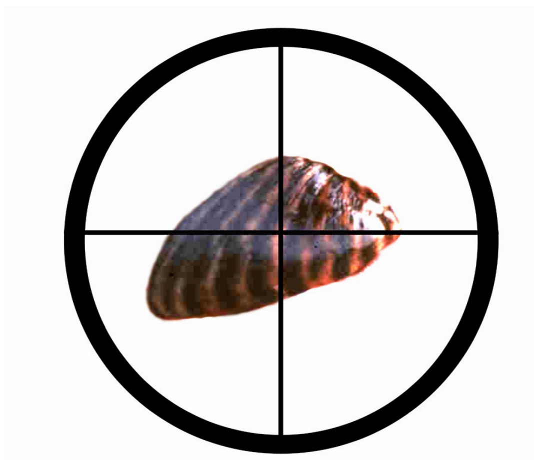
Waging War Against the Zebra Mussel

Nasreen A. Ilias
Marie C. Spong
James F. Tucker
Lewis and Clark College
Portland, OR 97219

Advisor: Robert W. Owens



Summary

We design a mathematical model that accounts for pH, calcium concentration, and food availability, the most important factors in zebra mussel reproduction and in growth and survival of juvenile mussels. Our model can predict whether a given site is likely to be a suitable environment for a zebra mussel population as well as its potential density. Our model corresponds well with the population data provided and with the threshold values of pH (7.4) and calcium (12 mg/L) for zebra mussel viability.

We recommend to the community of Lake B that they limit their use of deicing agents containing calcium, because our model predicts that an increase in

The UMAP Journal 22 (4) (2001) 399–413.

the calcium concentration in the lake will significantly enhance its suitability as zebra mussel habitat.

We find that using the goby fish to reduce zebra mussels is not a feasible option if the community is concerned with ecological impact, due to the invasive nature of the goby.

Environmental Factors in the Spread of Zebra Mussels

We first discuss the characteristics of a suitable breeding habitat and then address how the population is unintentionally introduced to new areas.

Population growth depends on successful reproduction and survival to adulthood. Veligers, zebra mussel larvae, are more sensitive to stress in their surrounding environment and therefore have more stringent survival requirements. Hence, we examine environmental conditions that can cause stress for the zebra mussel, especially in the larval and juvenile stages.

Ion Concentrations and pH

Calcium is required for the viability of zebra mussel populations because it is a major component in their shells. Alkalinity, which is directly linked to calcium concentrations, is an important variable in determining habitat suitability for zebra mussels. Calcium concentrations of 12 mg/L and alkalinity corresponding to 50 mg $CaCO_3$/L are required for adult zebra mussel populations [Heath 1993]. A calcium concentration of 12 mg/L is also the minimum required for embryo survival, though higher concentrations enhance egg fertilization and embryo survivorship [Sprung 1987].

Phosphorous and nitrogen are significant factors to zebra mussel population growth because they are critical nutrients for the freshwater phytoplankton that comprise the primary food source of the zebra mussel. Thus, they are an indirect measure of food availability [Baker et al. 1993].

The pH of the water is another critical factor. Adults require a pH of about 7.2; in lower pH environments, they experience a net loss of calcium, sodium, and potassium ions, and in very acidic waters adult zebra mussels eventually die because of ion imbalance [Heath, 1993]. Adults can survive in pH 7 environments, but eggs survive only between pH 7.4 to 9.4 [Baker et al. 1993].

Temperature

Adult mussels can survive temperatures from 0°C to 32°C, but growth occurs only above 10°C [Morton 1969] and breeding is triggered only in temperatures of at least 12°C [Heath 1993]. Higher temperatures increase overall egg production [Borcherding 1995] but also increase metabolism and demand for dissolved oxygen. Zebra mussels require 25% oxygen saturation (2 mg/L) at 25°C [Heath 1993]. Based on these values and the data provided for Lake A, we find that neither temperature nor dissolved oxygen is a limiting factor of zebra mussel proliferation there.

