtained:

(5) $$s_{i,t+1} = a_{i1}s_{1t} + a_{i2}s_{2t} + a_{i3}s_{3t} + a_{i4}s_{4t} \quad for\, i = 1...4 \;.$$

Because the natural progression of zebra mussels may be undesirable, *prevention* measures are available to reduce the probability of introduction and propagation. Letting f_1 measure the effectiveness of a prevention program, the transition probability matrix $\boldsymbol{A_p}$ with a prevention program in place is expressed:

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

Propagation can be thwarted with *early eradication* which is defined as the action required to destroy all zebra mussels as soon as they are detected. With *monitoring* as a component of the prevention program, we assume early eradication takes place in state 3 before the zebra mussels can cause significant damage or loss. The transition probability matrix $\boldsymbol{A_m}$ is represented by:

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

Without a prevention program in place, we assume there would be no monitoring and therefore zebra mussels would be detected with the onset of economic damages, i.e. in state 4. *Late eradication* is defined to be the measures taken to destroy all zebra mussels in Lake Okeechobee after reaching state 4. The transition probability matrix $\boldsymbol{A_r}$ is expressed:

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

Post-eradication, we assume the treated lake would be free of zebra mussels for a period of at n years during time which the transition probability matrix becomes,

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

With *prevention*, the zebra mussel state equation during states pre-introduction (state 1) and introduction (state 2) is defined:

(10) $S_t = A_p S_{t-1}$.

After zebra mussels are established, prevention measures would no longer be practical, thus prevention measures would be halted. During propagation (state 3) and critical mass (state 4), the transition matrix is $\boldsymbol{A_0}$ and the state equation reverts back to equation (4).

With *prevention and early eradication*, the state equation from pre introduction through introduction, propagation, and early eradication is:

(11) $S_t = A_m S_{t-1}$

With *late eradication*, the state equation from pre-introduction through introduction, propagation, critical mass, and eradication is:

(12) $S_t = A_r S_{t-1}$

For the remainder of the planning horizon after *early eradication* or *late eradication* the state equation is:

(13) $S_t = A_n S_{t-1}$

Economic comparison of the management choices requires estimates of the expected benefits and costs. For this problem, the management choice variable ***X*** is a (4x4) vector composed of the elements x_p and x_r.

$$(14) \quad X = \begin{bmatrix} x_p & x_p & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & x_p x_r & 0 \\ 0 & 0 & 0 & x_r \end{bmatrix}$$

The decision to invest in prevention is given by x_p=1 and x_r=0. The decision to invest in prevention and early eradication is given by x_p=1 and x_r=1. The decision to invest in late eradication is given by x_p=0 and x_r=1. The four management alternatives are shown in Table 2

Table 2. Four management alternatives

	$x_p = 0$	$x_p = 1$
$x_r = 0$	I Do nothing (status quo)	II Invest in prevention (prevention)
$x_r = 1$	III Eradicate when zebra mussels become problematic (late eradication)	IV Invest in prevention and eradicate before zebra mussels become problematic (prevention and early eradication)

Combining the two management choices yields a vector of four management alternatives:

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

The unit costs of implementing the management choices x_p and x_r are c_p and c_r which comprise the (2x1) management cost vector ***q***.

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

The cost of management C_t at time t is the product of unit cost ***q***, management choice ***X***, and the zebra mussel state $\boldsymbol{S_t}$ from equations (16), (14) and (1):

(17) $C_t = q'X\ S_t$.

Economic damage from zebra mussel infestation is ***d*** an X dependent variable of increased maintenance expenditure by consumptive water users in Lake Okeechobee. Ecosystem service loss with zebra mussel infestation ***e*** includes diminished wetland functions, loss in wildlife habitat, and reduced aquatic food supply in state 4. The benefit from zebra mussel infestation b is the added value to recreational and sport fishers from the improved water clarity and increased catch rate due to zebra mussel filter feeding. In this model, cost, damage, and loss are expressed as negative values and benefit is expressed as a positive value. The objective is to choose a management strategy ***X*** that maximizes ***Z*** the present value of total expected cost, damage, loss, and benefit with the threat of zebra mussel infestation. The objective is to:

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

subject to equations (1) through (17). In (18), **r** is the annual discount rate and ***T*** is the number of years in the planning horizon.