Saltatory Spread

Saltatory spread is the movement of a species in large leaps rather than by gradual transitions. It is believed that zebra mussels were introduced to the Great Lakes system in 1986 from larvae discharged in ballast water from a commercial ship [Griffiths et al. 1991]. As of 1996, zebra mussels had spread to 18 states in the United States (as far south as Louisiana) and two provinces in Canada, almost entirely within commercially navigated waters [Johnson and Padilla 1996]—strong evidence that commercial shipping was the primary vector of initial zebra mussel spread in the United States and Canada.

Most of the United States contains environments suitable for zebra mussel infestation [Strayer 1991], so the identification and elimination of saltatory spread to inland water systems is key to preventing infestation of the western United States. Transient recreational boating seems to be the most likely candidate for inland spread of the species. Based on this and other studies, it appears that recreational boating represents a substantial threat to the containment of the zebra mussel infestation in America.

Advective and Diffusive Spread

Zebra mussels live the first few weeks of their lives as planktonic larvae that are easily diffused or carried by moving water. This allows for the widespread dissemination of offspring by diffusion, currents, and wind-driven advection within a lake or watershed [Johnson and Carlton 1996], which largely explain the species rapid spread [Martel 1993]. However, veligers have been shown to have high mortality in turbulent waters, and mussel density in streams flowing out of infested lakes has been shown to decrease exponentially with the distance downstream [Horvath and Lamberti 1999]. Post-metamorphic zebra mussels have the ability to secrete long monofilament-like mucous threads that increase hydrodynamic drag and allow for faster advective spread [Martel 1993]. These juveniles can survive turbulence much better than veligers, which implies that they are the primary vector of downstream advective spread.

Zebra Mussel Population Model for Lake A

Using our model, we attempt to answer two important questions:

1. Given chemical information for a given site, is the site suitable for zebra mussels?

2. If a site is determined to be a suitable habitat, will it support a low- or a high-density zebra mussel population?

Rather than focusing on developing a complicated model that would predict the exact size of the population, we devised a simple, comprehensive model that answers these questions. The inspiration for our model was derived from Ramcharan [1992].

Assumptions

- The density of juveniles collected on the settling plates is proportional to the size of the adult population; this assumption allows us to use the provided data to predict the severity of the zebra mussel infestation.
- The chemical composition and concentrations (such as calcium levels) do not significantly vary with changes in the size of the zebra mussel population.

Examining the first data set from Lake A, we find that pH and calcium concentration are the two most important factors in determining whether a zebra mussel population is viable in a given site. This is reasonable, considering that the zebra mussels are very sensitive to pH and they need calcium to build their shells when developing from veligers to juveniles and onto adults.

We do not include temperature, because although it is important to the life cycle of the zebra mussel, as long as the temperature is high enough to signal spawning, reproduction will occur. All 10 sites in Lake A had suitable temperatures for spawning.

We developed a model equation (Model 1) utilizing the values provided for pH and calcium concentration for the 1992 to 1999 period that give a simple measure to predict the viability (V) of a zebra mussel invasion at a particular site. The coefficients of the two variables (pH and [Ca]) are used to weight the relative importance of the two factors. The range of values for pH for the ten sites is smaller than the range of values for calcium concentration, thus the coefficients function to equalize the importance of these two factors. The exact values of the coefficients were determined by successively modifying and refining the values until an equation was found that accurately reflected whether the lake site was a suitable habitat or not based on the population data. We chose the threshold value of 10.4 for viability because there appears to be a break there between the sites where zebra mussels survived and the sites where they were absent, and because 10.4 is close to the value from the equation with 7.4 for pH and 12 mg/L for calcium concentration.

$$V = 1.0\,\mathrm{pH} + 0.2\,[\mathrm{Ca}]$$

If $V > 10.4$, the site is a suitable habitat for zebra mussels.

Applying Model 1 to sites 1–10 in Lake A produces **Table 1**.

Table 1.

Calculated viability values for sites 1–10 in Lake A using model 1.