Empirical model parameters

Transition probabilities

Recreational and sport boats are the primary vector for transporting zebra mussels from infested lakes to Lake Okeechobee. We examined data from three national tournaments on Lake Okeechobee during 2006-2007 (Carson, 2007 and Eads, 2007) and observed that half the 926 anglers were from states with zebra mussel infested waters. The potential for trailered boats to vector zebra mussels was shown by Bossenbroek et al. (2001). They estimated that trailered boats in the Great Lakes area could convey enough live zebra mussels to colonize an uninfested body of water in a nearby state with a probability of between 1.18×10-5 and 4.11×10-5. We used an intermediate probability of 3.78×10-5 per boat, multiplied by 926 boats per year to obtain an annual probability of zebra mussel introduction of 3.5% per year ($a_{21} = 0.035$)

Upon introduction to Lake Okeechobee, zebra mussels would prosper according to Hayward and Estevez (1997). The scientists computed habitat suitability indices (HSI) of 0.83 and 0.91 for open water and shallow water containing dense aquatic plants. Given the high HSI values for Lake Okeechobee and the large expanse of suitable habitat, we assumed introduced zebra mussels would become established and propagate until critical mass was reached with a probability of 100% ($a_{32} = a_{43} = a_{44} = 1.0$). [1]

[1] These values were chosen to enhance the transparency of the empirical model. Simulations assuming $a_{32} = a_{43} = a_{44} = 0.83$ and $a_{32} = a_{43} = a_{44} = 0.91$ were also conducted. Results from those runs appear in the appendix in Table 6 and Table 7.

Time to reach carrying capacity according to Nalepa et al., (1995), Strayer et al. (1996), Burlakova, Karatayev, and Padilla (2006), Borcherding and Sturm (2002), and Lauer and Spacie (2004) is two to three years after detection. For our model, we assume zebra mussels will grow to produce dense mats sufficient to cause damages two years after introduction, thus the time lag between states 2 and 3, and between states 3 and 4 is one year.

Private economic damage

In the Great Lakes area, O'Neill (1996) and Deng (1996) estimated annual expenditure for chemical, mechanical and thermal maintenance. For a zebra mussel infestation in Lake Okeechobee, we assume water users would employ mechanical and thermal means to clear clogged intake pipes and spend $4.90 per million gallons pumped as reported by Deng (1996). Mean water withdrawal from Lake Okeechobee is 562,589 million gallons per year (USGS, 2006). Multiplying annual water use by average unit expenditure we arrived at economic damages of $2.76 million per year to consumptive water users ($d_2 = 2.76$). As most pipes in the Great Lake region are pre-treated with antifouling paint, we apply this damage estimate to treated pipes.

Anti-fouling paint helps to reduce maintenance expenditures by inhibiting zebra mussel colonization. In the Columbia River Basin, water users applied anti-fouling paint to interior pipe surfaces at a cost of $25.56 per square foot (Phillips, 2005). Based on a survey of Lake Okeechobee water users (Adams, 2007) we calculated the average interior surface area of intake pipes to be 300.58 square feet. With 504 major water users on the Lake, we calculate an intake pipe surface area of 151,492 square feet, which would require $3.87 million to treat with antifouling paint. Assuming the paint treatment lasts 10 years, annualized mitigation damage is $0.387 million ($d_3 = 0.387$).

We assume anti-fouling paint treatment saves consumptive uses about 22% in maintenance expenditures. Thus without treatment, Lake Okeechobee consumptive water users would pay \$5.98 per million gallons per year pumped to maintain pipes. Annual damages would be \$3.37 million (d_1 = 3.37).

Public ecosystem service loss

Surrounding Lake Okeechobee are 29,000 acres of Audubon Society wetlands and 31,000 acres of unnamed wetlands for a total of 60,000 acres of wetlands. Costanza, et al. (2003) estimated the value of wetland services to be \$1,083 per acre per year. Multiplying \$1,083 by 60,000 acres yields a wetland damage estimate of \$64.98 million per year (e = 64.98).

Private economic benefit

Between 1983 and 2002, anglers spent an average of 1,575,340 hours on Lake Okeechobee each year (FFWCC, 2003). The Florida Fish and Wildlife Conservation Commission reported average spending of \$20.65 per hour in 2002 (FFWCC, 2003). Using total expenditures to estimate the recreational value of freshwater fishing, we multiplied hours fished by value per hour to obtain a total recreational value of \$32.5 million per year. Assuming an increase in water clarity attributable to zebra mussels would yield a 1% increase in fishing hours. The benefit from zebra mussels is \$0.325 million per year in state 4 (b = 0.325).