Site	pH	[Ca] mg/L	V
1	7.68	26.8	13.04
2	8.00	22.3	12.46
3	7.74	17.6	11.26
4	7.84	16.5	11.14
5	8.02	16.9	11.40
6	7.59	13.4	10.27
7	7.66	16.9	11.04
8	7.82	16.6	11.14
9	7.95	15.7	11.09
10	7.86	12.0	10.26

The model predicts that sites 6 and 10 should not be suitable habitats, while the other eight sites should be. **Figure 1**, which plots date vs. juveniles/day for each of the sites, shows that the data agree well with our model. Sites 6 and 10 have virtually no zebra mussel population growth, and sites 1, 2, 3, 4, 5, and 9 all show evidence of infestation. Although it is predicted that sites 7 and 8 should be susceptible to invasion, enlargement of **Figure 1** shows that these two sites are not supporting large populations; correspondingly, V for sites 7 and 8 is relatively low. Also, the source of the zebra mussel invasion was site 1, hence the more southerly sites have had longer to form stable populations than the northern sites 7 and 8. With threshold pH of 7.4 and threshold calcium level of 12 mg/L, the model—which predicts that sites 6 and 10, whose values border on the threshold, are not likely to be habitable—is consistent with the literature.

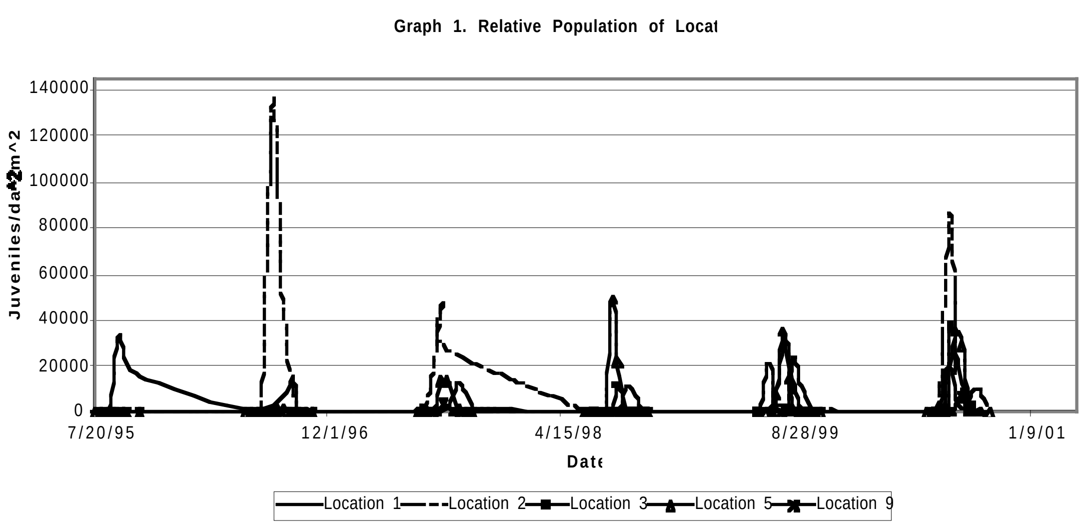


Figure 1. Relative populations at sites 1–10.

To improve upon Model 1, we account for trends observed in the second data set from Lake A in constructing a more descriptive model to answer question (2). By including parameters for total phosphorus and total nitrogen, we account for the role of food availability on density. Following Ramcharan [1992], we employ the natural logarithms of total phosphorus and total nitrogen. Once again, by successively altering the coefficients, we determine an equation for the density of populations in the lake sites. We define high density as more than 400,000 juveniles / m^2 on the settling plates collected at the peak of the reproductive season.

$$D = 1.0\,\mathrm{pH} + 0.2\,[\mathrm{Ca}] + 0.1 \ln\,[\mathrm{TP}] + 0.4 \ln\,[\mathrm{TN}].$$

$$\text{If}\ \begin{cases} D < 9.9, & \text{there will be no zebra mussels;} \\ 10 < D < 10.4, & \text{the site will support a low-density population;} \\ D > 10.5, & \text{the site will support a high-density population.} \end{cases}$$

By averaging the total phosphorus (TP) and total nitrogen (TN) values for each site in the second set of chemical data for Lake A, we calculated [TP] and [TN]. Using those values in Model 2, we calculated the density (D) for each site, as shown in **Table 2**.

Table 2.