Management cost

A plan to monitor and prevent zebra mussels from entering Lake Okeechobee was proposed in 2003 (U.S. Army Corps of Engineers, 2005). The plan included inspecting underwater structures, sampling waterway sediments, and distributing education alert materials to boaters, lake homeowners, and businesses. The cost of implementing the proposed plan is $152,800 per year ($c_p$ = .1528).

In 2006, an infestation of zebra mussels prompted the Virginia Department of Game and Inland Fisheries to pour 174,000 gallons of potassium chloride into Millbrook Quarry. At 100 parts per million the concentration was double the amount needed to kill zebra mussels but low enough to avoid harming humans or fish. The single treatment is expected to protect the quarry from zebra mussel infestation for 33 years. The cost for chemicals and labor was $365,000 (VDGIF, 2007). A similar treatment for Lake Okeechobee would require 628.6 million gallons of potassium chloride at a cost of $1.320 billion. This cost annualized over 33 years is $55.03 million ($c_r$ = 55.03).

A summary of the parameter values used in the Zebra Mussel Model appears in Table 3.

Table 3. Zebra Mussel Model Parameter Values

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 and monitoring (per year)	\$0.1528 mil
c_r	Cost of eradication (annualized)	\$55.03 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_p	Effectiveness of prevention measures	0.75
f_r	Effectiveness of eradication measures	1.00
r	Discount rate	0.02
t	Year	0,...,19
T	Planning horizon	20 years

Four management scenarios

With Management I (do nothing) public management costs are zero. Private water users become aware of zebra mussels when they incur damages d_1 in the first year of state 4. In the second year they will apply anti-fouling paint thereby incurring damages d_2 and d_3 in subsequent years. Public ecosystem loss is e for every year the system is in state 4. Public recreation benefit is b for every year the system is in state 4.

With Management II (prevention), public management cost is c_p when the system is in state 1 and 2 and zero in states 3 and 4. Private damage is d_3 during the first year that the system is in state 3 and d_2 and d_3 while in state 4. Public ecosystem loss is e for every year the system is in state 4. Public recreation benefit is b every year the system is in state 4.

With Management III (late eradication), public management cost is c_r after the system reaches state 4. Private water users become aware of zebra mussels when they incur damages d_1 during the first year in state 4. In subsequent years private damages drop to zero because the zebra mussels are eradicated. Public ecosystem loss is e for one year while the system is in state 4. Public recreation benefit is b for one year while the system is in state 4.

With Management IV (prevention and early eradication), public management cost is c_p while the system is in state 1 and 2, c_r when the system is in state 3, and zero otherwise. Private damage is zero. Public ecosystem loss and public recreation benefit are zero as the system never reaches state 4.

The empirical zebra mussel model was run on GAMS software (GAMS, 1998). A presentation and discussion of results follow.

Results

The least cost strategy is Management I in which nothing is done to prevent zebra mussels from entering Lake Okeechobee and nothing is done to arrest propagation after they arrive. Over 20 years management cost is $0. The present value of expected ecosystem damages in terms of lost wetland functions is -$219.5 million. Private water users sustain -$25.7 million in expected damages from increased maintenance expenditures and recreational anglers will gain +$1.1 million in expected fishing benefits. The net present value of “do nothing” is -$244.1 million.

The next least costly strategy is Management II in which prevention measures are implemented. Since prevention is only 75% effective, if zebra mussels arrive, we assume prevention measures would be halted and no further action would be taken to manage the growing mussel population. Over 20 years, the present value of expected public expenditure on prevention is -$2.5 million. The present value of expected ecosystem damages in terms of lost wetland functions is -$62.4 million. Private water users will endure -$7.2 million in expected damages due to increased maintenance and mitigation expenditures. Recreational anglers will enjoy +$0.3 million in expected fishing benefits. The net present value of managing the threat of zebra mussel with prevention is -$71.8 million, a gain of +$172.2 million over doing nothing.

The most costly strategy is Management III in which zebra mussels are eradicated from Lake Okeechobee after they begin causing damage. Over 20 years, the present value of expected public expenditure on eradication is -$185.9 million. The present value of expected ecosystem damage in terms lost wetland functions is -$23.8 million. Private water users will absorb expected damages of -$1.2 million and recreational fishers will gain +$0.12 million in expected fishing benefits. The net present value of late eradication is -$210.8 million, a gain of +$33.3 million compared to doing nothing.

The strategy with the smallest public ecosystem loss, least private economic damage, and the highest expected net present value is Management IV in which both prevention and eradication measures are used to mitigate infestation and resulting damages. Over 20 years, the present value of expected public expenditure on prevention and early eradication is -$55.4 million. Expected loss in ecosystem functions, damage to private consumptive use, and gain to recreational anglers is $0. The net present value from prevention and early eradication is -$55.4, a gain of +$188.7 million compared to doing nothing.

Among the four alternatives, the optimal strategy based on the net present value of expected costs, damages, losses, and benefits over the 20-year planning horizon as defined in equation 17 is *Management IV – Prevention and early eradication*. A summary of the simulation model results appears Table 4.

Table 4. Zebra mussel model simulation results

	Management Alternative			
	I	II	III	IV
	Do nothing	Prevention	Late eradication	Prevention and early eradication
	$ million			
Public management cost	0	-$2.5	-$185.9	-$55.4
Public ecosystem loss	-$219.5	-$62.4	-$23.8	-$0
Private economic damage	-$25.7	-$7.2	-$1.2	-$0
Private recreational benefit	+$1.1	+$0.3	+$0.12	+$0
NPV	-$244.1	-$71.8	-$210.8	-$55.4
ΔNPV	0	+$172.2	+$33.3	**+$188.7**

T = 20 years, r = .02

Discussion

Results show large gains to investment in prevention. With an expected outlay of \$2.5 million for prevention measures over 20 years, more than \$170 million in expected losses and damages can be avoided. If a prevention program is not in place before zebra mussels are introduced and begin causing damages, eradication may be warranted. Over 20 years, the expected expenditure for eradication is -\$185.9 million which would serve to reduce impending damages by -\$220 million. If a prevention program is in place and zebra mussels are detected before the can cause damage, early eradication would serve to supplant -\$70 million in expected damages for an incremental cost of -\$52.9 million over prevention alone.

Breakpoint parameter values

To test model robustness, we estimated breakpoint values for key parameters in the model. Here we define “breakpoint value” to be the value at which the relative preference of the four management strategies changes based on expected NPV.

Simulation results show that if the annual probability of zebra mussel arrival was only 0.0004 (rather than 0.035), prevention would not be warranted. The optimal strategy would be to wait for zebra mussels to arrive and eradicate them when they are detected.

If the probability that introduced zebra mussels will propagate and grow to critical mass is 0.052 (rather than 1), prevention would not be warranted. Instead, managers should eradicate zebra mussels when they are detected.

Recreational water users may advocate reduced zebra mussel management. Our simulations show that if the benefit from zebra mussels was instead \$71.6 million per year (compared to our assumed value of $0.325 million), the advantages of allowing zebra mussels to enter Lake Okeechobee would out weight the projected damages. In this case, neither prevention nor eradication would be warranted.

We found that if the annual cost of prevention ballooned to $8.7 million per year (versus our assumed value of $0.1528 million), prevention would be unwarranted as there would be no advantage over late eradication. There would however be a slight advantage to being able to eradicate early versus late. Likewise, if the effectiveness of prevention at reducing the arrival rate fell to 17% (versus 75%), there would be no gain in prevention over eradication. Finally, if prevention cost was $9.7 million per year, early eradication would be unwarranted and late eradication would be preferred.

If on the other hand the annual cost of eradication was $1,729 million per treatment (versus $1320 million), neither late nor early eradication would be warranted. With high eradication costs, prevention measures take on more importance as a means of mitigating potential damages. As a reference, $1,729 million is equivalent to an annualized cost of $72 million per year for 33 years or the same treatment at $1,320 million lasting for only 15 years.

Estimated breakpoint values and the relative rankings of management alternatives appear in Table 5.