Density values in sites 1–10 in Lake A.

site	ln[TP] mg / L	ln[TN] mg / L	D	low / high
1	−2.99	−0.598	12.5	high
2	−3.51	−0.892	11.8	high
3	−4.30	−0.796	10.5	high
4	−4.47	−0.814	10.3	low
5	−4.40	−0.879	10.6	high
6	−4.56	−0.852	9.5	absence
7	−4.12	−0.971	10.2	low
8	−4.39	−0.862	10.3	low
9	−4.16	−0.965	10.3	low
10	−3.01	−0.405	9.8	absence

Model 2 predicts that sites 1, 2, 3, and 5 should be able to support high density populations. The second set of population data used in **Figure 2** is consistent with the first set of population data. **Figure 2** shows that all four of the high-density sites have an average of more than 400,000 juveniles / m^2, which agrees with the prediction made by our model. In the enlargement of **Figure 2**, sites 4, 7, 8, and 9 have an average of less than 400,000 juveniles / m^2, while sites 6 and 10 have virtually no juvenile zebra mussels.

The most significant weakness of our model is that it does not predict population versus time. Our model simply classifies an area's risk of invasion by examining the levels of critical chemicals to which the zebra mussels are sensitive.

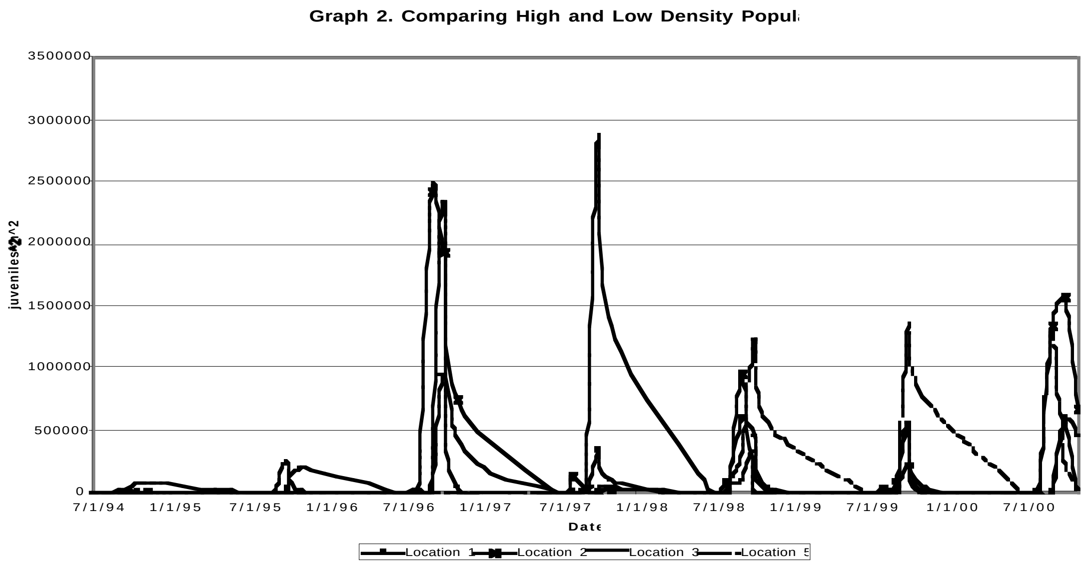


Figure 2. Comparison of high- and low-density populations.

Another weakness of our model is that it relies on chemical and population data from only one lake. By slightly varying the values of the coefficients and observing whether the altered model more accurately predicts the density of the zebra mussels in the newly incorporated lakes, a better model can be achieved. Information from other lakes could also be used to refine the value chosen for the division between low and high densities. Other factors, such as total ion concentration, could also be included in the model if the factor were shown in a variety of lakes to correspond to population densities.

We are not able to predict, using our model, how fast a population of zebra mussels will spread from one site to another within a lake. However, by qualitatively examining the data from Lake A, it appears to take only a few years for the population to spread from one area to another as long as the new site is suitable for zebra mussels. For example, in site 5 in 1994 and 1995, there were no zebra mussels collected, but from 1996 to 1998, the population rapidly increased to a high density. Since zebra mussels can very quickly reach high density populations in a supportive environment, it seems that knowing whether a given site is a suitable habitat is a more useful piece of information than the rate at which the population grows.

Using Model for Lake A to Predict for Lake B and Lake C

Using the equations from our models, we can average pH, calcium concentration, total phosphorus concentration, and total nitrogen concentration for

Lake B and Lake C and determine the level of risk of successful zebra mussel invasion in these two lakes. We averaged the values together for all of the years. We also assume that these two lakes are fairly uniform in chemical composition.

Table 3.

Viability and density values for Lake B and Lake C.

	pH	[Ca] mg/L	[TP] mg/L	[TN] mg/L	V	D
Lake B	7.63	11.5	6.02×10^{-3}	0.182	9.93	8.74
Lake C	4.74	1.15			4.97	

According to our Model 1, Lake B should not be at risk for a zebra mussel invasion because it is not a suitable habitat ($V < 10.4$); this prediction makes sense because the average calcium concentration is 11.5 mg/L, which is below the 12 mg/L threshold. Lake C is in no danger to an invasion, since $D = 4.97$, which corresponds to the fact that both the pH and the calcium concentration are far below the threshold values.

De-icing Policy for Community of Lake B

De-icing compounds increase the solute concentration in the melted ice, lowering its freezing temperature and preventing the ice from reforming. Thus, de-icing compounds are water soluble and can easily enter the water supply. The most commonly used de-icers are calcium chloride, calcium magnesium acetate, sodium chloride, and potassium acetate salts. Calcium magnesium acetate is popular because it has fewer negative environmental impacts, whereas calcium chloride is widely used because it lowers the freezing point of water more than sodium chloride.

Although these calcium containing compounds may be excellent choices for de-icing agents, our model indicates that using these compounds increases the risk of zebra mussel invasion. According to Model 2, if calcium levels increase in Lake B by 50% ($D = 9.9$), a low density population of zebra mussels can exist. Doubling the calcium levels ($D = 11.0$) will support a high density population. De-icing agent can therefore have a significant impact on the zebra mussel population. *We recommend that this community use sodium chloride or potassium acetate salts*, or decrease the amount of calcium salts used by mixing them with the other noncalcium salts or sand. We also suggest pre-wetting the salts before they are applied to the roads, to reduce the amount entering the water system. Lastly, the community should develop a strategy for anti-icing, applying de-icing agents before ice forms, thus decreasing the amount of de-icing agent used in each storm. These efforts should help prevent Lake B from becoming habitable by zebra mussels.

Methods for Reducing Zebra Mussel Populations

It is estimated that $3 billion will be spent in the next decade combating the zebra mussel infestation [Magee et al. 1996]. Besides damaging infrastructure (pipes, tubing, gratings), the zebra mussel is able to out-compete native species for space and food and can destroy commercial and recreational fish stocks. Since the zebra mussel body fat stores toxic chemicals, the introduction of these mussels into the food-chain could lead to human consumption of these harmful chemicals. There are three available options for dealing with zebra mussel infestation:

(1) Introduce a natural predator (the round goby).

(2 & 3) Eradicate and / or control the zebra population by utilizing preventative and reactive control strategies.

Introducing a natural predator, such as the round goby, may be more problematic than the zebra mussel infestation. Although the round goby shows selectivity in consuming zebra mussels over native clams, the goby will non-selectively consume a variety of bait, fishes, and invertebrates [Ghedotti et al. 1995]. In addition, the goby is extremely territorial and can aggressively occupy prime breeding areas and successfully compete for food against native species. Fortunately, there are more environmentally sound methods of controlling zebra mussel infestations.

Preventive and Reactive Strategies

Preventive control methods include implementing restrictive legislation and periodic monitoring of waterways to minimize introduction of zebra mussels and to improve early detection, thereby facilitating the development of appropriate strategies to eradicate or control the mussel population. Reactive strategies are a more aggressive mode of action in response to a potential or ongoing invasion and should be dependent on the level of infestation.