Table 5. Breakpoint parameter values for zebra mussel model

Symbol	Definition	Parameter Value	Breakpoint Value	Management Alternative I	II	III	IV
				Rank			
All	Base model parameters	Table 3	Table 3	4	2	3	1
a_{11}	Annual probability of zebra mussel not arriving in Lake Okeechobee	0.965	0.99960	3	3	1	2
a_{21}	Annual probability of zebra mussel arrival in Lake Okeechobee	0.035	0.00040				
a_{32}	Annual probability of zebra mussel moving from state 2 to state 3	1	.052	3	3	1	2
a_{43}	Annual probability of zebra mussel remaining in state 3 to state 4	1	.052				
a_{44}	Annual probability of zebra mussel remaining in state 4	1	.052				
b	Benefit (to fishing from zebra mussel)	$0.325 mil	$71.6 mil	1	1	3	2
c_1	Annual cost of prevention and monitoring	$0.1528 mil	$ 8.7 mil	3	2	2	1
c_2	Eradication cost	$55.03 mil	$72.08 mil	2	1	3	1
	Eradication cost (annualized)	$1,320 mil	$1,729 mil				
n	Eradication duration (years)	33	15	2	1	3	1
e	Value of wetland services (per year)	$64.98 mil	$48.09 mil	2	1	3	1
	Value of wetland services (per acre)	$1,083	$801.4	2	1	3	1
f	Effectiveness of prevention measures	75%	1%	3	3	2	1

Rank = 1 implies the *highest* expected NPV

Summary

The zebra mussel is expected to reach Florida in the near future and thus poses a threat to wetland ecosystem services and consumptive water uses. Several years ago the U.S. Army Corps of Engineers responded to the threat by outlining an education, monitoring, and prevention program for Lake Okeechobee. The program however was never funded. While bringing live zebra mussels in the state of Florida is illegal and punishable by fine, there is no other state or federal program to prevent zebra mussels from entering Lake Okeechobee. In lieu of prevention, eradication post arrival is an option, albeit a costly one.

This study examined the potential impact of zebra mussels on ecosystem services, consumptive water uses, and recreation in Lake Okeechobee. A probabilistic model was developed to simulate the arrival and spread of zebra mussels and assess the cost effectiveness of alternate management strategies. Results indicate that both prevention and eradication of zebra mussels are economically justified for Lake Okeechobee.

These findings are based on the data we used to parameterize the model. While we used the best data available to the study, some questions undoubtedly remain. To tackle these questions head on and advance the dialog on this topic, we conducted a series of sensitivity tests around key model parameters. Specifically we tested the probability that zebra mussels would arrive in Lake Okeechobee and the likelihood that they would survive and reproduce in this new environment. We also tested our assumptions on the effectiveness a prevention program that would cost only $152,800 per year and brought into question the cost of a prevention program that boasted 75% effectiveness. Because documented eradications of invasive mollusks are few,

we reexamined our assumptions regarding how much this action might cost presuming eradication was technically feasible and environmentally desirable.

The battery of sensitivity tests were presented in the form of breakpoint values, i.e. borderline values of the tested parameters that would cause a change in the relative ranking of the preferred alternatives. Under the baseline model parameters, Management IV was most preferred, that is offered the highest expected net present value. Next preferred were Management II, III, and I. Our sensitivity tests showed that the cost effectiveness of prevention is fairly robust over a wide range of model assumptions. For example, probability of arrival, habit suitability, and prevention effectiveness would have to be many times smaller or the cost of prevention would have to be many times larger to rule out prevention as a worthwhile public investment. In contrast a mere 30% increase in the cost of eradication would cause this management activity to be ruled out based on cost effectiveness. Likewise, it would only take a 26% reduction in projected wetland losses due to zebra mussels to conclude that eradication may not be worthwhile.

To evaluate the eradication of zebra mussels from Lake Okeechobee we used case studies from other locations to infer treatment procedures, chemical dosages, and overall cost. Better information will be required before managers will embark on a venture of this magnitude. Fortunately the decision to eradicate can be postponed until zebra mussels have arrived at which time hopefully more will be known. Because of the likely arrival of zebra mussels, their potential to induce economic and environmental damage and the uncertainty regarding the technical feasibility and cost effectiveness of eradication, this study provides empirical evidence for prevention as a sensible management option that is economically justified. While additional scientific study could lend better data to improve the precision of our model estimates, the imminent threat of zebra mussels will remain until a prevention program is in place.

References

Adams, D.C. "Economics and Law of Invasive Species Management In Florida," Ph.D. Dissertation, University of Florida, May 2007.

Buhle, E.R., M. Margolis, J.L. Ruesink, Bang For Buck: Cost-Effective Control Of Invasive Species With Different Life Histories, *Ecological Economics,* 52(2005):355-366.