Preventive Control Strategies: Legislation and Monitoring

Legislation is a useful way to coordinate research with monitoring facilities, commercial industries, and the public. The United States Nonindigenous Aquatic Nuisance Prevention Control Act of 1990 (P.L. 101–646) [Florida Caribbean Science Center 2001] recommends that recreational vessels exchange ballast water before entering new waters, since this is the primary mode of saltatory non-native species introduction [Boleman et al. 1997]. In addition, the U.S. Code [Legal Information Institute 2001] suggests implementing alternative ballast water management, including modifying the ballast tank and intake system to prevent the unintentional introduction of new species. The improved sighting, reporting, and education under this plan will help the public and commercial sectors prevent the spread of zebra mussels.

Reactive Control Strategies

Acute Zebra Mussel Infestation In cases of acute or localized infestations, applying the least expensive method of preventing infrastructure damage is to employ a *foul release coating* in concert with mechanical cleanings and mechanical filtration. Coating pipes and surfaces in contact with the water with antifouling polymers, such as silicones and fluorochemicals, creates a slippery surface that makes it difficult for zebra mussels to attach [Magee et al. 1996]. These reagents are effective for 2–5 years [Boelman et al. 1997].

An alternative and equally successful method of infrastructure protection is the application of *zinc thermal spray* (ZTS) on metal surfaces. In addition to preventing corrosion, ZTS is the most durable and long-lasting zebra mussel repellent. The slow dissolution of heavy metal ions from ZTS is toxic to zebra mussels. In addition, the US Army Corps of Engineers Zebra Mussel Control Handbook suggests that low release of heavy metals and a large dilution factor produce minimal secondary effects on nontarget species. However, before implementing this strategy, it is critical that the environmental effects studied and the implementation meet federal standards.

Mechanical cleaning is a labor-intensive method of removing zebra mussel from infrastructure. The drawback to simply brushing and scraping zebra mussels off surfaces is that the scrubbings need to be repeated regularly. The removed zebra mussels also have to be transported and disposed of in landfills.

The final strategy for dealing with acute zebra mussel infestation is installing *mechanical filtration systems*. Water screen filters and strainers can be placed on water intakes. A mesh size of 25–40 mm is able to stop the inflow of veligers and translocation of larger zebra mussels. However, this system requires continuous maintenance.

Global Zebra Mussel Infestation Severe and large-area infestation and population expansion need to be treated with aggressive methods, since it is more beneficial to address the widespread infestation problem rather than fight specific site-related mussel-density problems. Since these methods require widespread application, the expense associated with implementation is higher than the strategies for dealing with acute infestation. There is also a potential for harming native organisms and commercial industries. However, after intense scrutiny, the following methods are the most effective ways to control and potentially eradicate severe zebra mussel infestations.

Thermal treatment. The discharge of heated water is a cost-effective and efficient method for controlling and eradicating the macrofouling zebra mussel. Since zebra mussels are able to acclimate to temperature changes, extreme temperature changes are required to kill the mussels. These extreme temperature changes will also kill a number of native species residing in the lake. There are two thermal treatment strategies that can be employed: acute thermal treatment and chronic thermal treatment [Boelman 1997]. Acute thermal treatment involves rapidly increasing the water temperature to lethal levels followed by a rapid return to original temperature levels. This method is most appropriate for treating infestation in waterways where a higher temperature cannot be maintained for an extensive period of time. Greatly increasing the water temperature for a period of 3–9 hours can yield 100% mortality.

Chronic treatment involves continuously maintaining a higher water temperature and is a cost-effective strategy for industries that generate and discharge heated water. This method prevents new zebra mussel infestations. This strategy is lethal to most if not all organisms that use the water. The water temperature, in this method, must be raised to greater than or equal to 34°C and must be maintained for 6–24 hours to kill the entire zebra mussel population.

Chemical treatments. Chemical treatments are an alternative to thermal treatment but are more environmentally invasive. Both oxidizing and nonoxidizing chemical treatments are available. Oxidizing treatments are most toxic to zebra mussels when applied rapidly due to the mussel's sensitivity to oxidizing compounds, whereas nonoxidizing chemicals can be administered over a longer period of time with equal effectiveness.

Of the oxidation treatments available, *chlorination* is the most widely used method for eradicating zebra mussels. There are large environmental consequences to this method, and terrestrial organisms and birds may also be killed.