Borcherding, J., and W. Sturm. "The Seasonal Succession of Macroinvertebrates, in Particular the Zebra Mussel (*Dreissena polymorpha*) in the River Rhine and Two Neighboring Gravel-Pit Lakes Monitored Using Artificial Substrates." *International Review of Hydrobiology* 87(2002):165 – 181.

Bossenbroek, J.M., C.E. Kraft, and J.C. Nekola. "Prediction of Long-Distance Dispersal Using Gravity Models: Zebra Mussel Invasion of Inland Lakes." *Ecological Applications* 11(6)(2001):1778 – 1788.

Burlakova, L.E., A.Y. Karatayev, and D.K. Padilla. "Changes in the Distribution and Abundance of *Dreissena polymorpha* Within Lakes Through Time." *Hydrobiologia* 571(2006):133 – 146.

Carson, R. Personal Communication. FLW Outdoors, February 2007.

Costanza, R., R. d'Arge, R deGroot, S. Farber, M. Grasso, B. Hannon, K. Limburg, S. Naeem, RV O'Neill, J. Paruelo, R.G. Raskin, P. Sutton, & M. Van Den Belt, "The Value Of The World's Ecosystem Services And Natural Capital," *Nature*, 387(1997): 283-260.

Deng, Y. "Present and Expected Economic Costs of Zebra Mussel Damages to Water Users with Great Lakes Intakes." Ph.D. Dissertation, The Ohio State University, August 1996.

Drake, J.M., and J.M. Bossenbroek. "The Potential Distribution of Zebra Mussels in the United States." *BioScience* 54(10)(2004): 931 – 941.

Eads, B. Personal Communication. Fishers of Men Tournament, February 2007.

Finnoff, D., J.F. Shogren, B. Leung, D. Lodge, "The Importance of Bioeconomic Feedback in Invasive Species Management," *Ecological Economics*, 52(2005):367-381.

Florida Department of Environmental Protection, Division of Water Resource Management. *Basin Status Report—Lake Okeechobee*. November 2001.

GAMS Development Corporation, Washington DC, 1998.

Griffiths, R.W., D.W. Schloesser, J.H. Leach, and W.P. Kovalak. "Distribution and Dispersal of the Zebra Mussel (*Dreissena polymorpha*) in the Great Lakes Region." *Canadian Journal of Fisheries and Aquatic Sciences* 48(1991):1381 – 1388.

Hayward, D., and E.D. Estevez. *Suitability of Florida Waters to Invasion by the Zebra Mussel (Dreissena polymorpha)*. Mote Marine Laboratory Technical Report No. 495, 1997.

Hebert, P.D.N., B.W. Muncaster, and G.L. Mackie. "Ecological and Genetic Studies in *Dreissena polymorpha* (Pallas): A New Mollusk in the Great Lakes." *Canadian Journal of Fisheries and Aquatic Sciences* 46(1989):1587 – 1591.

Johnson, L.E., and J.T. Carlton. "Post-Establishment Spread in Large-Scale Invasions: Dispersal Mechanisms of the Zebra Mussel *Dreissena polymorpha*." *Ecology* 77(6)(1996):1686 – 1690.

Lauer, T.E., and A. Spacie. "Space as a Limiting Resource in Freshwater Systems: Competition Between Zebra Mussels (*Dreissena polymorpha*) and Freshwater Sponges (Porifera)." *Hydrobiologia* 517(2004):137 – 145.

Leung, B, D.M. Lodge, D. Finnoff, J.F. Shogren, M.A. Lewis, and G. Lamberti, "An Ounce of Prevention or a Pound of Cure: Bioeconomic Risk Analysis of Invasive Species," *Proceeding of the Royal Society Biological Studies, 269*(2002):2407-2413

Macaulay , C. "Evolution Takes Its Chance In Darwin's Cullen Bay Marina," 1999, www.marine.csiro.au/leafletsfolder/cullenbay.html, (Accessed June 23, 2007).

Nalepa, T.F., J.A. Wojcik, D.L. Fanslow, and G.A. Lang. "Initial Colonization of the Zebra Mussel (*Dreissena polymorpha*) in Saginaw Bay, Lake Huron: Population Recruitment, Density, and Size structure." *Journal of Great Lakes Research* 21(4)(1995):417 – 434.

O'Neill, C.R., Jr. "Economic Impact of Zebra Mussels – Results of the 1995 National Zebra Mussel Information Clearinghouse Study." *Great Lakes Research Review* 3(1997):35 – 42.