Potassium permanganate is another commonly used oxidizing chemical. To obtain 100% zebra mussel mortality, a higher concentration of and a longer exposure to potassium permanganate is required than for chlorinated compounds. The advantage to using potassium compounds is that they are nontoxic to higher organisms like fish but are highly toxic to zebra mussels. Also, potassium permanganate by-products do not form carcinogenic compounds as is the case when using chlorinated reagents.

Nonoxidizing molluscicides, such as Mexel 432, are the best available chemical treatments, albeit more expensive than oxidation treatments. The greatest advantage to this strategy is that molluscicides have fewer direct consequences on native organisms and fewer long-term environmental impacts since many of these molluscicides rapidly biodegrade into harmless substances. These reagents induce their effect in three ways:

- On clean surfaces, the film prevents settlement.
- On infested surfaces, the molluscicides attack the zebra mussel byssal threads, causing the mussels to detach.

- The molluscicides form a film on zebra mussels that remain in the system, causing lesions on the gill and ultimately killing the organism. For this reason molluscicides are also lethal to other mussels. Application of these chemicals needs to be repeated on a daily basis to sustain the film until all zebra mussels are killed.

Future species-specific treatments. Although target-specific chemicals are not currently available, research is developing methods for targeting invasive species and interfering specifically with their reproduction cycle through biochemical compounds like serotonin. These targeted treatments would be highly advantageous in terminating zebra mussel propagation without affecting other aquatic organisms or damaging the environment.

Response to Community Leaders

For such small critters, zebra mussels can range from being a mild nuisance to a large environmental and economic cost. The introduction of these species into our lakes and rivers has created situations where communities are forced to control or eradicate zebra mussel populations. The most important question is how to do this in the most environmentally and economically sound manner. In order to develop a solution for this irritating infestation problem, we must first assess how extensive the problem is. We must identify

- how the zebra mussels were or are being introduced to the lake,
- if the lake provides a supportive environment for zebra mussels, and
- if there other aquatic organisms or terrestrial organisms (including humans!) that depend on the lake or use it as a food source.

Isolating the source of zebra mussel introduction to the lake is important so that the community can prevent reintroduction of the mussel or other nonnative species that are a threat to indigenous aquatic organisms. This preventive measure will contribute to making the reactive strategies for controlling the zebra mussel invasion more successful and therefore more cost effective.

There are two types of reactive control strategies that can be implemented:

- introduction of a natural predator to the lake system or
- the use of mechanical or chemical methods to control or eradicate the zebra mussel population.

Introducing a natural zebra mussel predator, such as the round goby fish, to the lake system can be a cost-effective and simple solution to the infestation problem. However, if the lake sustains other aquatic organisms or is used by commercial industries (such as fishing), the costs associated with introducing the goby may be much higher. The goby is an aggressive territorial fish that prefers zebra mussels but will nonselectively consume bait, fish, and invertebrates. As a consequence, the goby can destroy fishing stocks and out-compete native species for food.

Another alternative is the use of mechanical or chemical strategies to control the zebra mussel population. For mild to moderate infestation, the following strategies are effective:

- Mechanical cleaning of pipes and surfaces exposed to water, followed by coating these surfaces with foul release coating. This coating contains environmentally sound antifouling polymers such as silicones and fluorochemicals, which create a slippery surface making it difficult for zebra mussels to attach.

- Installing simple mechanical filtration systems requires periodic maintenance but effectively prevents zebra mussels from clogging intake pipes.

Severe infestation requires more aggressive and environmentally abrasive strategies to control the zebra mussel population. Both of the following strategies are more expensive than the two methods discussed above and have more extensive environmental impacts.

- Thermal treatment is the discharge of heated water into the lake system. The water temperature can be raised rapidly (acute treatment) or slowly for an extended period of time (chronic treatment). In either case, 100-percent of the zebra mussels can be killed. However, this method kills most other aquatic organisms as well.

- An equally effective method is treating the lake with chemicals. There are two viable options in this approach. The first is using chlorinated compounds, which in a short duration will kill the entire zebra mussel population, as well as many other aquatic organisms and even birds. The drawback of this approach is the production of carcinogenic by-products that may remain in the environment for an extended period of time. A better alternative to chlorinated compounds is potassium permanganate. This chemical must be applied at larger concentrations for a longer period of time to kill mussels (including native species) without harming other organisms.