Phillips, S., T. Darland, and M. Systsma. *Potential Economic Impacts of Zebra Mussels on the Hydropower Facilities in the Columbia River Basin*. Pacific States Marine Fisheries Commission Report, 2005.

Pimentel, D., L. Lach, R. Zuniga, and D. Morrison. "Environmental and Economic Costs of Nonindigenous Species in the United States." *Bioscience* 50(1999):53 – 65.

Riccciardi, A, R.J. Neves, and J. B. Rasmussen, "Impending Extinctions Of North American Freshwater Mussels (*Unionoida*) Following The Zebra Mussel (*Dreissena Polymorpha*) Invasion," *J. Animal Ecology*, 67(1998):613-619.

Strayer, D.L., J. Powell, P. Ambrose, L.C. Smith, M.L. Pace, and D.T. Fischer."Arrival, Spread, and Early Dynamics of a Zebra Mussel (*Dreissena polymorpha*) Population in the Hudson River Estuary." *Canadian Journal of Fisheries and Aquatic Sciences* 53(1996):1143 – 1149.

Strayer, D.L. "Effects of Alien Species on Freshwater Mollusks in North America." *Journal of the North American Benthological Society* 18(1)(1999):74 – 98.

Thorp, J.H., J.E. Alexander, and G.A. Cobbs. "Coping with Warmer, Large rivers: A Field Experiment on Potential Range Expansion of Northern Quagga Mussels (*Dreissena bugensis*)." *Freshwater Biology* 47(2002):1779 – 1790.

University of Florida, "Discovery of invasive zebra mussels prompts warnings from state officials," University of Florida News," //http.news.ufl.edu/1998/10/07/zebra-2/ (Accessed: June 20 2007).

U.S. General Accounting Office (USGAO). *Invasive Species Clearer Focus and Greater Commitment Needed to Effectively Manage the Problems*. Report to Executive Agency Officials, GAO-03-1, October, 2001.

U.S. Army Corps of Engineers (USACE) "Okeechobee Waterway Zebra Mussel Monitoring Plan," www.saj.usace.army.mil (Accessed: October 12 2005).

U.S. Army Corps of Engineers (USACE). *Environmental Effects of Zebra Mussel Infestations.* Technical Note ZMR-1-14, 1995.

U.S. Geological Survey (USGS). *Zebra Mussels Cause Economic and Ecological Problems in the Great Lakes*. GLSC USGS Fact Sheet 2000-6, created August 15, 2000.

U.S. Geological Survey (USGS). *USGS real-time water data for Florida*. Internet site: http://waterdata.usgs.gov/fl/nwis/rt (Accessed: October 10, 2006).

U.S. Geological Survey (USGS). 2007. *Non-indigenous Aquatic Species Database*. Internet site: http://nas.er.usgs.gov/taxgroup/mollusks/zebramussel/ (Accessed: June 15, 2007).

Virginia Department of Game and Inland Fisheries (VDGIF). *Millbrook quarry zebra mussel eradication.* Internet site: http://www.dgif.state.va.us/zebramussels/ (Accessed February 5, 2007).

Appendix

Table 6. Zebra mussel model simulation results (using HSI = .83)

	Management Alternative			
	I	II	III	IV
	Do nothing	Prevention	Late eradication	Prevention and early eradication
	$ million			
Public management cost	-$0	-$2.5	-$150.9	-$45.3
Public ecosystem loss	-$178.2	-$50.6	-$19.5	-$0
Private economic damage	-$20.9	-$5.9	-$1.0	-$0
Private recreational benefit	+$0.9	+$0.3	+$0.1	+$0
NPV	-$198.1	-$58.7	-$171.3	-$45.3
ΔNPV	$0	+$139.4	+$26.8	**+$152.8**

T = 20 years, r = .02

Table 7. Zebra mussel model simulation results (using HSI = .91)

	Management Alternative			
	I	II	III	IV
	Do nothing	Prevention	Late eradication	Prevention and early eradication
	$ million			
Public management cost	-$0	-$2.5	-$167.3	-$50.1
Public ecosystem loss	-$197.6	-$56.1	-$21.5	-$0
Private economic damage	-$23.2	-$6.5	-$1.1	-$0
Private recreational benefit	+$1	+$0.3	+$0.1	+$0
NPV	-$219.8	-$64.9	-$189.9	-$50.1
ΔNPV	$0	+$154.9	+$29.9	**+$169.7**

T = 20 years, r = .02