With any environmental problem, a balance has to be reached between the needs of the community and the effects on the environment. The community will have to weigh carefully the problems caused by the zebra mussels with both the economic and environmental costs associated with each method of removal.

References

Baker, P., S. Baker, and R. Mann. 1993. Criteria for predicting zebra mussel invasion in the mid-Atlantic Region. School of Marine Science, Virginia Institute of Marine Science.

Boelman, S.F., F.M. Neilson, E.A. Dardeau, Jr., and T. Cross. 1997. Zebra mussel (*Dreissena polymorpha*) control handbook for facility operators. Miscellaneous Paper EL-97-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, 1997.

Borcherding, J. 1995. Laboratory experiments on the influence of food availability, temperature and photoperiod on gonad development in the freshwater mussel *Dreissena polymorpha*. *Malacologia* 36 (1–2): 15–27.

Florida Caribbean Science Center, Biological Resources Division of the United States Geological Survey, Department of the Interior. 2001. Nonindigenous Aquatic Nuisance Prevention and Control Act of 1990 (P.L. 101-646). `http://nas.er.usgs.gov/control.htm` .

Ghedotti, M.J., J.C. Smihula, and G.R. Smith. 1995. Zebra mussel predation by round gobies in the laboratory. *Journal of Great Lakes Research* 21 (4): 665–669.

Griffiths, R.W., W.P. Kovalak, and D.W. Schloesser. 1991. The zebra mussel, *Dreissena polymorpha* (Pallas, 1771), in North America: Impact on raw water users. In *Proceedings: EPRI Service Water System Reliability Improvement Seminar*, 11–27. Palo Alto, CA: Electric Power Research Institute.

Heath, R.T. 1993. Zebra mussel migration to inland lakes and reservoirs: A guide for lake managers. Kent State University, Ohio: Sea Grant College Program.

Horvath, T.G. and G.A. Lamberti. 1999. Mortality of zebra mussel, *Dreissena polymorpha*, veligers during downstream transport. *Freshwater Biology* 42: 69–76.

Johnson, L.E., and J.T. Carlton. 1996. Post-establishment spread in large-scale invasions: Dispersal mechanisms of the zebra mussel. *Ecology* 77 (6): 1686–1690.

Johnson, L.E., and D.K. Padilla. 1996. Geographic spread of exotic species: Ecological lessons and opportunities from the invasion of the zebra mussel *Dreissena polymorpha*. *Biological Conservation* 78: 23–33.

Legal Information Institute. 2001. U.S. Code, Title 16, Chapter 67, Subchapter I, Sec. 4701: Findings and purposes. `http://www4.law.cornell.edu/uscode/16/4701.html` .

Magee, J.A., D.A. Wright, and E.M. Setzler-Hamilton. 1996. Penaten to control zebra mussel attachment. The University of Maryland System, Center for Environmental and Estuarine Studies.

Martel, A. 1993. Dispersal and recruitment of zebra mussel (*Dreissena polymorpha*) in a nearshore area in west-central Lake Erie: The significance of postmetamorphic drifting. *Canadian Journal of Fisheries and Aquatic Science* 50: 3–12.

Morton, B.S. 1969. Studies on the biology of *Dreissena polymorpha* Pall. III. Population dynamics. *Proceedings of the Malacological Society of London* 38: 471–482.

Ramcharan, C.W., D.K. Padilla, and S.I. Dodson. 1992. Models to predict potential occurrence and density of the zebra mussel, *Dreissena polymorpha*. *Canadian Journal of Fisheries and Aquatic Sciences* 49: 2611–2620.

Sprung, J.M. 1987. Ecological requirements of developing *Dreissena polymorpha* eggs. *Archiv für Hydrobiologie* 79 (Suppl.) 69–78.

Strayer, D.L. 1991. Project distribution of the zebra mussel, *Dreissena polymorpha* in North America. *Canadian Journal of Fisheries and Aquatic Sciences* 48: 1389–1395.